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Alongshore differential topographically controlled wave-breaking and rip current circulation

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Wave-induced 2DH circulation

- **2D horizontal circulation ↔ vertical vorticity field**

- **2DH wave-averaged approach**

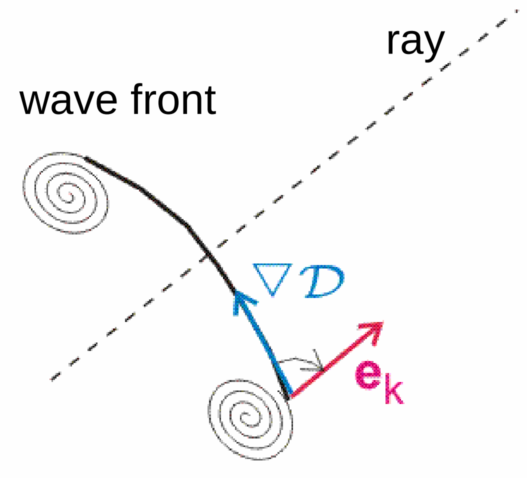
  ⇨ generation of mean flow vertical vorticity is an old problem (*see Bowen (1969)*) but still an open one

  ⇨ improvement of 2DH circulation modeling is a necessary step for the development of more complex quasi-3D (*e.g. Haas et al. (2003)*) or 3D (*e.g. Mellor (2003), Ardhuin (2008), Reniers et al. (2008)*) approaches.

Wave-induced vertical vorticity

Vorticity generation by a bore in shallow water

NSWE theory ⇨ non-uniformities along the breaking-wave crest drive vertical vorticity, *Peregrine (1998)*



For 2DH wave-averaged approaches, what is the resulting effect of this mechanism integrated over a wave period ?

2DH mean current vorticity ⇨ Bowen (1969) a pioneering work

$$\frac{\partial \mathbf{U}_T}{\partial t} + (\mathbf{U}_T.\nabla)\mathbf{U}_T + g\nabla\bar{\zeta} = \mathbf{R} + \mathbf{V}_s + \mathbf{F}_r$$

$\mathbf{U}_T = \frac{1}{\bar{h}}\overline{\int_{-d}^{\zeta} \mathbf{u}_H \, dz}$: mean transport horizontal velocity

$R_i = -\frac{1}{\bar{h}}\frac{\partial S_{ij}}{\partial x_j}$

$$\frac{\partial \omega_T}{\partial t} + \nabla.\left(\omega_T \mathbf{U}_T\right) = \nabla \wedge \mathbf{R} + \nabla \wedge \mathbf{V}_s + \nabla \wedge \mathbf{F}_r$$

Outside the surf zone: $\nabla \wedge \mathbf{R} = 0$.

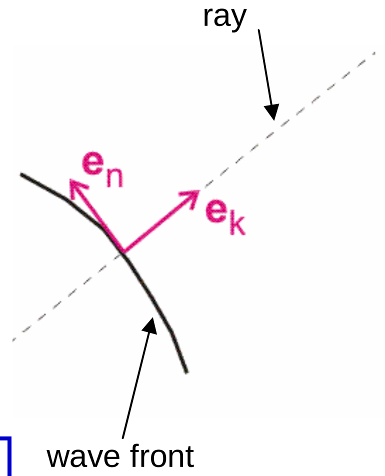
Inside the surf zone: the forcing term $\nabla \wedge \mathbf{R}$ is implicitly related to wave energy dissipation (see *Longuet-Higgins and Stewart 1973 and Battjes 1988*).

Reformulation of the mean momentum equation: *Smith (2006)*

$$\bar{h}\mathbf{U}_T = \overline{\int_{-d}^{\zeta} \mathbf{u}_H \, dz} = \bar{h}\mathbf{U} + \underbrace{\overline{\int_{-d}^{\zeta} \tilde{\mathbf{u}}_H \, dz}}_{\tilde{\mathbf{M}}}$$

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial x_j}\left(A(c_{gj} + U_j)\right) = -\frac{D_{b_m}}{\sigma}$$

$$A = E/\sigma \qquad \tilde{M}_i = A k_i$$



$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}.\nabla)\mathbf{U} + g\nabla\bar{\zeta} = \mathcal{D}\mathbf{e}_k - \nabla\tilde{J} + \frac{\tilde{\mathbf{M}}}{\bar{h}} \wedge (\nabla \wedge \mathbf{U}) + \mathbf{V}_s + \mathbf{F}_r$$

$$\tilde{J} = E\frac{k}{\sinh(2k\bar{h})} \qquad \mathcal{D} = \frac{D_{b_m}}{\bar{h}c_\phi}$$

