Numerical modeling of the air-sea interaction in wave breaking and consequences in terms of the air-sea gas exchanges

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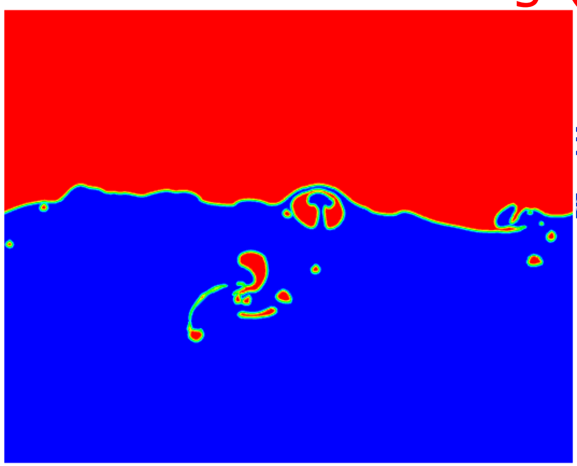
Air-sea gas flux climatology Workshop, IFREMER 24-27 Settember 2013

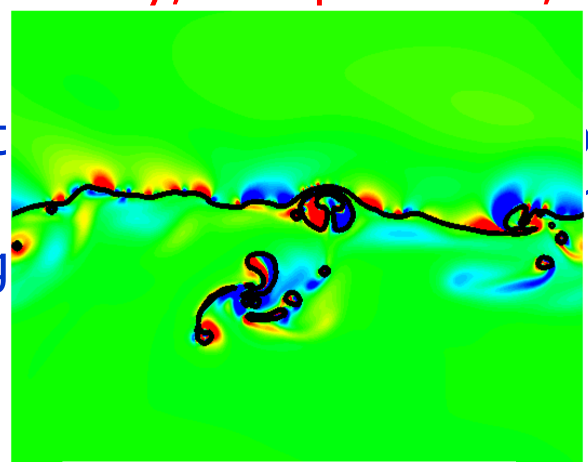
- **Content**: detailed simulations of wave breaking processes and of the consequent air-sea interaction by two-fluids methods

- **Analysis**: free surface dynamics (air entrainment and degassing, bubbles, drops and sprays), vorticity and velocity fields (in both air and water), energy dissipation, momentum transfer and breaking induced flow in air and water

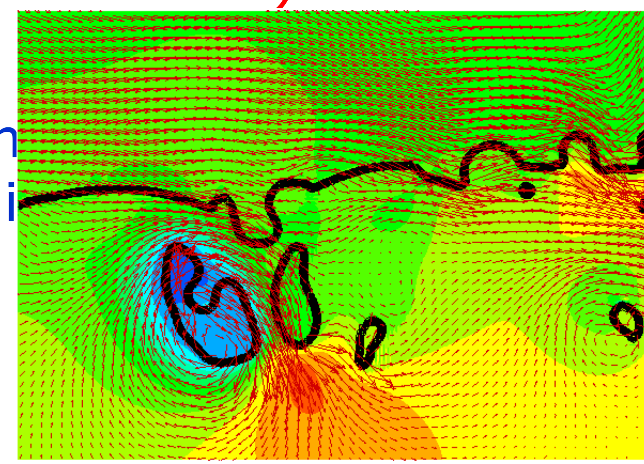
- **Limits:** small scales (up to 60 cm wavelength), 2D. Many other effects are missing (salinity, temperature, surfactants). Wind not



Air/water domains

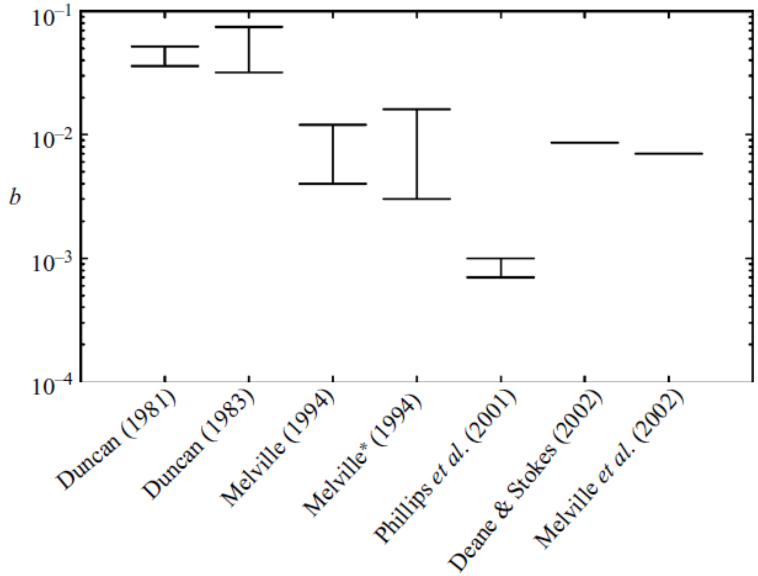


Vorticity contours



Velocity field, dyn. pressure

Role of breaking on wave dynamics



for wave forecasting, but the breaking

$$\cdot \nabla N = S_{nl} + S_{in} + S_{diss} ,$$

uncertainty, not much in the whitecap

ficient (Drazen, Melville, Lenain, JFM 2008)

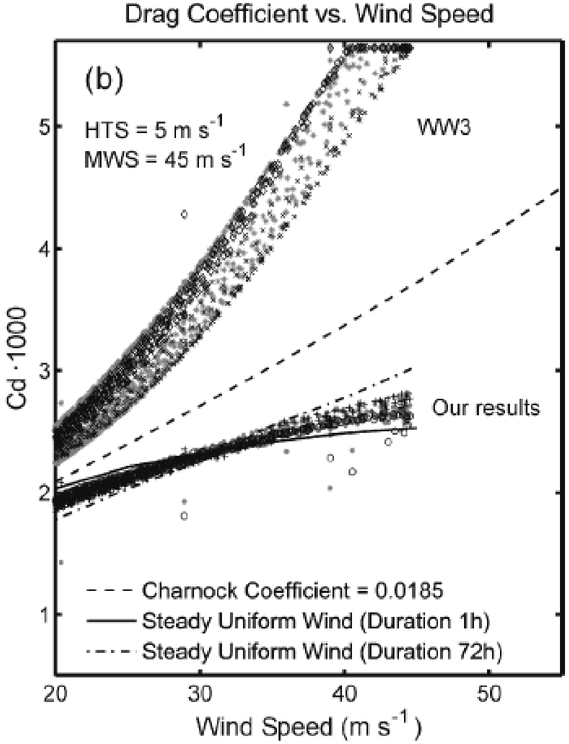
Contemporary spectral wave modeling techniques seem to have intrinsic limitations that might be overcome with gradual introduction of new methods toward an eventual deterministic depiction of the sea surface.

Cavaleri, *Wave Modeling: where to go in the future*, Bull. Amer. Met. Soc., 2006

from the atmosphere to the sea. Breaking waves, or white-capping as they are commonly referred to in deep water, have not yet been fully understood. While some progress has been made recently (see Banner et al. 2000), we are basically linked to the empirical approach suggested by Hasselmann (1974) more than 30 years ago. In effect, the parameterized white-capping formulation is the tuning knob by which we make our models more or less fit the recorded data.

Motivations for atmosphere-ocean interaction

…but wave breaking, bubbles, sprays and aerosol have also an important role in governing the drag at the see surface at high wind speeds (hurricanes)



Hurricane winds produce a large number of breaking waves and sea spray. Breaking waves and spray may significantly change the wind stress. Makin and Kudryavtsev (2002) predicted that breaking waves significantly enhance the sea drag over younger seas. Andreas and Emanuel (2001) considered spray effects on momentum transfer and concluded that this effect could be large as well. It is our intention to include these processes in our future modeling efforts. It is important to

Moon, Ginis and Hara, *Effect of Surface Waves on Air–Sea Momentum Exchange. Part II: Behavior of Drag Coefficient under Tropical Cyclones*, J. Atm. Sc., 2004

… and of course in the gas exchanges at the sea surface

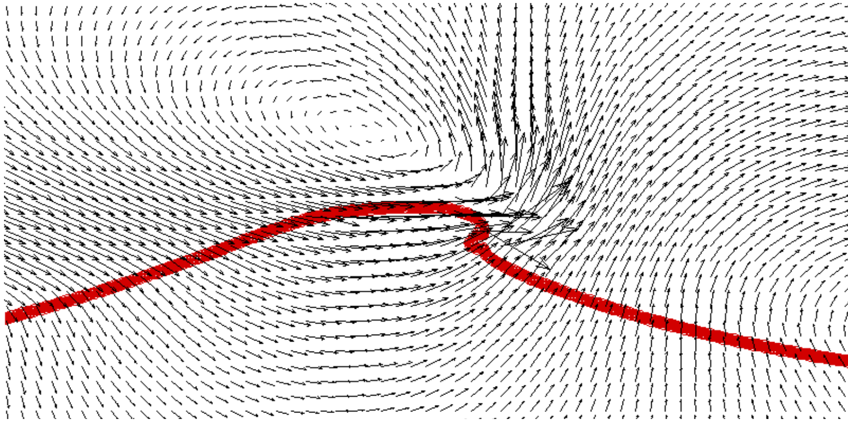
Numerical simulations of wave breaking processes

- Navier-Stokes solver for a fluid with density and viscosity smoothly varying across the interface

