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The Vertical Structure of Shear and Dissipation in the Ocean Surface Layer

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Abstract

We compare measured profiles of upper layer shear and rates of kinetic energy dissipation with the predictions of a one-dimensional turbulence model proposed by Craig and Banner (1994). Their formulation contains an unknown parameter, the "roughness length" z_o, which we determine by fitting computed and observed dissipation rates. The resulting model, without further adjustment, is then used to compute downwind current profiles which compare favorably with observations of shear obtained in winter on the Northern California Shelf as part of the Shelf Mixed Layer Experiment (SMILE).

1 Introduction

Wind–driven mixing in the ocean surface layer is mediated by the surface wave field, in part via wave breaking, and in part through wave–current interaction. The latter results in the formation of Langmuir cells, whose associated large–scale circulation provides an efficient mechanism for vertical transport within the mixed layer. We focus here on the vertical structure of mean shear and turbulence in the "wave zone" – the layer immediately below the surface of thickness $\mathcal{O}(k_p^{-1})$, where k_p is the wavenumber of the dominant waves – that is directly affected by the waves, both through breaking, and irrotational straining. We present observational evidence that the vertical distributions of dissipation and shear in this region are related to the wave field, and present a fully specified one–dimensional turbulence model that successfully reproduces existing observations of these quantities.

2 Specification of a Turbulence Closure Model

In this section we briefly review the model of upper layer mixing proposed by Craig and Banner (1994), and find a parameterization of the turbulence length scale by fitting the model to field observations of the near–surface rate of kinetic energy dissipation. The details of this are discussed fully in Terray and Drennan (1999, in preparation). The Craig–Banner model employs a "Mellor–Yamada Level 2 1/2" closure, but is extended to include wave breaking, which is modeled as a surface flux of kinetic energy. Equations are retained for the mean horizontal velocity, **U**, and turbulent kinetic energy, q^2. These are closed by (*i*) expressing the momentum and kinetic energy fluxes in terms of gradient transports, (*ii*) introducing an algebraic closure for the dissipation rate, and (*iii*) specifying the turbulence length scale. Because the energy flux from breaking is large (Terray *et al.*, 1996, 1997), the dynamics in the near-surface region is determined by the balance of turbulent kinetic energy transport and dissipation, rather than the usual equality between shear production and dissipation which is characteristic of flows over solid boundaries (Craig and Banner, 1994). The dynamical equations are given by

$$\left.\begin{aligned} \partial_t \mathbf{U} + \mathrm{f}\times\mathbf{U} &= \boldsymbol{\tau}/\rho \\ \partial_t q^2 + \partial_z \mathcal{F} &= -\epsilon \end{aligned}\right\} \tag{1}$$

where **f** is the Coriolis parameter. We express the momentum flux, $\boldsymbol{\tau}$, energy flux, $\mathcal{F}$, and dissipation rate, ϵ, as $\boldsymbol{\tau}/\rho = S_m\, q\, \ell\, \partial_z \mathbf{U}$, $\mathcal{F} = S_q\, q\, \ell\, \partial_z\, q^2$, and $\epsilon = q^3/B\,\ell$, where ℓ denotes the turbulence length scale, which must be specified *a priori*, and $S_m = 0.39$, $S_q = 0.2$ and $B = 16.6$ are model constants whose values are determined by comparison to shear flows.

The model is completed by specifying boundary conditions. At the surface we take $\boldsymbol{\tau}(0)/\rho = (u_*^2, 0)$ and $\mathcal{F}(0) \equiv F = const.$, where u_* is the friction velocity in the water, and F denotes the energy flux from breaking. At the bed, $(z = -H)$, we take $\mathbf{U} = 0$ and $\partial_z q^2 = 0$. Note that the choice of H is not critical to the discussion here – provided that it is substantially greater than the Ekman scale $0.25 u_*/\mathrm{f}$, the near-surface region is essentially independent of the water depth.

The length scale ℓ is the remaining unknown. To fix it we appeal to observations of the rate of decay of kinetic energy dissipation, ϵ, with depth, $z < 0$. Data from three separate experiments are shown in Figure 1. Following Terray *et al.* (1996, 1997), we have scaled depth by the significant wave height, H_s, and the dissipation rate by F_o/H_s, where F_o is the energy flux from the wind to the waves. The data span the range of nondimensional depth $0.5 \leq z/H_s \leq 14$, and wave age $5 \leq c_p/u_{*a} \leq 28$ (here c_p is the phase speed of the dominant waves, and u_{*a} is the friction velocity in the air). The observations taken from Terray *et al.* (1996) and Anis and Moum (1995) consist of profiles whose mean logarithmic slope is -2.3±0.4. The consistency of this result with the slope of the non–dimensional dissipation rate shown in the figure suggests that the collapse of the data under this scaling is not the result of spurious correlation. We remark in passing that the wavenumber of waves at the peak of the spectrum, k_p, also can be used instead of H_s to scale length with equivalent results – the data do not favor one over the other.