Vorticity equation for the wave-induced circulation: *Bonneton et al (DCDS-S 2010)*

$$\frac{\partial \omega}{\partial t} + \nabla . \left(\omega (\mathbf{U} + \frac{\tilde{\mathbf{M}}}{\bar{h}}) \right) = \underbrace{\nabla \wedge (\mathcal{D} \mathbf{e}_k)}_{\sim \nabla \mathcal{D} \wedge \mathbf{e}_k} + \nabla \wedge \mathbf{V}_s + \nabla \wedge \mathbf{F}_r$$

$$\mathcal{D} = \frac{D_{b_m}}{\bar{h} c_\phi}$$

vorticity forcing term

<u>Remark</u> : the gradient of mean elevation (setup/setdown)

is not a driving force for the circulation

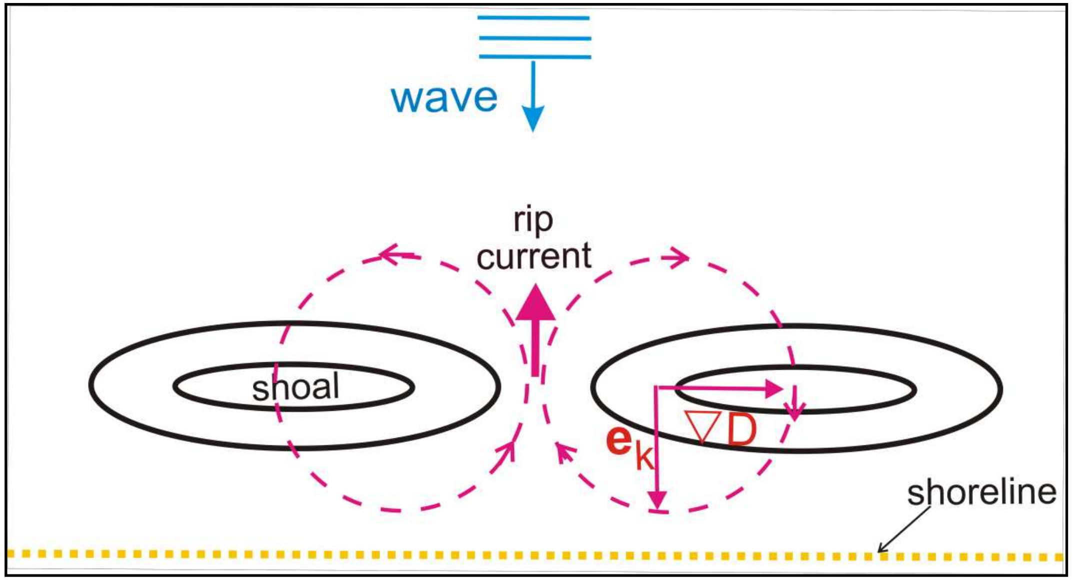
but: $$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}.\nabla)\mathbf{U} + g \nabla \bar{\zeta} = \mathcal{D} \mathbf{e}_k - \nabla \tilde{J} + \frac{\tilde{\mathbf{M}}}{\bar{h}} \wedge (\nabla \wedge \mathbf{U}) + \mathbf{V}_s + \mathbf{F}_r$$

Wave-induced vertical vorticity | 2DH approach

Vorticity equation for the wave-induced circulation: *Bonneton et al (DCDS-S 2010)*

$$\frac{\partial \omega}{\partial t} + \nabla . \left(\omega (\mathbf{U} + \frac{\tilde{\mathbf{M}}}{\bar{h}}) \right) = \underbrace{\nabla \wedge (\mathcal{D}\mathbf{e}_k)}_{\sim \ \nabla \mathcal{D} \wedge \mathbf{e}_k} + \nabla \wedge \mathbf{V}_s + \nabla \wedge \mathbf{F}_r$$

$$\mathcal{D} = \frac{D_{b_m}}{\bar{h} c_\phi}$$



Vorticity equation for a stationary wave forcing

$$\frac{\partial \omega}{\partial t} + \nabla . \left(\omega (\mathbf{U} + \frac{\tilde{\mathbf{M}}}{\bar{h}}) \right) = \nabla \mathcal{D} \wedge \mathbf{e}_k + \nabla \wedge \mathbf{V}_s + \nabla \wedge \mathbf{F}_r$$

$$V_{s_i} = \frac{1}{\bar{h}} \frac{\partial}{\partial x_j} \left(\nu_t \bar{h} (\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}) \right)$$

$$\nabla \mathcal{D} \wedge \mathbf{e}_k + \underbrace{\nabla \wedge \mathbf{V}_s}_{\sim \nu_t \nabla^2 \omega} \simeq 0$$

$\mathcal{D}$ and ν_t are the key parameters

- 2DH SWAN/MARS coupling model based on

  Smith's equations: *Bruneau (2009, PhD.)*

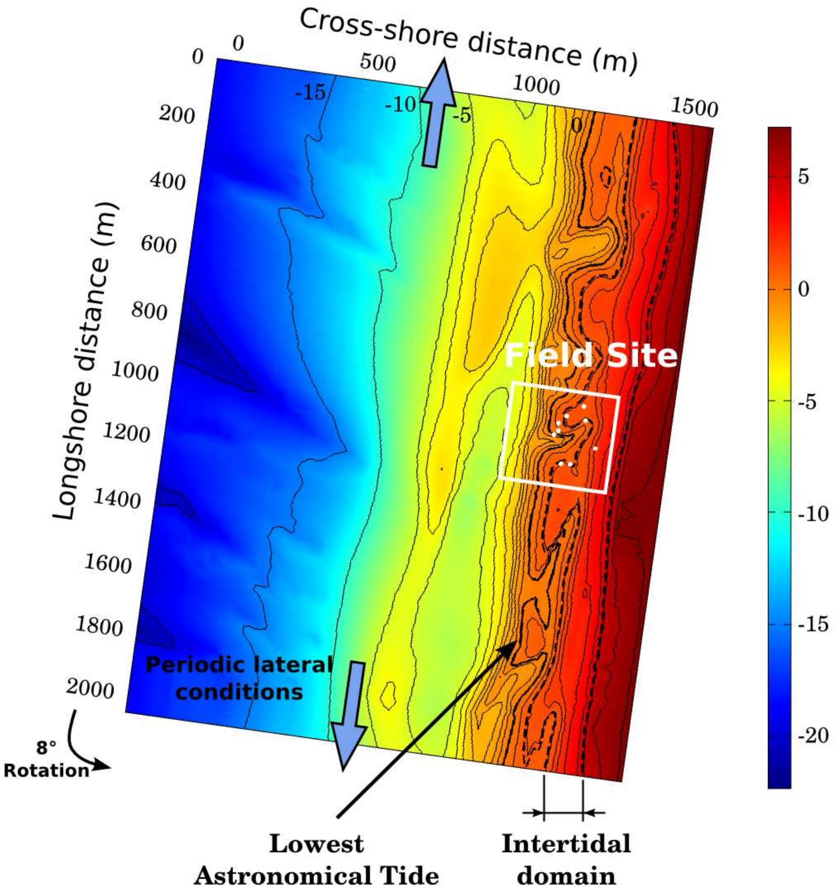
  classical parametrisations:

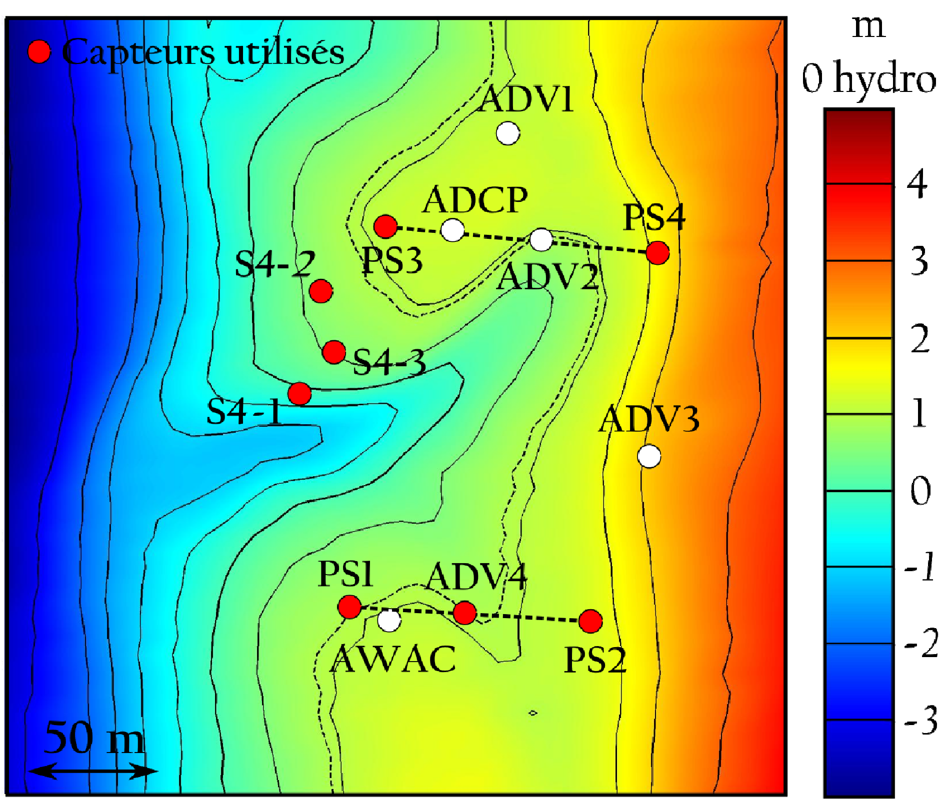
  $\mathcal{D}$ ⇨ Battjes and Janssen (1978) ν_t ⇨ Battjes (1975)