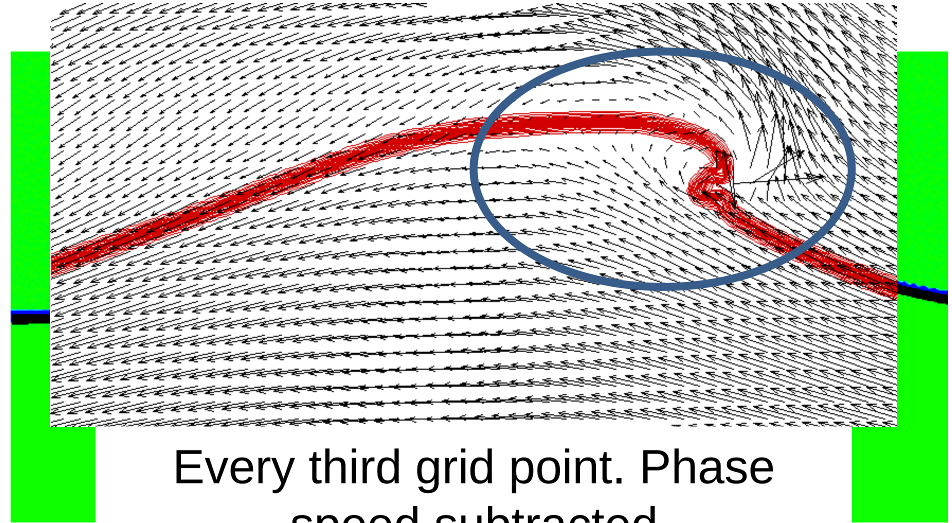
- Two different kind of breaking processes:
  1. Breaking of a steep wave as that generated by dispersive focussing: energy dissipation, air entrainment, drops, bubbles and degassing (30 cm wavelength)
  2. Breaking as a result of the modulational instability: recurrent breaking, energy dissipation in each breaking event, breaking induced air flow (60 cm wavelength)

- Of course there are experiments done in laboratories. However, in most of the experiments the breaking is generated by dispersive focussing, which is less frequent in open ocean. Due to limitation in tank lengths there is not enough space for the modulational instability to develop.
- Furthermore, even in highly refined laboratory experiments it is rather difficult to get a complete picture of the velocity field near the interface (e.g. due to light reflections from bubbles in PIV techniques)

Dispersive focussing breaking: spilling case



Every fifth grid point

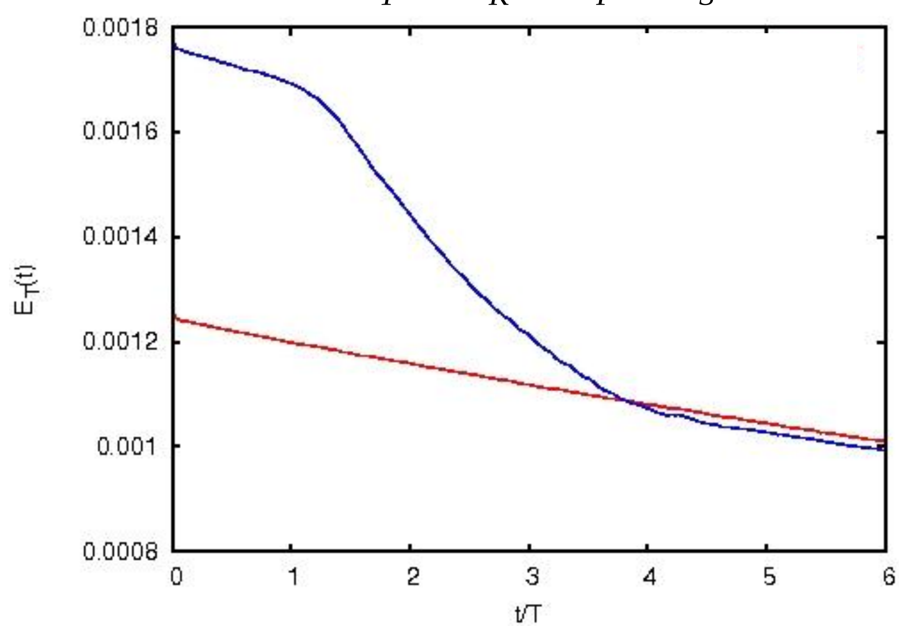


Every third grid point. Phase speed subtracted

The resolution is not fine enough to describe the air entrainment at the toe of the breaker (red region 3 mm thick)

Total mechanical energy

$$E_T = E_K + E_P + E_S$$

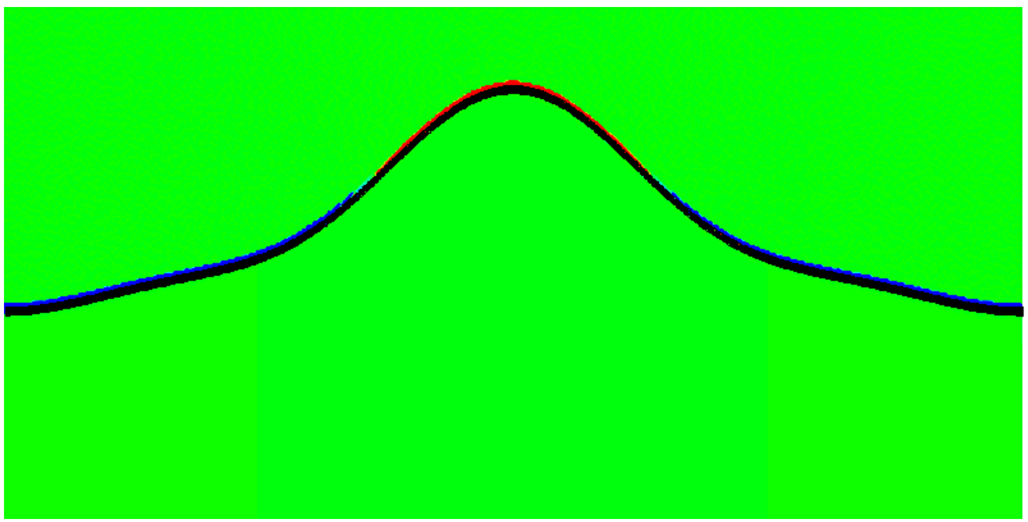


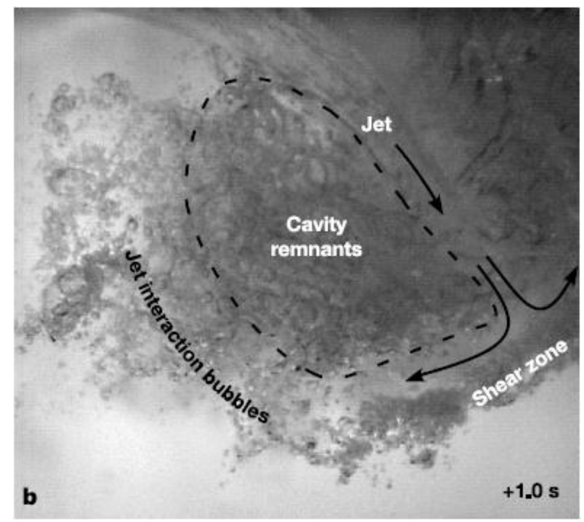
Comparison with the steepest non-breaking case ($\varepsilon = 0.30$) shows that the occurrence of breaking dissipates the extra energy content until reaching the steepest non-breaking solution.

Dispersive focussing breaking: strong plunging breaking events

Stronger plunging breaking event, with significant air entrainment.

Highly rotational flow generated by the cavity closure, and by the successive cavity collapse into a bubble cloud





