SCRIPPS INSTITUTION OF OCEANOGRAPHY

University of California San Diego

Lagrangian transport by breaking deep-water surface waves at the air-sea interface

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Melbourne 2019

Photo: Nick Statom

Ken Melville (1946-2019)

Overview

Surface waves and wave breaking modulate the transfer of **mass**, **momentum**, and **energy** across the two phase air-sea interface (Cavaleri et al 2012).

- Improved understanding crucial for enhanced coupled air-sea models of weather and climate.
- Design of coastal and offshore structures, **advection of flotsam and pollution**

Examine the Lagrangian transport due to deep-water breaking waves using numerical, theoretical, field and laboratory techniques.

Motivation

An oceanographer goes on R/P FLIP and accidentally falls off. Where will they go?

Waves at sea

L Grare

What is the wave induced transport at the surface?

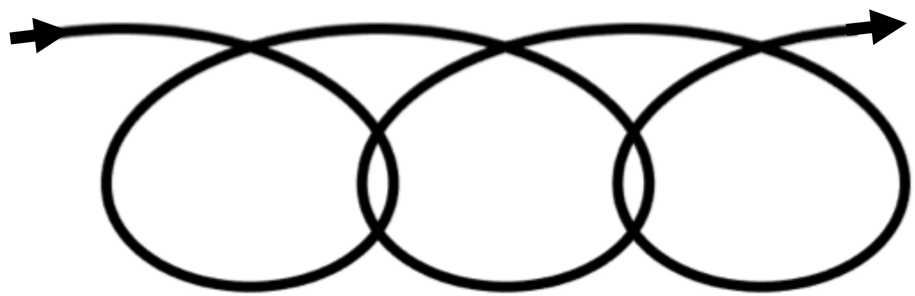
Waves at sea

L Grare

How does the Lagrangian transport due to deep-water wave breaking compare to the classical drift (i.e. Stokes drift) for non-breaking waves?

Wave-induced transport – the classical approach

Deep-water *linear monochromatic irrotational* waves transport mass (Stokes drift).



When averaging over fast waves, Stokes drift, $\mathbf{u}_s$, enters models of upper ocean dynamics through **vortex force:**

$$\mathbf{u}_s \times \boldsymbol{\omega}$$

- Langmuir circulations (Craik & Leibovich 1976, GLM)
- Wave-driven ocean circulation (McWilliams & Restrepo 1999; van den Bremer and Breivik 2017)

Wave-induced mass transport – the classical approach

However, ocean waves are not monochromatic, are often nonlinear, and break.

When averaging ... models
of upper ocean ...

- Langmuir circulations (Craik & Leibovich 1976, GLM)
- Wave-driven ocean circulation (McWilliams & Restrepo 1999)

Wave-induced mass transport – the classical approach

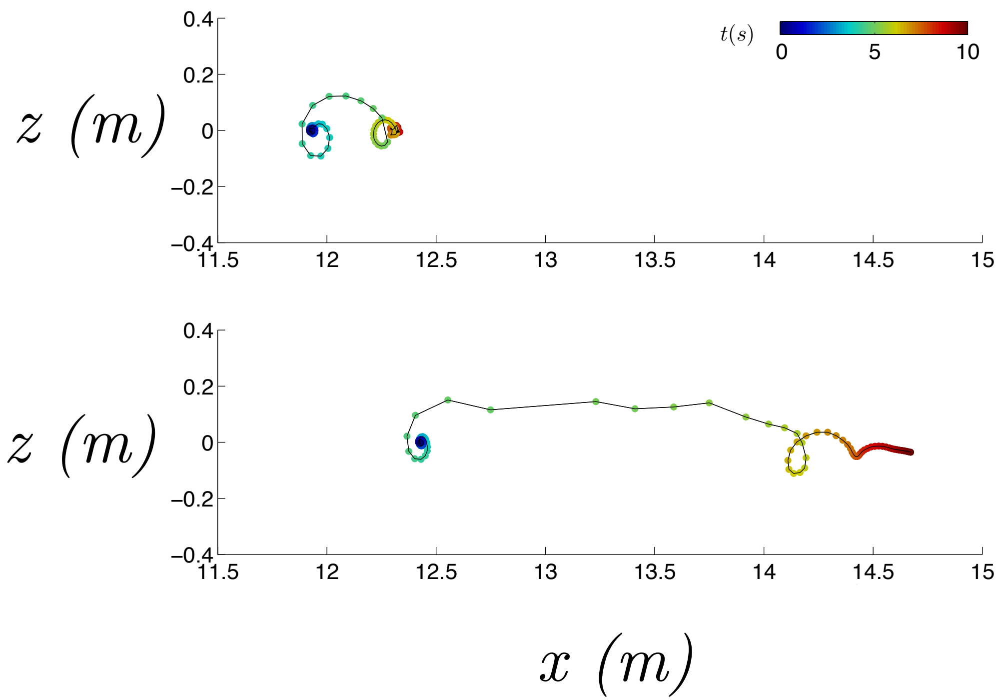
However, ocean waves are not monochromatic, are often nonlinear, and break.

What is the wave-induced drift for these more realistic scenarios, particularly for breaking waves?

Preliminary observation

Particle trajectories in **focusing region** of deep-water wave packet

Direction of wave propagation



Non-breaking

Breaking

Direct numerical simulations (Deike, Pizzo, Melville 2017)

Can we quantify this additional transport due to breaking?

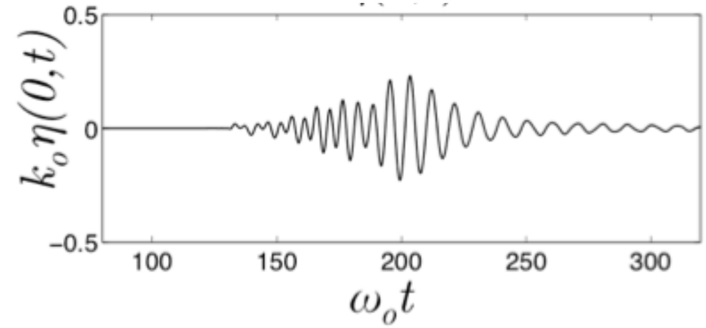
Wave breaking: Laboratory experiments

Dispersive focusing technique (Longuet-Higgins 1974)

