# Measurements of Wave Breaking and Dissipation over the Continental Shelf

W. Kendall Melville
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093-0213
phone: (858) 534-0478     fax: (858) 534-7132     email: kmelville@ucsd.edu

## LONG-TERM GOALS

The long-term goals of this research are to quantify the incidence of surface wave breaking and its role in dissipating wave energy which is then available to generate currents and turbulence in the upper ocean.

## OBJECTIVES

The objectives of this project are to develop and use remote and in situ techniques to measure the kinematics and dynamics of breaking and relate them to the dynamics of the wave field and the surface mixed layer. Of particular interest is the dissipation of surface wave energy by breaking.

## APPROACH

The approach revolves around the use of aerial imaging from light aircraft in the coastal zone and quantitative image sequence analysis using techniques of Particle Imaging Velocimetry (PIV) to measure the kinematics of whitecaps. Kinematic measurements can be used to investigate aspects of surface mixing including estimates of the rate of mixing of the surface layer. In conjunction with simple scaling arguments to relate the kinematics of breaking to the dynamics, and laboratory experiments on breaking, the remote data can be used to investigate wave dissipation and the momentum flux from waves to currents. In situ measurements of waves and currents will be compared with the remote measurements.

The key people within our research group were Eric Terrill who oversaw the *in situ* measurement program, and Peter Matusov, who has been involved in all aspects of the airborne measurements and data analysis.

## WORK COMPLETED

This project has focused on the Shoaling Waves Experiment conducted off Duck, N. Carolina in the fall of 1999. During that experiment our imaging system, the Modular Aerial Imaging System (MASS) was flown on the Long-EZ by Tim Crawford of NOAA. Using the data acquired from that experiment we have developed algorithms based on both PIV and simpler techniques to analyze the image sequences to measure $\Lambda(c)$ dc, the mean length of breaking fronts per unit area of ocean traveling with speeds in the range (c, c+dc) (Phillips, 1985). This statistic forms the basis of a hierarchy of moments

| | | Form Approved OMB No. 0704-0188 |
|---|---|---|

# Report Documentation Page

| 1. REPORT DATE **30 SEP 2001** | 2. REPORT TYPE | 3. DATES COVERED **00-00-2001 to 00-00-2001** |
|---|---|---|
| 4. TITLE AND SUBTITLE **Measurements of Wave Breaking and Dissipation over the Continental Shelf** | | 5a. CONTRACT NUMBER |
| | | 5b. GRANT NUMBER |
| | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | 5d. PROJECT NUMBER |
| | | 5e. TASK NUMBER |
| | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Scripps Institution of Oceanography,,University of California, San Diego,,La Jolla,,CA, 92093** | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT
**The long-term goals of this research are to quantify the incidence of surface wave breaking and its role in dissipating wave energy which is then available to generate currents and turbulence in the upper ocean.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a REPORT **unclassified** | b ABSTRACT **unclassified** | c THIS PAGE **unclassified** | **Same as Report (SAR)** | **8** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

that can be used to investigate the kinematics and dynamics of breaking. Figure 1 shows examples of the image data, the traditional whitecap coverage and an example of the PIV processing on a single whitecap.

Two moorings were deployed to measure near-surface turbulence (ADV and Dopbeam sensors) and temperature fields and bubbles entrained by breaking waves. Two bottom ADCP/pressure packages were deployed to measure waves and currents on the shelf. One mooring suffered a failure during a hurricane and was redeployed. One of the moorings was inexplicably destroyed by the Canadian Coast Guard vessel *Creed* during good weather.

## RESULTS

A first set of MASS data from SHOWEX has been analyzed, written up and submitted for publication (Melville & Matusov, 2000). We have shown that during SHOWEX $\Lambda(c)dc$ increases like the wind speed cubed, $U_{10}{}^3$, and decays exponentially with the breaker speed, c. Since the breaking statistics depend on the directional wave spectrum, and since there is no universal wave spectrum over the full range of breaking waves, we do not expect any universal shape for $\Lambda(c)dc$. Simple physical and dimensional arguments provide interpretations of the various moments of $\Lambda(c)$. For example, the first moment is proportional to the rate of mixing of the surface area by breaking, the third is proportional to the volume mixed, the fourth is proportional to the momentum flux from waves to currents and the fifth is proportional to the wave dissipation. These moments are shown in Figure 2. Note that as you move to higher moments the mode of the distribution moves to larger values of c. Since c scales approximately with the phase speed of the breaking waves, this implies that while small-scale waves contribute most to the length of the breaking fronts, longer waves are responsible for momentum transfer and dissipation. Since the vector **c** and not just the speed are measured, we can examine the directional distribution of $\Lambda(\mathbf{c})$ and its moments can be measured. Examples in Figure 3 show that for the SHOWEX data, $\Lambda(\mathbf{c})$ and its moments are approximately symmetric about the wind direction.

