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The role of breaking deep-water surface waves in air-sea interaction

Photo: Peter Sutherland

KITP 2018

Overview

Wave breaking modulates the transfer of mass, momentum, and energy across the air-sea interface.

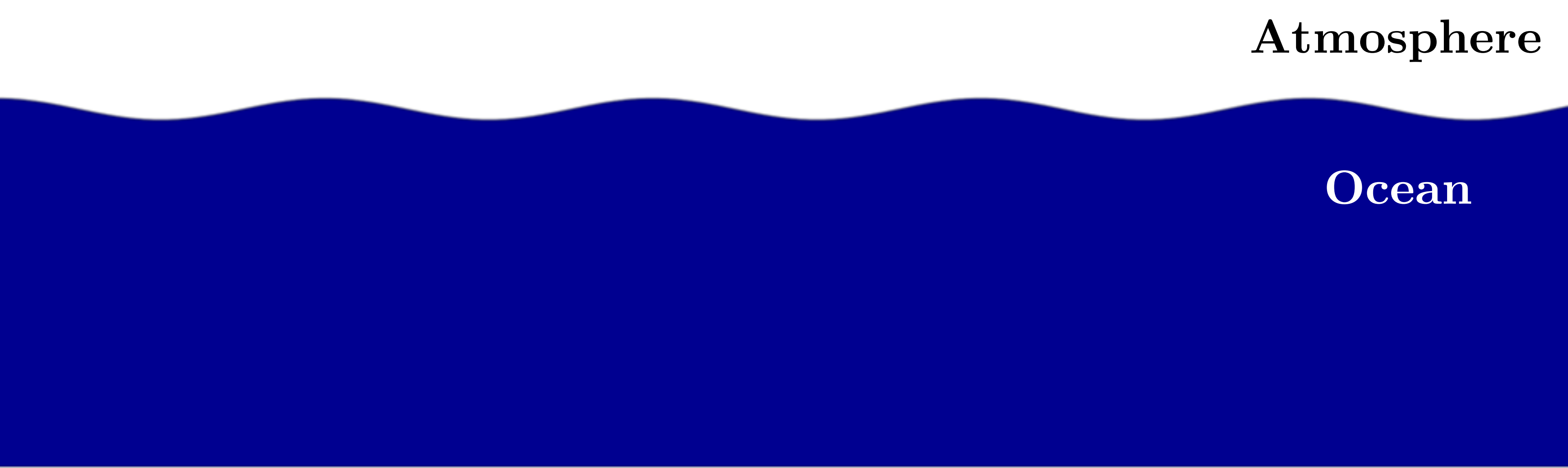
What do we know about breaking, and how do we account for it in models of larger scale processes?

- For example: Should we include bulk budgets of momentum flux transferred by breaking in surface stress, or do we need a more sophisticated model?

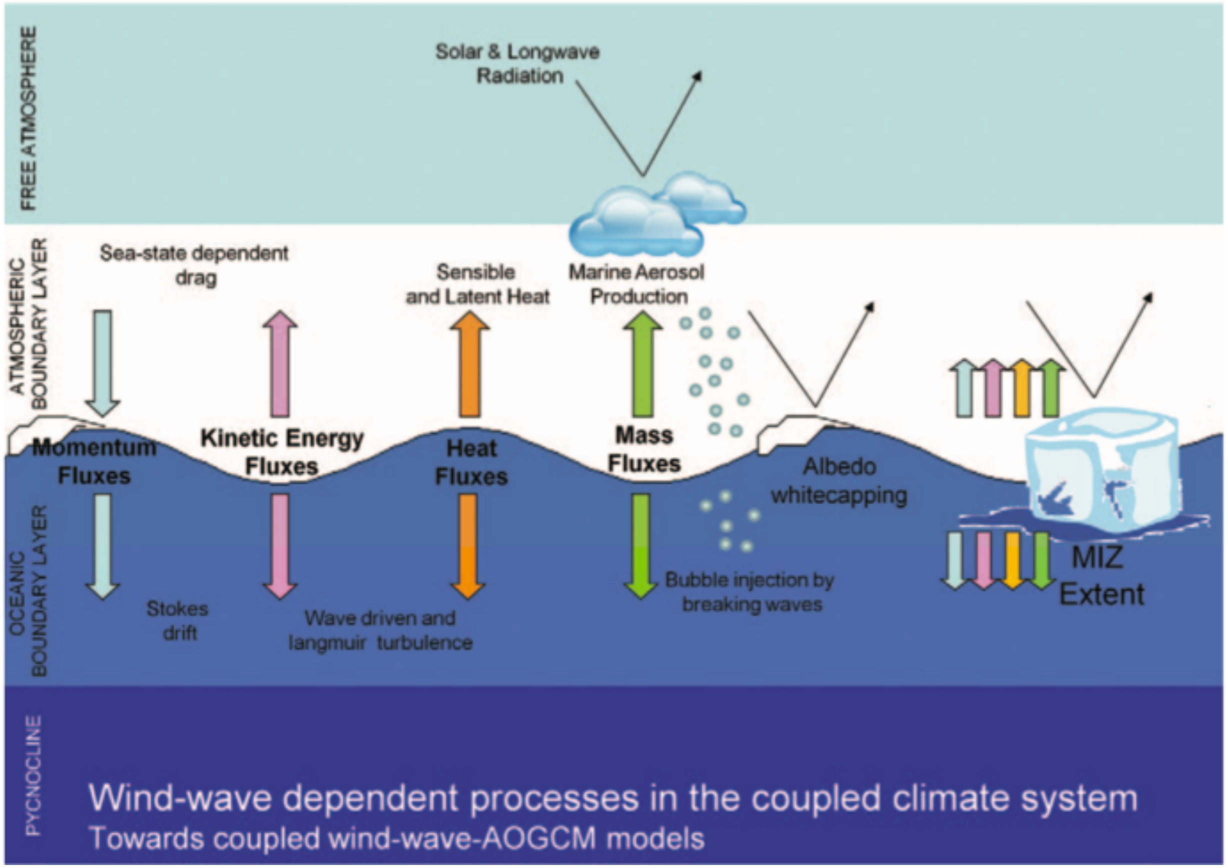
- I: Background
- II: Laboratory experiments on wave breaking and scaling arguments
- III: Extension to the field
- IV: Implementation in numerical models
- V: Some open problems

The upper ocean (Gill 1982)

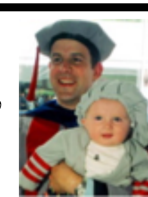
- 40% of solar radiation incident on atmosphere is absorbed in first 10 m of ocean
- First 10 m of ocean has same weight as atmosphere above it
- First 2.5 m of water column has same heat capacity as (dry) atmosphere above it



Air-sea boundary layer



Despite the differences in length scales **O(1 mm–100 m)** and time scales **O(1 ms–1 h),** physics are closely linked.

Caveleri,  and Hemer (2012)

Waves at sea

Complexities of studying wave breaking

- Breaking is a two-phase turbulent unsteady flow, making problem out of reach using known **analytical** techniques.

- Scales of breaking packets range from O(1)mm (bubbles and capillary waves) to O(10)km (groups of swell), i.e. 7 orders of magnitude.
    - **Direct numerical simulation** over this *entire* range beyond current capabilities.

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La Jolla Cove

Photo: Brendan G

20 second period, 10 waves in a group corresponds to a wave group that is over 6km long.

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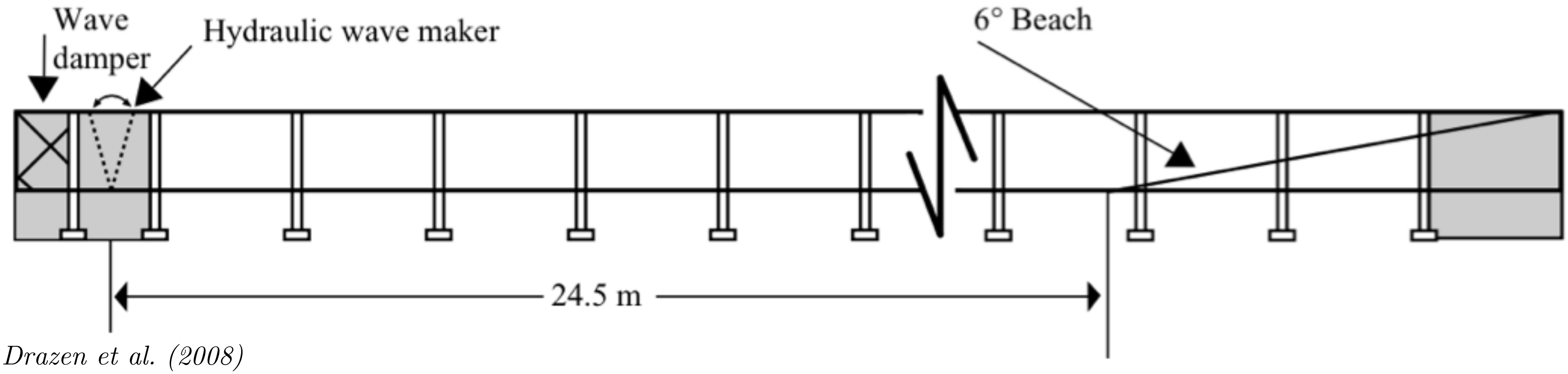
- Difficulty of making **measurements at sea** due to intermittency and nonlinearity of breaking, and **large forces on instruments.** Plus, there is the **cost.**

Wave breaking: Laboratory experiments

To isolate features of breaking in controlled environment, create breaking waves in the **laboratory**.

Wave channel at SIO



Drazen et al. (2008)

- 30m long
- $\frac{1}{2}$ m wide
- Filled with 60cm of water

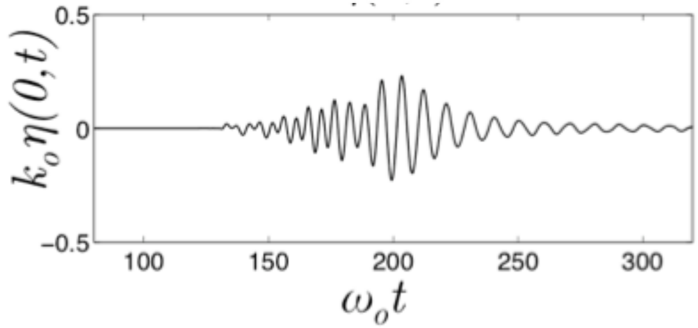
Wave breaking: Laboratory experiments

Dispersive focusing technique (Longuet-Higgins 1974)

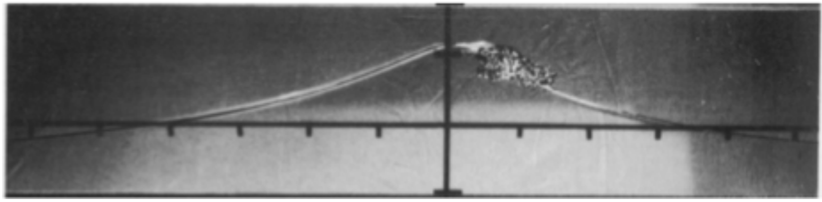
$$\eta(x,t) = \sum_{n=1}^{32} a_n \cos(k_n(x - x_b) - \omega_n(t - t_b));$$