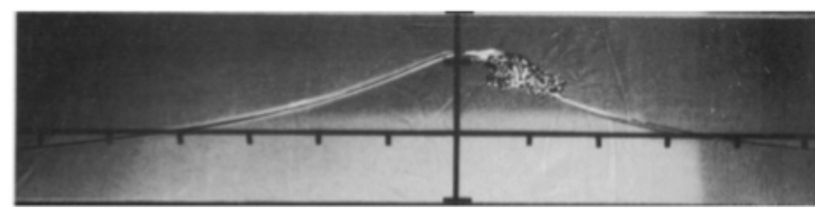
$$\eta(x,t) = \sum_{n=1}^{32} a_n \cos(k_n(x - x_b) - \omega_n(t - t_b));$$

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

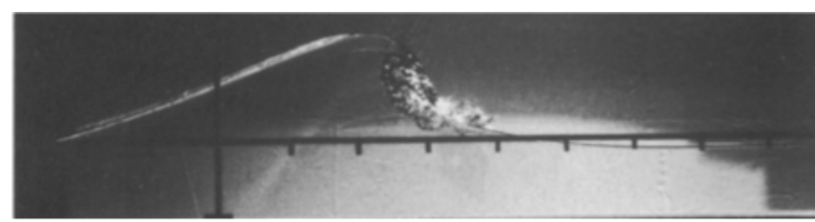
Initial conditions



S=0.27 spilling breaker



S=0.36 plunging breaker



Rapp and Melville (1990)

Wave packet parameter

Linear prediction of maximum slope at focusing (known a priori)

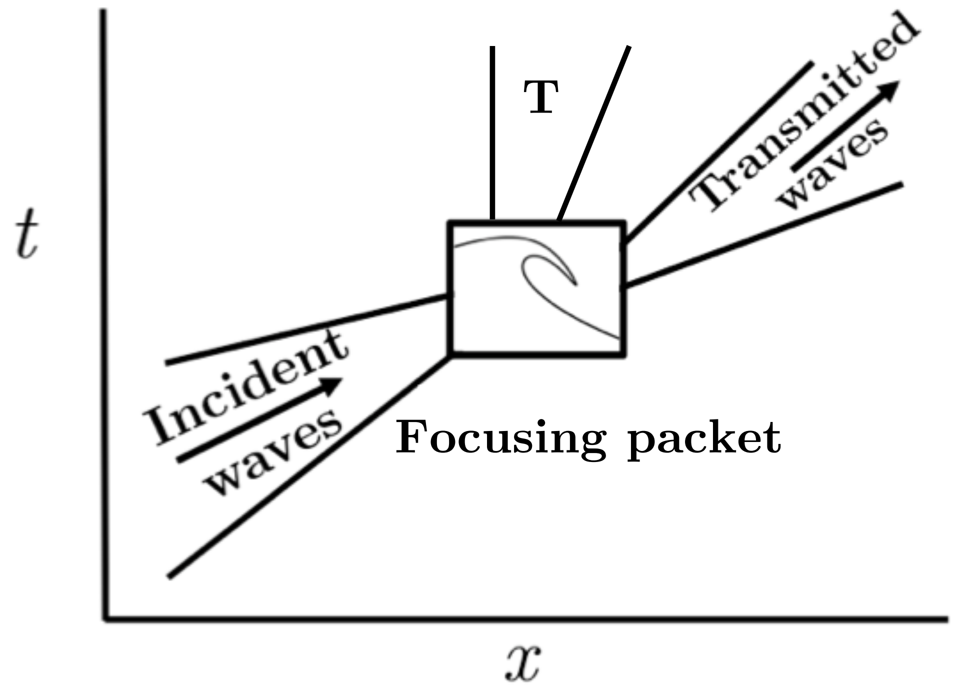
$$S \equiv \sum_{n=1}^{32} a_n k_n$$

Note, S<1.

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

Lagrangian transport by breaking surface waves

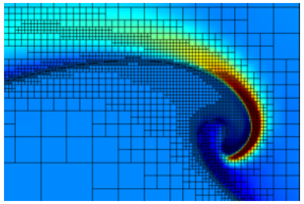
Luc Deike[1,2,3,†], Nick Pizzo[3] and W. Kendall Melville[3,†]



Given properties of the incident waves, can we describe the transport (T) due to focusing and breaking waves?

Numerical experiments

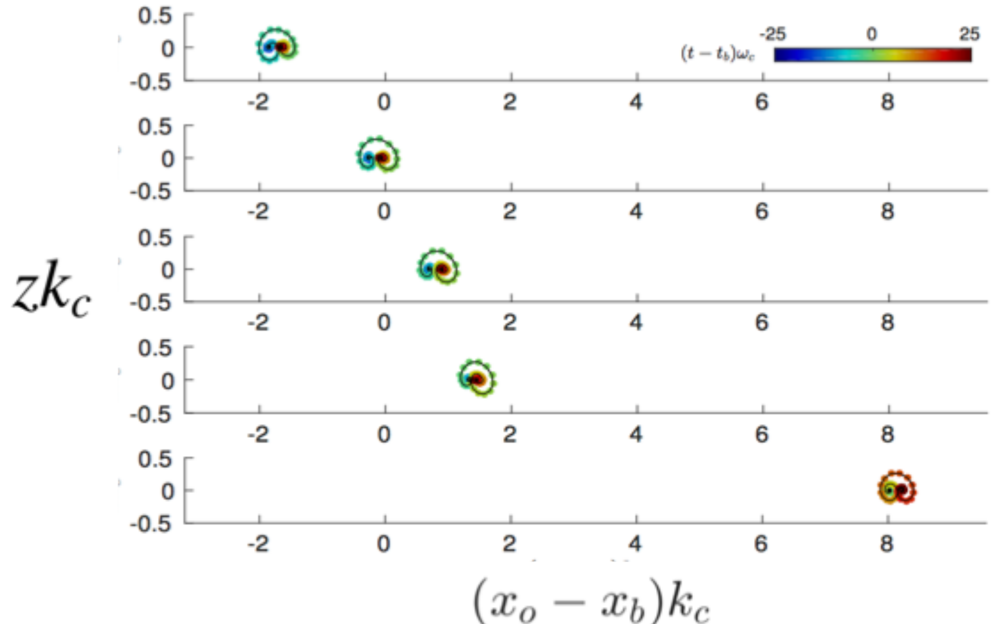
- Direct Numerical Simulations (DNS) of 2d Navier-Stokes using open-source solver Gerris
- Two phase flow with surface tension *(Popinet 2009)*
    - Adaptive discretization



