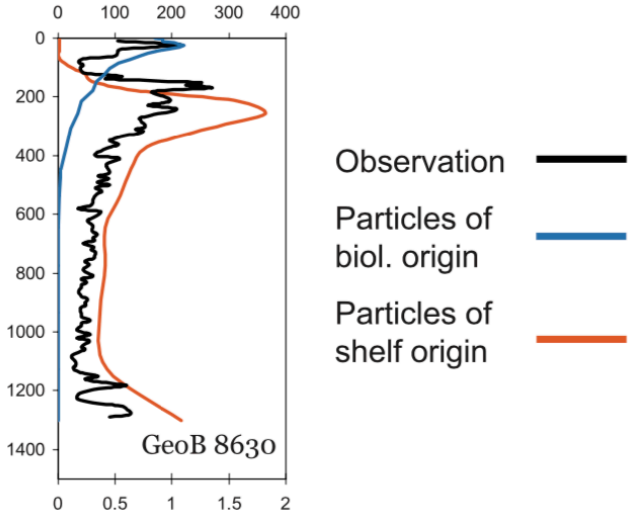
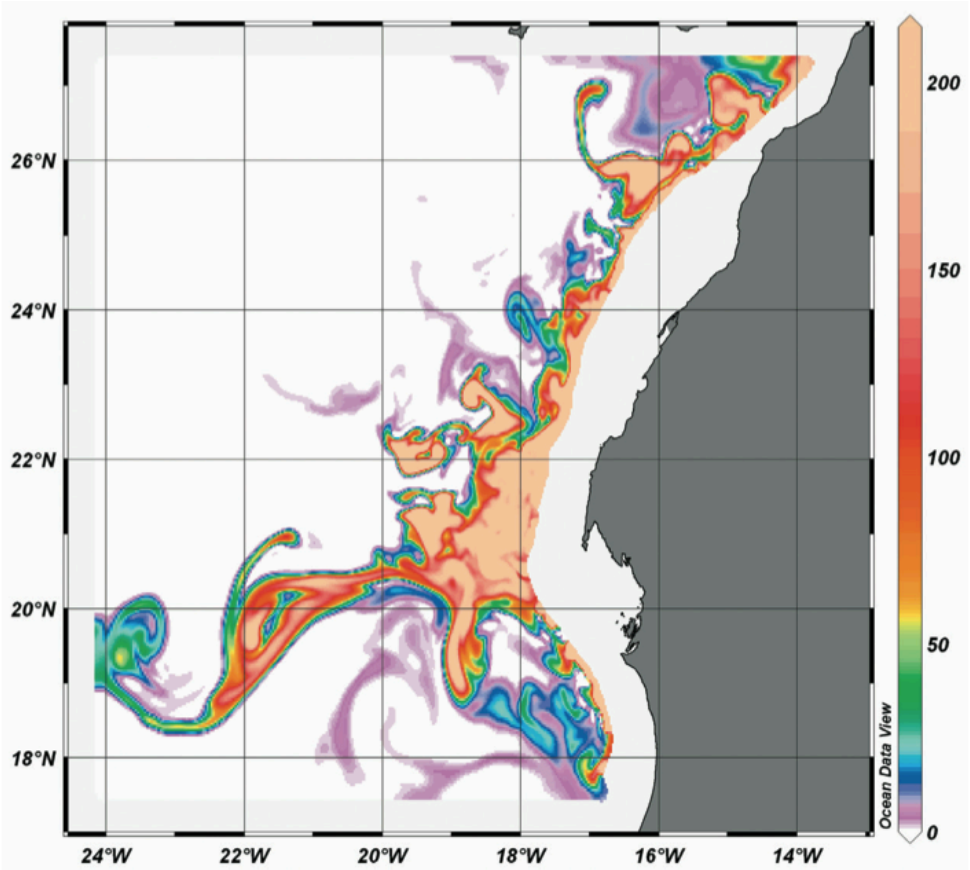
CROCO Sediment dynamics: From regional to nearshore problems

R. Benshila, P. Marchesiello, F. Dumas …

From shelf-ocean exchanges …

CROCO sediment transport off West Africa (Karakas et al., 2006)





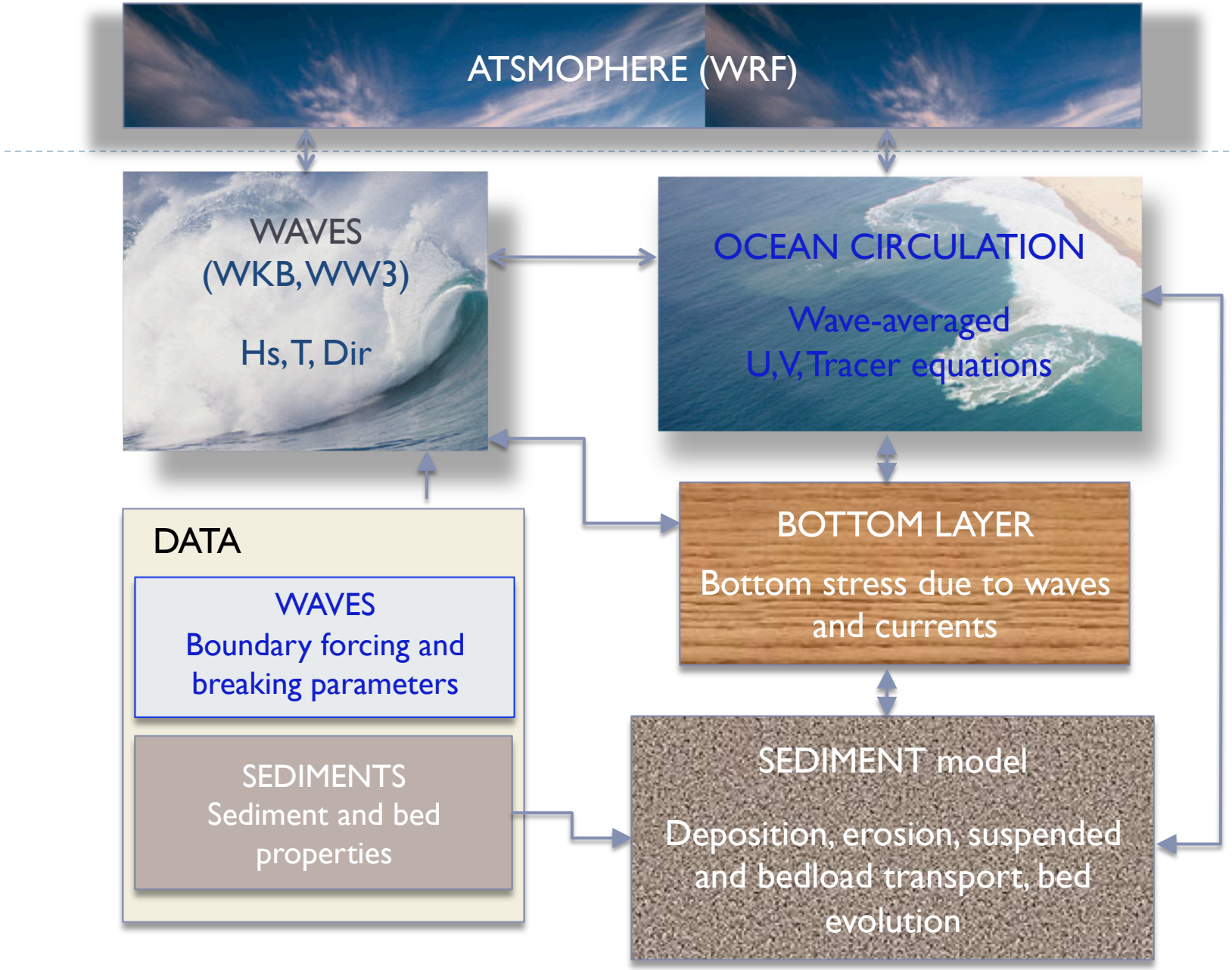
Sediment concentration (rel. units) at 500m

… to surf-shelf exchanges

… to surf-shelf exchanges

Imperial Beach, 29 September 2009:
« *rip current ejection events are the dominant cross-shore surf-shelf exchange mechanism* »
Hally-Rosendahl et al., JGR 2014

- How important?
- Processes: flow instability or flash rip?
- 2D, 3D, NH dynamics?
- Stratification? Rotation?
- Sediment processes?


ATSMOPHERE (WRF)
WAVES
(WKB, WW3)
Hs, T, Dir
OCEAN CIRCULATION
Wave-averaged
U, V, Tracer equations
DATA
WAVES
Boundary forcing and
breaking parameters
SEDIMENTS
Sediment and bed
properties
BOTTOM LAYER
Bottom stress due to waves
and currents
SEDIMENT model
Deposition, erosion, suspended
and bedload transport, bed
evolution

Wave-averaged CROCO

Uchiyama, McWilliams and Shchepetkin, 2010

Bernoulli Head

Non-conservative forces
- acceleration due to breakers
- bottom friction and streaming
- vertical mixing

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla_\perp)\mathbf{u} + w\frac{\partial \mathbf{u}}{\partial z} + f\hat{\mathbf{z}}\times\mathbf{u} + \nabla_\perp\phi - \mathbf{F} = -\nabla_\perp\mathscr{K} + \mathbf{J} + \mathbf{F}^w,$$

$$\frac{\partial \phi}{\partial z} + \frac{g\rho}{\rho_0} = -\frac{\partial \mathscr{K}}{\partial z} + K,$$

$$\nabla_\perp\cdot\mathbf{u} + \frac{\partial w}{\partial z} = 0,$$

Vortex force (including Stokes-Coriolis)

$$\frac{\partial c}{\partial t} + (\mathbf{u}\cdot\nabla_\perp)c + w\frac{\partial c}{\partial z} - \mathscr{C} = -(\mathbf{u}^{\mathrm{St}}\cdot\nabla_\perp)c - w^{\mathrm{St}}\frac{\partial c}{\partial z} + \frac{1}{2}\frac{\partial}{\partial z}\left[\mathscr{E}\frac{\partial c}{\partial z}\right].$$

