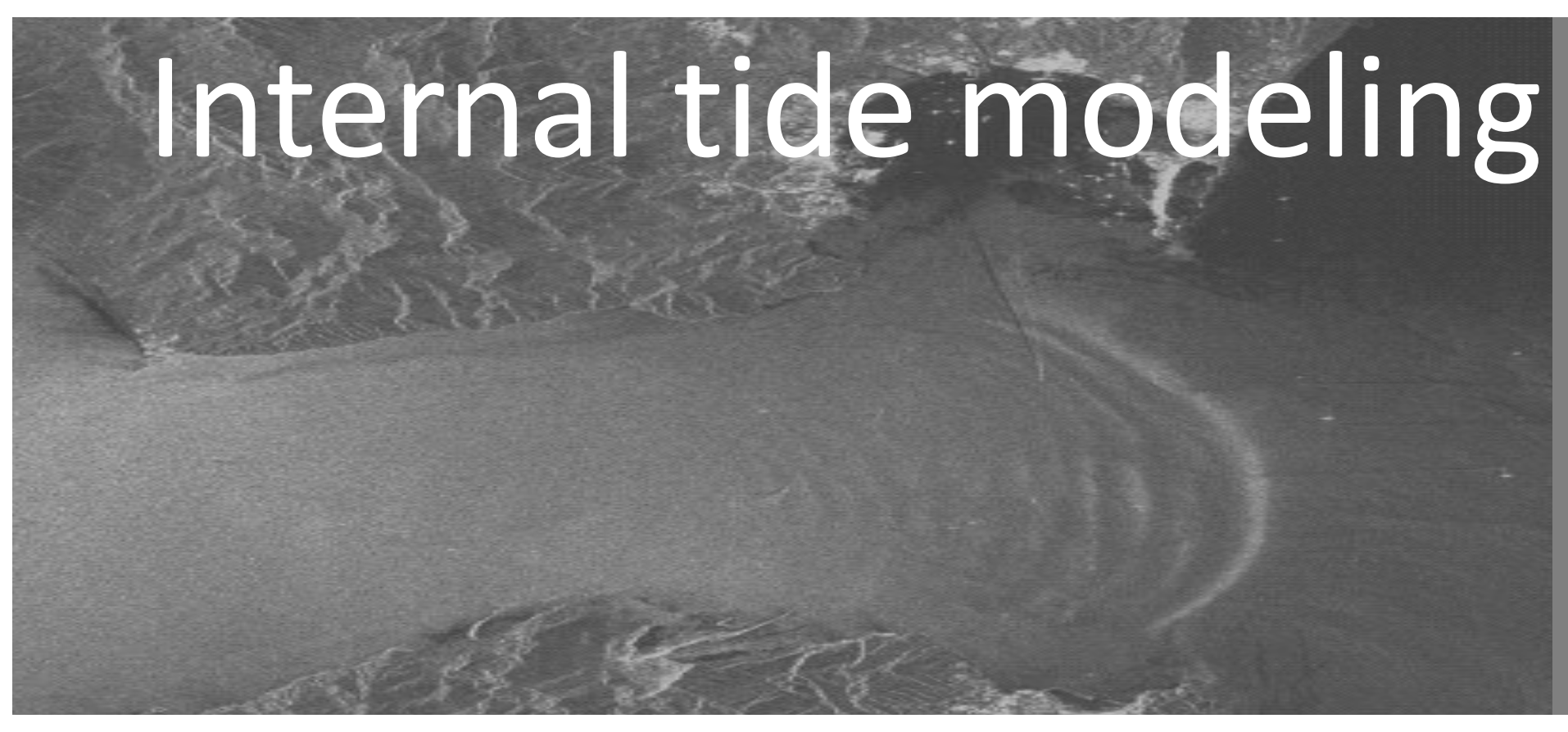
