Modeling Ocean Waves at a Variety of Scales

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Outline

- Brief overview of recent model developments and applications.
- A closer look at three topics:
  1. Bubble entrainment and effects on turbulence in breaking wave crests
  2. Extensions of a "nonhydrostatic" model NHWAVE to include a wider range of effects
  3. Looking to the future: intermediate-depth wave breaking: What is "deep" and what is "shallow"?

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  3. Looking to the future: intermediate-depth wave breaking: What is “deep” and what is “shallow”?

- Model development: CACR history of developing public-domain open source models:

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  2. FUNWAVE – fully nonlinear Boussinesq model for time-resolved, weakly dispersive surface waves (90's – present)

  3. NearCoM – coupled wave/circulation model for wave- and tidally-driven currents (90's –present)

  4. NHWAVE – 3-D RANS model for time-resolved fully-nonhydrostatic processes (2010-present)

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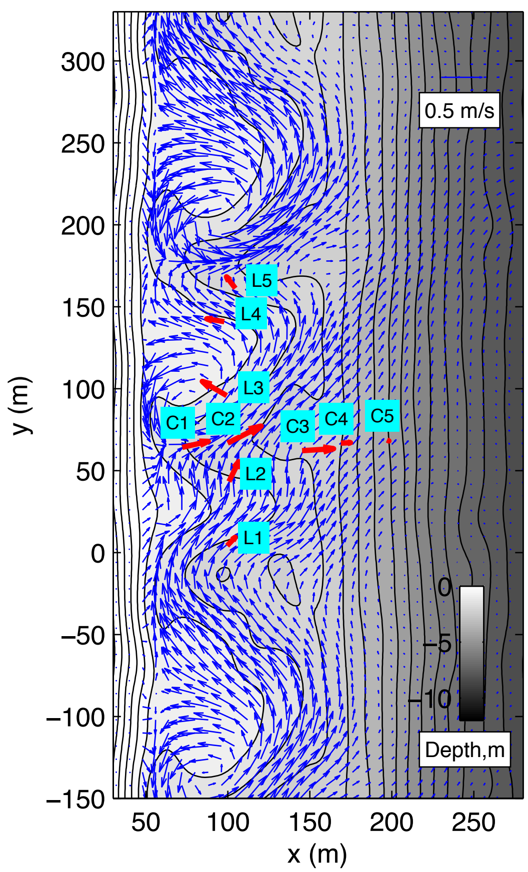
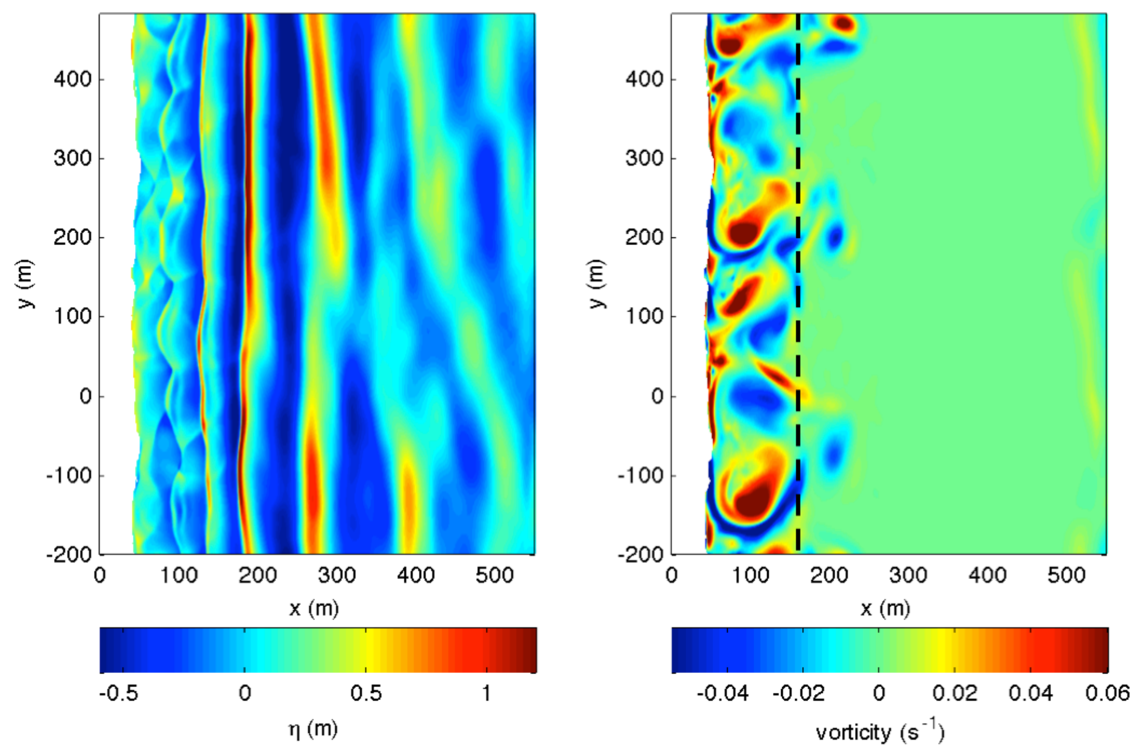
- FUNWAVE-TVD:
  - Boussinesq model with extended dispersion and full nonlinearity.
  - Hybrid finite volume/finite difference scheme
    - Godunov-type finite volume scheme with a variety of TVD limiters
    - Time stepping using a 2d order Runge-Kutta scheme, allows adaptive time stepping.
    - Accurate wetting and drying using Riemann solvers.
    - Wave breaking using several options:
      - Explicit breaking term of Kennedy et al (JWPCOE, 2000)
      - Boussinesq -> NLSWE transition and resulting shock formation and capture (Tonelli and Petti, many others)
  - Parallelized using MPI
  - Applications: Surf zone, nearshore wave propagation, tsunamis

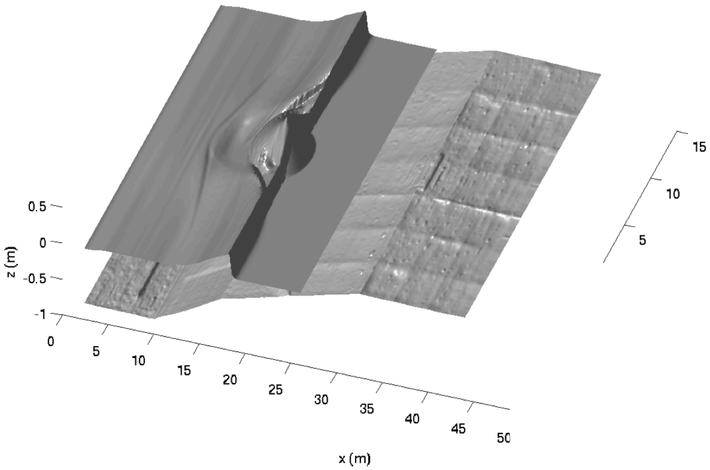
Surf zone: Rip current generation on a complex beach planform

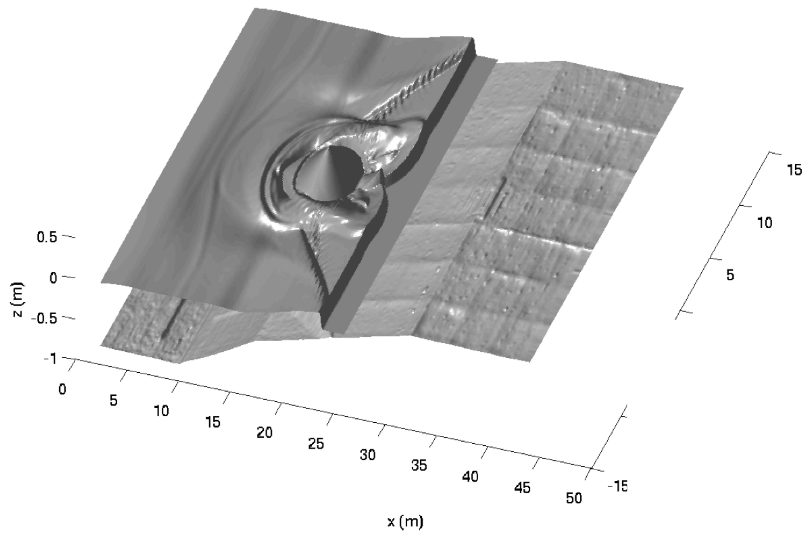


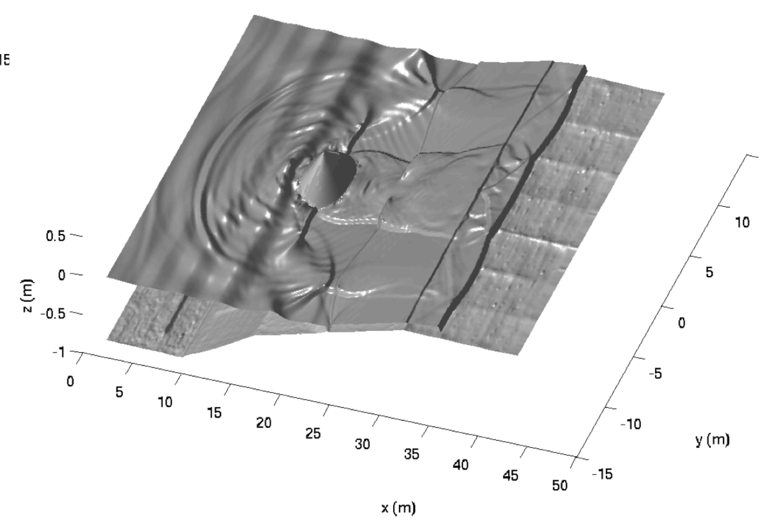


Shi et al, 2012; Geiman et al, 2011

Shi et al, Ocean Mod 2012.
Model revisions largely motivated by need to improve moving shoreline treatment

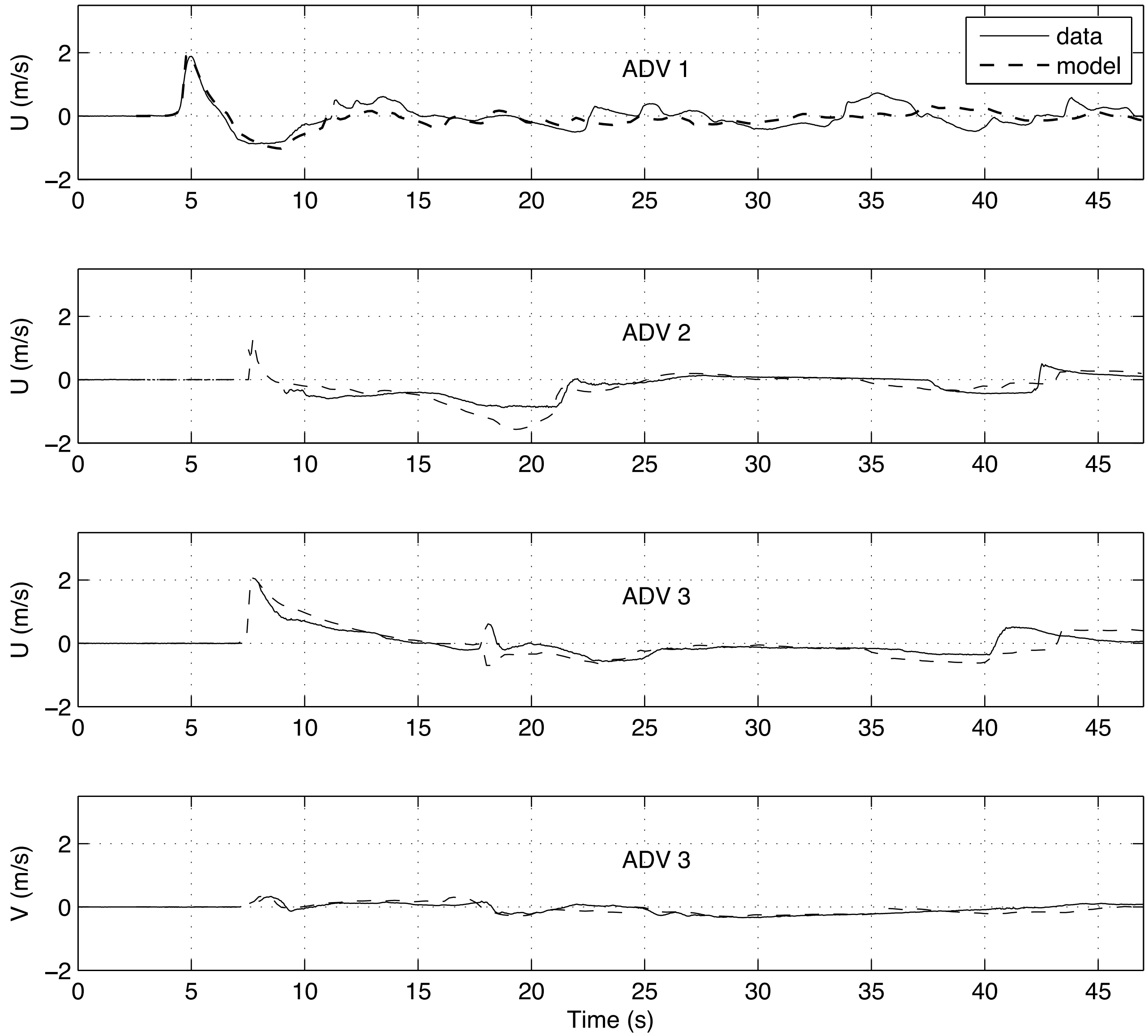




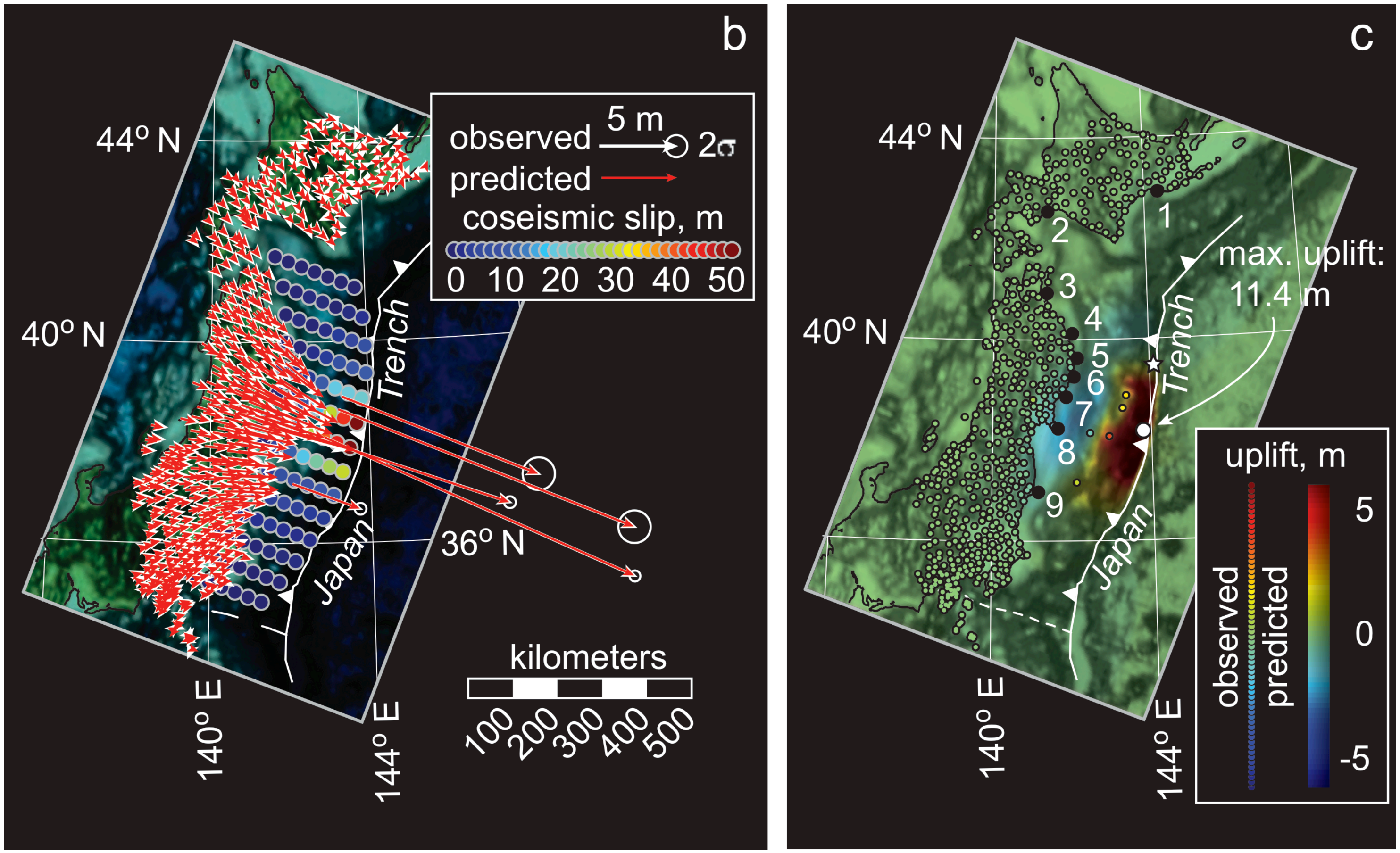


Solitary wave overtopping an island located at a shelf break (data from Lynett)