Stokes advection

Wave-induced tracer mixing

$$\hat{\zeta} = -\frac{p_{atm}}{g\rho_0} - \frac{A^2 k}{2\sinh[2\mathscr{H}]}$$

Quasi-static sea-level

USGS Sediment model

Blaas et al. (2007); Warner et al. (2008)

- ✓ Wave input (specified, WKB, or WW3)
- ✓ Wave-current combined bottom stress (Soulsby, 1995)
- ✓ Erosion (armoring), deposition, suspended transport
- ✓ Bedload transport and flux divergence
- ✓ Bed model (sand, mud, or mixed)
- ✓ Morphological evolution (with acceleration factor)
- ✓ Wetting and drying
- ✓ Positive-definite advection schemes (WENO, TVD)
- ✓ Sediment influence on density

Suspended transport

Blaas et al. (2007)

- Suspended sediment transported as a tracer with additional source/sink terms.
- multiple sediment classes
- For each class: grain size, density, settling velocity, erosion rate, bed porosity, and critical shear stress for erosion

Suspended sediment transport

$$\frac{\partial C}{\partial t} + \frac{\partial U_i C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(K_H \frac{\partial C}{\partial x_{1,2}} + K_V \frac{\partial C}{\partial x_3}\right) + Sources / Sinks$$

Erosion formulation

$$Source = E_0 (1-\varphi) \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \qquad \text{when } \tau_b > \tau_{ce}$$

Deposition formulation

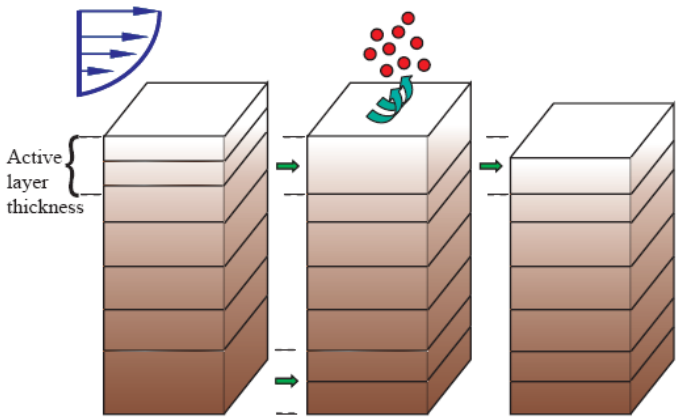
$$Sink = w_s \frac{\partial C}{\partial z}$$

Bed model

Warner et al. (2008)

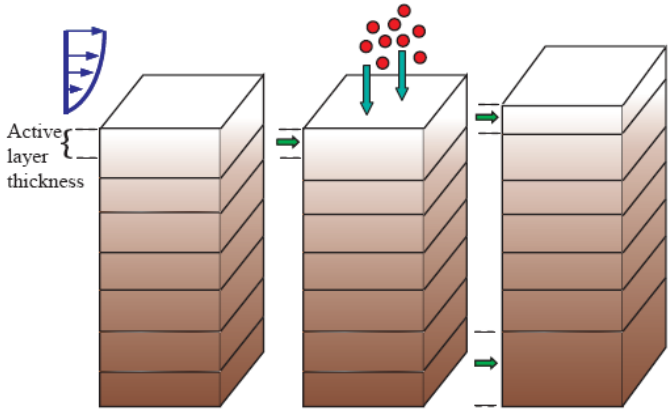
→ role of the active layer

Active layer thickness (Harris and Wiberg, 1997).
$Z_a = k_1(\tau_w - \tau_c) + k_2 D_{50}$



Erosion. ($\tau_b > \tau_c$)
Mix sediment from lower layers so that surface layer is at least z_a thick. Split bottom layer. Erode from surface layer.

$$\text{erosion\_flux}_i = \text{MIN}\begin{bmatrix} dt*E_i*(1\text{-poro})*\text{frac}_i*(\tau_w/\tau_{c,i} - 1) \\ \rho_i*(1\text{-poro})*\text{frac}_i*z_a + \text{dep\_flux}_i \end{bmatrix}$$



Deposition.
Rule: create new layer if deposition > 5 mm (user defined). Mix surface layer to be at least z_a thick. Combine bottom layer.

$$\frac{\partial C_i}{\partial t} = -w_{s,i}\frac{\partial C}{\partial z}$$

Bedload transport

Warner et al. (2008)

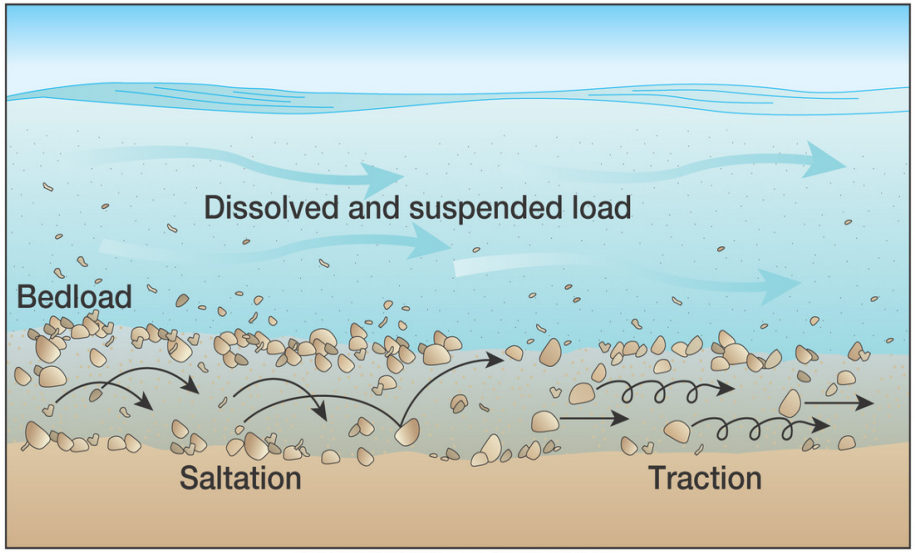
MPM or Soulsby and Damgaard (2005): Bedload transport due to combined asymmetrical waves and currents (with bed slope effects)

$$q_{bl} = \Phi\sqrt{(s-1)gD_{50}^3\rho_s}$$

$$\Phi_x = \max(\Phi_{x1}, \Phi_{x2})$$

$$\Phi_{x1} = A_2\theta_{\mathrm{m}}^{1/2}(\theta_{\mathrm{m}} - \theta_{\mathrm{cr}})$$

$$\Phi_{x2} = A_2(0.9534 + 0.1907\cos 2\phi)\theta_{\mathrm{w}}^{1/2}\theta_{\mathrm{m}} + A_2(0.229\Delta\theta_{\mathrm{w}}^{3/2}\cos\phi)$$



Wave asymmetry parameter:

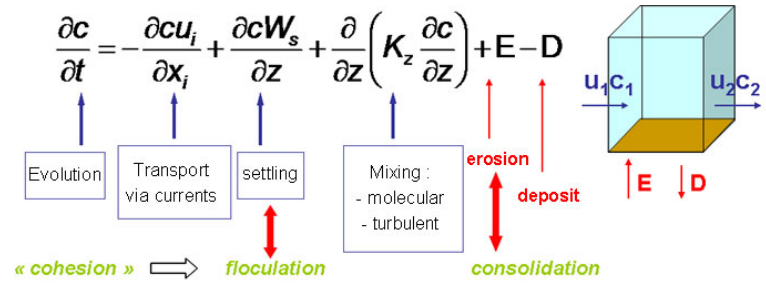
$$\Delta = \frac{\theta_{W,2}}{\theta_W}$$

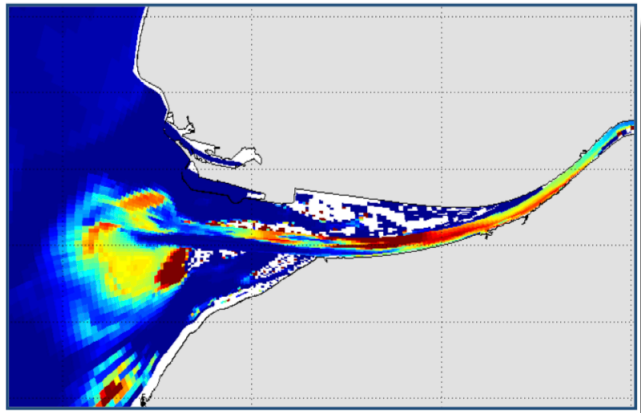
ratio between amplitude of second and basic harmonics of the oscillatory shear stress (from Stokes' 2nd order theory)

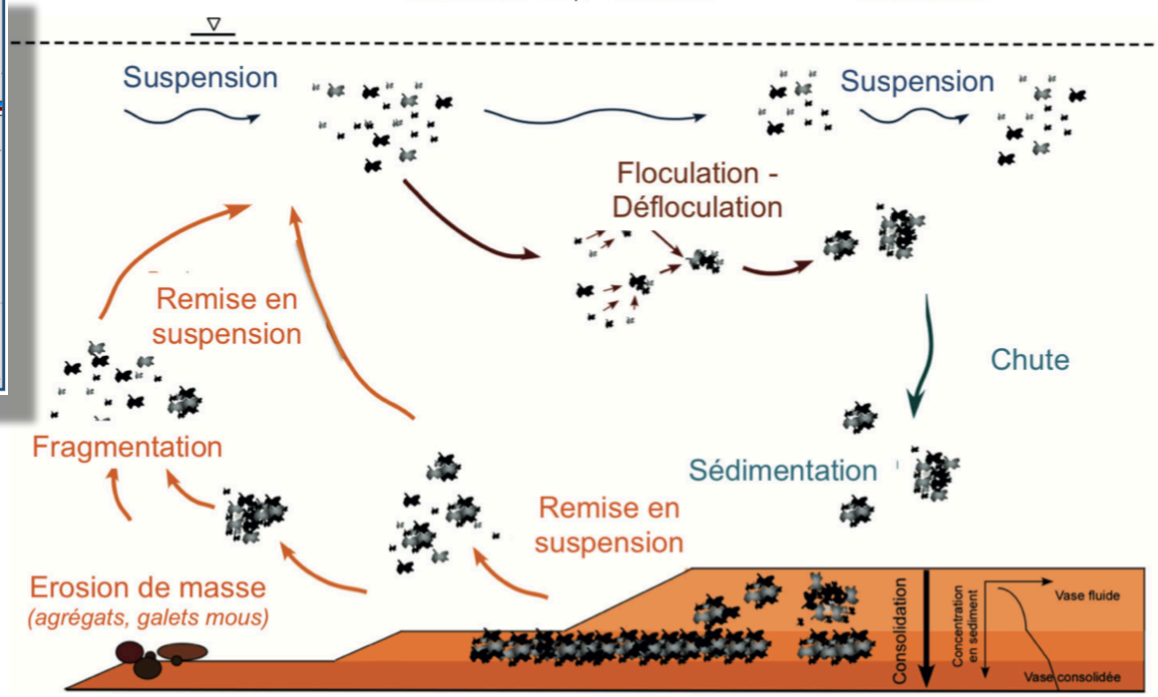
MUSTANG (LeHir et al., 2011)
Mud and Sand Transport Modeling