$$\omega^2 = gk, \; c = (g/k)^{1/2}$$

Initial conditions



S=0.27 spilling breaker

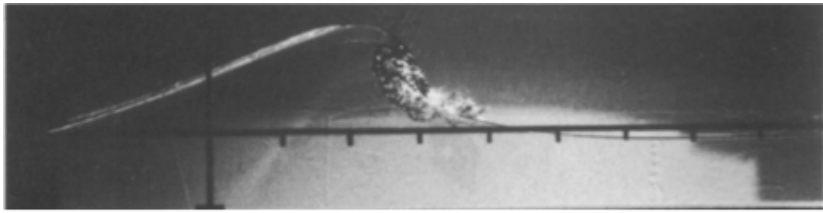


Wave packet parameter

Linear prediction of maximum slope at breaking

$$S = \sum_{n=1}^{32} a_n k_n$$

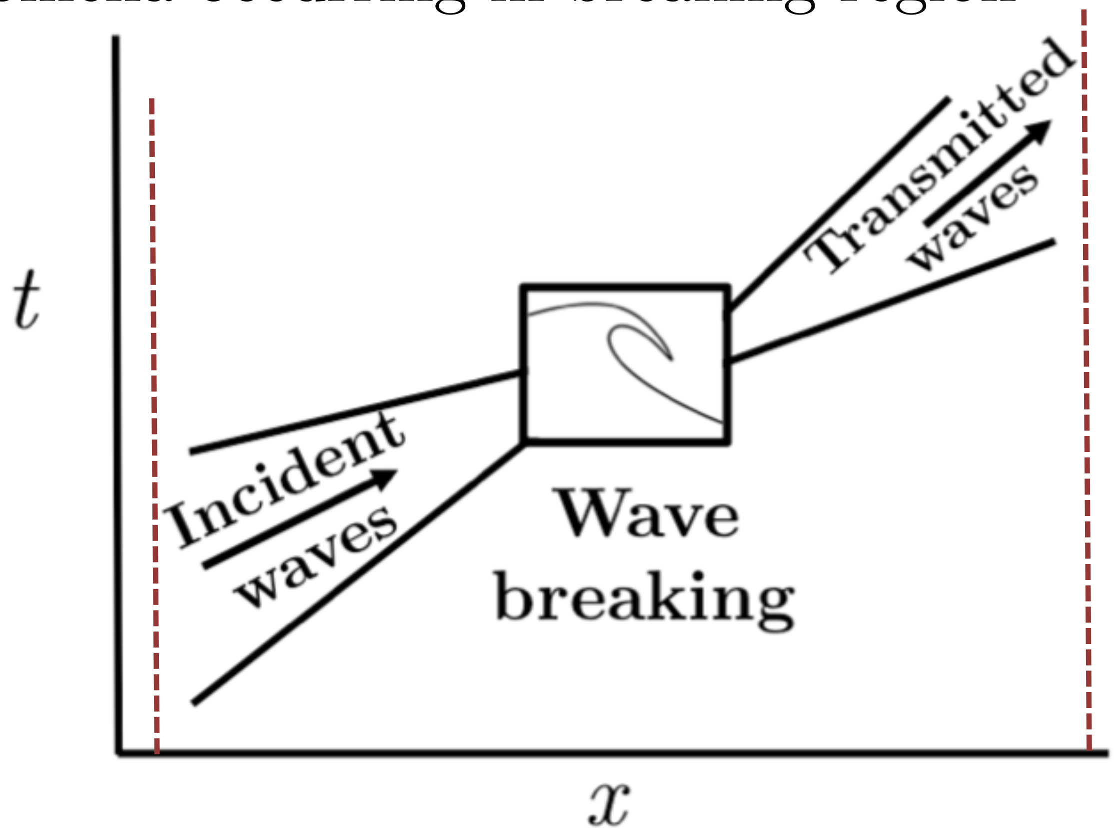
S=0.36 plunging breaker



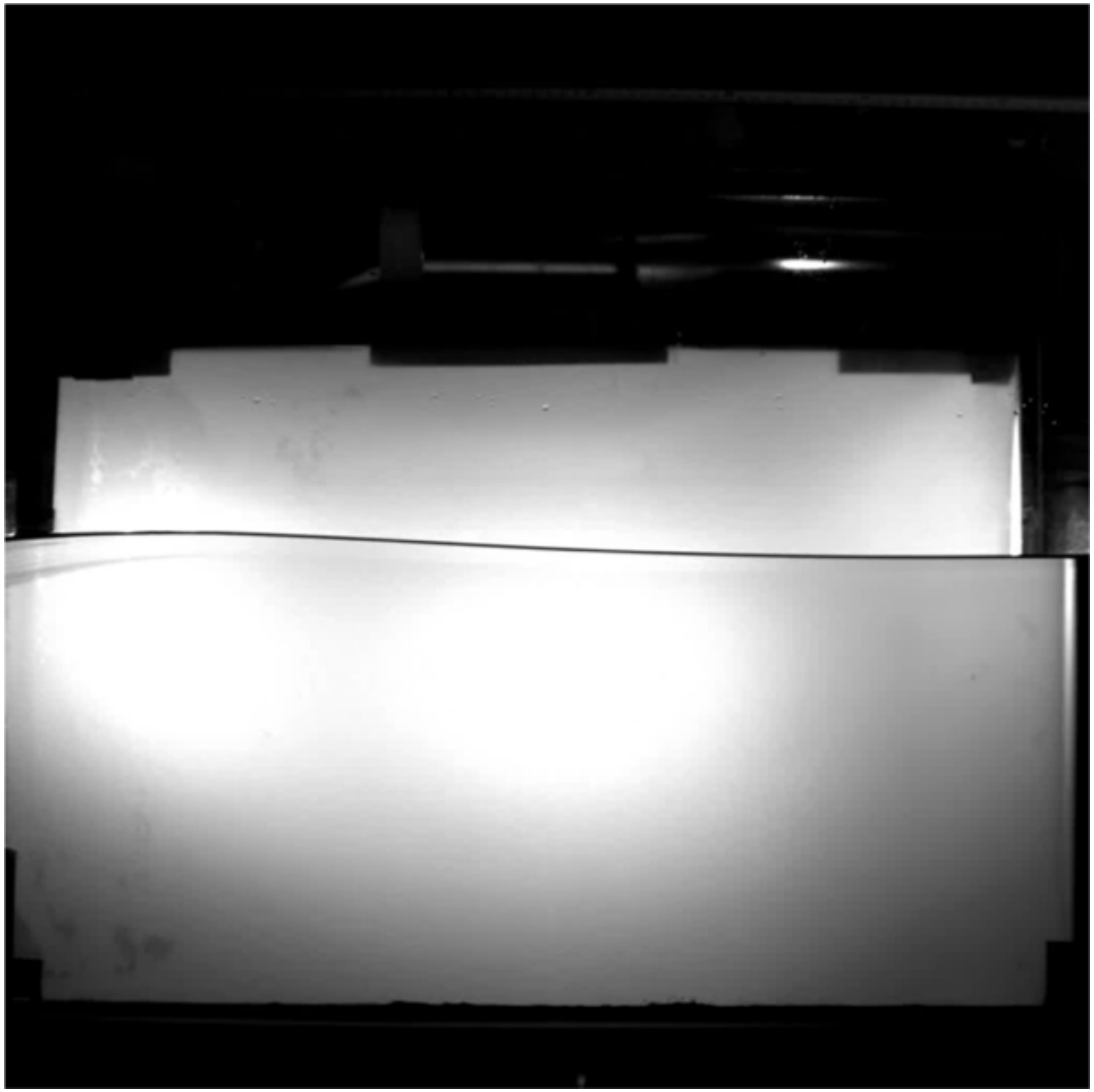
Rapp and Melville (1990)

Wave breaking: Laboratory experiments

- **Focusing** wave group
- "**Black box**" experiments.
  - Measure what goes in and what comes out.
- **Do not need to measure** many of the complicated phenomena occurring in breaking region



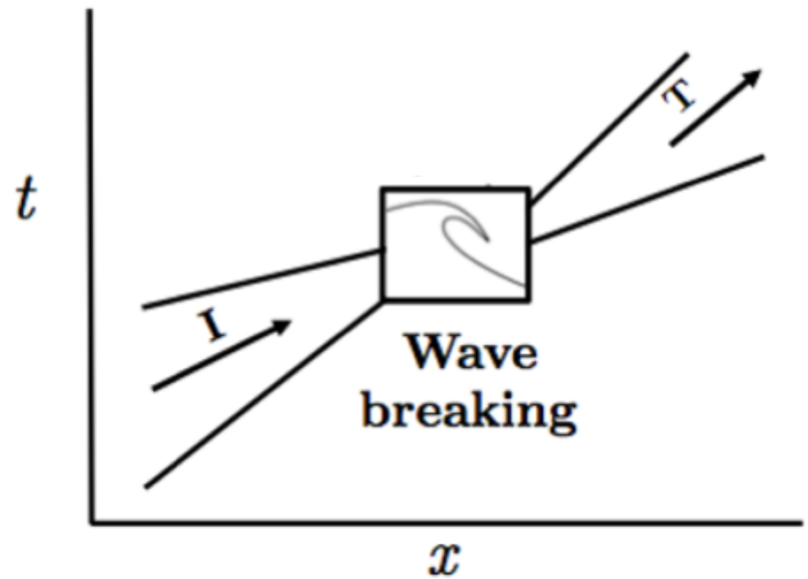
Wave breaking: Laboratory experiments



4 seconds in real time

Video: Luc Lenain

Energy dissipation by deep-water wave breaking



Given I, can we describe the energy remaining in T?

Duncan (1983), Phillips (1985), Rapp and Melville (1990), Melville (1994), Banner and Peirson (2007), Drazen et al. (2008), Romero et al (2012)

Motivation

- Breaking is an energy transfer from surface waves to currents and turbulence (available for mixing surface layers of ocean)

- Important for understanding coupling between waves and upper ocean dynamics, and improved surface-wave prediction schemes, e.g. radiative transfer equation:

$$\frac{\partial N}{\partial t} + (\boldsymbol{c}_g + \boldsymbol{U}) \cdot \nabla N = S_{nl} + S_{in} + S_{diss},$$

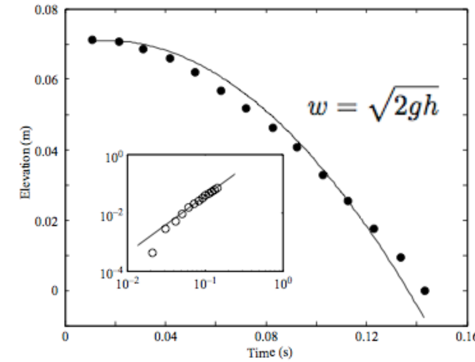
$N(\boldsymbol{k}) = g\psi(\boldsymbol{k})/\sigma$ Action spectral density

$\psi(\boldsymbol{k})$ Energy spectral density

The scales of a plunging breaking wave

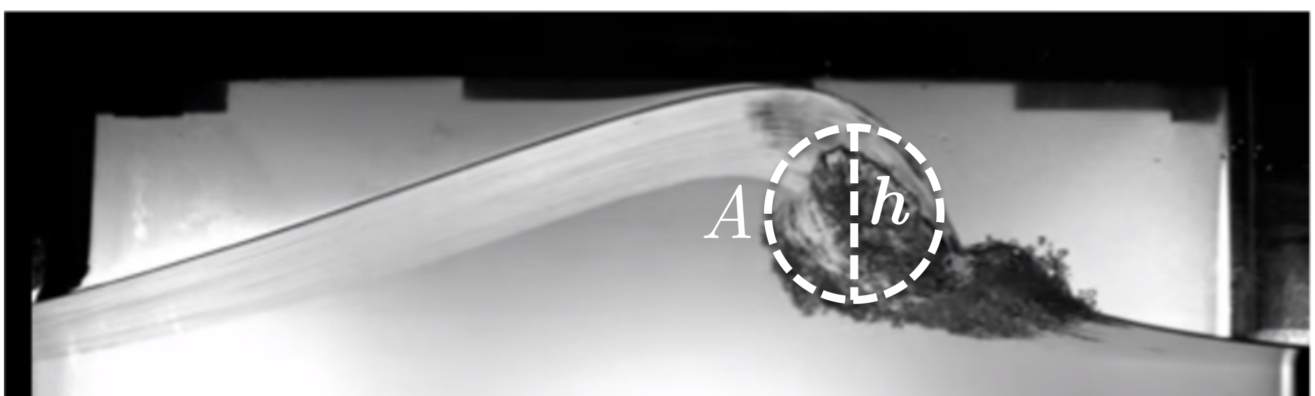
(i) Toe of breaking wave follows ***ballistic trajectory***

$w = (2gh)^{1/2}$



Drazen et al. (2008)

(ii) Area of entrainment $A \cong \pi h^2/4$ (Rapp and Melville 1990)



