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A novel technique for measuring the rate of turbulent dissipation in the marine environment

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[1] We present a new technique for the estimation of profiles of the rate of dissipation of turbulent kinetic energy (ε, TKE) in the marine environment using a standard acoustic Doppler current profiler (ADCP). The technique is based on the structure function method used in radar meteorology. The new method is validated through comparisons of ε estimates from a structure function with simultaneous measurements of profiles of ε made using a freefall profiler, and estimates of the rate of production of TKE using the ADCP variance method. There is a good agreement between the estimates, although some differences in absolute values. A difference in ε estimates between the upstream and downstream beams is attributed to the presence of a significant Reynolds stress.
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1. Introduction

[2] Vertical exchange driven by turbulent mixing is a key process in determining momentum and heat fluxes and material transport pathways in the marine environment. In recent years, our ability to measure a turbulence parameter, the rate of dissipation of turbulent kinetic energy, ε, has led to major advances in our understanding of the vertical exchange processes and their parameterization [*Burchard et al.*, 1998; *MacKinnon and Gregg*, 2003; *Sharples et al.*, 2001; *Simpson et al.*, 1996]. These advances have largely been based on profile measurements made using loosely tethered micro-structure profilers. The major drawback of this type of measurement is that they are labor intensive and require a dedicated ship. Data sets thus tend to be sparse, intermittent and rarely exceed one or two days duration.

[3] Measurements of Reynolds stress and turbulence parameters over limited spatial scales (single point to O(m)) have been made close to the sea bed using small-scale probes such as electro-magnetic current meters [*Bowden and Fairbarn*, 1956; *Heathershaw*, 1979] and acoustic Doppler velocimeters [*Kim et al.*, 2000]. Recently, acoustic Doppler current profilers (ADCPs) have been applied to the more challenging task of making remote estimates of turbulence parameters extending into the interior of the flow. *Gargett* [1999] used an instrument modified with a fifth, vertically orientated, beam to estimate ε by applying a large-eddy technique to the vertical beam measurements. *Lorke and Wüest* [2005] use conventional acoustic Doppler profilers to estimate ε in a low energy limnic environment employing an inertial dissipation technique. The rate of production of turbulent kinetic energy (P) is readily estimated from the velocity variance of opposite ADCP beams using the variance method [*Howarth and Souza*, 2005; *Lu and Lueck*, 1999; *Rippeth et al.*, 2002; *Stacey et al.*, 1999], when the ADCP sensors are carefully levelled.

[4] In this paper we explore the possibility of adapting a structure function method developed by radar meteorologists for the measurement of ε in the atmosphere [*Lhermitte*, 1968; *Sauvageot*, 1992] to the marine environment. The structure function method uses the turbulent cascade theory of Kolmogorov which relates the spatial correlations of velocity to the turbulent kinetic energy (TKE) dissipation rate. This technique differs from that proposed by *Gargett* [1999], which uses a vertical eddy resolving approach combined with Taylor scaling, and that proposed by *Lorke and Wüest* [2005], which employs a temporal spectra fitting approach.

[5] We report the results of two experiments in which velocity measurements were made using a conventional four beam ADCP. In the first experiment, we compare profiles of ε made using the structure function technique with simultaneous measurements of ε using a free fall profiler and with estimates of P made by applying the variance technique to data collected from a conventional bed mounted ADCP in Red Wharf Bay in the Irish Sea. The second set of measurements were made using a four beam ADCP deployed in an energetic tidal channel, the Menai Strait, North Wales.

2. Method

2.1. Theory

[6] A second order structure function $D(z, r)$ can be defined at a location z using the velocity, v', with the temporal mean removed, such that,

$$D(z,r) = \overline{(v'(z) - v'(z+r))^2} \quad (1)$$

$D(z,r)$ is the mean-square of the velocity fluctuation difference between two points separated by a distance r. The velocity difference between two points separated by r is largely due to eddies with a length scale comparable to r and an associated velocity scale of s' (which is thus a function of r and z). i.e.

$$D(z,r) \sim s'^2 \quad (2)$$

[7] The Taylor cascade theory relates the characteristic length scale and characteristic velocity scale of isotropic turbulent eddies in the inertial sub range with the dissipation