Deane & Stokes, 2002

Dispersive focussing breaking: strong plunging

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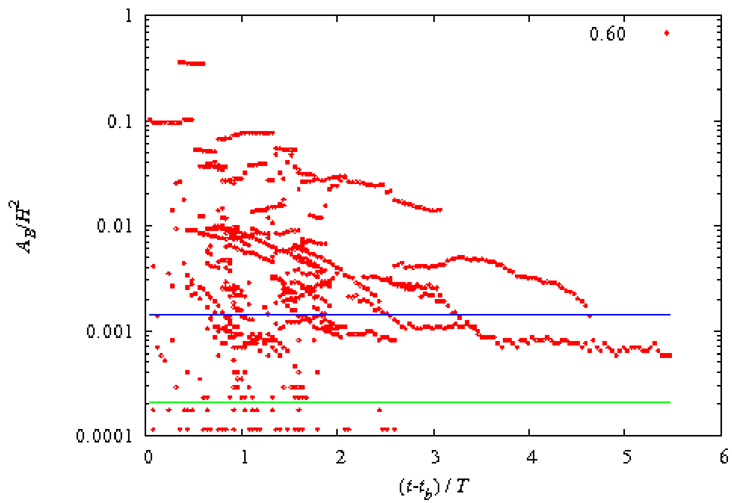
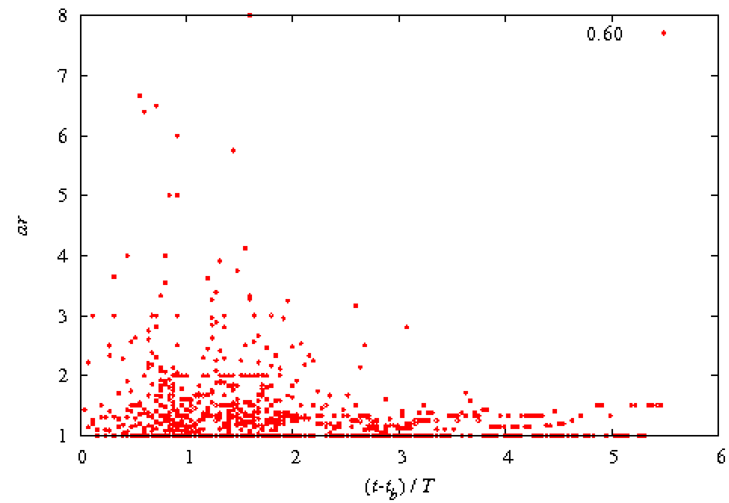
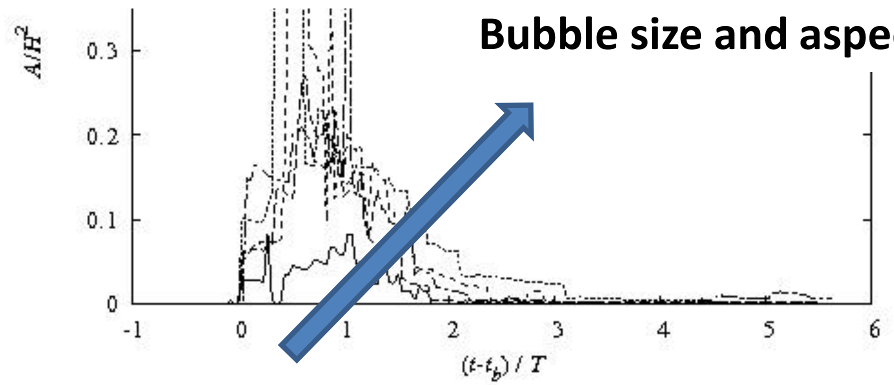
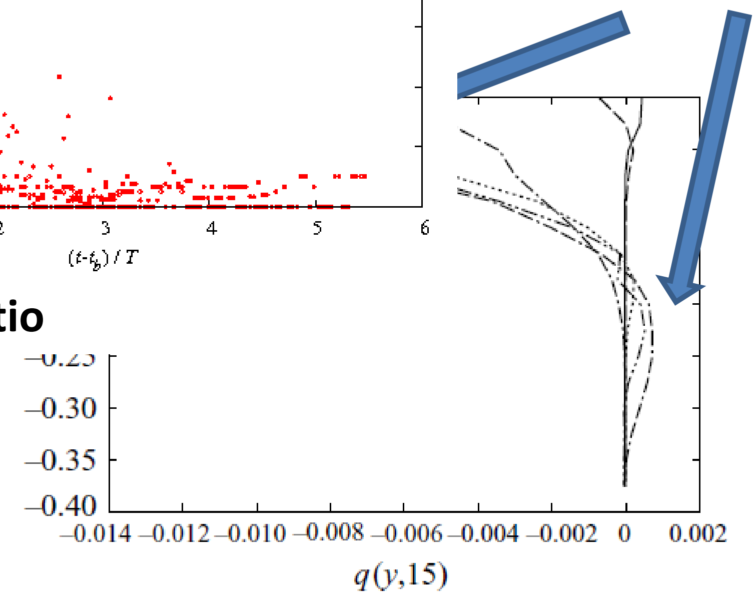




Bubble size and aspect ratio



Air entrainment



Flux of horizontal momentum

Dispersive focussing breaking: strong plunging
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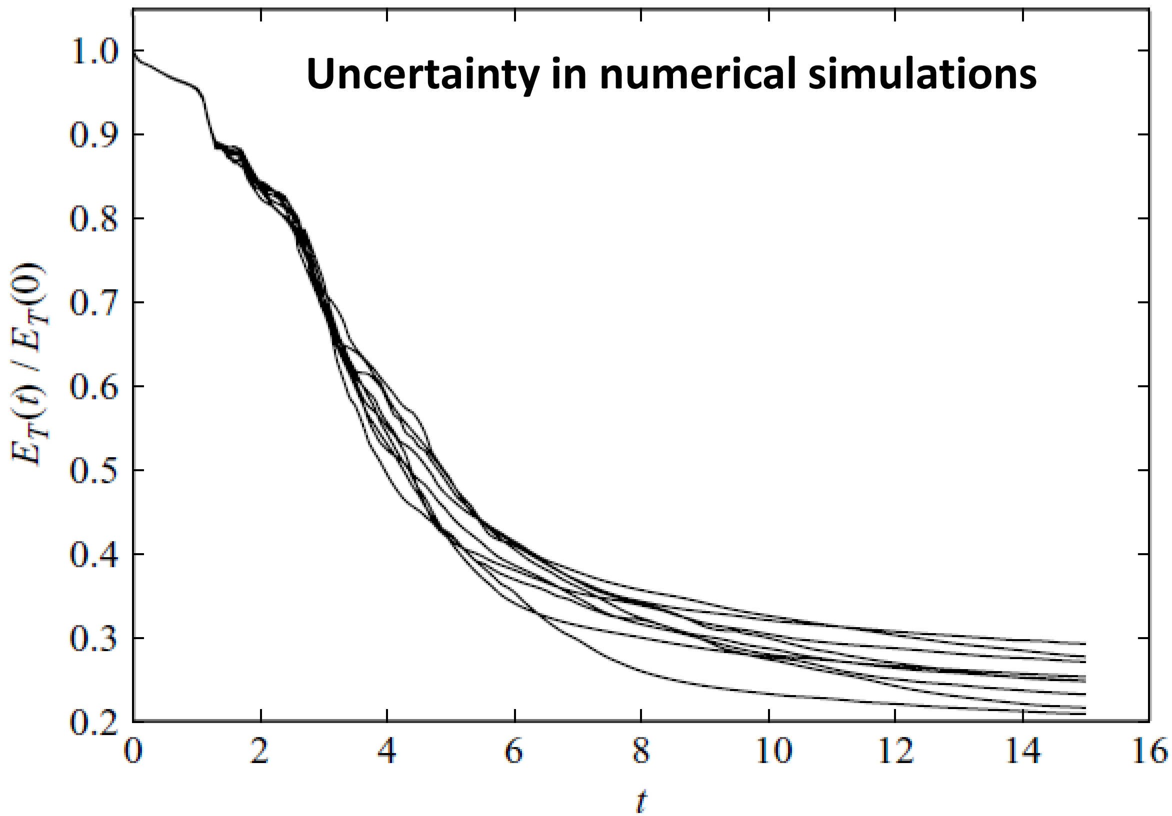
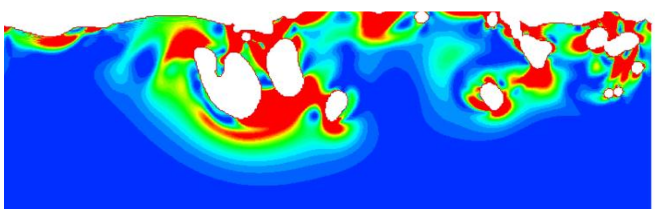
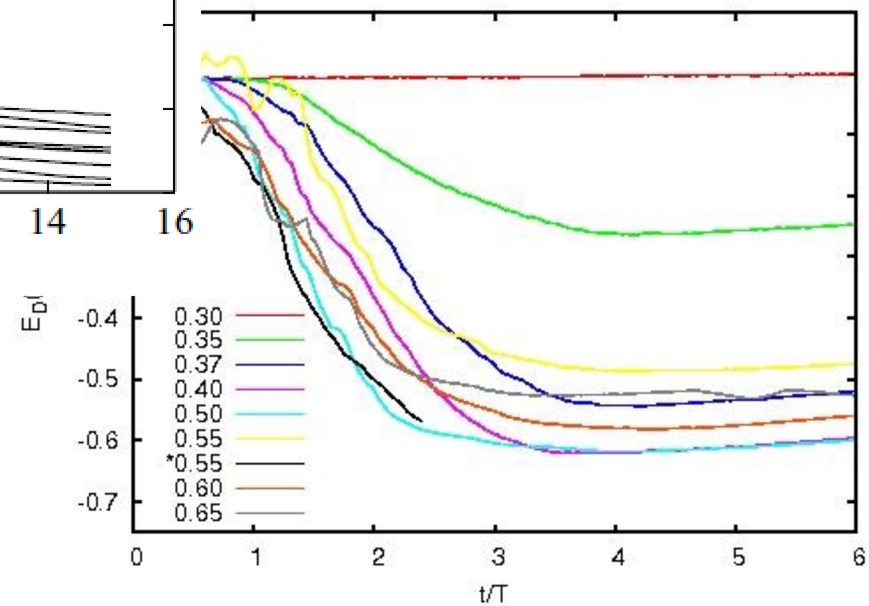


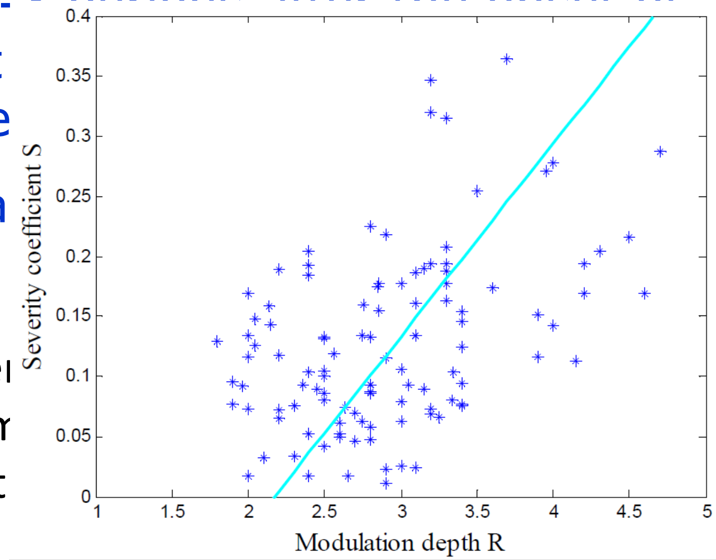




Breaking of modulated wave trains

The breaking induced by modulational instability has remarkable differences with respect to that due to dispersive focussing. In the latter the most relevant phenomena end within 2- the breaking and, furthermore, the amount established in terms as a fraction of the pre