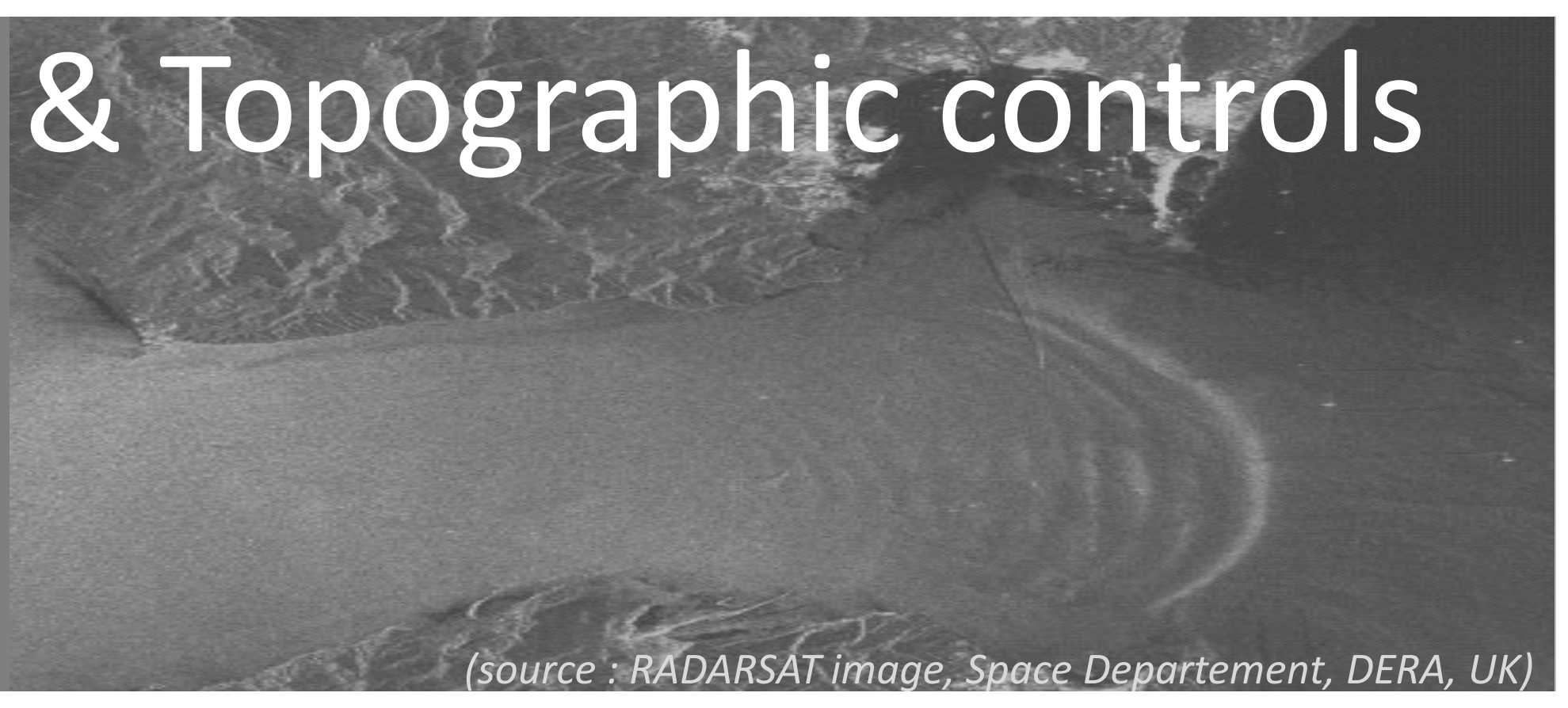