The in situ data from the surface moorings shows that the dissipation of turbulent kinetic energy (TKE) measured by the Dopbeam correlates with the modulation of the surface waves or wave groups. An example of this data is shown in Figure 4. Analysis of the Dopbeam, ADV and temperature data continues.

## IMPACT/APPLICATIONS

During this project we have shown that methods of PIV developed in the laboratory can be used to analyze airborne imagery to measure the kinematics and, with supporting assumptions, the dynamics of wave breaking. These results are novel and are the consequence of the convergence of technical developments in the areas of imaging, position/motion detection (DGPS and inertial systems) and imaging software. While we have concentrated on visible imagery, the same approach could be taken with IR and hyperspectral imagery to study the kinematics of different fields including temperature.

While not yet completed, the *in situ* data shows great promise for making acoustical measurements of ocean microstructure directly in the wavenumber domain. This avoids the use of Taylor's hypothesis to move from the frequency domain to wavenumber domain; an approach that is fraught with problems in the surface wave zone which is dominated by the orbital; motion of the waves.

**TRANSITIONS**

We expect to be able to transition the imaging system to the measurement of breaking and spray generation in hurricanes.

**RELATED PROJECTS**

Related projects are described on our web page at http://airsea.sio.ucsd.edu.

**REFERENCES**

Phillips, O.M. 1985 Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. J. Fluid Mech., **156**, 505-531.