Cohesive sediments:

- Flocculation
- Consolidation



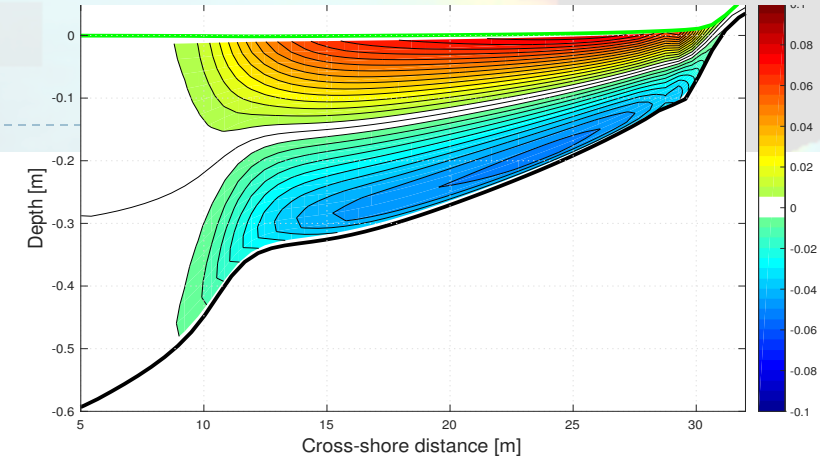


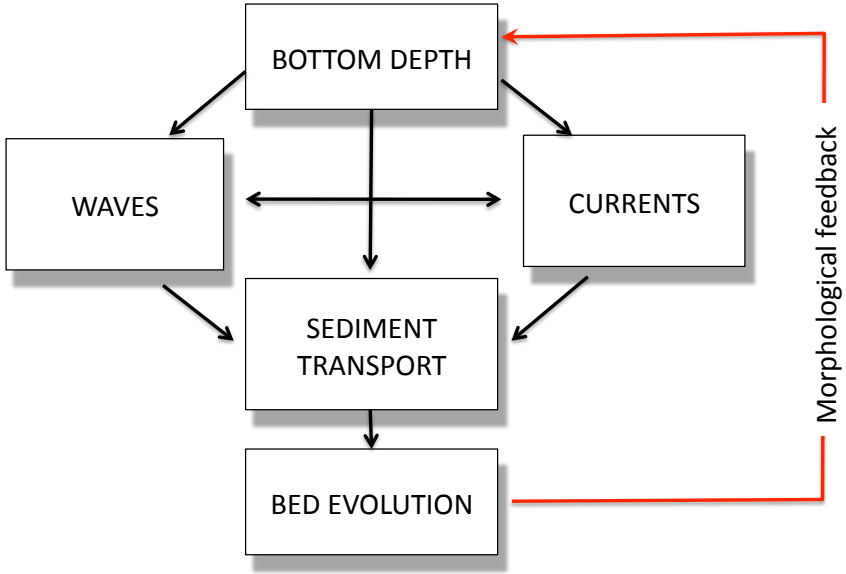


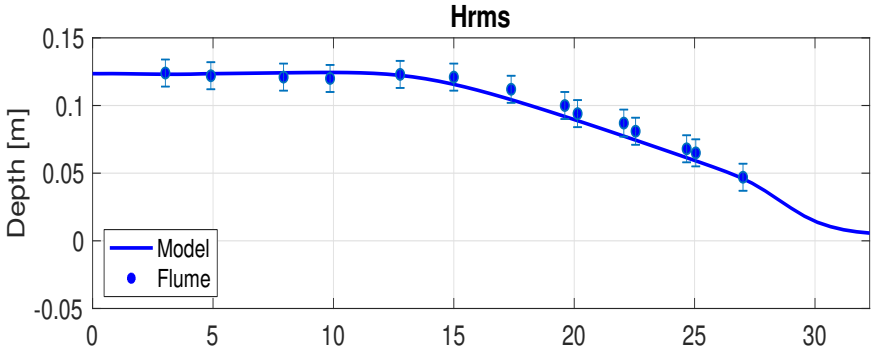
Morphodynamics

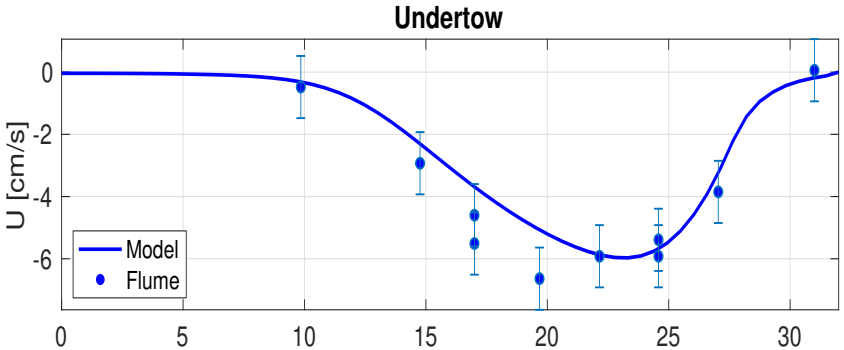
Warner et al. (2008)

- Currents-sediment coupling
  - Numerical treatment: volume and constancy preserving scheme
  - Speed-up equilibration: morphological factor (Roelvink, 2006)
  - Test case: Sand Bar formation (Roelvink & Stive 1989)









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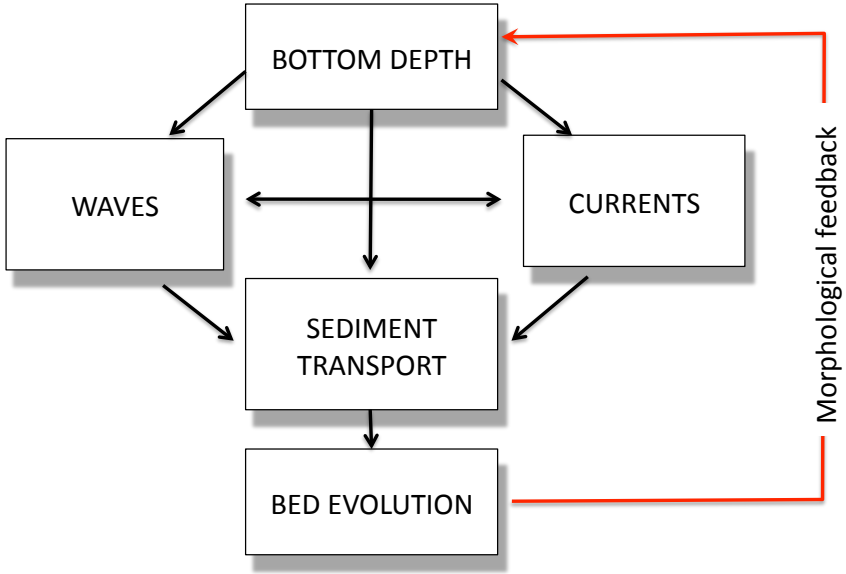

