Wave Breaking and Near-Surface Turbulence

David M. Farmer
Graduate School of Oceanography (educational)
University of Rhode Island
Narragansett, RI 02882
Phone: (401) 874-6222 fax (401) 874-6889 email: dfarmer@gso.uri.edu

Johannes Gemmrich
Institute of Ocean Sciences
Fisheries and Oceans Canada (foreign government)
PO Box 6000, Sidney, B.C., Canada V8L 4B2
phone: (250) 363-6339 fax: (250) 363-6798 email: gemmrichj@dfo-mpo.gc.ca

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LONG-TERM GOALS

Our long term goal is to understand and develop robust parameterizations of vertical exchange near the ocean surface, and to identify and parameterize the link between exchange processes and their remotely sensed signatures.

OBJECTIVES

The full potential of remote sensing techniques for studying air-sea interaction is limited by our understanding of the mechanisms determining the remotely sensed signals. Remote sensing from above the ocean surface, such as infra red imaging, can detect the effects of near surface turbulence on the surface properties. Our objectives are to identify the link between such remotely sensed surface signatures and the subsurface processes through direct measurement of turbulence. A further objective is to improve our understanding of, and ability to parameterize, wave characteristics, wave breaking, air entrainment and bubble size distributions, and near-surface turbulence.

APPROACH

We monitor the turbulent velocity field with pulse-to-pulse coherent Doppler profilers with 20 Hz pulse rate, ~1m path length and 6 mm spatial resolution. The Doppler sonars are mounted on a wave-following float so as to maintain a fixed depth of ~ 1m from the free surface. This arrangement allows probing of the wave zone, including the region above the trough line. The velocity profiles directly yield wave-number spectra, which are then averaged to 1s sampling. Dissipation rates are estimated from averaged spectra consistent with an inertial sub-range. The bubble size distribution is measured with a resonator placed close to the acoustic Doppler profiler. Video recordings of the float allow verification of wave breaking events and provide estimates of size and propagation speed of whitecaps. The wave field is monitored with side-scanning sonars deployed at greater depth.

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14. ABSTRACT
Our long term goal is to understand and develop robust parameterizations of vertical exchange near the ocean surface, and to identify and parameterize the link between exchange processes and their remotely sensed signatures.

15. SUBJECT TERMS

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WORK COMPLETED

We have developed a surface tracking float supporting three Doppler sonars, two resonators and a thermistor and pressure sensor. A four week experiment was carried out on RP FLIP in September/ October 2000. During this experiment simultaneous measurements of the turbulent velocity field and the bubble field were acquired in the same vicinity as infra red imagery obtained by Dr. A. Jessup (APL, UW). The directional surface wave field was monitored with a suite of Doppler sonars mounted on the hull of FLIP. Measurements of the thermal structure of the surface layer were acquired with two strings of self-recording thermistors to a depth of 70 m. The turbulence data have been analyzed and a manuscript has been prepared for submission to the Journal of Physical Oceanography.

RESULTS

Vertical transport of heat, gases and particles in the near-surface zone depend on turbulent transport. Although previous studies have pointed strongly to the role of wave breaking as the cause of enhanced turbulence in the ocean surface layer, the direct link between a breaking event and enhanced dissipation remains to be established. Our simultaneous and coincident video imagery of wave breaking and measurements of the turbulent velocity and bubble field just beneath the surface permit allow us to analyze the relationship between wave breaking and turbulence.

At wind speed $U \sim 13$ m/s we find the time averaged dissipation is ~ 60 times larger than expected in a constant stress layer (Figure 1). However, our high sampling rate reveals a bimodal structure of the near-surface turbulence. Shear-generated turbulence, consistent with wall-layer scaling, is overlaid by breaking-wave induced turbulence. The latter is 2-3 orders larger than shear-induced turbulence and consists of brief events of <<60 s duration.

The average evolution of turbulence and bubble field beneath breaking waves is shown in Figure 2. The breaking crest is generally the highest crest within the wave group, roughly 50% higher than the previous or subsequent crests. Associated with the breaking crests are the largest dissipation levels. Dissipation increases rapidly on the forward face of the wave crest and the observed 3000-fold increase represents a lower bound for the dissipation beneath breaking waves. The increase in turbulence levels occurs up to a quarter wave period prior to the bubble cloud reaching the sensor depth.

