Modern Tools – Models

Jim Kirby

The Past and Future of Nearshore Processes Research:
Reflections on the Sallenger Years and a New Vision for the Future

Kitty Hawk, NC

5/1/14

My relation to Abby? No professional overlap, but …

Goldsmith, V., Byrne, R. J., Sallenger, A. H., and Drucker, D. M., 1975, The influence of waves on the origin and development of the offset coastal inlets of the southern Delmarva Peninsula, Virginia, in L. E. Cronin (Ed.), Estuarine Research: Academic Press, NY, no. 2, p. 183-200.

Then …

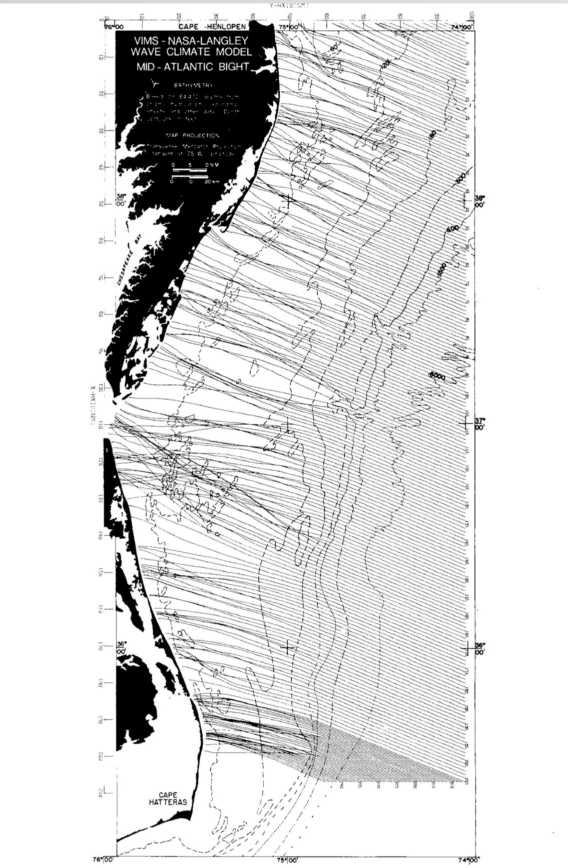


Figure B34.- Wave rays computed with following input conditions: AZ = 112.5°; T = 14 sec; Tide = 0.

Goldsmith et al (1974)

Now

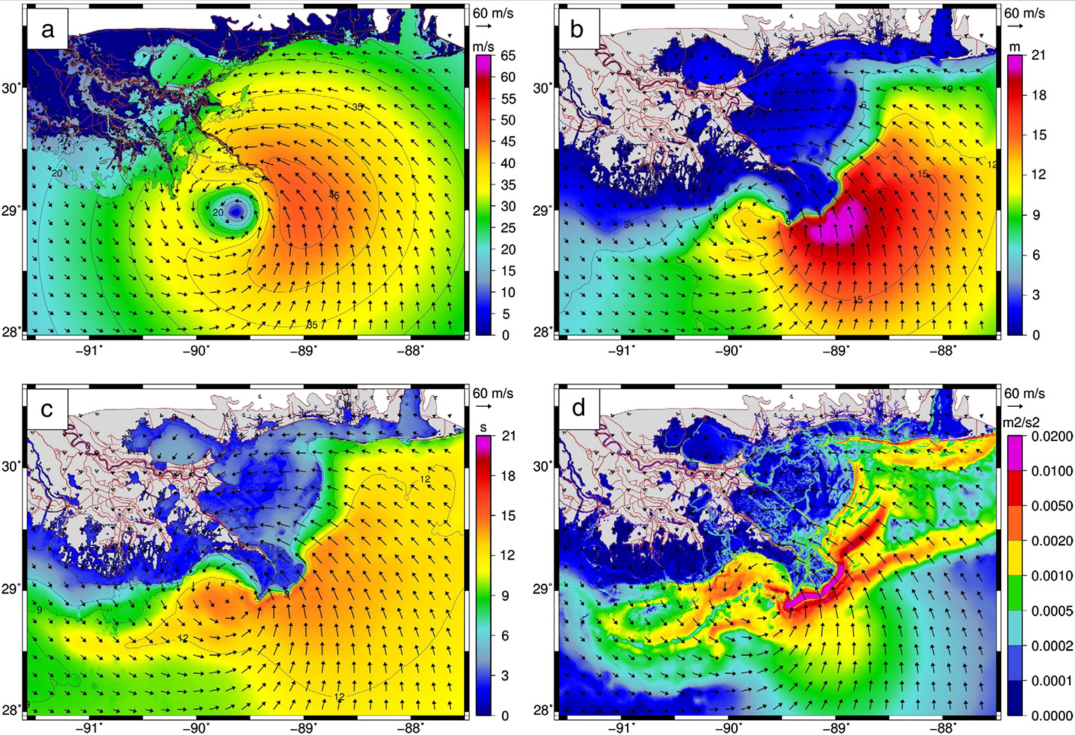
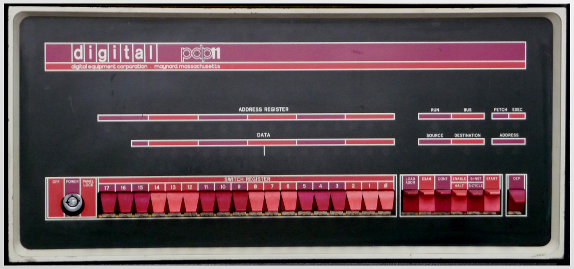


Fig. 9. Hurricane Katrina winds and waves at 1000 UTC 29 August 2005 in southeastern Louisiana. The panels are: (a) wind contours and vectors (m s^{-1}), shown with a 10 min averaging period and at 10 m elevation; (b) significant wave height contours (m) and wind vectors (m s^{-1}); (c) mean wave period contours (s) and wind vectors (m s^{-1}); and (d) radiation stress gradient contours (m2 s^{-2}) and wind vectors (m s^{-1}).

Dietrich et al (2011)

Then …

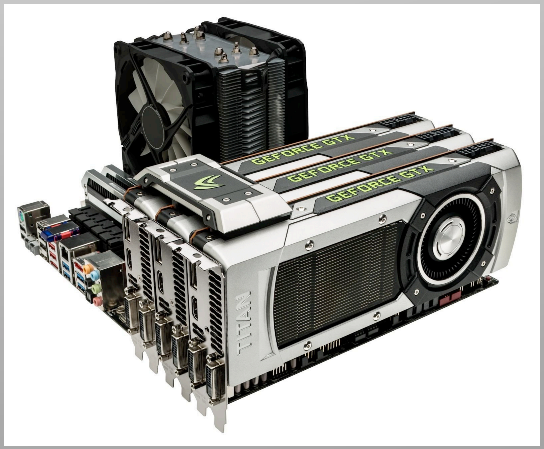


PDP 11

IBM 360

Now

Stampede. University of Texas at Austin

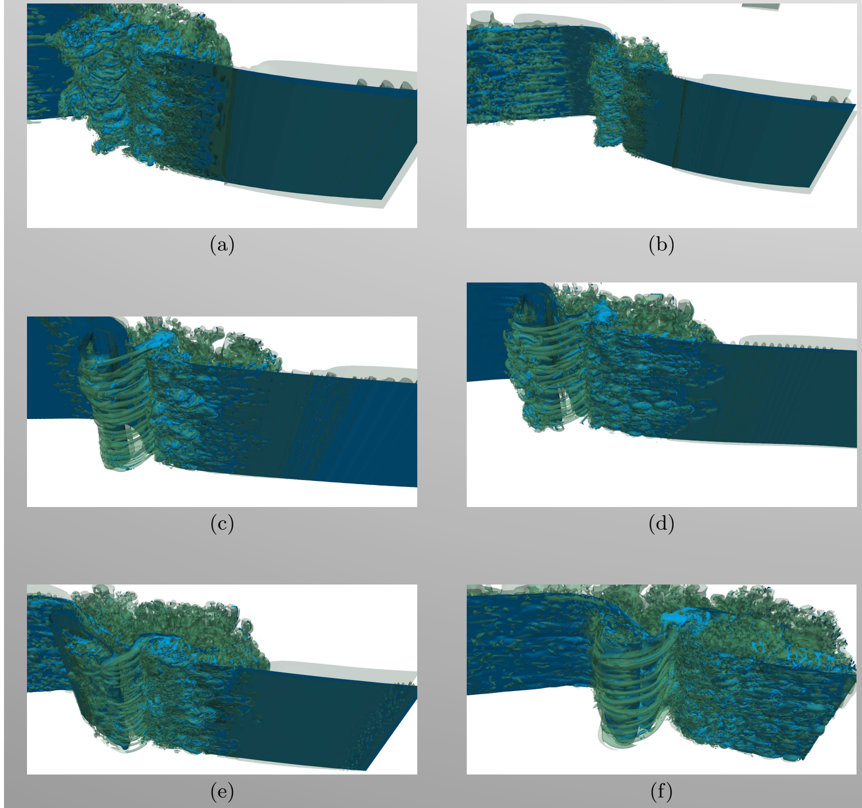


Nvidia Titan

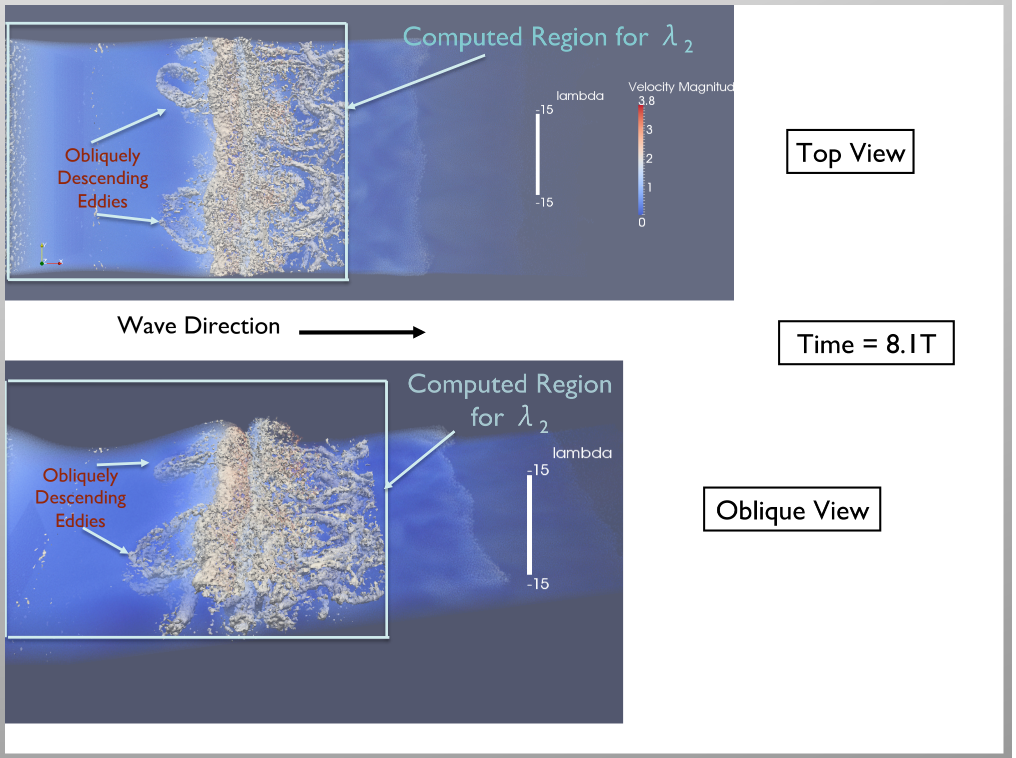
High resolution modeling of wave breaking

Approaches?

Conventional (finite volume, finite difference, …)

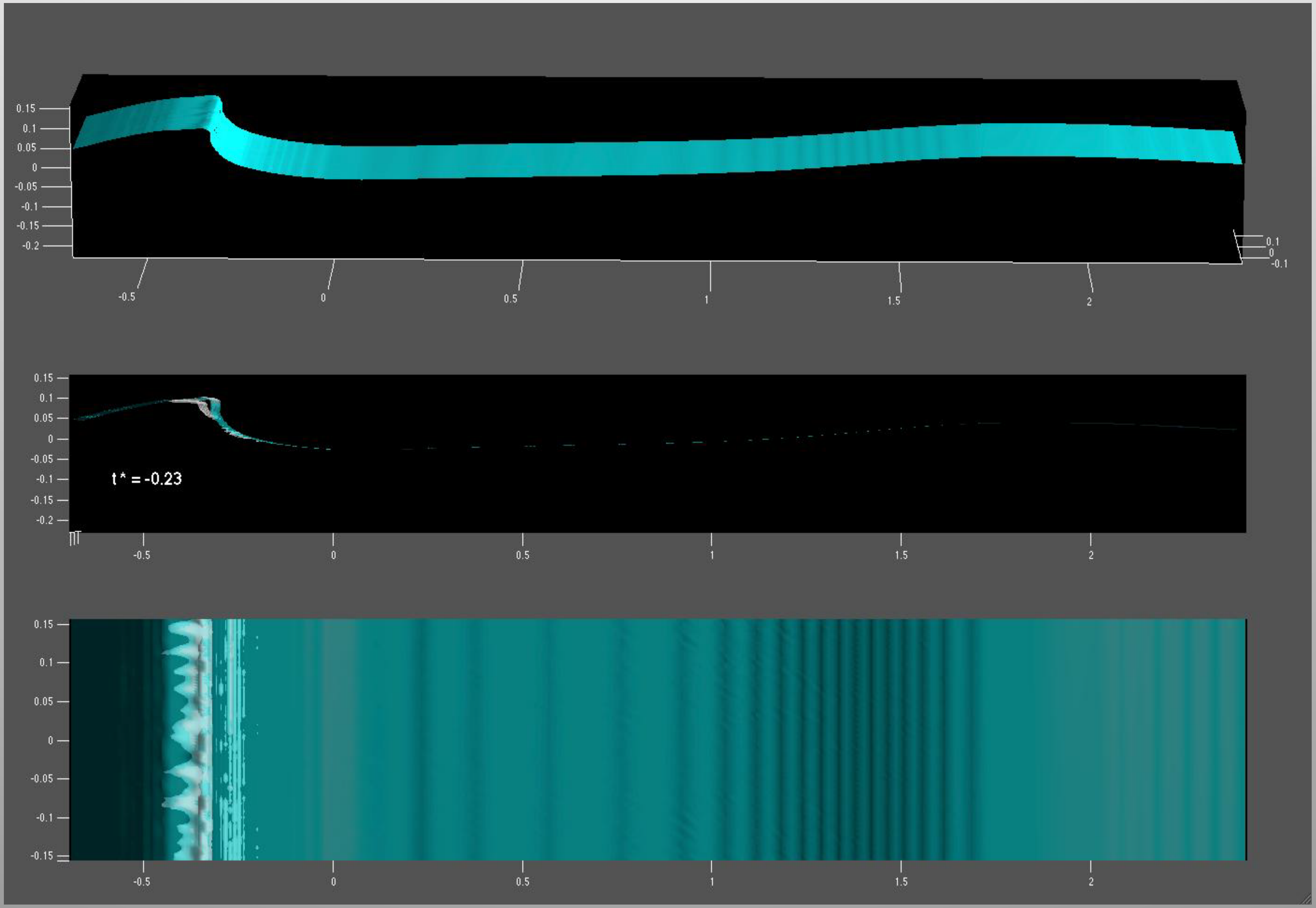

(a) (b) (c) (d) (e) (f)