Internal tide modeling from laboratory to ocean scales : Hydraulic & Topographic controls

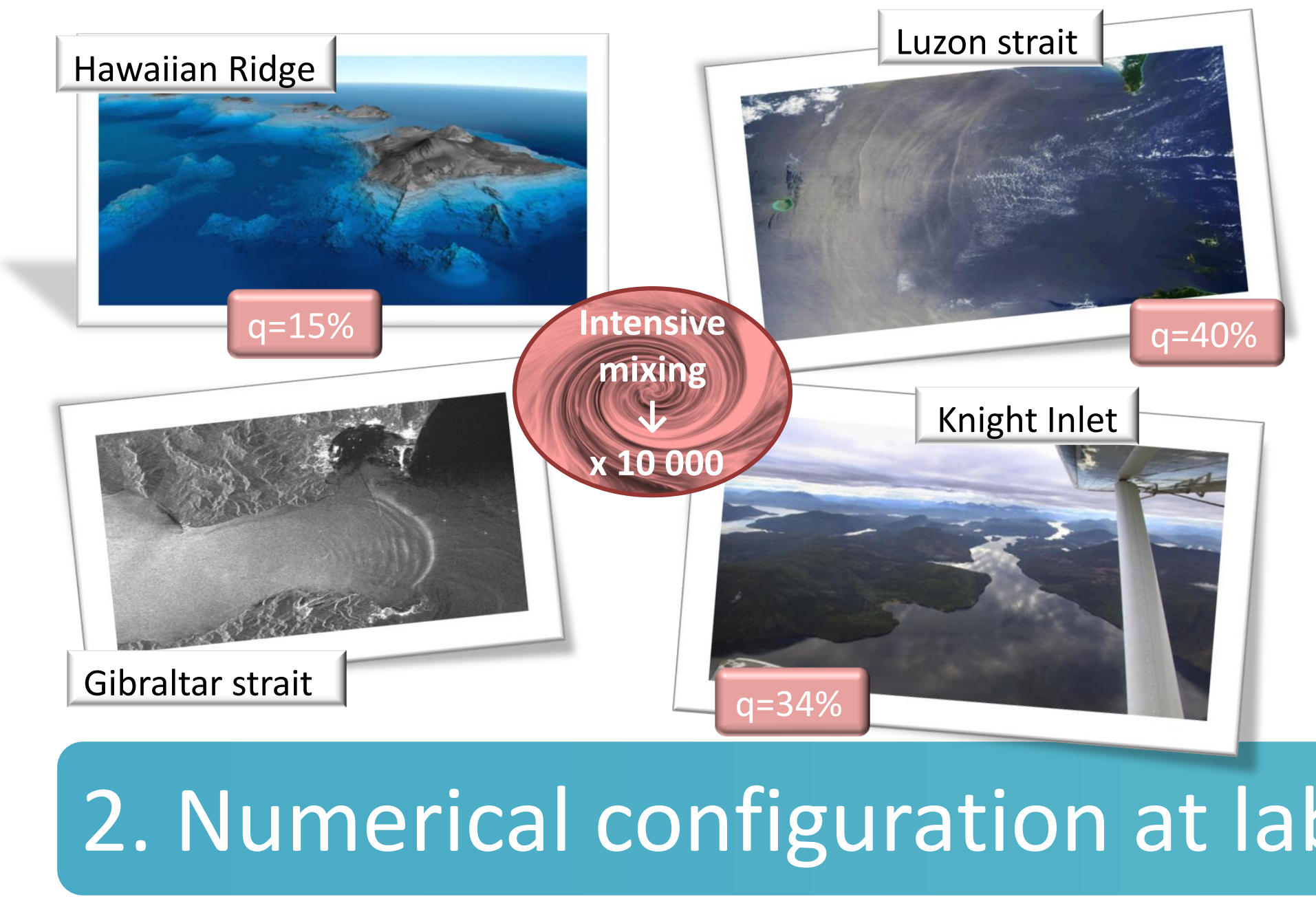
L. Bordois[1, 2]*, F. Auclair[1], A. Paci[2], Y. Dossmann[3], C. Nguyen[1]
*lucie.bordois@aero.obs-mip.fr
[1] Laboratoire d'Aérologie (LA), Toulouse, FRANCE
[2] CNRM-GAME, Toulouse, FRANCE
[3] Laboratoire de Physique, ENS, Lyon, FRANCE