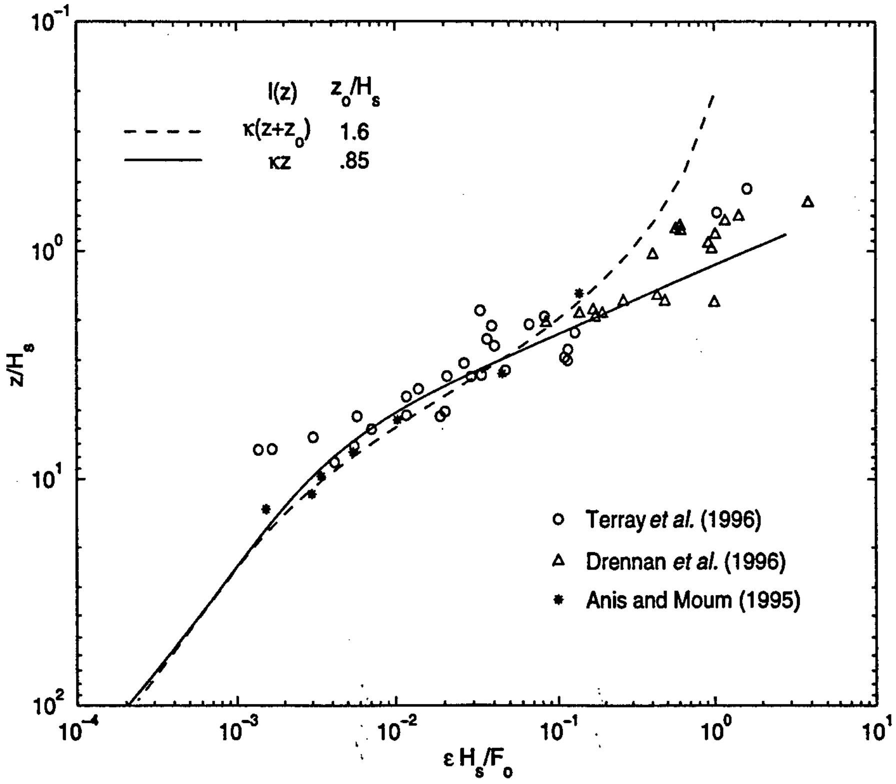

Figure 1: Symbols are measured rates of near-surface dissipation, non-dimensionalized using a wave-dependent scaling (Terray *et al.*, 1996). The curves denote model results based on the Craig–Banner length scale (dashed), and the 'κz' length scale defined in Equation 2 (solid).

Craig and Banner proposed a length scale varying as $\ell = \kappa(z_o + |z|)$ over the upper half of the water column ($\kappa = 0.4$ denotes the von Kármán constant). The "roughness length", z_o, is unspecified in their prescription, and must be determined empirically. Since the observed dissipation rates collapse to a single curve when lengths are scaled by H_s, we assume that z_o/H_s is a constant, and determine its value from a least-squares fit to the data. The best fit using the Craig–Banner length scale is obtained by taking $z_o/H_s = 1.6$, and is shown in Figure 1 as the dashed curve. Note that it does not account for the high values of dissipation observed close to the surface, and we have verified that no choice of z_o/H_s fits the data well in this region (Terray and Drennan, 1999, *loc. cit.*).

This difficulty lead us to consider an alternate length scale having the form

$$\ell(z) = \begin{cases} \kappa z_o, & |z| \leq z_o \\ \kappa |z|, & z_o < |z| < H/2 \end{cases} \tag{2}$$

Our best fit to the data using this length scale gives $z_o/H_s = 0.85$, and is shown in the Figure by the solid curve.

3 Observations and Modeling of the Near–Surface Shear

Figure 2 summarizes the results of measurements of the downwind shear in the upper mixed layer obtained from four different experiments. Depths are normalized by k_p, and shears by $u_*/\kappa z$ – so that a wall–layer would have a non–dimensional shear equal to unity. Whereas the wind and wave conditions were relatively stationary within each experiment, their variation between experiments was larger, spanning the ranges $17 < c_p/u_{*a} < 50$ and $0.1 < k_p z < 2$ in wave age and non-dimensional depth, respectively. We have further restricted our consideration to those cases having negligible stratification. There appears to be a general trend from less shear at the surface to more at depth, with maximum values of order the wall–layer result. However the measured values of shear display more variation than do those of dissipation, and the scaling fails to collapse the data as well – particularly with regard to the transition depth between the low shear region close to the surface and the higher shear layer below. While the reason for this is not clear, it suggests that additional dimensionless parameters, such as wave age or the relative direction between the wind and waves might be relevant. This is consistent with the closure model we are using (Craig and Banner, 1994; Craig, 1996), which predicts that the non-dimensional current, U/u_*, is a function of z/z_o and the normalized energy flux, F_o/u_*^3, both of which depend on the degree of development of the waves (Terray *et al.*, 1996, 1997). Unfortunately detailed information about the wave field is not available for several of the experiments shown in Figure 2, and therefore the resolution of these issues must await future experimental clarification. Instead, we focus here on a single data set, denoted in the figure by open circles (Santala, 1991), that was obtained during an extended period of relatively stationary forcing.