**PUBLICATIONS**

Melville, W.K. & Matusov, P. 2000 Measurements of the distribution of breaking waves at the ocean surface: a simple statistical description. *Nature*, submitted.
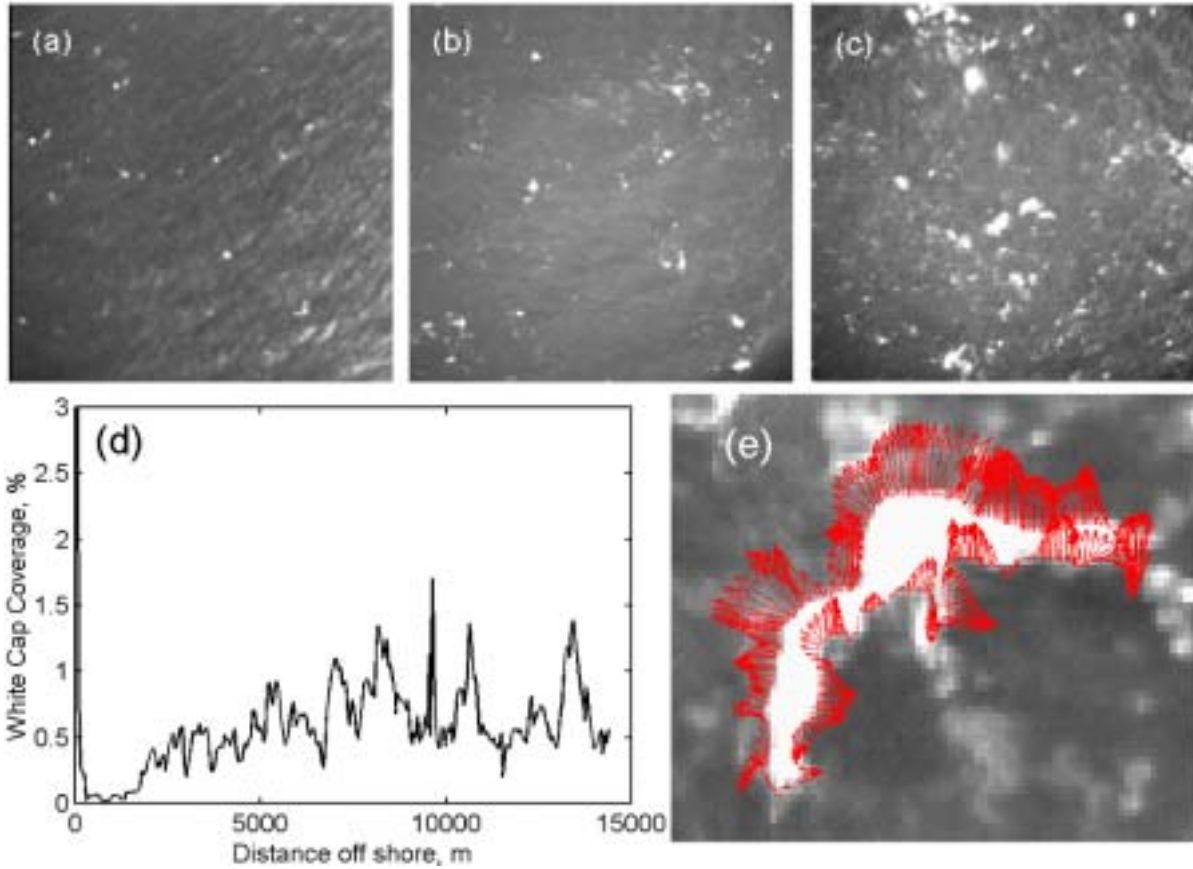
*Figure.1a-c: Images showing approximately 160 m x 160m of the sea surface for mean wind speeds, $U_{10}$, of 7.2, 9.8 and 13.6 m s$^{-1}$, respectively, in SHOWEX. Note the increasing density of whitecaps with $U_{10}$ and their random shapes.*
*Figure 1d Whitecap coverage as the aircraft flew offshore. Note the large fluctuations at spatial scales of O (1- 10) km that may be due to both local wind and wave modulations.*
*Figure 1e: The result of processing a single whitecap using the PIV technique in which the normal velocity of the boundary of the whitecap is resolved.*