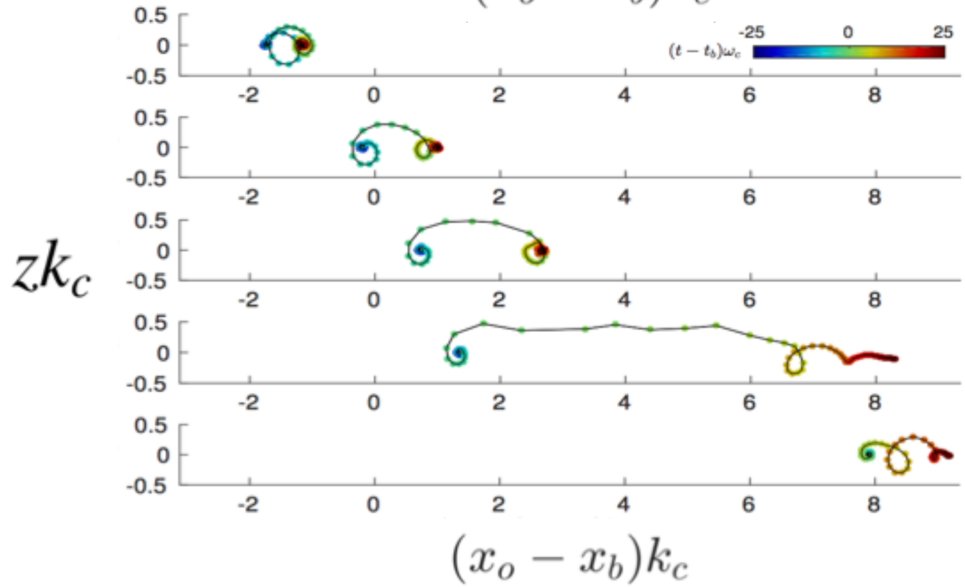
- Dispersive focusing technique employed (Longuet-Higgins 1974, Rapp & Melville 1990)
- **Track particle trajectories during focusing/breaking**