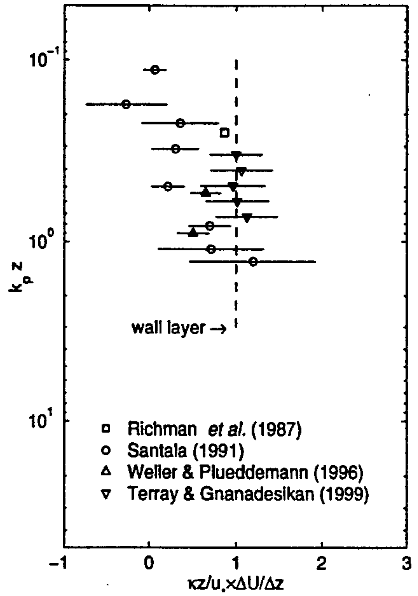

Figure 2: Mean downwind shear from measured current profiles.

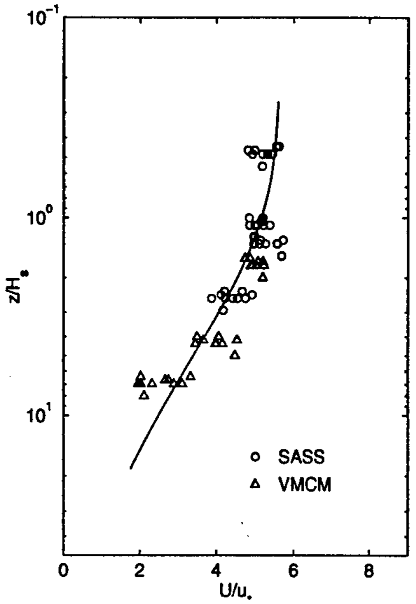

Figure 3: Measured and modeled downwind current from SMILE (Santala, 1991).

These data were collected as part of the "Shelf Mixed-Layer Experiment" (Santala, 1991), which took place in the winter and early spring of 1988–1989 on the California shelf approximately halfway between Point Arena and the Russian River (38° 38.8′ N, 123°29.3′ W). Currents were measured from two moorings located within 500 meters of one another on the 100 m isobath. The first buoy (SASS) was a large triangular space frame suspended beneath three cylindrical surface floats. Six BASS acoustic current meters were arranged in a rigid vertical array along the centerline of the frame at nominal depths of 1–5 m. SASS was equipped with an inertial package, consisting of a 2–axis gimbaled gyro, an accelerometer triplet (leveled by the gyro), and a compass. The measurements obtained from the inertial system were used to convert measured velocities into an earth–referenced coordinate system, as well as to correct the bias caused by the wave–correlated motion of the buoy (Santala and Terray, 1991). The second mooring was a conventional discus buoy. It carried a standard suite of meteorological instrumentation (wind speed and direction, air temperature, humidity and long– and short–wave radiation), and supported 10 VMCM current meters at depths between 4 and 47 meters. Hence the topmost VMCM overlapped the bottom of the BASS array. Temperature and salinity were measured from both the VMCM mooring and SASS buoy, and were used to estimate water column stability. Further details of the instrumentation and data processing can be found in the Ph.D. thesis of Santala (1991).

We focus here on ten data sets spanning 27–28 February, 1989. With the exception of one run, which was half as long, each collection period lasted approximately 40 minutes. The BASS current meters were sampled at 4 Hz, whereas the VMCMs recorded 15 minute averages. The winds during this interval were reasonably steady, with the 10 m wind speed having a mean of $U_{10} = 13.6\,(1.2)$ m/s (the number in the parenthesis is one standard deviation). The waves were also steady with a significant height and peak period of $H_s = 2.3\,(0.14)$ m, and $T_p = 7.8(0.38)$ s. The wind and peak wave directions were aligned to 4° (8°). During this period the water column was essentially neutral above 20 m depth, and stably stratified below. We confine ourselves to measurements taken within the topmost 16 m. Vertical profiles of the mean downwave current for each run are shown in Figure 3. The shears in the region $z/H_s \gg 2$ are consistent with wall–layer values, but are smaller closer to the surface. The curve shows the result of the modified Craig–Banner model.

4 Discussion

We have presented observational evidence that turbulence within the upper mixed layer is enhanced relative to a wall–layer, and have shown that the disparate data sets collapse under a wave–related scaling. Dissipation measurements have been used to calibrate a low order turbulence closure model, due to Craig and Banner (1996), which yields an excellent fit to the observations. We argue in favor of a modified turbulence length scale (Equation [2] above). The best fit of our model to the dissipation data yields a roughness length $z_o \simeq 0.85 H_s$. We then present measurements of near–surface shear. Observations show a general trend from less shear close to the surface to greater values at depth, although there is considerable variability between experiments. The observations by Santala (1991), in particular, vary from essentially no shear near the surface to a logarithmic velocity profile in the region where $z \gg H_s$. Application of the modified Craig–Banner model to those data yields good agreement with the observed downwave current.

Acknowledgements

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