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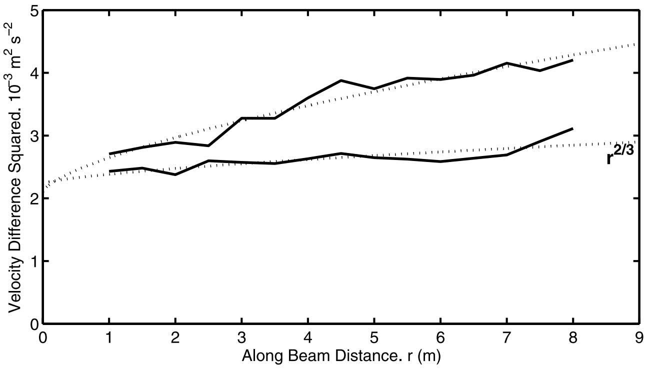

Figure 1. The $r^{2/3}$ fit on along beam ADCP data. The dotted lines are the polynomials from equation 5 fitted to along beam velocity data from a 2s ensemble (bold lines). The x-intercept relates to the variable N from Equation 5, which accounts for the inherent Doppler noise in the velocity measurement. The upper line has a greater slope than the bottom line and therefore gives a higher dissipation estimate.

rate ε of the turbulent regime containing the turbulent eddies as [*Gargett*, 1999]

$$\varepsilon \sim \frac{s'^3}{r} \tag{3}$$

i.e.

$$D(z, r) = C_v^2 \varepsilon^{2/3} r^{2/3} \tag{4}$$

where C_v^2 is a constant, which in atmospheric studies has been found to be between 2.0 and 2.2 [*Sauvageot*, 1992].

[8] Equation 4 will hold for values of r within the inertial sub-range, i.e. $l_K \ll r \ll l_O$ where l_K is the scale of dissipation (Kolmogorov microscale) and l_O is the vertical scale of the largest energy containing eddies (Ozmidov scale in stratified flow).

2.2. Data Processing

[9] For each acoustic beam the along beam component of the water velocity is estimated from the Doppler shift in the return signal for a series of heights above the transducer. The water column is divided into depth bins and the along beam velocity is calculated for each bin from a 1 or 2 second ensemble average (depending on the dataset). The time series for each bin is then averaged over a period long enough to give statistical reliability but short enough that the time series can be assumed stationary. For the instrument setup and semidiurnal tidal conditions at the locations of interest, a 10 minute averaging period is selected. The temporal mean is then subtracted for each bin, leaving the turbulent velocity fluctuations, v'.

[10] A 'centered difference' technique is then used to obtain the turbulent velocity difference for each height bin of each acoustic beam. The turbulent velocity differences are squared and then averaged over 10 minutes to obtain $D(z, r)$ (from Equation 1). Differences between adjacent bins are discarded as the velocities are not totally independent as a consequence of the weighted average used in the RDI ADCP signal processing software [*RDInstruments*, 1996]. The fundamental limitations on r at the lower end is the Kolmogorov microscale (i.e. for a low limit of dissipation of 10^{-6} W m^{-3}, the Kolmogorov dissipation scale is $\approx 5 \times 10^{-3}$ m, i.e. more than an order of magnitude smaller than the smallest possible bin size using current coherent Doppler technology). At the upper end the limitation is the Ozmidov scale (in a stratified environment) and the minimum distance to the boundary (in a homogeneous environment). The value of $r^{2/3}$ fitted to the data is limited to a length comparable to the largest eddies in the inertial subrange. To examine the sensitivity of the technique to the maximum value of r, the data was tested with a number of maximum values for r, ranging from 4 to 12 m (in the vertical). The results of this sensitivity analysis show a small increase in estimates of ε with increased r by $\sim$10% per metre for the up and downstream beams, and by $\sim$4% for the beams oriented transverse to the mean flow. In a stratified environment, estimates of ε would be expected to decrease as r approaches the Ozmidov scale. However, in a well mixed environment such as those studied here, the greater vertical averaging increases the accuracy of estimates of ε.