This is not the case for the breaking genera modulational instability:



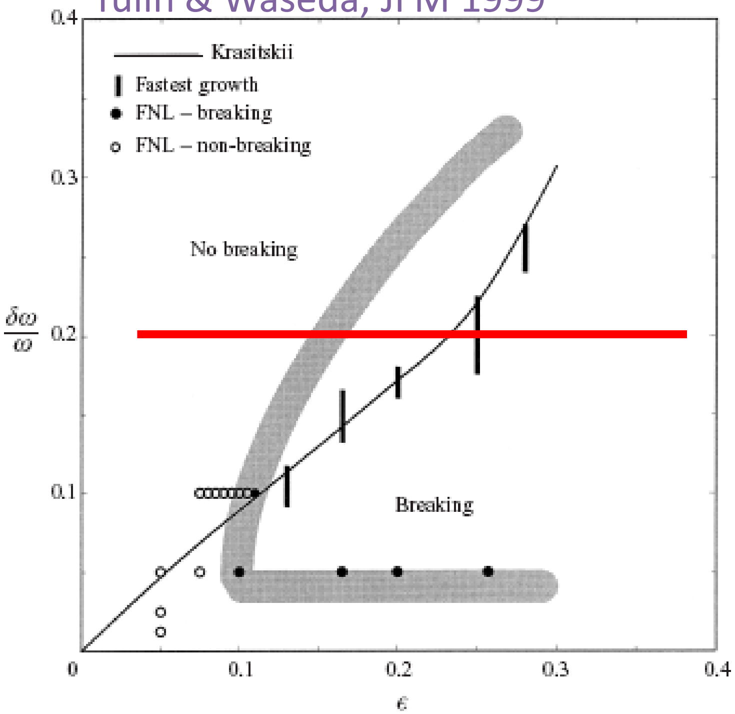
Galchenko et al, JPO 2010

- In modulate wave systems, the breaking is recurre time due to the demodulation process, and the am event is unknown as it strongly depends on amplit components and on the modulation depth.
- The range of variation is much wider with respect estimates of the associated dissipation levels are available (see Babanin et al., JFM 2010; Babanin et al., JPO, 2011, Galchenko et al., JPO 2010)
- Furthermore, in open ocean waves start to break as soon as they exceed a sort of threshold steepness. Generally, the steepness do not get up to the values used in the previous simulations, and thus the breaking is milder, and the water layer affected by the breaking is narrower.

Initial conditions: Benjamin-Feir instability case

- Case study: fundamental component with sideband perturbation (Song and Banner, JPO 2002)

Tulin & Waseda, JFM 1999



$$\ldots(k_0 x) + A^+ \sqrt{g/k^+}\, \exp\left(k^+ y^*\right)\sin(k^+ x)$$

$$+ A^- \sqrt{g/k^-}\, \exp\left(k^- y^*\right)\sin(k^- x)$$

$$\ldots^+ x) + A_1 \cos(k^- x)$$

...ues of the

Nav.