Reproduction of measured velocities in model



Tsunami application: Tohoku (2011) event

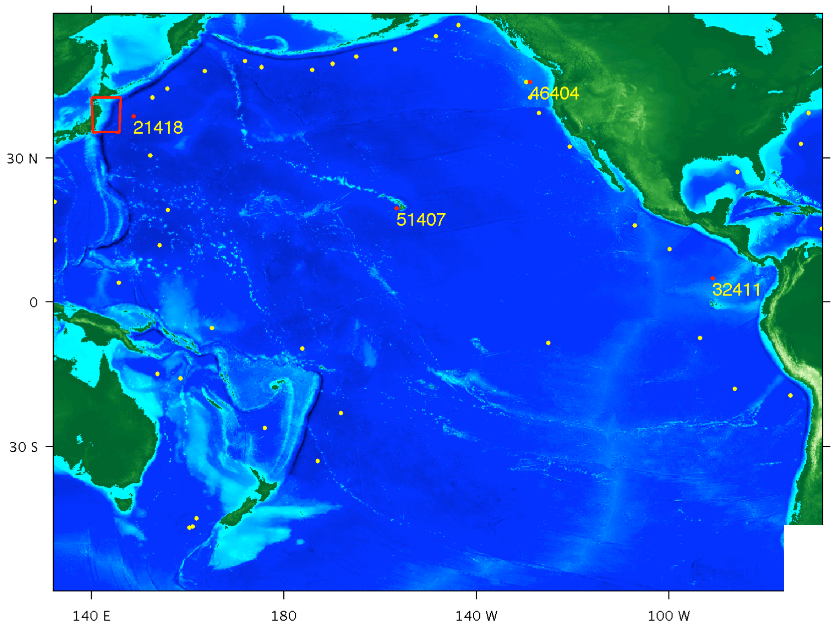


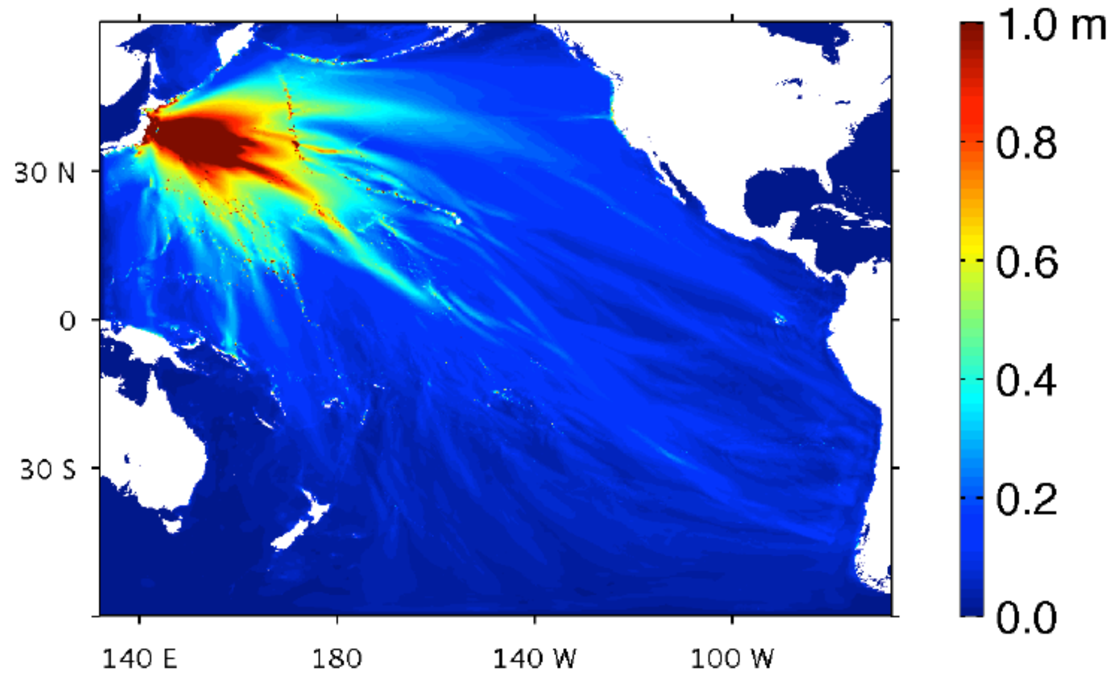
Ground-based GPS inversion

Plate boundaries and GPS buoys

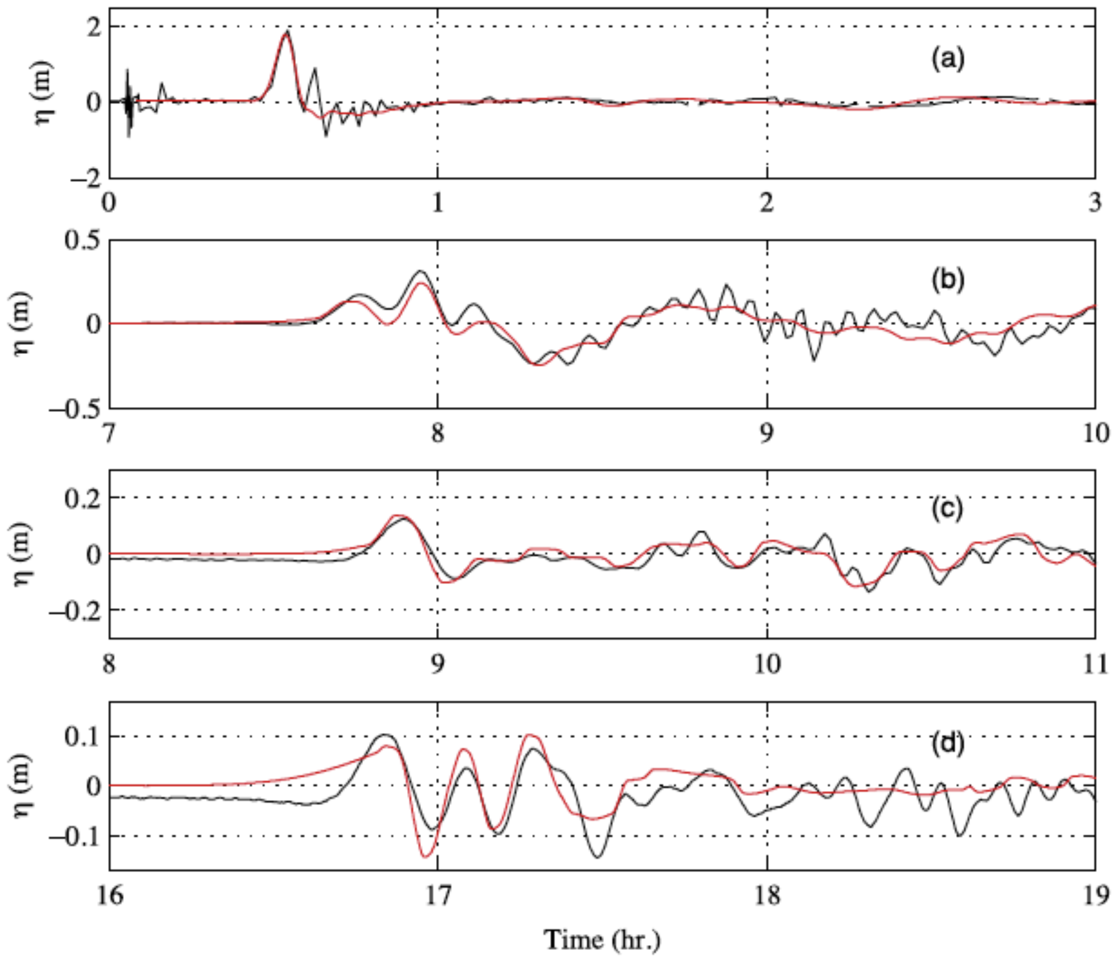
Grilli et al, PAG 2013

Maximum wave height





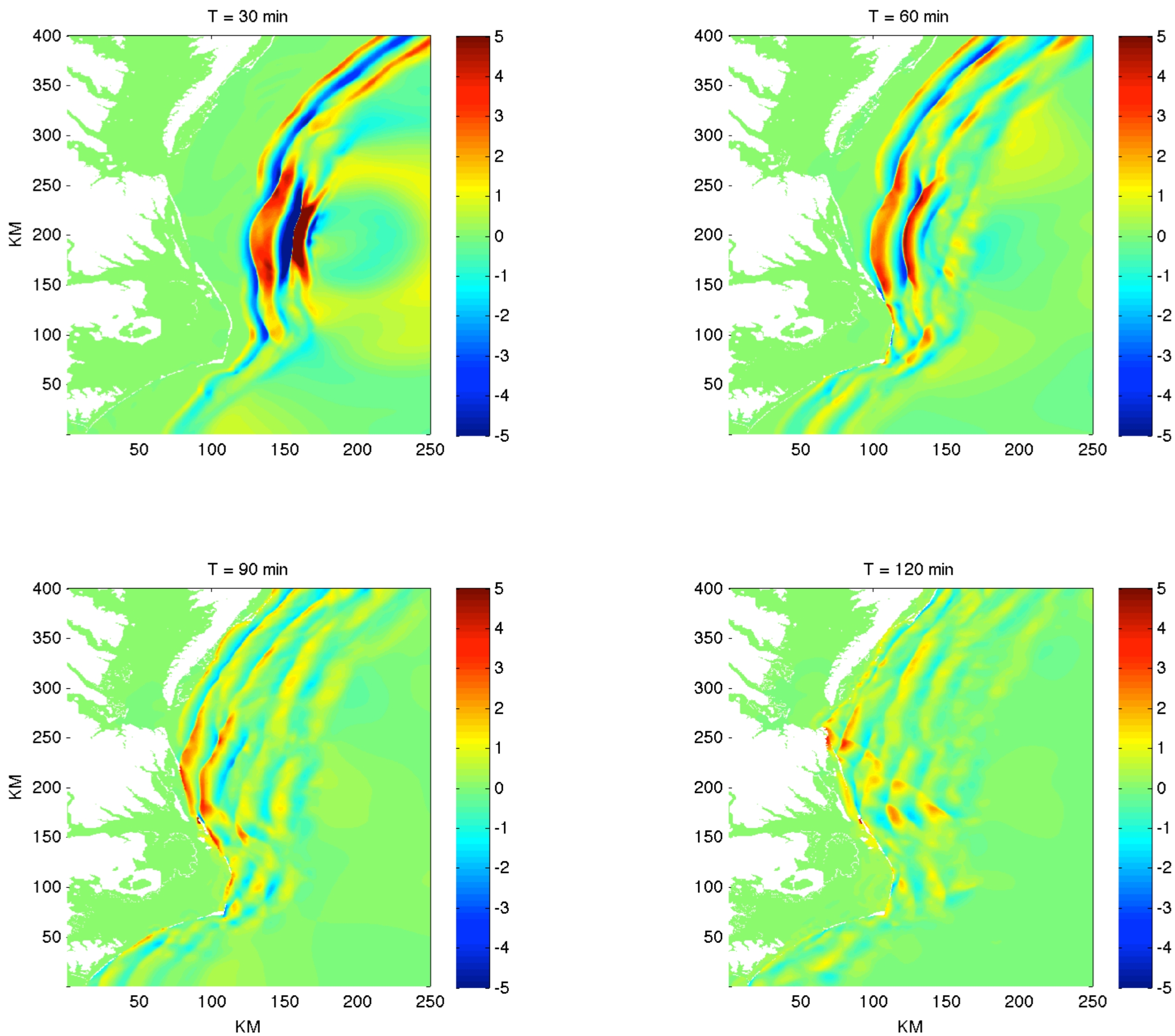
Tohoku (2011): Reproducing event at DART buoys



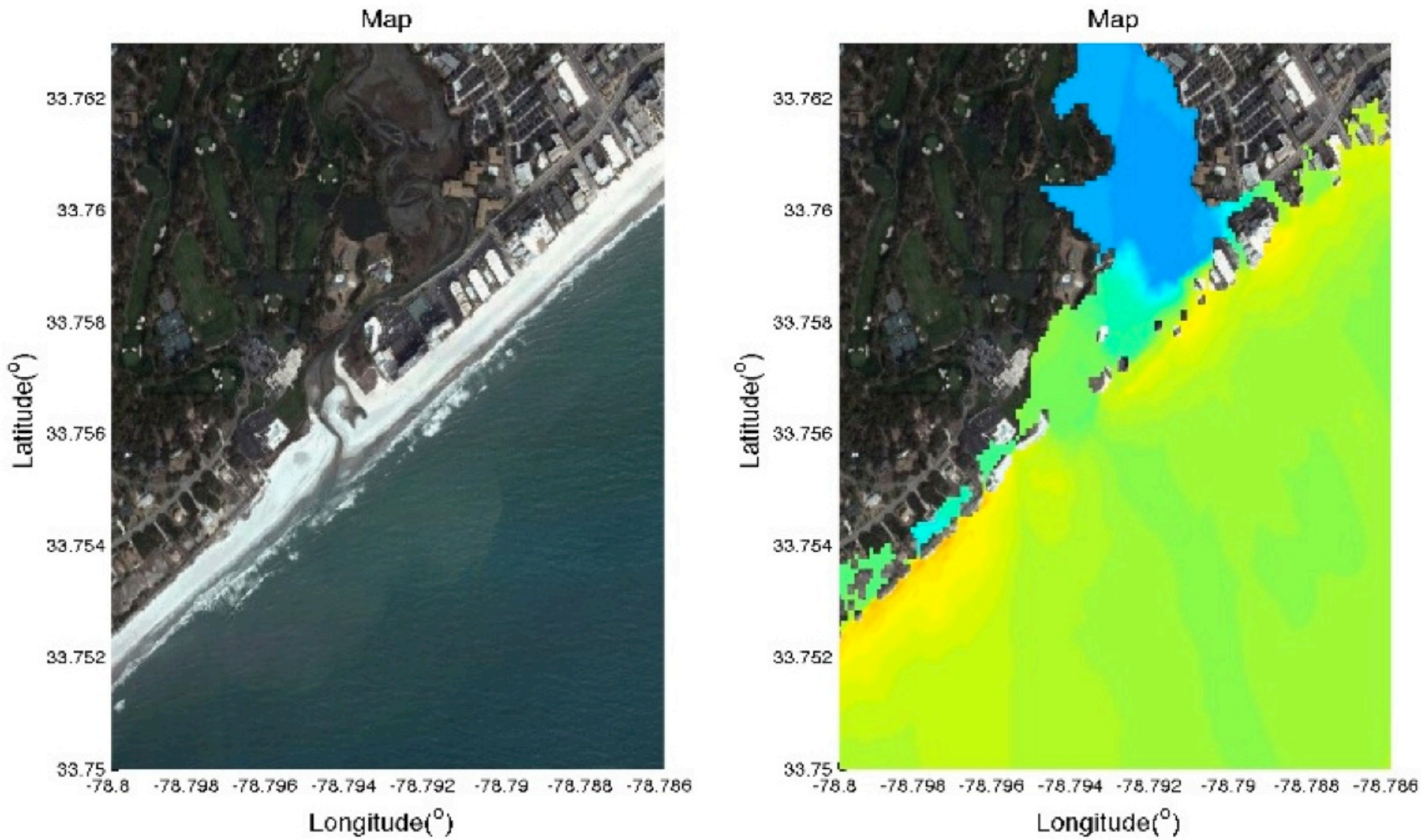
- Japan
- Hawaii
- Oregon
- Panama

U. S. East Coast hazard analysis

Currituck slide



Local inundation: simulations down to 5-10 m resolution



Myrtle Beach, SC

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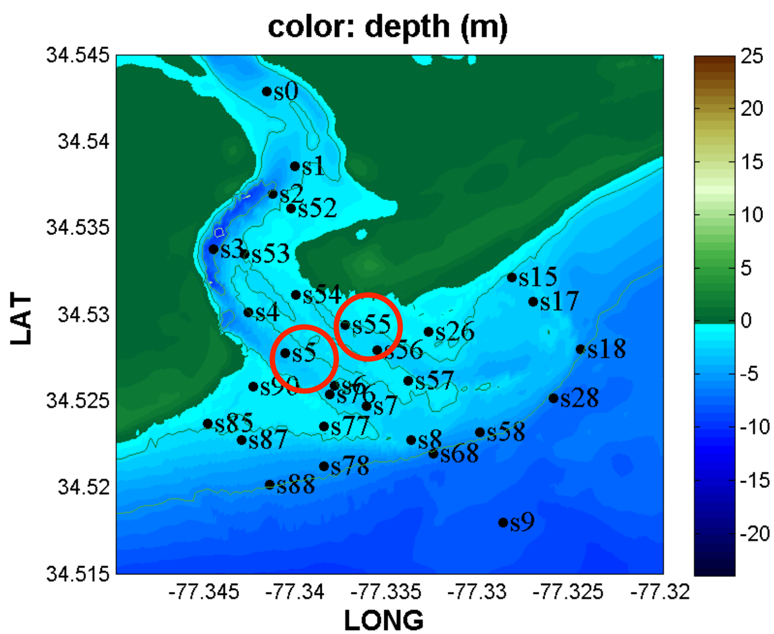
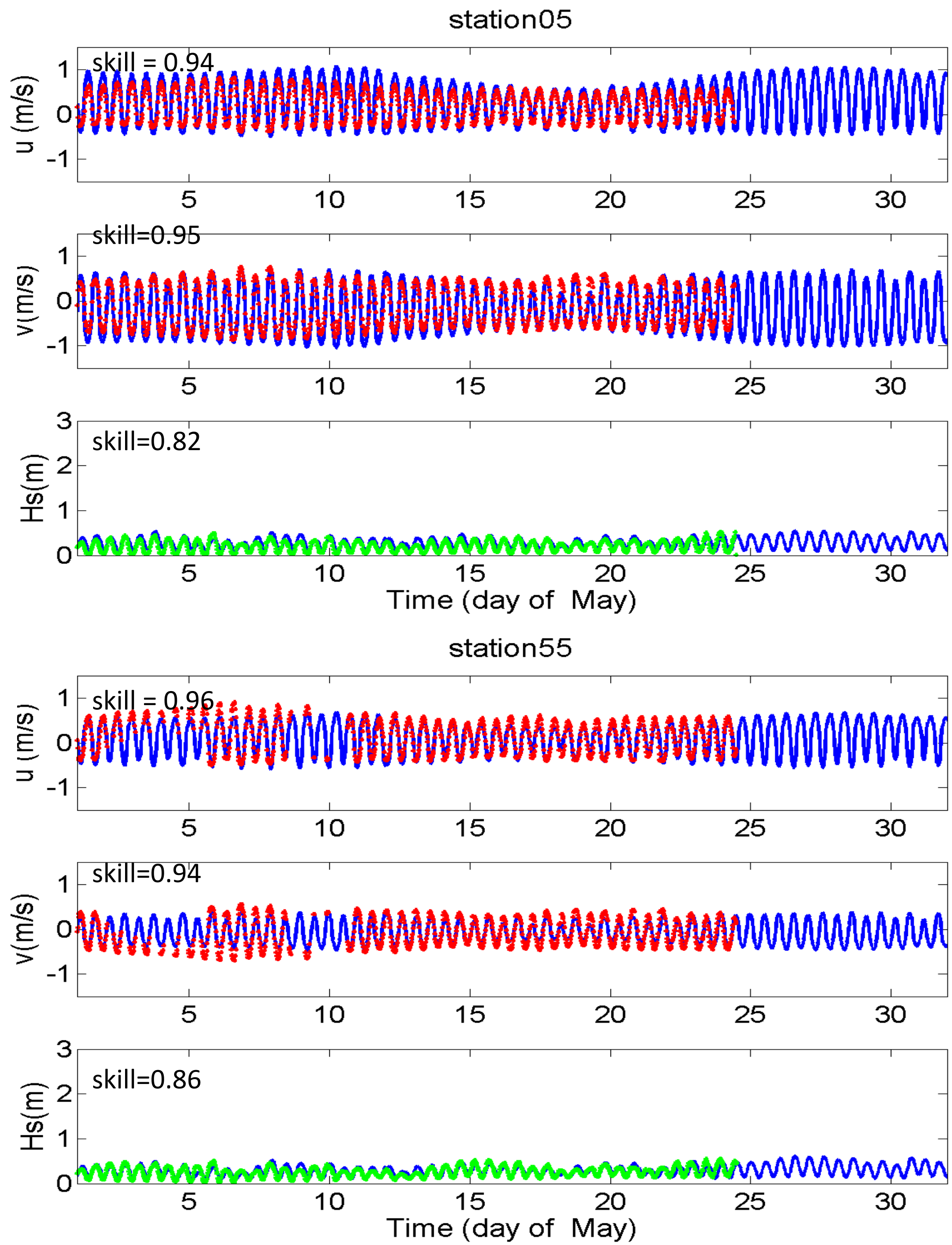
- NearCoM – coupled model for waves and currents
  - Quasi-3D model for hydrostatic circulation processes (SHORECIRC)
  - Closely coupled to wave model (SWAN)
  - Recently converted to finite volume form and fully parallelized (same scheme as FUNWAVE)
  - Morphology modules (including acceleration effects to facilitate long term morphology calculations)
  - Principle applications are to modeling wave and tidally-driven processes in shallow, unstratified coastal and estuarine regions.