Scaling of energy dissipation ε_l

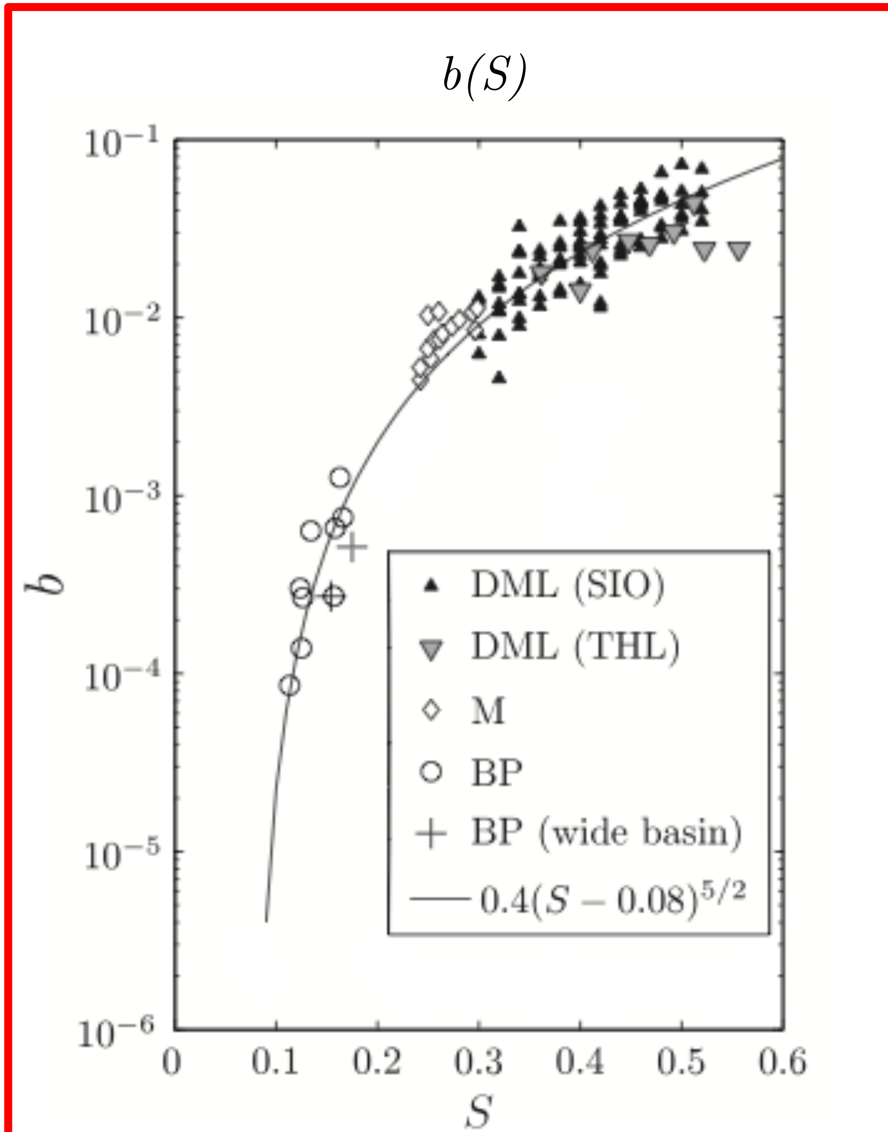
Drazen, Melville, Lenain (2008): inertial scaling (Taylor 1935) of energy dissipation rate ε_l , per unit length of breaking crest, due to a two dimensional *plunging* breaking wave:

$$\epsilon_l = \rho A \chi \left(\frac{w^3}{h} \right) = \chi \frac{\pi}{\sqrt{2}} g^{\frac{3}{2}} h^{\frac{5}{2}} = \mathrm{b} \frac{\rho c^5}{g}; \quad \mathrm{b} \equiv \beta (hk)^{\frac{5}{2}}$$

where χ, β are constants of O(1), ρ the density of water, b is the 'breaking strength parameter', k the wavenumber and hk (local) slope

Energy dissipation

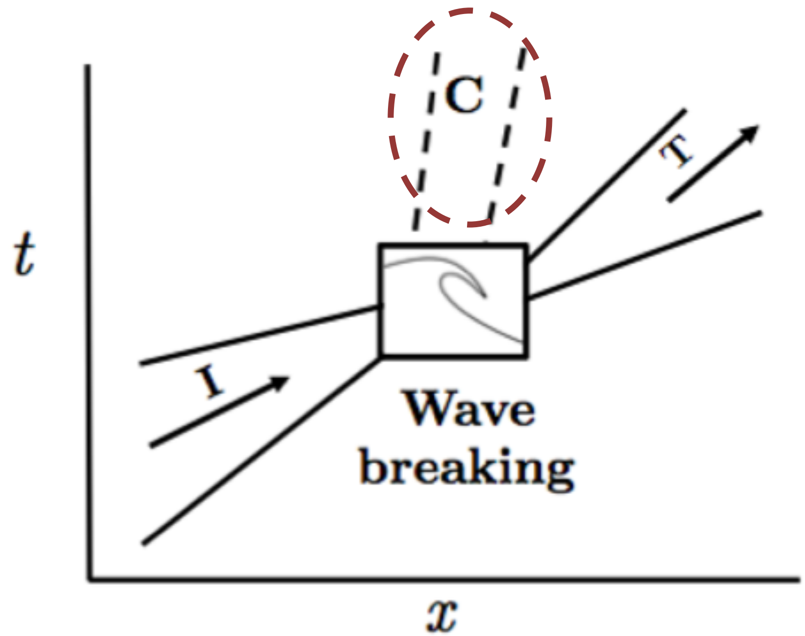
Romero et al. (2012) included a threshold to show b holds over ***all available laboratory ranges of S.***



hk ***linearly*** related to S for broadband packets

Romero et al. (2012)

Current generation by deep-water wave breaking



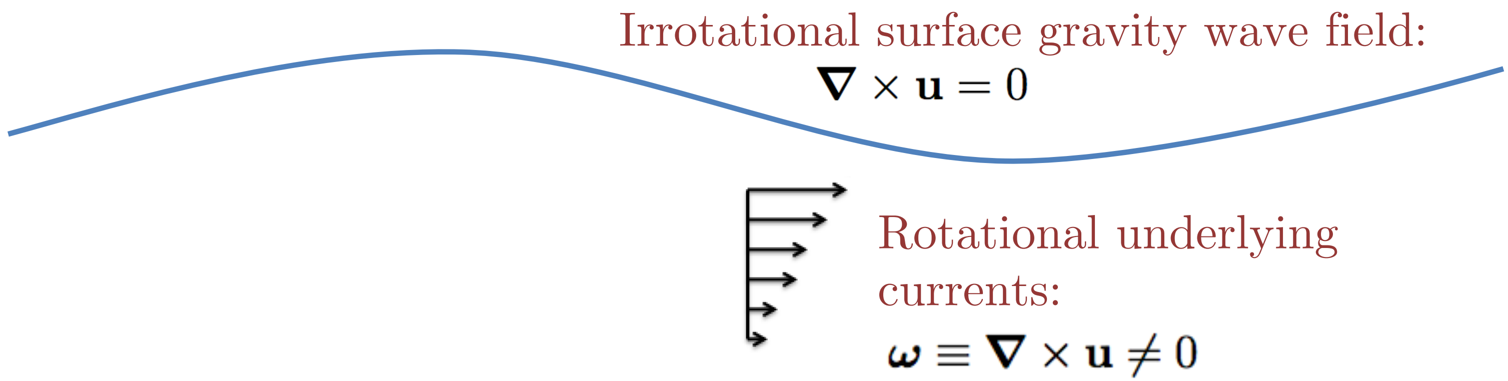
C: breaking-generated currents

Given I, can we describe the structure and properties (circulation and energy) of C?

*P., N.E. & Melville, W.K. 2013 Vortex generation by deep-water breaking waves. *Journal of Fluid Mechanics*. vol. **734**, 198-218.

*P., N.E., Deike, L. & Melville, W.K. 2016 Current generation by deep-water breaking waves. *Journal of Fluid Mechanics*. vol. **803**, 292-312.

Motivation

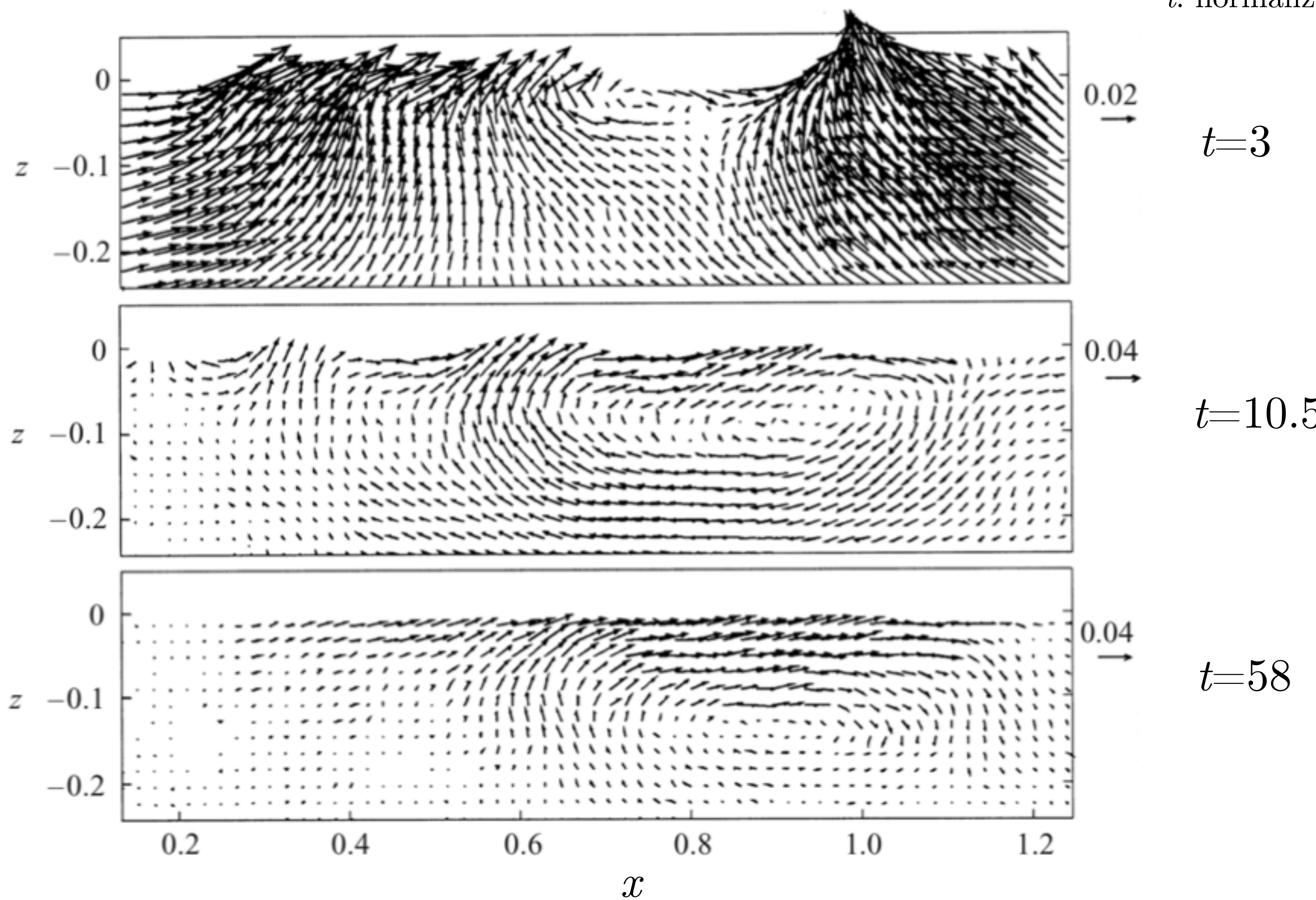


- Breaking transfers **momentum** and **energy** from the **irrotational** surface gravity wave field to the underlying **rotational currents.**
  - **This generates the wind-driven currents**
- The structure of the breaking induced flow modulates upper ocean processes (e.g. Langmuir circulation).