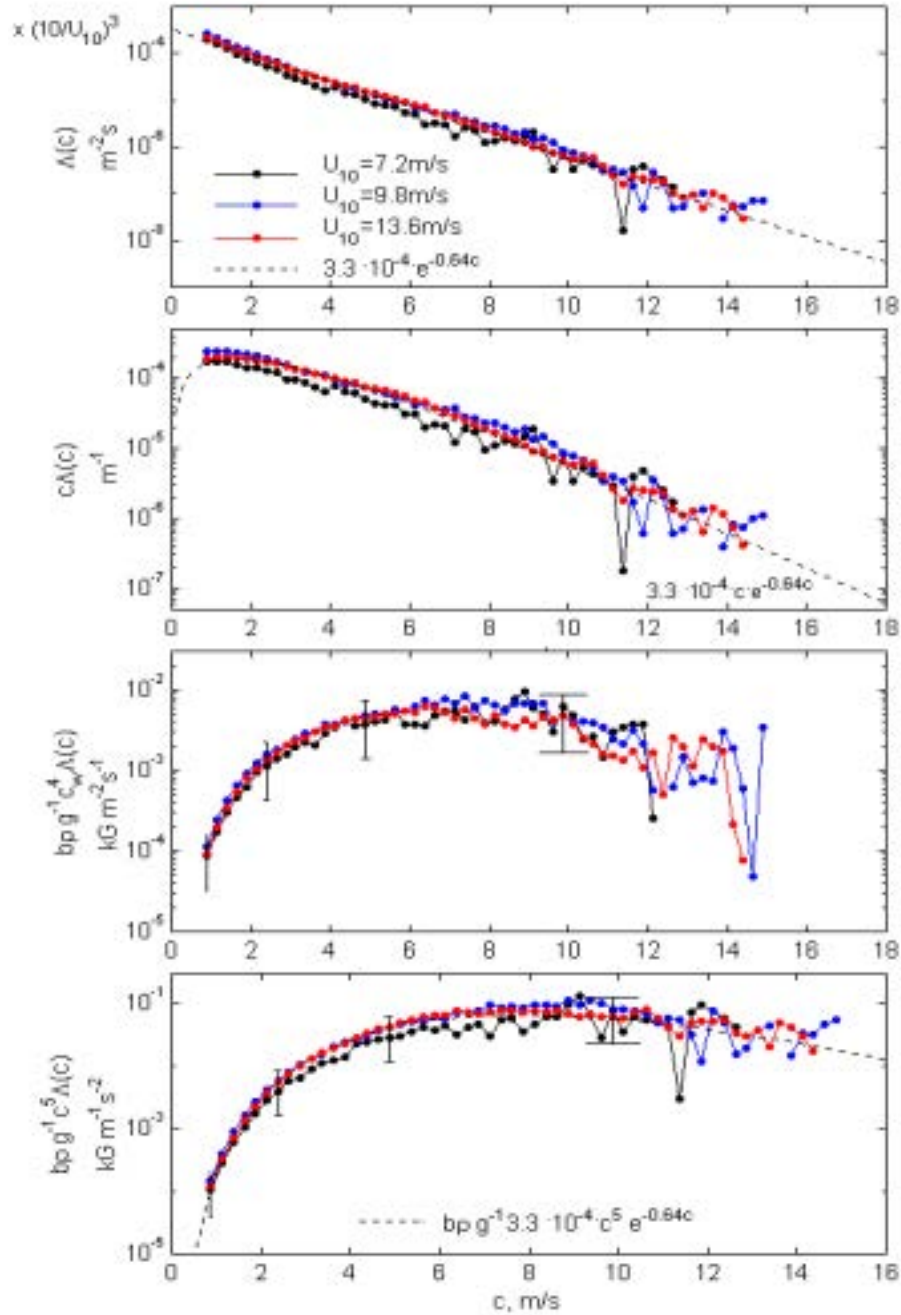
*Figure 2a. Binned measurements of Λ(c) weighted by $U_{10}^{-3}$ showing that the average length of breaking fronts in (c, c+dc) per unit area of sea surface increases like $U_{10}^3$ and decays exponentially with c: Λ(c) = $3.3x10^{-4}.e^{-0.64c}$.*
*Figure 2b. The weighted first moment of Λ(c) which corresponds to the fractional area swept out (turned over) by breakers in the speed range (c,c+dc) per unit time.*
*Figure 2c. The weighted fourth moment of Λ(c), $c^4Λ(c)_w$, which corresponds to the momentum flux from waves to currents due to whitecaps, with the subscript "w" referring to the component in the wind direction.*
*Figure 2d. The weighted fifth moment of Λ(c), which corresponds to the energy lost from the wave field due to breaking: "wave dissipation".*