Numerical experiments

Non-breaking packet



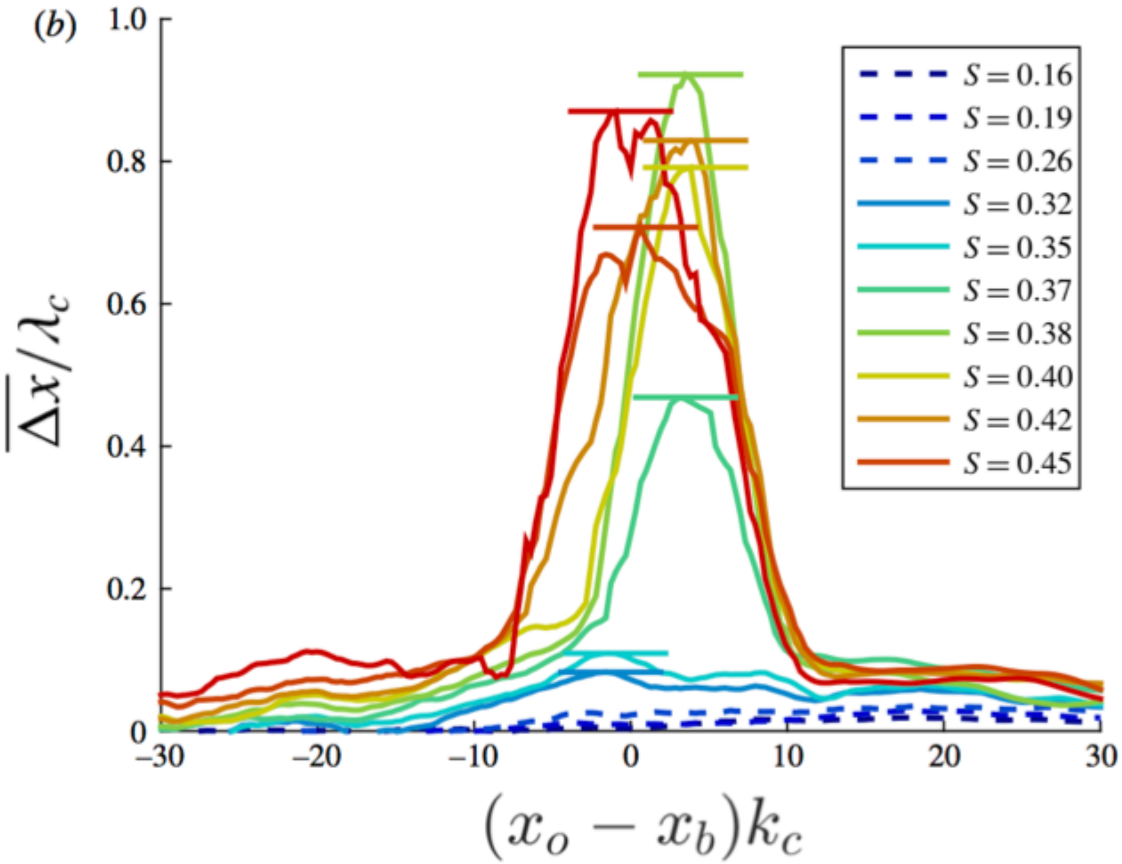
Breaking packet



x_0: initial particle location

x_b: focusing location

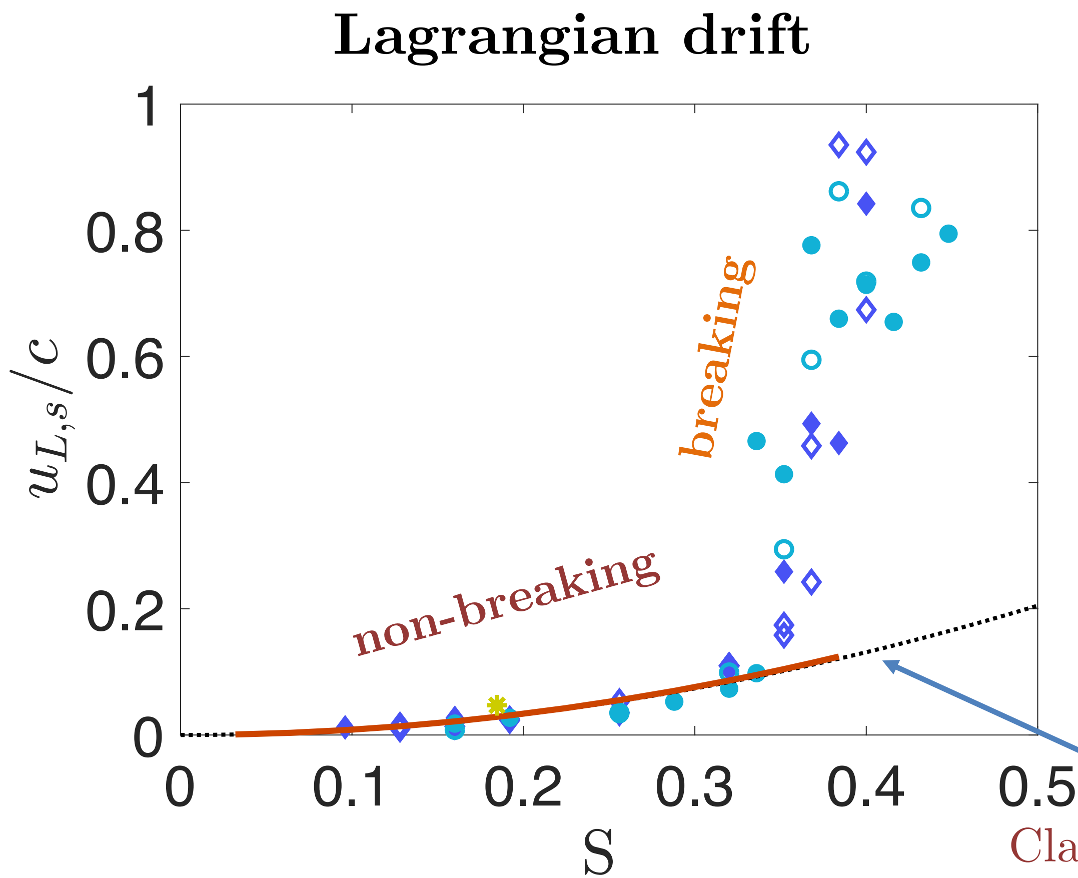
Averaged drift



- Running mean, averaged over λ_c.
- Strongly peaked around breaking location

Total drift

- Integrate, divide by focusing length and time scale (Rapp & Melville 1990)
- Normalize by characteristic phase velocity c.



Classical Stokes drift, $u_L \sim S^2$

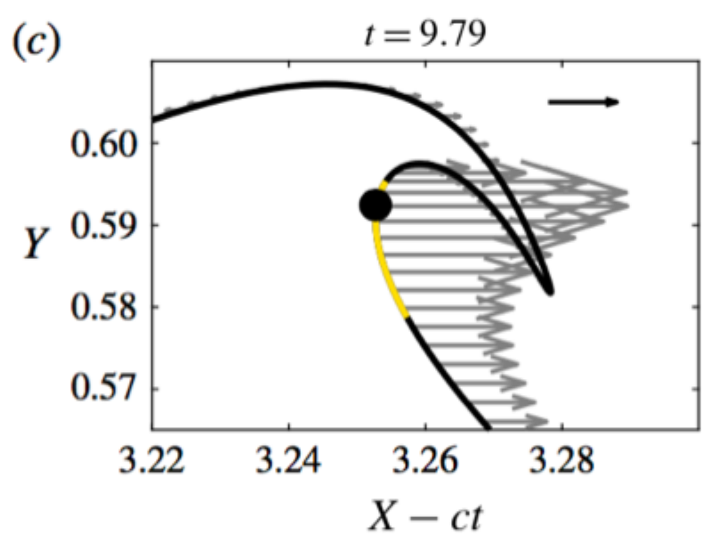
How do we make sense of the drift induced by breaking?

Particle kinematics near focusing (Pizzo 2017)

For particles traveling near the phase velocity c of the underlying wave, the acceleration is given by

$$A_m = c^2\left(\frac{\eta_x\eta_{xx}}{1+\eta_x^2}\right) - \frac{(\eta_{tt}+g)\eta_x}{1+\eta_x^2},$$

Particles experience large, geometrically forced, accelerations in the region of breaking.

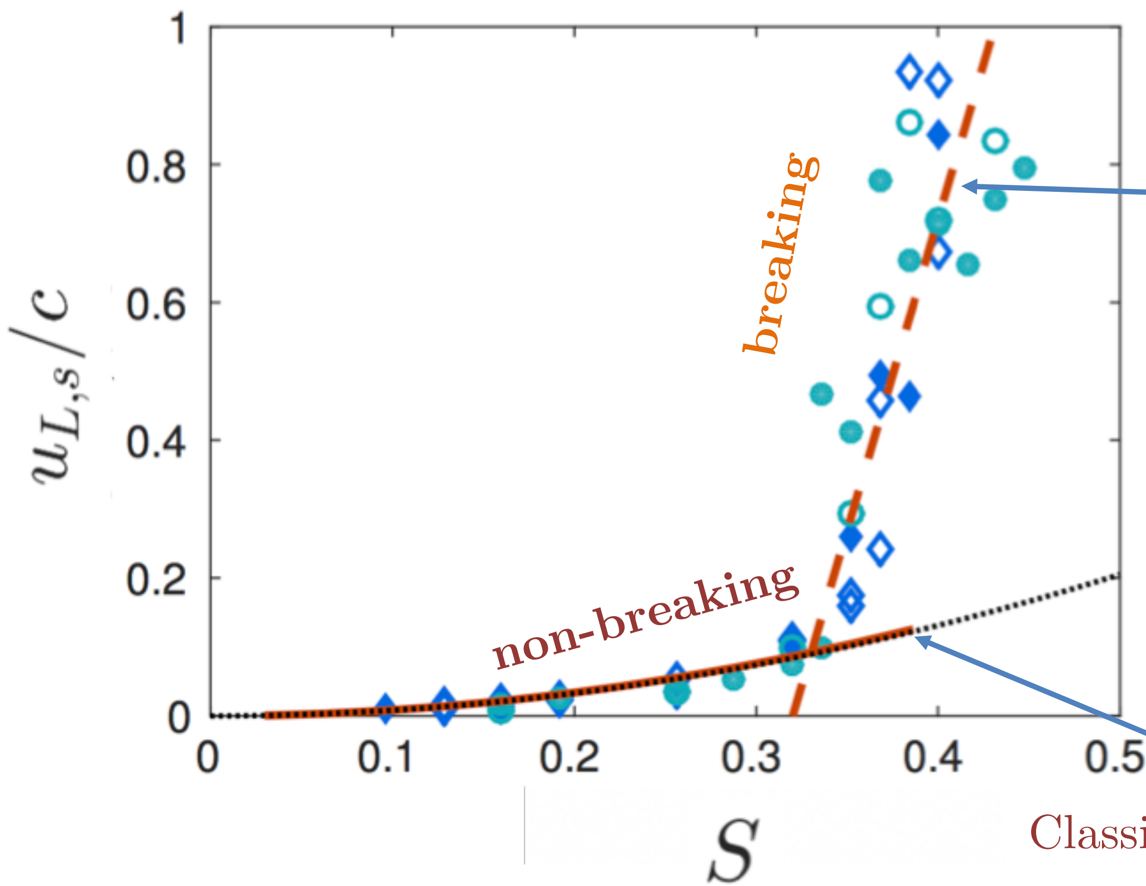


Acceleration near the tip of a breaking wave (due to normal mode superharmonic instability of steep Stokes wave)

(Pizzo 2019; sub judice)

Scaling arguments show $A_m/g \sim S$.