Laboratory experiments

- Ensemble-averaged flow induced by 2d plunging breaking wave in the region of breaking *(Melville et al. 2002)*

t: normalized time



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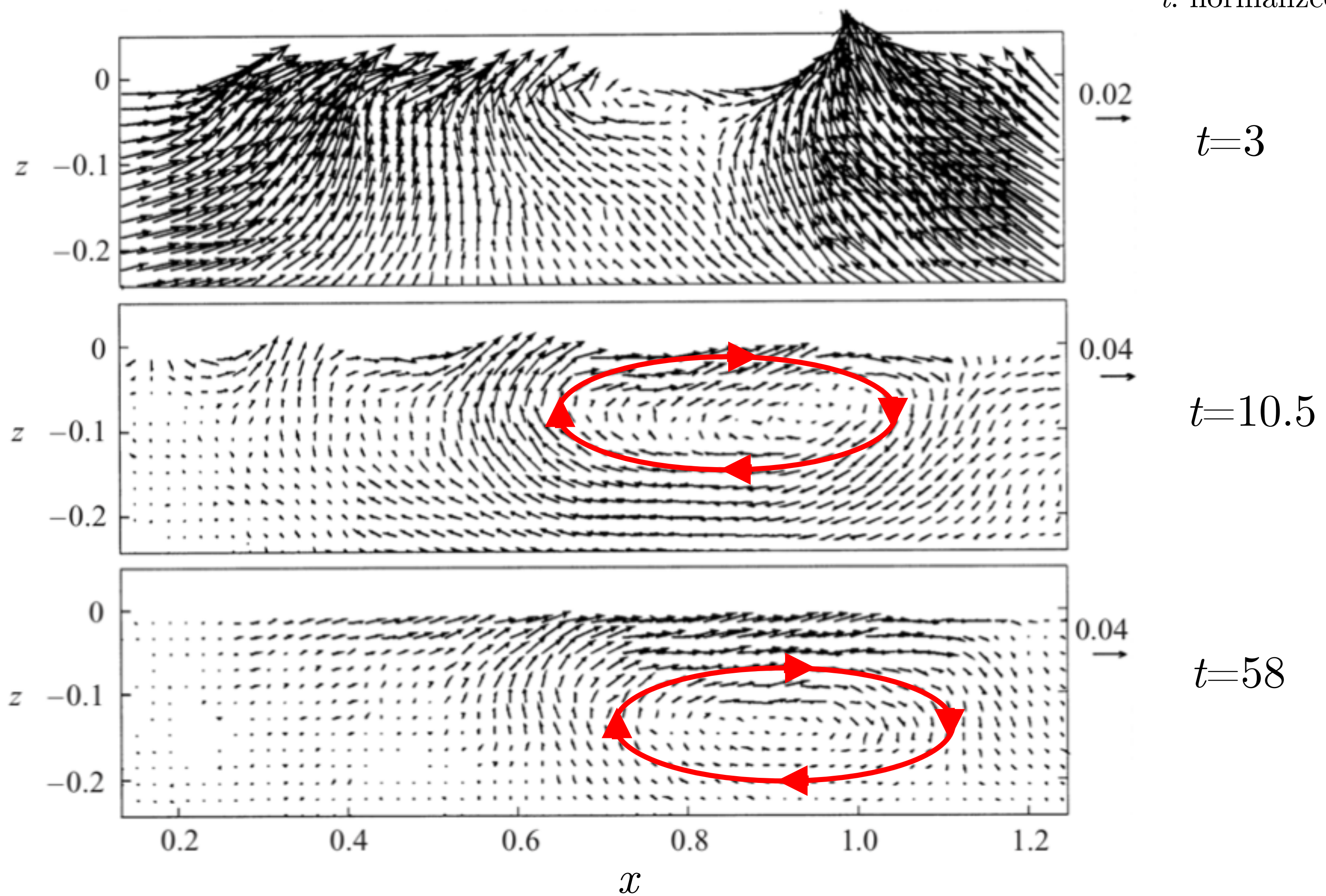
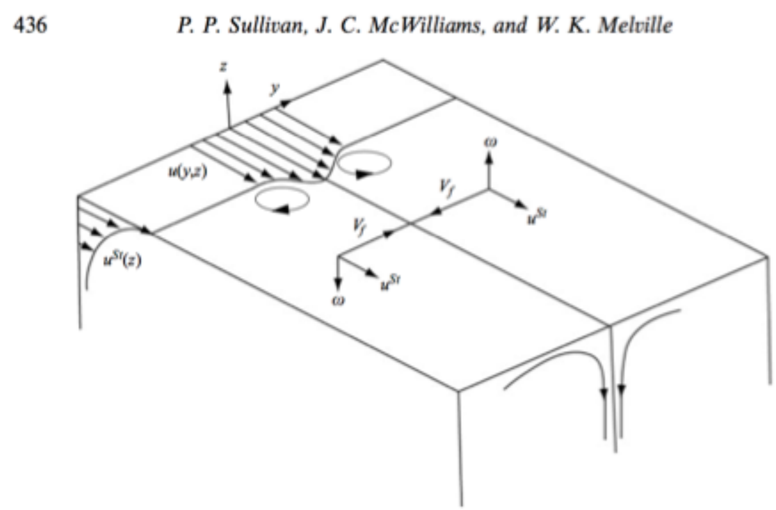


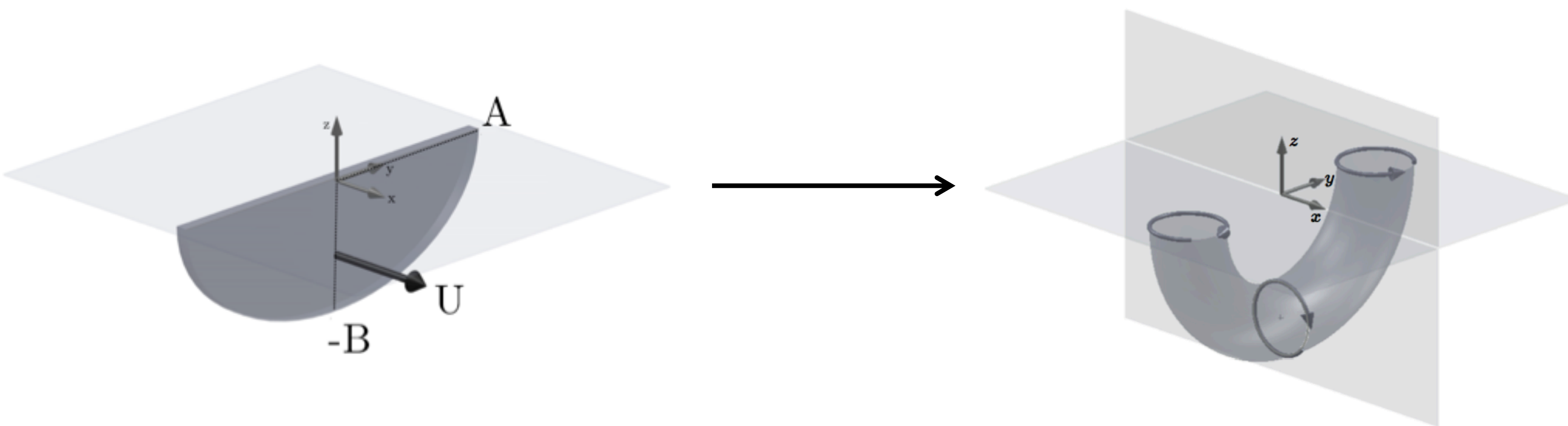
The structure of breaking-induced flow

Vortex tubes must be closed loops or start and end on a boundary, which implies structure of vorticity induced by breaking in deep water is **equivalent to a half torus** (*Peregrine 1999*).



Vortex generation model

Model breaking as a thin elliptical disk. Disk is dissolved, flow rolls up where it's strongest, i.e. along the perimeter, **leaving an elliptical vortex ring** (Helmholtz 1858, Klein 1910, Taylor 1953, Dhanak & de Bernardinis 1981).



Vortex generation

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> In addition it may be noticed that it is easy in nature to study these motions of circular vortex-rings, by drawing rapidly for a short space along the surface of a fluid a half-immersed circular disk, or the nearly semicircular point of a spoon, and quickly withdrawing it.

- Helmholtz (1858; English translation by P.G. Tait in 1867)

(Wikipedia)

Vortex generation

Source: *Physics girl: youtube.com/user/physicswoman*

Field

How do these results extend to the field?

Laboratory to field

Phillips (1985) $\Lambda(\mathbf{c})$: Breaker front length per unit area of sea surface per unit increment of breaking velocity **c**.

Moments have important physical interpretations

$$R = \int c\Lambda(c)\mathrm{d}c,$$

Fraction of surface area turned over by breaking fronts per unit time. Gas/heat transfer (Jessup et al 1997)

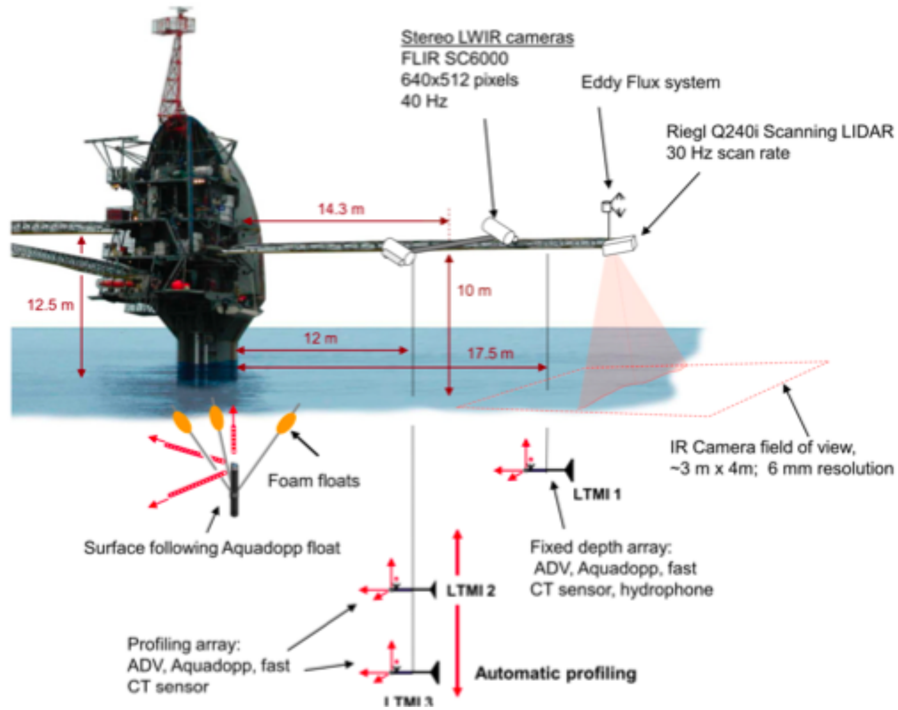
$$F_E = \frac{\rho_w}{g}\int bc^5\Lambda(c)\mathrm{d}c.$$

Energy dissipated by breaking waves per unit area of ocean surface.

Experimental set up to measure $\Lambda(c)$

(Sutherland and Melville 2013, 2015)

- Field campaigns on R/P FLIP
- IR stereo cameras (captured non-air-entraining breakers)
- Subsurface measurements of dissipation



Sutherland & Melville (2015)

Energy dissipation

$$F_E = \frac{\rho_w}{g} \int b c^5 \Lambda(c) \mathrm{d}c.$$

How to find the local slope in b$=\beta(hk)^{5/2}$?

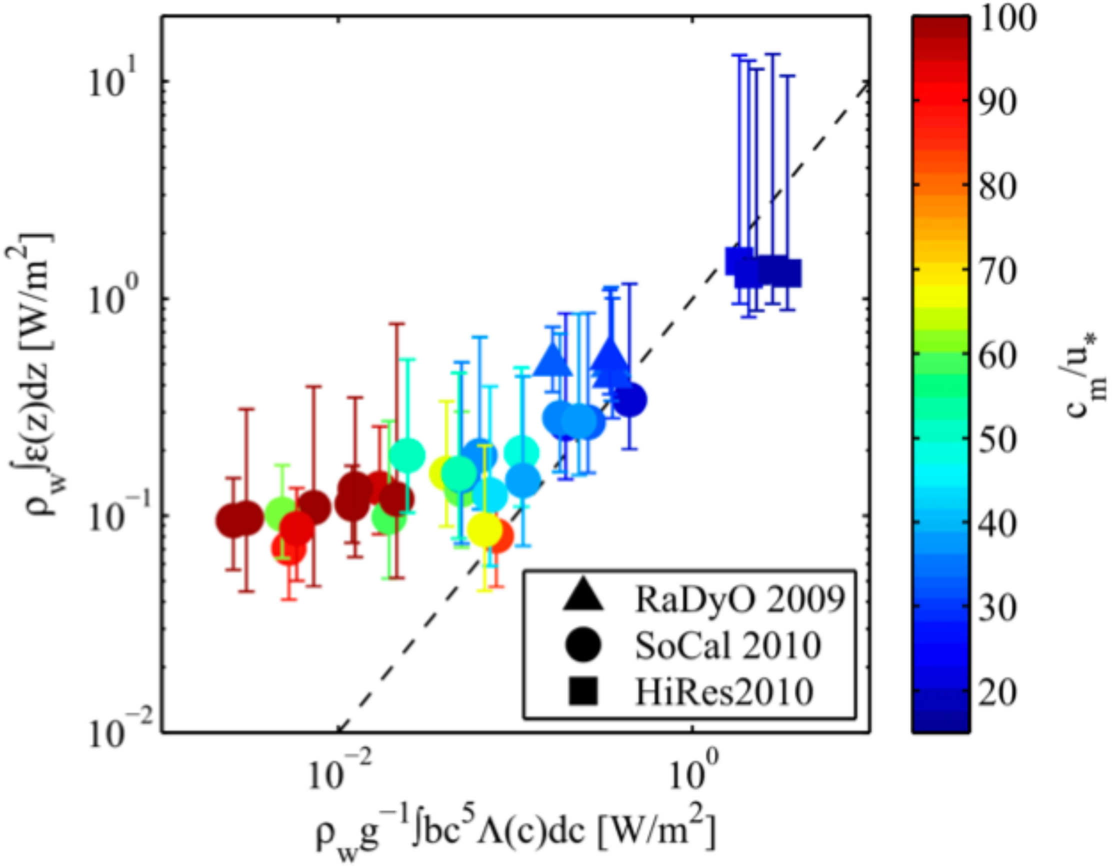
Romero et al. (2012): semi-empirical spectral model of the breaking parameter in the field

$$b(k) = A_1 (B(k)^{1/2} - B_T^{1/2})^{5/2}.$$

$B(k)$ is the azimuthally-integrated saturation spectrum (which is related to the local slope squared), while B_T and A_1 are constants determined through closure of the radiative transfer equation from the field data of Kleiss and Melville (2010)