New River Inlet, NC (Chen, Hsu, Shi)



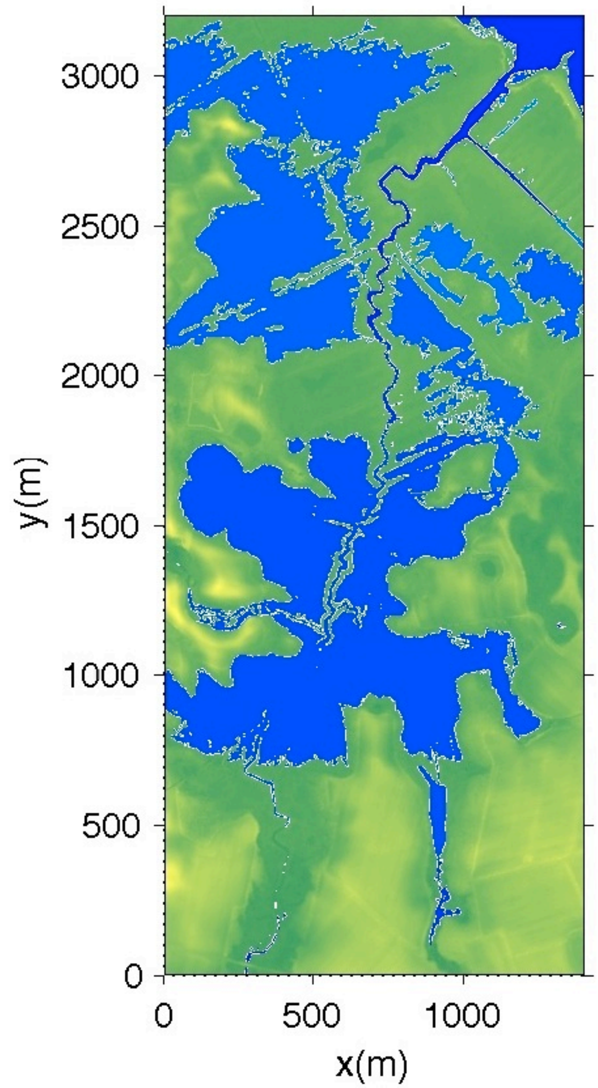
Data provided by Britt Raubenheimer and Steve Elgar (WHOI)



Model Prediction

Measured data

Circulation in tidal marsh – Brockonbridge Gut, Delaware



Mieras, Kirby, Shi

Delaware Sea Grant

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NHWAVE – nonhydrostatic, surface and terrain-following Euler or RANS model (Ma et al, Ocean Mod 2012)

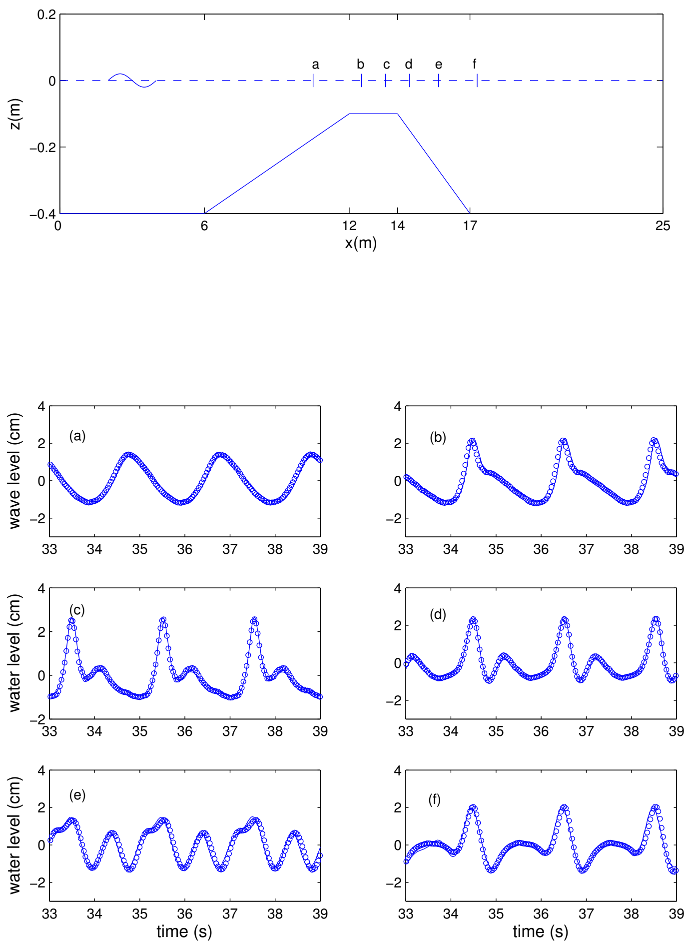
Solve equations in a domain bounded above and below by surfaces which are single-valued functions of *(x,y,t)*

$$\frac{\partial \boldsymbol{\Psi}}{\partial t} + \nabla \cdot \boldsymbol{\Theta}(\boldsymbol{\Psi}) = \mathbf{S} \qquad \mathbf{S} = \mathbf{S}_h + \mathbf{S}_p + \mathbf{S}_\rho + \mathbf{S}_\tau$$

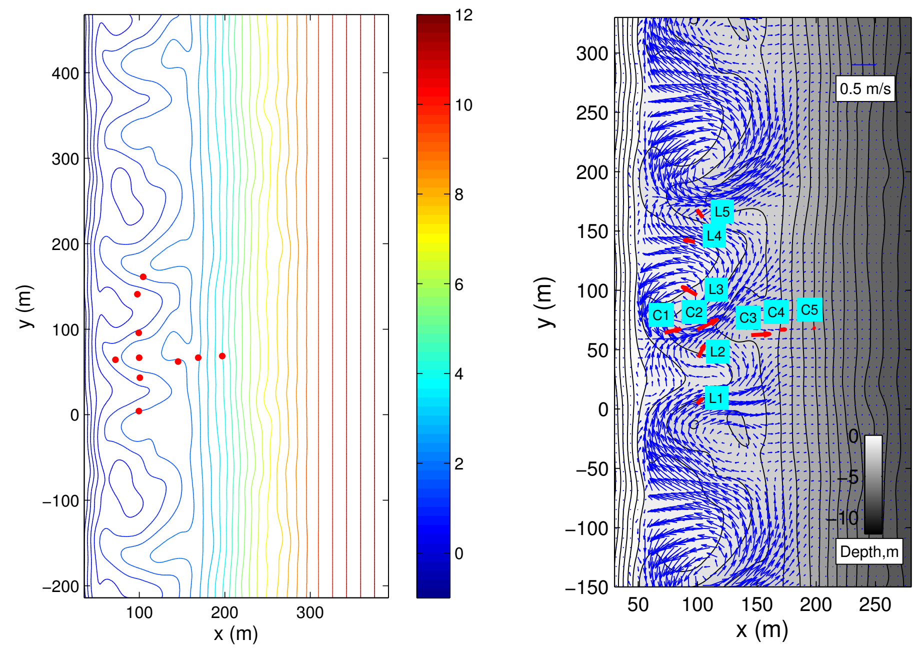
$$\boldsymbol{\Psi} = \begin{pmatrix} D \\ Du \\ Dv \\ D\omega \end{pmatrix} \qquad \boldsymbol{\Theta} = \begin{pmatrix} Du\mathbf{i} + Dv\mathbf{j} + \omega\mathbf{k} \\ (Duu + (\frac{1}{2}g\eta^2 + gh\eta))\mathbf{i} + Duv\mathbf{j} + u\omega\mathbf{k} \\ Duv\mathbf{i} + (Dvv + (\frac{1}{2}g\eta^2 + gh\eta))\mathbf{j} + v\omega\mathbf{k} \\ Duw\mathbf{i} + Dvw\mathbf{j} + w\omega\mathbf{k} \end{pmatrix}.$$

- Numerical scheme: Godunov TVD (as in previous models), two step, second order Runge Kutta scheme.
- Spatial differencing for finite volume terms based on Box-Keller scheme with pressure defined on top surface of cell.
- Each step in RK scheme employs a split step solution to update velocity and pressure:
    1. Predictor step using full hydrostatic pressure, no dynamic pressure (stop here if doing a hydrostatic simulation)
    2. Solve Poisson equation for pressure field
    3. Corrector step updates velocity using dynamic pressure

NHWAVE (Ma et al, 2012)

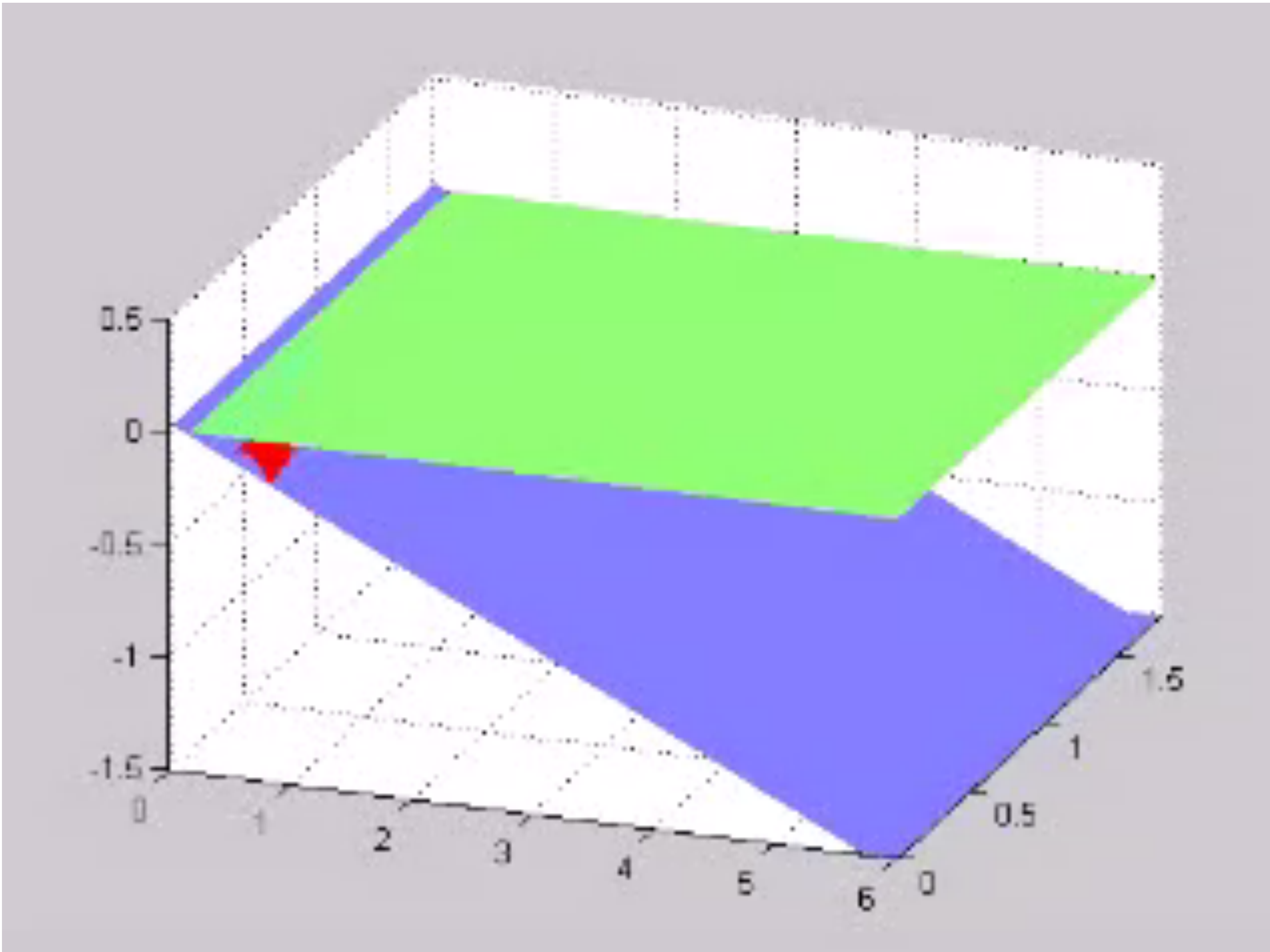


Dispersive waves over shoal



Rip current cells on a complex beach

Landslide applications: solid body slides in NHWAVE



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Turbulent bubbly flow under unsteady breaking waves

M. Derakhti[1] and J. T. Kirby[1]

1. Center for Applied Coastal Research, University of Delaware

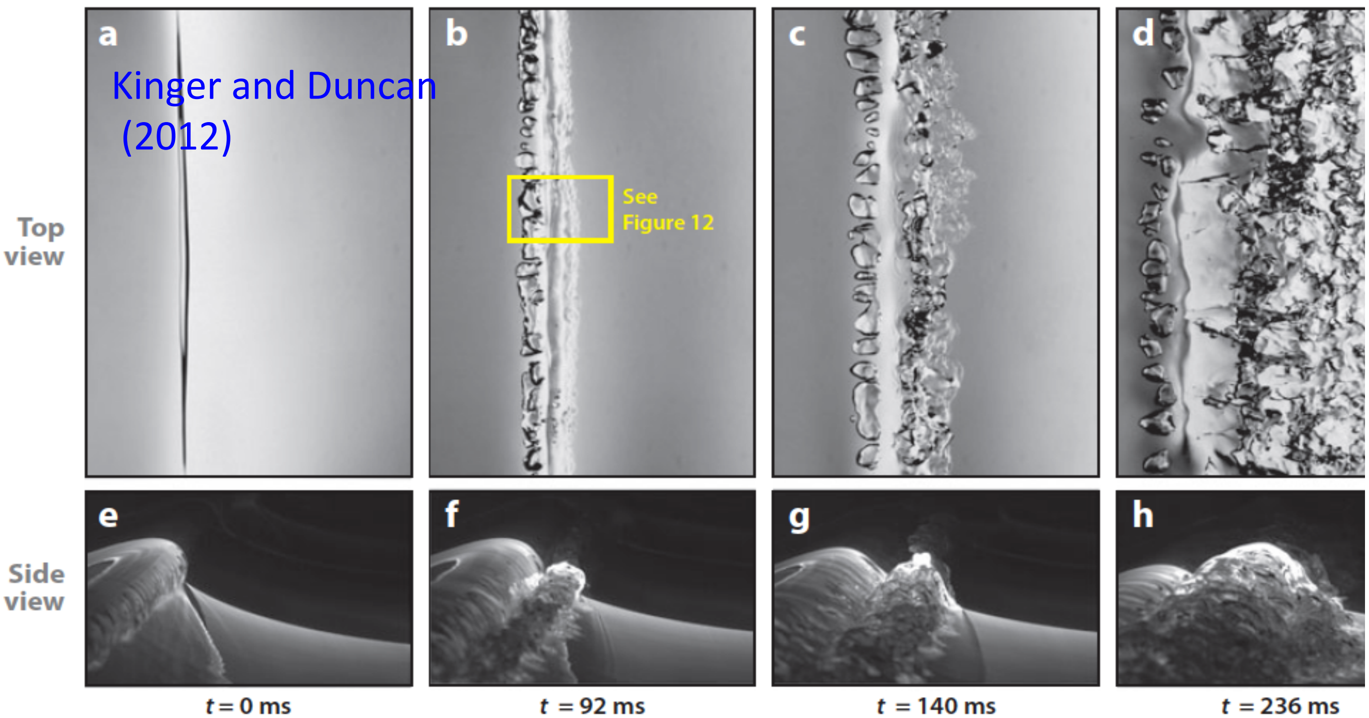
Goals:

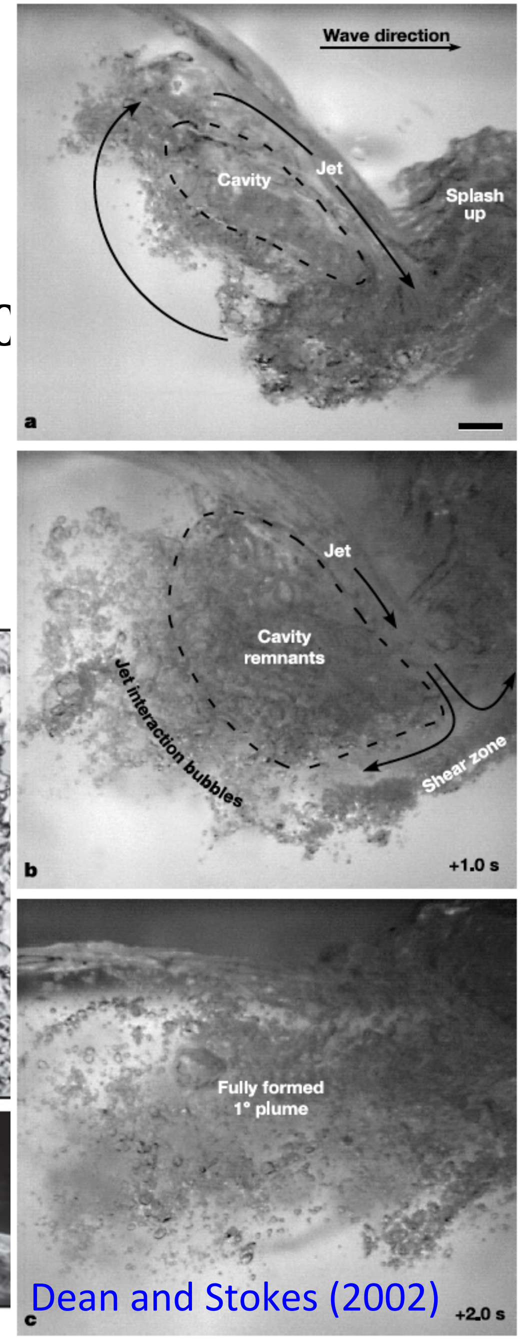
- Understand processes related to entrainment, retention and transport of air bubbles at wave crest scales in the surf zone,
- Use this information in parameterized form to model optical properties of larger scale surf zone.