$$\varepsilon_0 = A_0 k_0 = (0.10 - 0.02 - 0.18)$$

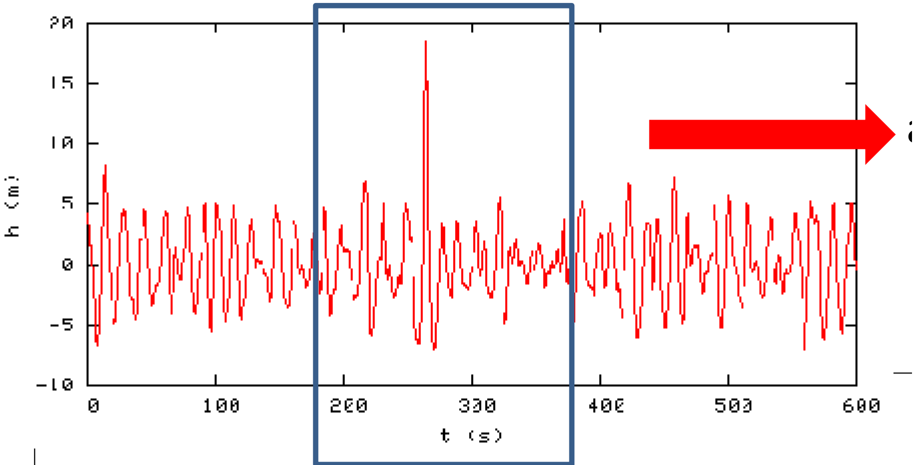
$$A_1 / A_0 = 0.1,$$

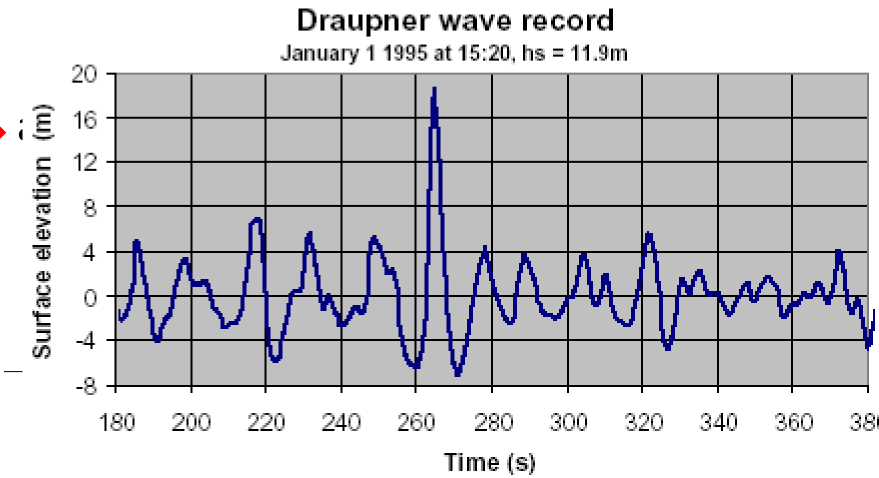
$$k^+ = k_0 + \Delta k,$$

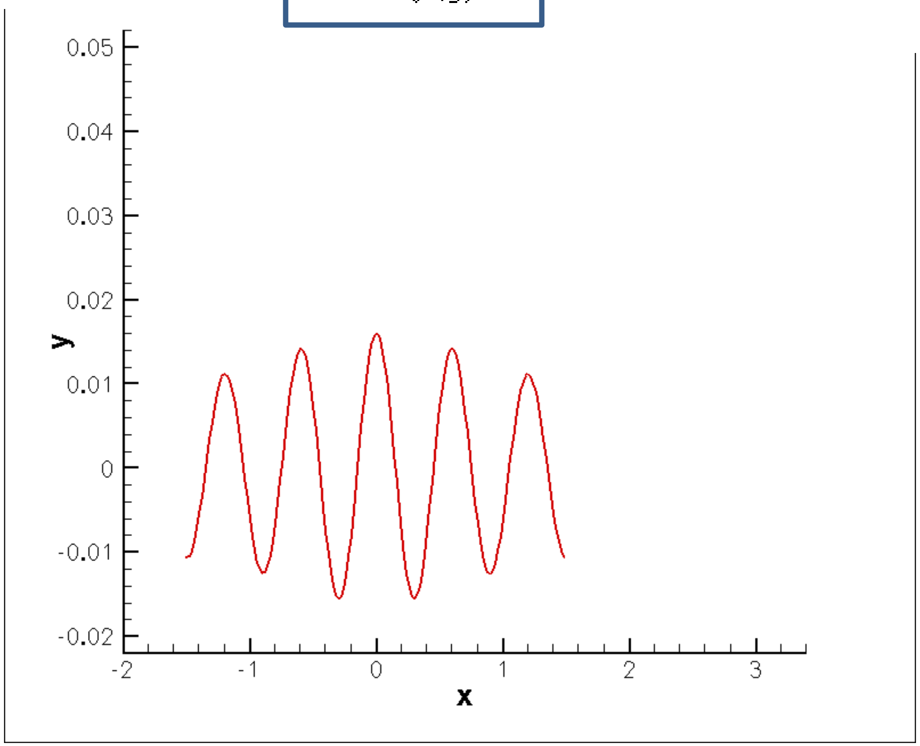
$$k^- = k_0 - \Delta k,$$

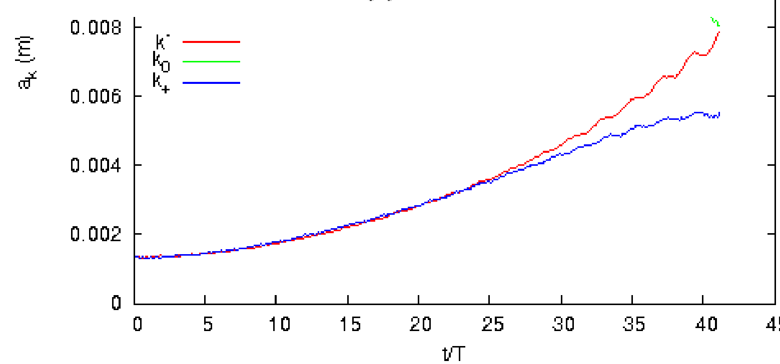
$$\Delta k = k_0 / 5$$

FNL potential flow simulations







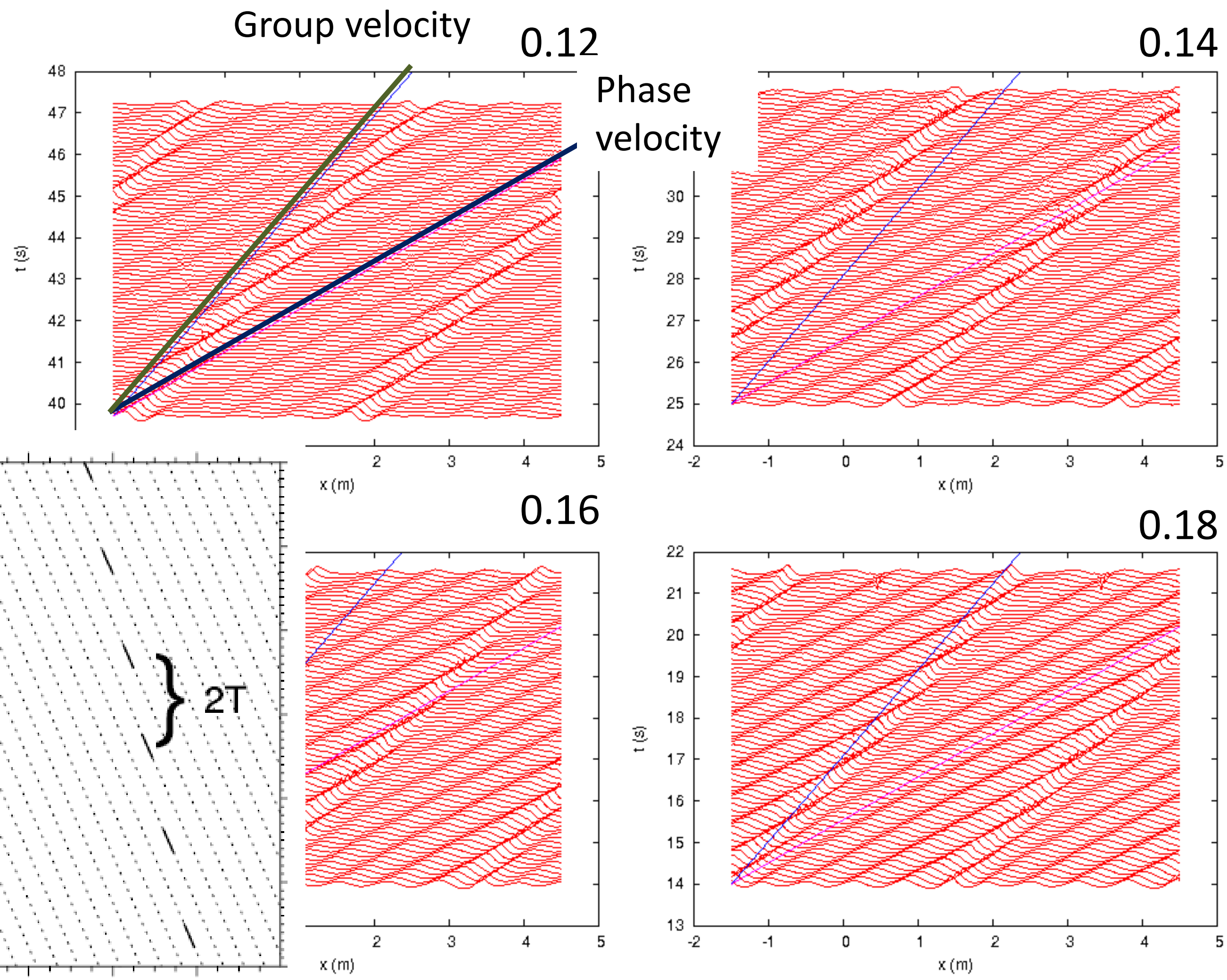


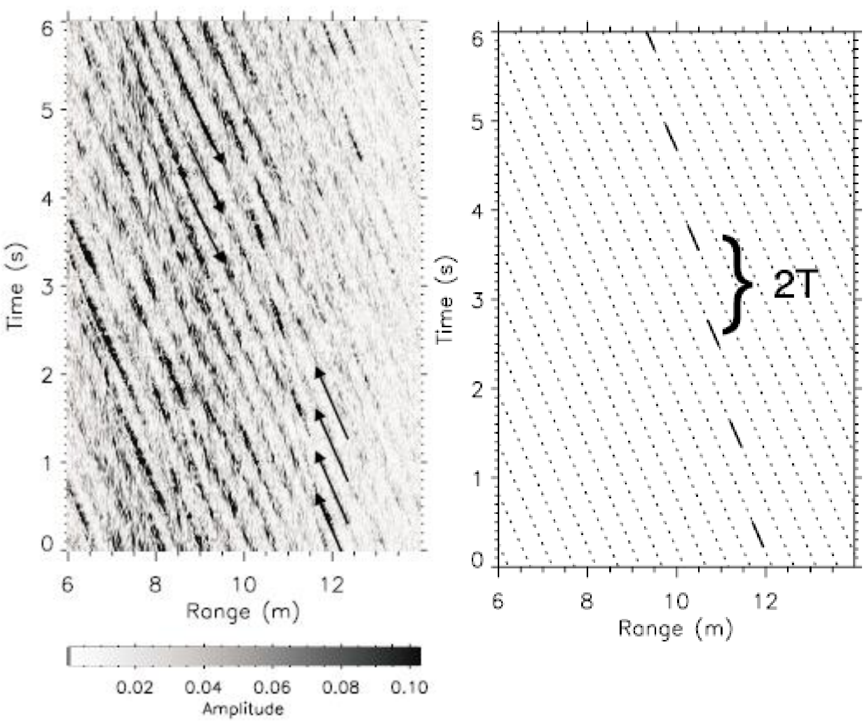
ε_0	t_I / T
0.12	65
0.14	42
0.16	30
0.18	25

0.14

Two-fluids models after the breaking onset

Not just a single event, but recursive breaking due to the modulation and demodulation processes (agrees with exp. observations)



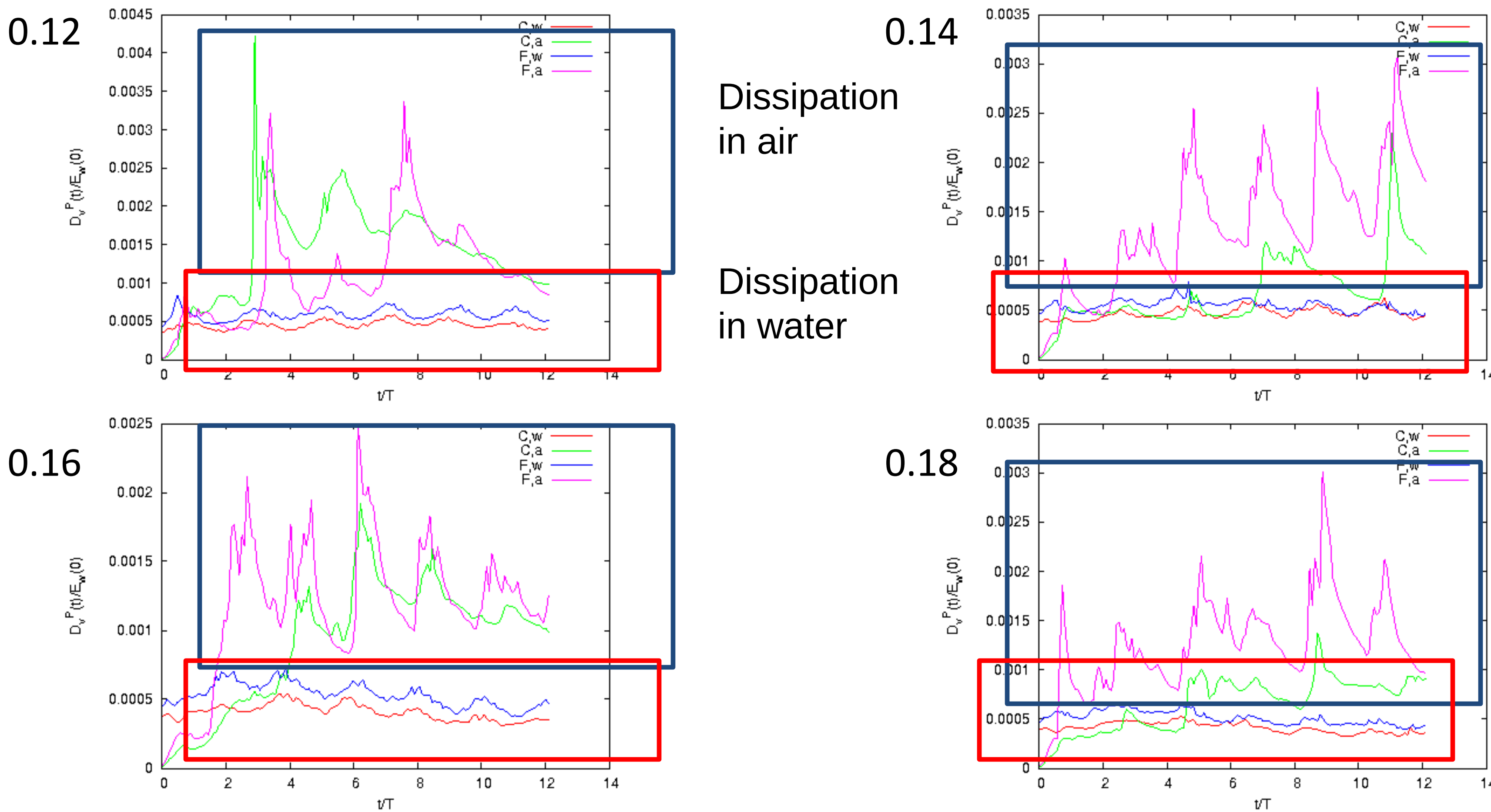


Lamont-Smith, Fuchs and Tulin, 2003

Viscous dissipation in air and water domains

Viscous dissipation
on two grids are sh

Generally, viscous dissipation levels in air larger than those in water. Also the high dissipation level last longer so that a much larger energy fraction seems to be dissipated in air rather than in water