Total drift



Scaling argument (Pizzo 2017)

$$\boxed{u_{LB}/c=\alpha(S-S_0)}$$

S: Slope at focusing (strength of breaking), ***S<1***

S_0: breaking threshold

α*: Scaling constant best fit to data*

Classical Stokes drift, $u_L \sim S^2$

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

Summary

- Numerical wave tank experiments conducted
- Lagrangian drift due to breaking may be nearly order of magnitude larger than nonbreaking waves.
- Proposed model based on kinematics near focusing that describes additional transport.

Lagrangian transport by non-breaking and breaking deep-water waves at the ocean surface

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Use scaling model of Lagrangian drift for one breaking wave and observed breaking statistics to estimate total contribution of breaking to wave driven transport at the surface.

Wave induced drift at the ocean surface (classical approach)

Stokes drift in the ocean (Kenyon 1969; *assume all waves traveling in same direction*):

$$U_S = 2\int \phi(k)\sqrt{gk}k\,dk,$$

ϕ ($\mathbf{k}$): Omnidirectional wave spectrum

$$\phi(k) = \int kF(\mathbf{k})d\theta = \int kF(k,\theta)d\theta$$

How does this compare to the Lagrangian drift due to breaking?

Breaking statistics

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 (Sutherland & Melville 2013, 2015).

Drift induced by breaking

Amount of breaking area per unit area ocean between speeds c and c+dc:

$$\mathbf{c}\mathcal{T}\Lambda(\mathbf{c})\mathrm{dc},\ \mathcal{T}=2\pi \mathrm{c}/\mathrm{g},$$

$\mathcal{T}$ wave period which scales with the duration of breaking (Rapp & Melville 1990).

Mean transport speed of broken fluid is $\mathrm{u_{LB}}$, then

$$U_{LB}=\int u_{LB}c\mathcal{T}\Lambda(c)dc=2\pi\alpha\int(S-S_0)\frac{c^3}{g}\Lambda(c)dc,$$

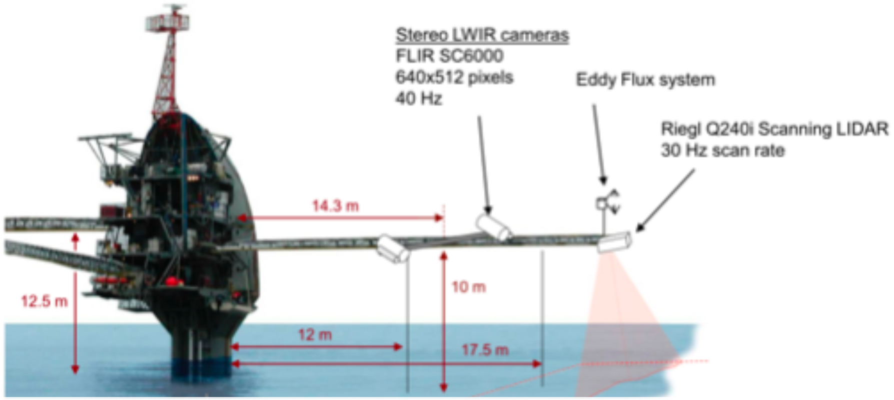
where α is the scaling constant found in the numerical simulations.

Observations

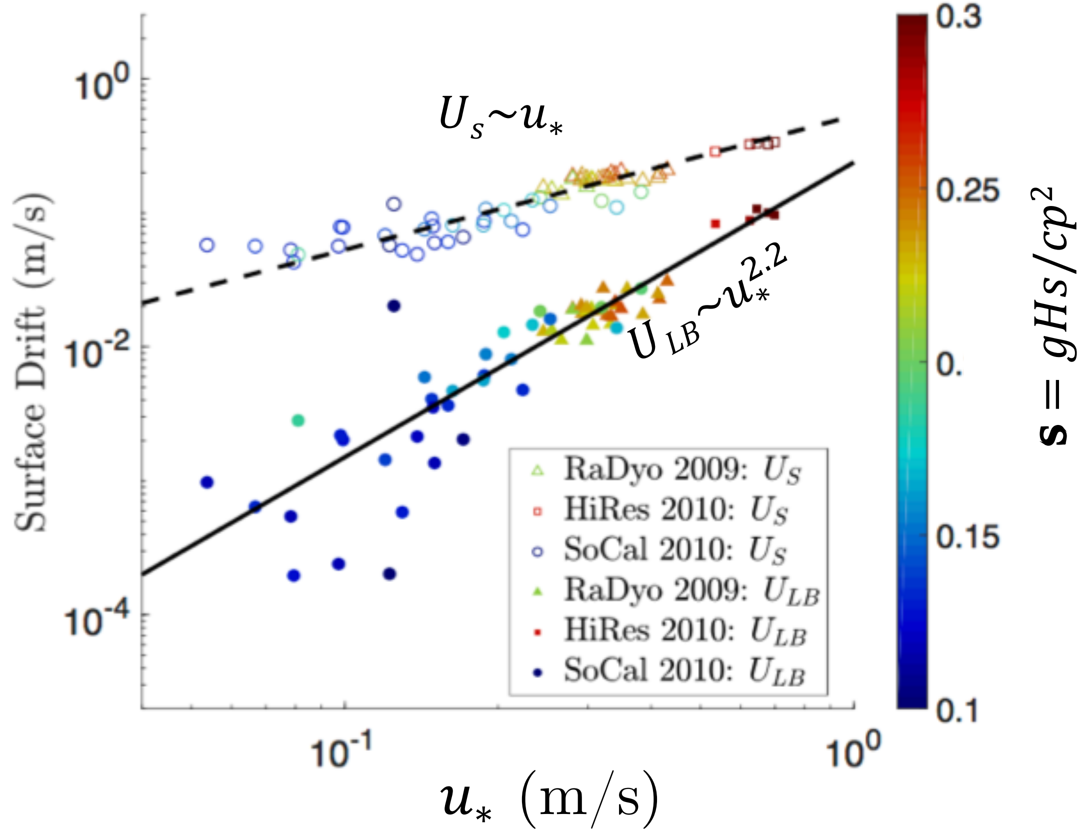
Radyo2009, SoCal2010, HiRes2010 (Sutherland & Melville 2013, 2015)

[Wind speeds ranging from 1.6 - 16 m/s, significant wave heights ranging from 0.7-4.7 m and wave ages ranging from 16-150.]