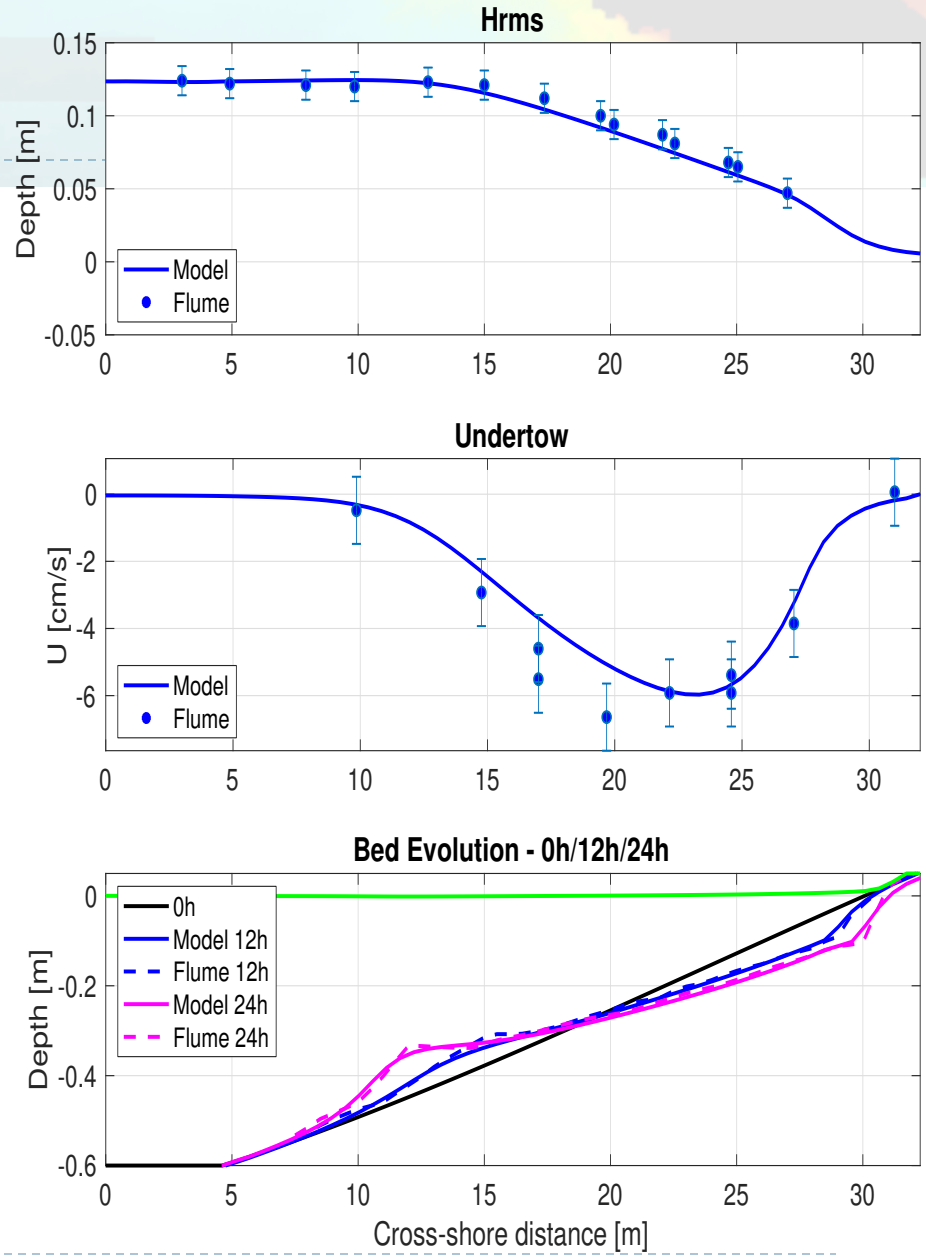

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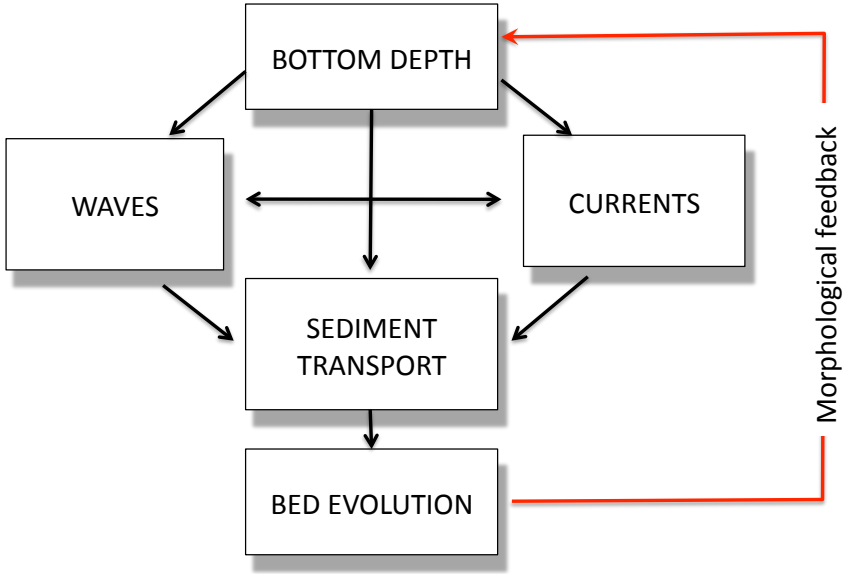

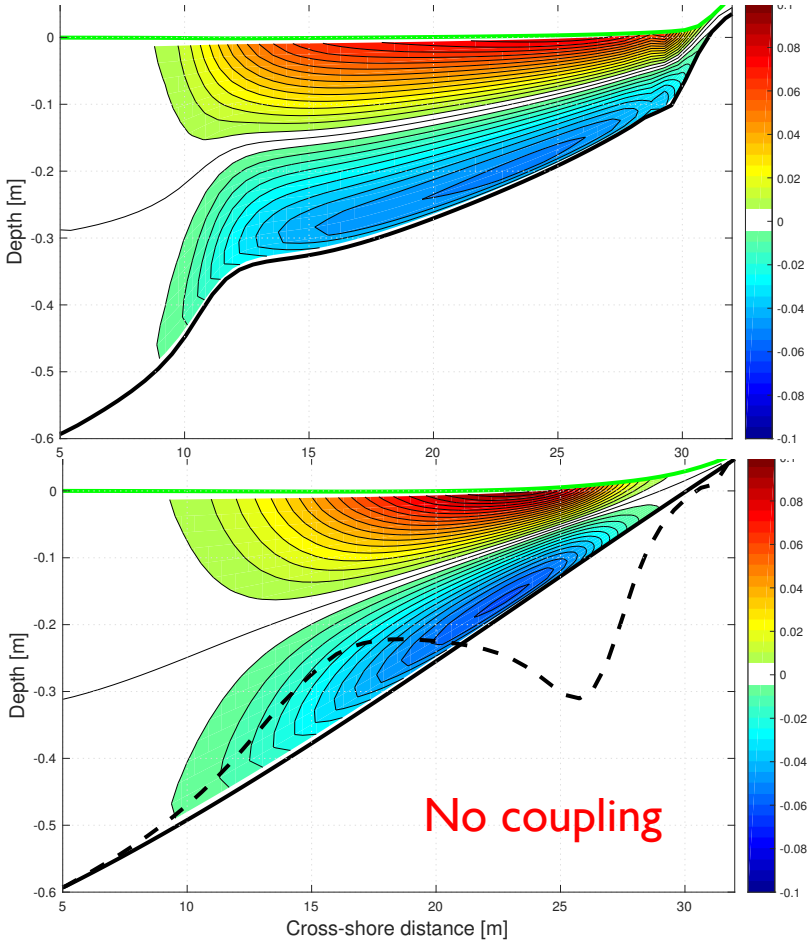

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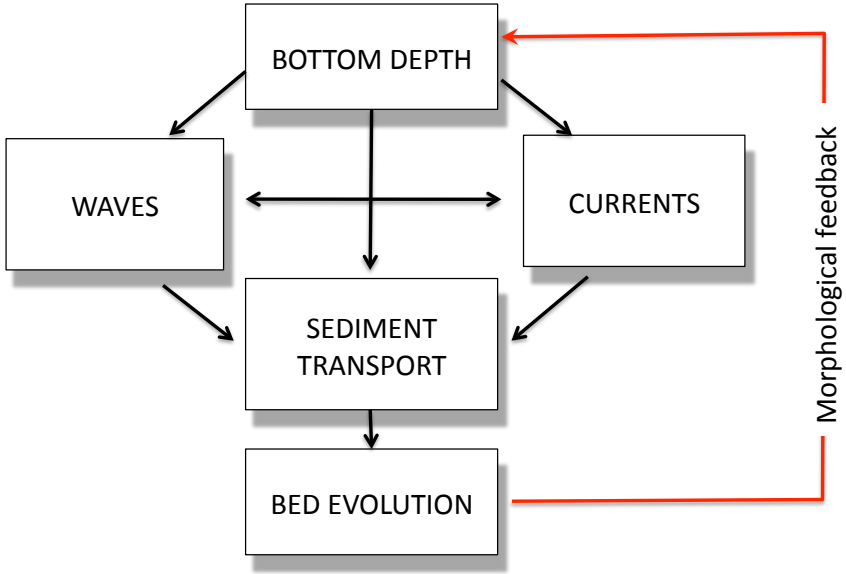