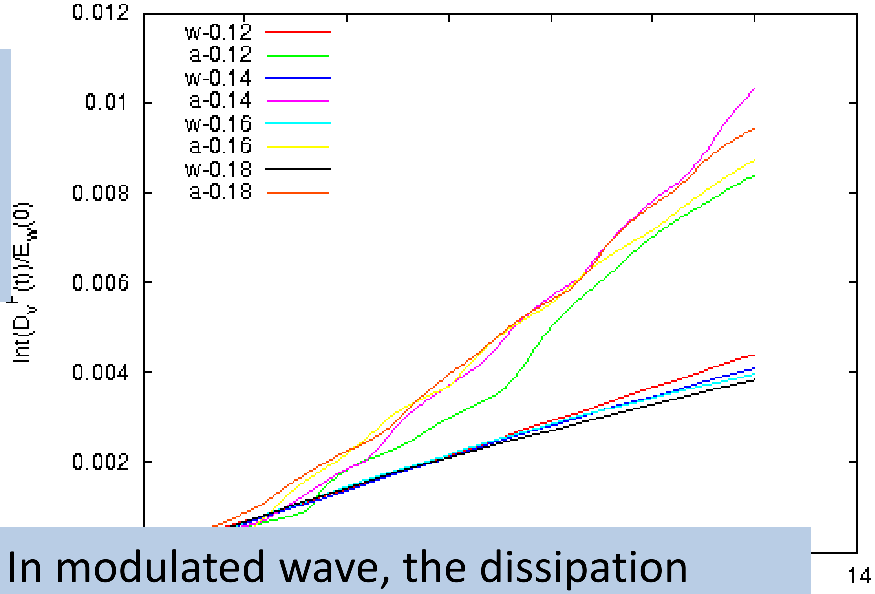


Time integral of viscous dissipation

When scaled by the initial energy content in

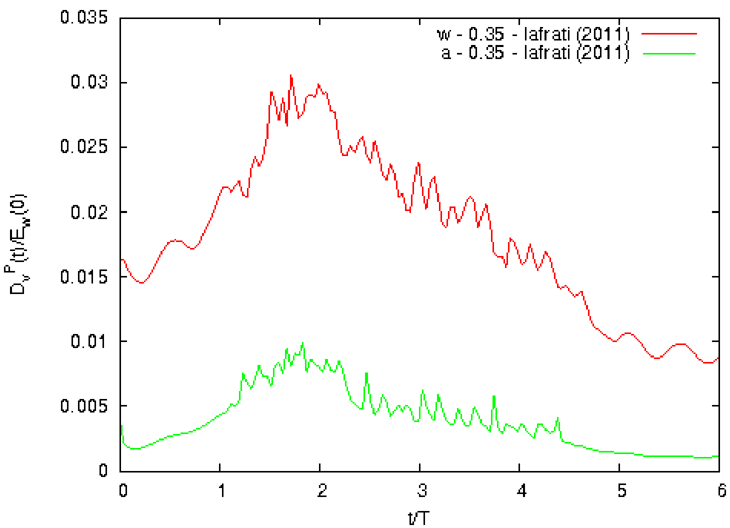
This is different from what found in the breaking of steep waves obtained by linear superposition of different wave components (Iafrati, JGR 2011)

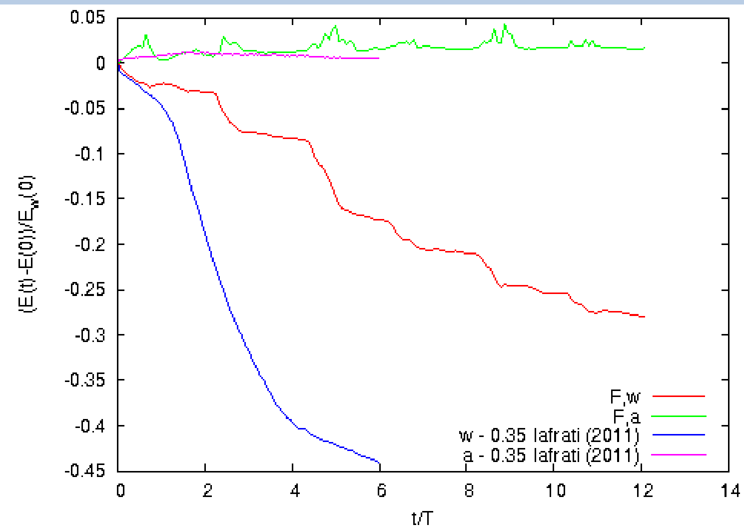
For the time interval considered here (i.e. about 5-6 breaking events), the dissipation in the air region is about 2/2.5 times larger than in water.



Dissipation in water (red) 5/6 times larger than that in air

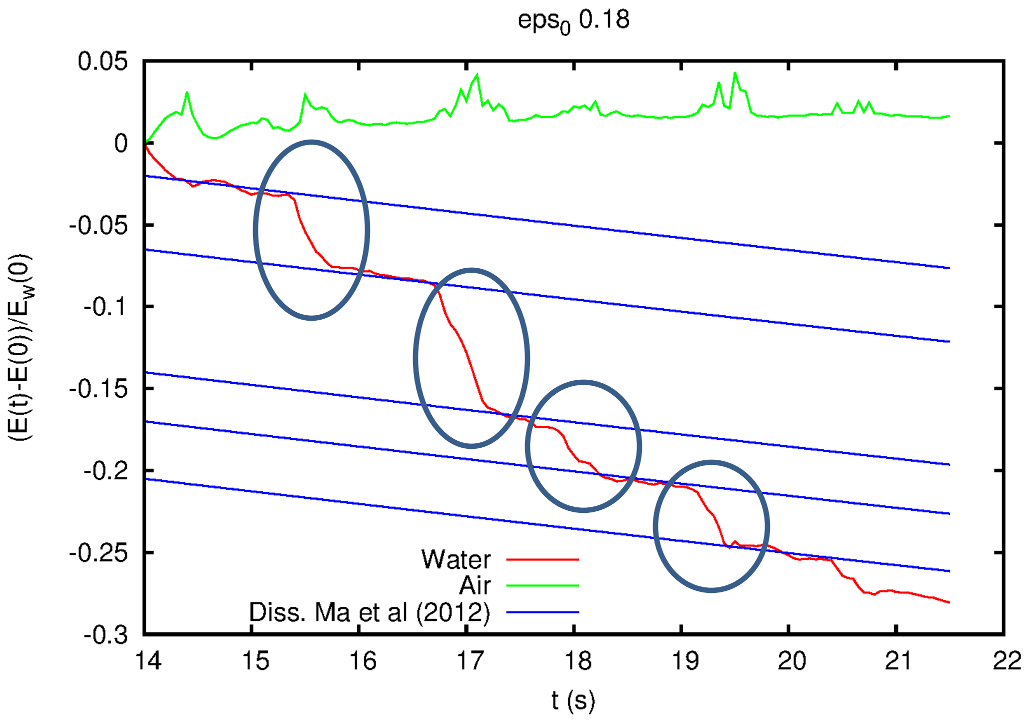
In modulated wave, the dissipation occurs i steps, whereas in the linear superposition it occur in a unique event





Energy dissipation in a single breaking process

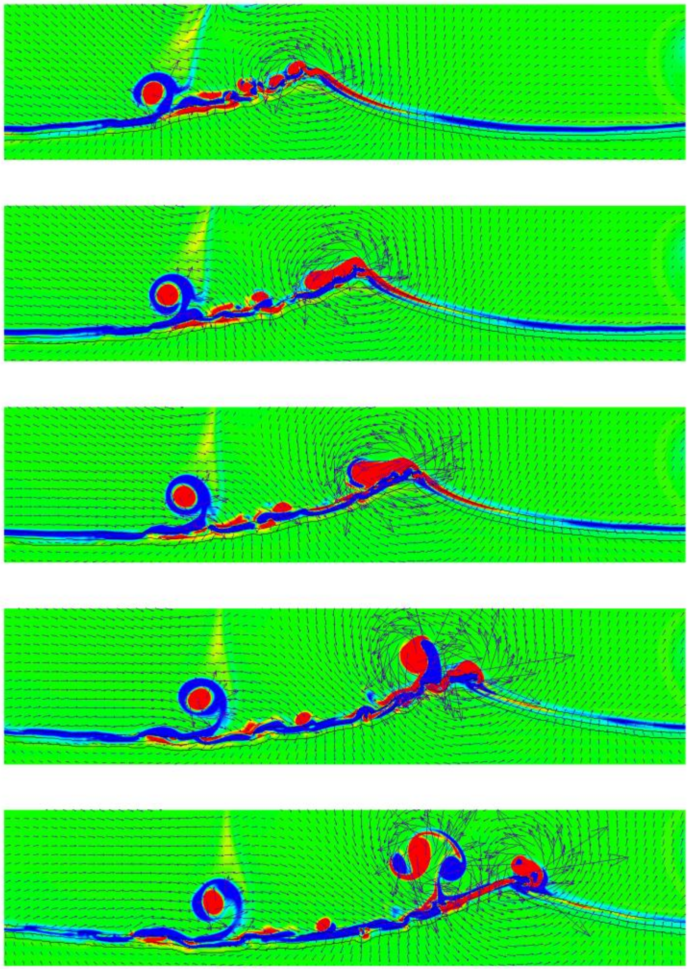
The energy content in water exhibits steps concurrent with the breaking occurrence. Between two successive breaking events the energy has a decay rate essentially equal to that measured in a tank for non-breaking waves with similar wavelength.