The ocean upper layer
Unsteady breaking

Problem characteristics

- **3D**
- **Unsteady two phase turbulent flc**
- **Bubbles have size distribution**
- **Complex interface**





Different approaches

Mixture theory
ke – σ coordinate
+
Bubble entrainment model

Poly-dispersed bubbly flow
VOF-LES
+
Bubble entrainment model

Two phase
VOF-DNS
air + water

O(10km)
Field scale problems

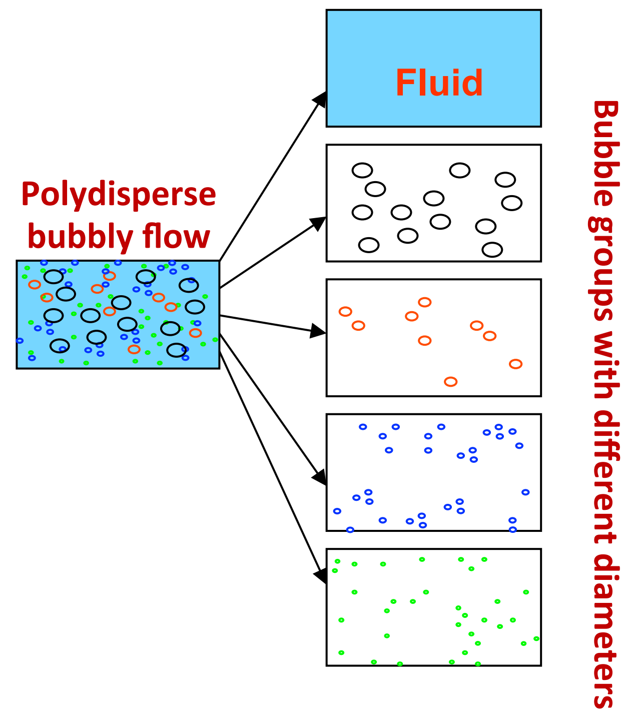
O(10m)
laboratory scale problems

O(10cm)
Small scale problems

Problem characteristics

- 3D
- Two phase flow with bubble size distribution (0.1 to 10 mm in laboratory breaking waves)
- Unsteady turbulent flow with non turbulent and transition regions
- Complex interface

Selected approach



- Bubbles are divided into 20 groups from 0.1 to 8 mm diameter

    Accounts for the actual bubble size distribution

- Bubbles are introduced at the free surface using the entrainment model

    Avoids bubble entrainment details

- 3D Eulerian-Eulerian framework

    Not resolve the interface between individual bubbles and liquid

    Accounts for the momentum exchange between bubbles and liquid

- Turbulence is modeled using LES with dynamic Smagorinsky model
- Bubble-induced dissipation is considered using eddy viscosity approach
- Second order VOF method for free-surface tracking

    Resolves complex interface

Filtered poly-disperse two-fluid model

(Carrica et al. 1999, Ma et al. 2011, Lakehal et al. 2002, Derakhti and kirby 2013)

Liquid phase

$$\frac{\partial(\alpha^l \rho^l)}{\partial t} + \frac{\partial}{\partial x_j}(\alpha^l \rho^l \tilde{u}_j^l) = 0$$

$$\frac{\partial(\alpha^l \rho^l \tilde{u}_i^l)}{\partial t} + \frac{\partial}{\partial x_j}(\alpha^l \rho^l \tilde{u}_i^l \tilde{u}_j^l) = -\frac{\partial}{\partial x_j}(\alpha^l \tilde{p})\delta_{ij} + \alpha^l \rho^l g_i + \frac{\partial}{\partial x_j}\left[\alpha^l(\tilde{\sigma}_{ij}^l - \tau_{ij}^l)\right] + \mathrm{M}^{gl}$$

Drag, lift and added mass forces

SGS model

$$\tau_{ij}^{l,d} \equiv \tau_{ij}^l - \frac{\delta_{ij}}{3}\tau_{kk}^l = -2\nu_{sgs}^l \tilde{S}_{ij}^l,$$

$$\nu_{sgs}^l = \nu_{SI}^l + \nu_{BI}^l$$

$$\nu_{SI}^l = (C_s\tilde{\Delta})^2|\tilde{S}|,$$

Shear-induced eddy viscosity

$$(C_s)^2 = -\frac{L_{ij}M_{ij}}{2\tilde{\Delta}^2 M_{ij}M_{ij}},$$

Germano etal 1991, Lilly 1992

$$L_{ij} = \widehat{\tilde{u}_i^l \tilde{u}_j^l} - \widehat{\tilde{u}}_i^l \widehat{\tilde{u}}_i^l \quad \text{and} \quad M_{ij} = \alpha^2 |\widehat{\tilde{S}}|\widehat{\tilde{S}}_{ij} - \widehat{|\tilde{S}|\tilde{S}_{ij}}.$$

$$\nu_{BI}^l = C_{\mu,BI}\sum_{k=1}^{NG}\alpha_k^b d_k^b |\tilde{\mathbf{u}}_{r,k}|,$$

Bubble-induced eddy viscosity Sato&Sekoguchi (1975)

Gas phase

Bubble entrainment

Neglect the inertia of bubbles

$$\frac{\partial N_k^g}{\partial t} + \frac{\partial}{\partial x_j}(\tilde{u}_{k,j}^g N_k^g) = B_k^g + S_k^g$$

Bubble break up

$$0 = -\frac{\partial}{\partial x_j}(\alpha_k^g \tilde{p})\delta_{ij} + \alpha_k^g \rho^g g_i + \mathrm{M}_k^{lg} \quad k = 1, \cdots, NG$$

NG is the number of bubble groups

Entrainment model

$$B_k^b = \frac{c_b}{4\pi}\left(\frac{\sigma}{\rho^l}\right)^{-1}\alpha^l \left(\frac{f(a_k)\Delta a_k}{\sum_{k=1}^{NG} a_k^2 f(a_k)\Delta a_k}\right)\varepsilon_{sgs,SI}^l,$$

$$\varepsilon_{sgs,SI}^l = 2\nu_{SI}^l \tilde{S}_{ij}\tilde{S}_{ij} = \nu_{SI}^l|\tilde{S}|^2$$

SGS dissipation or production rate of SGS kinetic energy

Isolated single unsteady breaking wave event

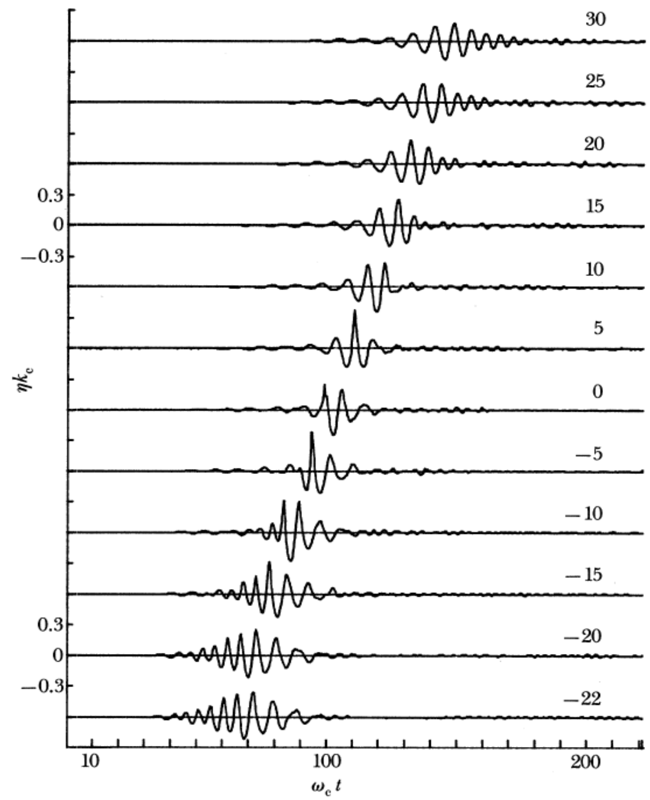
- All corresponding experiments conducted in a glass walled channel 25~30 m long, ~ 0.7 m wide, with still water depth 0.6 m by Melville and students
- Single breaking wave event formed by dispersive focusing method

- N = 32 number of waves in the packet at the inlet boundary condition

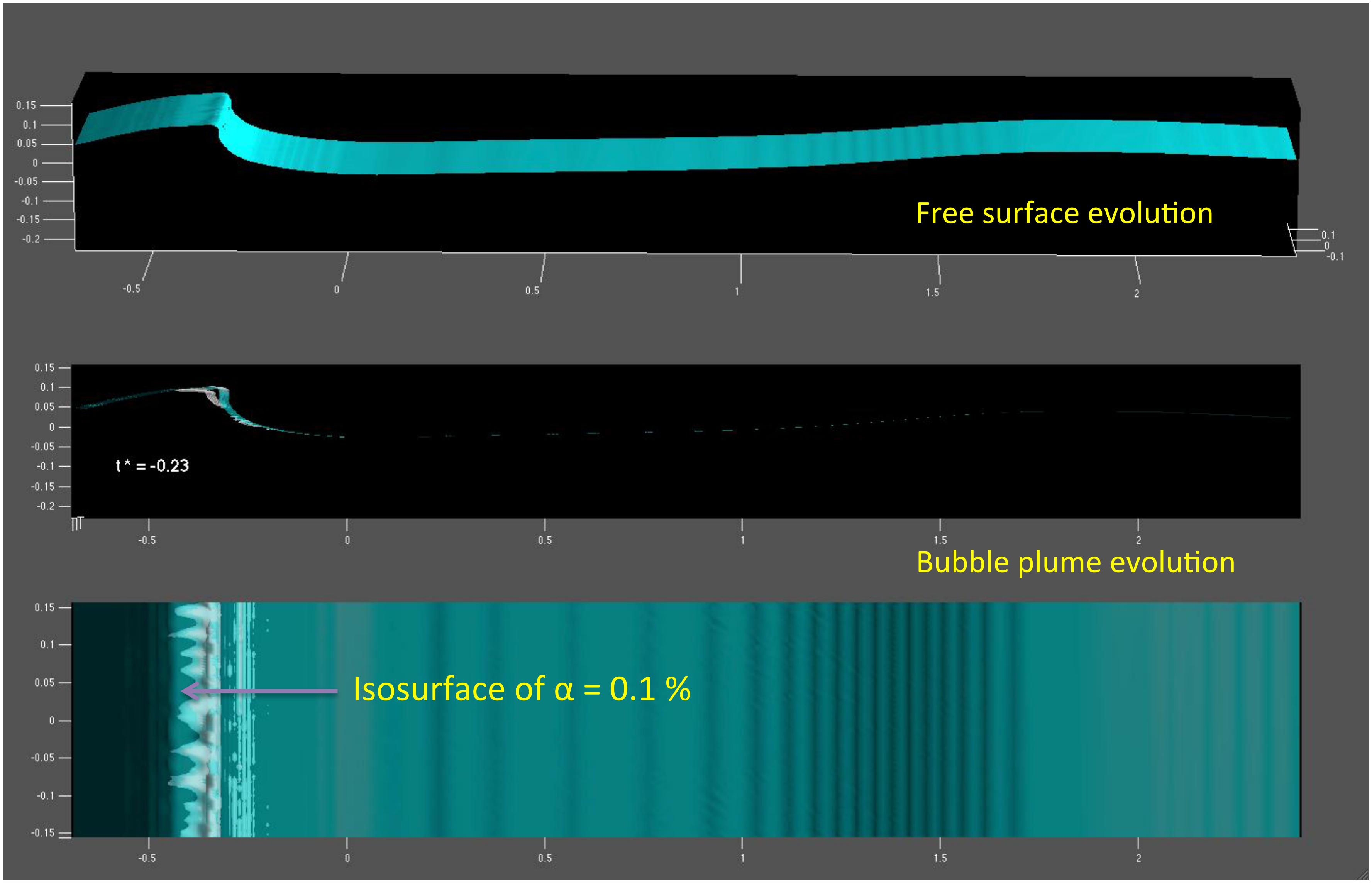
- Short waves, followed by faster long waves, focus at a predefined location

- Range of plunging and spilling cases have been considered

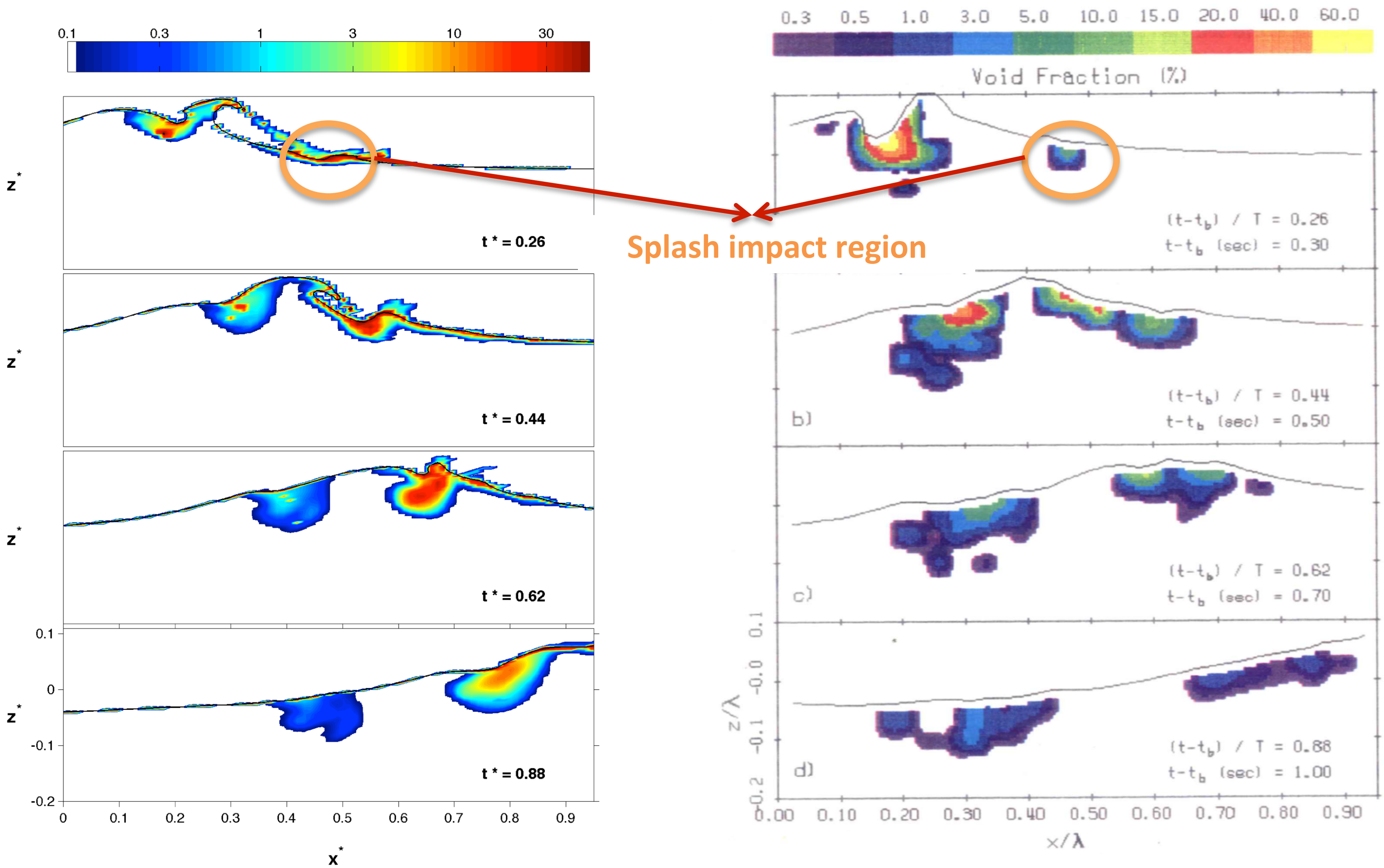
$$\eta(0,t) = \sum_{i=1}^{N=32} a_i \cos[2\pi f_i (t - t_b) + k_i x_b],$$