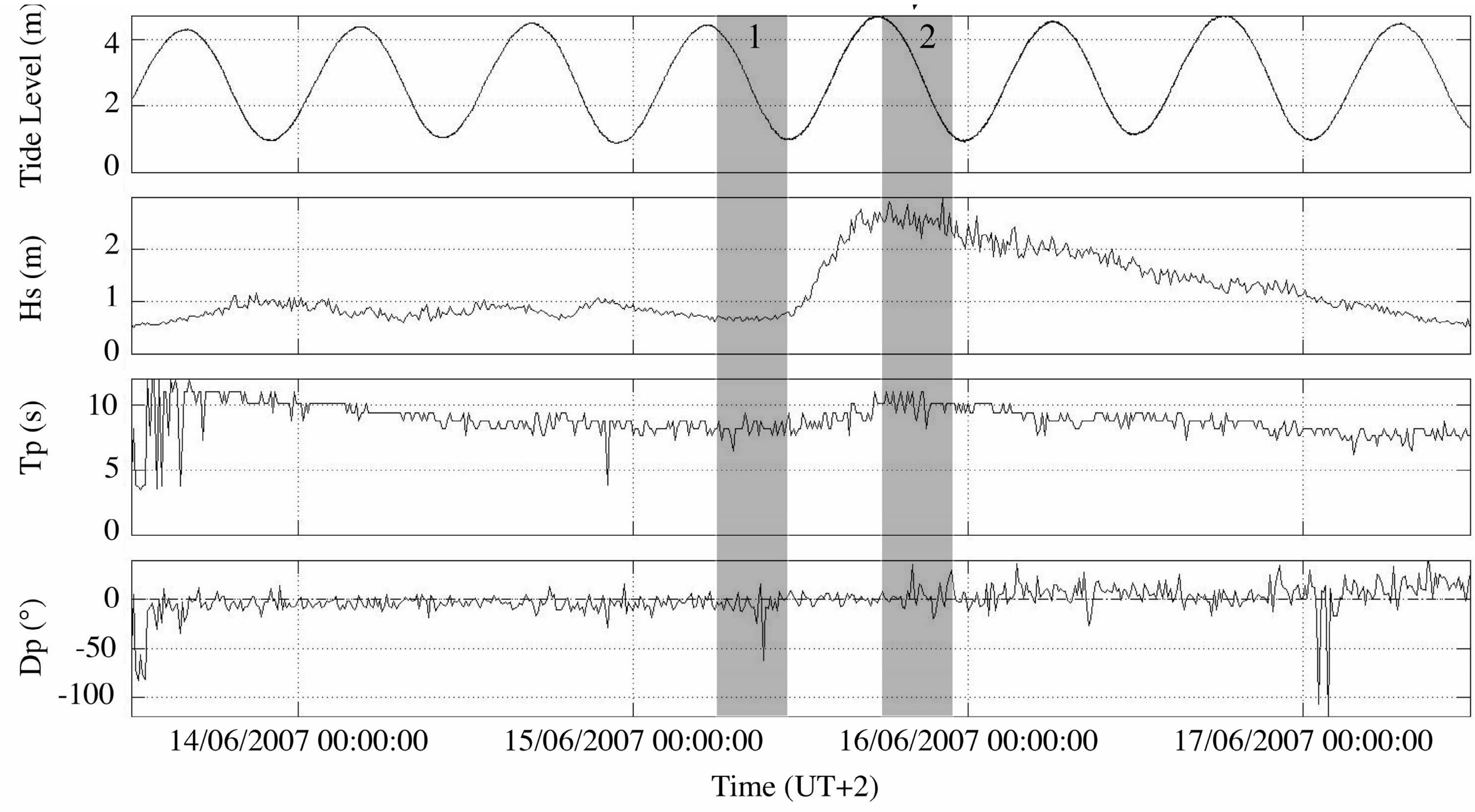
- comparisons with field measurements

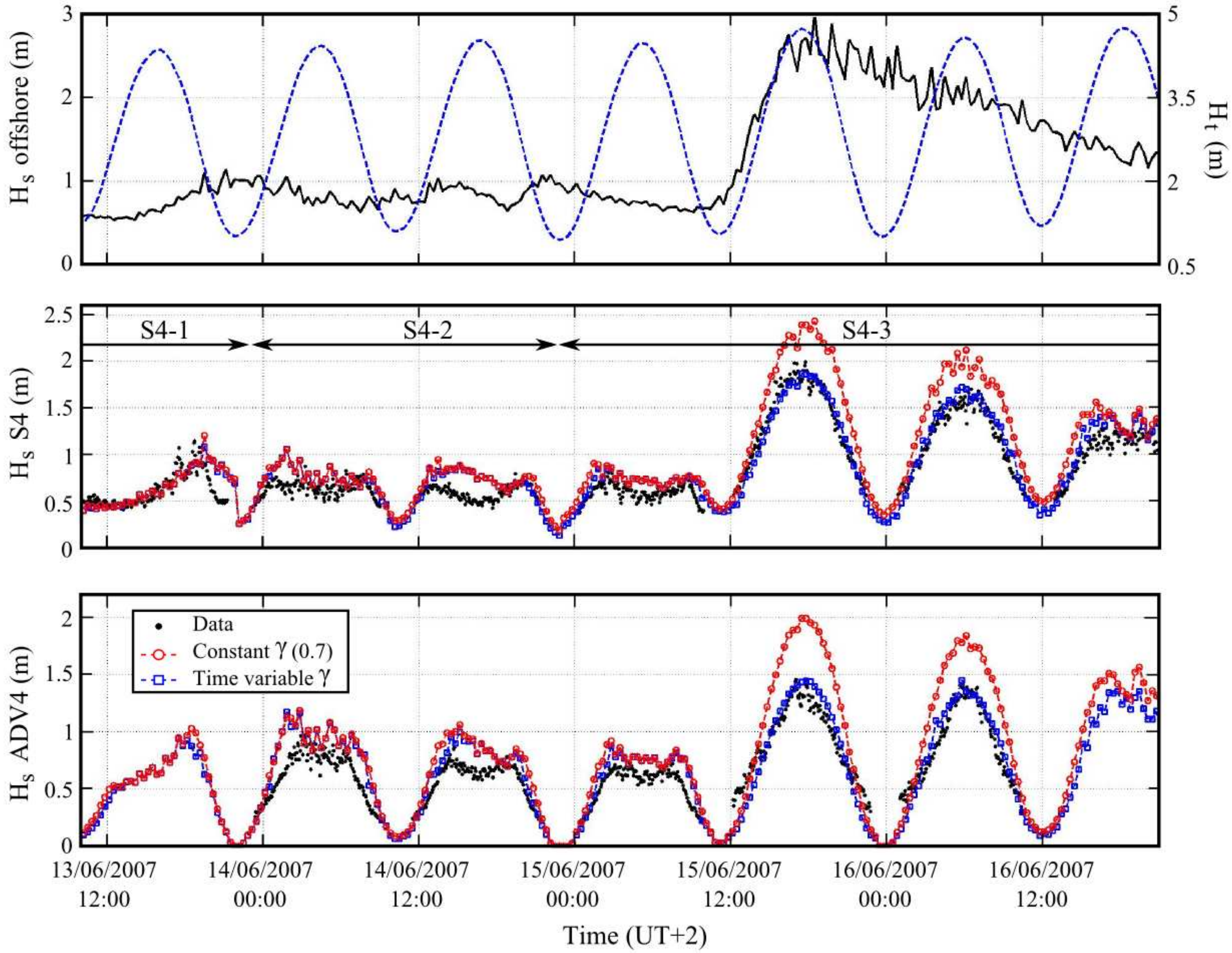
  Biscarosse Beach 2007**:** *Bruneau et al (2009, CSR)*