Or Lagrangian methods (SPH)



High resolution modeling of wave breaking

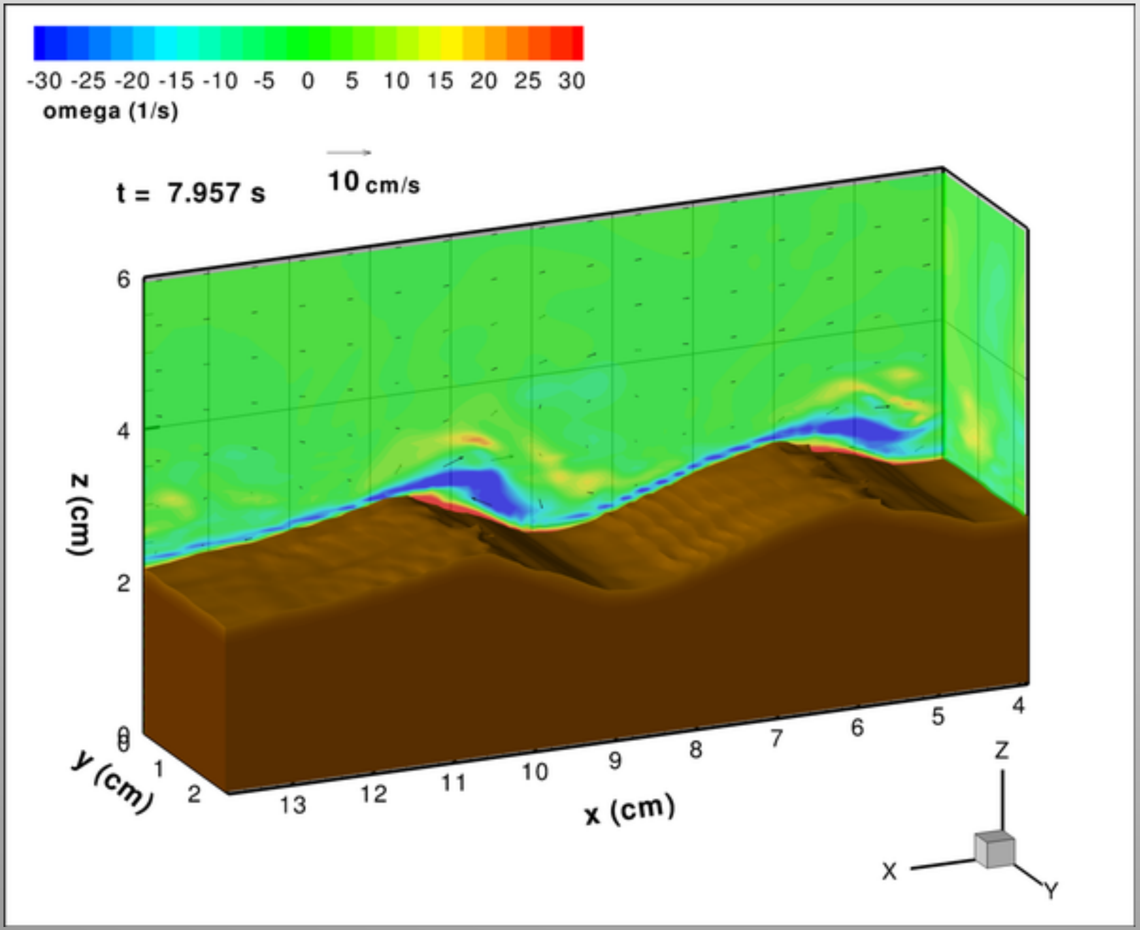
Approaches? LES, multiphase continuum model (lower resolution)



Derakhti and Kirby, 2013

Mixture Theory Simulations

Validation with laboratory measurements:



Simulation Specifics

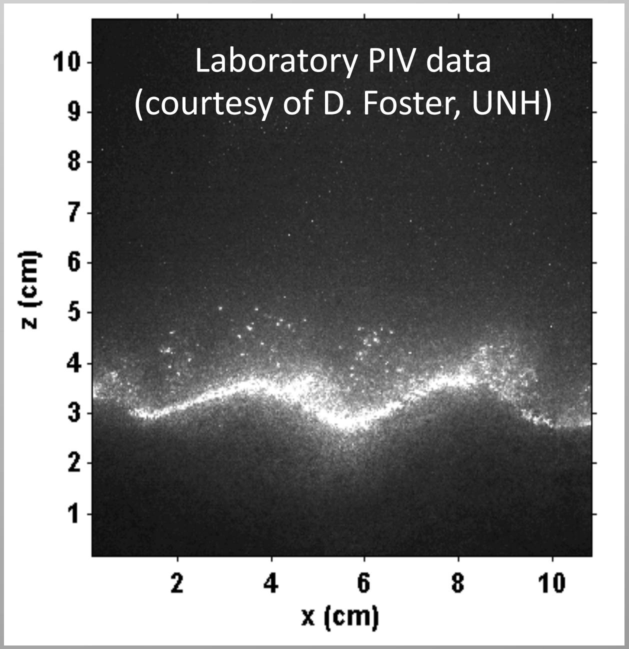
10.6 cm x 2.4 cm x 14.2 cm

$U_{0,max}$ = 12 cm/s

T = 2 s

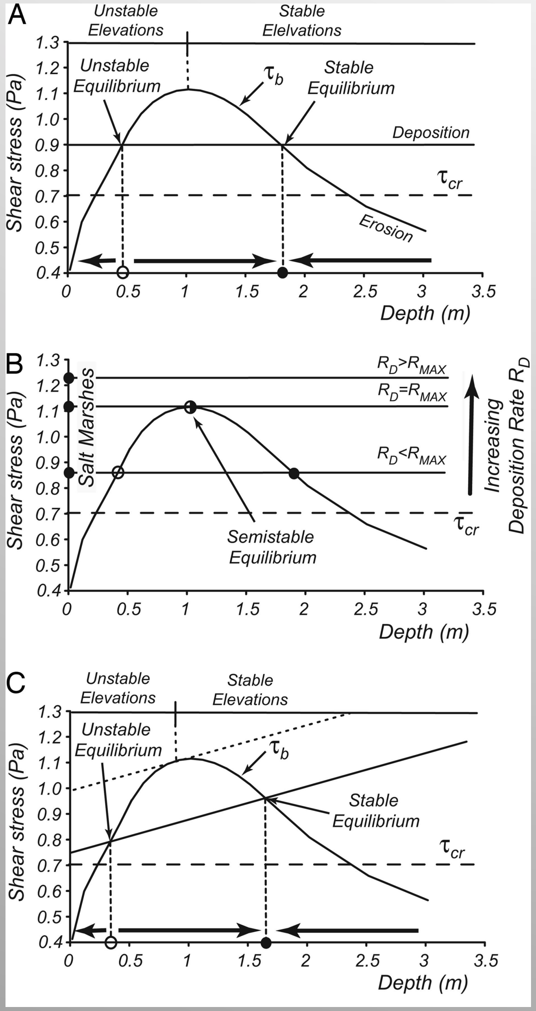
d = 0.054 cm

t_{total} = 40 s



Laboratory PIV data
(courtesy of D. Foster, UNH)

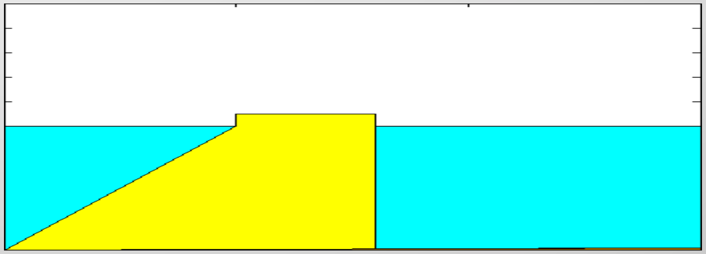
At the other end of the spectrum – continuing insight from simple process-based models



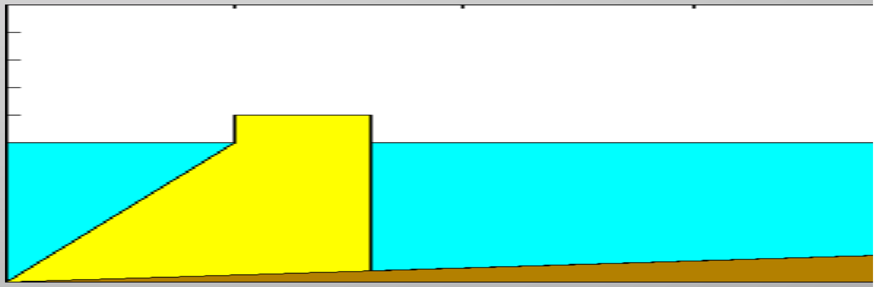
Equilibria in tidal flat/salt marsh elevations

Dynamics of landward migration of barrier islands

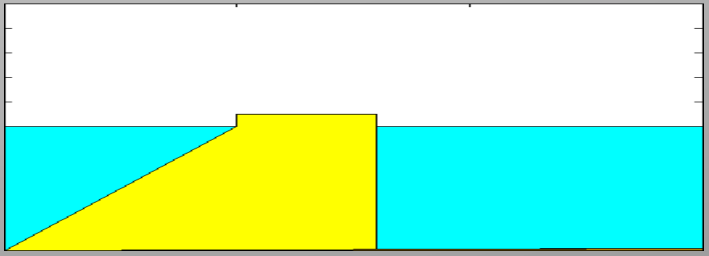
Height Drowning



Dynamic Equilibrium

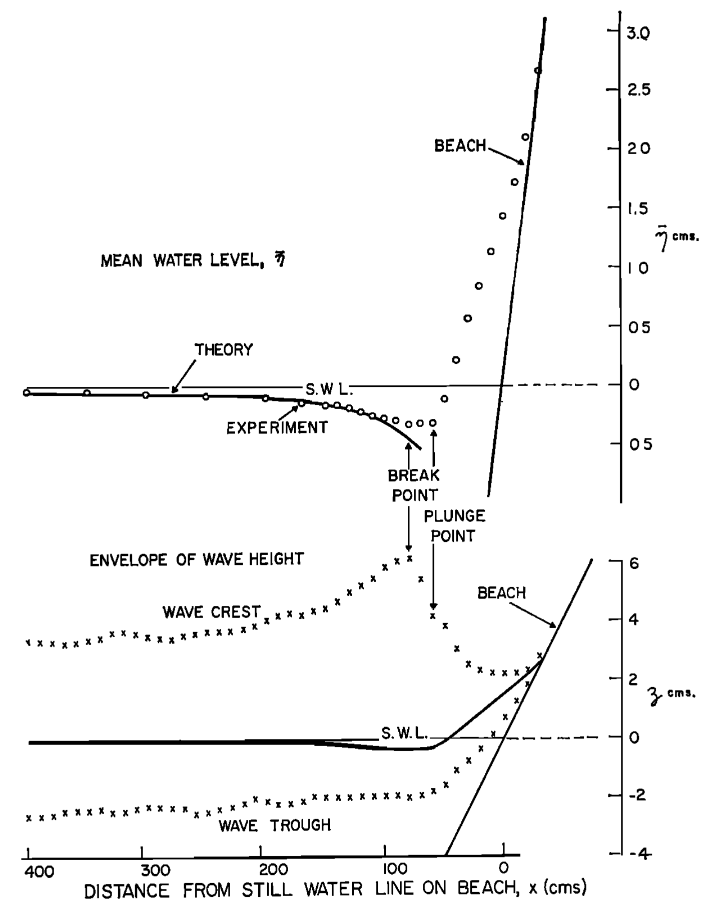


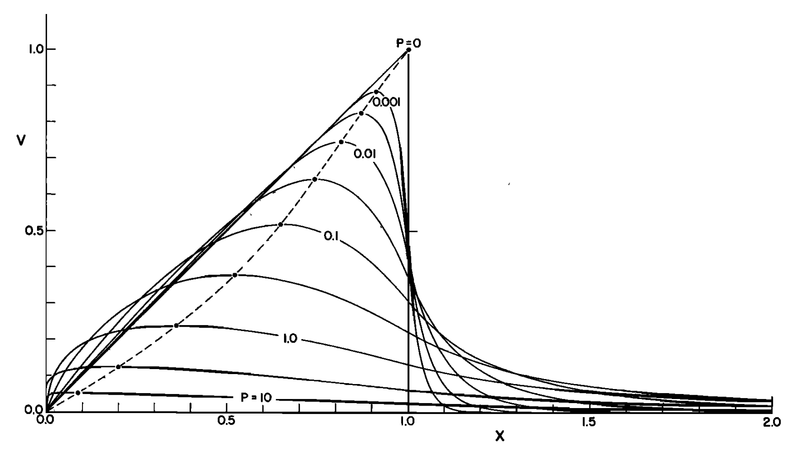
Width Drowning



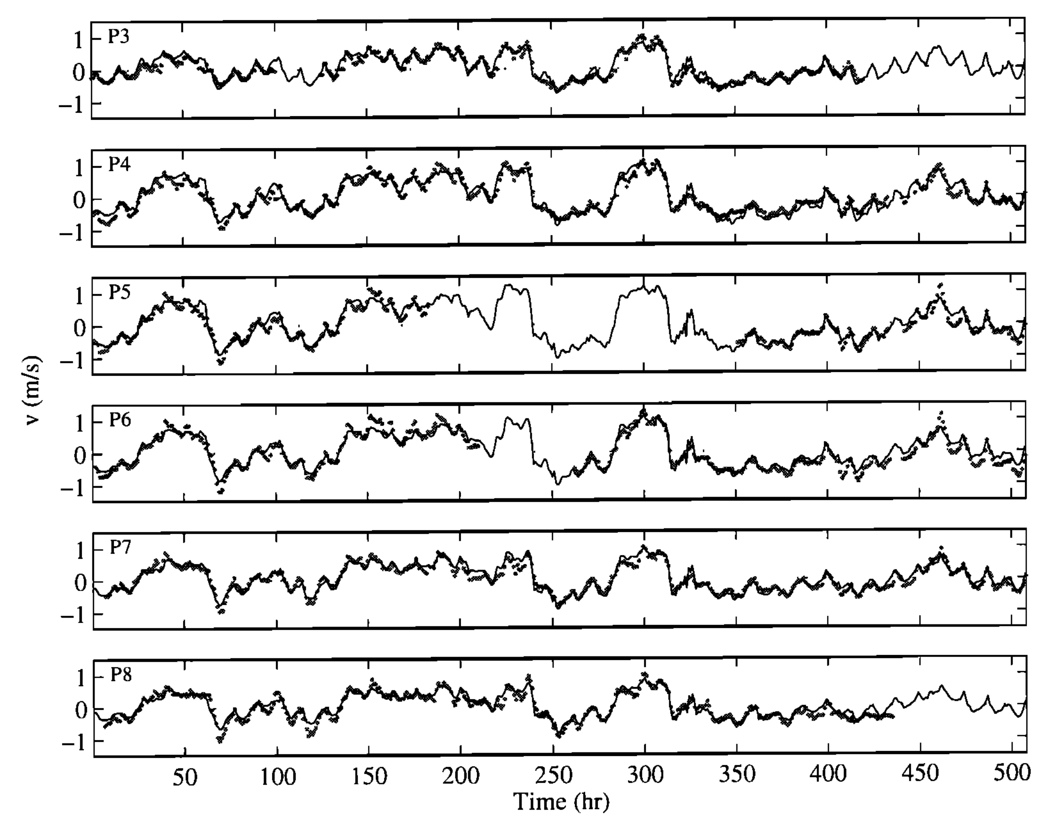
Guiding paradigm for modeling? Wave-averaged mean flow + wave forcing