Free surface and bubble plume evolution for the large plunging breaker

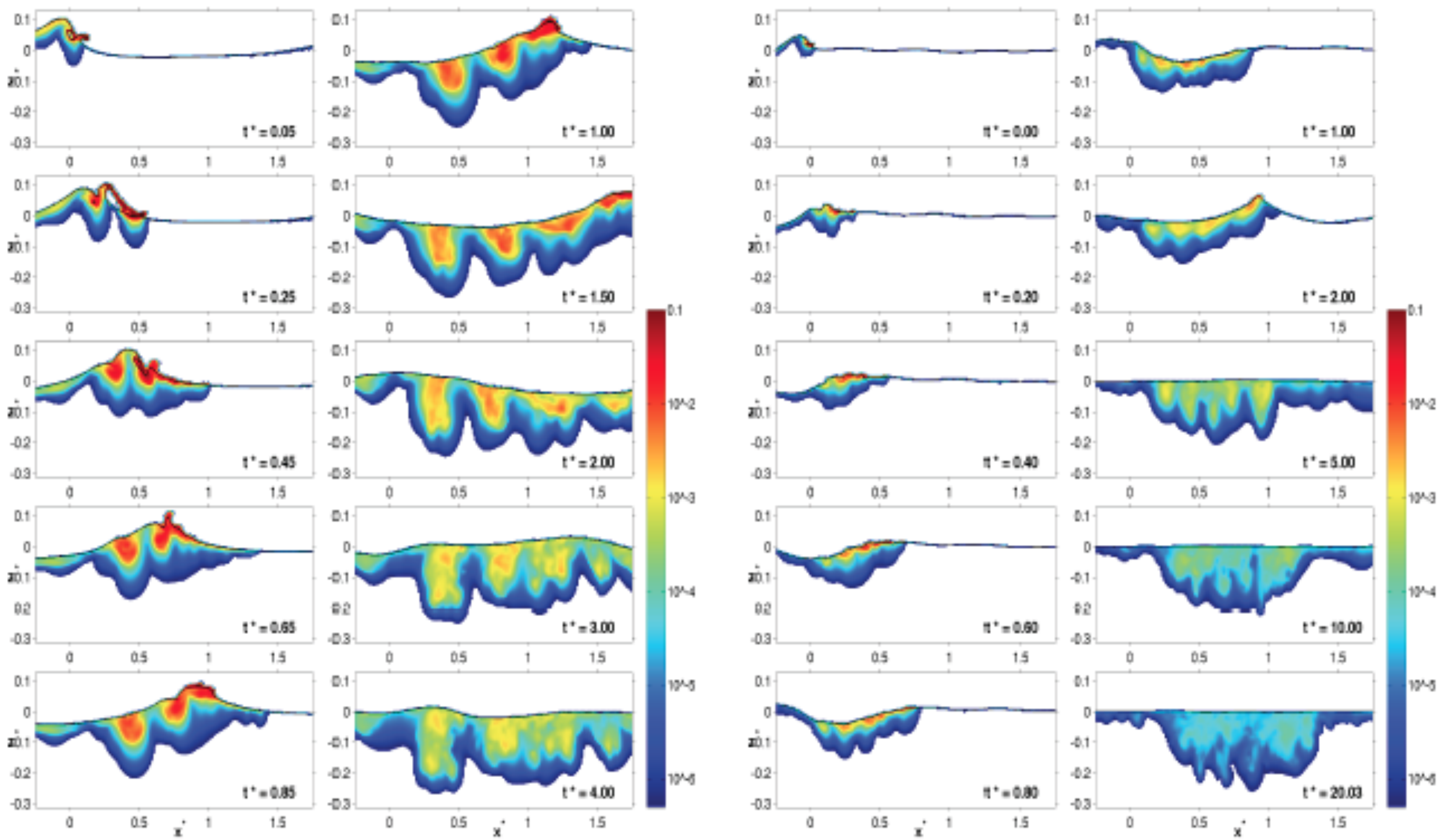


Evolution of bubble void fraction comparing to the measurements by Lamarre and Melville (1991)



Large plunging breaker

TKE evolution

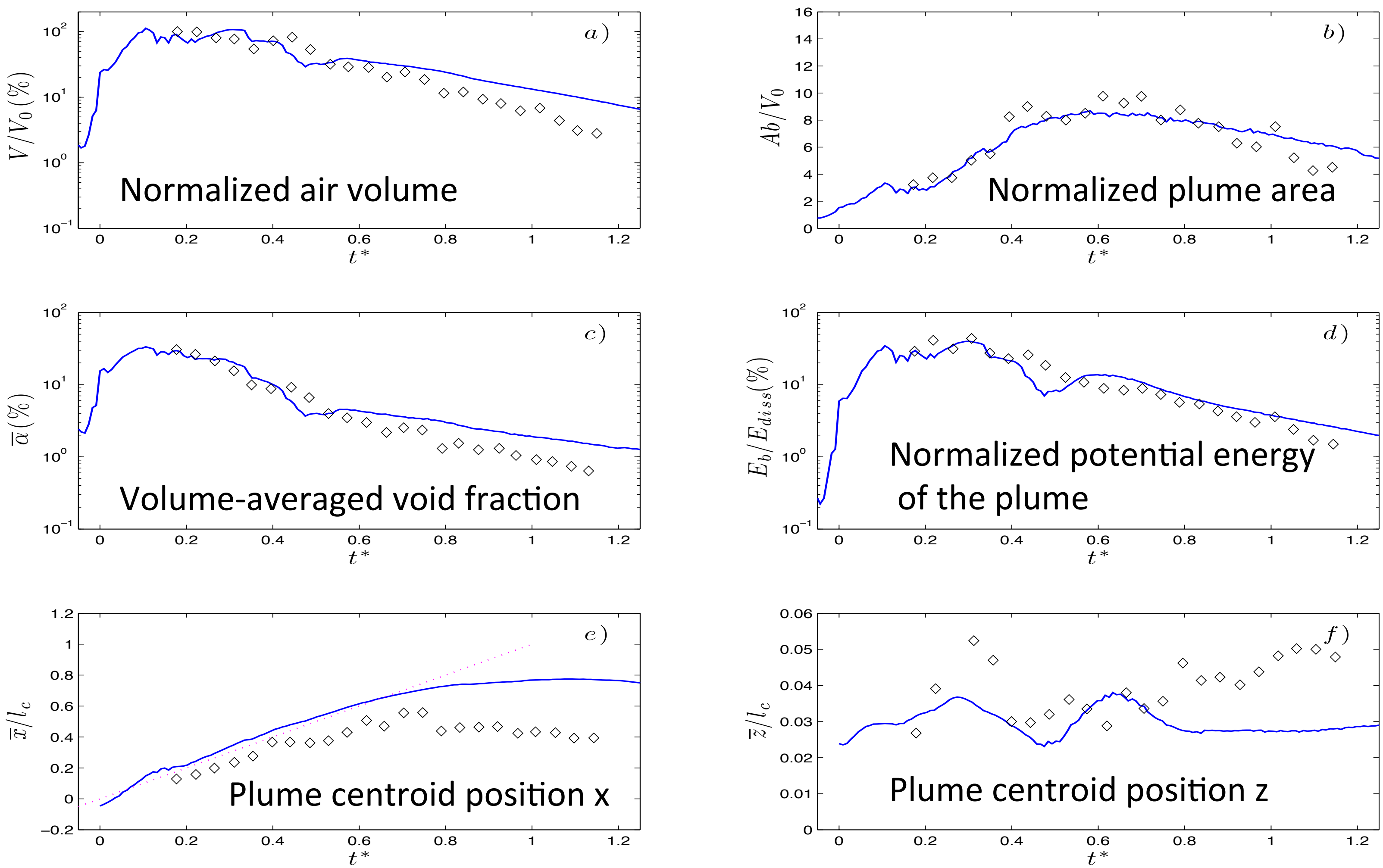


Lamarre and Melville (1991) – Most energetic case

Rapp and Melville (1991) – plunging case

TKE normalized by C^2, where C = phase speed ~ 1.73 m/s
Rapp and Melville 1990 estimated the levels of turbulence initially of 0.02C and decaying slowly to 0.005C after over 60 wave periods or normalized TKE on the order of 5*10^-4 to 25*10^-6

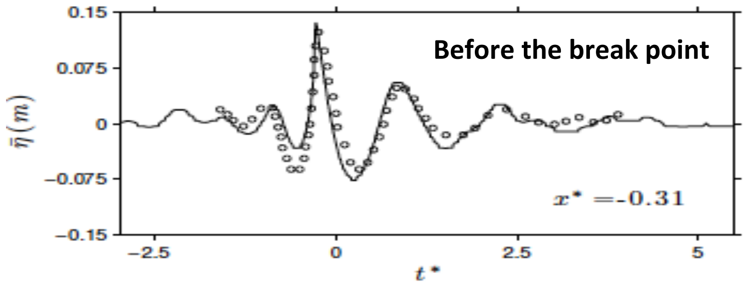
Integral properties of the injected bubble plume

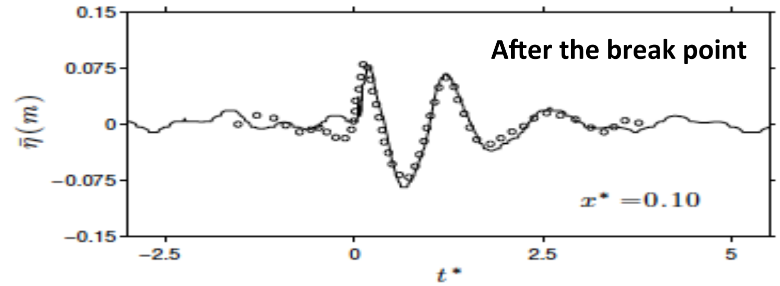


(blue line) model results, (diamonds) experiment measurements

Lamarre and Melville (1991) – Most energetic case

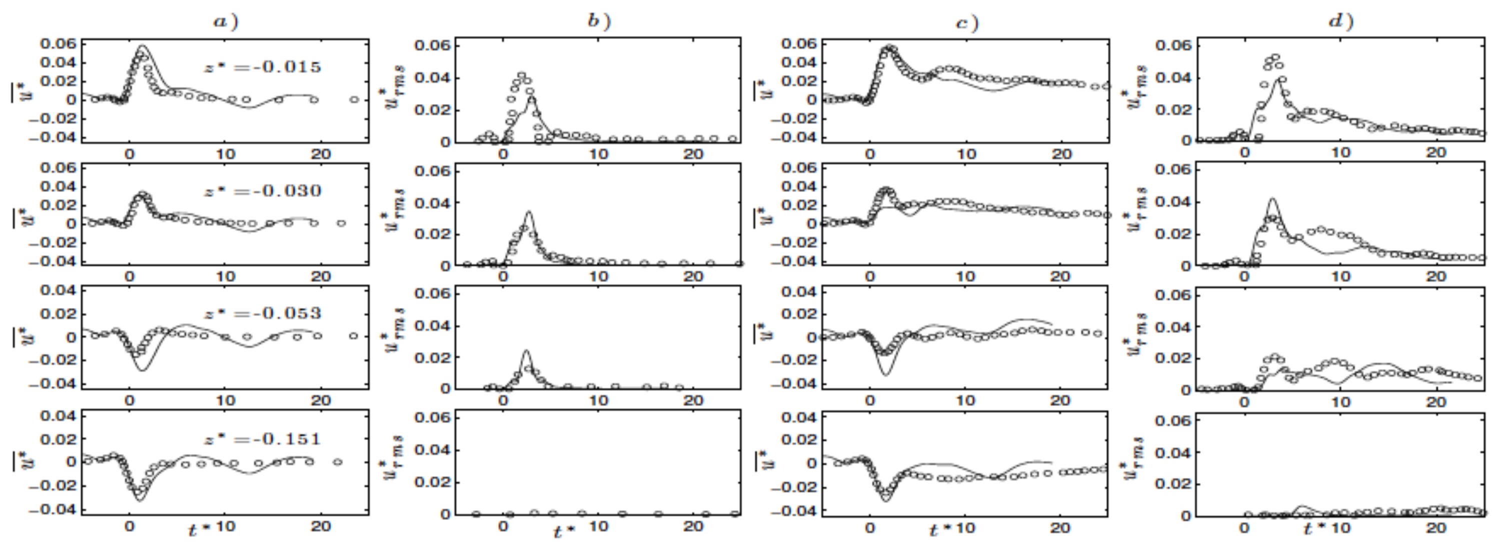
Free surface evolution comparing to Exp.





Rapp and Melville (1990), Plunging breaker, P3

Mean and r.m.s. of turbulent velocities comparing to Exp.



Normalized low-pass filtered spanwise averaged and r.m.s. velocities for P3 at $(a-b)$ $x^* = 0.15$ and $(c-d)$ $x^* = 0.60$ in different elevations. Circles are the measurements of the corresponding case adopted from RM figure 42 and figure 46.

Shear- vs bubble-induced dissipation rate

Total SGS dissipation rate:

$$\varepsilon_{sgs} = -\tau_{ij}^{d} \mathcal{S}_{ij} = \varepsilon_{SI} + \varepsilon_{BI}$$

$$\tau_{ij}^{l,d} \equiv \tau_{ij}^{l} - \frac{\delta_{ij}}{3}\tau_{kk}^{l} = -2\nu_{sgs}^{l}\tilde{\mathcal{S}}_{ij}^{l} \quad |\tilde{\mathcal{S}}| = \sqrt{2\tilde{\mathcal{S}}_{ij}^{l}\tilde{\mathcal{S}}_{ij}^{l}}$$

$\tilde{\mathcal{S}}_{ij}^{l} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i^l}{\partial x_j} + \frac{\partial \tilde{u}_j^l}{\partial x_i}\right)$ is the resolved rate of strain

Shear-induced dissipation rate:

$$\varepsilon_{SI} = \nu_{SI} |\mathcal{S}|^2$$

$$\nu_{SI}^{l} = (C_s\tilde{\Delta})^2|\tilde{\mathcal{S}}|,$$

From dynamic Smagorinsky model

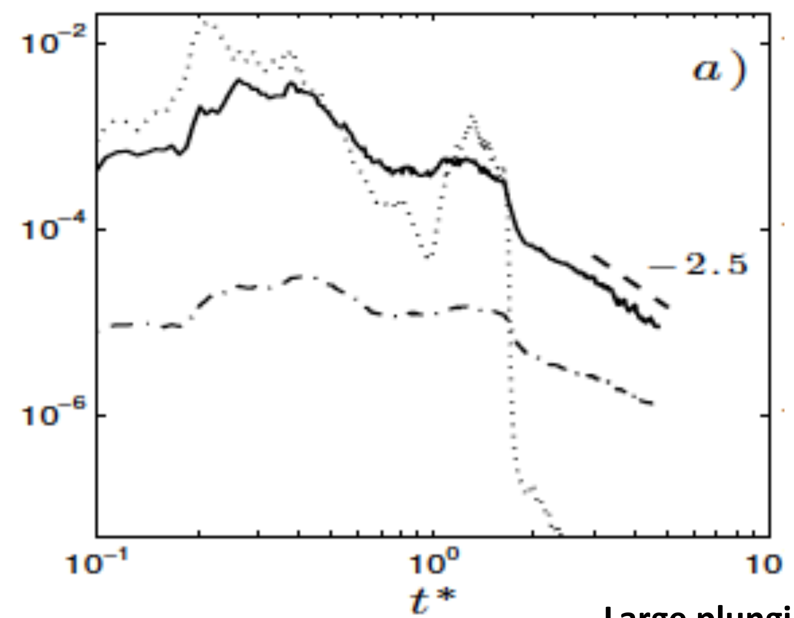
Bubble-induced dissipation rate:

$$\varepsilon_{BI} = \nu_{BI} |\mathcal{S}|^2$$

$$\nu_{BI}^{l} = C_{\mu,BI}\sum_{k=1}^{NG}\alpha_k^b d_k^b|\tilde{\mathbf{u}}_{r,k}|,$$

After Sato&Sekoguchi (1975)

Dissipation rate per unit length of crest



—— shear-induced $\breve{\overline{\varepsilon_{SI}}}/L_c^2$

• • • bubble-induced $\breve{\overline{\varepsilon_{BI}}}/L_c^2$

– · – viscous dissipation $\breve{\overline{\varepsilon_r}}/L_c^2$

Large plunging breaker

$|\tilde{\mathcal{S}}| = \sqrt{2\tilde{\mathcal{S}}_{ij}^{l}\tilde{\mathcal{S}}_{ij}^{l}}$ is the norm of the resolved strain rate tensor.

Total dissipation per unit length of breaking crest

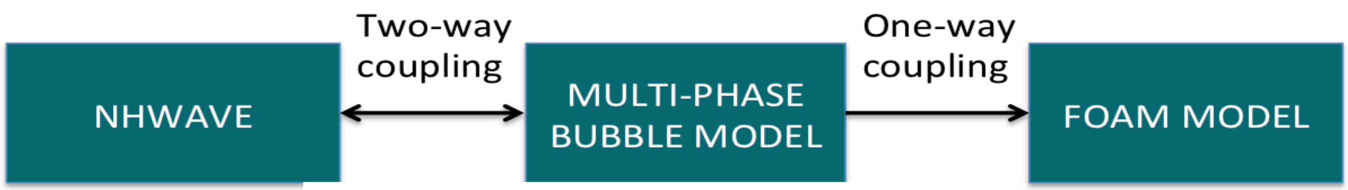
- **Bubble-induced dissipation accounts for more than 50% of the total dissipation, which is compatible with the measurements of potential energy of the bubble plume by Lamarre and Melville (1991).**

- **Although the total dissipation differs between different breaker types, the ratio of bubble- and shear-induced dissipation is invariant with respect to breaking type and intensity.**

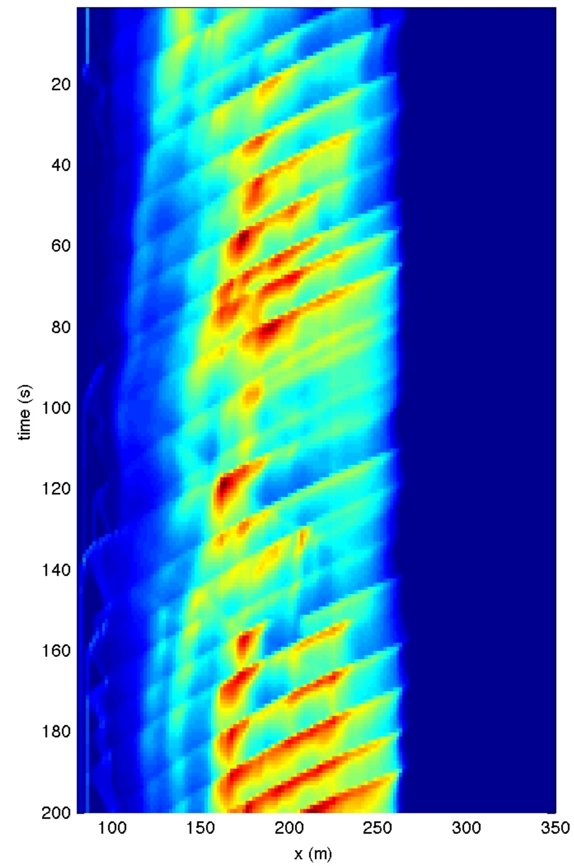
- **The corresponding simulations without the inclusion of dispersed bubbles underpredict the total dissipation about 35%.**

