Enhanced dissipation of kinetic energy beneath surface waves

Y. C. Agrawal*, E. A. Terray†, M. A. Donelan‡, P. A. Hwang*, A. J. Williams III†, W. M. Drennan‡, K. K. Kahma§ & S. A. Kitaigorodskii||

* Quest Integrated Inc., 21414 68th Avenue South, Kent, Washington 98032, USA
† Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA
‡ National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario L7R 4A6, Canada
§ Finnish Institute of Marine Research, SF-00931 Helsinki, Finland
|| Department of Earth and Planetary Science, The Johns Hopkins University, Baltimore, Maryland 21218, USA

TRANSFER of momentum from wind to the surface layer of lakes and oceans plays a central part in driving horizontal and vertical circulation of water masses. Much work has been devoted to understanding the role of waves in momentum transfer across the air–sea interface, but less is known about the energetics of the near-surface turbulence responsible for the mixing of momentum and mass into the underlying water column. In particular, it has remained unclear whether the structure of the turbulence in the surface layer can be described by analogy to wall-bounded shear flows or whether waves, either through breaking or wave–current interaction, introduce new length- and timescales which must be modelled explicitly. Here we report observations of turbulence in Lake Ontario, taken under conditions of strong wave breaking, which reveal a greatly enhanced dissipation rate of kinetic energy close to the air–water interface, relative to the predictions of wall-layer theory. Because wave breaking is intermittent, short-term measurements of the kinetic energy dissipation in the near-surface layer may therefore result in considerable underestimates, and any general treatment of upper mixed layer dynamics will have to take wave breaking explicitly into account.

The data presented here were acquired during 1985–1987 as part of the WAVES (Water-Air Vertical Exchange Study) programme in Lake Ontario. Observations were collected from a research tower standing in 12 m of water, 1.1 km east of the western shore of the lake. The tower was designed to minimize flow disturbances. Westerly winds produce fetch-limited waves at the tower that are of the order of 30 cm significant height. In contrast, the 300 km easterly fetch can produce waves of several metres in significant height. The data presented here are from westerly, strong wind (greater than 8 m s^{-1}) cases only.

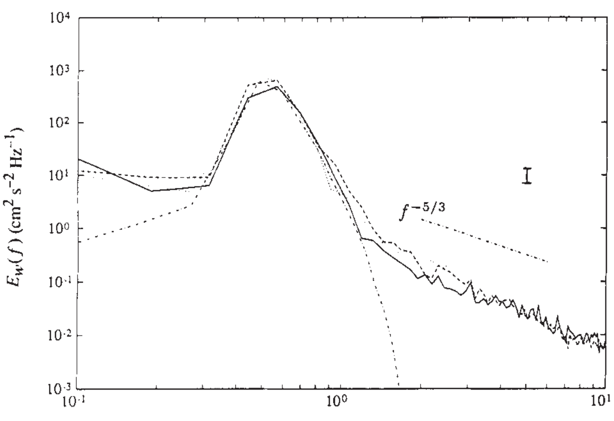

FIG. 1 Concurrent 256-s vertical velocity spectra E_w plotted against frequency from LDV at 50 cm (—), drag sphere at 50 cm (- -) and BASS at 56 cm (· · ·), with linear wave theory (50 cm) (·–·–·). The vertical band shows the 90% confidence interval. Wind speed, 11.5 m s^{-1}.

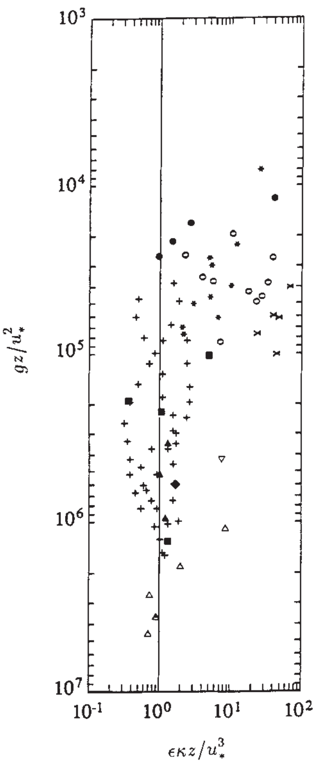

FIG. 2 Dissipation in 'wall layer' coordinates $\epsilon\kappa z/u_*^3$ versus zg/u_*^2. The prediction of wall-layer theory appears as the vertical line. Data are: WAVES (drag sphere (○), BASS (∗), LDV (●)), tower[6] (■), profilers[7] (+), tower[11] (△), profilers[12] (◆), tower[13] (×), profilers[14] (▲), towed hot film[15] (▽), all using a common drag coefficient relation[8].