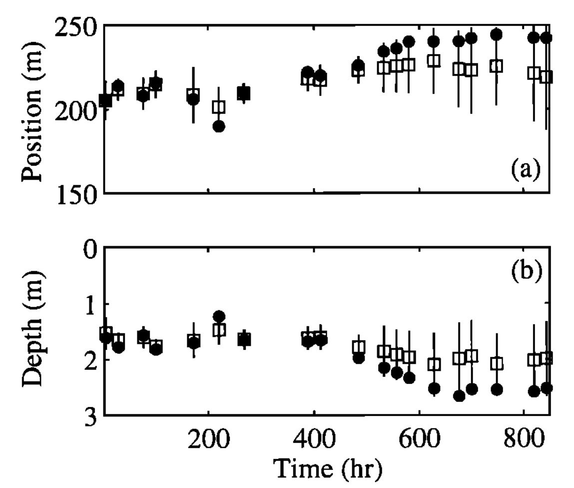
Longuet-Higgins and Stewart in early 60′s: Radiation stress
Craik, Leibovich in mid 70′s: vortex-force formalism





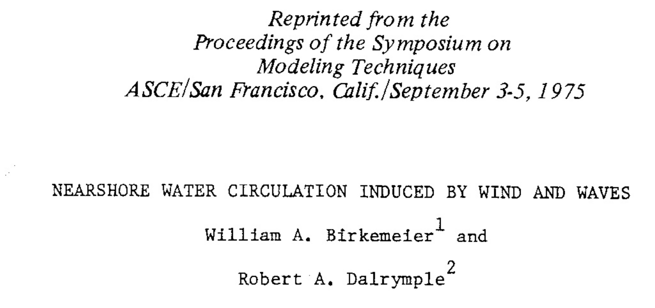
Model (further elaborated) provides good reproduction of mean longshore currents in longshore uniform conditions, start to break down in more markedly 2D conditions





Growing maturity of ocean modeling (nearshore or otherwise)

1975:

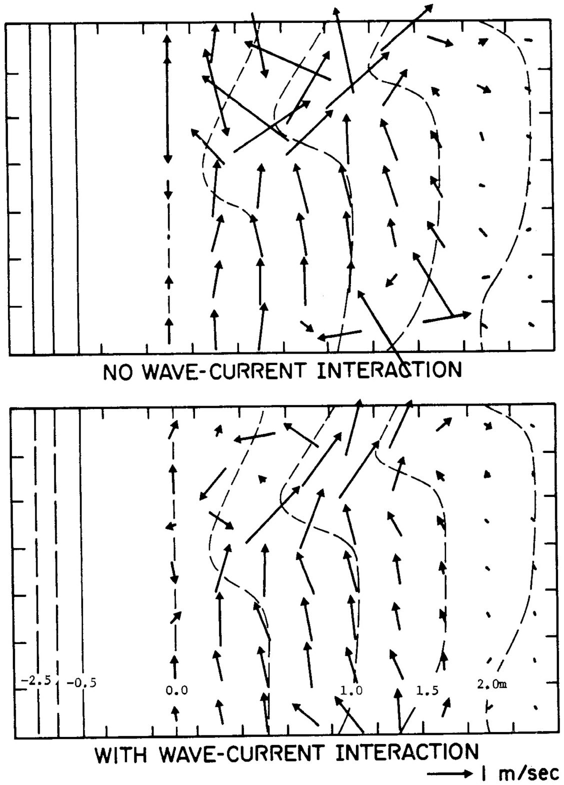


Reprinted from the
Proceedings of the Symposium on
Modeling Techniques
ASCE/San Francisco, Calif./September 3-5, 1975

NEARSHORE WATER CIRCULATION INDUCED BY WIND AND WAVES

William A. Birkemeier[1] and

Robert A. Dalrymple[2]


NO WAVE-CURRENT INTERACTION

WITH WAVE-CURRENT INTERACTION

Figure 7 Surf Zone Velocity Vectors over Trough Showing the Effect of Wave-Current Interaction

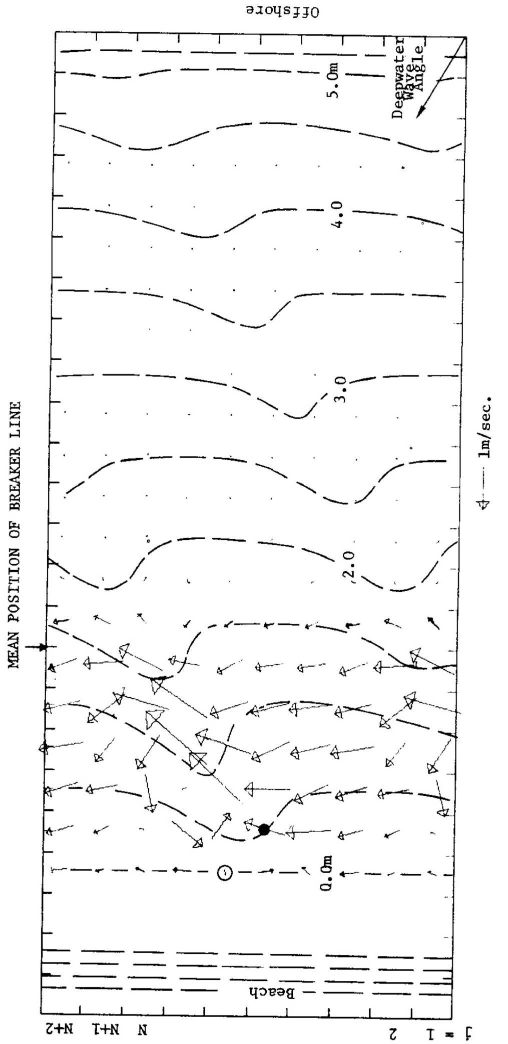
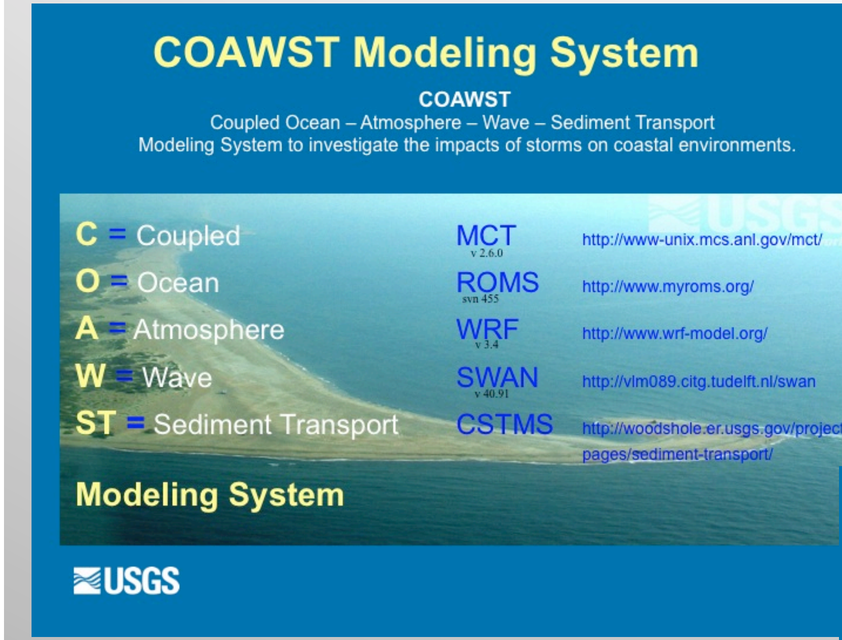


Figure 8 Velocity Vectors Over Periodic **Beach After 540 sec. of Wave** Action. Note the Presence of a Meandering Longshore Current Due to Oblique Wave Attack. Δx = Δy = 10m

Now: Coupled, multiphysics systems:

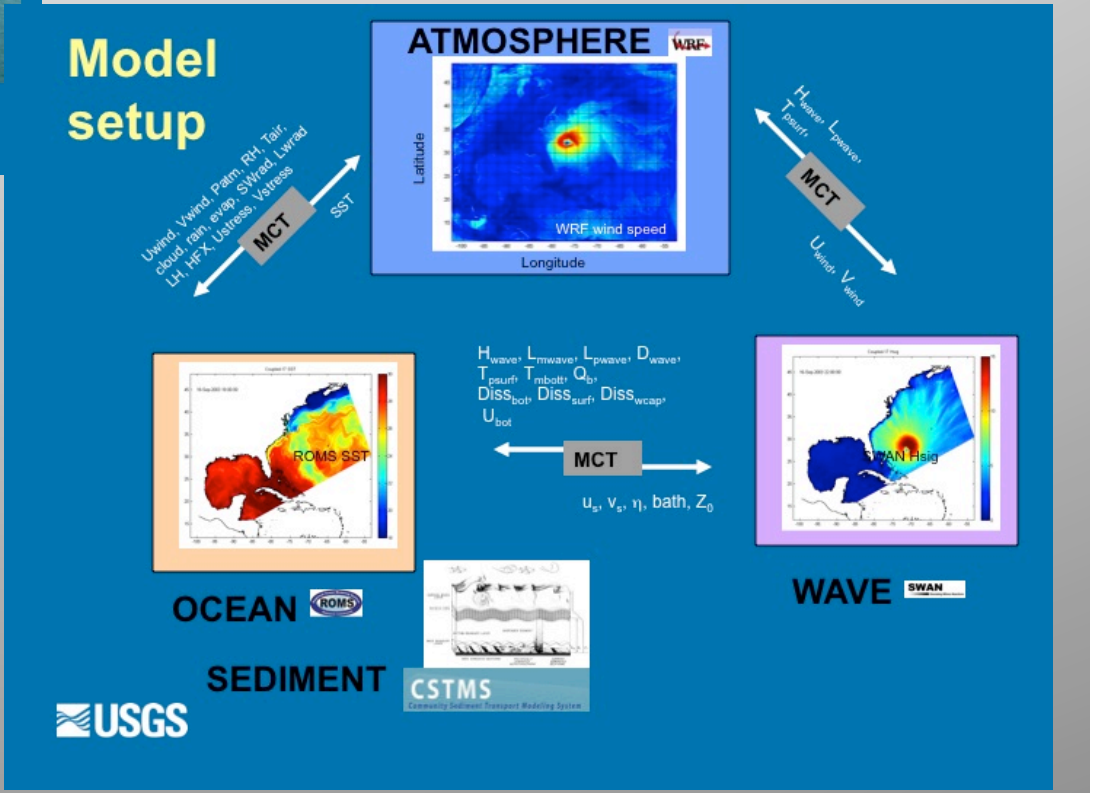


COAWST Modeling System

COAWST
Coupled Ocean – Atmosphere – Wave – Sediment Transport
Modeling System to investigate the impacts of storms on coastal environments.

C = Coupled	MCT v 2.6.0	http://www-unix.mcs.anl.gov/mct/
O = Ocean	ROMS svn 455	http://www.myroms.org/
A = Atmosphere	WRF v 3.4	http://www.wrf-model.org/
W = Wave	SWAN v 40.91	http://vlm089.citg.tudelft.nl/swan
ST = Sediment Transport	CSTMS	http://woodshole.er.usgs.gov/project-pages/sediment-transport/

Modeling System



Model setup

ATMOSPHERE (WRF)

Uwind, Vwind, Patm, RH, Tair, cloud, rain, evap, SWrad, Lwrad, LH, HFX, Ustress, Vstress ← MCT → SST

H_{wave}, L_{pwave}, T_{psurf} ← MCT → U_{wind}, V_{wind}

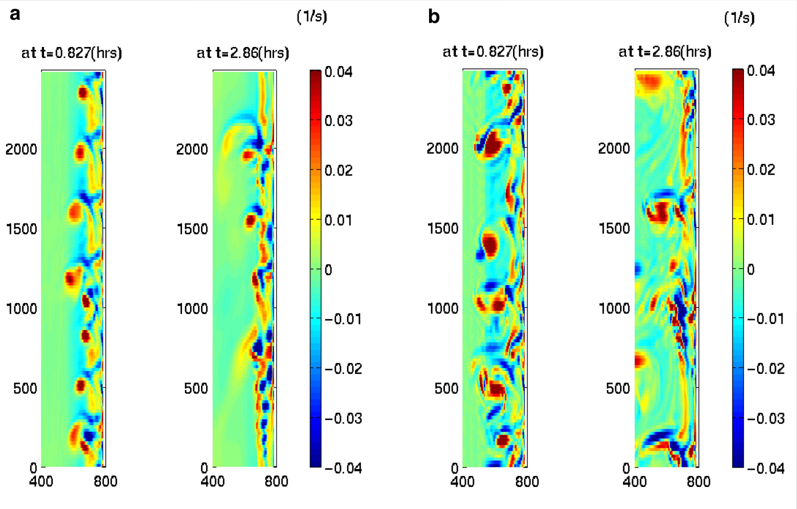
H_{wave}, L_{mwave}, L_{pwave}, D_{wave}, T_{psurf}, T_{mbott}, Q_b, $Diss_{bot}$, $Diss_{surf}$, $Diss_{wcap}$, U_{bot} ← MCT → u_s, v_s, η, bath, Z_0

OCEAN (ROMS)

SEDIMENT (CSTMS)

WAVE (SWAN)