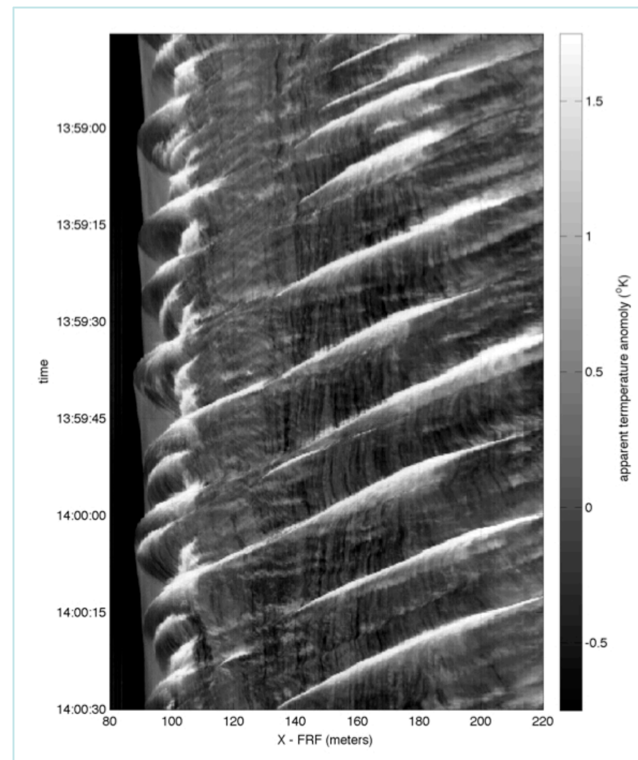
Case no.	LM (J/m)	$\hat{\epsilon}_{total}(J/m)$	$\hat{\epsilon}^{nb}_{total}/\hat{\epsilon}_{total}$ (%)	$\hat{\epsilon}^{SI}_{sgs}/\hat{\epsilon}_{total}$ (%)	$\hat{\epsilon}^{BI}_{sgs}/\hat{\epsilon}_{total}$ (%)
Large plunging	17.8	14.7	63.7	45.9	52.9
Plunging	8.6	7.7	64.8	45.4	53.0
Weakly plunging/spilling	4.3	2.6	65.9	43.2	53.7
Spilling		1.4	64.5	42.3	51.6

Large scale: NHWAVE with multiphase extensions



Modeled near-surface air content (void fraction and foam density) compared to visible-band image intensity





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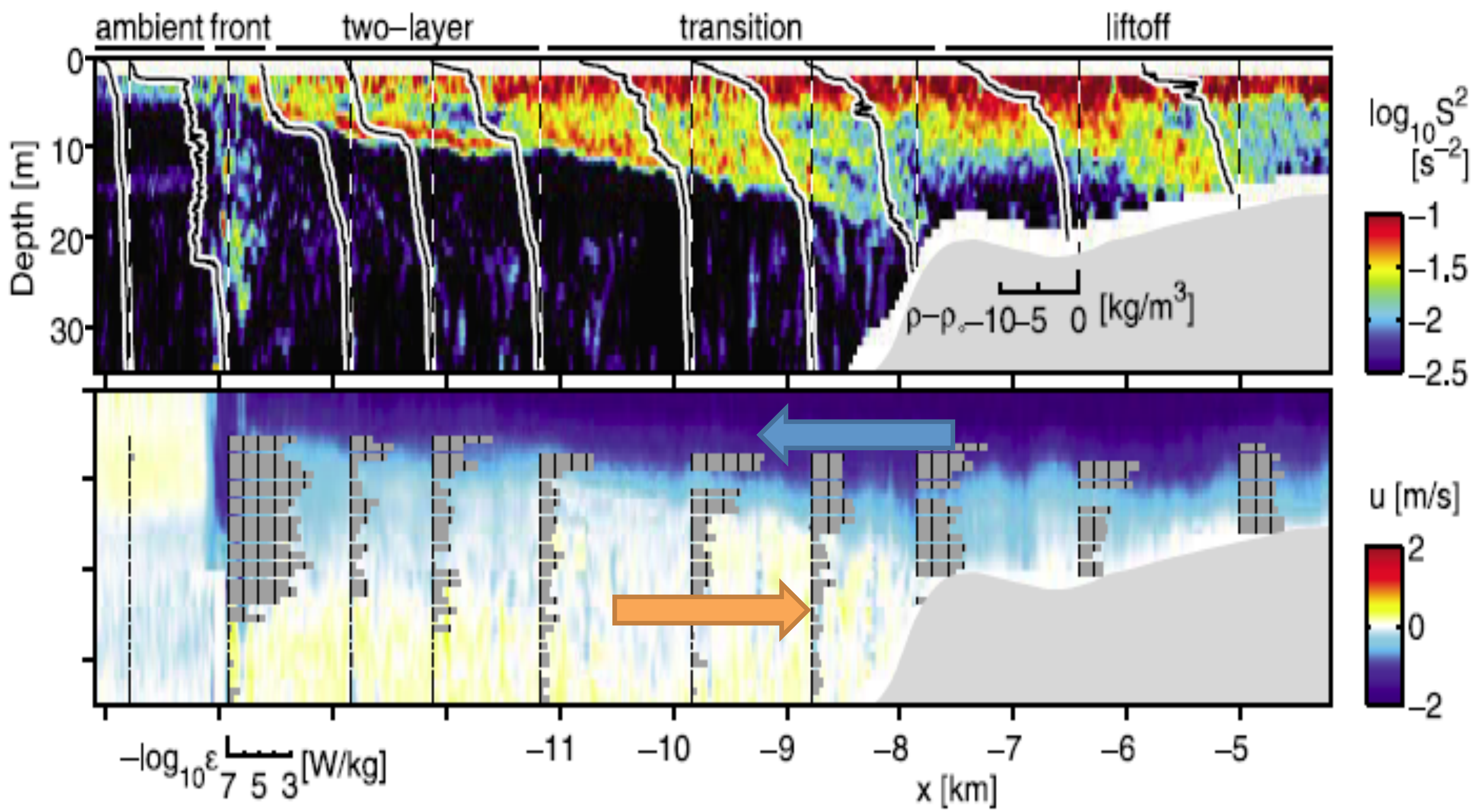
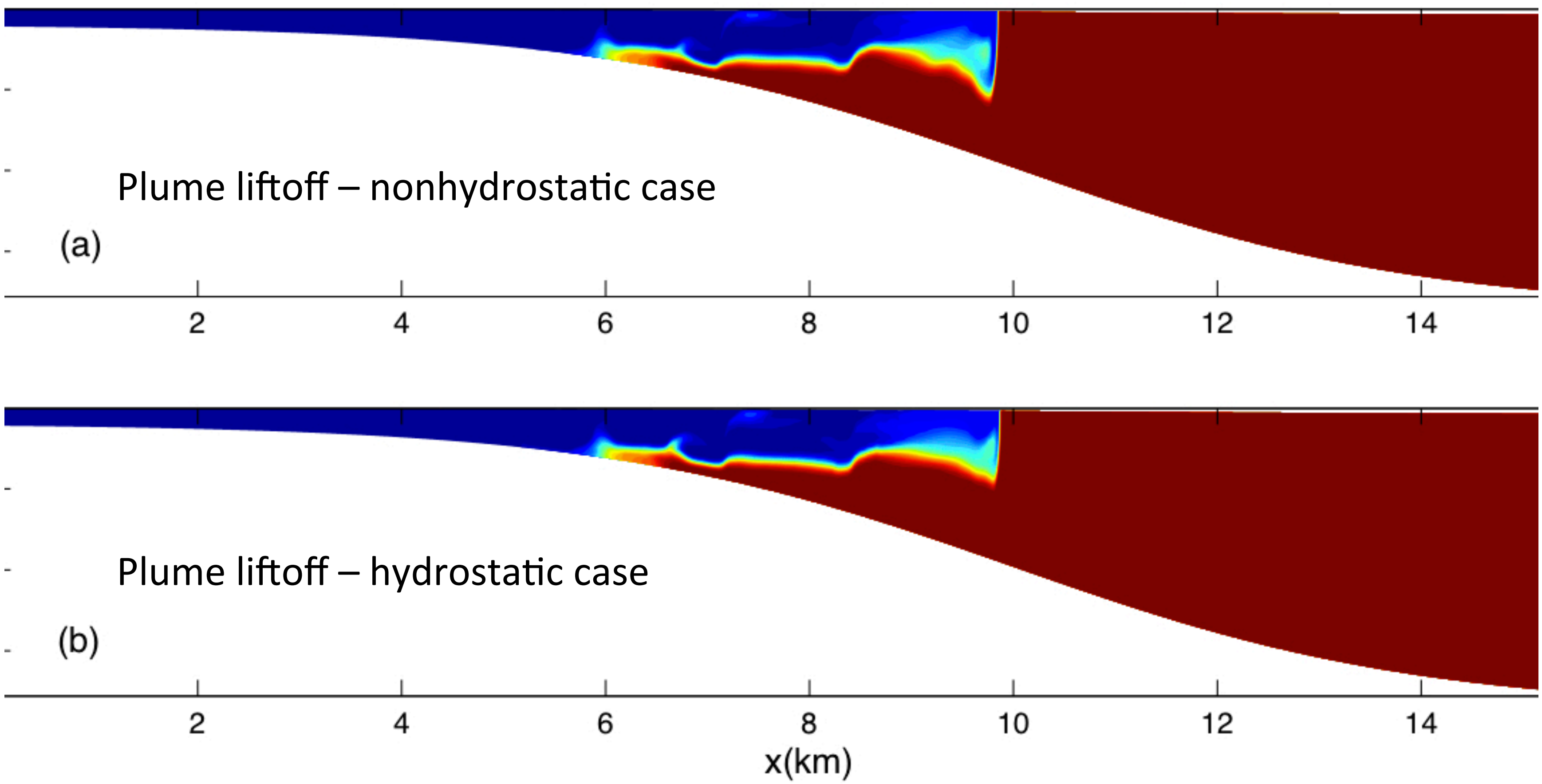
    3. Looking to the future: intermediate-depth wave breaking: What is "deep" and what is "shallow"?

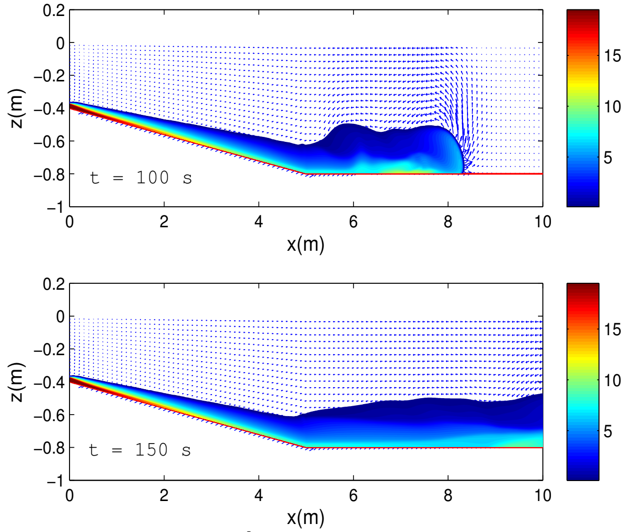
Application area: Mouth of Columbia River (Hsu, Shi, Kirby)



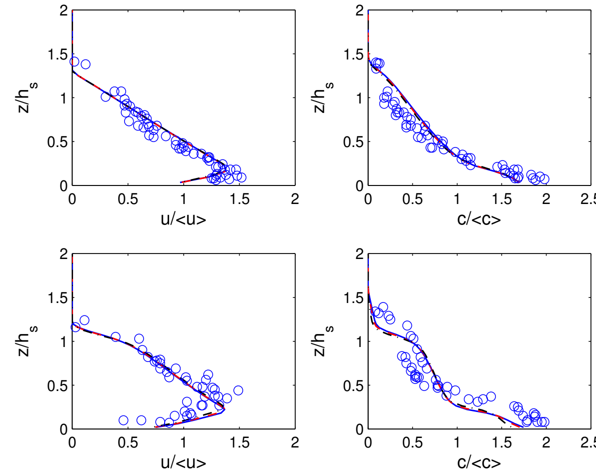
Kilcher and Nash (2010)

NHWAVE extended to include salinity stratification and suspended sediment component





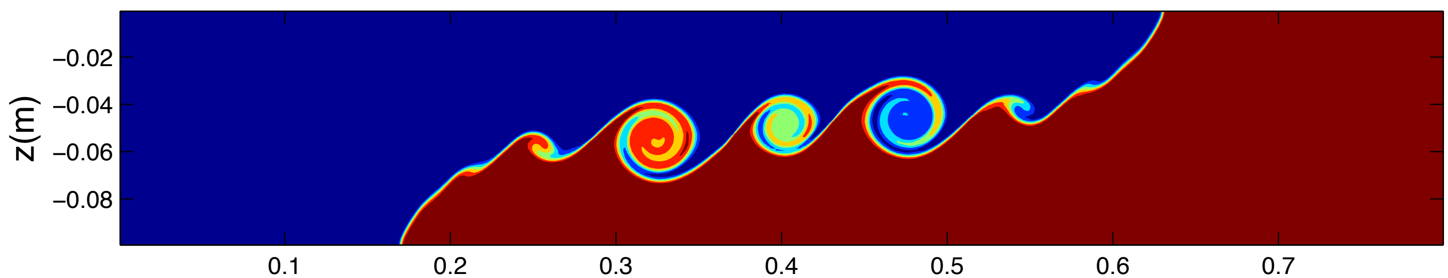
Unsteady gravity current



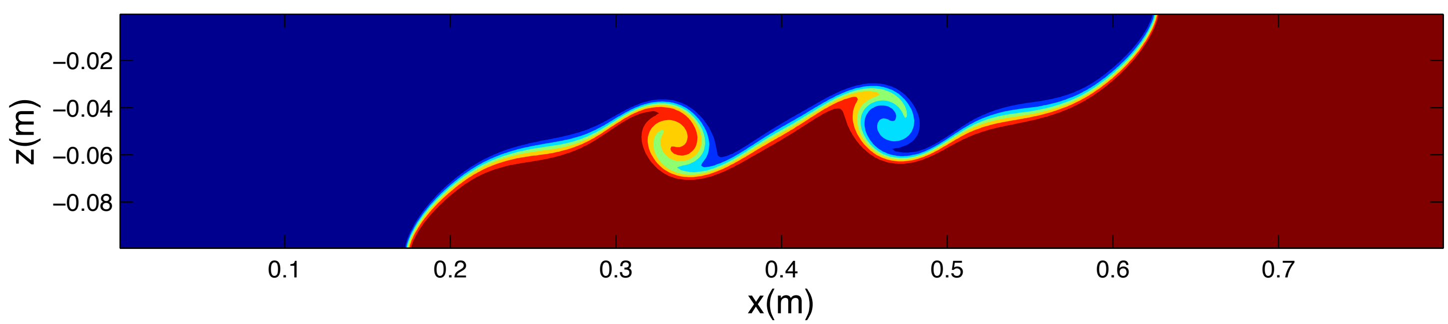
Model reproduction of velocity and concentration fields (Garcia)

Interface rollup in lock exchange problem:

Nonhydrostatic

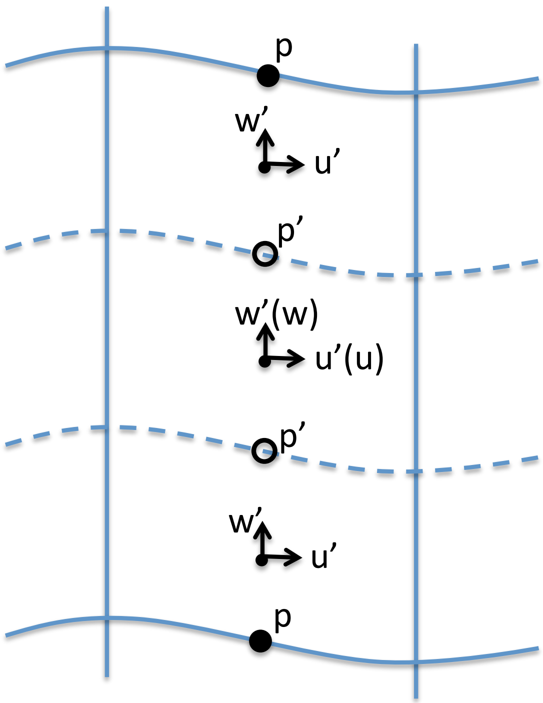


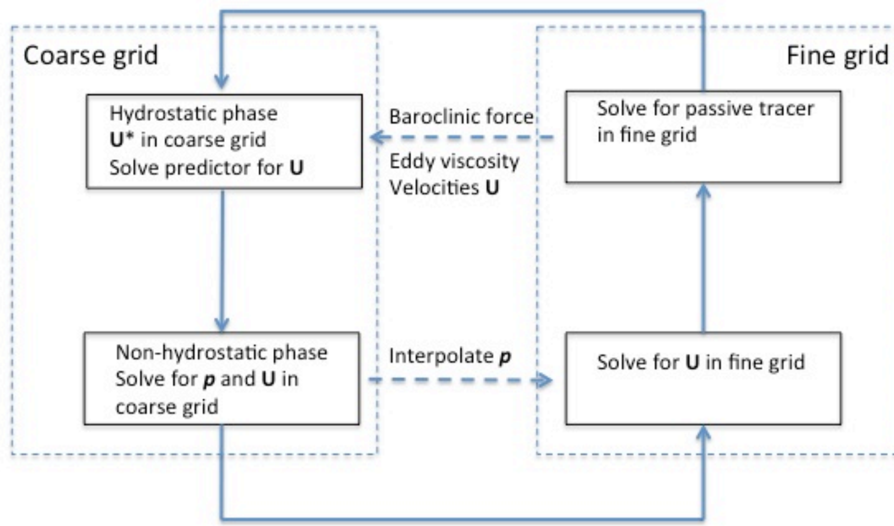
Hydrostatic



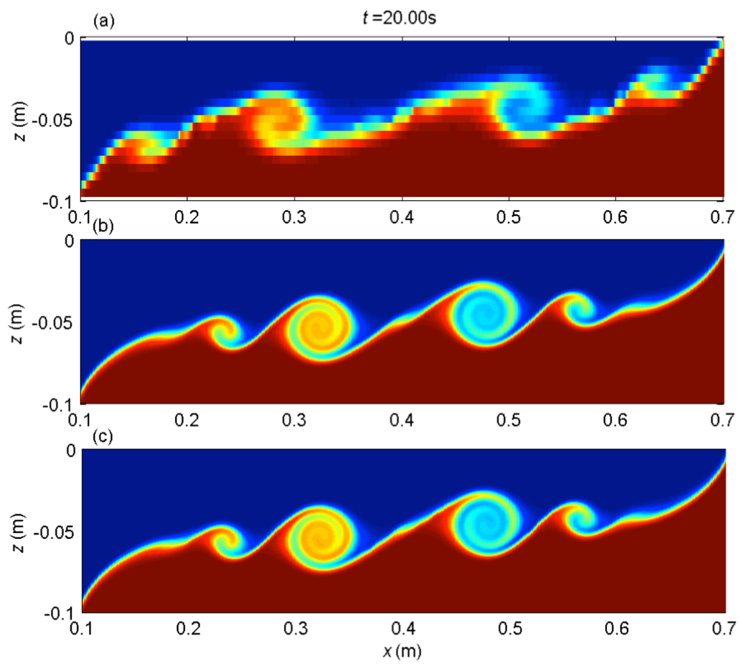
- Inclusion of continuous density stratification and of tracers with or without fall velocity leads to excessive vertical resolution requirements, compared to Euler gravity wave examples.
- Formally, pressure does not contribute to the generation of vorticity and strong shear in the flow field.
- Can accurate solutions for the velocity and concentration fields be obtained without corresponding resolution of the pressure field?