Thus, wave-enhanced turbulence is not only caused by air entrainment and the associated conversion of potential energy to turbulent kinetic energy, but also by dynamical processes related to the steep wave itself. Possible sources of turbulent kinetic energy are wave-turbulence interaction such as Reynolds stresses working against the shear of the rotational component of the wave orbital motion. (Thais & Magnaudet, 1996). The observed velocity and time scales are consistent with such a process. Following the turbulence generation by the breaking wave, the float is advected in and out of the turbulent patch by subsequent waves. The evolution of the subsequent dissipation maxima represents the decay of the wave-induced turbulence, $\varepsilon \propto t^n$, with $-4.3 < n < -2.9$, in good agreement with the theoretical dissipation decay rate for isotropic turbulence of $n = -4.25$. A simple extrapolation then yields the unresolved maximum enhancement at the breaking crest: $log(\varepsilon_{max}/\varepsilon_{min}) = 4.6$. The corresponding Hinze scale a_H ~2mm, has implications for the initial break-up of entrained air. Air fraction beneath breaking waves increase rapidly. The presence of air bubbles can be tracked for at least five wave periods following the breaking event. These increased air fractions are associated with a shift in the bubble size distribution towards larger bubbles.

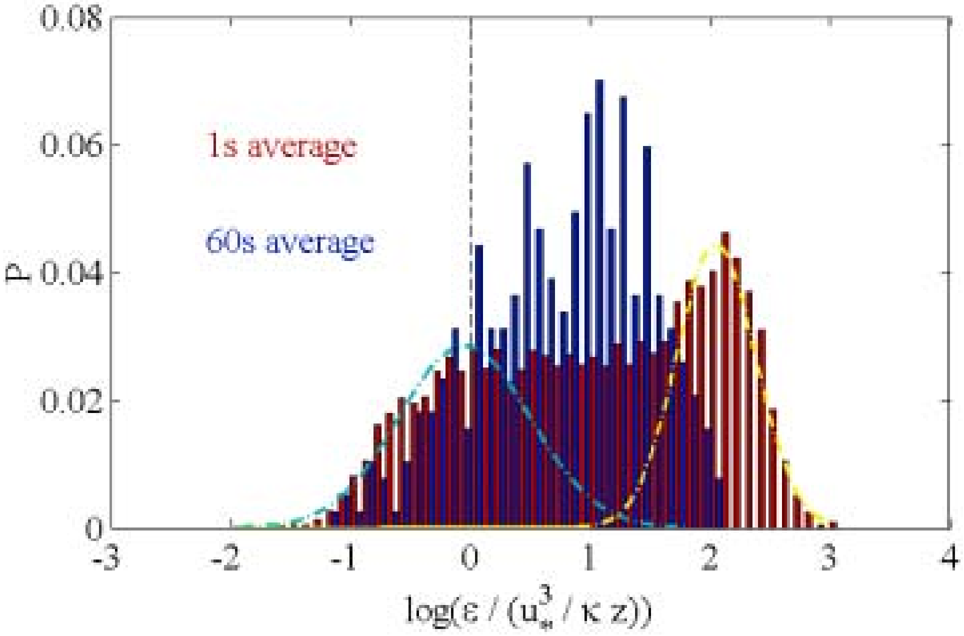

Figure 1: Distribution of dissipation enhancement (red bars). The distinct pattern of higher dissipation levels (red bars) has been shown to be associated directly with wave breaking. Dash-dotted lines depict contribution of turbulent shear production (light blue) and wave-breaking induced turbulence (yellow). This information is lost in the commonly used longer averaging period (blue bars).