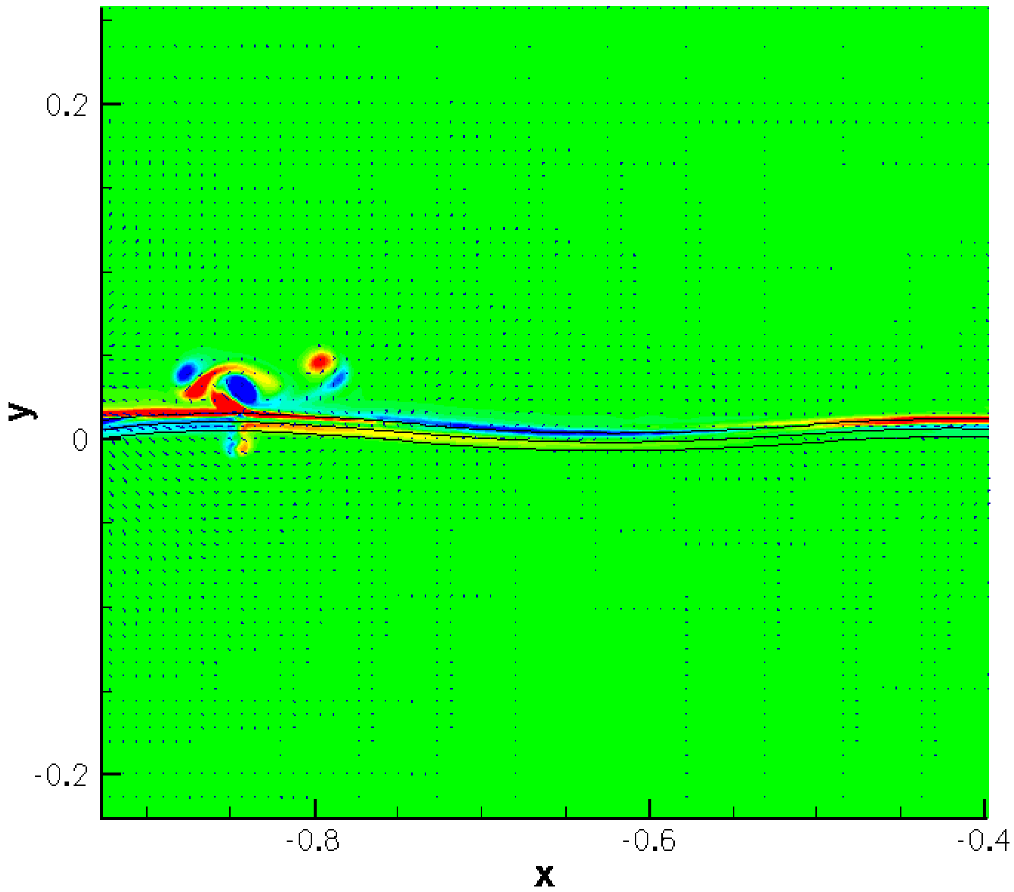


Two-fluids modelling and breaking induced wind

A large vorticity field is induced in air due to the flow separation at wave crest occurring during the steepening process before the breaking (max and min vorticity levels at 30 s^{-1})

NOTE: there is no wind in these simulations

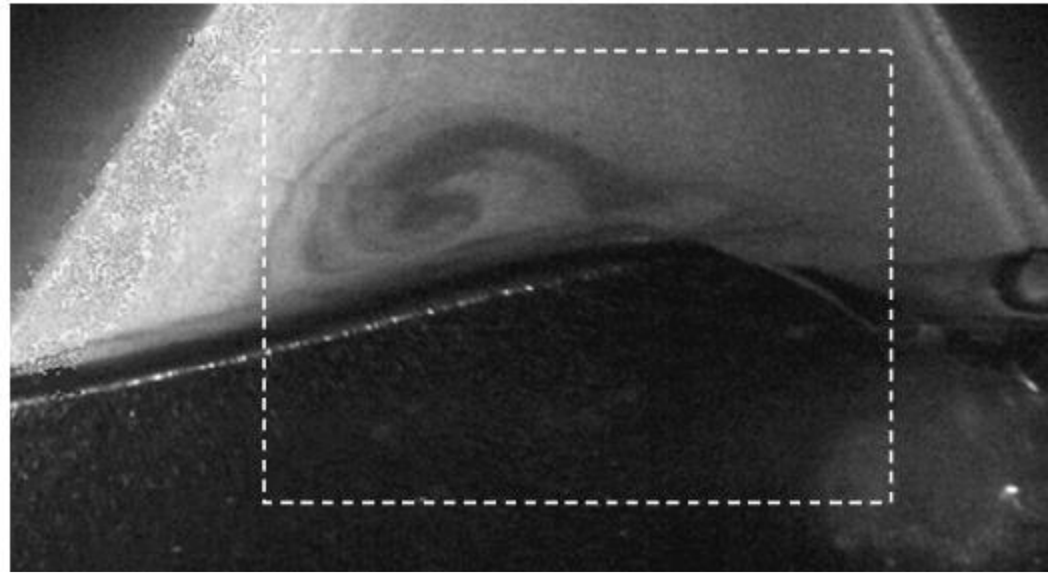


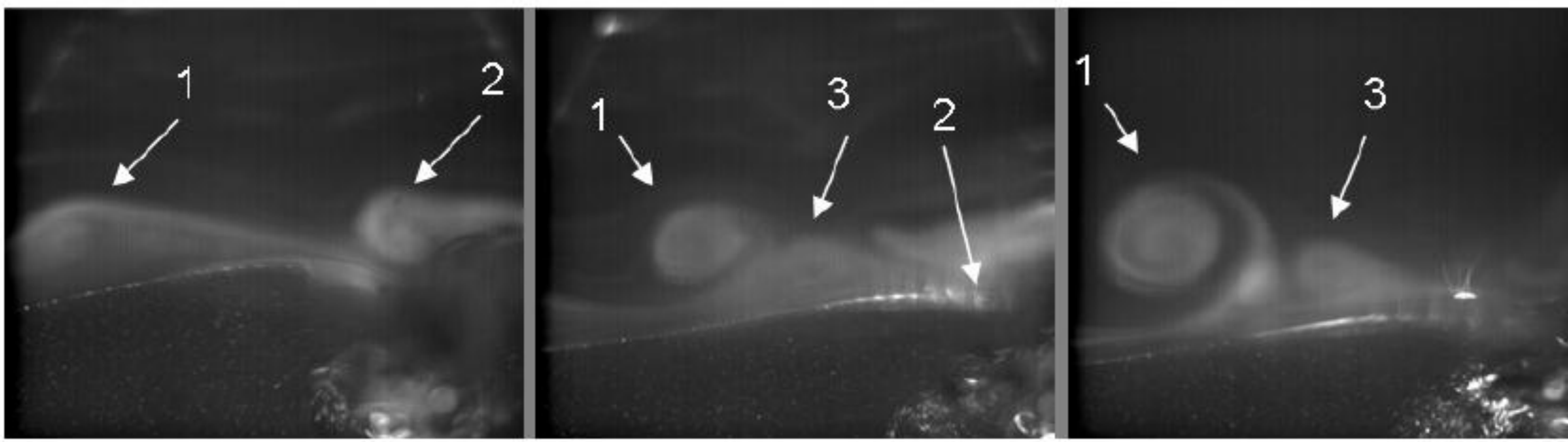


Two-fluids modelling and breaking induced wind

The phenomenon has been also observed in laboratory

Due to the lack of detailed experimental data in the air phase and to the differences in the breaking mechanism it is not possible to establish a more quantitative comparison





