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Variable behavior in pycnocline mixing over shelf seas

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[1] Vertical mixing, driven by turbulence in the ocean, underpins many of the critical interactions that allow life on earth to flourish since vertical buoyancy flux maintains global overturning circulation and vertical nutrient fluxes are critical to primary production. Prediction of the ocean system is therefore dependent on accurate simulation of turbulent processes that, by their very nature, are chaotic. A growing evidence base exists that provides insight into these complex processes and permits investigation of turbulence relative to better determined, and therefore predictable, parameters. Here we examine three time series of the dissipation rate of turbulent kinetic energy (ε) in "stability space". We reveal an ordered structure within the mean distribution of ε that compares well to a variety of proposed models of oceanic turbulence. The requirement for differing site-specific tuning and only partial success however raises questions over "missing physics" within such models and the validity of measurement techniques. **Citation:** Palmer, M.R., J.A. Polton, M.E. Inall, T.P. Rippeth, J.A.M. Green, J. Sharples, and J.H. Simpson (2013), Variable behavior in pycnocline mixing over shelf seas, *Geophys. Res. Lett.*, *40*, 161–166, doi: 10.1029/2012GL054638.

1. Introduction

[2] In terms of its importance to the global carbon cycle, shelf seas seriously *punch above their weight*. Despite occupying a mere 7% of the ocean surface, seasonal or permanent stratification combined with high levels of nutrients results in shelf seas accounting for 15–30% of total oceanic primary production [*Wollast*, 1998]. In consequence, they have been identified as hosting significant air-sea CO_2 fluxes [*Thomas et al.*, 2004], and seasonally stratified shelf seas in particular have been identified as providing an important sink for atmospheric CO_2 [*Borges et al.*, 2005; *Cai et al.*, 2006; *Bozec et al.*, 2006].

[3] The first-order paradigm for the water column structure in seasonally stratified temperate shelf seas is well established as a balance between the stratifying influence of surface heating and the input of mechanical energy to mix the water column at the upper and lower boundaries, due to wind stress and the tidal shear, respectively [e.g., *Simpson and Hunter*, 1974; *Simpson and Bowers*, 1981]. High-resolution shelf sea models have some success in reproducing this paradigm [e.g., *Holt and Umlauf*, 2008], with vertical exchange calculated by second moment turbulence closure schemes [e.g., *Umlauf and Burchard*, 2005] that are essentially controlled by the estimated local stability of the flow. "Calibration" of a background mixing level is however typically required in such schemes in order for a given model to correctly predict the diapycnal flux through this critical interface [*Rippeth*, 2005]. The requirement for local tuning of pycnocline mixing reduces the success of models on shelf-wide scales since differing forcing mechanisms and mixing processes require specific methods and levels of tuning. The key limitation on the skill of these models in predicting the spatial and temporal variability in ecosystem dynamics and carbon exchange is consequently the capability to accurately represent the true nature of pycnocline turbulence and mixing. Further development of regional shelf sea models for accurate prediction of coastal and shelf sea biogeochemical cycles is therefore dependent on improving predictions of pycnocline exchange. Confidence in future predictions of the global carbon cycle is subsequently dependent on an improved ocean turbulence model that can be validated against observations.

[4] Recent decades have seen significant advances in our understanding of ocean turbulence facilitated by developments in observational technology. In particular, the advent of microstructure profilers [e.g., *Dewey et al.*, 1987; *Wolk et al.*, 2002] has vastly improved understanding of ocean turbulence from across all parts of our oceans, providing a method for estimation of fluxes of heat, salt and nutrients, suspension and disaggregation of sediments and permitted explicit closure of energy budgets. An extensive dataset now exists that permits the thorough investigation of pycnocline turbulence in terms of stability criteria such that proposed turbulence closure schemes and mixing parameterizations can be tested and improved upon.