Numerics: Decimating the pressure solution

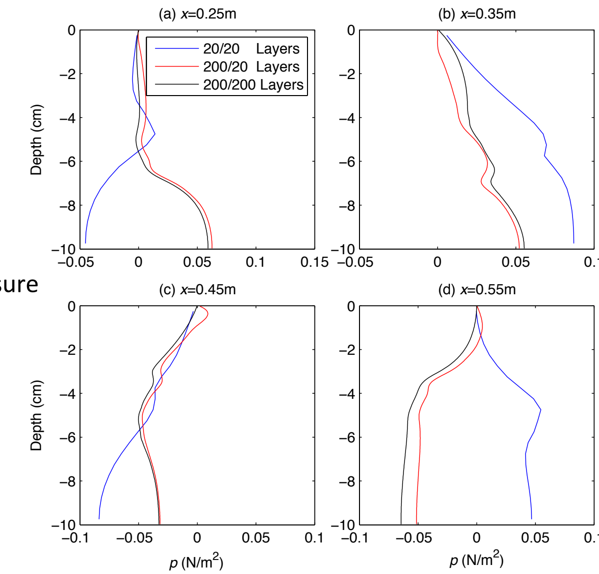




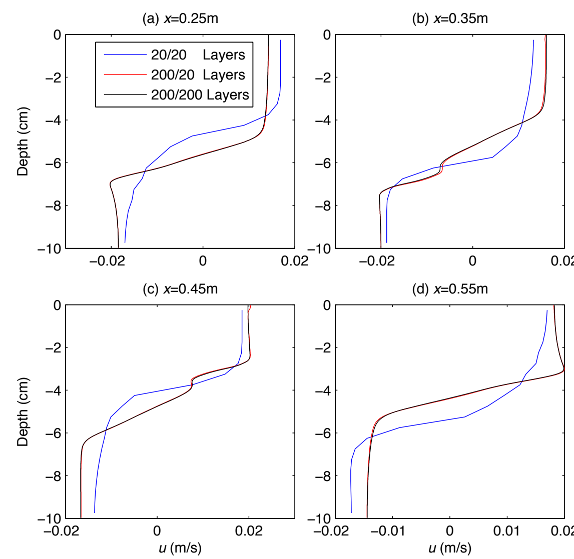
Lock-exchange problem: pressure, and U results



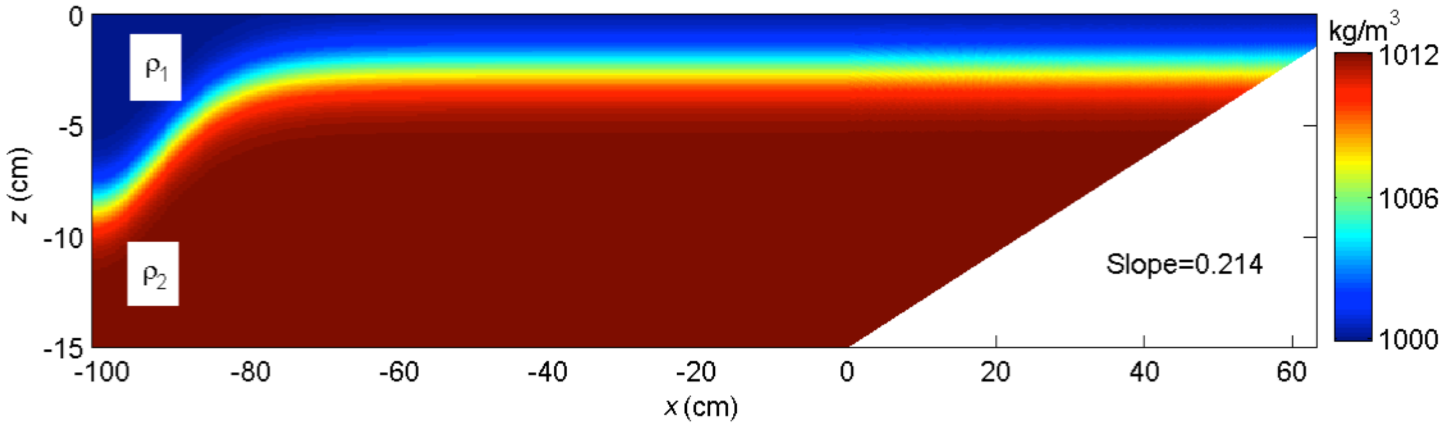
Dynamic pressure



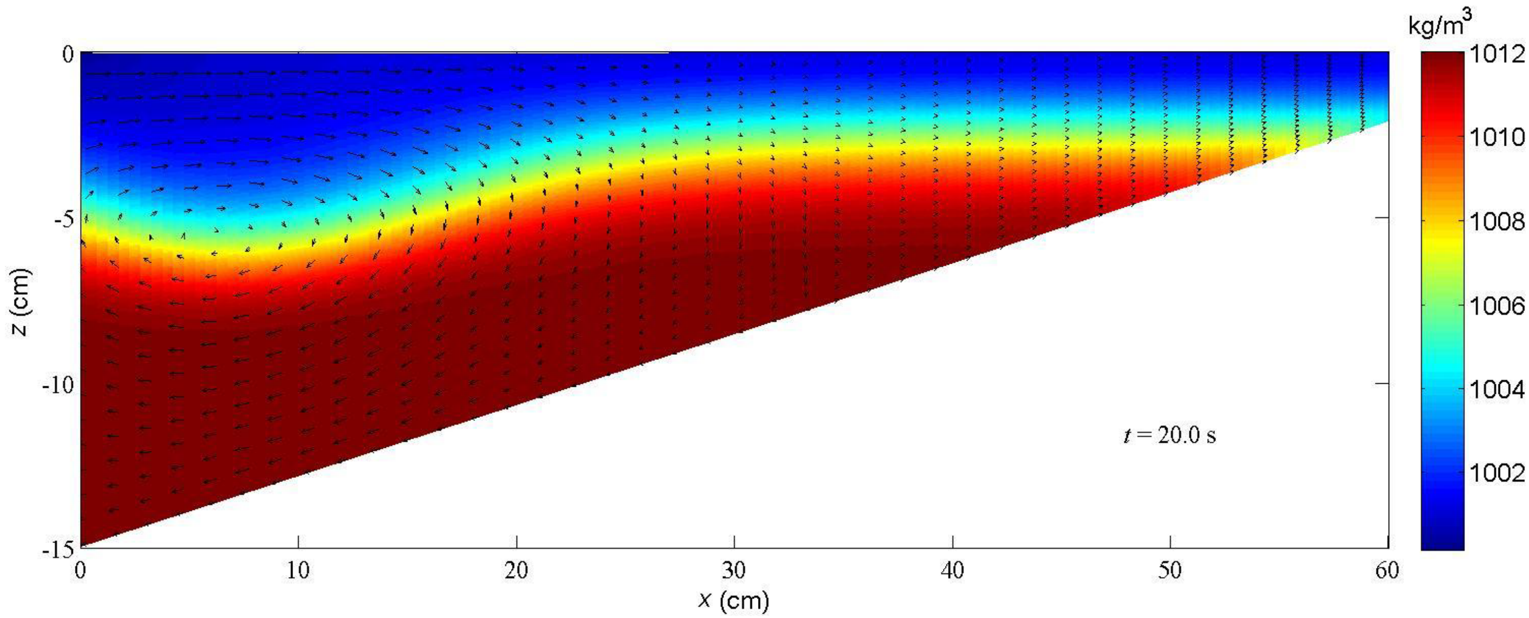
Horizontal velocity



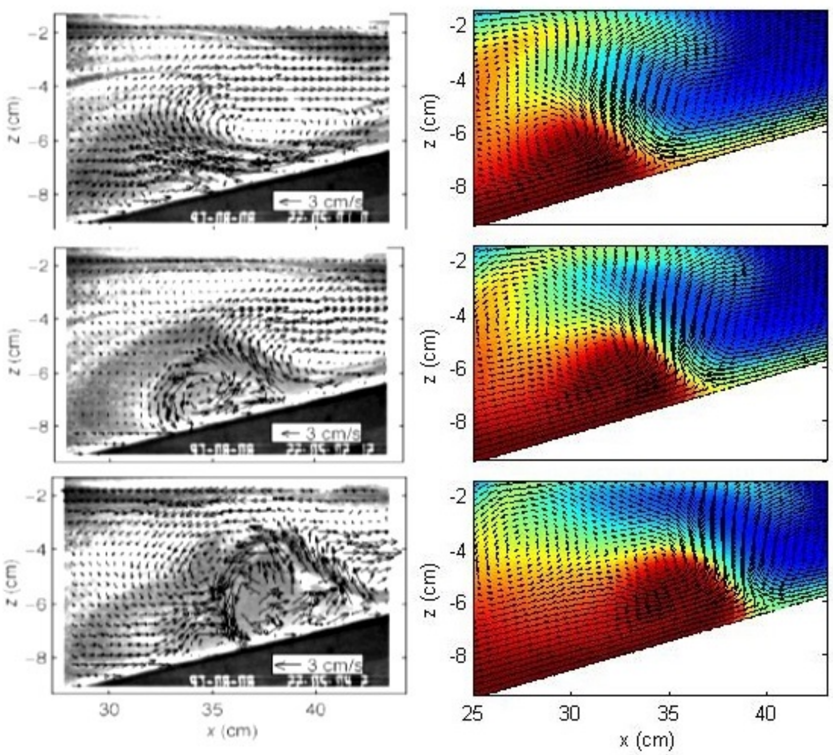
Simulations 20/20, 200/20, 200/200 layers.
(velocity grid/pressure grid)



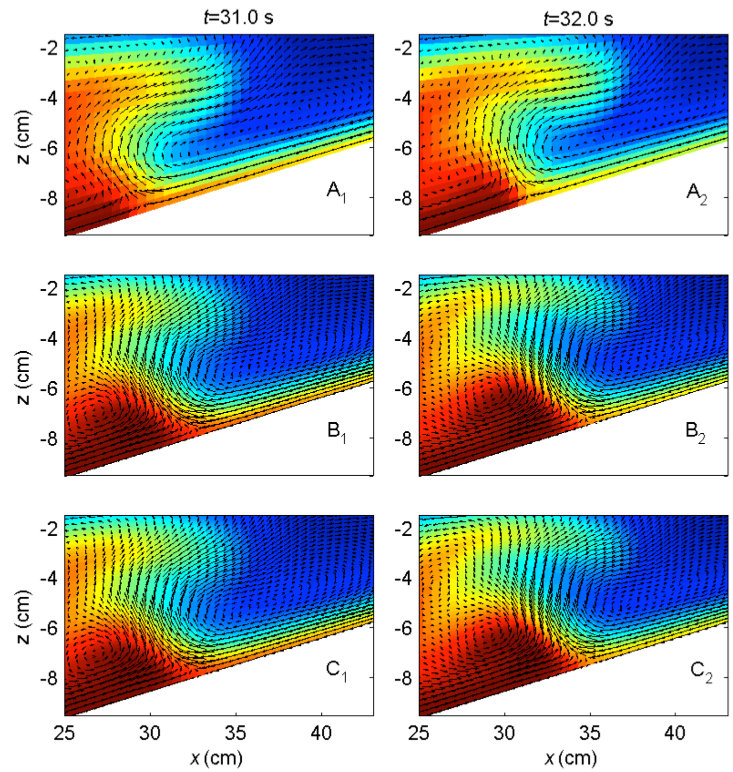
kg/m3
1012
1006
1000
ρ1
ρ2
Slope=0.214
z (cm)
x (cm)
0
-5
-10
-15
-100
-80
-60
-40
-20
0
20
40
60



kg/m3
1012
1010
1008
1006
1004
1002
t = 20.0 s
z (cm)
x (cm)
0
-5
-10
-15
0
10
20
30
40
50
60



Measurements (Michallet and Ivey, 1999)
And NHWAVE with 200/200 layers



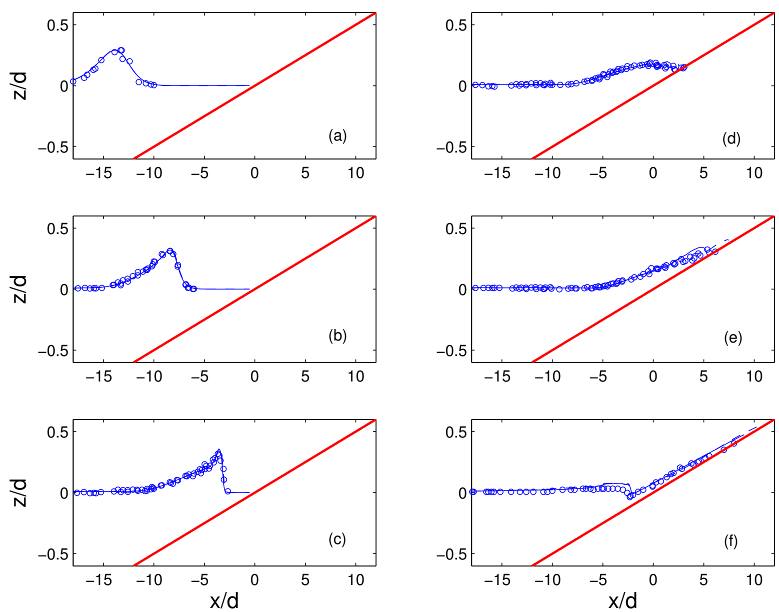
NHWAVE with 20/20, 200/20 and 200/200 layers

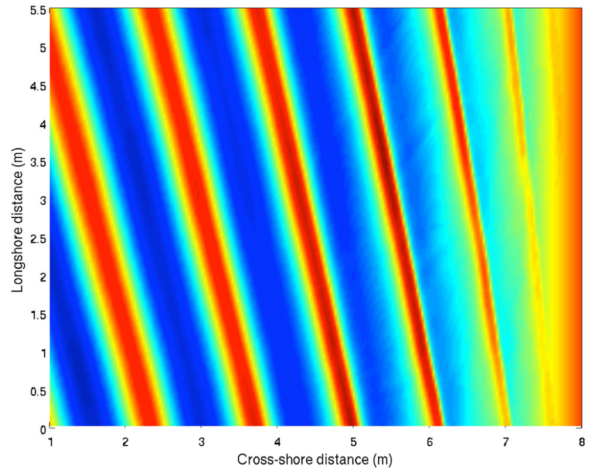
Outline

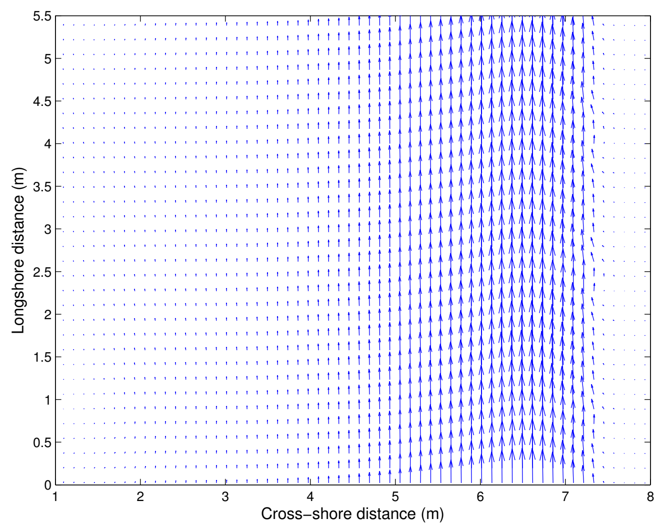
- Brief overview of recent model developments and applications.
- A closer look at three topics:
  1. Bubble entrainment and effects on turbulence in breaking wave crests
  2. Extensions of a "nonhydrostatic" model NHWAVE to include a wider range of effects
  3. Looking to the future: intermediate-depth wave breaking: What is "deep" and what is "shallow"?