- R/P FLIP
- IR stereo cameras (captured air/non-air-entraining breakers) to measure breaking statistics
- Directional wave spectrum



Drift versus wind friction velocity



s: measure of wave steepness (i.e. larger **s** corresponds to steeper waves)

Stokes drift has larger values, but dependence on wind speed is stronger for breaking induced drift. Breaking drift up to 30% of Stokes drift.

Summary

- Used model of one breaking wave, together with breaking statistics, to estimate Lagrangian transport at the ocean surface due to wave breaking.

- **Not shown: scaling arguments connecting bulk scale estimates of Stokes drift and drift induced by breaking to environmental variables.**

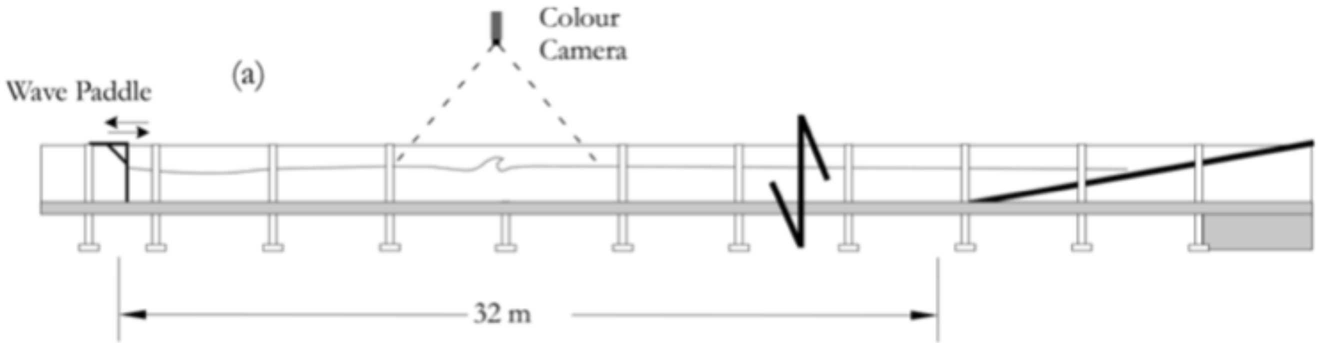
- Estimated drift induced by breaking **reaches 30% of Stokes drift** for environmental conditions considered here.

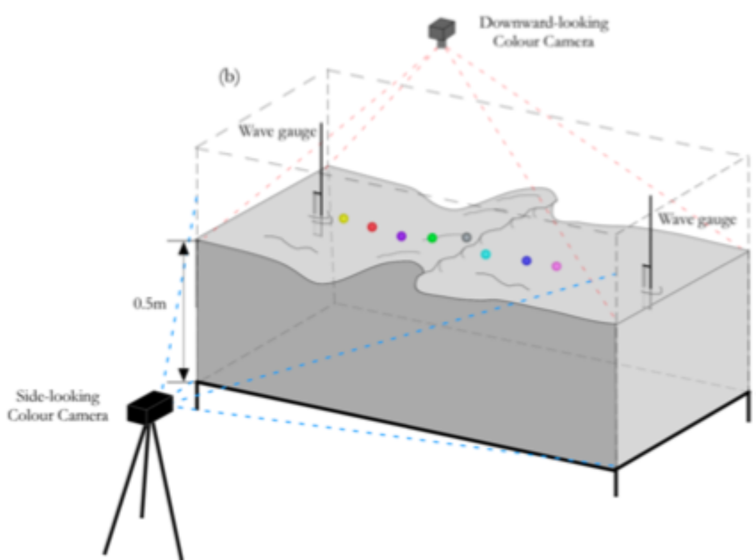
Laboratory experiments

Lenain, Pizzo, Melville (2019)

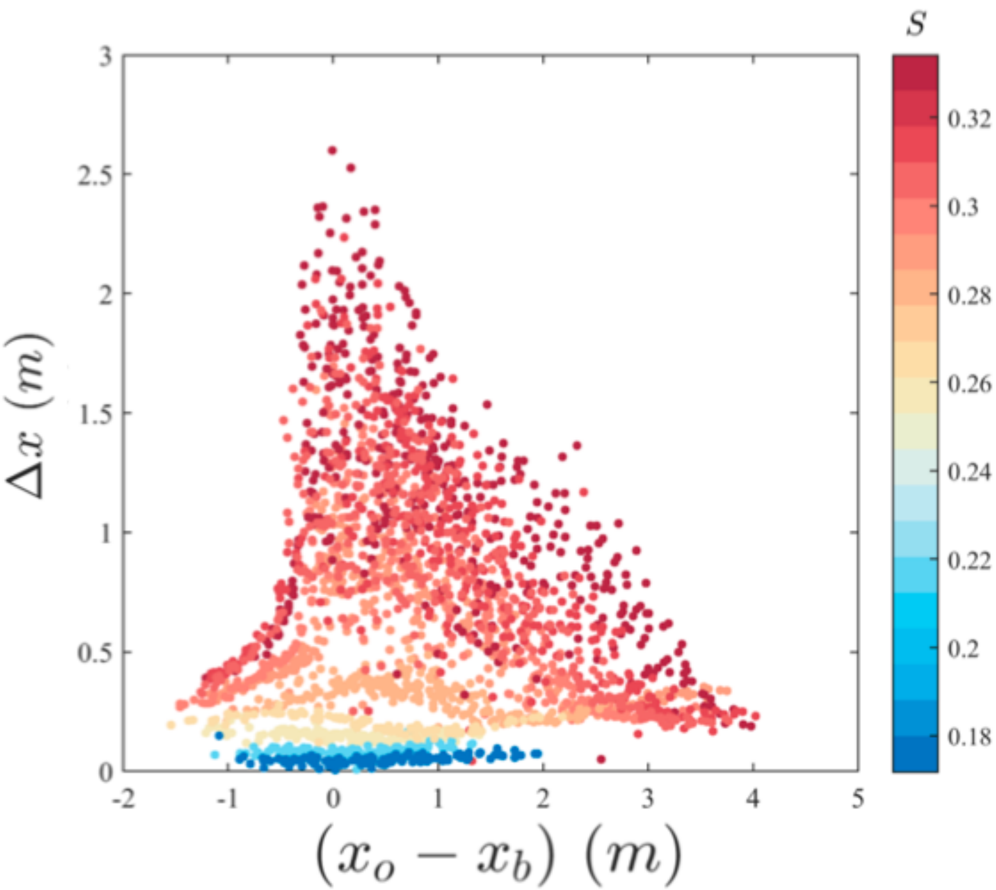
Can we better constrain the scaling constant α?