(source : RADARSAT image, Space Departement, DERA, UK)

Introduction : A process study in supercritical regions

Some examples …



Supercritical regions :

- Regions with **supercritical tidal flow** and **supercritical topography**
- Energetic internal tide generation site with intensive mixing
- A diversified mixing distribution (q) related to the multiplicity of processes controlling turbulent mixing in this area

Objective : **describing and identifying the different regimes of internal wave in these regions**

1. Numerical approach : SNH modeling

SNH model resolves the nonhydrostatic & non-Boussinesq equations :

$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho\vec{v}) = 0$	continuity
$\frac{d\rho\vec{v}}{dt} = -\vec{\nabla}P + \rho\vec{g} - 2\rho\vec{\Omega}\Lambda\vec{v} + \rho\nu\Delta\vec{v} + \rho\lambda_{(2)}\vec{\nabla}(\vec{\nabla}.\vec{v})$	momentum
$\frac{d\theta}{dt} = \Phi_\theta$	heat
$\frac{dS}{dt} = \Phi_S$	salinity
$\rho = \rho(\theta, S, P)$	state

Features of SNH model :

⇒nonhydrostatic[1]
⇒non-Boussinesq[2]
⇒high resolution
⇒free surface
⇒Moving bottom[3]

Time splitting

Non-Boussinesq mode		External mode		Internal mode
Δt_{NBQ}	<<	Δt_{EXT}	<<	Δt_{INT}

2. Numerical configuration at laboratory scale

Laboratory scale (DNS)

2 D vertical
No rotation
Tidal forcing : sinusoïdal ridge oscillation
Stratification : three-layer
Resolution : dx≈1-2 mm, 60-100 sigma levels
Molecular diffusion and viscosity :
$\nu = 10^{-6}$ m²/s, $K_p = 10^{-7}$ m²/s