[11] The mean squared velocity difference $D(z, r)$ is then fitted to an equation of the form,

$$D(z, r) = N + Ar^{2/3} \tag{5}$$

(see Figure 1) in order to find a value for A. N is an offset which represents an uncertainty due largely to inherent Doppler noise and other errors in the ADCP velocity estimates (or due to non-turbulent velocity fluctuations, e.g. waves). Assuming that the uncertainties in the along beam velocities can be accounted for by a variance, σ_N^2, which is independent of height, then the noise will be independent of the range r and the offset will be $N = 2\sigma_N^2$. The uncertainty in the ADCP estimates will be dependent on the system frequency, number of pings, bin size and other system variables.

[12] Defining coefficient A as;

$$A = C_v^2 \varepsilon^{2/3} \tag{6}$$

(where C_v^2 = 2.1, a value used in radar meteorology [*Sauvageot*, 1992]) from which ε is readily obtained, thus providing estimates of ε and the uncertainty in the along beam velocity estimate ($N = 2\sigma_N^2$).

3. Results

[13] The first data set was collected from Red Wharf Bay off the north coast of Anglesey at a site (53°22.8′N, 4°12.5′W), where the water depth ranged from 19 m at low water to 25 m at high water, and there is a rectilinear tidal flow and maximum currents of order 1 m s^{-1}. The water column was homogeneous throughout most of the observational period with weak stratification in the upper part of the water column around low water. The location was selected as having a flat bottom and being far from any major topographic features so that, to a first order, a local equilibrium between the rates of production and dissipation of TKE can be assumed (i.e. $\varepsilon \approx$ P).

[14] A self contained 1200 kHz RDI workhorse ADCP deployed on a rigid bed frame was set up with a 1 m vertical bin size and 'pinged' at a rate of 2Hz. The data were ensemble

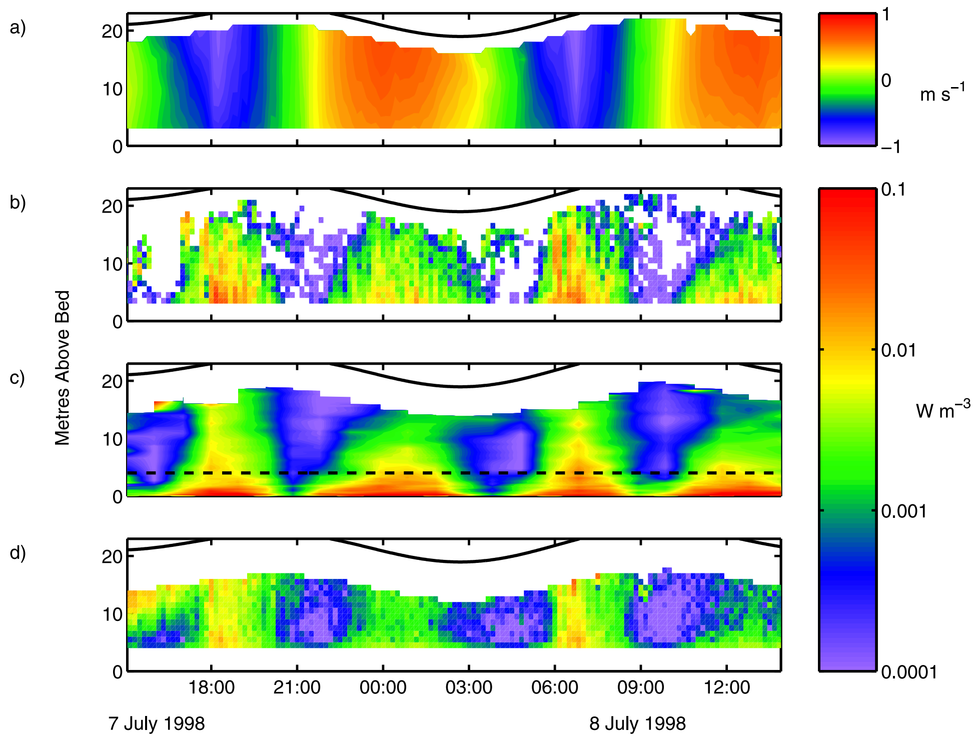

Figure 2. Data collected in Red Wharf Bay: (a) the along stream component of velocity (+ve towards 321°T), (b) TKE shear production rate using the ADCP variance method (c) TKE dissipation rate (ε) from FLY profiles. (d) TKE dissipation rate (ε) from the structure function method (Equation 6). The white gaps indicate no or unreliable estimates. The dashed line in Figure 2c indicates the lower boundary of the structure function estimates. Note the restricted ADCP range near bed and near surface due to the instrument blanking interval and the mounting.