32 m glass channel at SIO





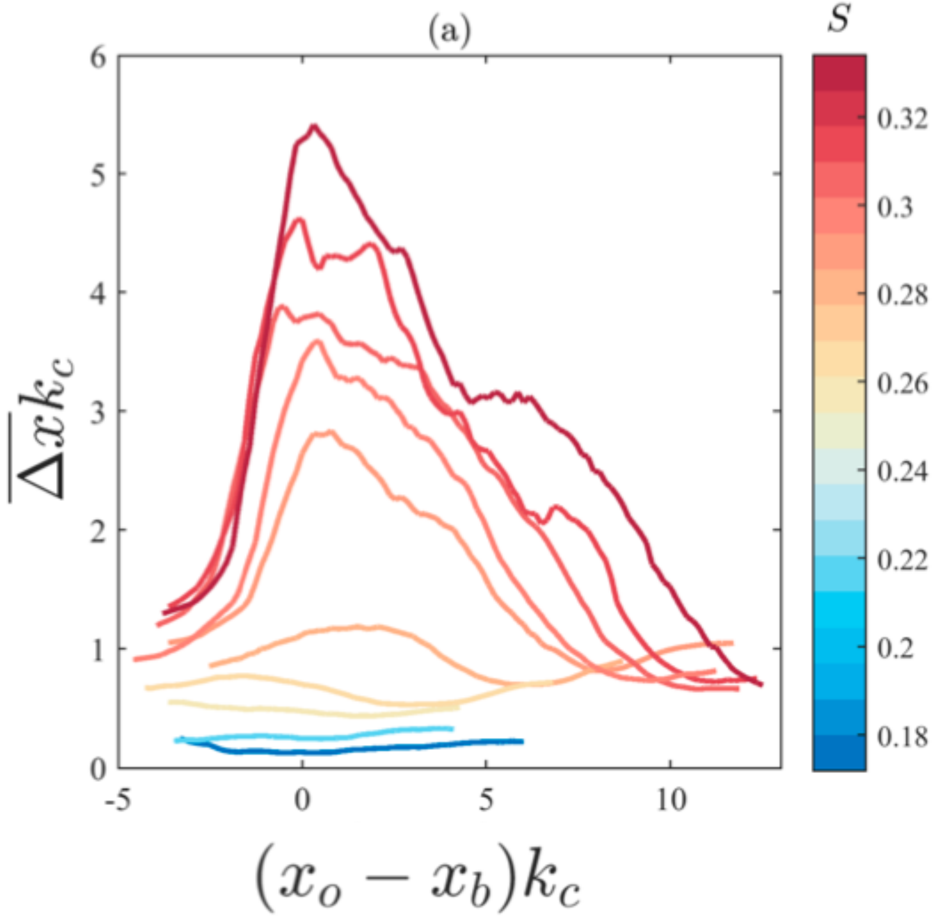
Drift induced by focusing



- 401 runs
- Fixed non-dimensional bandwidth (0.75)
- Vary slope S
- 8 particles per run