Scaling model predictions versus direct measurements

Subsurface measurements of dissipation



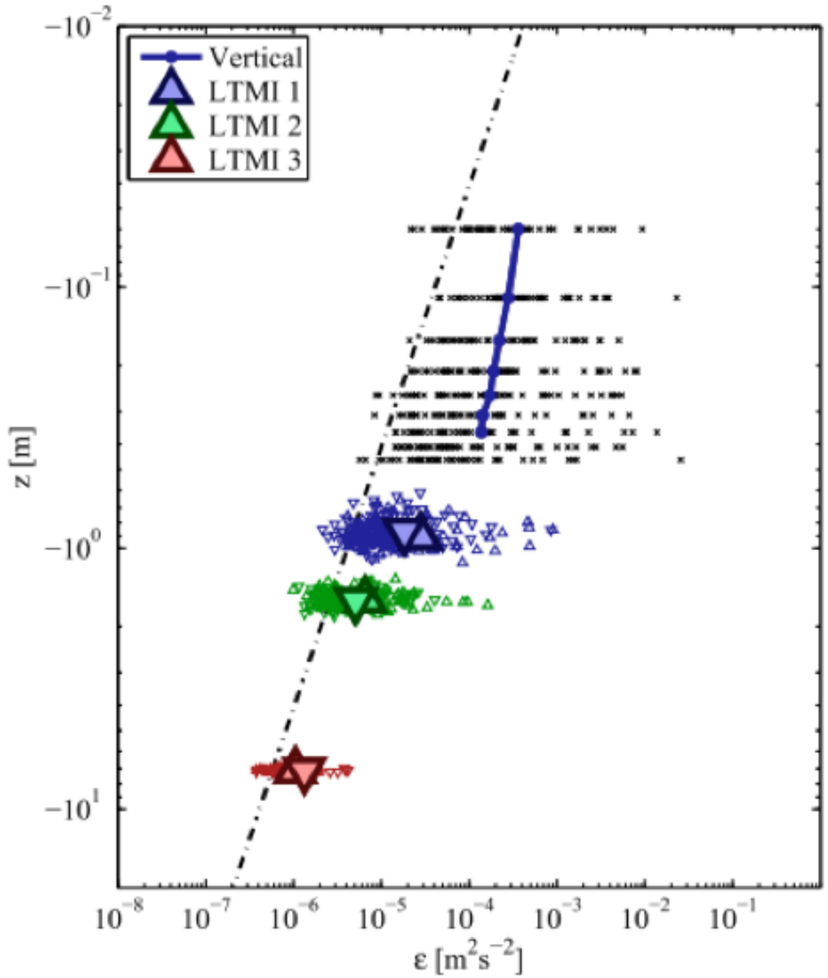
c_m: mean wave phase speed

Sutherland & Melville (2015)

Observations based on scaling and Phillips (1985)

For young seas, breaking is responsible for energy dissipation.

Measurements vs law of the wall



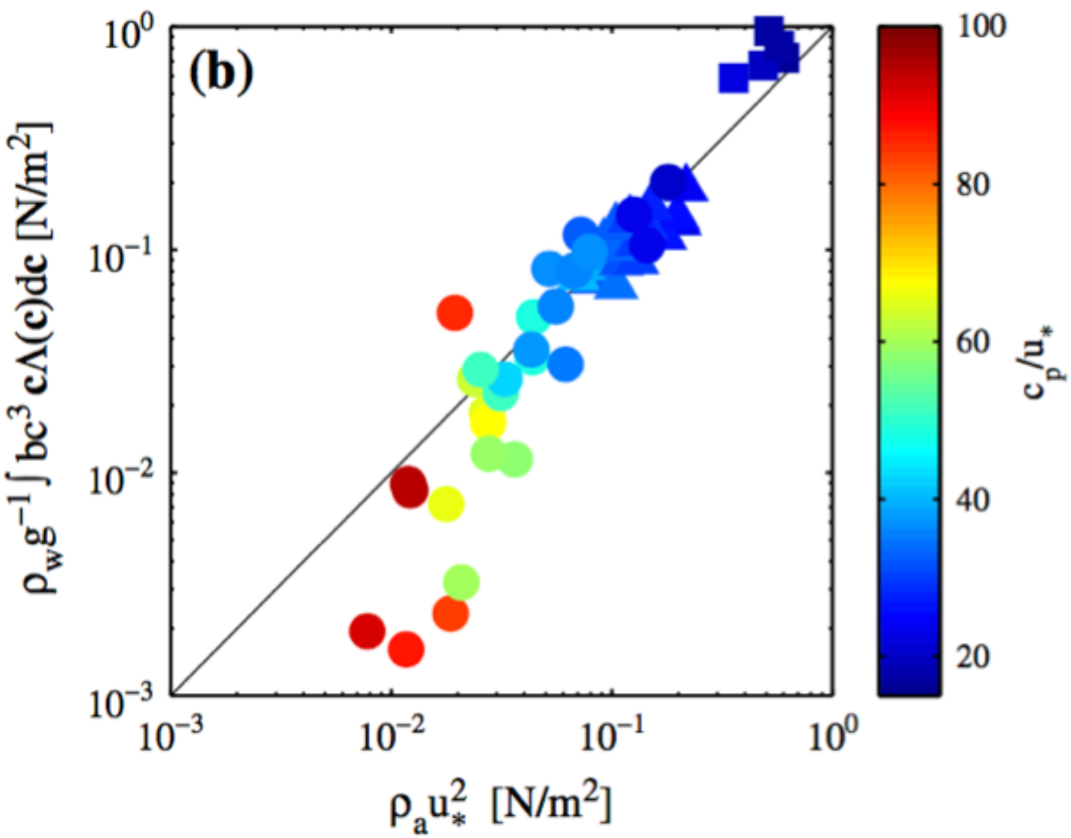
Sutherland & Melville (2015)

Colored points: measurements
Dashed: Law of the wall
Blue Line: 20 minute average
Triangles: 20 min average, up-current/cross-current

Dissipation orders of magnitude larger than law of wall prediction

Momentum flux budget

Momentum flux budget



Sutherland & Melville (2013)

Nearly all momentum flux in young seas accounted for by breaking

For young seas, nearly all momentum flux and energy is locally deposited into the water column by breaking.

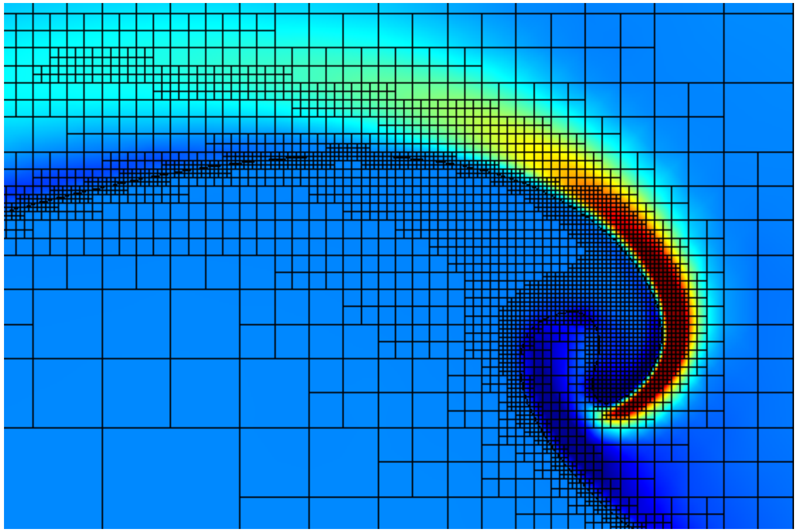
Numerical modeling

- How do these scaling arguments and models (using field data) help guide numerical experiments?

- Scaling/observations constrains bulk scale quantities
  - Does the geometry, kinematics, and dynamics of breaking matter? If so, at which scales?

DNS (Luc Deike)

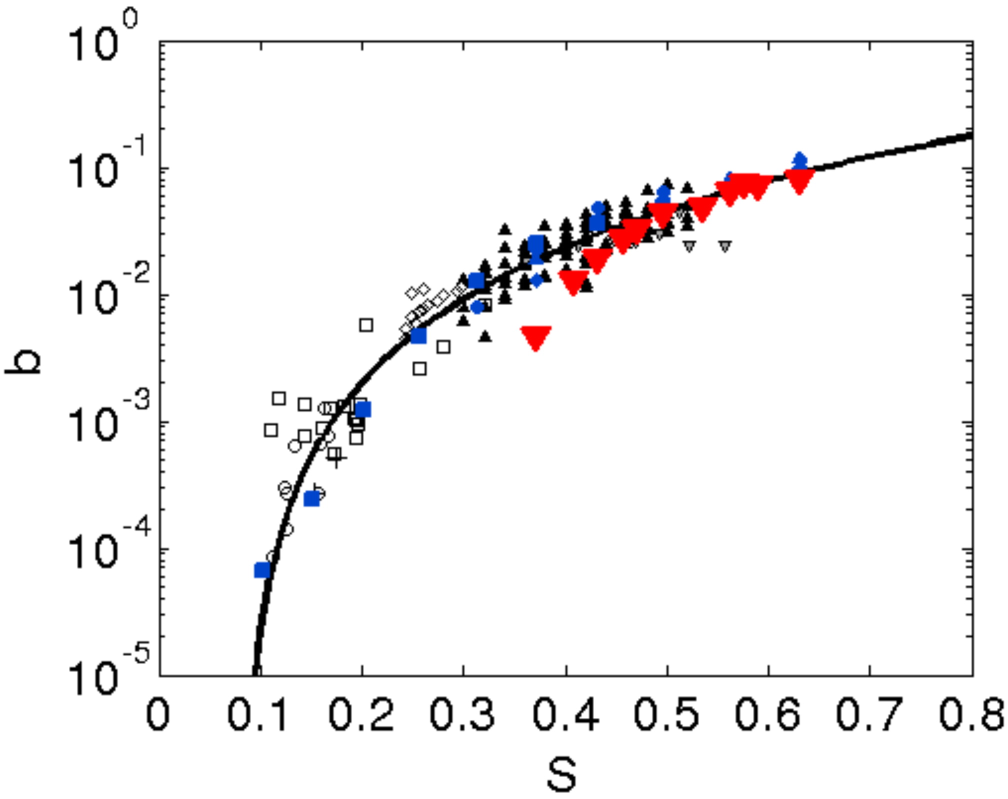
- Direct Numerical Simulations (DNS) of 2d Navier-Stokes using open-source solver Gerris
- Two phase flow with surface tension *(Popinet 2009)*
  - Adaptive discretization



DNS of breaking

- Numerical wave tank (Deike, Pizzo, Melville 2017)

Energy dissipation rate



Black: Lab data

Red: 3d DNS

Blue: 2d DNS

Line: $0.04(S\text{-}0.08)^{5/2}$

Deike et al (2015)

LES

J. Fluid Mech. (2007), *vol.* 593, *pp.* 405–452. © 2007 Cambridge University Press 405
doi:10.1017/S002211200700897X Printed in the United Kingdom

Surface gravity wave effects in the oceanic boundary layer: large-eddy simulation with vortex force and stochastic breakers

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LES

- Solves Craik-Leibovich equations plus **body force** (parameterizing breaking – SMM 2004)
- Study cases with Stokes drift and breaking versus cases with no waves (only a surface stress)

- Computational domain (300, 300,-110) m
    - Horizontal grid spacing 1m; vertical - stretched
    - Neutral stratification in mixed layer depth, then stably stratified