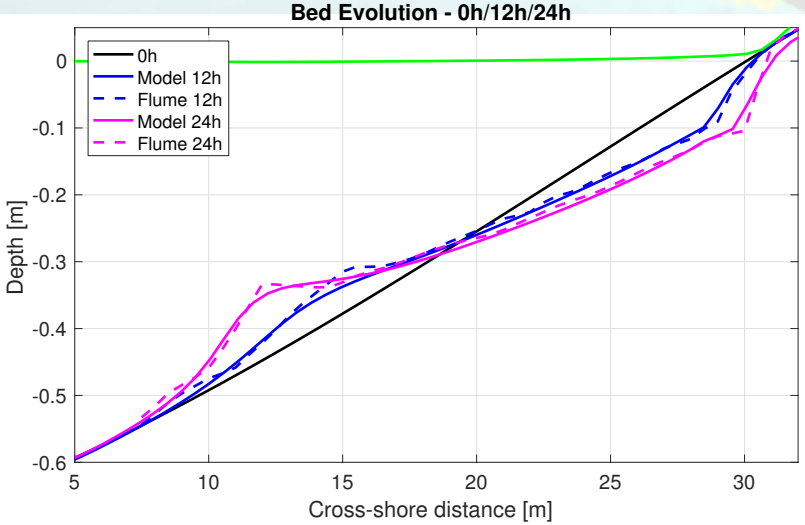

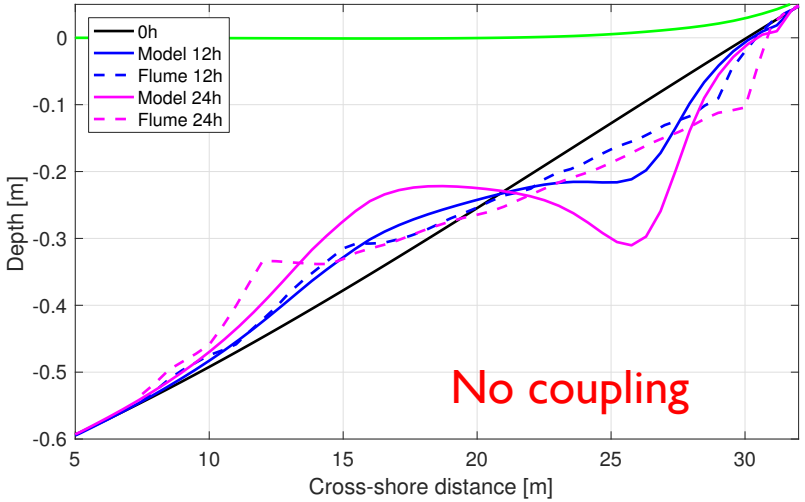

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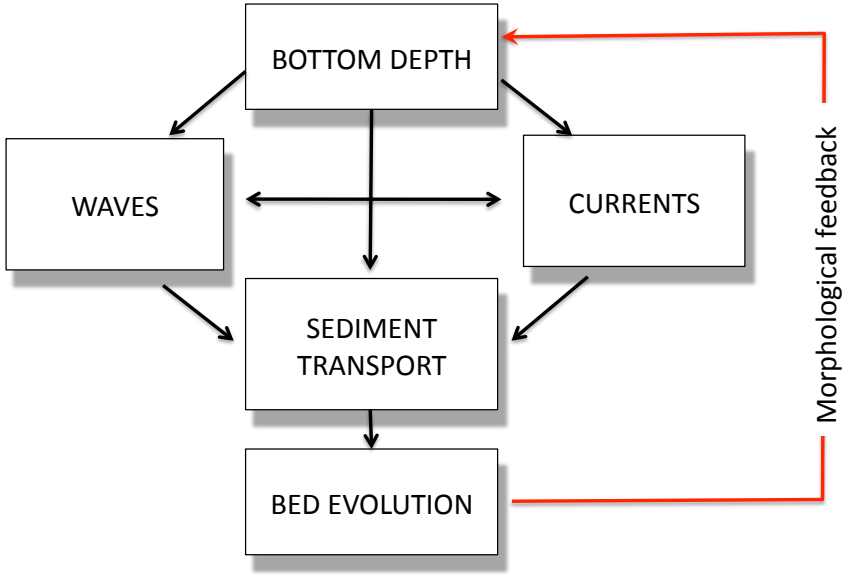
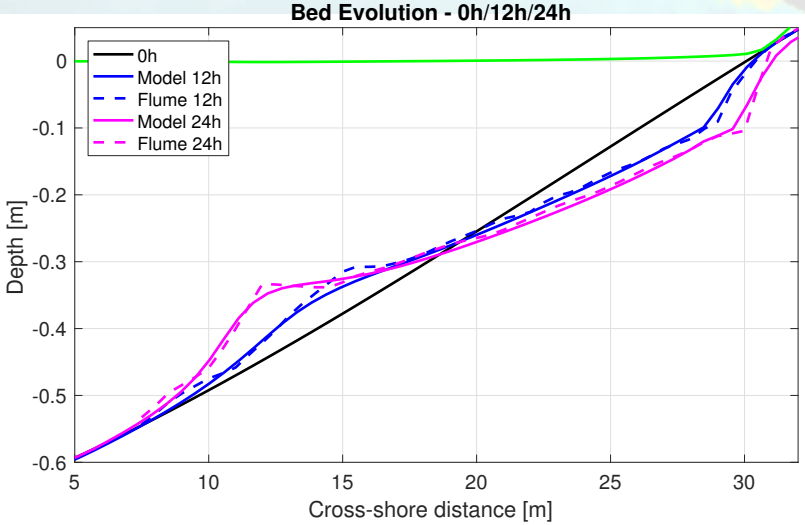
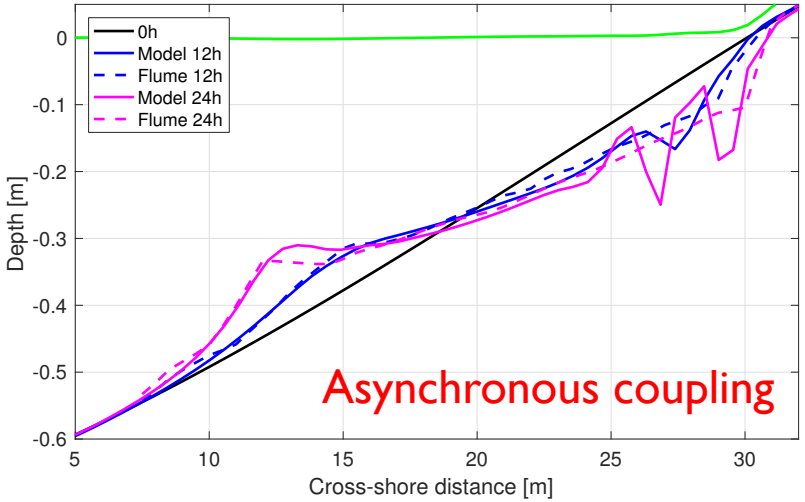


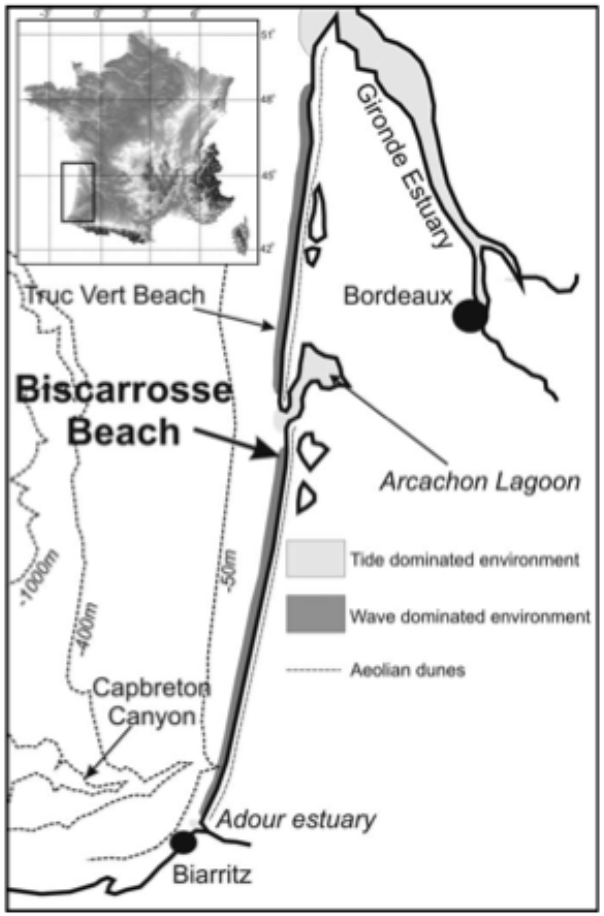


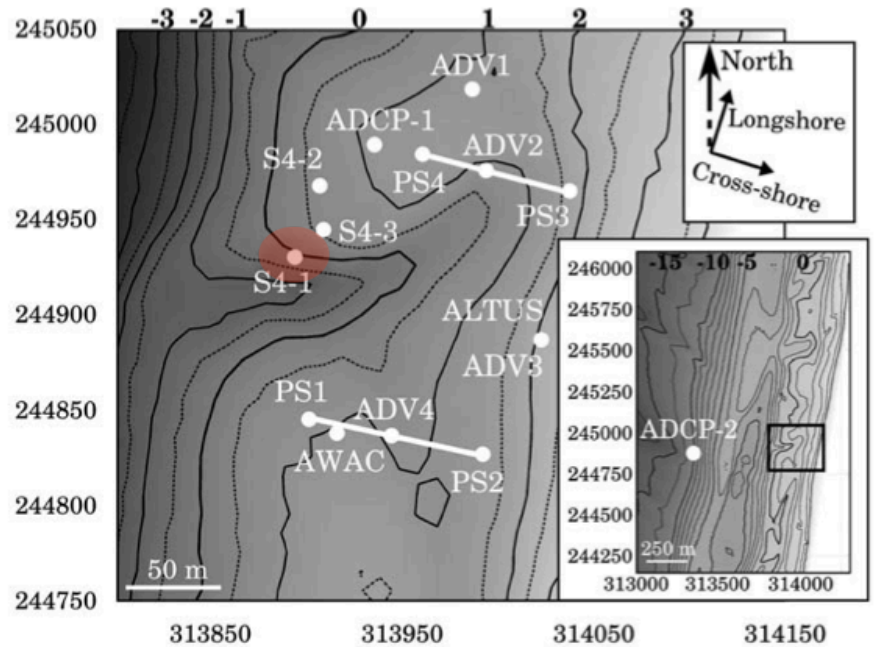


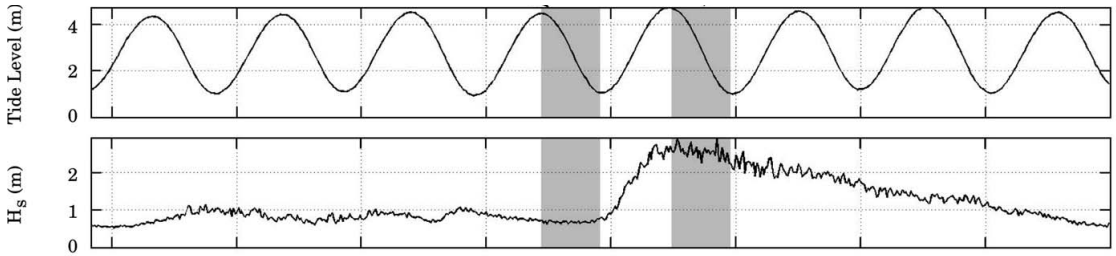
REAL NEARSHORE CASES

Biscarosse rip currents

Experiment 13-17 June 2007 (Bruneau et al., 2009)







WKB monochromatic wave model

Wave crest conservation with depth-induced and current-induced wave refraction (no diffraction and reflection) and conservation of wave action :