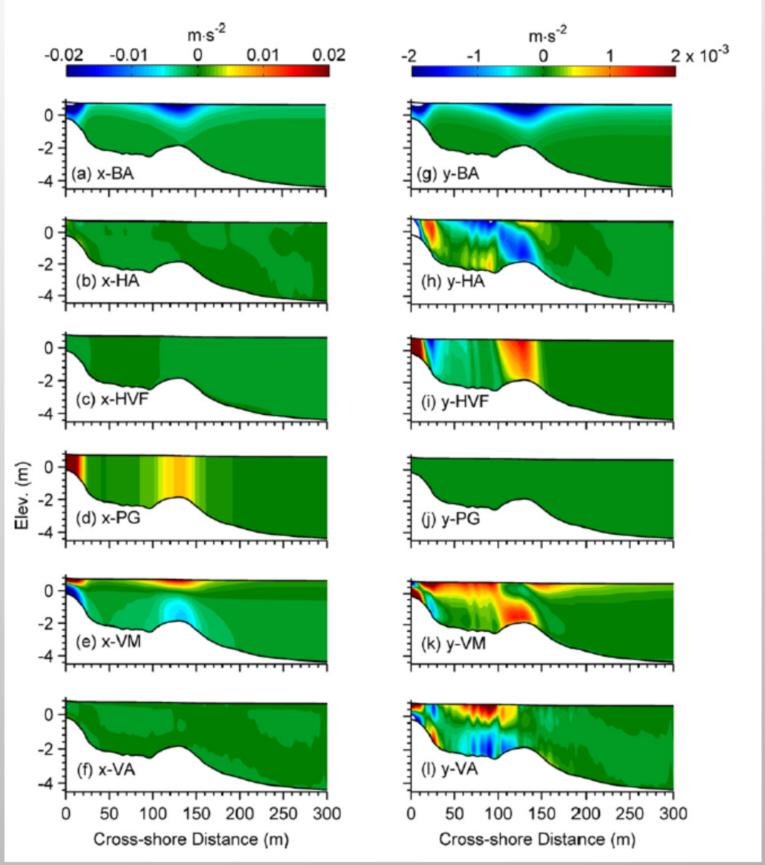
Three dimensional effects



Quasi-3D

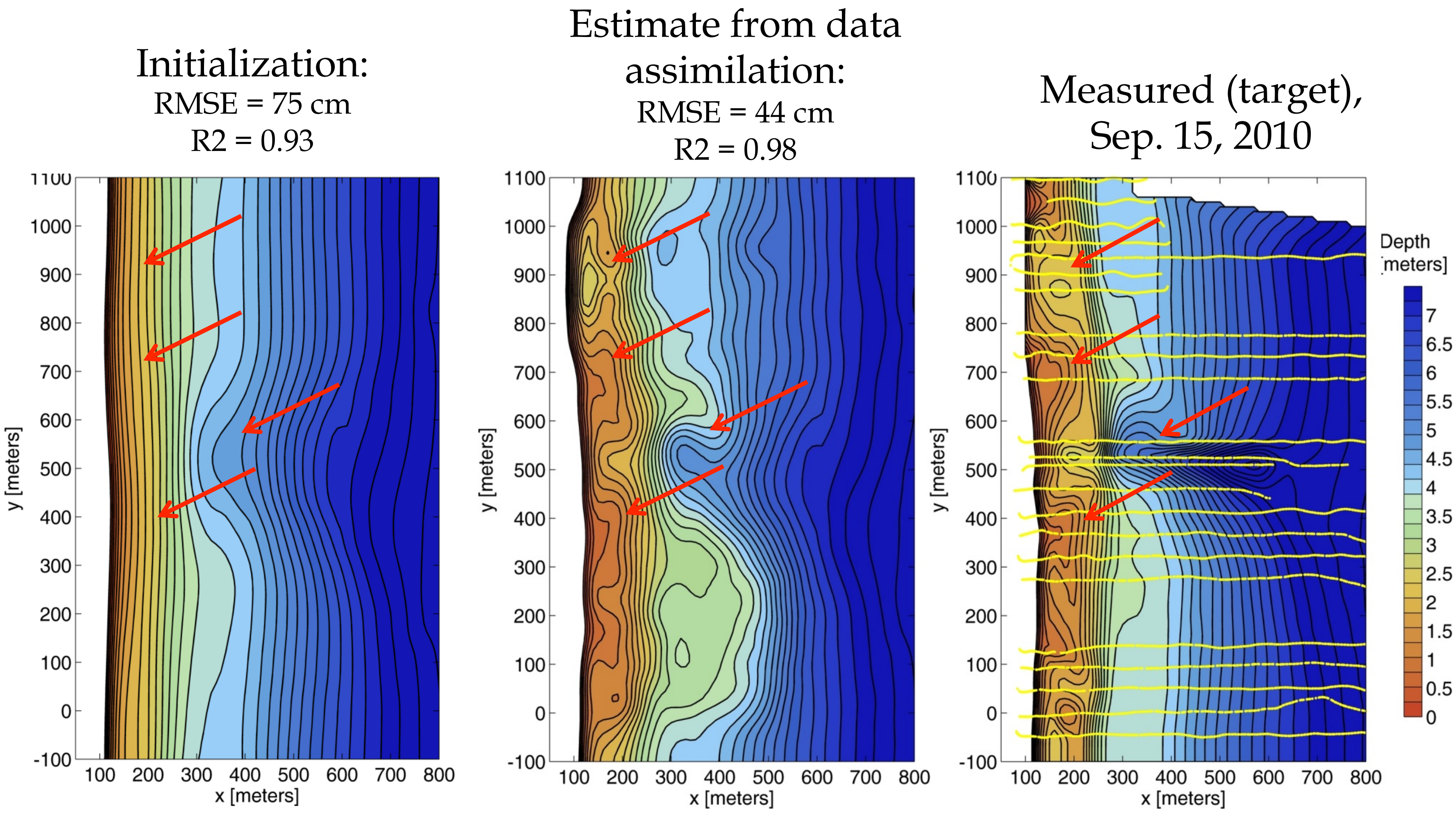
2D

Shorecirc – Zhao et al 2003)



3D (COAWST)

Bathymetric inversions using data assimilation: rivers, beaches, inlets



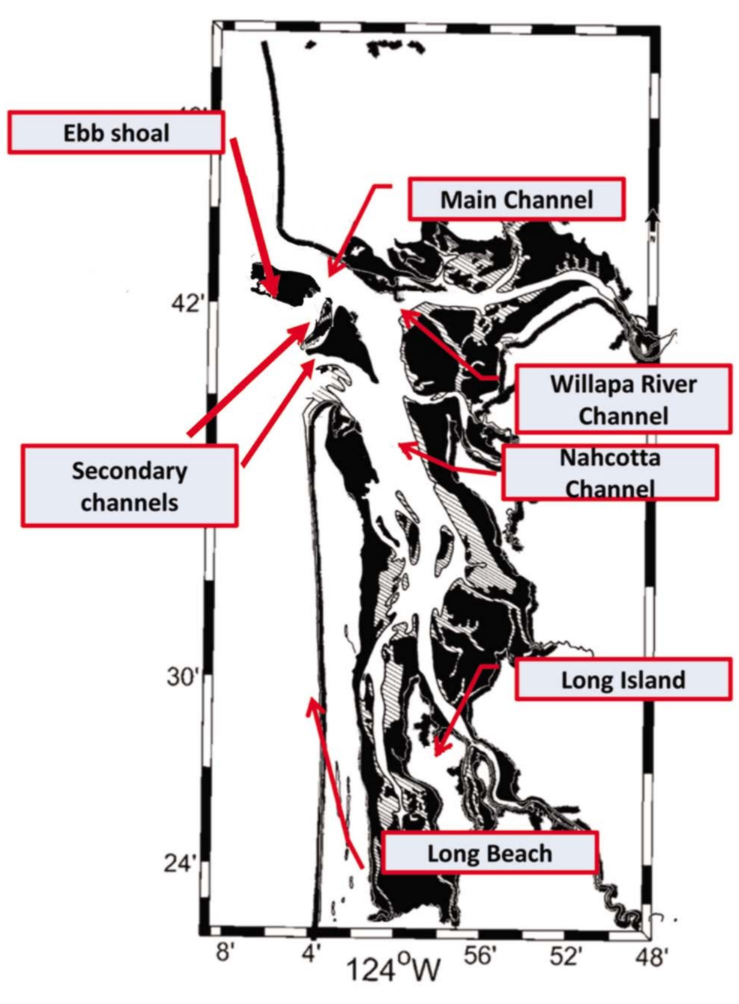
Initialization:
RMSE = 75 cm
R2 = 0.93

Estimate from data assimilation:
RMSE = 44 cm
R2 = 0.98

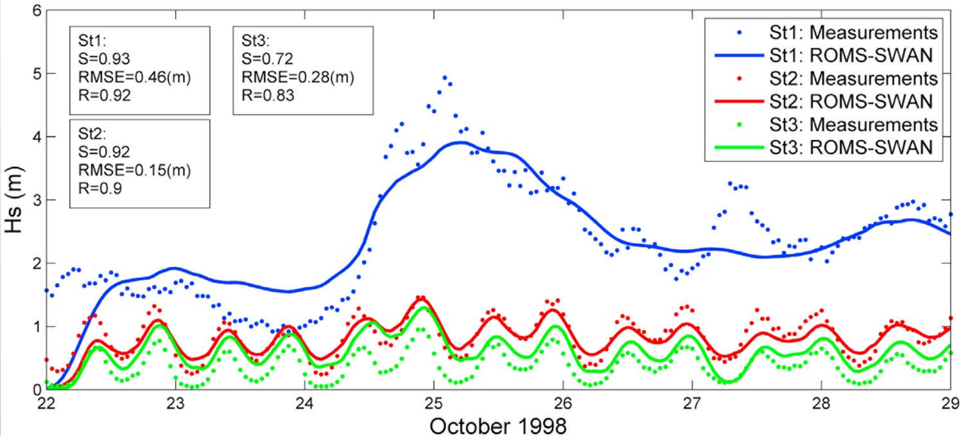
Measured (target), Sep. 15, 2010

→ Wilson et al.

Models adaptable to complex environments, generally reproduce measured results



Olabarrieta et al (2011), Wilapa Bay



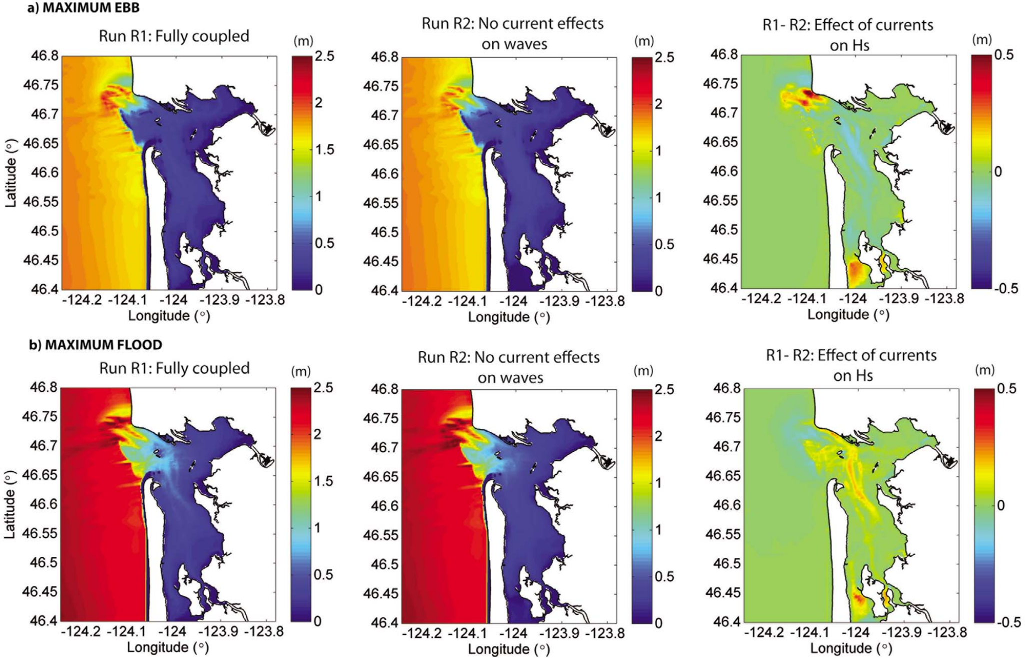
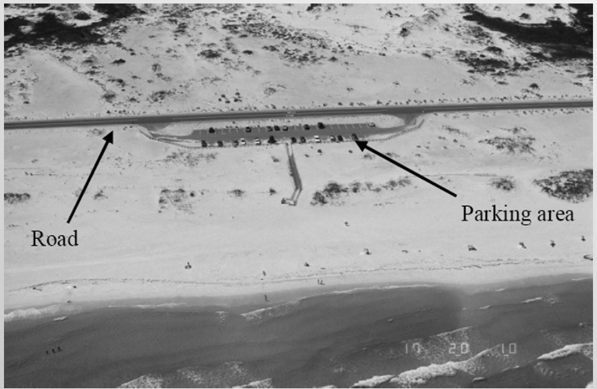
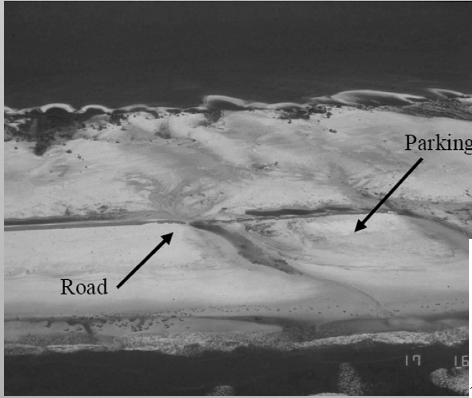
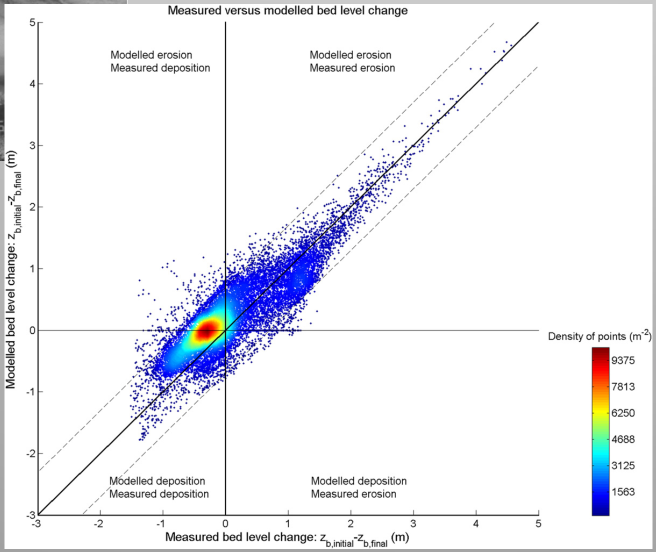


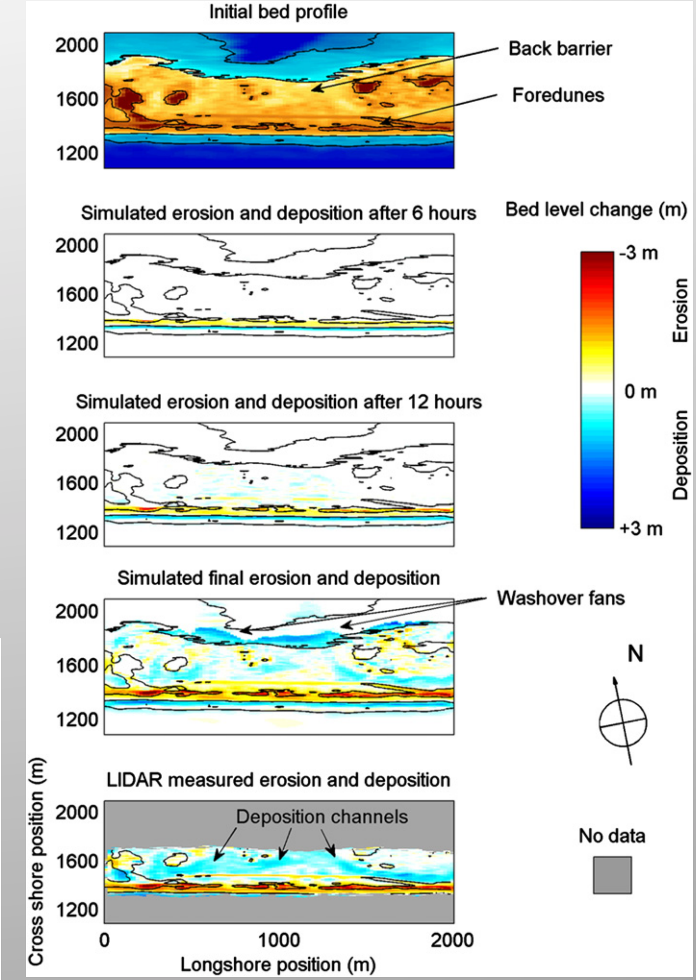
Figure 16. Significant wave heights on 24 October during maximum (a) ebb and (b) flood.