LES

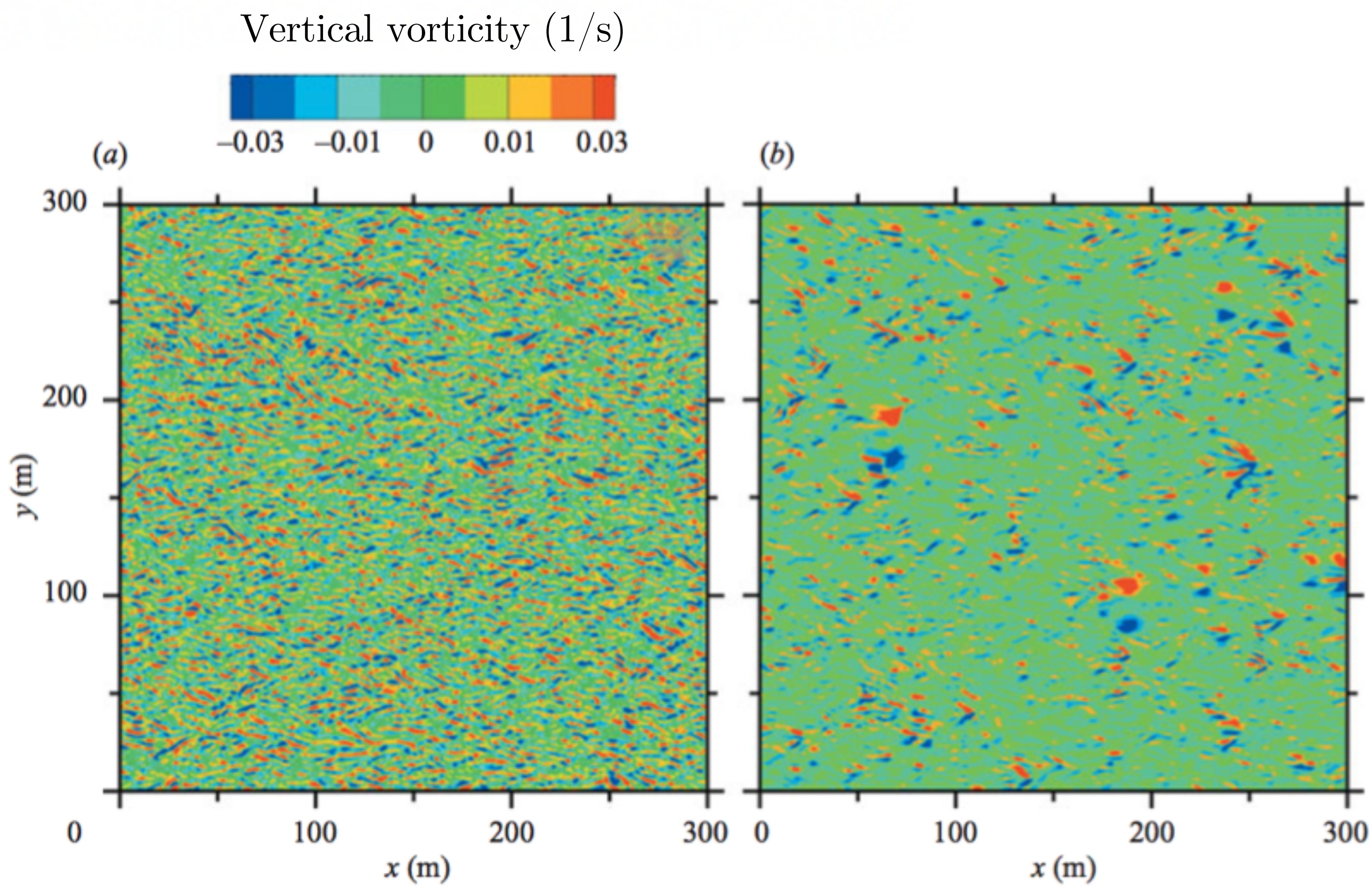


FIGURE 16. Snapshot of vertical vorticity $\bar{\boldsymbol{\omega}}\cdot\hat{\mathbf{z}}$ at $z = -1.14$ m for two simulations with Stokes drift driven by: (*a*) uniform stress and (*b*) breaking with wave age $c_p/u_{*a} = 19$. Note the paired plus and minus signed vertical vorticity that occurs at the lateral (y) ends of each breaker. The colour bar shown at the top of the figure is in units of per second.

LES

Vertical velocity

Uniform stress

Waves and breaking ($c_p/u_* = 30$)

Waves and breaking ($c_p/u_* = 23$)

Waves and breaking ($c_p/u_* = 19$)

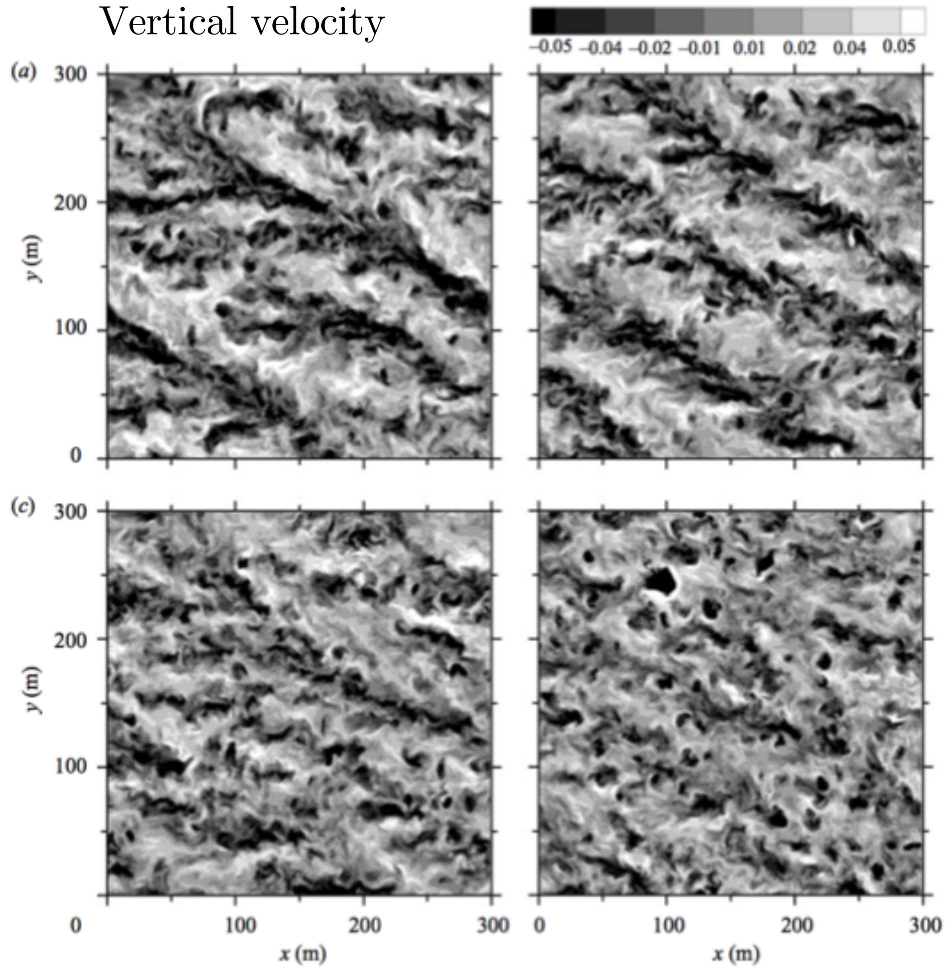
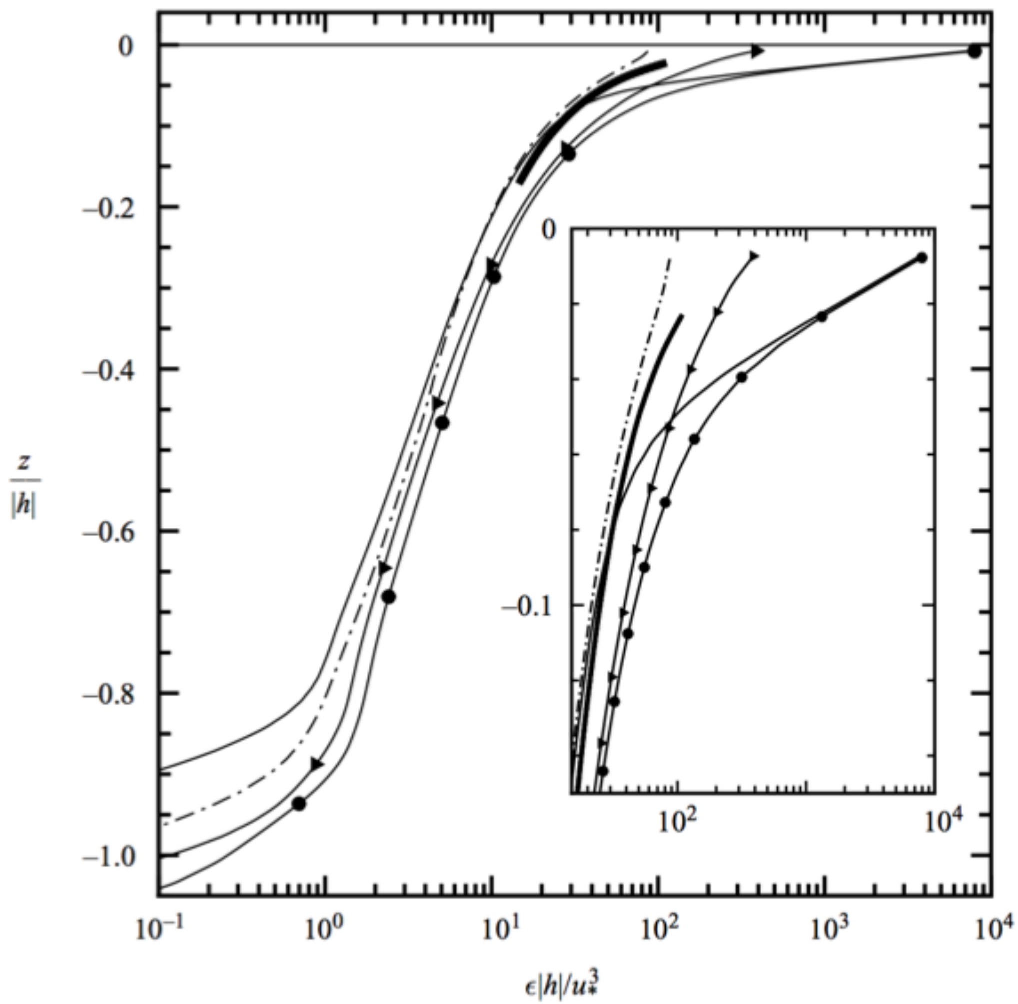


FIGURE 14. Vertical velocity contours at $z = -13.38$ m for the same flows as in figure 13. Note the appearance of the coherent round downwelling jets in (*c*) and (*d*). The grey-scale bar shown at the top of the figure is in units of metres per second.