[5] Previous studies have found well-ordered distributions of shelf sea pycnocline ε in *stability space* [e.g., *MacKinnon and Gregg*, 2003a; *van der Lee and Umlauf*, 2011]. This paper expands on previous work by *Palmer et al.* [2008] who found that the distribution of pycnocline turbulence measured in the Celtic Sea was well described by the parameterization proposed by *MacKinnon and Gregg* [2003a]. Here we introduce the data from two additional, contrasting locations in the northwest European shelf seas and, for the first time, reveal similarly contrasting behavior of pycnocline turbulence when examined in the same *stability space*. Data are compared to the characteristics of proposed turbulence models to provide insight into the mixing mechanisms at each site and test the capability of such models in predicting shelf sea pycnocline turbulence.

[6] The candidate mechanisms that promote shelf sea pycnocline mixing are divisible into two distinct categories:

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(1) interaction between stratified flow with topography that generates internal waves with a wide range of length, time, and energy scales. Enhanced turbulence can arise from the elevated levels of shear associated with propagating waves at the pycnocline interface [e.g., *Moum et al.*, 2003] or if the topographic wave becomes gravitationally unstable and breaks [e.g., *Thorpe*, 2010]; (2) surface-driven flows that promote entrainment at the base of the well-mixed surface layer through enhanced interfacial shear. Typical within shelf sea regions are near-inertial oscillations driven by the wind [*van Haren et al.*, 1999]. Within coastal regions [*O'Donnell et al.*, 2008] or at high latitudes, density-driven surface flows will result in a similar entrainment of pycnocline and bottom layer water into the surface layer.

2. Observations of pycnocline turbulence

[7] In this paper, we examine data collected from three different shelf sea sites (Figure 1), all of which were strongly stratified throughout the duration of the experiments:

1. CS3 is a flat site in the NE corner of the Celtic Sea, over 300 km from the shelf break and sufficiently far from any on-shelf topographic feature that the internal tide and internal solitary waves are only a weak influence on pycnocline shear. As reported in *Palmer et al.* [2008], the dominant control on pycnocline shear is inertial oscillations that are observed to promote a stasis of only marginal stability in the pycnocline. The site is representative of large areas of temperate shelf sea that are strongly influenced by meteorological forcing.
2. A site in the fjord-like, semi-enclosed Clyde Sea. The site is approximately 60 m deep and is situated 12 km from the 40 m deep fjord entrance sill. Pycnocline shear is dominated by baroclinic flow associated with the passing internal tide generated at the entrance sill that separates the Clyde and Irish Seas [*Liu et al.*, 2012; *Inall and Rippeth*, 2002]. The site is representative of on-shelf regions influenced by up-stream generation of internal tides, such as close to the shelf break and banks.
3. Jones Bank in the Celtic Sea [*Inall et al.*, 2011] lies over 200 km east of the continental shelf break and is approximately 100 km west of the UK. Jones Bank is shallow sloping and low profile, rising 30 m over its 50 km long major axis in approximately 130 m of surrounding sea. Pycnocline shear is dominated by strong lower layer currents under hydraulic control during off-bank tidal flow and explosive bursts of mixing due to associated hydraulic jumps. Pycnocline shear is also present at the near-inertial frequency due to regular wind forcing and flow interaction with the bank. The site is representative of on-shelf regions of enhanced mixing due to local interaction between stratified flow and topography.

[8] At each of the sites, vertical profiles of shear microstructure were collected using a free-falling turbulence profiler from which ε is derived following the methods of *Dewey et al.* [1987] and *Rippeth et al.* [2003]. The profilers also measured the vertical structure of temperature and salinity from which density (ρ) is derived. The buoyancy frequency (N) was then calculated $N^2 = -g/\rho_0\, d\rho/dz$ (s^{-2}) which provides a measure of the strength of vertical stratification. Each of the profiler time series was made in close proximity to a moored Acoustic Doppler Current Profiler (ADCP) which provides measurements of the major (u) and minor (v) components of horizontal current velocity from which the vertical shear (S) can be calculated from $S^2 = (du/dz)^2 + (dv/dz)^2$. We may therefore calculate a gradient Richardson number from $\mathrm{Ri} = N^2/S^2$ to describe the stability within the pycnocline at each site. The theoretically necessary condition for shear instability is $\mathrm{Ri} \leq \frac{1}{4}$ [*Howard*, 1961].