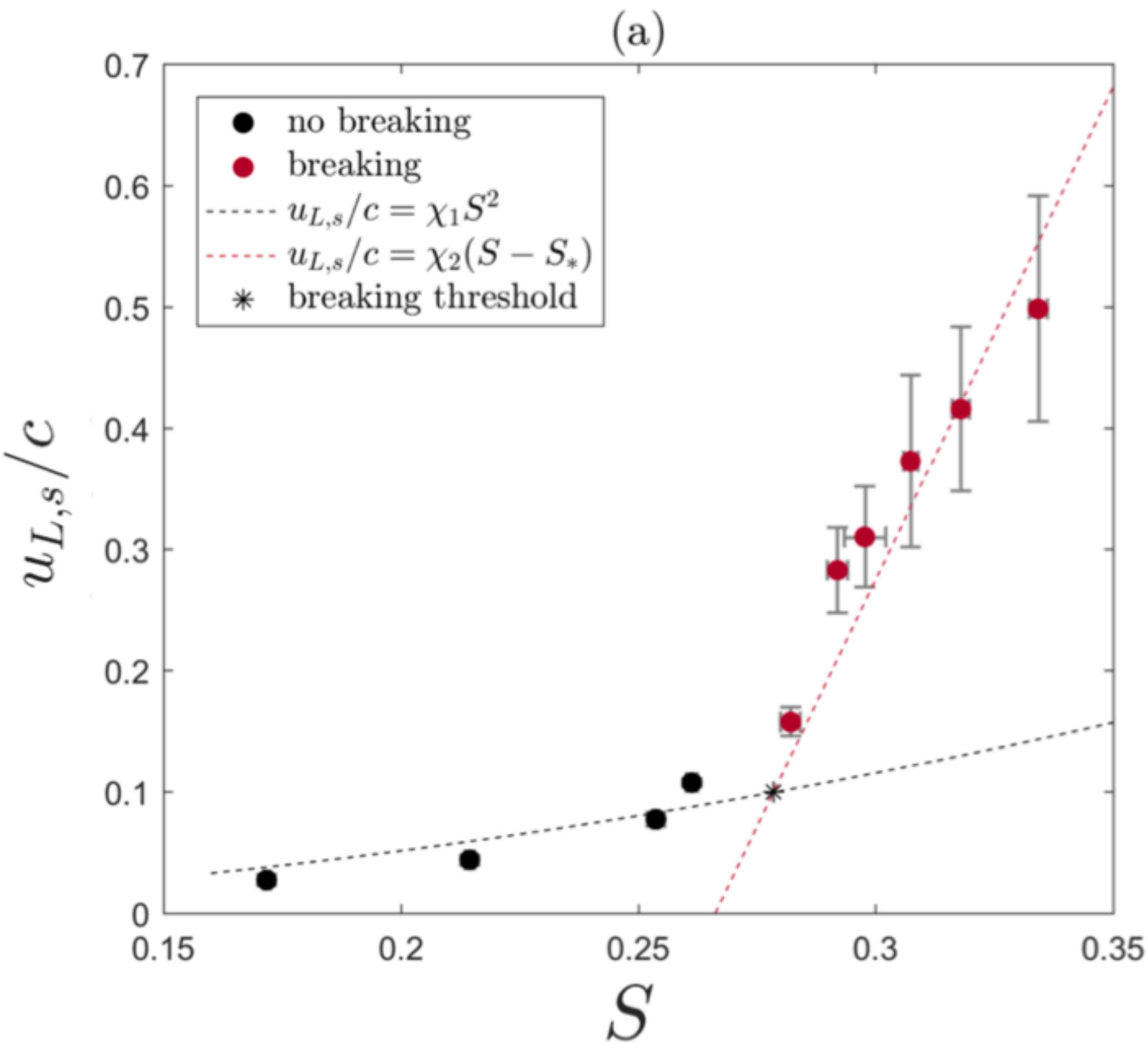
Averaged drift induced by focusing

- Running mean, over $\lambda/4$
- Breaking threshold around 0.28

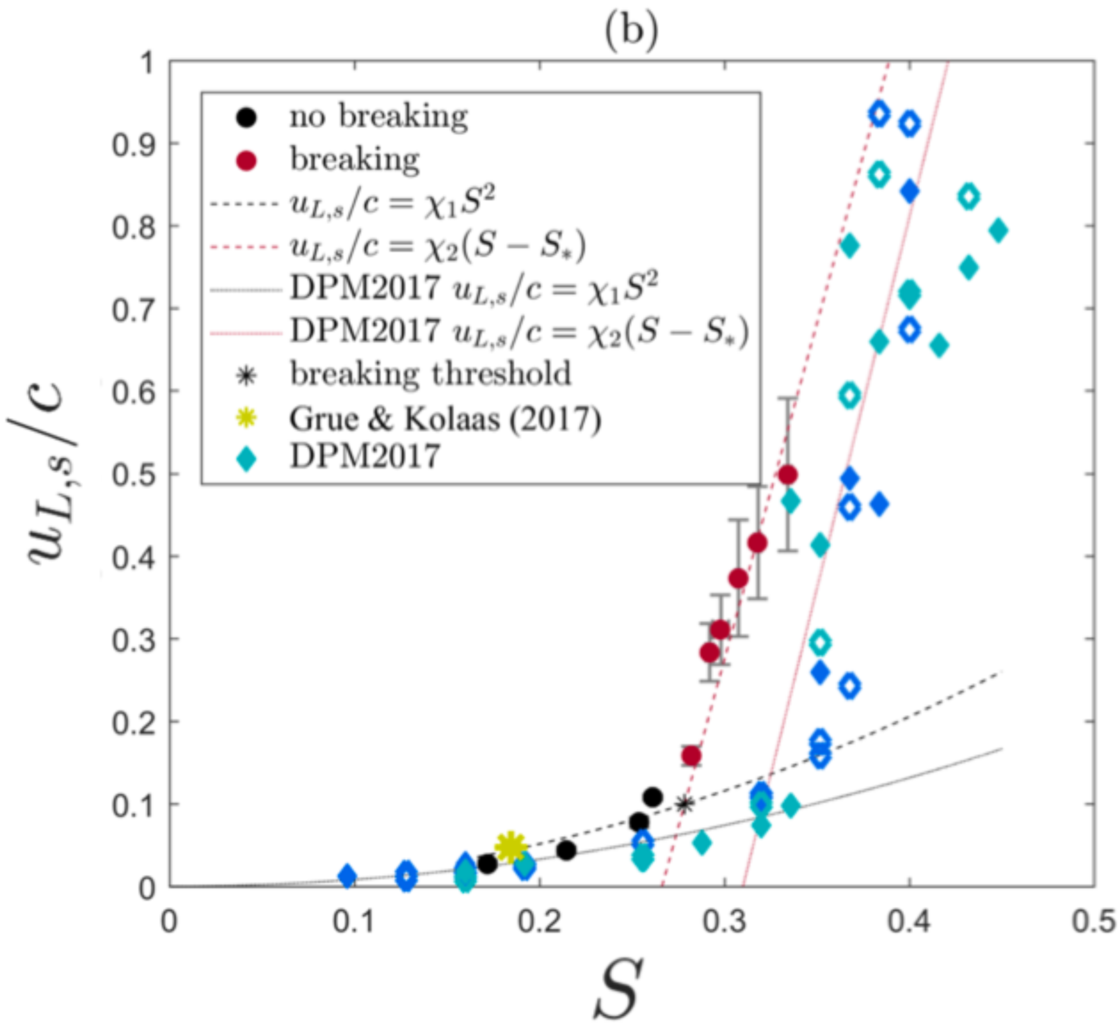


- Asymmetric
- Strongly peaked

Total drift


(a)
no breaking
breaking
$u_{L,s}/c = \chi_1 S^2$
$u_{L,s}/c = \chi_2(S - S_*)$
breaking threshold
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.15
0.2
0.25
0.3
0.35
$u_{L,s}/c$
S

Total drift



$\alpha_{\mathrm{Lab}} = 8$
$\alpha_{\mathrm{DNS}} = 9.5$

Qualitative agreement with DNS.

Conclusions

- Drift induced by breaking is up to 30% of that due to the classical Stokes drift (vorticity).
- Increasing importance with increasing u_*.
- Laboratory experiments recently conducted to better constrain α.

Breaking can contribute significantly to the wave driven transport at the ocean surface.

I. Deike, L., Pizzo, N.E., & Melville, W.K. 2017 Lagrangian transport by breaking waves. Journal of Fluid Mechanics. **829**, 364-391.
II. Pizzo, N.E. 2017 Surfing surface gravity waves. Journal of Fluid Mechanics. **823**, 316-328.
III. Pizzo, N.E., Melville, W.K., Deike, L. 2019 Lagrangian drift at the ocean surface. Journal of Physical Oceanography.
IV. Lenain, L. Pizzo, N.E., Melville, W.K. 2019 Laboratory Studies of Lagrangian Transport by Breaking Surface Waves. Journal of Fluid Mechanics, Rapids.

Current work

(with Luc Lenain, Laurent Grare, James Sinnis)

- Bandwidth effects on transport
- Connecting the energy dissipation rate and the mass transport

Questions?