Dissipation rates



Solid line: Breaking
Dashed: Surface stress
Triangle: Stokes drift
Circle: Stoked drift plus breaking

Mixed layer depth h=-32m

Conclusions

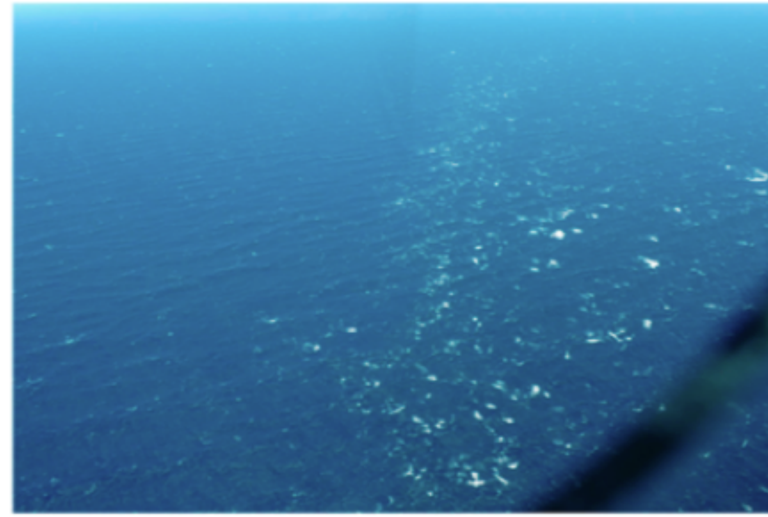
- Wave influences profound on both mean flow and turbulent statistics
- Waves sufficient to generate upper ocean dynamics (i.e. do not need a surface stress)
- Breaking enhances dissipation near surface, with vortex force altering dynamics deeper than O(wave height)
- Changes downwelling patterns of LC

OBLs are importantly different from their wall-bounded shear-layer counterparts because of surface waves

- No feedback between waves and currents
- Speculative breaking statistics

Open questions

Romero et al (2017)



- Role of breaking at fronts

- Mass transport by breaking

(P. 2017, Deike, P, Melville 2017, P. Deike, Meville 2018)

- Kinematics of steep and breaking waves (behavior of c) (P Melville 2016, 2018)

- Strong wave-current interactions
- Breaking onset

J. Fluid Mech. (2017), *vol.* 829, *pp.* 364–391.
doi:10.1017/jfm.2017.548

Lagrangian transport by breaking surface waves

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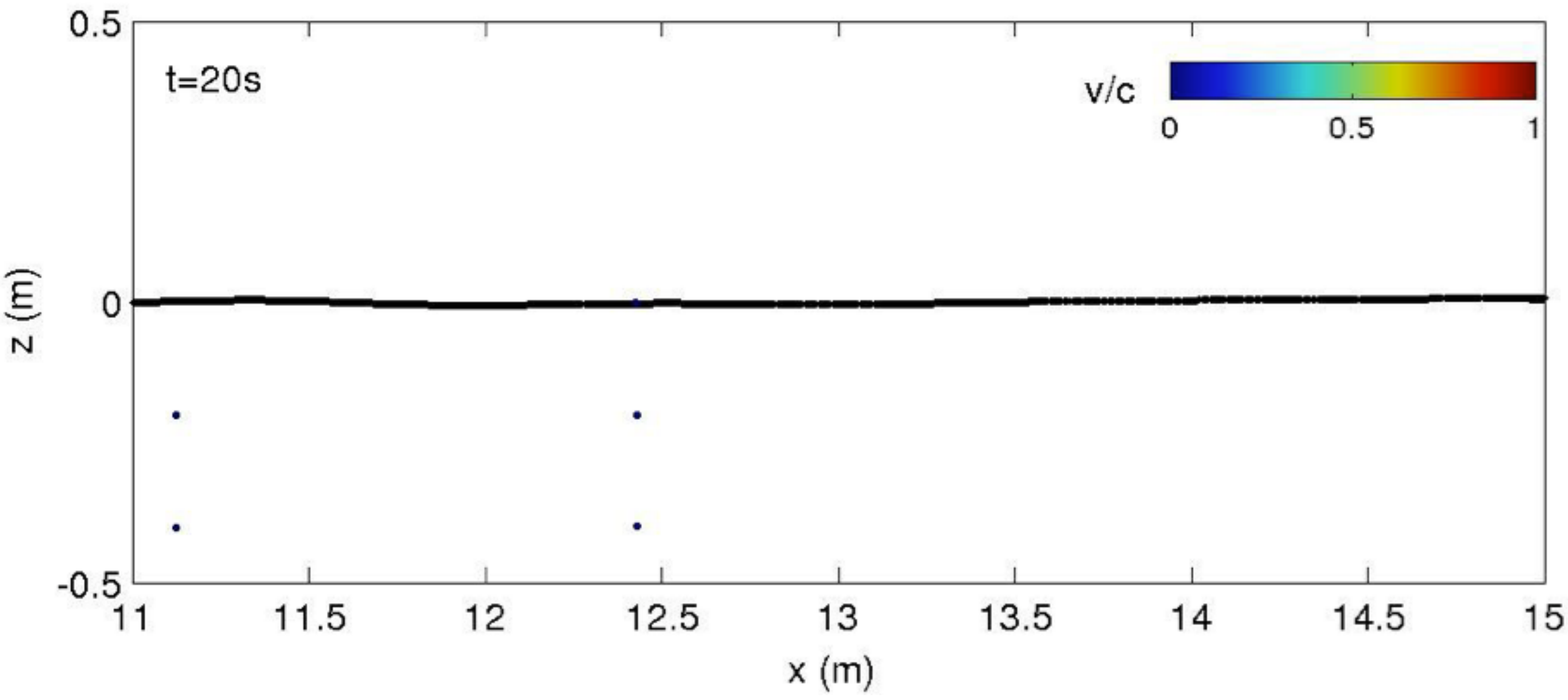
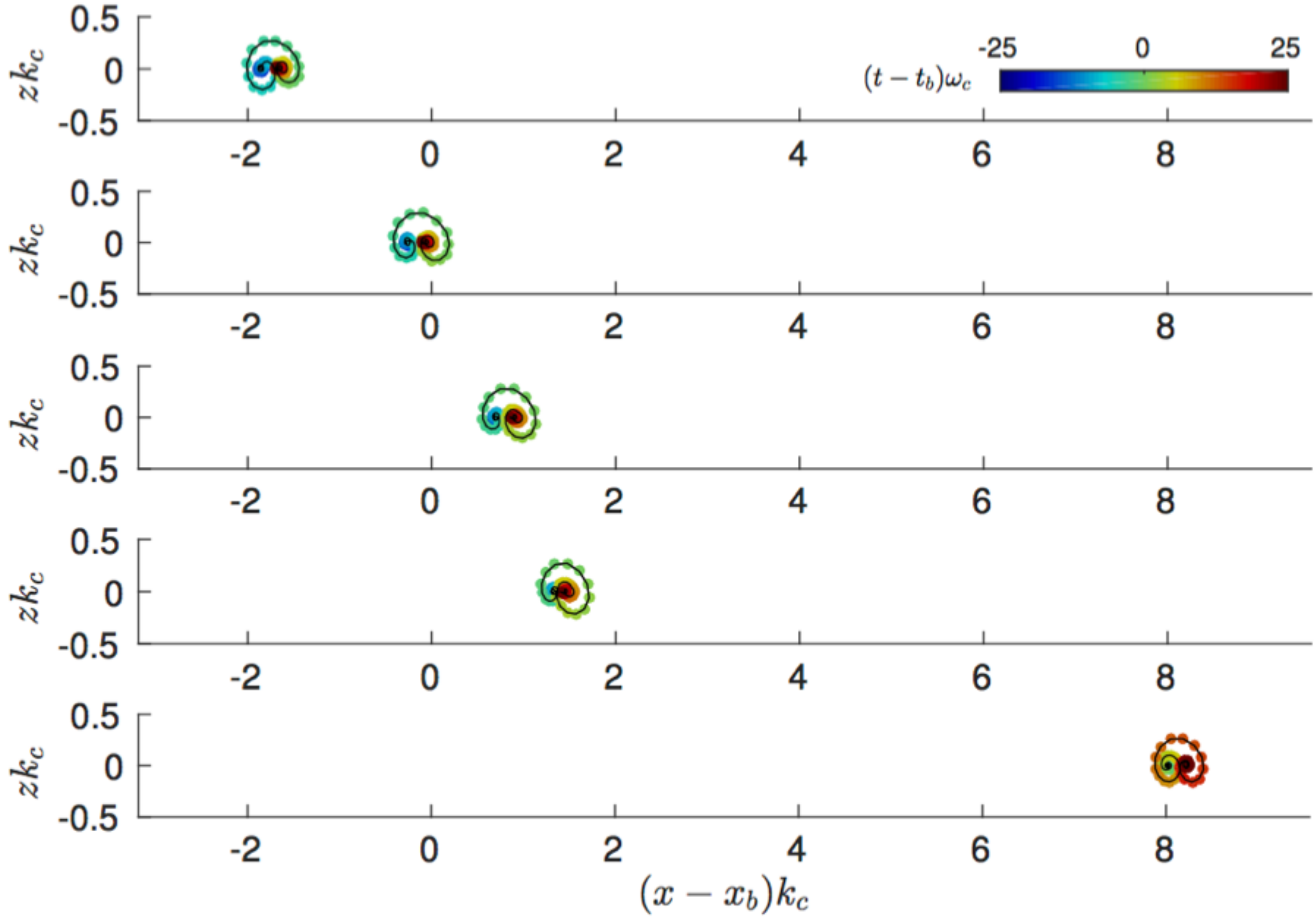
(Received 4 May 2017; revised 22 July 2017; accepted 2 August 2017; first published online 19 September 2017)

Characterize drift due to non-breaking and breaking deep water wave packets.