Improving capabilities in sediment transport and morphology applications









Limitations of wave-averaged formulations?
(in either the forcing or the dynamics of the wave-averaged flow field)

(1) Underprediction of complexity in wave driven flow fields

- Lack of complexity in structure of the wave-averaged forcing (groupiness, spatial structure.)
- Additional input from the instantaneous wave structure

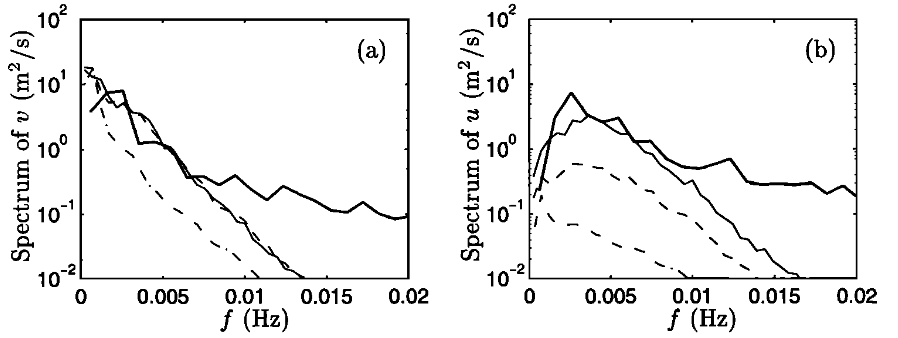
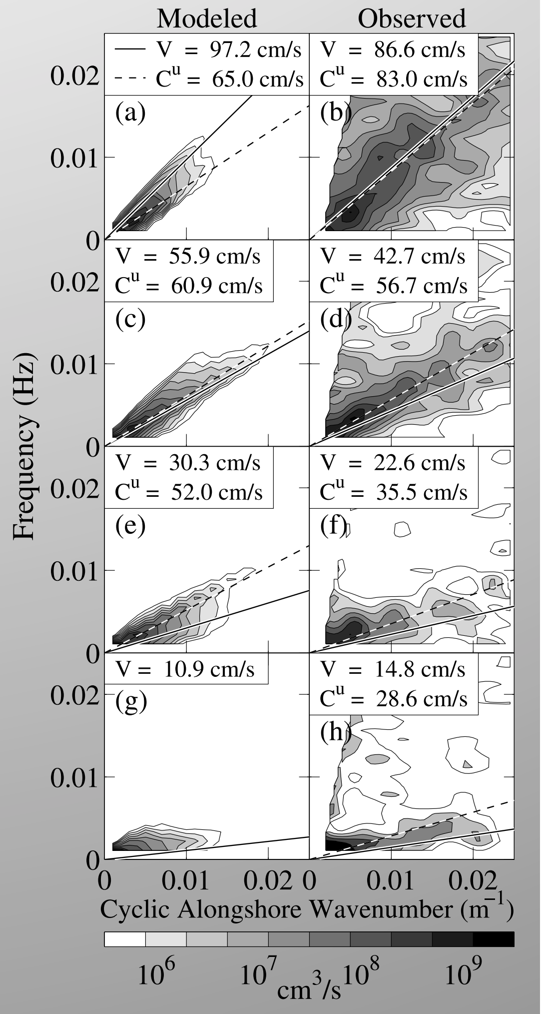


Figure 10. Frequency spectra of (a) longshore and (b) cross-shore velocities for data (thick solid lines) on October 18, $c_f = 0.003$ and $M = 0$ (thin solid lines), $M = 0.25$ (dashed lines), $M = 0.5$ (dash-dotted lines)

Rapid roll-off of spectral density in low frequency current motions:

Simulation of Superduck experiment (Ozkan-Haller and Kirby, 1999) …



… and Sandyduck (Noyes et al, 2005)

Where is the added complexity coming from?

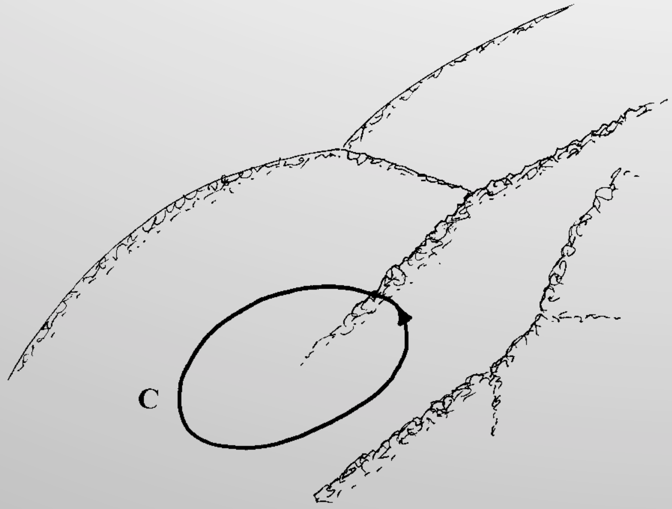


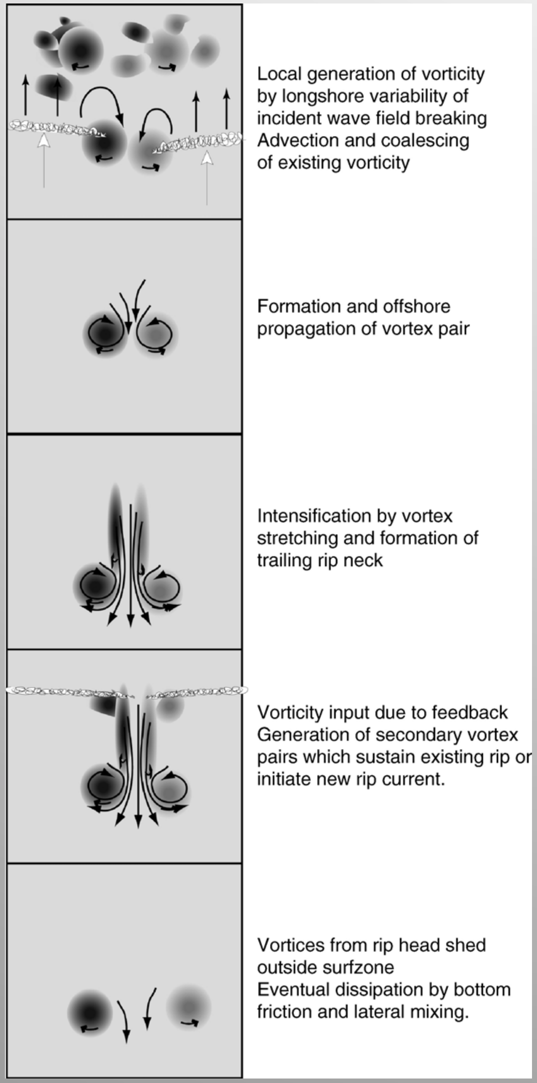
Figure 8. A sketch of a bore of finite length with a material circuit cutting it.

Peregrine (1998)

Clark et al, 2012

Figure 1. Photograph of breaking waves (propagating toward the shore from lower-right to upper-left) showing the triangular patches of residual white foam marking the location where breaking occurred. As the waves break, they transfer momentum to the water column and generate vorticity. The initially small breaking region on the lower right expands as the wave moves toward shore on the upper left. This pattern is typical in the surfzone, with the shape of the triangle varying with wave conditions.

Dependence on crest geometry for forcing automatically favors wave-resolving models



Local generation of vorticity by longshore variability of incident wave field breaking
Advection and coalescing of existing vorticity

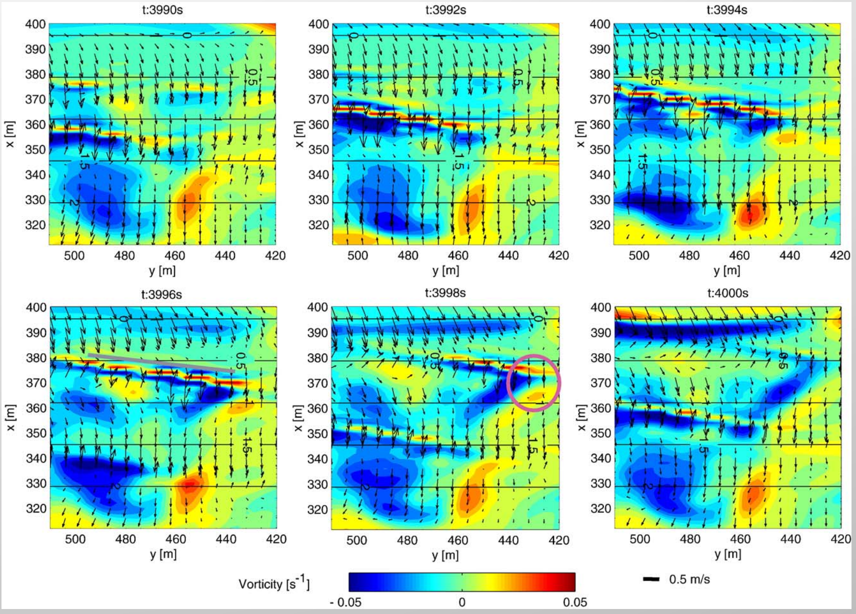
Formation and offshore propagation of vortex pair

Intensification by vortex stretching and formation of trailing rip neck

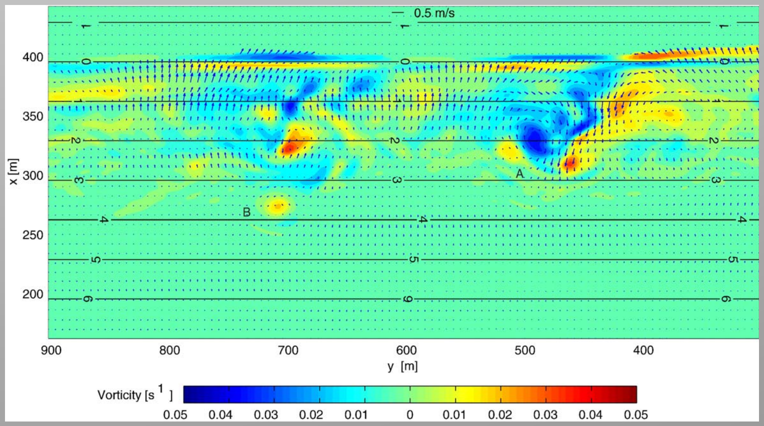
Vorticity input due to feedback
Generation of secondary vortex pairs which sustain existing rip or initiate new rip current.

Vortices from rip head shed outside surfzone
Eventual dissipation by bottom friction and lateral mixing.

Fig. 16. Conceptual model of transient rip generation.

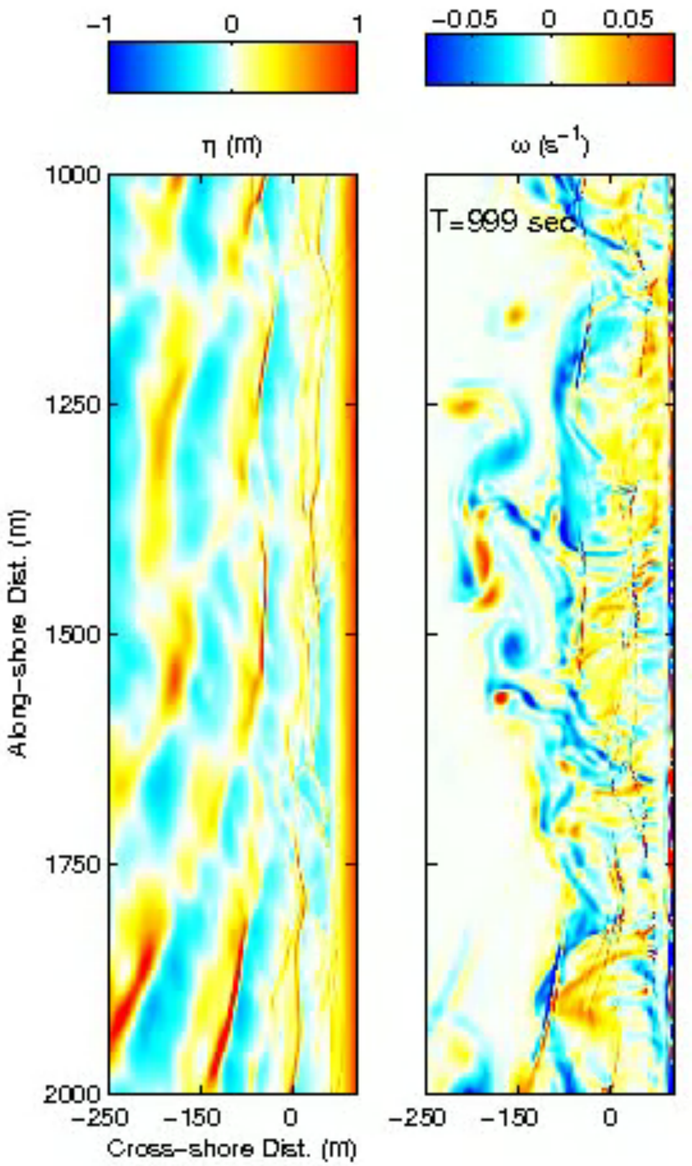


. 4. Series of snapshots of a instantaneous velocity and vorticity. The lines of adjacent positive and negative vorticity are caused by breaking wave crests, as icated by the line in frame t=3996 s. The circle in the frame for t=3998 s highlights shedding of negative vorticity from the end of the wave crest.