averaged over 2 seconds (i.e. 4 pings). Beam 3 of the ADCP was orientated to the northeast and aligned parallel to both the local coastline and the main component of tidal flow. The ADCP pitch angle (beams 3 and 4) was initially 3.5° but settled to $\sim$1° for the second tidal cycle of the deployment. The instrument roll (beams 1 and 2) was less significant (0.5°). A Fast-Light-Yoyo (FLY) microstructure profiler was operated from the *RV Prince Madog* for a period of 24 hours. The loosely tethered FLY profiler falls through the water column at a speed of 0.7–0.8 m s^{-1} while measuring shear data on a scale of $\sim$1.5cm from which ε is estimated. During each hour of the observations 10–12 FLY profiles were made (full experimental details are given by *Rippeth et al.* [2003]).

[15] For this first deployment, the separation r was limited to an along beam distance of 5.3m, which corresponds to a vertical distance of 5 m. This limiting scale was shortened near the boundaries so that the distance between differenced bins was always less than the distance from the centre bin to the boundary. These limiting scales are within the fundamental limitations on r as stratification was weak. An averaging period of 10 minutes is used.

[16] Estimates of P and ε from the ADCP along beam velocity data and ε from velocity microstructure are shown in Figure 2. The flow is predominantly a result of a rectilinear semidiurnal tide which consists of a short, strong flood phase, with velocities up to 0.85 m s^{-1}, and a longer slower ebb phase, with maximum velocities of 0.65 m s^{-1}. The TKE production rate (P) varied with a quarter diurnal frequency and a maximum P which coincided with the strongest flow. Production was highest near the bed where the Reynolds stress and shear is largest. No P estimates are available below 4 mab due to the height of the bed mounting frame and the ADCP blanking interval. Maximum values for production rate of 5 $\times$ 10^{-2} W m^{-3} are estimated during peak flood tide, while on the ebb tide the maximum value was 1 $\times$ 10^{-2} W m^{-3}. The values of P decrease by an order of magnitude over the first 10 m above the bed. The threshold for the TKE production estimates due to noise is estimated to be of the order 5 $\times$ 10^{-4}W m^{-3} [*Rippeth et al.*, 2003] and so P estimates are not reliable in the upper part of the water column around slack water. The velocity microstructure measurements indicate that the dissipation rate follows a similar quarter diurnal pattern with stronger dissipation on the flood phase of the tide than the ebb. The FLY profiler makes reliable measurements across much of the water column (from $\sim$5 m below the surface to 0.15 m above the bed) and hence samples the higher dissipations close to the bed. The maximum value of dissipation observed in this region is about 10^{-1} W m^{-3}. The noise threshold of the FLY profiler is estimated to be $\sim$10^{-6} W m^{-3}.

[17] A logarithmically average value of ε using the structure function method for all 4 beams is shown in Figure 2d. The evolution is qualitatively similar to the velocity microstructure estimates of ε and the ADCP production rate estimates. The microstructure and structure function ε profiles track each other reasonably well. However, comparisons of ε for the different acoustic beams (Figure 3) show that the upstream facing beam consistently gives a higher estimate of

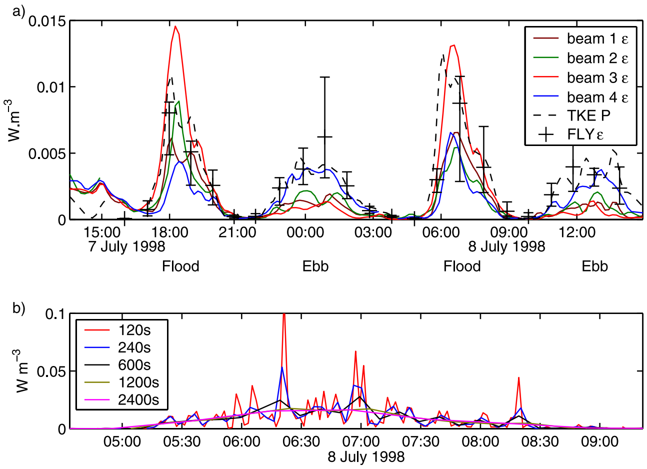

Figure 3. (a) The dissipation and production values at 7.5 metres above bed. As measured by the structure function method each of the 4 beams, the variance method and the FLY profiler (black crosses – 95% confidence intervals are also shown). The ADCP data has had a 30 minute moving filter passed over it. (b) Dissipation estimated from beam 4 using different averaging periods.