Biscarrosse beach, 08/06/2007


Cross-shore distance (m)
0
500
1000
1500
Longshore distance (m)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
-15
-10
-5
0
Field Site
Periodic lateral conditions
8° Rotation
Lowest Astronomical Tide
Intertidal domain
5
0
-5
-10
-15
-20

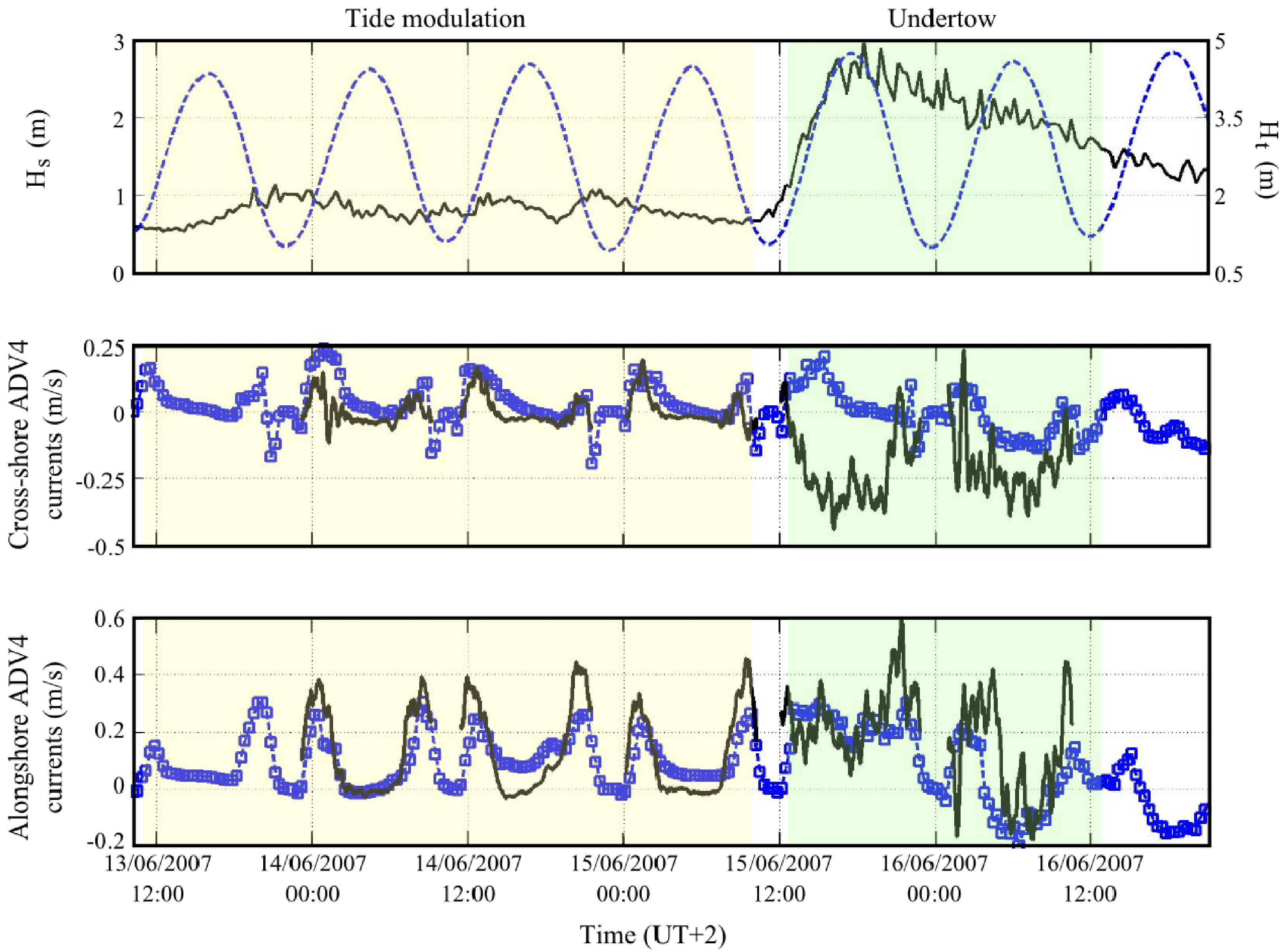

Capteurs utilisés
ADV1
ADCP
PS4
PS3
ADV2
S4-2
S4-3
S4-1
ADV3
PS1
ADV4
AWAC
PS2
50 m
m
0 hydro
4
3
2
1
0
-1
-2
-3