Water velocity components in the near-surface layer were measured with three different types of velocimeters mounted at different locations on the tower: an acoustic current meter array[1] (BASS), drag-sphere velocimeters[2] and a laser Doppler velocimeter[3] (LDV). These sensors cover a range of scales: from 15 cm for BASS to 4 mm for the drag sphere and 1 mm for the LDV. BASS and drag-sphere data were continuous, lasting several hours, whereas the LDV was sequentially positioned at a range of depths between the surface and 50 cm, collecting 256-second records at each depth. In addition to the velocimeters, the tower was equipped with wave gauges, a water surface thermometer and meteorological sensors.

The dissipation results included here are derived from vertical velocity spectra, using only the high-frequency part of the spectrum well beyond the wave peak. They are obtained from the $-5/3$ slope inertial range of the velocity spectra[4]. Cross comparison of the drag-sphere, BASS and LDV spectra from roughly the same depths indicates strong consistency (Fig. 1). As these instruments are completely different in geometry and principle of measurement and were placed a few metres apart, such agreement should dispel doubts arising from possible flow disturbances contributing to the turbulence. The spectral levels at intermediate wavenumbers (between the scales of energy input and the very small scales where viscosity erodes the turbulence) reflect the energy flux from large to small scales and hence the dissipation rate. The conversion of measured frequency spectra to wavenumber space was carried out using the r.m.s. orbital velocity instead of the mean advection. In the presence of waves, it has been shown that at frequencies much higher than those of the waves, the use of r.m.s. velocity is appropriate[4,5].

In Fig. 2, we plot our dissipation estimates as a function of depth using data from all three instruments combined with those

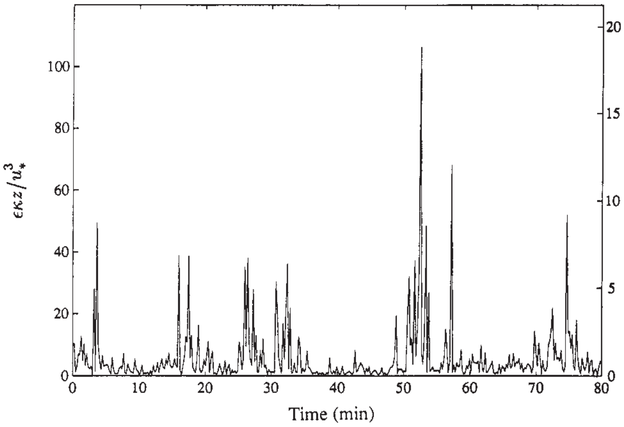

FIG. 3 Time-dependent dissipation estimates, $\varepsilon\kappa z/u_*^3$ (or $\varepsilon/\bar{\varepsilon}$), based on intervals of 13 s, the shortest data length yielding spectra with a discernible −5/3 slope beyond the wave peak. Wind speed: 12 m s^{-1}.

compiled in refs 6 and 7. For comparison, we present these data with the dissipation normalized using wall-layer scaling[7]. The dissipation rate ε is scaled with the friction velocity u_* and depth z as $\varepsilon/(u_*^3/\kappa z)$, and is unity for a wall layer ($u_* = \sqrt{\tau/\rho}$, where τ is the frictional stress at the surface due to the wind, κ is von Karman's constant and ρ is the water density; u_* is significant in that it represents a characteristic velocity of the turbulence). The depth is scaled with u_*^2/g which is proportional to the r.m.s. height of fully developed wind-forced waves. The wind stress is derived from the measured wind based on a widely accepted formula[8]. As the state of development of the wave field was not supplied with most of the data sets taken from the literature, we omit explicitly identifying this effect, although it is likely that some of the scatter in Fig. 2 is due to the dependence of the relationship between wind and stress on wave development. The data encompass a wide range of sampling periods—from fractions of a minute to over an hour. Ninety-minute estimates of average dissipation, such as those obtained by the BASS and drag-sphere instruments, have a standard error of roughly 30%; error estimates for other cases were generally not available. Clearly our near-surface data are not well represented by wall-layer scaling (a suitable scaling will be addressed in a subsequent publication). Figure 2 presents a reasonably consistent picture of high near-surface dissipation blending into wall-layer values at greater depths.