the TKE ε than the downstream beam (by a factor of up to 3). For example, during the flood tides (6th July 1700–2100 and 7th July 0500–0900), beam 3 is pointing upstream and beam 4 is directed downstream with $\varepsilon_3 > 3\varepsilon_4$. The ε estimates made from beams 1 and 2 (the beams which are orientated perpendicular to the flow) lie between those estimated using beams 3 and 4. The sensitivity of the ε-estimate to the orientation of the beam relative to the flow will be investigated through a further ADCP deployment described below.

[18] Comparisons of the structure function and microstructure estimates of ε are given in Table 1. During the first tidal cycle there is a significant difference in the ratio between the two phases of the tide. A similar result was obtained for the ε_{FLY}/P ratio using the same data [*Rippeth et al.*, 2003] and is explained by the presence of surface gravity waves, particularly when the wind blows against the ebbing tide, producing a bias in the stress estimates. A full evaluation of the effect of surface gravity waves on the structure function technique is beyond the scope of this paper. For the second tidal cycle, by which time the wind had died away and the waves diminished, the ratio is $\varepsilon_{SF}/\varepsilon_{FLY} = 0.68 \pm 0.23$, with no significant difference between the flood and ebb phases of the tide. The average value of the inherent Doppler noise is ~30% larger than the value given by RDI's PlanADCP software. This ratio of measured to predicted Doppler noise is consistent with previous studies [*Williams and Simpson*, 2004].

[19] Variation in the averaging time period did not significantly change the mean dissipation estimates (Figure 3b). Shorter averaging periods introduce more variability into the ε estimates. Whether the increased variability is due to turbulent events or increased noise is not clear.

[20] The mismatch between the upstream and downstream beams is likely due to anisotropic effects in shear and Reynolds stress. In order to investigate the effect of shear and Reynolds stress a second experiment was undertaken in an energetic tidal channel, the Menai Strait [*Rippeth et al.*, 2002], where the horizontal advection of turbulence is thought to be an important term in the local TKE balance. The flow in the Menai Strait is again dominated by a strong and rectilinear semidiurnal tidal. The ADCP was located on the west side of the Strait, out of the main channel flow on the flood phase of the tide, but in the main flow on the ebb. It was setup to collect data in mode 12 (rapid pinging mode), with 12 'subpings' averaged over each second to produce a single velocity estimate. The vertical bin size was set to be 0.5 m and the along beam velocity data recorded. On the ebb tide strong flows (>1 m s^{-1}), Reynolds stresses (>2 N m^{-2}) and mid water dissipation rates (>2 × 10^{-1} W m^{-3}) were estimated for the water column above the ADCP. During the flood tide the ADCP measured much lower currents (maximum ~0.2 m s^{-1}), although strong Reynolds stresses (~1.5 N m^{-2}) and dissipation rates (~0.1 W m^{-3}) were observed. We assume that the occurrence of high stresses and dissipation rates in the absence of a strong mean flow on the flood tide is due to advection by a weak secondary cross channel flow, bringing turbulence from the main channel into the region of the strait where the ADCP was located.

[21] There is a linear relation between the square of the velocities and the Reynolds stress on the ebb tide. However, on the flood tide strong stresses were observed during periods of low flow (Figure 4a), i.e. the velocities and stresses are no longer correlated. The difference in dissipation rates between the up and downstream beams correlate with the Reynolds stress and the shear – i.e. the difference in dissipation rates increased with both increasing Reynolds stresses and shear. However, large differences in the dissipation rates were observed at low velocities during the ebb, and the correlation is not symmetric about zero. The implication of this result is that the discrepancy between the upstream and downstream beam dissipation rate estimates is a consequence of anisotropy in stress and/or shear.