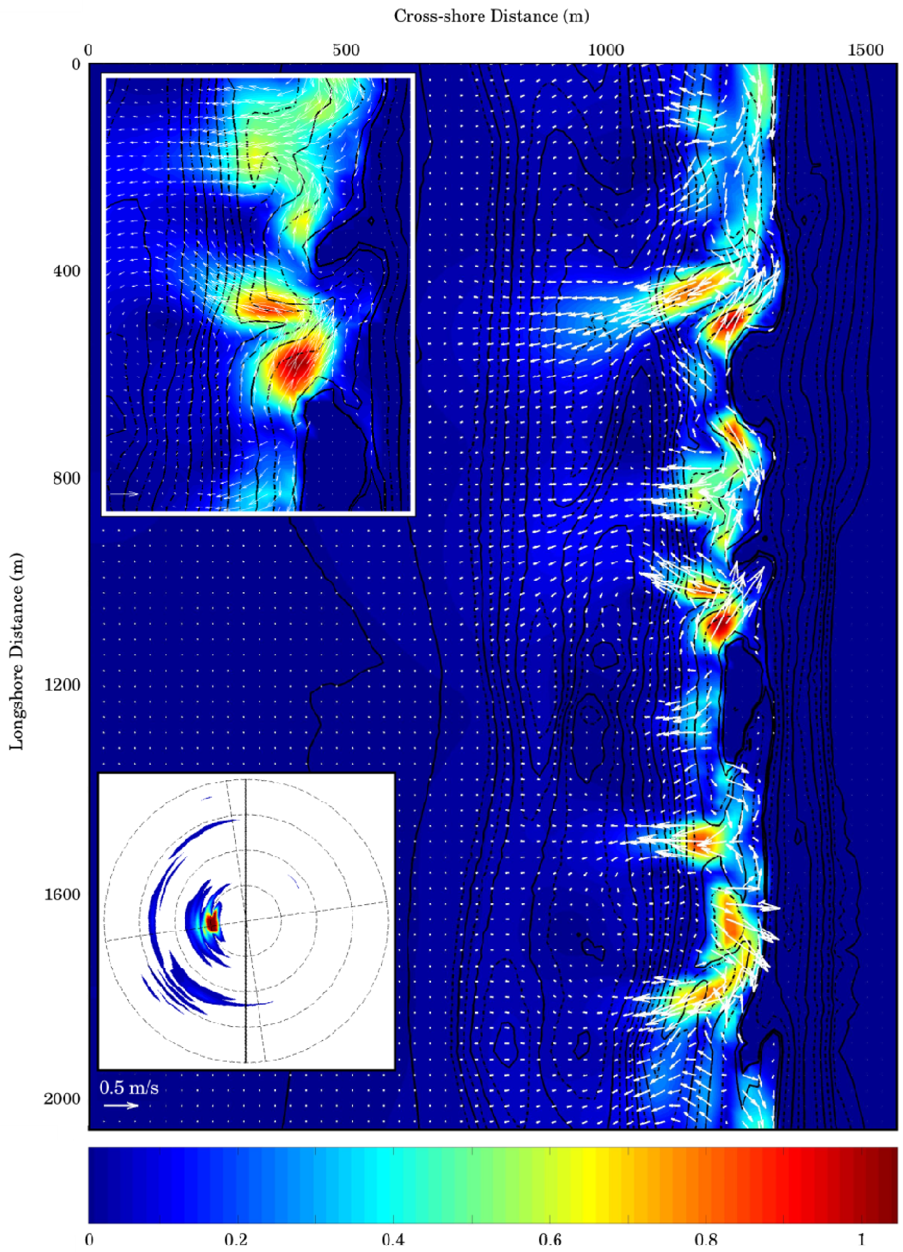

Tide Level (m)
4
2
0
1
2
Hs (m)
2
1
0
Tp (s)
10
5
0
Dp (°)
0
-50
-100
14/06/2007 00:00:00
15/06/2007 00:00:00
16/06/2007 00:00:00
17/06/2007 00:00:00
Time (UT+2)