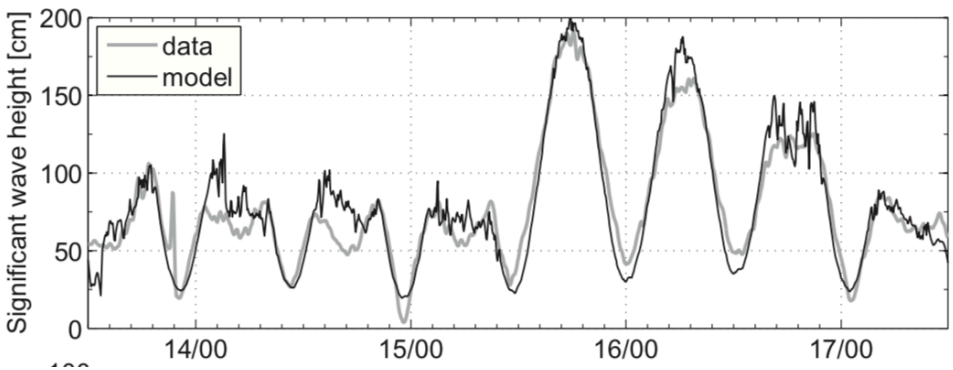
$$\frac{\partial \mathbf{k}}{\partial t} + \mathbf{c}_g \cdot \nabla_\perp \mathbf{k} = -\tilde{\mathbf{k}} \cdot \nabla_\perp \tilde{\bar{\mathbf{u}}} - \frac{k\sigma}{\sinh 2kD} \nabla_\perp D$$

$$\frac{\partial \mathscr{A}}{\partial t} + \nabla_\perp \cdot (\mathscr{A} \mathbf{c}_g) = -\frac{\epsilon^w}{\sigma}, \quad \epsilon^w = \epsilon^b + \epsilon^{wd}$$

wave breaking dissipation
(→ flow acceleration)

$$\frac{\partial \mathscr{A}^r}{\partial t} + \nabla \cdot (\mathscr{A}^r \mathbf{c}) = \frac{\alpha_r \epsilon^b - \epsilon^r}{\sigma}$$

$$\mathbf{c}_g = \bar{\mathbf{u}} + \frac{\sigma}{2k^2}\left(1 + \frac{2kD}{\sinh 2kD}\right)\mathbf{k}.$$



The flow can be time-filtered for consistency with assumptions

Biscarosse beach : Validation of wave breaking dissipation

Church and Thornton 1993 :

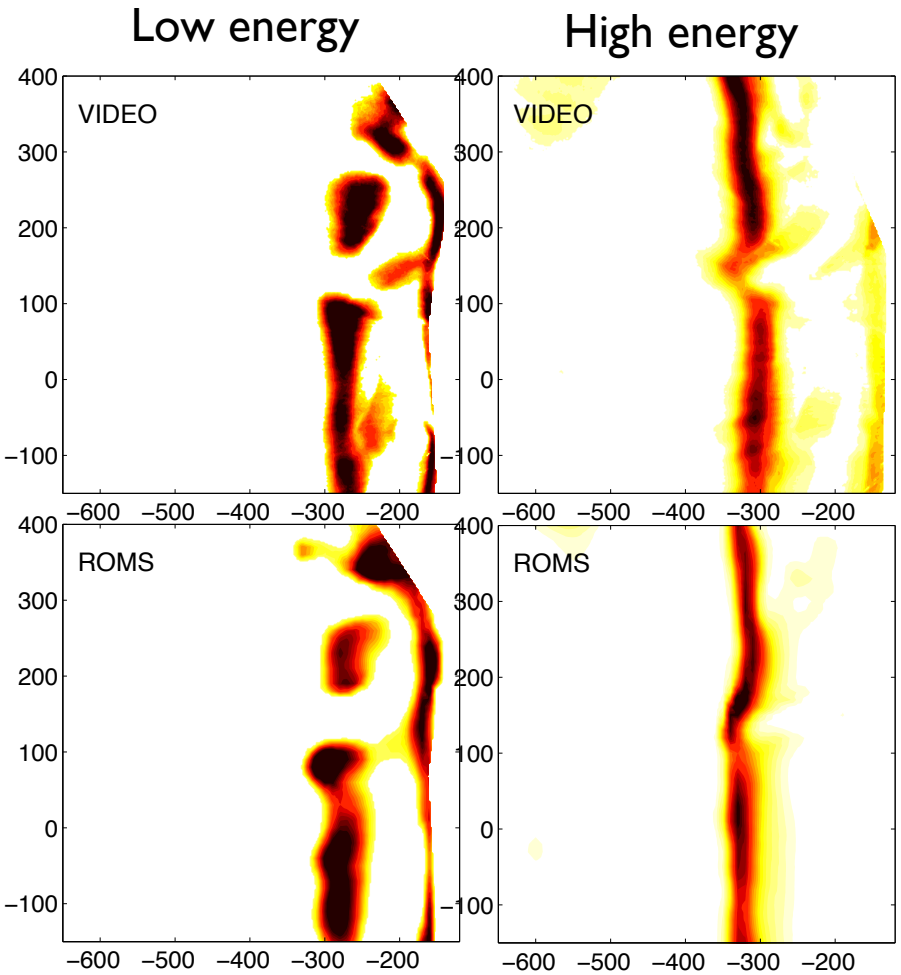
$$\varepsilon_b = \frac{3\sqrt{\pi}}{16}\rho g f_p B r^3 \frac{H_{\mathrm{rms}}^3}{h} N \left[1 - \frac{1}{\left(1 + (H_{\mathrm{rms}}/\gamma h)^2\right)^{5/2}}\right],$$

where

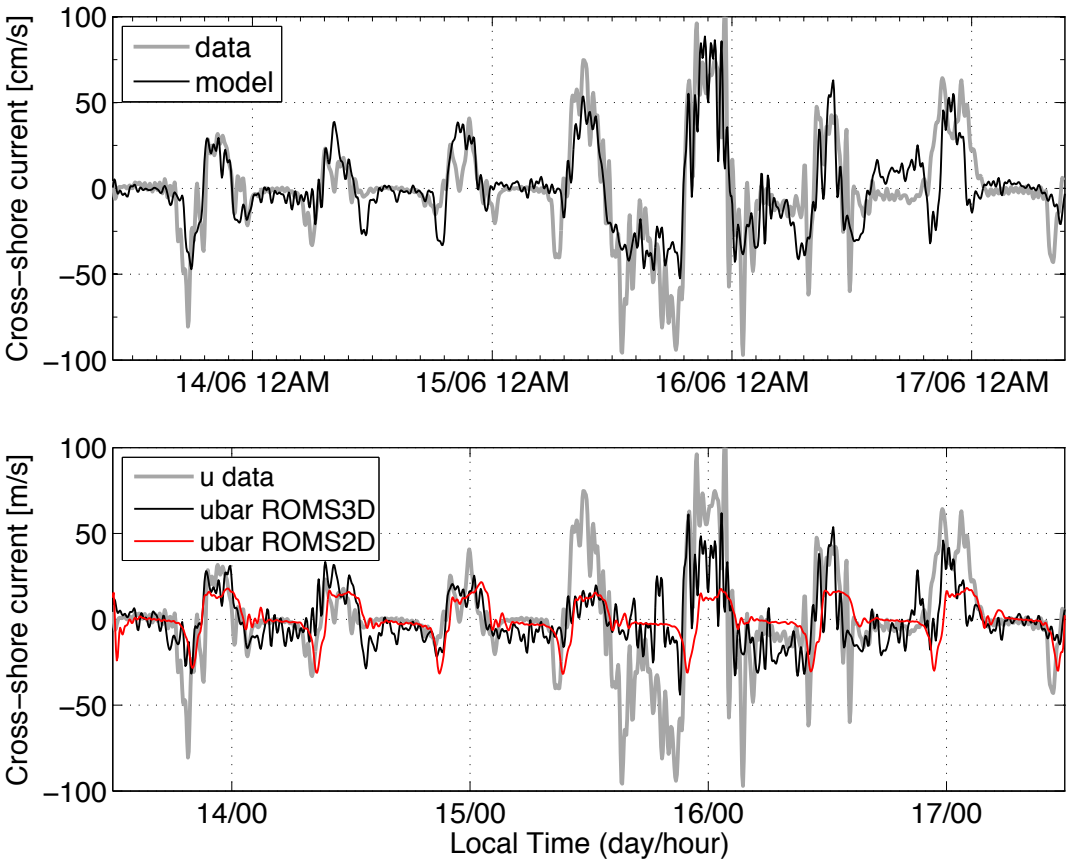
$$N = 1 + \tanh\left[8\left(\frac{H_{\mathrm{rms}}}{\gamma h} - 1\right)\right].$$

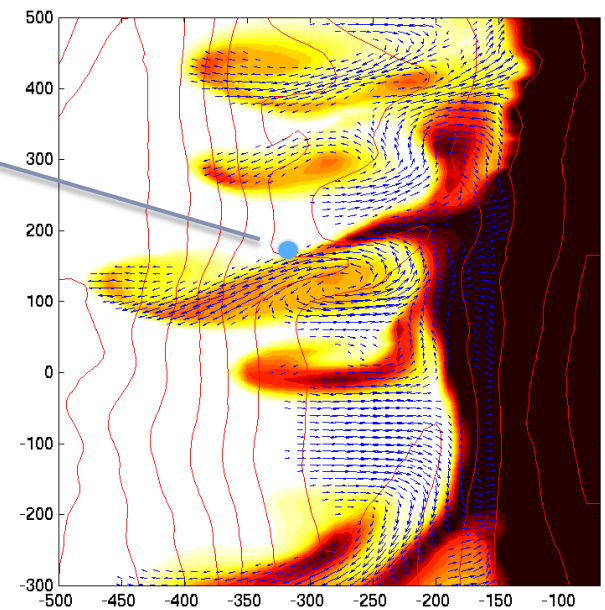
Wave height-to-depth ratio $\gamma = 0.3$