[9] *Palmer et al.* [2008] found a well-ordered distribution of ε in terms of N and S (stability) space. Following this work, we will for the first time similarly arrange the Clyde Sea data used by *Liu et al.* [2012] and new data collected at Jones Bank to investigate whether there is coherent behavior that may provide insights into the nature of turbulence at each site (Figure 2). Stability diagrams from each location demonstrate apparently ordered distributions, although the nature of the distribution is radically different in each case.

3. Predicting pycnocline turbulence

[10] Microstructure measurements made over the last three decades have provided the basis for empirical scalings of

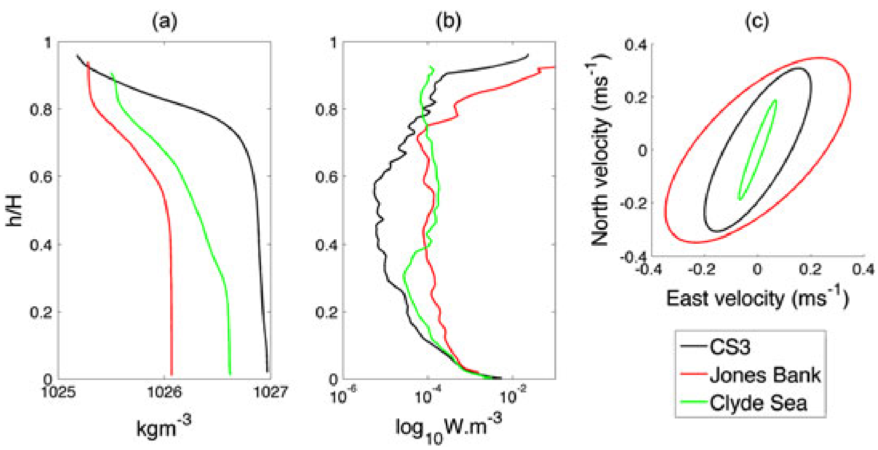

Figure 1. Profiles of time averaged (a) density (Clyde Sea data shifted +1 kg m^{-3}) and (b) ε demonstrate how pycnocline turbulence is weak when compared to bottom boundary layers at each of the three sites. Only the Clyde Sea has a distinct ε maximum associated with the pycnocline. (c) The approximate tidal current ellipses are shown for reference.

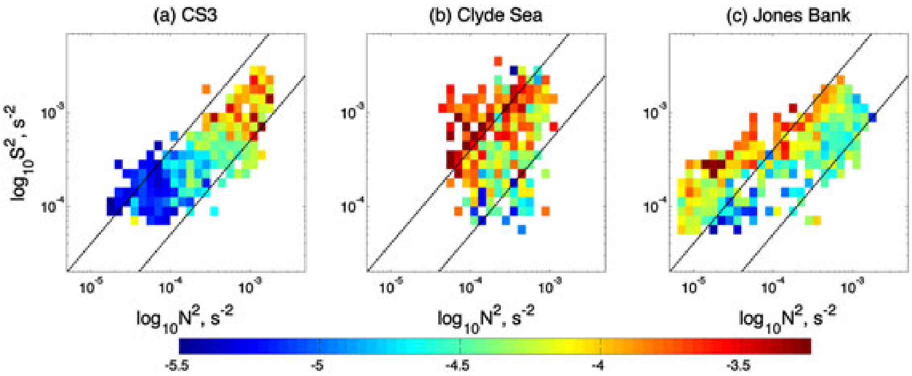

Figure 2. Pycnocline measurements of ε ($\log_{10}$Wm^{-3}) were averaged onto $\log_{10}(0.1\ s^{-2})$ N and S space from three sites: (a) CS3, (b) the Clyde Sea, and (c) Jones Bank. Ri $= \frac{1}{4}$ and Ri = 2 are indicated by upper and lower dashed lines, respectively.

