Modulation of air-sea fluxes by microscale breaking waves.

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Air-sea gas flux 2016
Energy, momentum, and mass transfer between the atmosphere and ocean are all controlled by the surface wave field.
**Experimental configuration**

**FLIP**
- Stable
- Minimal air-flow or wave field distortion
- Long booms

**3 Experiments:**
- Hawaii, Southern California, Northern California

- **70 20-minute records:**
  - Wind speed $U_{10} = 1.6 – 16 \text{ m/s}$
  - Significant wave height $H_s = 0.7 – 4.7 \text{ m}$
  - Wave age $c_m/u_* = 16 – 150$

**Stereo LWIR cameras**
- FLIR SC6000
- 640x512 pixels
- 40 Hz

**Eddy Flux system**
- $u', v', w', T \rightarrow \tau, u_*, U_{10}$

**Fixed depth array:**
- ADV, Aquadopp, fast CT sensor, hydrophone

**IR Camera field of view**

**Foam floats**

**Surface following Aquadopp float**

**Profiling array:**
- ADV, Aquadopp, fast CT sensor

**Automatic profiling**
Stereo infrared

- 2x FLIR SC6000 Long wave infra red (LWIR)

- Surface temperature structure is used as a passive tracer over short $\Delta t$
  - active breakers
  - remnants of past breakers
  - surface signature of turbulence

- FOV $\sim 3 \text{ m } \times 4 \text{ m}$; 6 mm resolution

8$\mu$m to 9.2$\mu$m IR wavelengths
2x$10^{-5}$m penetration depth
Stereo infrared surface reconstruction

Reconstructed surface, 2009/09/08 11:07:29.5. U10 = 7.7 m/s, Hs = 2.4 m
Images taken December 6, 2010, 22:02:32.75 [UTC], U10 = 6.5 m/s, Hs = 1.1 m
\( \Lambda(c) = \text{Distribution of breaker crest length per unit area of sea surface per unit increment of breaking crest speed } c. \)

\[
L = \int \Lambda(c) dc = \text{Total crest length per unit area [m}^{-1}\text{]}
\]

\[
R = \int c\Lambda(c) dc = \text{Fractional overturn per unit time [s}^{-1}\text{]}
\]

Related to heat and gas transfer.
Breaker crest length distribution. $\Lambda(c)$
Surface renewal

\[ R = \int c \Lambda(c) \, dc \quad \text{Fractional overturn per unit time} \ [s^{-1}] \]
$\Lambda(c) = \text{Distribution of breaker crest length per unit area of sea surface per unit increment of breaking crest speed } c.$

$$F_m = \frac{\rho_w}{g} \int b c^3 c \Lambda(c) dc = \text{Stress} \ [N/m^2]$$

$$F_E = \frac{\rho_w}{g} \int b c^5 \Lambda(c) dc = \text{Dissipation} \ [W/m^2]$$

Breaking strength parameter
Depends on wave slope
Parameterized as a function of spectral saturation (Romero et al. 2012)
Momentum flux by breaking

$\rho_w g^{-1} \int \frac{v}{h} \left( c_i \right) \, de \quad [N/m^2]$

$\rho_a u_i^2 \quad [N/m^2]$

$c_i / \rho_a$

Measured wind stress
Measuring TKE dissipation near the sea surface is challenging:
- Waves + turbulence have motions at the same spatial and temporal scales
- Instrument wakes
- Intermittent processes
...
**Vorticity** $\omega = \nabla \times u$ for separation of irrot. waves from turbulence

Helmholtz decomposition:

$$u = -\nabla \phi + \nabla \times A$$

- $u_I$: Irrotational velocity
- $u_R$: Rotational velocity

Vorticity field contains no irrotational wave component
Energy dissipation by wave breaking

$U_{10} = 6.5 \text{ m/s}$
$H_s = 1.1 \text{ m}$
$T_p = 4.9 \text{ s}$

TKE Dissipation
Thermal structure PIV

Surface elevation
Stereo imagery
Sub-surface TKE dissipation

\[ z = 0 \]

**Near-surface float**

\[ u(x,t) - v(y,t) - w(z,t) \]

**Lowered profiler**

- Fast CT probe
- \( w(z,t) \)
- \( u(x,t) \)
- ADV head, 10 or 16 MHz
- Data Cable
- ADV body
- XSens IMU
- Instrument housing

**Aquadopp Profiler HR**

- 2MHz, pulse coherent

**Fixed Depth**

**Profiling**

- \( \varepsilon \) [m²/s³]
- \( z \) [m]

**Graph**

- Vertical
  - LTMI 1
  - LTMI 2
  - LTMI 3

**Legend**

- \( \varepsilon \) [m²/s³]
Comparison with wall-layer

\[ (c_m/u_*)^{3.15} \]
Dissipation by breaking vs. total near-surface TKE dissipation

- Agreement in young waves

- Disagreement in light winds / old waves

Sub-surface measurements connected to surface measurements using a $z^{-1}$ profile
Turbulence profile comparison with LES

*Sullivan, McWilliams, and Melville 2007*

Breakers applied as body forces

Body force shape functions from Melville, White, and Veron, 2002

Breaker distribution from Melville and Matusov 2002

Langmuir Circulations

\[ l_b = \frac{c_p^2}{g} \]

\[ c_p/u_* = 19 \]

\[ 23 \]

\[ 30 \]
Breaker crest length distribution. $\Lambda(c)$
Conclusions

- Small scale breaking is dynamically important (surface renewal, stress, and dissipation).
- When small scale breaking is included, wave dissipation can be balanced with dissipation by breaking and measured wind stress can be balanced by momentum flux by breaking over a broad range of conditions.
- Energy is dissipated very near the surface; the majority of energy is dissipated at depths $< H_s$ from the sea surface.

- Developed a new method to measure TKE dissipation at the wavy sea surface.

[link: psutherland.ca/publications.html]


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