5
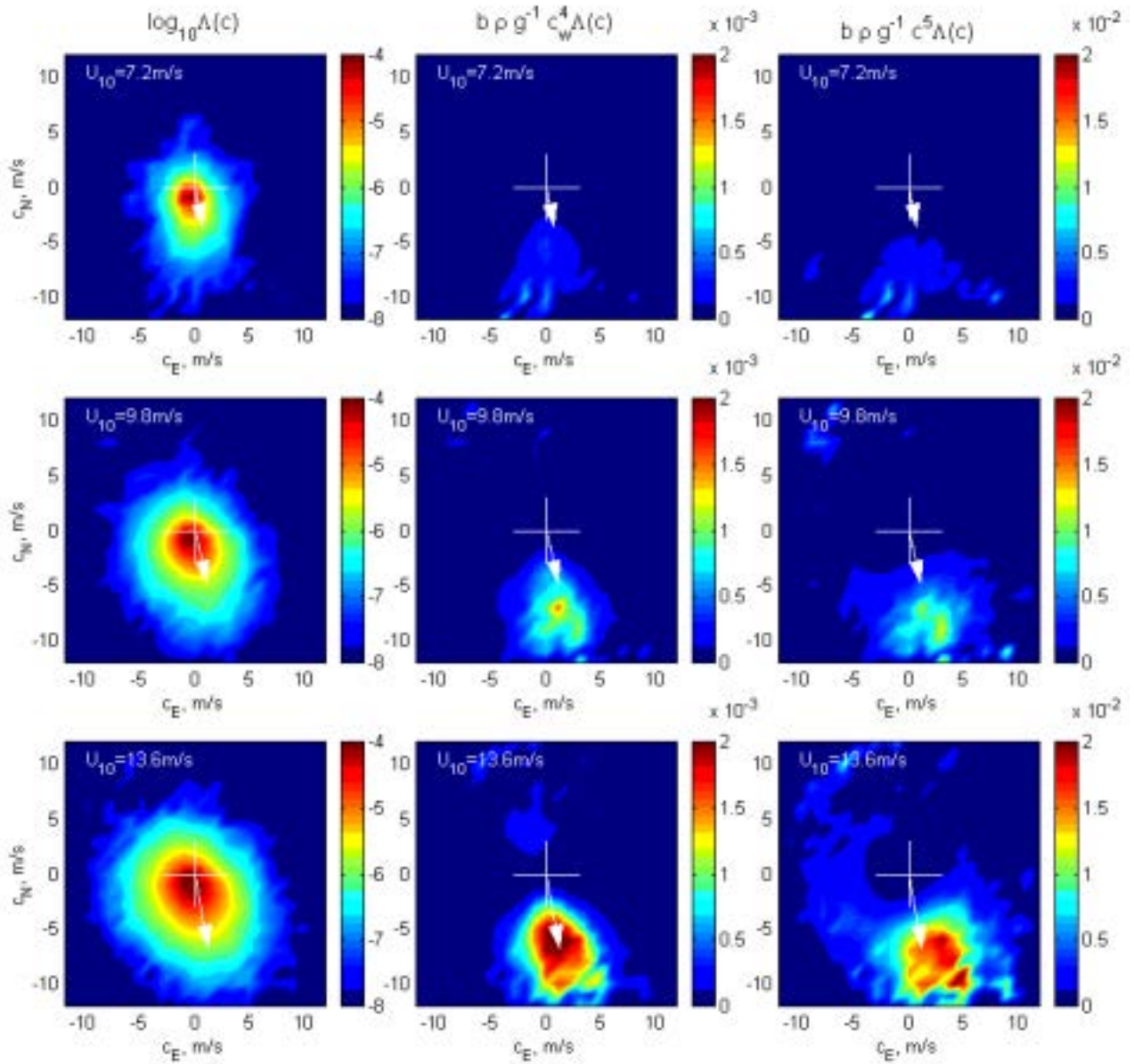
*Figure 3a. Distributions of Λ(c), with respect to the northerly and easterly components of c ($c_N$, $c_E$), along with the average wind direction (arrow). Note that the dominant orientation is close to the wind direction.*
*Figure 3b. The corresponding momentum flux from waves to currents due to breaking for the three wind-speeds. Note that as the wind increases the region of significant momentum flux becomes approximately symmetrical about the downwind direction (c.f. Fig. 2b).*
*Figure 3c. The corresponding distribution of the dissipation with ($c_N$, $c_E$).*
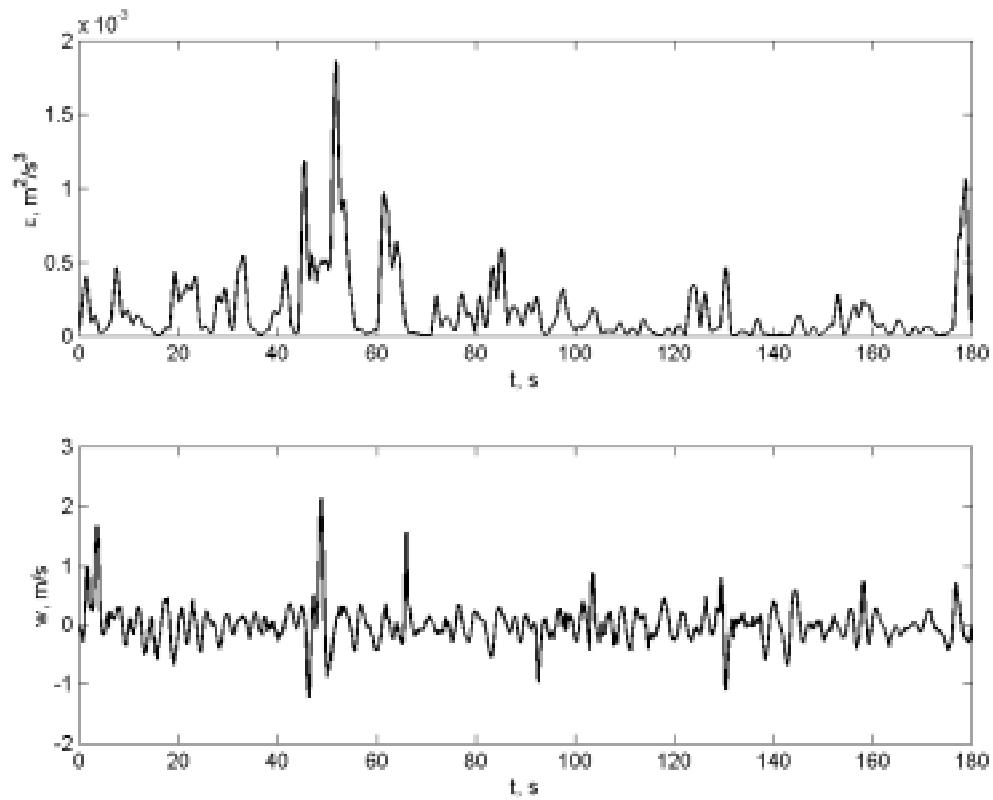
*Figure 4 Top: Inertial estimates of dissipation from the Dopbeam acoustic Doppler near the surface in SHOWEX.*
*Figure 4 Bottom: Simultaneous measurements of the vertical component of orbital velocity measured with an ADV on the same mooring. Note the corelation between the modulation of the wave field and the dissipation, especially around 45-50 s.*