turbulence dependent on bulk parameters that have led to limited levels of success in predicting pycnocline mixing. *Gregg* [1989] provides an established open ocean parameterization that relates ε to *S* and *N* by employing the nonlinear internal wave-wave interaction theories of *McComas and Muller* [1981] and *Henyey et al.* [1986], and the *Garrett and Munk* [1975] model of the oceanic internal wave shear spectrum (S_{GM}); *Gregg* [1989] derived ε from

$$\varepsilon = \alpha_1 \frac{\langle N^2 \rangle}{N_0} \frac{S^4}{S_{GM}^4} \quad (1)$$

where α_1 scales the simulated ε to provide an acceptable level of fit to observed values of ε and N_0 represents background pycnocline *N*. Within shelf seas, the decay of internal wave energy is less ordered as energy is partitioned between higher order modal structures. MacKinnon and Gregg, herein *MG* [2003a], employ a modified version of *Gregg* [1989] to address this to match observations of ε on the New England Shelf such that

$$\varepsilon = \alpha_2 \frac{N}{N_0} \cdot \frac{S}{S_0} \quad (2)$$

where α_2 represents a local scaling parameter and S_0 represents background pycnocline *S*. Various authors have identified a similar distribution of shelf sea ε in parameter space to *MG* [2003a] where shear is dominated by low-mode, low-frequency internal waves at the near-inertial and tidal frequency; however, α_2 is observed to span a broad range similar to that of observed levels of ε (examples in Wm^{-3}, 1.7×10^{-7} *van der Lee and Umlauf* [2011]; 6.9×10^{-7} *MG* [2003a]; 1.1×10^{-6} *MG* [2005]; 1.8×10^{-5} *Palmer et al.* [2008]). This necessary local adjustment strongly suggests that critical aspects of the physical processes that they seek to predict are not well represented.

[11] *Kunze et al.* [1990], herein KWB, proposed a further parameterization of open ocean turbulence attributable to internal waves based on scaling of measured *N* and *S* to represent the available turbulent kinetic energy (TKE) within an unstable event, i.e., Ri$\leq\frac{1}{4}$. Assuming that TKE production ≈ ε, *Kunze et al.* [1990] proposed

$$\varepsilon = fr \cdot \Delta z^2 \left\langle \left(\frac{S^2 - 4N}{24} \right) \left(\frac{S - 2N}{4} \right) \right\rangle \quad (3)$$

where *fr* represents the fraction of the water column that is gravitationally unstable (0.1) and angle brackets denote temporal averaging. While (3) was developed using open ocean measurements, its lack of dependence on the wave-wave interaction such as that employed by *Gregg* [1989] suggests it may be equally applicable to turbulence driven by shear instability on the shelf.

[12] Current shelf sea models typically rely on a "turbulence closure scheme" to predict the turbulent parameters from which vertical exchange is derived [e.g., *Shchepetkin and McWilliams*, 2005; Holt and Umlauf, 2008]. Rather than the largely empirical formulations of (1)–(3), such models are based on laboratory and theoretical experiments [Richardson, 1922; Miles, 1961; Howard, 1961] and aim to describe the behavior of turbulence during shear instability. As such, these models are controlled by Ri and are typified by the second moment turbulence closure schemes such as those developed by Mellor and Yamada, herein *MY* [1974, 1982] and *Canuto et al.* [2001]. ε is derived from the total turbulent kinetic energy that such schemes predict as a function of stability, turbulence being suppressed beyond a critical threshold. Such closure schemes however are primarily descriptions of boundary-driven mixing; able to reproduce observed tidal current and turbulent dissipation profiles in mixed water columns but notoriously failing to reproduce the observed levels of turbulent dissipation within the shelf sea pycnocline [*Simpson et al.*, 1996; *Burchard et al.*, 2008].

[13] Reproducing such a complex component of our natural environment as internal mixing is always likely to be a challenge for large-scale hydrodynamic models due to the "sub-grid scale" processes they aim to simulate. We may however test the turbulence parameterizations and closure scheme described by forcing them with typical values of N and S as observed at our three sites (Figure 3).