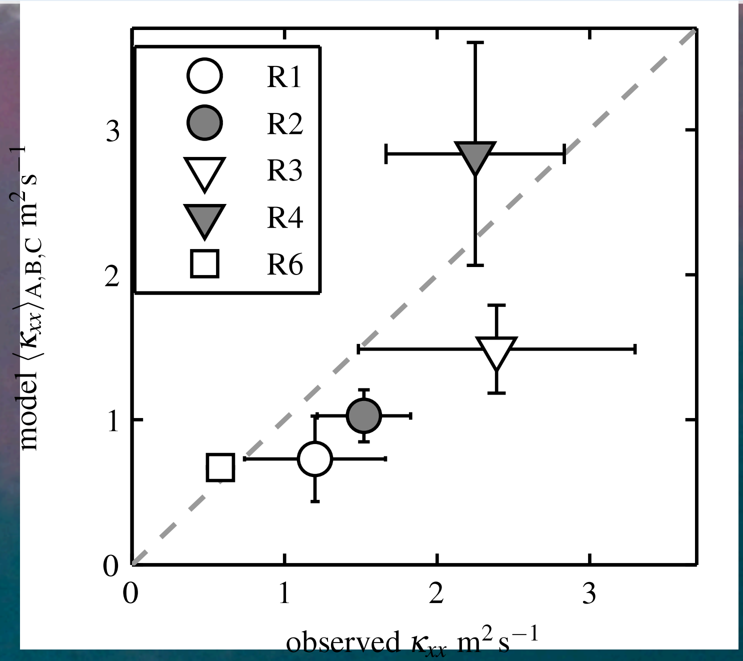


. 5. Wave and depth-averaged current for run 5 at t=4160 s for the centre of the longshore extent of the domain. A rip current (A.) and discrete vortices (B.) can be n, clearly associated with regions of strong vorticity.

Wave-resolving Boussinesq models for surfzone eddies

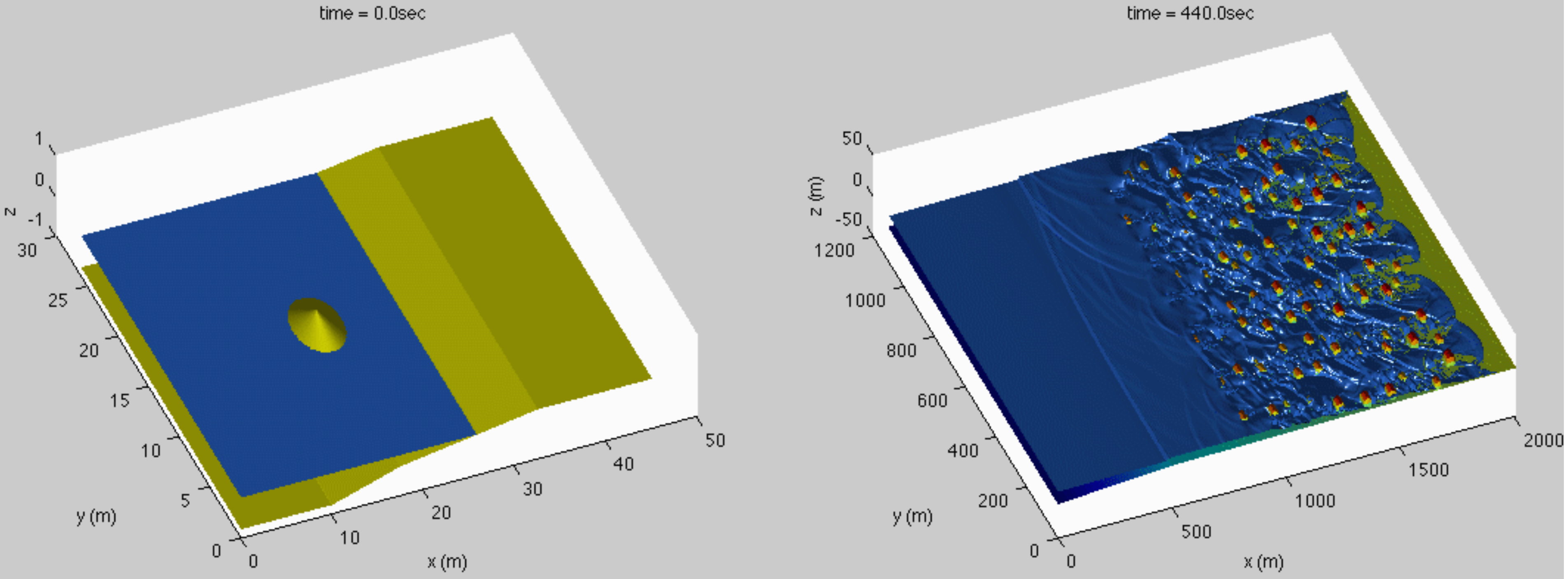


Model reproduces observed surfzone tracer diffusivity



Resolution of swash mechanics at individual wave scales

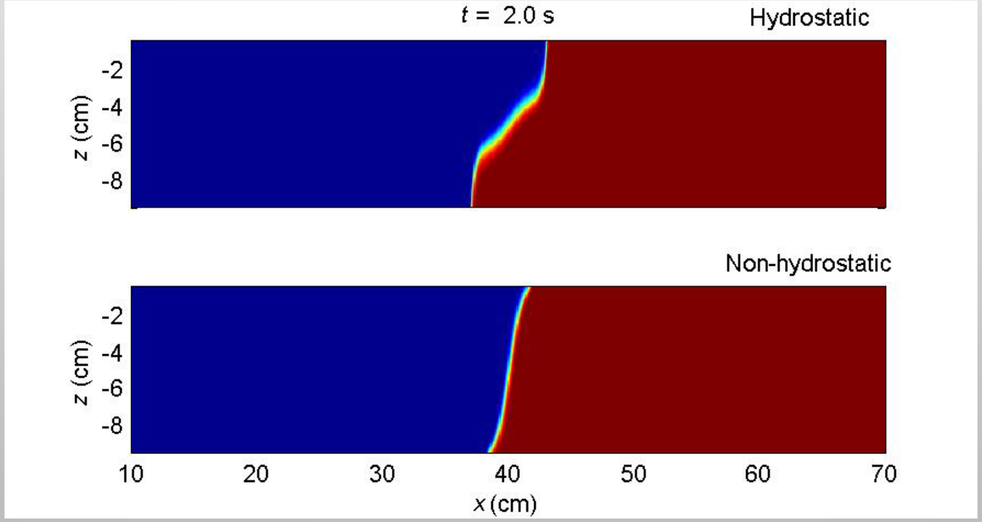
Tsunami = mega-swash?

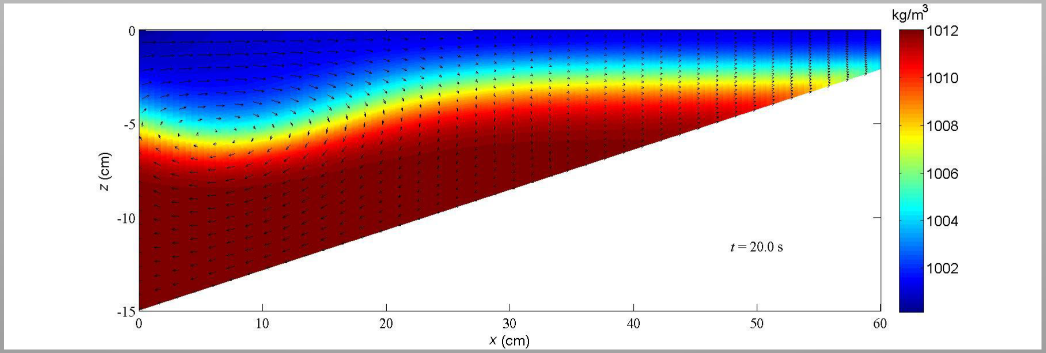


Limitations of wave-averaged formulations?

(in either the forcing or the dynamics of the wave-averaged flow field)

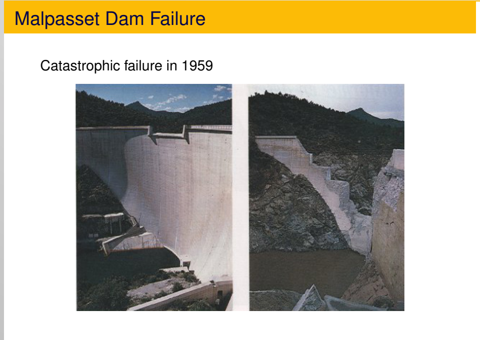
(2) Limitations of hydrostatic approximations





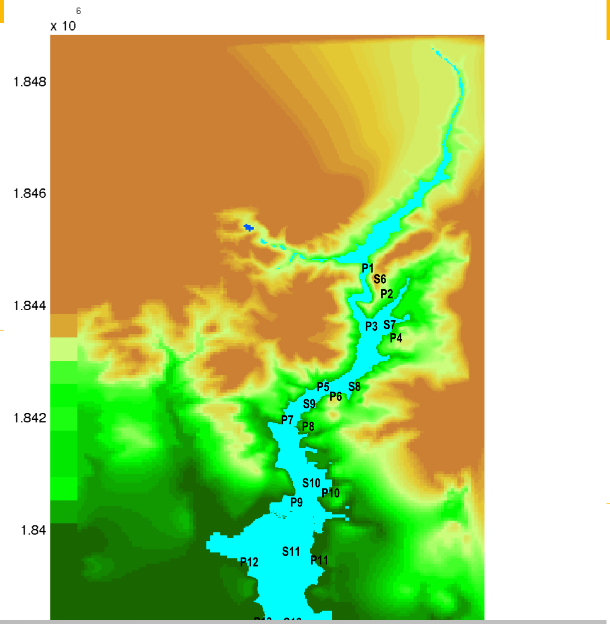
Modeling Issues? Resolution in space.

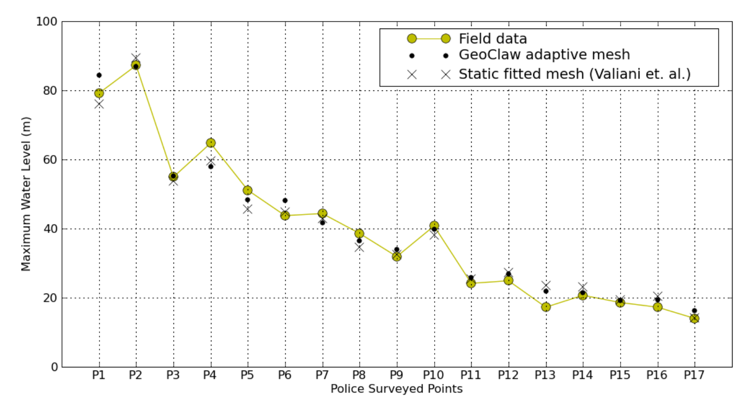
(1) Adjust model resolution to emphasize areas with rapid variations (Automatic Mesh Refinement – AMR)