Wave breaking (in NHWAVE) from shallow to deep water

Results for depth-limited wave breaking have been extensively tested in 3D nonhydrostatic models such as NHWAVE and SWASH

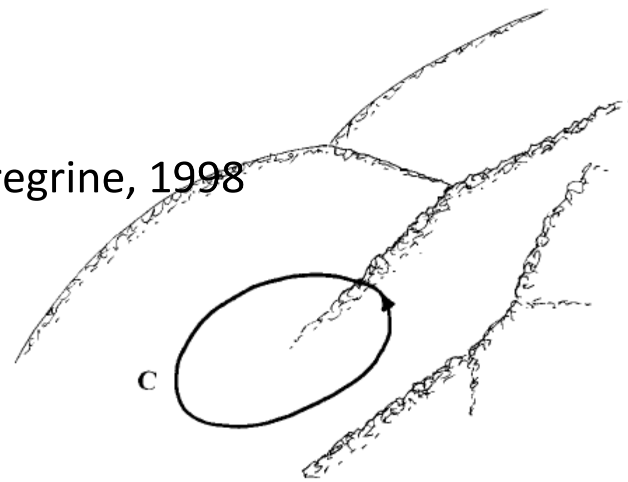


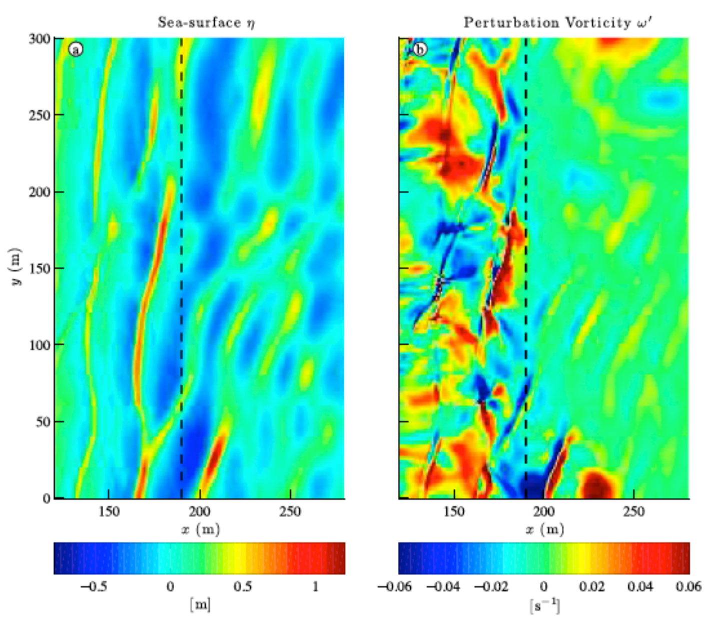


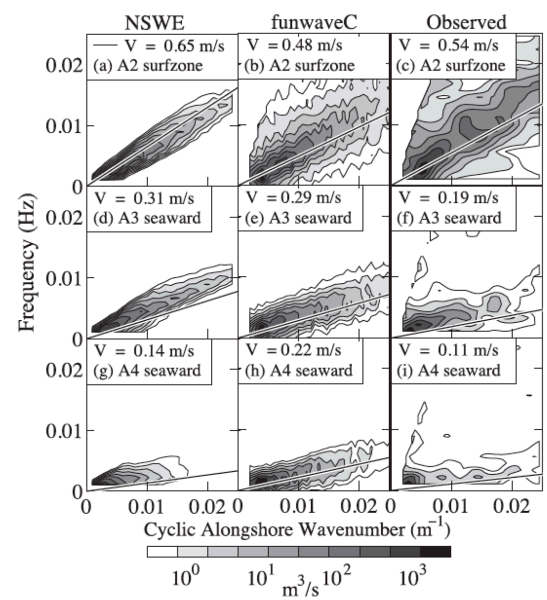


Short breaking wave crests in shallow water provide a mechanism for generation of persistent vorticity in the surf zone

Peregrine, 1998

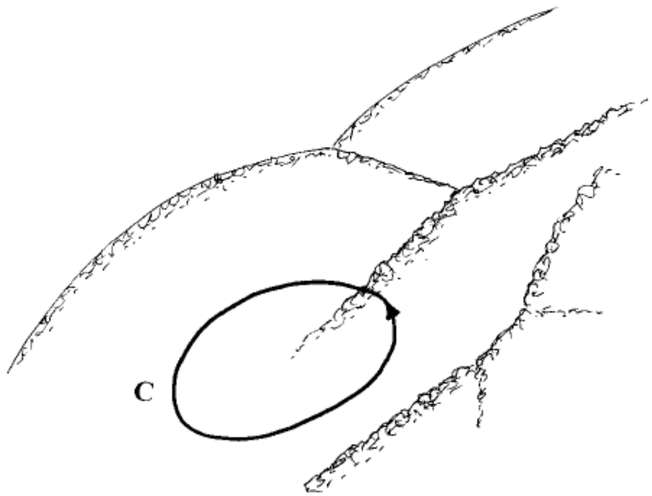






Feddersen, JPO 2014

How is deep water different?

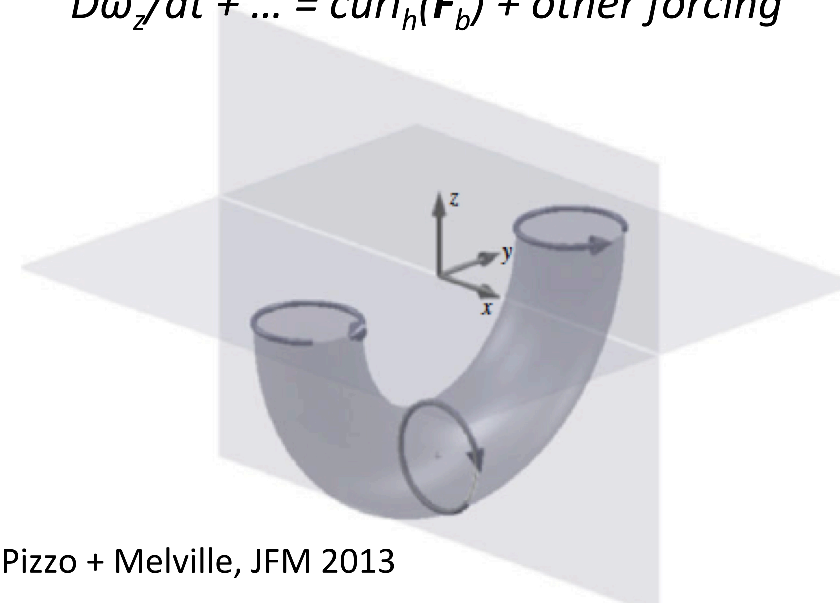


Surf zone: Flow field is primarily horizontal, depth uniform

$d\mathbf{U}/dt + \ldots = \mathbf{F_b}$ + *other dissipative effects*

$D\omega_z/dt + \ldots = curl_h(\mathbf{F}_b)$ + *other forcing*

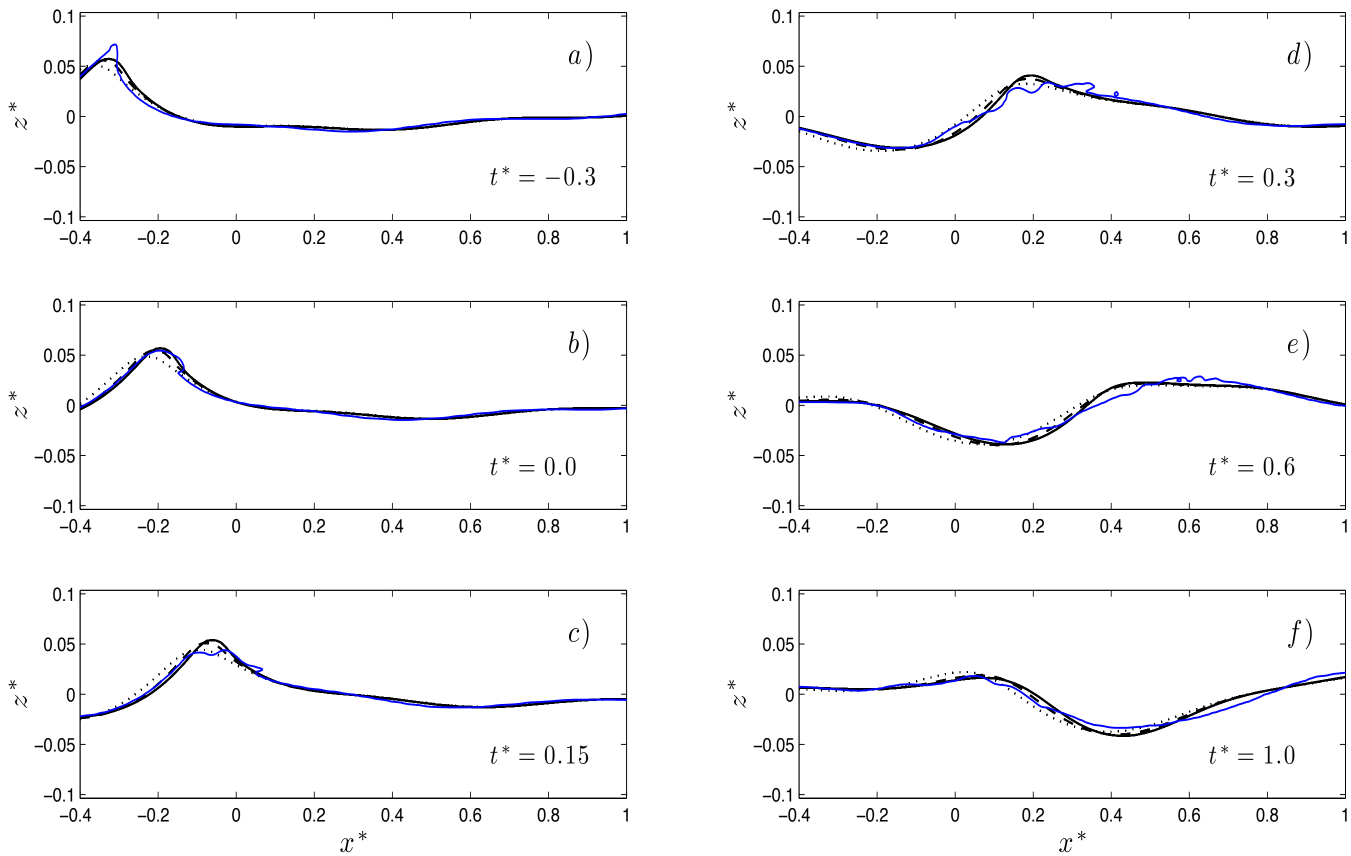
Deep water whitecaps: Finite breaking crest width + depth of wave motion << water depth -> reconnection of vertical vortex cores under breaking event.



Pizzo + Melville, JFM 2013

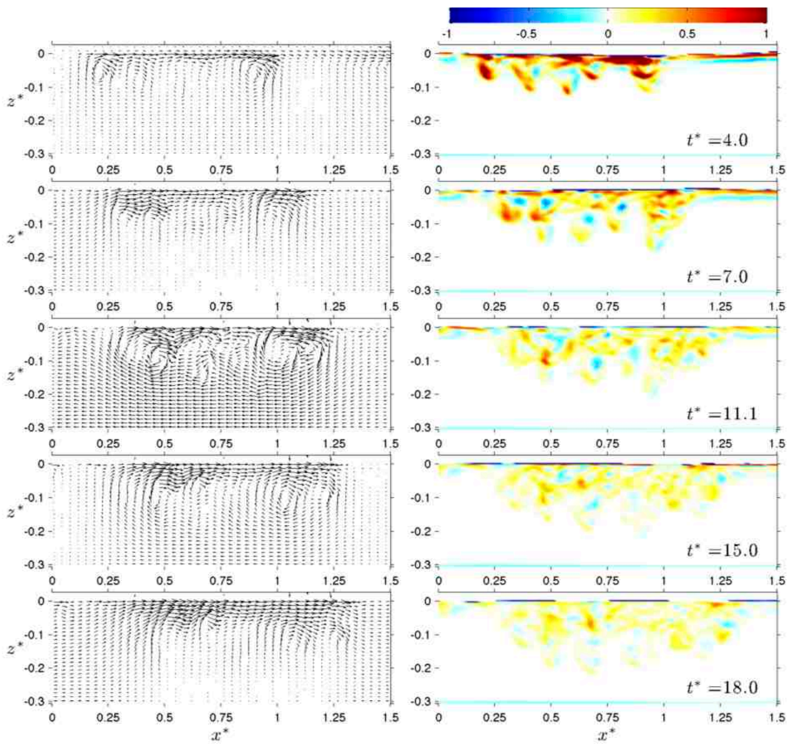
So, where is the boundary between these two regimes? What does a shift from one to the other imply about form of breaking induced vorticity?

Prefer to pursue this using NHWAVE, but can the model predict deep water breaking?

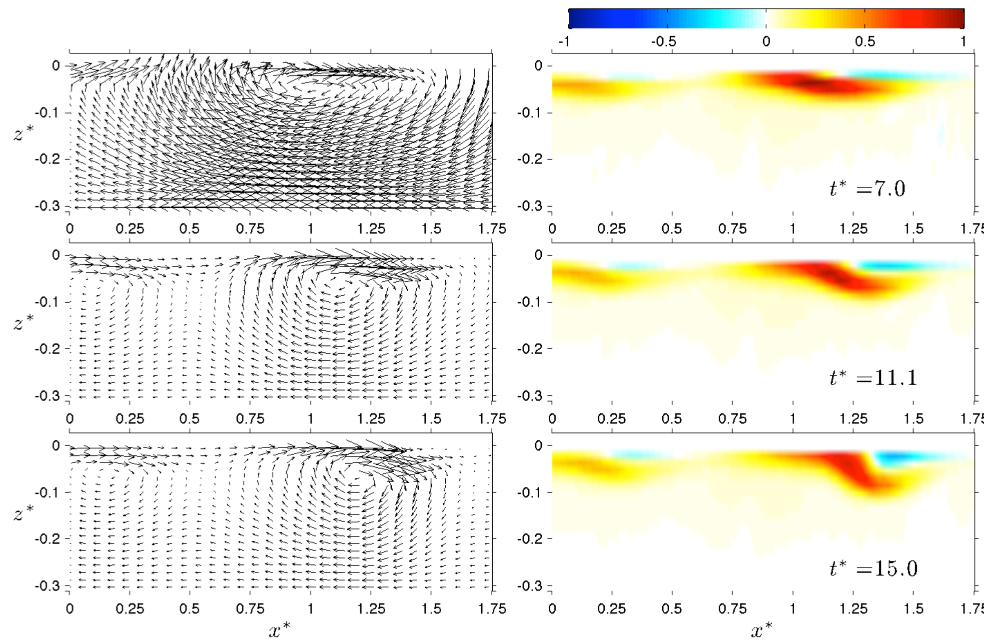


Surface snapshots for *S*=0.278, Rapp + Melville. Fine solid line = TRUCHAS.
Other lines are NHWAVE at 3 vertical resolutions – 5, 10 and 20 levels

Generation and persistence of a horizontal vorticity patch

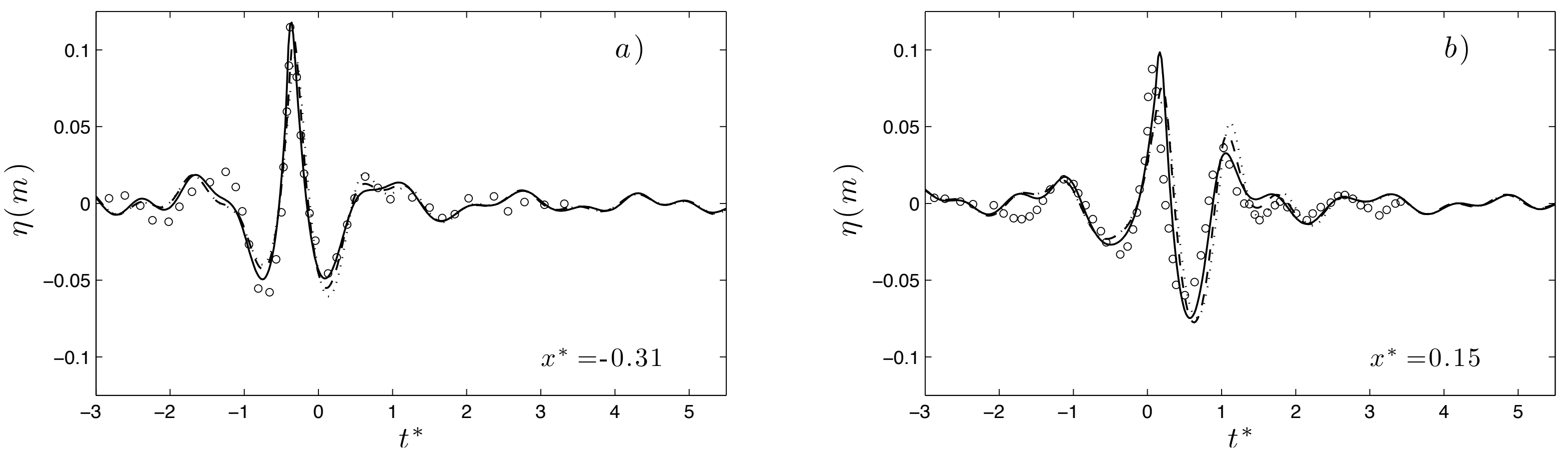


Full 3D LES/VOF



NHWAVE

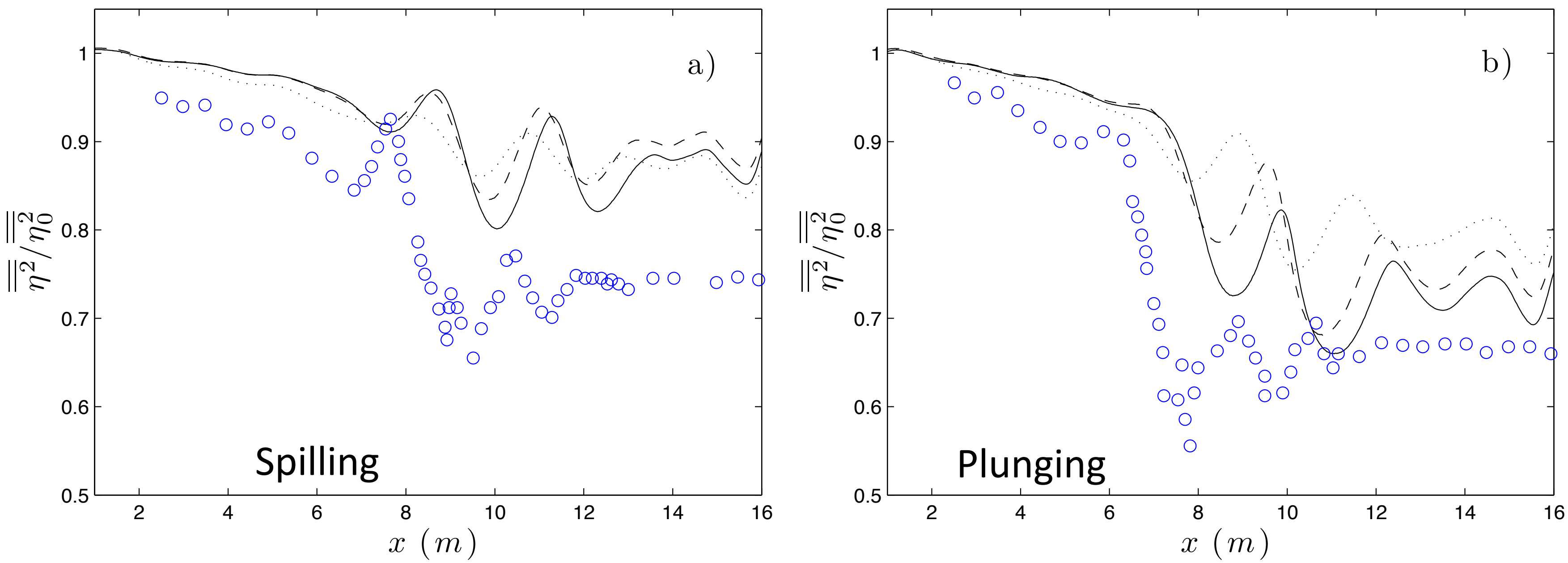
Times series of surface at fixed locations before and after breaking



Model identifies breaking events reliably and without any imposed breaking criteria. Breaking handled completely by numerics, as in typical shock-capturing approaches for the NLSWE's. Result is possibly unexpected, even encouraging, but …

… the shock capturing scheme does everything :^(

- Turbulence production in *k*-*ε* model never triggered – no generation of an eddy viscosity
- Wave energy dissipation under-estimated, particularly in spilling breakers
- Generated vortex structures persist for unrealistically long times.



Fixes?

- Two-level approach described above?
- Attempt to estimate turbulence properties at free surface in order to provide BC's for turbulence model (Brocchini and Peregrine, JFM 2001)