4. Discussion

[14] Each of our observed distributions of ε in stability space exhibits traits that are replicated in either one or a combination of the chosen turbulence models.

- As has previously been reported by *Palmer et al.* [2008], turbulence at CS3 is well described by the parameterization of *MG* [2003a]. The agreement given the similar low-mode, low-frequency, and low-energy environment reported by *MG* [2003a]; however, the result is no less intriguing; ε fails to demonstrate any Ri dependence so the poor comparison with stability-based functions is to be expected. This failure, we suggest, is due to either (1) the processes that lead to pycnocline turbulence at CS3

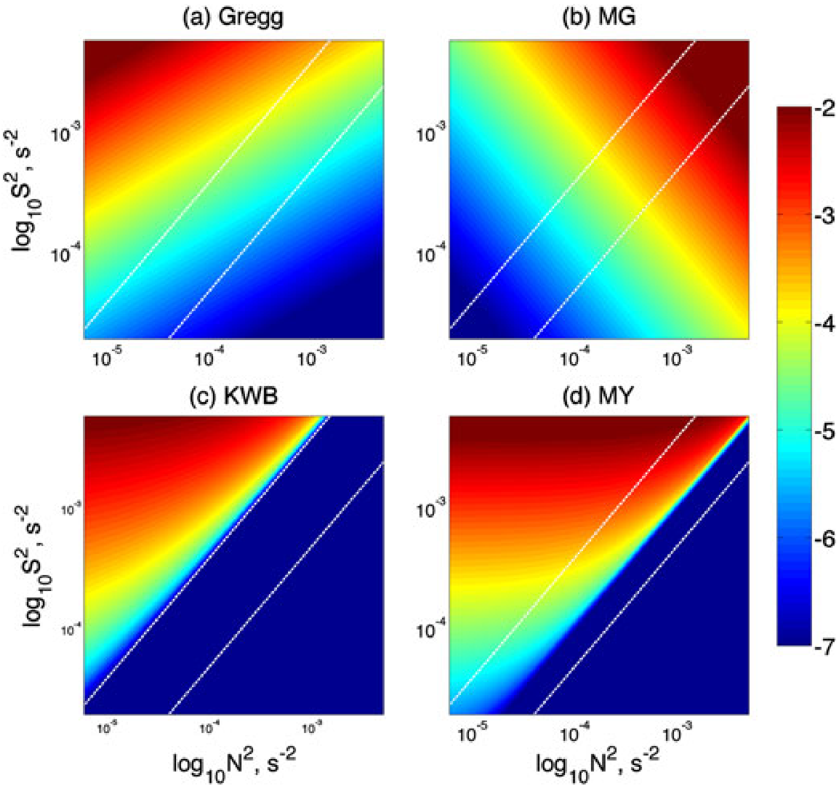

Figure 3. The predicted distribution of ε ($\log_{10}\mathrm{Wm}^{-3}$) in N and S space is demonstrated for (a) *Gregg* [1989], (b) *MacKinnon and Gregg* [2003a, 2003b, MG], and (c) *Kunze et al.* [1990, KWB] parameterizations and for (d) the level 2.5 Mellor-Yamada (MY) turbulence closure scheme using the stability functions of *Galperin et al.* [1988]. In each case, ε is tuned to match a similar range of ε to observations.

are fundamentally different to those described by shear instability or (2) the transition to turbulence in this entrainment type environment (case 2 in our introduction) is not adequately resolved by our measurements. Considering local mixing length and time scales may help to explain this result; at CS3, small turbulent length scales (O[10 cm]; *Palmer et al.*, 2008) and comparatively low shear ($S^2 < 3 \times 10^{-3}\,\mathrm{s}^{-2}$) result in a low Reynolds number ($\mathrm{Re} = oul/\mu$, where u and l are characteristic turbulent velocity and length scales and μ is the fluid kinematic viscosity) environment (typically $\mathrm{Re} < 1 \times 10^4$) such that fully developed turbulence may not occur and shear instabilities are rapidly arrested by viscous forces [*Gibson*, 1986]. Turbulent time scales (l/u) would subsequently be short, typically only a few seconds, meaning that turbulent shear attributable to observed ε may not be immediately resolved by the ADCPs used in this study which were located 100 s of meters from the profilers for logistical reasons.