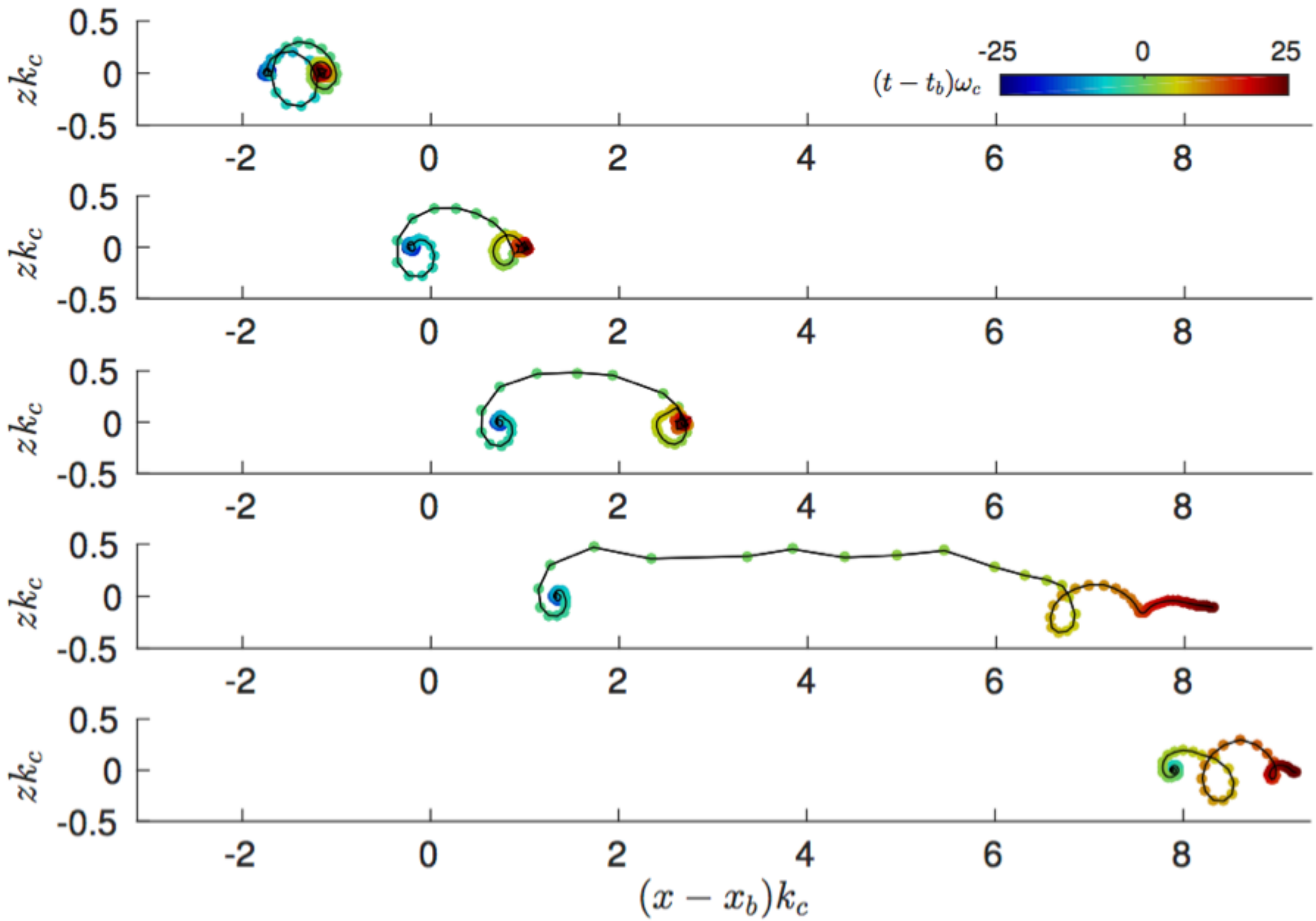
Particle kinematics in breaking



Non-breaking packet

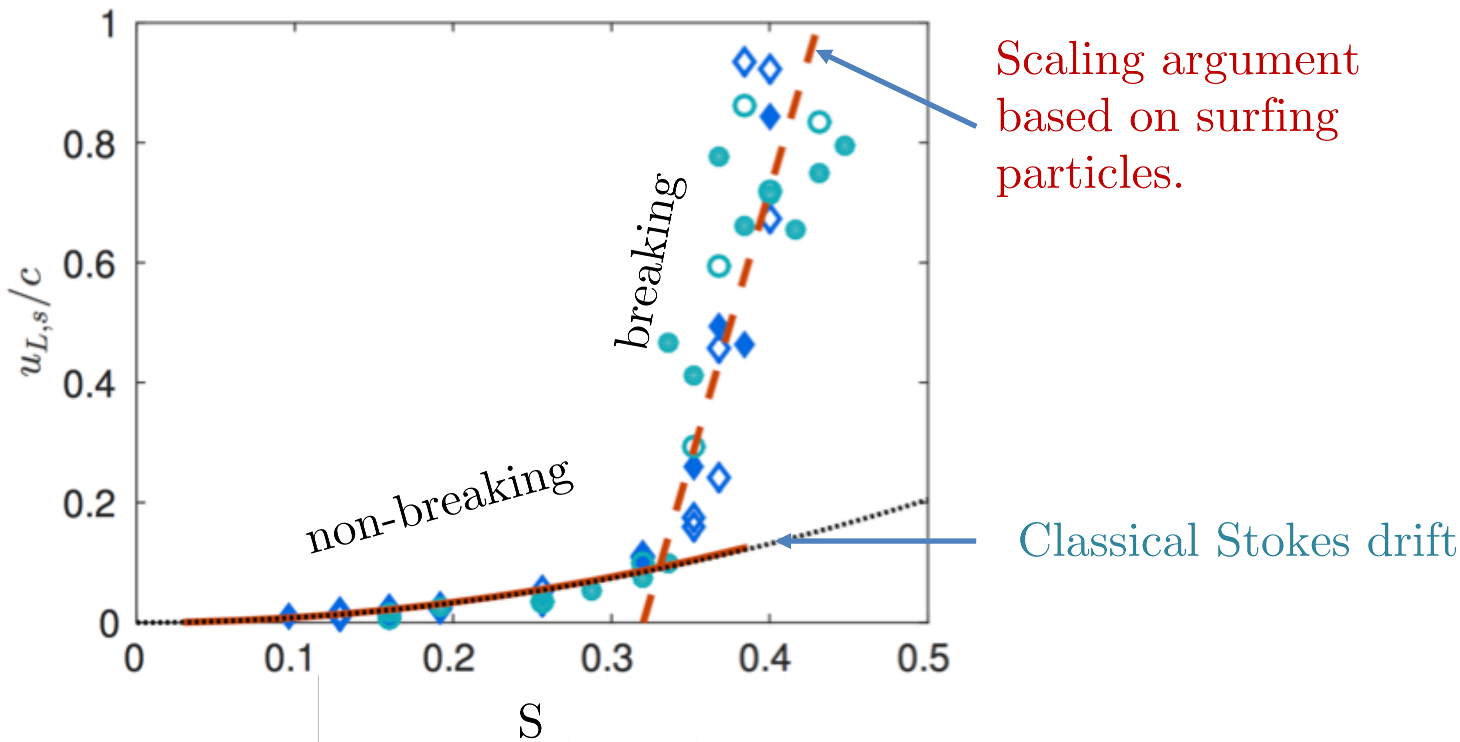


Breaking packet



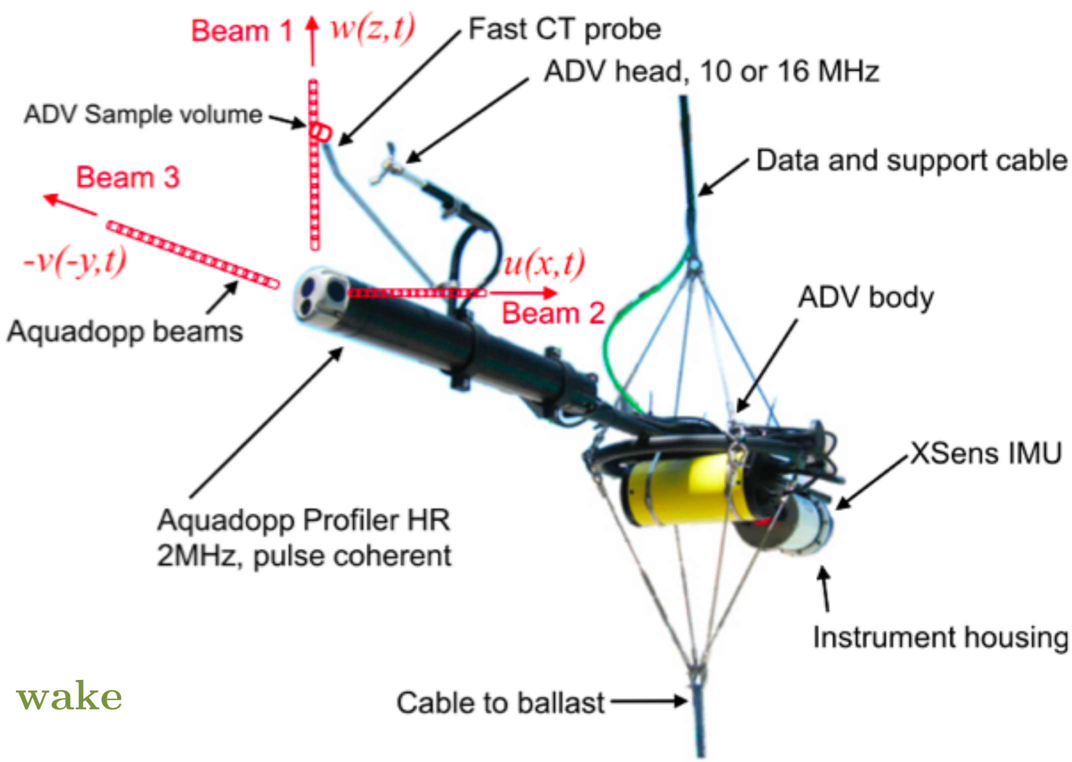
Can we relate the drift of these surfing particles to the variables characterizing the breaking wave?

Lagrangian drift in focusing wave packets



Lagrangian drift due to breaking may be nearly order of magnitude larger than nonbreaking waves.

Dissipation rate computed using structure functions



Avoiding turbulent wake

FIG. 2. Subsurface LTMI. Not shown is a vane designed to keep the body of the Aquadopp orthogonal to the mean flow, with beam two pointing upstream. Instruments with vane attached are shown in Fig. 3.

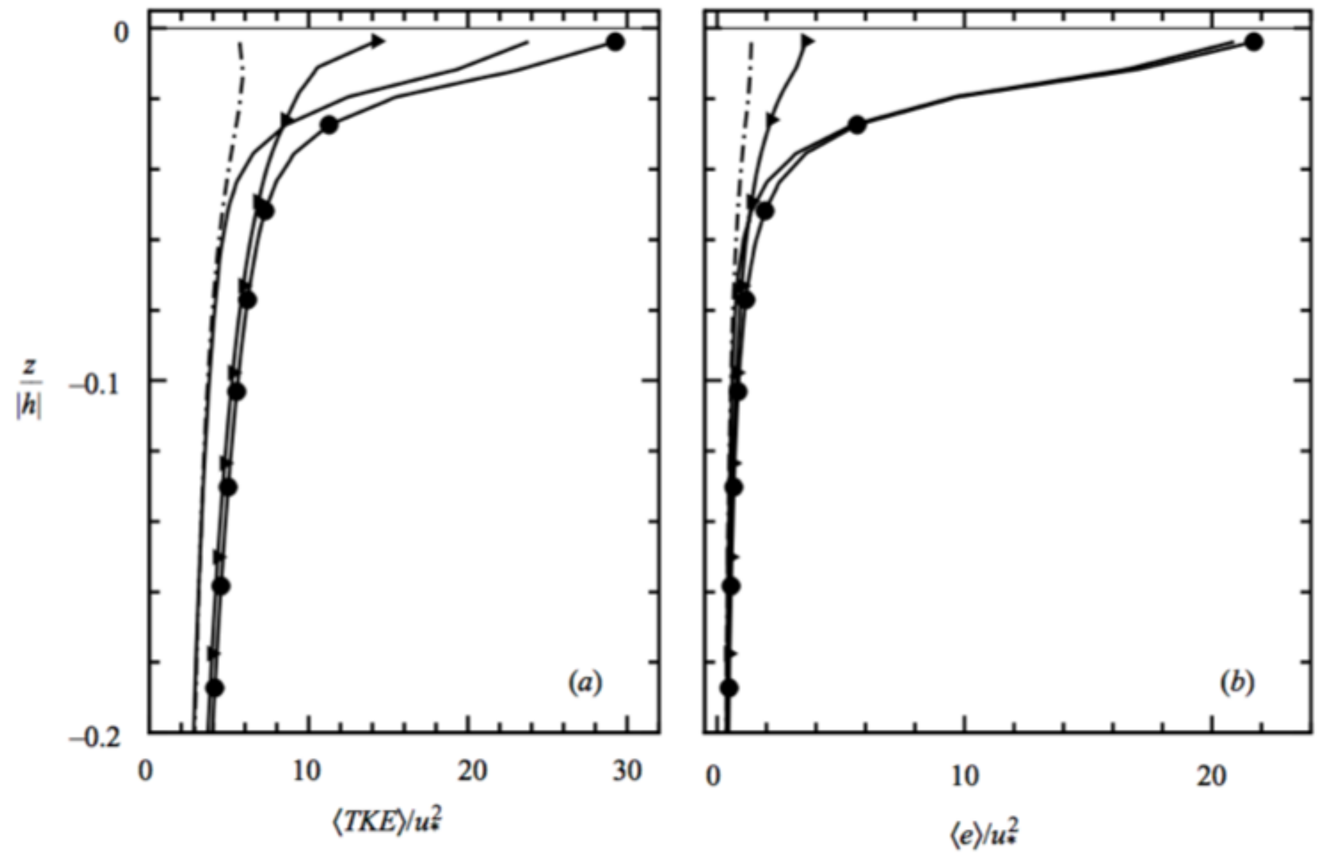
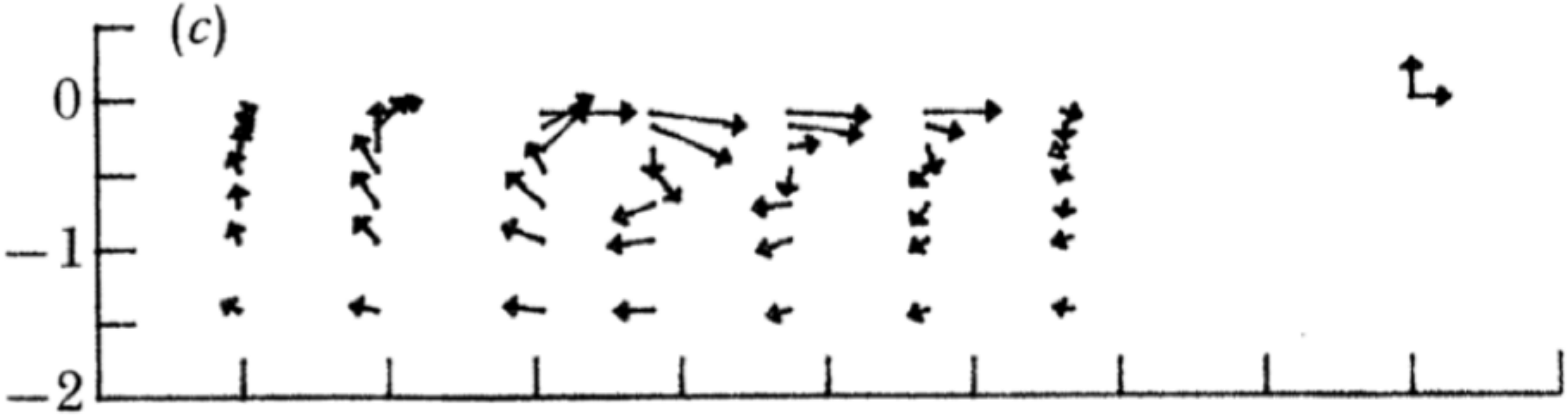


FIGURE 8. TKE profiles close to the water surface $-0.2 < z/|h| < 0$ for simulations with-no wave effects, dash-dot line; Stokes drift only, ►; breaking only, solid line; Stokes drift plus breaking, •. The wave age is $c_p/u_{*a} = 30$. Panel (*a*) total (resolved plus SGS) and (*b*) subgrid-scale energy.

Air-sea boundary layer

Ocean boundary layer supports air-sea fluxes, surface gravity waves, boundary-layer turbulence, Ekman currents, air (gas) entrainment, etc...

Despite the differences in length scales **O(1 mm–100 m)** and time scales **O(1 ms–1 h),** physics are closely linked.


(c)
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−1
−2