% of broken wave face $Br = 1.3$

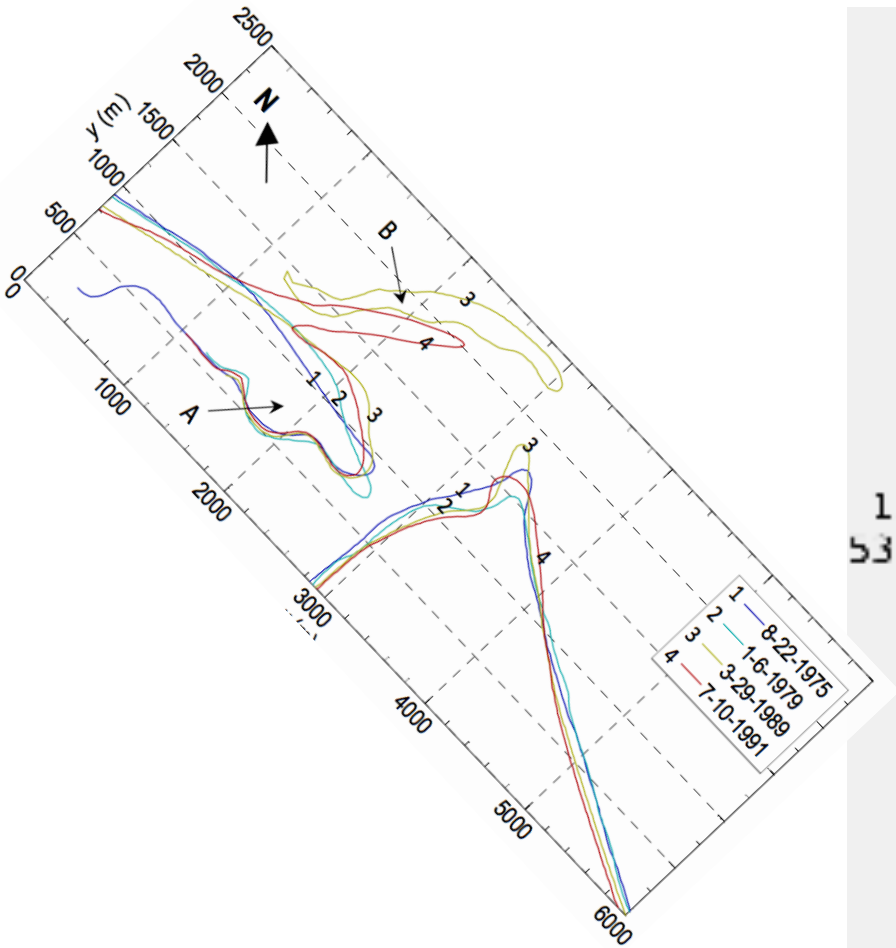


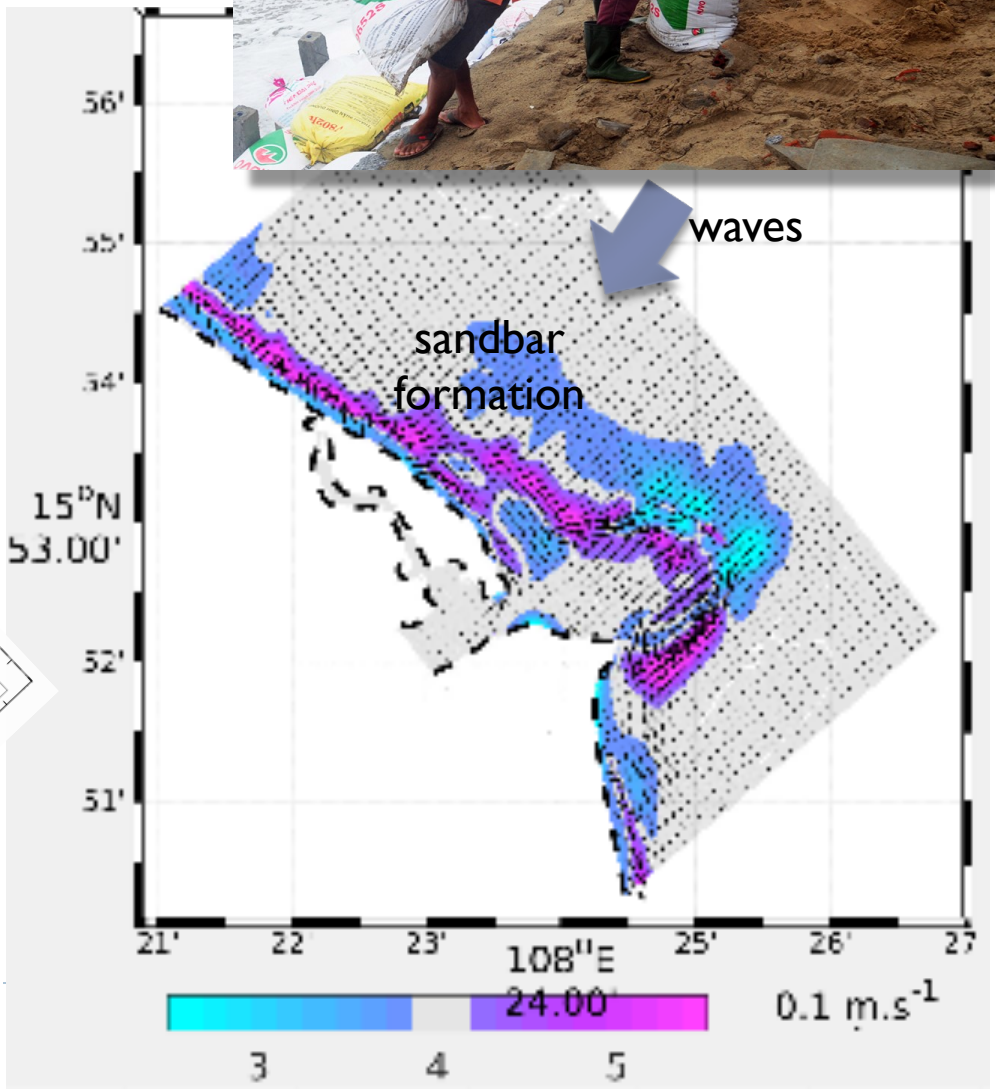
Biscarosse beach: 2D vs. 3D models



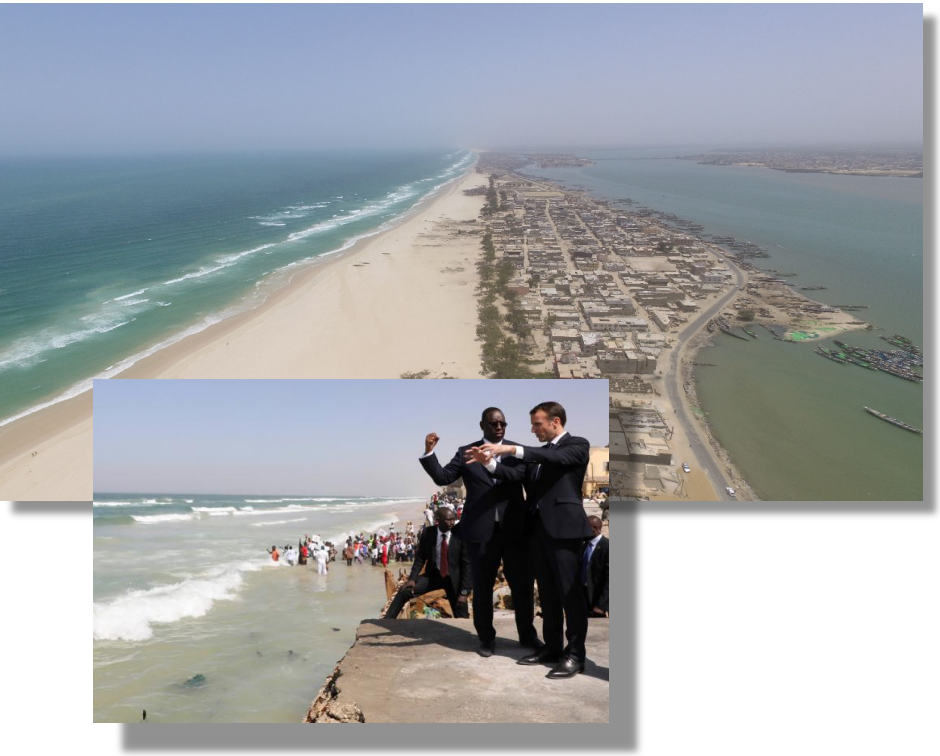


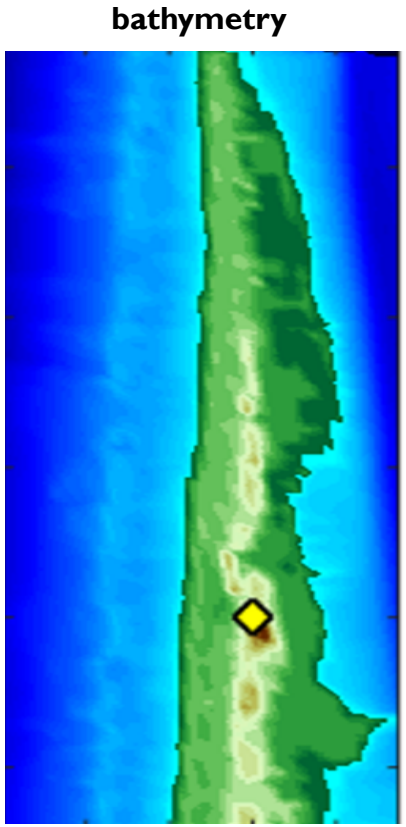
Hoi-An AFD project (2016)