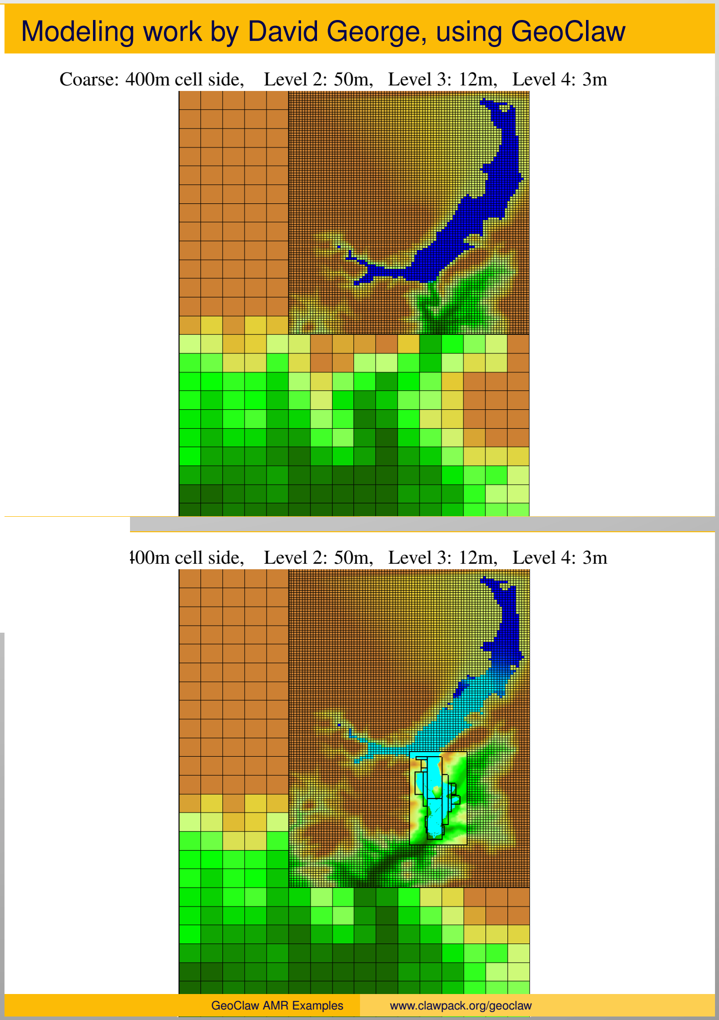


Malpasset Dam Failure

Catastrophic failure in 1959







Modeling work by David George, using GeoClaw

Coarse: 400m cell side, Level 2: 50m, Level 3: 12m, Level 4: 3m

400m cell side, Level 2: 50m, Level 3: 12m, Level 4: 3m

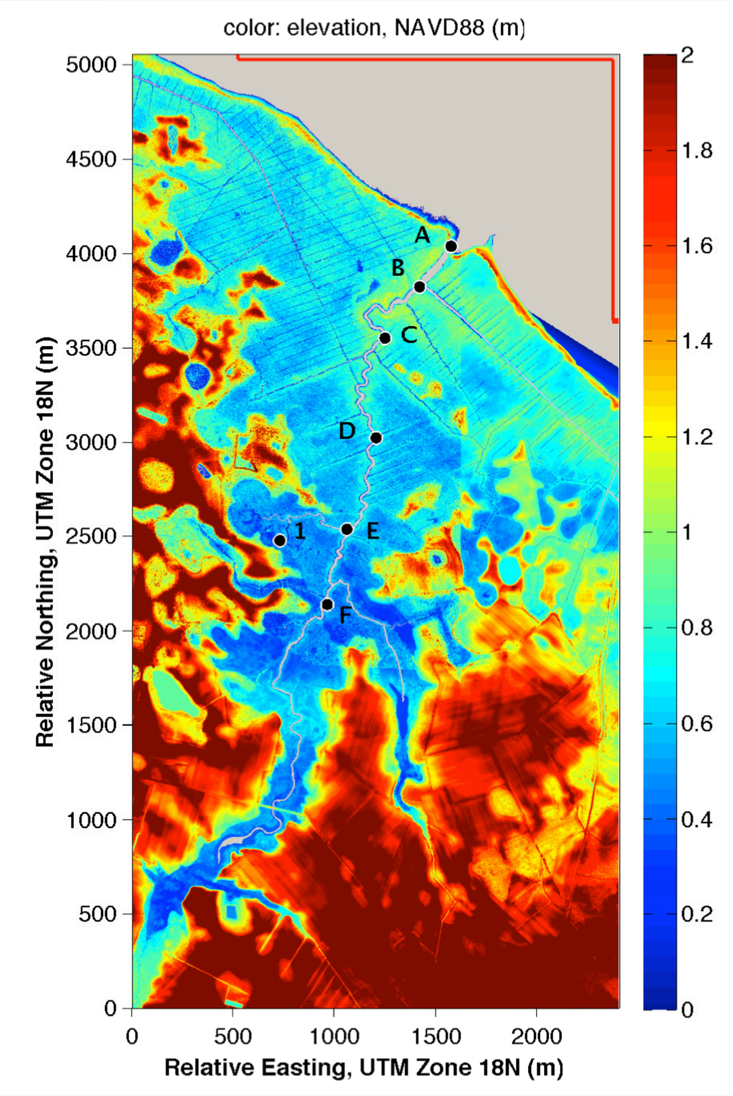
GeoClaw AMR Examples

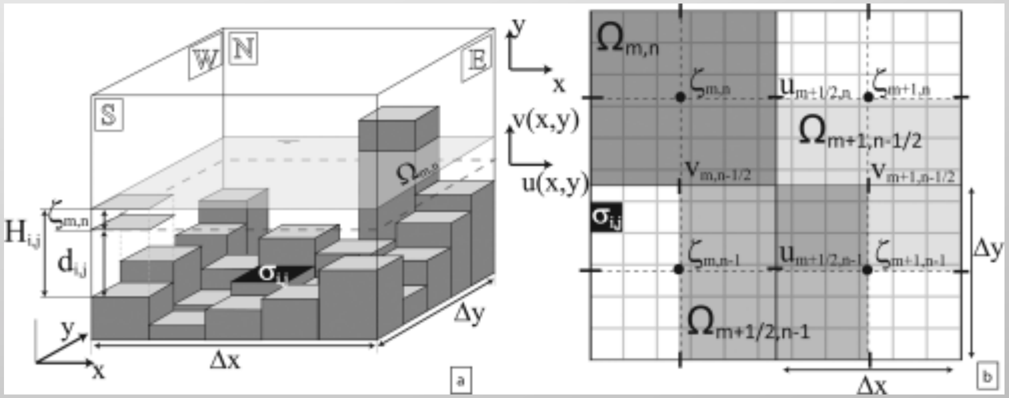
www.clawpack.org/geoclaw

Thanks to Randy LeVeque, UW

Modeling Issues? Resolution in space.

(2) Resolve subgrid features at high resolution, somewhat reduced physics.





Subgrid modeling

Modeling Issues? Resolution in time

Morphology acceleration and strategies for achieving it

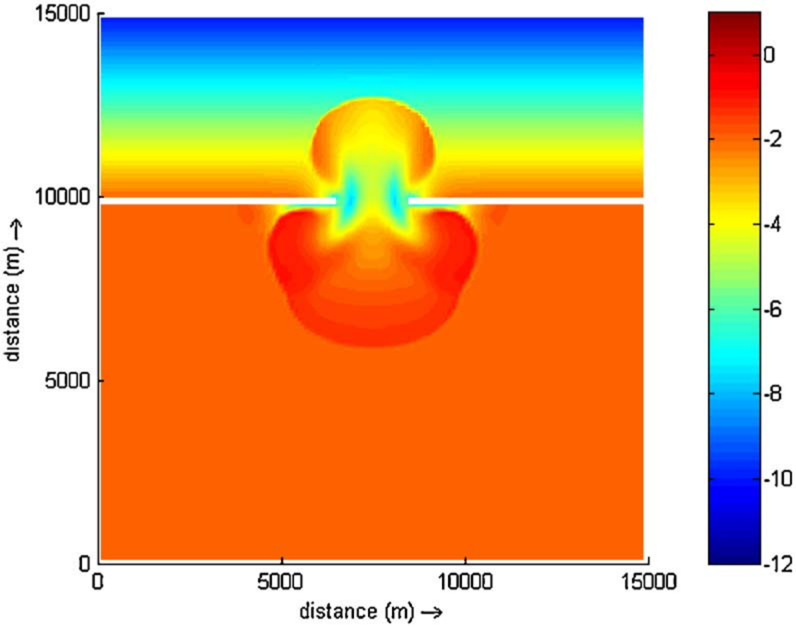


Fig. 7. Bathymetry after 55 tides, using online approach, morphological factor $n = 1$.

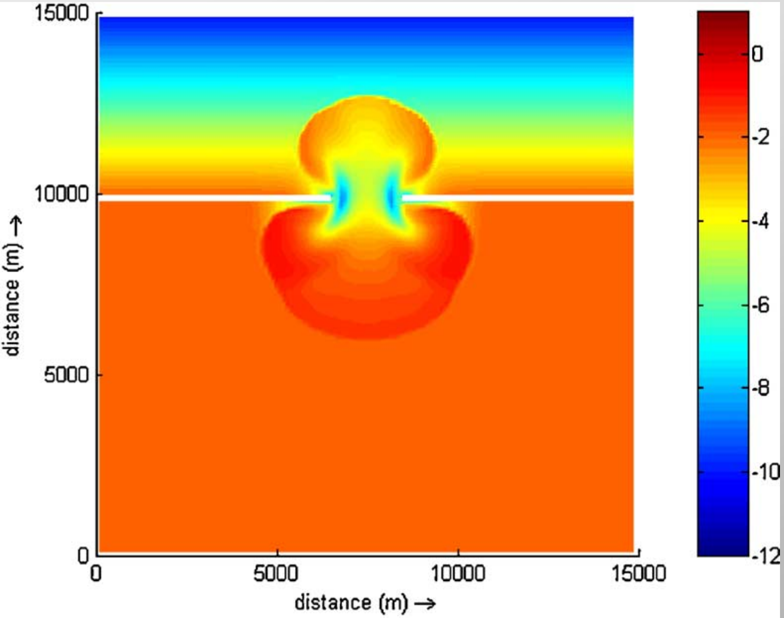
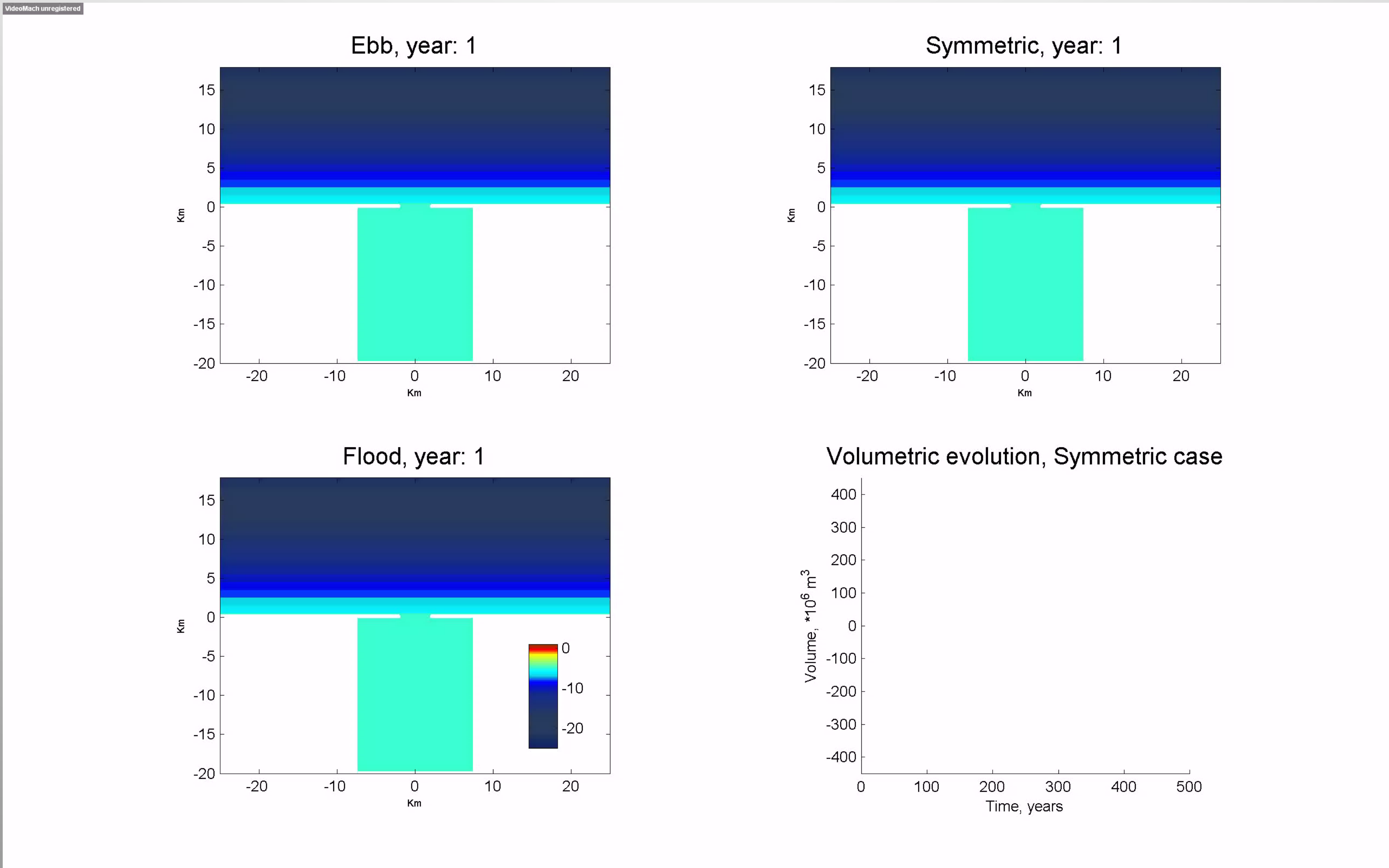


Fig. 8. Bathymetry after 55 tides, using online approach, morphological factor $n = 11$.

Example: Morphology of a tidal basin in response to external overtide dominance



Modeling Issues? Resolution of physics and other model elements

Problem: Explosion of complexity in extensions to Boussinesq models to cover a wider range of depths, physics

Example: O(kh^4) model of Gobbi and Kirby (1999)

$$\eta_t + \nabla \cdot \mathbf{M} = 0, \quad \mathbf{M} = \int_{-h}^{\delta\eta} \nabla\phi \, \mathrm{d}z.$$

$$\begin{aligned}
\mathbf{M} = H\nabla\tilde{\phi} + \mu^2 H\Bigg\{ & \left[(A-1) F_1(\tilde{\phi}) + 2\left(Bh - \frac{H}{2} \right) F_2(\tilde{\phi}) \right] \nabla h \\
& + \left(Ah - \frac{H}{2} \right) \nabla F_1(\tilde{\phi}) + \left(Bh^2 - \frac{H^2}{3} \right) \nabla F_2(\tilde{\phi}) \Bigg\} \\
& + \mu^4 H \Bigg\{ \Bigg[(A-1) F_3(\tilde{\phi}) + 2\left(Bh - \frac{H}{2} \right) F_4(\tilde{\phi}) + 3\left(Ch^2 - \frac{H^2}{3} \right) F_5(\tilde{\phi}) \\
& + 4\left(Dh^3 - \frac{H^3}{4} \right) F_6(\tilde{\phi}) \Bigg] \nabla h + \left(Ah - \frac{H}{2} \right) \nabla F_3(\tilde{\phi}) \\
& + \left(Bh^2 - \frac{H^2}{3} \right) \nabla F_4(\tilde{\phi}) + \left(Ch^3 - \frac{H^3}{4} \right) \nabla F_5(\tilde{\phi}) + \left(Dh^4 - \frac{H^4}{5} \right) \nabla F_6(\tilde{\phi}) \Bigg\}
\end{aligned}$$

$$\mathbf{U}_t = -\nabla\eta - \frac{\delta}{2} \nabla(|\tilde{\mathbf{u}}|^2) + \Gamma_1(\eta, \tilde{\mathbf{u}}_t) + \Gamma_2(\eta, \tilde{\mathbf{u}}),$$

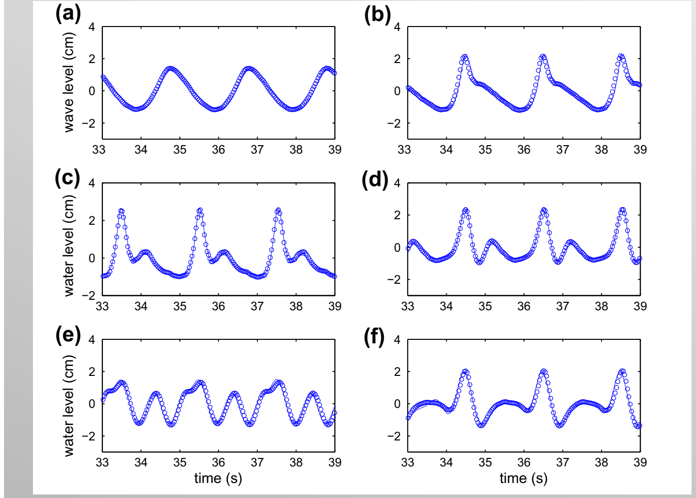
$$\begin{aligned}
\mathbf{U} \equiv \tilde{\mathbf{u}} & + \mu^2 \left[(A-1) h (2\nabla h F_{22} + \nabla F_{21}) + (B-1) h^2 \nabla F_{22} \right] \\
& + \mu^4 \big[(A-1) h (2\nabla h F_{42} + \nabla F_{41} + 2\nabla h F_{44} + \nabla F_{43}) \\
& + (B-1) h^2 (\nabla F_{42} + 3\nabla h F_{45} + \nabla F_{44}) + (C-1) h^3 (4\nabla h F_{46} + \nabla F_{45}) \\
& + (D-1) h^4 \nabla F_{46} \big],
\end{aligned} \tag{43}$$

$$\begin{aligned}
\Gamma_1 \equiv \mu^2 \nabla & \left[\delta\eta F_{21t} + (2h\delta\eta + \delta^2\eta^2) F_{22t} \right] + \mu^4 \nabla \big[\delta\eta (F_{41t} + F_{43t}) \\
& + (2h\delta\eta + \delta^2\eta^2)(F_{42t} + F_{44t}) + (3h^2\delta\eta + 3h\delta^2\eta^2 + \delta^3\eta^3) F_{45t} \\
& + (4h^3\delta\eta + 6h^2\delta^2\eta^2 + 4h\delta^3\eta^3 + \delta^4\eta^4) F_{45t} \big],
\end{aligned} \tag{44}$$

$$\begin{aligned}
\Gamma_2 \equiv -\mu^2 \delta\nabla \Big\{ & \tilde{\mathbf{u}} \cdot \left[(Ah - H)(\nabla F_{21} + 2\nabla h F_{22}) + (Bh^2 - H^2) \nabla F_{22} \right] \\
& + \frac{1}{2} (F_{21} + 2HF_{22})^2 \Big\} - \mu^4 \delta\nabla \Big\{ \tilde{\mathbf{u}} \cdot \big[(Ah - H)(\nabla F_{41} + 2\nabla h F_{42} + \nabla F_{43} \\
& + 2\nabla h F_{44}) + (Bh^2 - H^2)(\nabla F_{42} + \nabla F_{44} + 3\nabla h F_{45}) \\
& + (Ch^3 - H^3)(\nabla F_{45} + 4\nabla h F_{46}) + (Dh^4 - H^4) \nabla F_{46} \big] \\
& + \frac{1}{2} \left| (Ah - H)(\nabla F_{21} + 2\nabla h F_{22}) + (Bh^2 - H^2) \nabla F_{42} \right|^2 \\
& + \frac{1}{2} \left[(F_{21} + 2HF_{22})(F_{41} + 2HF_{42} + F_{43} + 2HF_{44} + 3H^2 F_{45} + 4H^3 F_{46}) \right] \Big\}.
\end{aligned}$$