- In the Clyde Sea, ε follows a rough pattern of Richardson number dependence so a stability-function-based turbulence model may be considered appropriate in such environments. The diffuse distribution of ε however suggests that the transition to turbulent flow is more complex than the rapid transition predicted by either KWB or MY. While there does appear to be a critical threshold beyond which turbulence is significantly enhanced in the majority of cases $\left(\mathrm{Ri} < \frac{1}{2}\right)$, there remains an active level of ε in the remainder of stability space that is not captured by either method. The sub-critical region is better described by the scaling of *Gregg* [1989] that predicts a gradual increase in ε with decreasing Ri. However, the noisy distribution of Clyde Sea data makes it difficult to draw any firm conclusions from this. Pycnocline ε is more energetic than CS3, and the Ozmidov turbulent length scale ($\mathrm{Oz} = (\varepsilon/N^3)^{1/2}$) is significantly greater, O[10 m], than the vertical resolution (dz ~ 1 m). This suggests that S and N are vertically suitably resolved.
- Jones Bank ε displays the best agreement with KWB and shares similarity with MY, following a transition to the strongest turbulent levels at a critical point around $\mathrm{Ri} < \frac{1}{4}$. Within the sub-critical region $\left(\mathrm{Ri} < \frac{1}{4}\right)$, there is a clear reduction in turbulent intensity with reduced shear similar to that predicted by both methods. What KWB and MY fail to capture however is that the Jones Bank pycnocline maintains a relatively weak but significant level of turbulent energy dissipation above that critical threshold. Within the marginally stable environment $\left(\frac{1}{4} < \mathrm{Ri} < 2\right)$ where the remainder of the data resides, data follows a distribution similar to that predicted by MG, ε increasing with both S and N. Within the sub-critical region $\left(\mathrm{Ri} < \frac{1}{4}\right)$, mixing length scales are large enough (Oz > 10 m) to provide confidence in estimates of S and N. For the remainder of data however, length scales range from a few meters to only 20 cm, suggesting that ε may be poorly resolved in stability space.

[15] It is apparent from these three case studies and the four chosen turbulence models that much of the observed behavior of pycnocline turbulence and subsequent vertical mixing and diapycnal exchange is replicable with the right choice of model and appropriate "tuning" of free parameters.

What this study demonstrates however is the difficulty of simulating the complexity and variability of the shelf sea pycnocline. If local observations are required to make the correct choice of turbulence model and appropriate tuning parameters, then the predictive capability of regional scale ocean models is severely restricted. This small subset of what is an ever-growing global dataset of turbulence and hydrographic measurements may hold the key to more general solutions. The capability exists to provide extensive testing and validation of the numerous turbulence models proposed for use on shelf seas, but the community must look beyond the basic constraints of stability space. The high levels of variability between applications of these models indicate an underlying misrepresentation of the physics they are designed to simulate.

[16] While every effort is made to make profiler measurements adjacent to the mooring site, this is not always possible. The typical separation distance of 500 m to 1 km is short compared to the wavelengths of the dominant, low-frequency internal waves which are the primary candidate internal mixing mechanism at our three sites (e.g., 20 km internal tide) but are of similar order to higher frequency processes (e.g., 1 or 2 km solitary waves). Where small-scale processes contribute significantly to the local shear and dissipation, we may therefore expect poor resolution of the local Ri. This may help to explain the apparent noise in our Clyde Sea distribution and the counter-intuitive distribution of ε at CS3.

[17] This study identifies clear differences in ε distribution under differing forcing conditions and promotes the question of whether the mechanistic transition to turbulence and mixing from laminar, sheared flow is the same in all circumstances. These results suggest otherwise. However, our interpretation of such data is also limited since few datasets manage to capture coincident measurements at the appropriate mixing length scale.

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