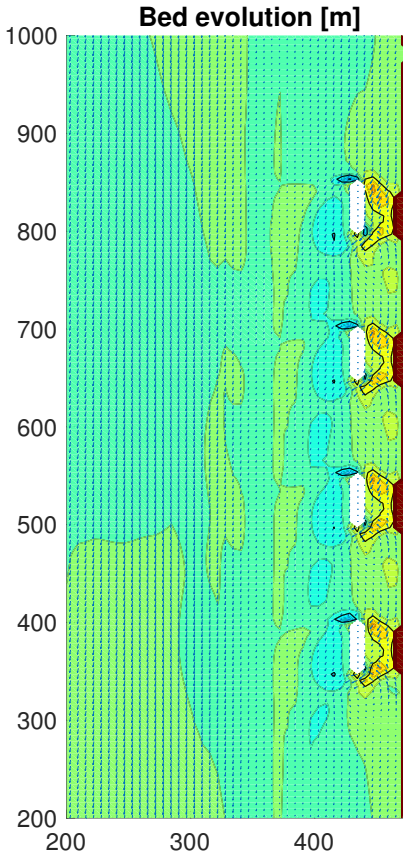




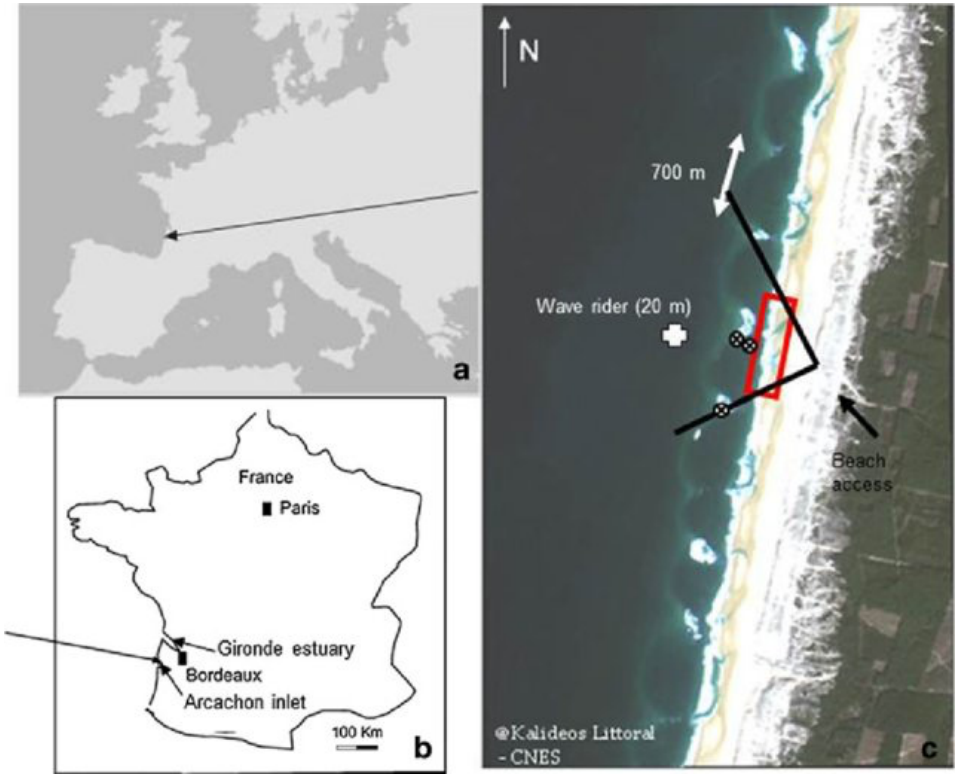
Protection against erosion Saint-Louis, Senegal (AFD, 2018)

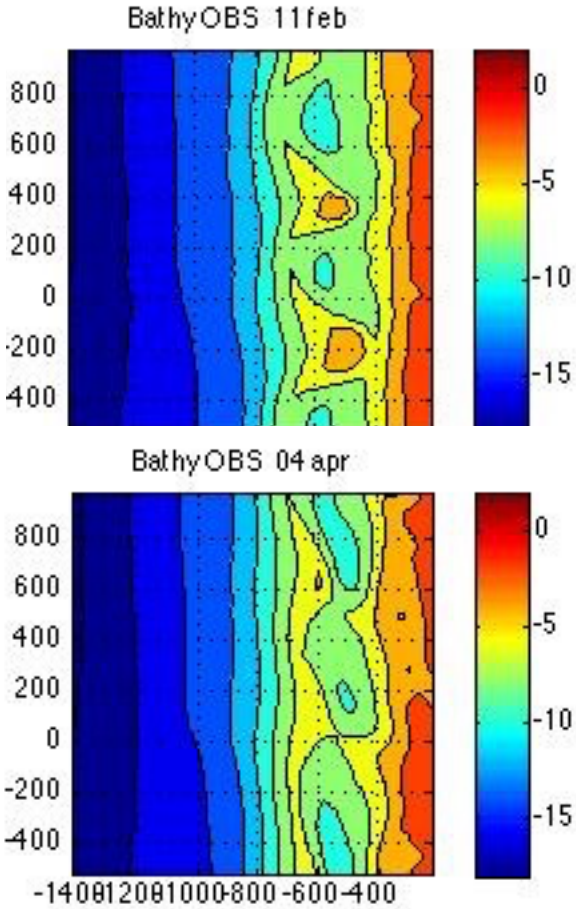






ECORS Truc-Vert 2008 experiment
Model intercomp., MEPELS (J. Chauchat)

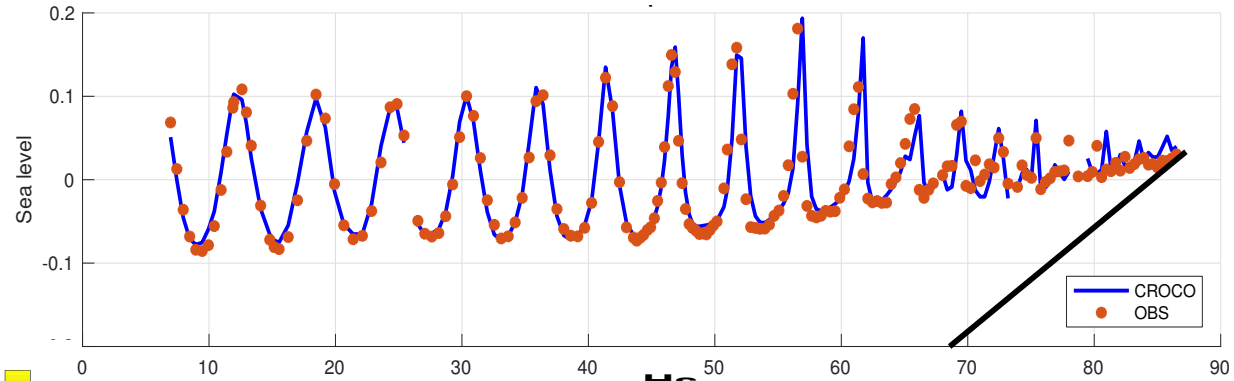


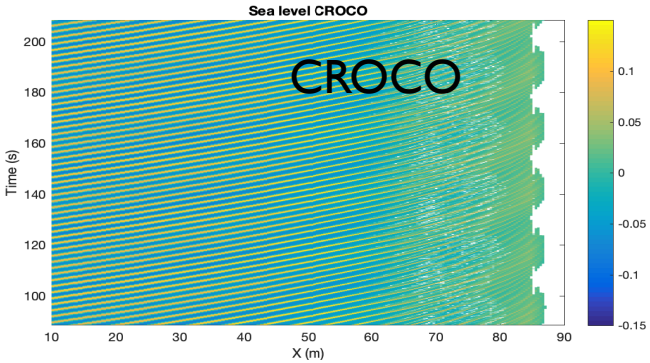


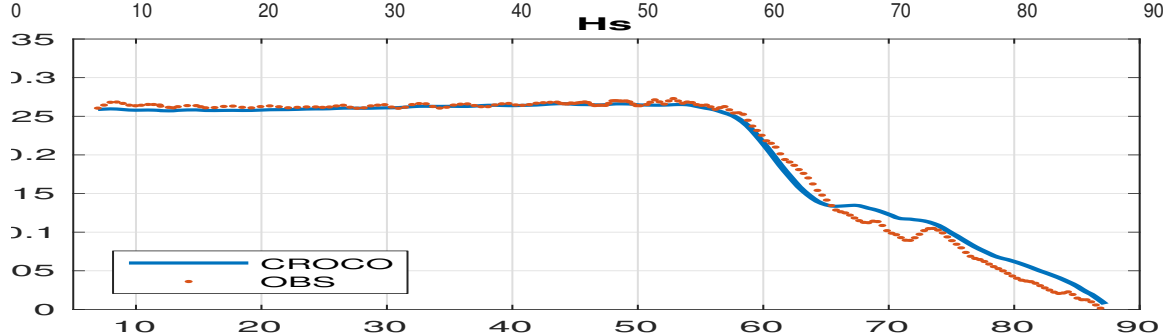
Wave-resolving CROCO

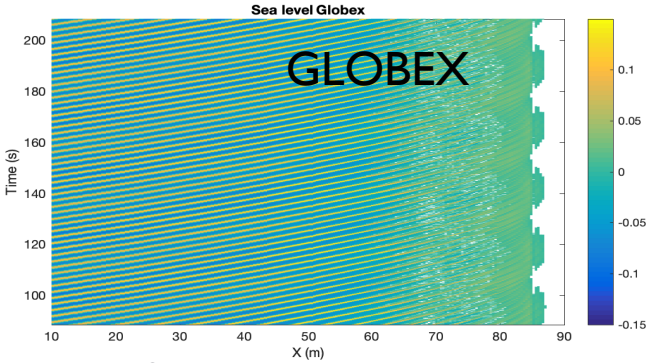
Validation of wave breaking (GLOBEX B2, Michalet et al., 2014)

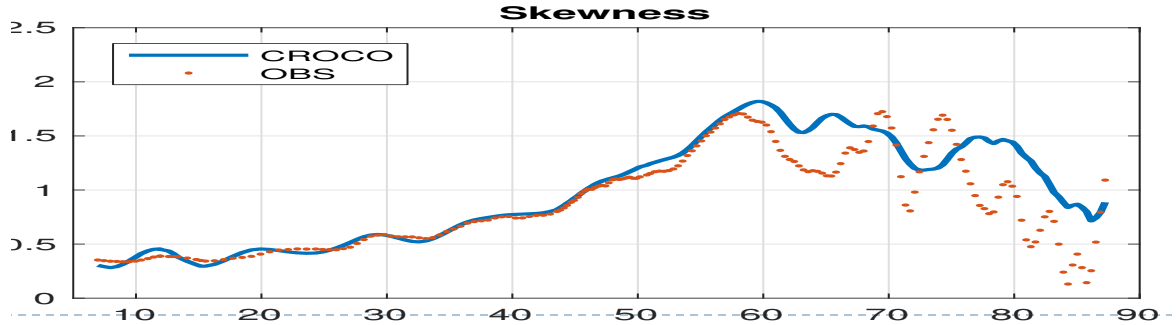
SGS model:
WENO + k- ε











Sediment dynamics formulations in wave-resolving model ?

- Surfzone turbulence effect on sediment resuspension
- Sediment concentration effect on turbulence and bottom drag
- Formulations for resuspension, bedload transport, bottom drag …

CONCLUSIONS

- CROCO provides 3D hydrostatic and non-hydrostatic solvers for problems from regional to nearshore dynamics
- Two sediment models are implemented and needs completion (e.g., cohesive sediments)
  - USGS model & MUSTANG (community efforts)
  - Need for common test case: COMODO-Sediments?