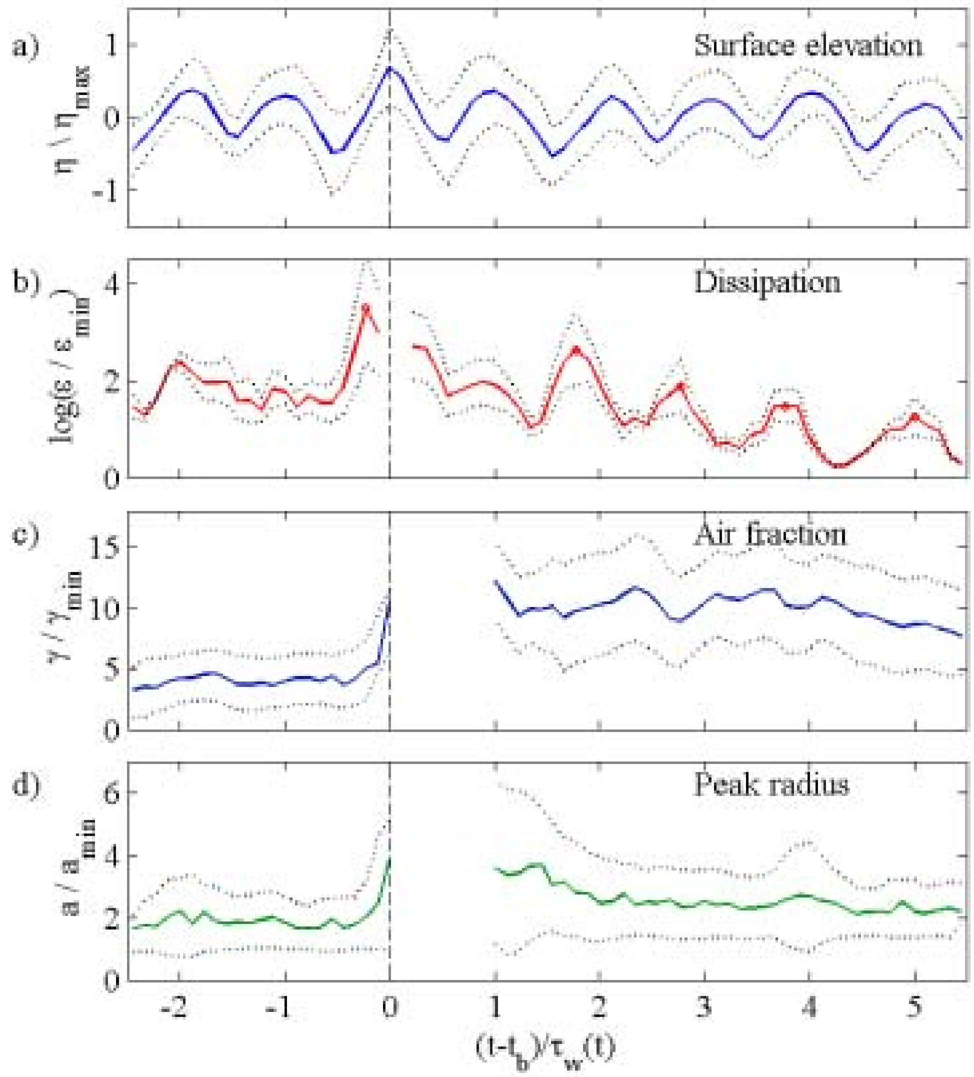

Figure 2: Average signal associated with wave breaking. Time is normalized by the local wave period τ_w, centered at the passage of the breaking crest. The breaking wave is generally the largest of the wave group (a) and is associated with the largest dissipation. Subsequent dissipation peaks (dots) describe the decay of turbulence $\varepsilon \propto t^n$, $-4.3 < n < -2.9$ (b). A strong increase in subsurface air fraction (c) and increased bubble size (d) is delayed by ~0.2 τ_w, and lasts more than 5 wave periods.

The conditionally averaged dissipation is largest just beneath wave crests, but has a strong depth dependence above the mean water line $\varepsilon \propto z^{2.3}$ (Figure 3). The average dissipation above the mean water line is more than twice that between the wave trough and mean water line. The strong dissipation above the trough line, a region not accessible by tower–based observations, illustrates the importance of surface following measurements and data interpretation.

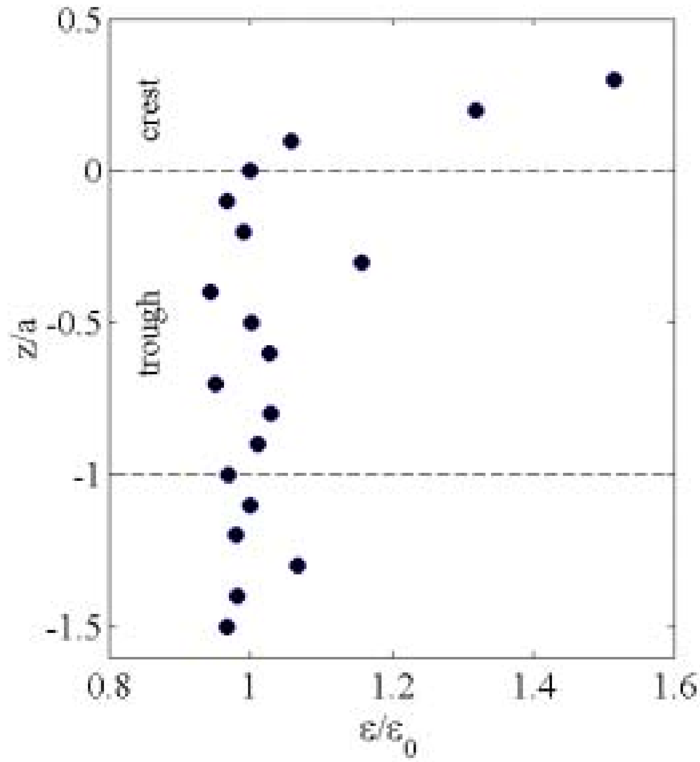

Figure 3: Average dissipation profile within waves. Depth z is normalized by the wave amplitude a. Dissipation increases rapidly above the mean water line z/a=0.

IMPACT/APPLICATIONS

Potential future impact for Science and/or Systems Applications

These measurements of wave induced turbulence in the open ocean provide a basis for understanding and modeling vertical transfer near the sea surface and its remotely sensed characteristics. They also highlight the importance of the wave region above the trough line, commonly neglected in turbulence models.

TRANSITIONS

Near surface turbulence measurements are being used by other FAIRS participants, in particular, Dr A Jessup, in the interpretation of infra red images.

RELATED PROJECTS

This work is closely linked to collaborative ONR-funded research with M Banner to develop robust parameterization of wave breaking.

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