γ–parametrisation: Smith and Kraus, 1990

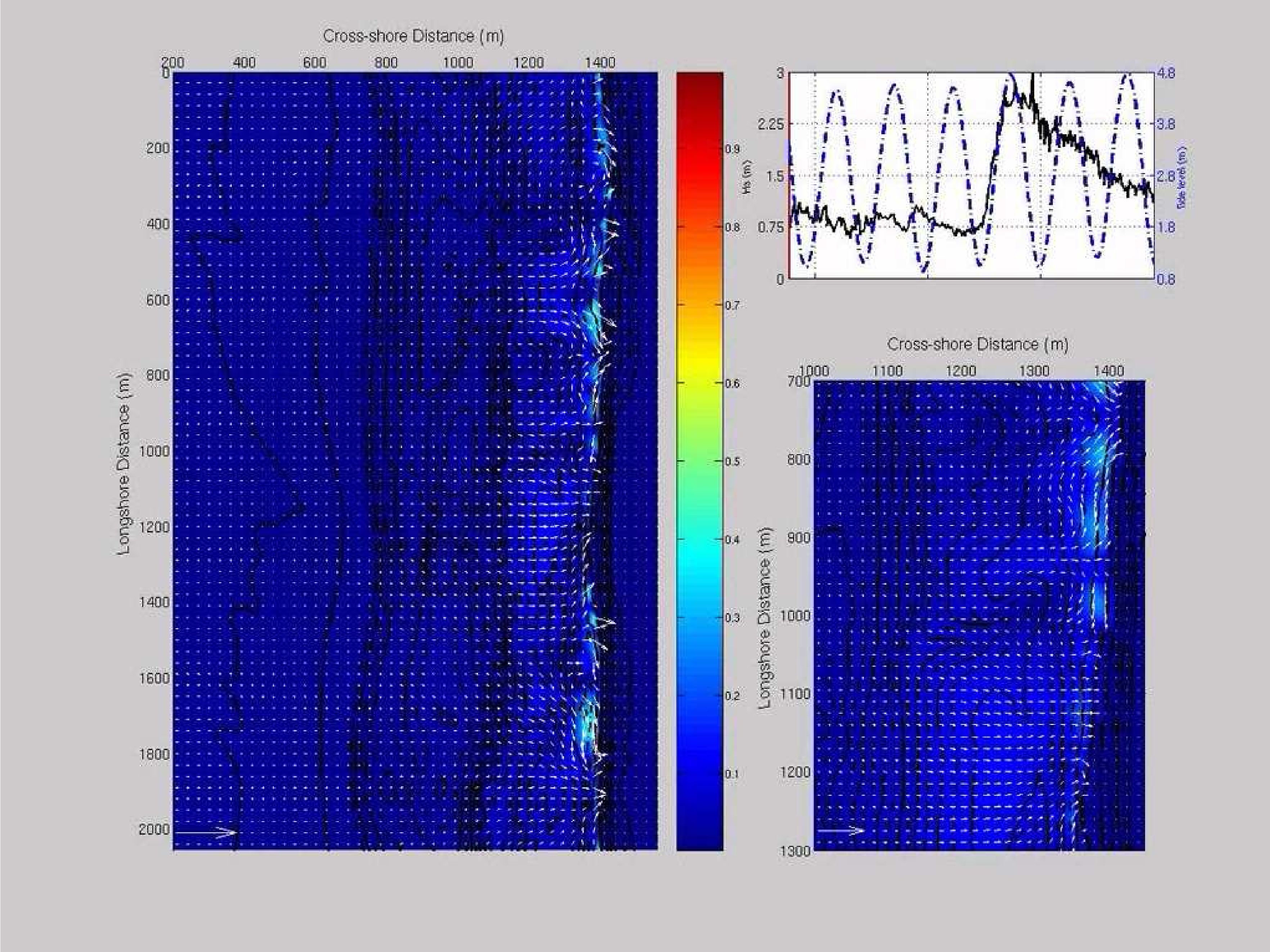
Intertidal zone measurements



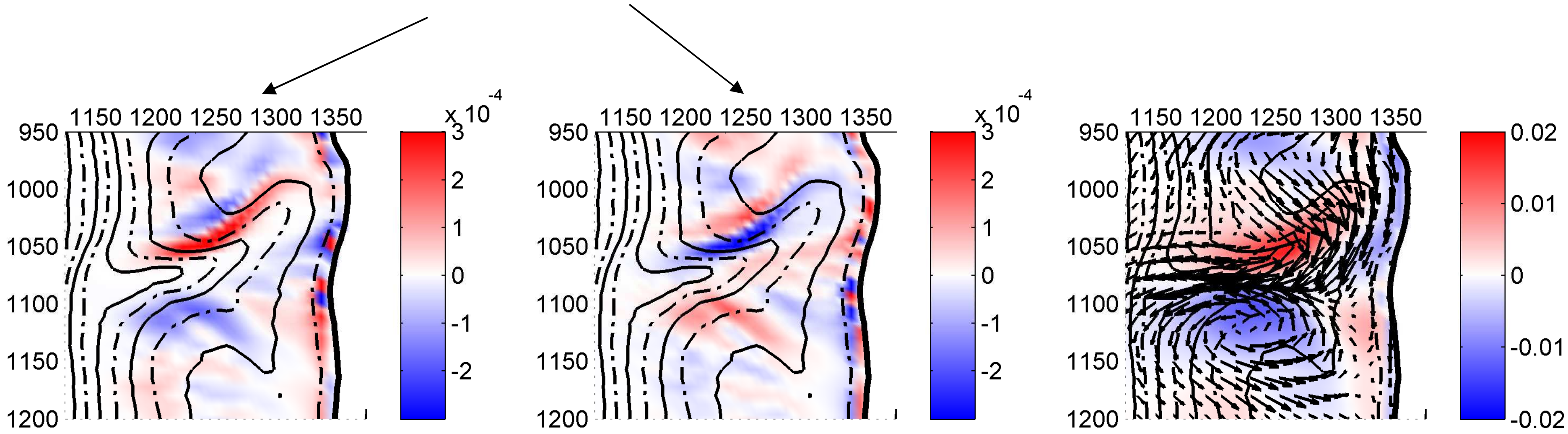


MARS / SWAN model

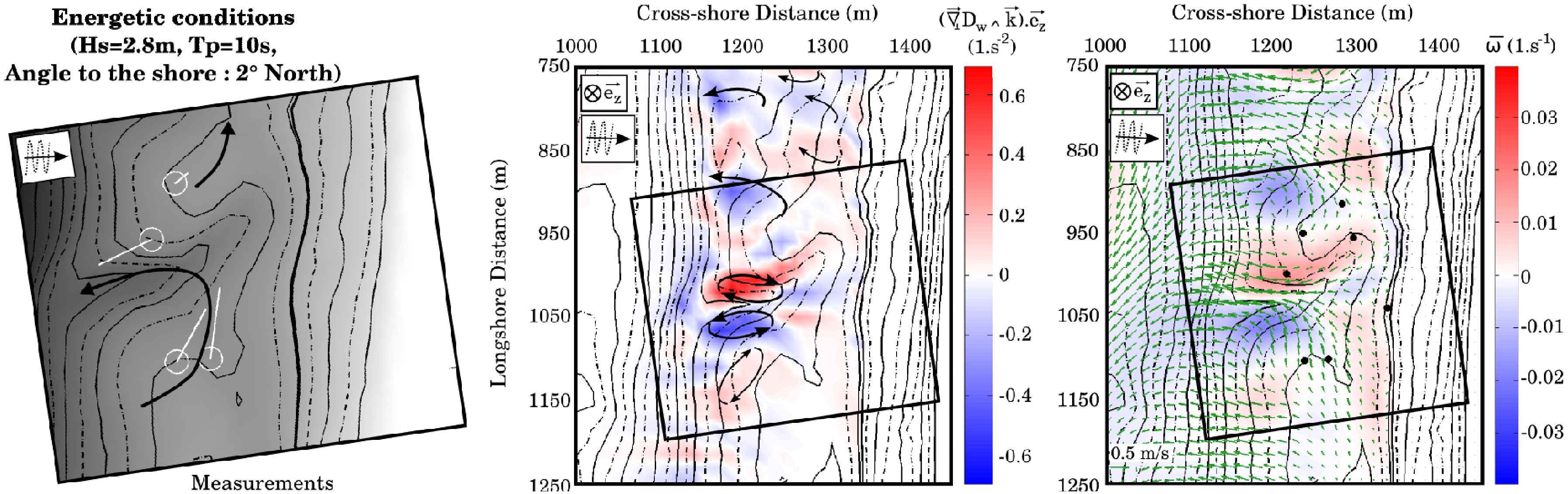
Bruneau, Bonneton, Castelle and Pedreros (2008)


Cross-shore Distance (m)
200
400
600
800
1000
1200
1400
Longshore Distance (m)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Hs (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
3
2.25
1.5
0.75
0
4.8
3.8
2.8
1.8
0.8
Tide level (m)
Cross-shore Distance (m)
1000
1100
1200
1300
1400
Longshore Distance (m)
700
800
900
1000
1100
1200
1300

$$\nabla \mathcal{D} \wedge \mathbf{e}_k + \nabla \wedge \mathbf{V}_s \simeq 0$$



Hs=0.9m , θ =10°, mid-tide



Bruneau, Bonneton, Castelle and Pedreros (2008)

Conclusion and perspectives

The rip current mean circulation is driven by wave-energy dissipation gradients, perpendicular to the direction of wave propagation, which are due to non-uniformities along the bore crests