The profiler measurements of Soloviev[7] lie below ours for small values of gz/u_*^2. In part this may be due to the scaling because at the low wind speeds characteristic of Soloviev's data[7] wall-layer scaling may persist to smaller values of non-dimensional depth. In addition, if the production of turbulence is intermittent—for example, through wave breaking—then the short time samples of the profiling devices will tend to underestimate the mean dissipation rate. For illustration we explore the intermittency of the observed dissipation computed from the spectral level of the inertial sub-range in the drag sphere data observed at 1 m depth. Similar intermittency was observed by the LDV and BASS. A time history of dissipation estimates using a 13-s averaging time is shown in Fig. 3. The left-hand ordinate of the plot shows the measured dissipation rate, ε, normalized by the corresponding wall-layer value; the right-hand ordinate indicates the ratio of ε to its mean over the entire record. The probability distribution of the dissipation rate is roughly log normal. We emphasize that we are discussing the variability of 13-s averages of dissipation estimated from spectral levels and not the instantaneous dissipation that is associated with a log-normal distribution in the classical Kolmogorov theory of turbulence. It is immediately apparent that the dissipation estimates are highly intermittent with 14 values in excess of 5 times the mean, and one value of 18 times the mean. The spectral sampling error in each estimate of dissipation is ~15%, and is much smaller than the observed intermittency. The mode of the distribution corresponds to an estimate of 1/5 the mean, and is approximately the expected wall-layer value. We note here that the LDV sampling time was 55 min (13 sets of 256-s records) and that of the BASS and drag spheres at least 90 min, whereas typical profilers rise rapidly through the upper layers[7]. The profilers spend at most a second or two in the wave zone and thus yield essentially random instantaneous samples from a distribution with far greater kurtosis than that of Fig. 3. Therefore an objective observer, tossing profilers through the wave zone, would, in this case, recover a value for the dissipation in general agreement (a factor of 3) with the wall-layer estimate 5 times out of 10 tosses.

The overall character of the time-dependent dissipation estimates (Fig. 3) suggests that dissipation in the upper layers is fed by energy production from two processes. The background level of dissipation is close to the wall-layer estimates and presumably arises from either the micro-breaking of small waves[9], whose phase velocity is close to the friction velocity in the air, U_*, or, in the case of light winds, by the breakdown of the shear layer at the surface driven by the wind stress (τ) acting on the surface drift current, whose speed is also comparable to U_* (ref. 10). In either event, the energy flux from the atmosphere will be of the order of τU_*. The intense events seen in Fig. 3 result from an additional intermittent source of turbulence and, as discussed above, dominate the average. The net dissipation rates observed in strong winds at short fetch require a much higher energy flux from the wind than the wall-layer estimate of τU_*. Although we cannot identify the source of these events with certainty, one likely possibility is that they are associated with the breaking of larger waves (that is, whitecaps). This interpretation is supported by energy flux estimates based on the delivery of energy to steep waves, at frequencies above the peak of the spectrum, which yield results consistent with our observations of enhanced kinetic energy dissipation near the surface. □

Received 24 March; accepted 20 July 1992.

1. Williams III, A. J. *Mar. Geol.* **66**, 345–355 (1985).
2. Donelan, M. A. & Motycka, J. *Rev. scient. Instrum.* **49**, 298–304 (1978).
3. Agrawal, Y. C. & Belting, C. J. *Deep Sea Res.* **35**, 1047–1067 (1988).
4. Lumley, J. L. & Terray, E. A. *J. phys. Oceanogr.* **13**, 2000–2007 (1983).
5. Terray, E. A. & Bliven, L. F. in *The Ocean Surface* (eds Toba, Y. & Mitsuyasu, H.) 395–400 (Reidel, Dordrecht, 1985).
6. Jones, I. S. F. in *The Ocean Surface* (eds Toba, Y. & Mitsuyasu, H.) 437–442 (Reidel, Dordrecht, 1985).
7. Soloviev, A. V., Vershinsky, N. V. & Bezverchnii, V. A. *Deep Sea Res.* **35**, 1859–1874 (1988).
8. Large, W. G. & Pond, S. *J. phys. Oceanogr.* **11**, 324–336 (1981).
9. Longuet-Higgins, M. S. *J. Fluid Mech.* **240**, 659–679 (1992).
10. Wu, J. *J. Fluid Mech.* **68**, 49–70 (1975).
11. Arsenyev, S. A., Dobroklonsky, S. V., Mamedov, R. M. & Shelkovnikov, N. K. *Izv. atmos. ocean. Phys.* **11**, 530–533 (1975).
12. Dillon, T. M., Richman, J. G., Hansen, C. G. & Pearson, M. D. *Nature* **290**, 390–392 (1981).
13. Kitaigorodskii, S. A., Donelan, M. A., Lumley, J. L. & Terray, E. A. *J. phys. Oceanogr.* **13**, 1988–1999 (1983).
14. Oakey, N. S. & Elliott, J. A. *J. phys. Oceanogr.* **12**, 171–185 (1982).
15. Stewart, R. W. & Grant, H. L. *J. geophys. Res.* **67**, 3177–3180 (1962).

ACKNOWLEDGEMENTS. We acknowledge financial support from the NSF, ONR and PERD.