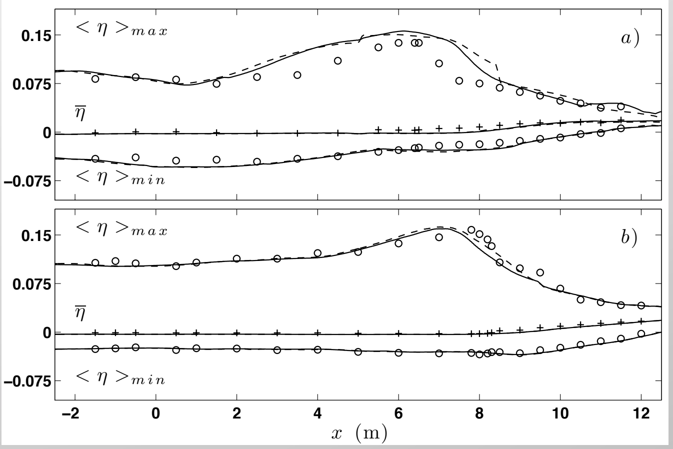
These extensions can be carried out to as high an order as desired, but, clearly, programming and basic understanding of the model can become an issue.

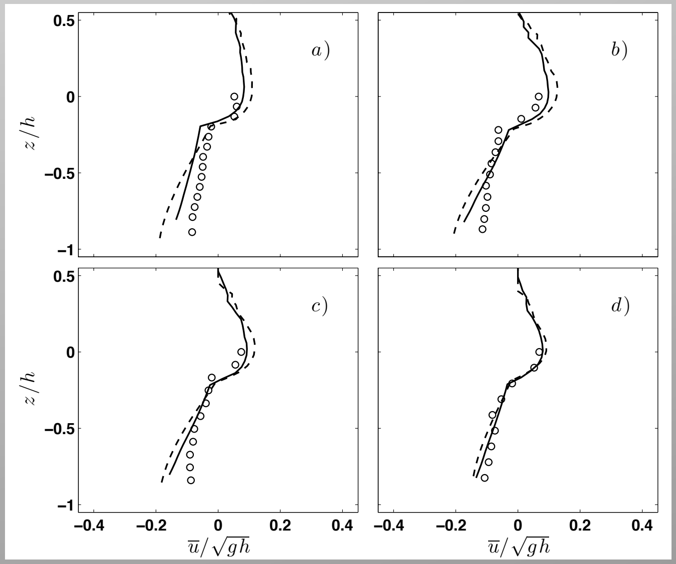
Alternate: 3D Nonhydrostatic models (SWASH, NHWAVE)

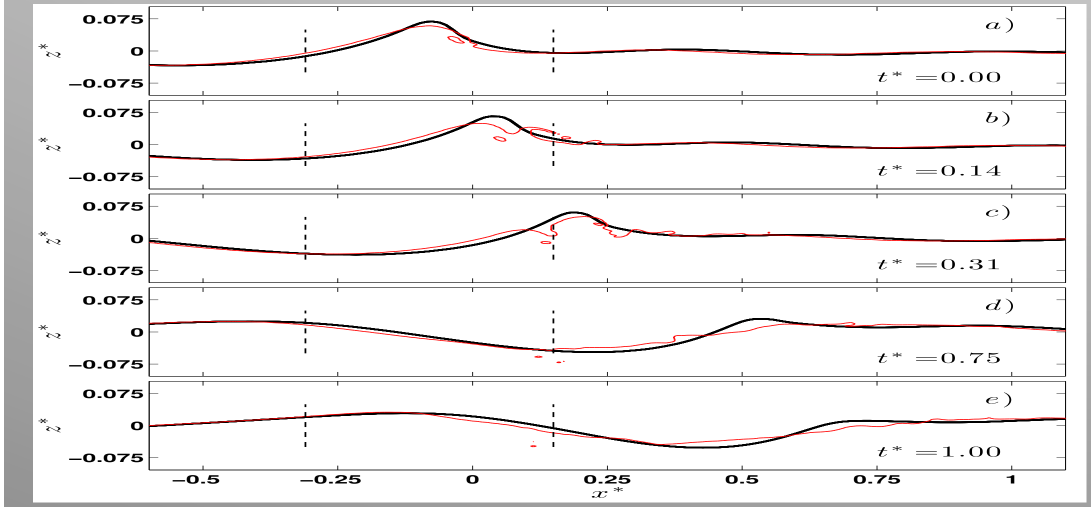


Excellent wave dispersion properties

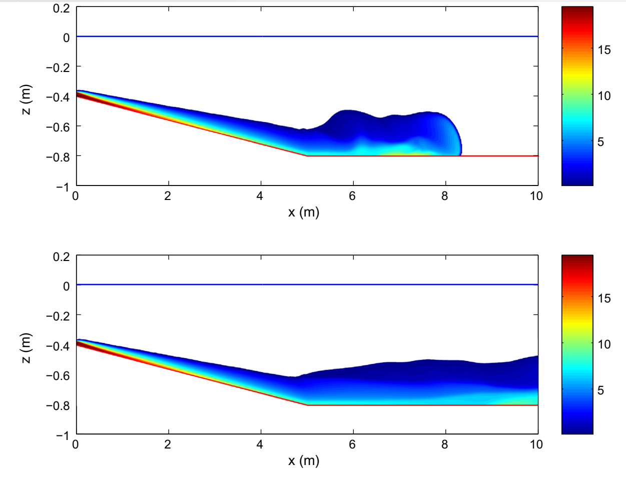
Good reproduction of surf zone and deep water breaking and mean flows



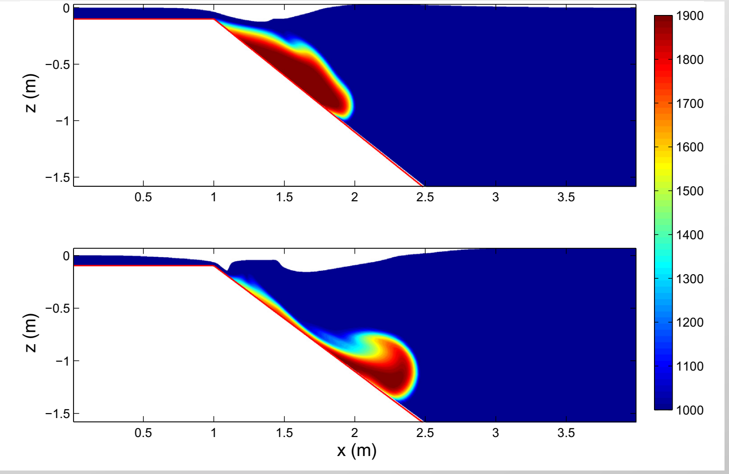




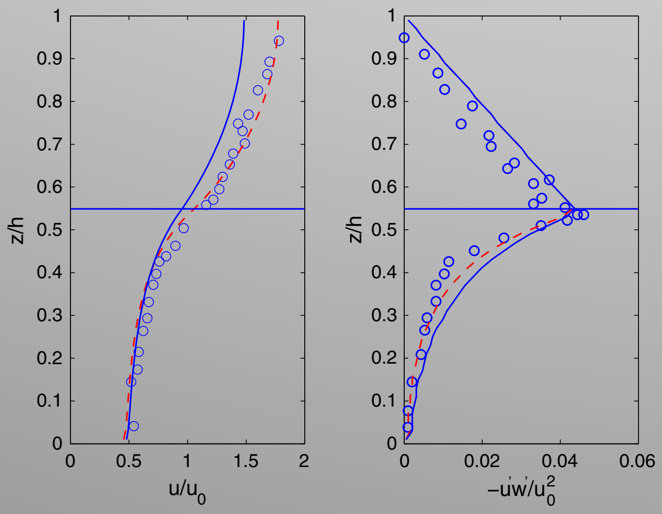
Model extensions to additional physical applications



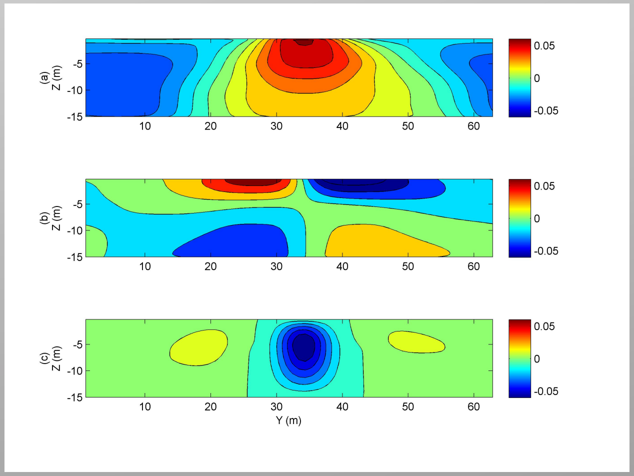
Gravity current



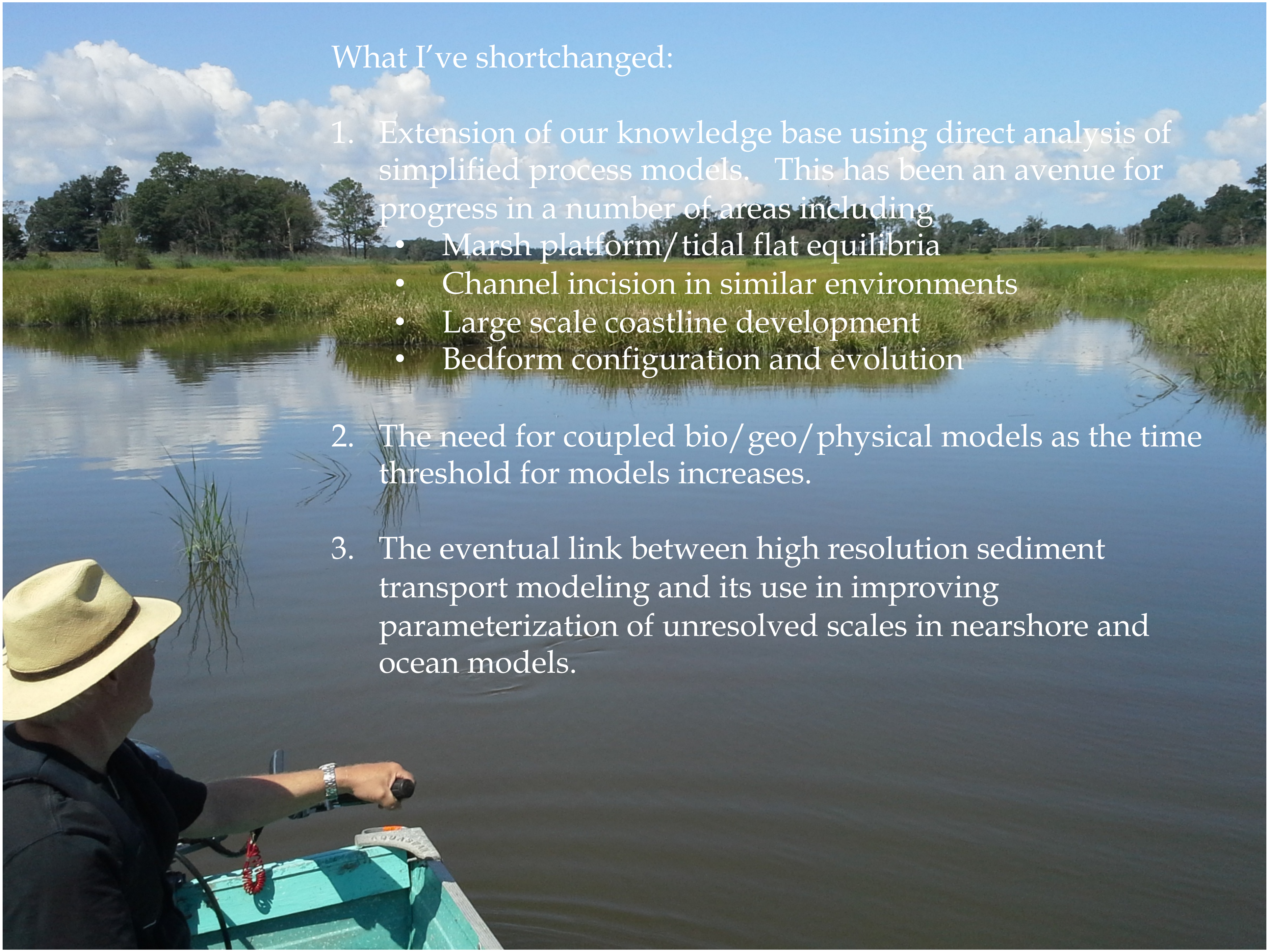
Tsunami generation by deforming slide



Waves in vegetation canopies



Langmuir cells in finite depth



What I’ve shortchanged:

1. Extension of our knowledge base using direct analysis of simplified process models. This has been an avenue for progress in a number of areas including
    - Marsh platform/tidal flat equilibria
    - Channel incision in similar environments
    - Large scale coastline development
    - Bedform configuration and evolution
2. The need for coupled bio/geo/physical models as the time threshold for models increases.
3. The eventual link between high resolution sediment transport modeling and its use in improving parameterization of unresolved scales in nearshore and ocean models.