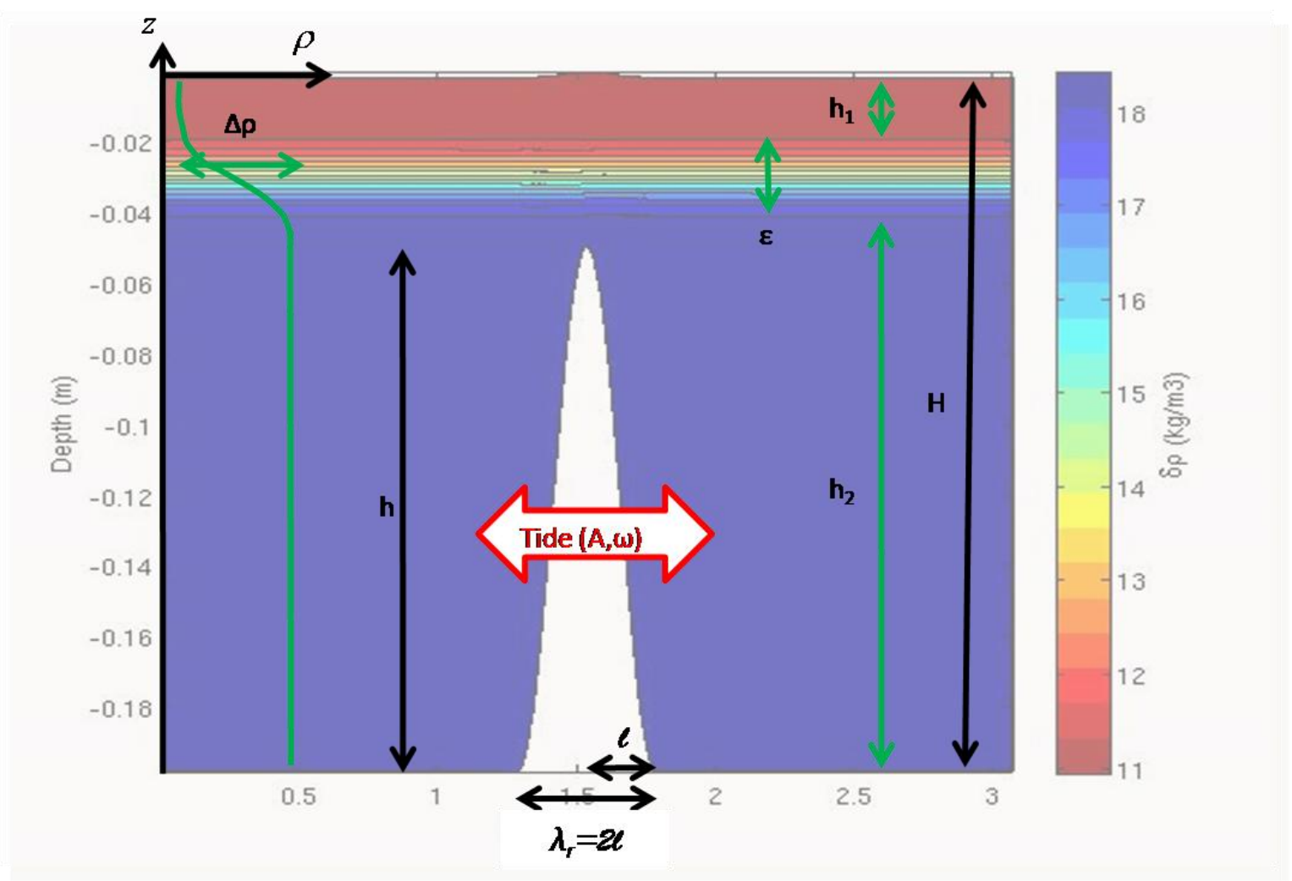


Fig. *Vertical section of the density at t=0 s. Variable physical and geometrical parameters in our numerical configurations.*

Focus on **non-linear internal waves** propagating along the **pycnocline** and emitted **primarily** in « **supercritical regions** » :

- Hydraulic control (supercritical tidal flow)
- Strong interaction between the pycnocline and the topography (efficient primary generation)
- Supercritical slope
- Strong non linearities leading to internal solitary wave (ISW) formation

Key parameters

Modal Froude number
$F_n = U_{tide} / c_n \geq 1$

Topographic blocking degree
$B = h / h_2 \geq 0.6$[4]

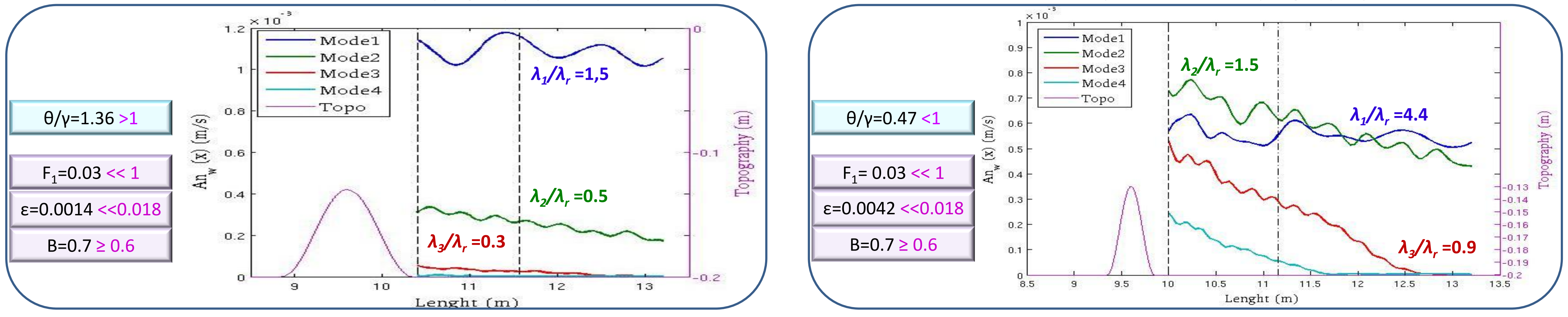
Supercritical slope
$\theta / \gamma < 1$