$$\frac{\partial \omega}{\partial t} + \nabla . \left(\omega (\mathbf{U} + \frac{\tilde{\mathbf{M}}}{\bar{h}}) \right) = \underbrace{\nabla \wedge (\mathcal{D} \mathbf{e}_k)}_{\sim \nabla \mathcal{D} \wedge \mathbf{e}_k} + \nabla \wedge \mathbf{V}_s + \nabla \wedge \mathbf{F}_r$$

$$\mathcal{D} = \frac{D_{b_m}}{\bar{h} c_\phi}$$

vorticity (circulation) forcing term

$\mathcal{D}$ and ν_t are the key parameters for describing rip current circulation

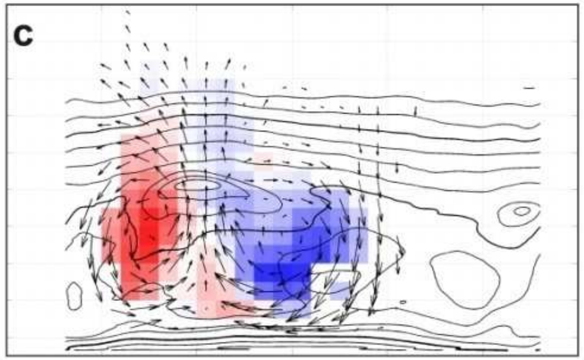
Conclusion and perspectives

Further works are required to better characterize ω, ν_t and $\mathcal{D}$

- ❑ ω, ν_t ⇨ drifter-based method

  - laboratory experiments: e.g. *Castelle et al. (2010)*

  - field experiments: *e.g. MacMahan et al. (2009)*

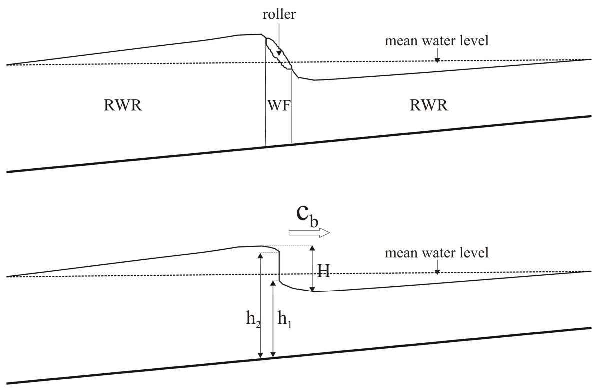


- ❑ $\mathcal{D}$ ⇨ theoretical NSW shock-wave approaches

$$\nabla \wedge (D\mathbf{e}_k)$$

$$\mathcal{D} = \frac{g}{4c_b T}\frac{(h_2 - h_1)^3}{h_2 h_1}$$

Bonneton et al. (2010)



⇨ quantitative experimental validations