4. Summary and Discussion

[22] We have presented a basic theory and technique to measure turbulent dissipation rate (ε) profiles in the ocean using a standard off-the-shelf acoustic Doppler current profiler. TKE dissipation rate estimates made using this method compare well with simultaneously collected FLY microstructure profiler dissipation rates (ratio ~ 0.68) and TKE production rates estimated using the same ADCP data by applying the variance method (ratio ~ 0.47).

[23] The advantage of this technique is that it can be used to provide relatively long term continuous time series of ε-profiles with power and memory capacity the limiting

Table 1. Ratio of Structure Function Dissipation to FLY Dissipation for the Main Dataset and for Subsamples[a]

Data Subset	Structure ε/FLY ε	Lower 95% CI	Upper 95% CI
All data	0.88	0.69	1.17
Tidal Cycle 1	1.09	0.83	1.57
Tidal Cycle 2	0.68	0.51	0.97
Flood 1	0.76	0.62	0.97
Flood 2	0.52	0.40	0.73
Ebb 1	1.55	1.06	2.89
Ebb2	0.86	0.60	1.48

[a]The 95% confidence intervals were calculated using a bootstrap resampling technique.

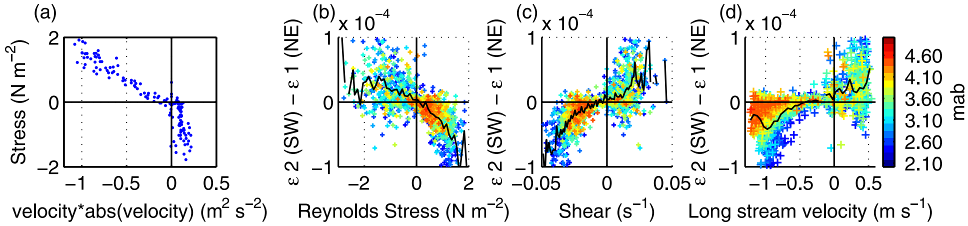

Figure 4. Observations of the difference in dissipation estimates from the up and downstream beams ($\varepsilon_{\text{beam1}} - \varepsilon_{\text{beam2}}$) from the ADCP deployment in the Menai Strait. (a) Reynolds stress vs velocity^2 at 3.1 mab (flood direction, which is positive flow is towards north east). (b) $\varepsilon_{\text{beam1}} - \varepsilon_{\text{beam2}}$ vs Reynolds stress, (c) $\varepsilon_{\text{beam1}} - \varepsilon_{\text{beam2}}$ vs along stream shear and (d) $\varepsilon_{\text{beam1}} - \varepsilon_{\text{beam2}}$ vs along stream velocity. The colours in Figures 4b, 4c, and 4d are the height above the bed at which the dissipation rates, Reynolds stresses and velocities were measured. The black lines in Figures 4a, 4b and 4c are averages of the data.

factors. There are restrictions on the applicability of the technique in stratified environments where the maximum value of r is restricted by the Ozmidov scale (typically up to 5 m in a weakly stratified tidal channel [*Stansfield*, 2001] and of the order <0.1 m to 0.4 m in the thermocline of seasonally stratified shelf seas [*Rippeth et al.*, 2005]). However, if an accurate estimate of the noise N can be made, the dissipation can be calculated over a much reduced scale of twice the bin size; i.e. from equation 5 and equation 6;

$$\varepsilon = \frac{(D(z,r) - N)^{\frac{3}{2}}}{C_v^3 r} \tag{7}$$

As it is possible to extract the rms Doppler noise, N, which we find varies only slightly with height above the bed. This modification thus promises to allow the estimation of ε using the structure function technique on scales appropriate to the stratified marine environment.

[24] The observation that the upstream facing ADCP beam consistently gives a larger value of ε indicates that the assumption of isotropy required for Taylor's cascade theory is not strictly true. Other than this isotropic effect there is no requirement for the ADCP to be oriented vertically, as is the case with the variance technique and so it should be possible to deploy an ADCP on a range of platforms, e.g. non-gimbaled bed frames, mid-water buoys or possibly moving vessels, in order to make estimates of ε.

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