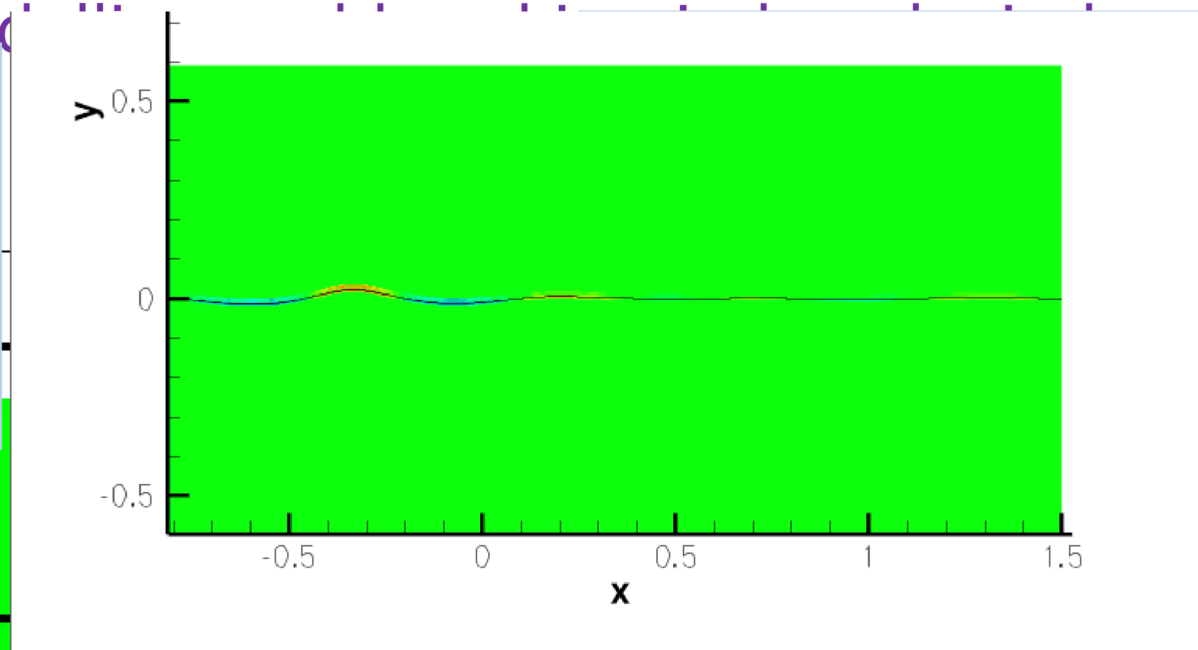
A.H. Techet & A.K. McDonald

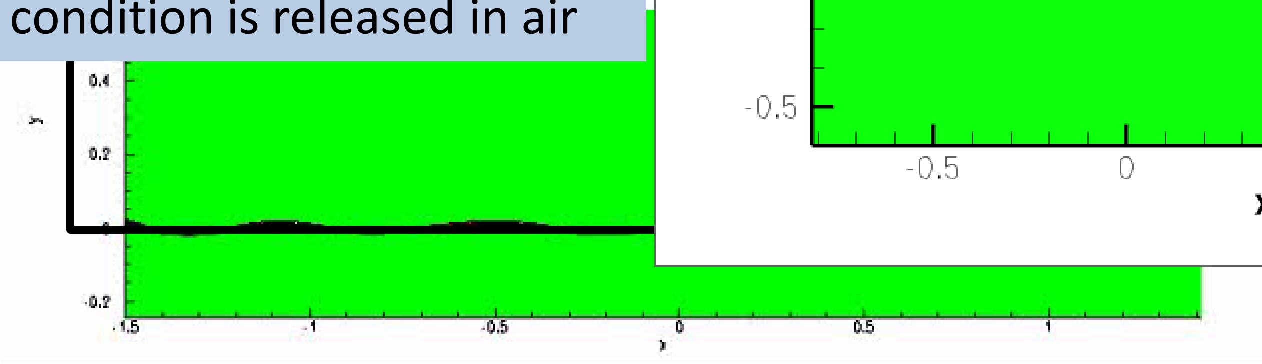
High speed PIV of breaking waves on both sides of the air-water interface

PIV ‘05, Pasadena (CA)

Two-fluids mo

NOTE: the dipole formation in air is not observed in absence of breaking. In that case only some vorticity associated to the initial condition is released in air

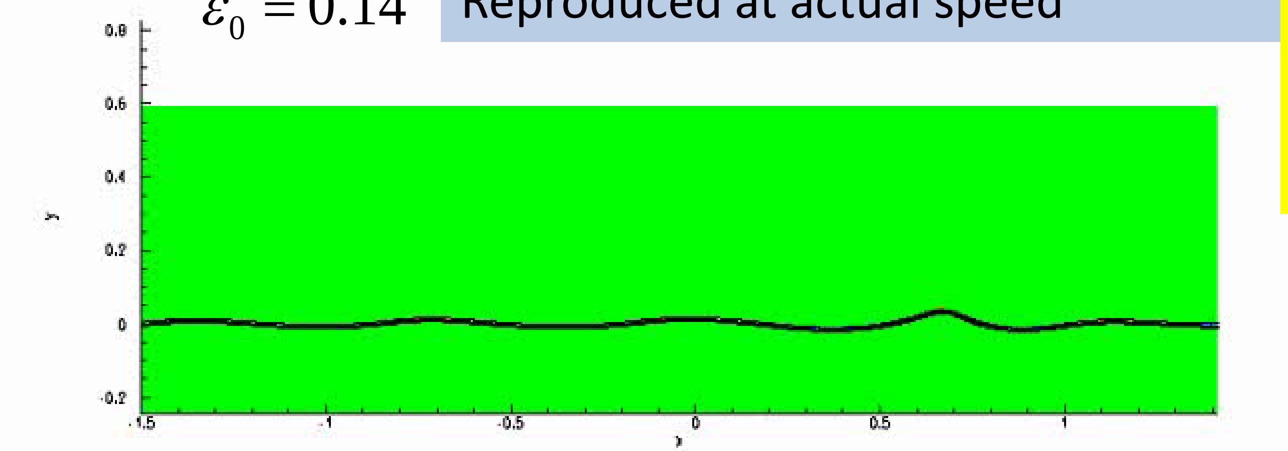




to propagate further into the air. Studies with higher computational domains needed. **Important 3D effects are not included here**

$\varepsilon_0 = 0.14$

Reproduced at actual speed

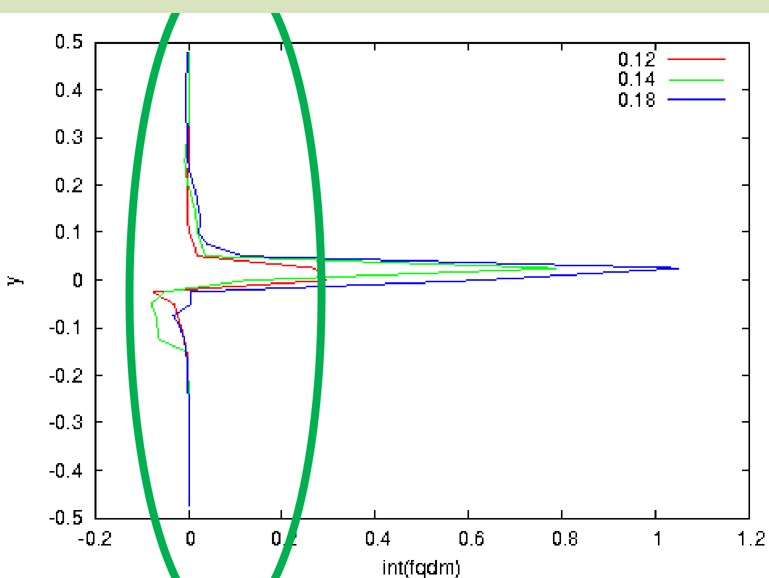


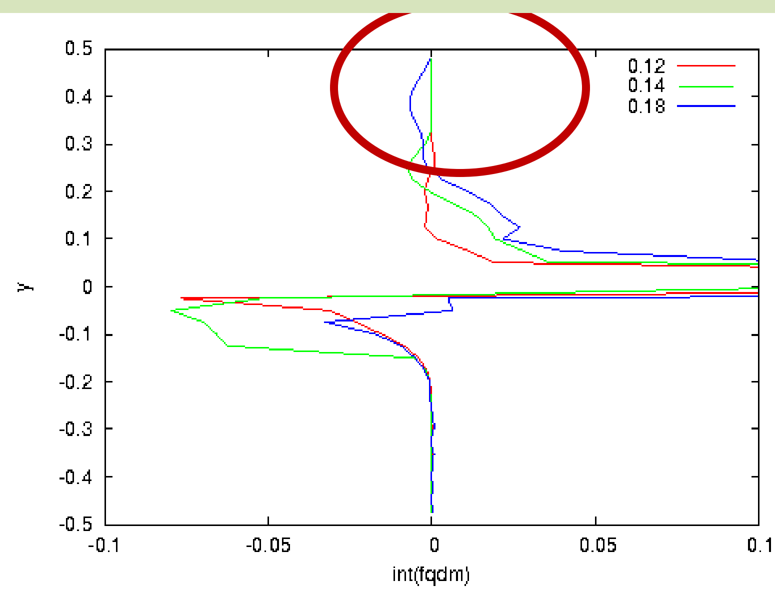
Induced air flow – Momentum transfer

The vertical flux of horizontal momentum transferred across planes lying at different vertical positions is integrated along the domain and in time.

Large amount of horizontal momentum tranferred upwards (uv>0). The air layer affected by the momentum transfer grows with the initial steepness (larger flow induced in air side). Looking more carefully to the profiles, it is seen that at 0.18 the flow is reversed due to the presence of the upper boundary and the sign changes.

Similarly, there is a downward transfer of momentum in water although the layer is narrower and doesn't seem to grow substantially with the steepness.





Results at t=8.5 s from the beginning of NS simulations

Conclusions and future work

- Numerical simulations of the flow in air and water during breaking events providing a detailed description of the velocity field;
- Several information can be derived (e.g. energy, vertical transfer of momentum, air entrainment, bubble and drop formations) which can have a relevance for the air-sea gas transfer and for the sea spray

- Deeper studies (i.e. simulations for different spectrum characteristics) are needed to derive a relation between the pre-breaking spectrum and the energy dissipation as well as with the modification of the spectrum as a result of the breaking.

- Some important limitations which we hope to reduce in the near future: larger scale, more refined grid for improved description of the finest details, wind effects.

References:
Iafrati, JFM (2009);
Iafrati, JGR (2011),
Iafrati, Babanin, Onorato, PRL (2013);
Iafrati, Babanin, Onorato, submitted (2013)