Non-linearity parameter
$\varepsilon = Ah/lH \geq 0.018$[5]

3. Topographic control on vertical mode generation

Linear regime

Above subcritical topography | Above supercritical topography



Above subcritical topography:
$\theta/\gamma=1.36 > 1$
$F_1=0.03 << 1$
$\varepsilon=0.0014 << 0.018$
$B=0.7 \geq 0.6$

Above supercritical topography:
$\theta/\gamma=0.47 < 1$
$F_1= 0.03 << 1$
$\varepsilon=0.0042 << 0.018$
$B=0.7 \geq 0.6$

Fig. *Orthogonal projection of vertical velocity modes profiles calculated with modal decomposition method on **Sim0** (subcritical topography) and on **Sim1** (supercritical topography) vertical velocity field for 80-110 second period*

⇒ Topographic control on vertical mode generation : a resonance phenomenon : A_n maximal for $\lambda_n/\lambda_r \approx 1$

⇒A « strong » multimodal structure above supercritical topography : $A_n \neq 1/n$

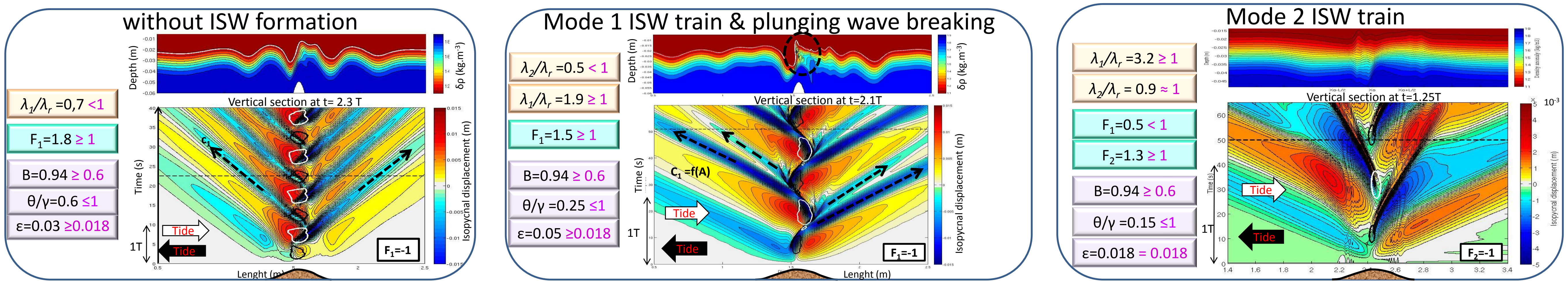
⇒ Another key parameter :

Topographic criterion
$\lambda_n / \lambda_r \geq 1$

4. Topographic control on soliton formation

Non-Linear regime

mode 1 hydraulic control | Mode 2 hydraulic control



Without ISW formation:
$\lambda_1/\lambda_r = 0,7 < 1$
$F_1=1.8 \geq 1$
$B=0.94 \geq 0.6$
$\theta/\gamma=0.6 \leq 1$
$\varepsilon=0.03 \geq 0.018$

Mode 1 ISW train & plunging wave breaking:
$\lambda_2/\lambda_r = 0.5 < 1$
$\lambda_1/\lambda_r = 1.9 \geq 1$
$F_1=1.5 \geq 1$
$B=0.94 \geq 0.6$
$\theta/\gamma = 0.25 \leq 1$
$\varepsilon=0.05 \geq 0.018$

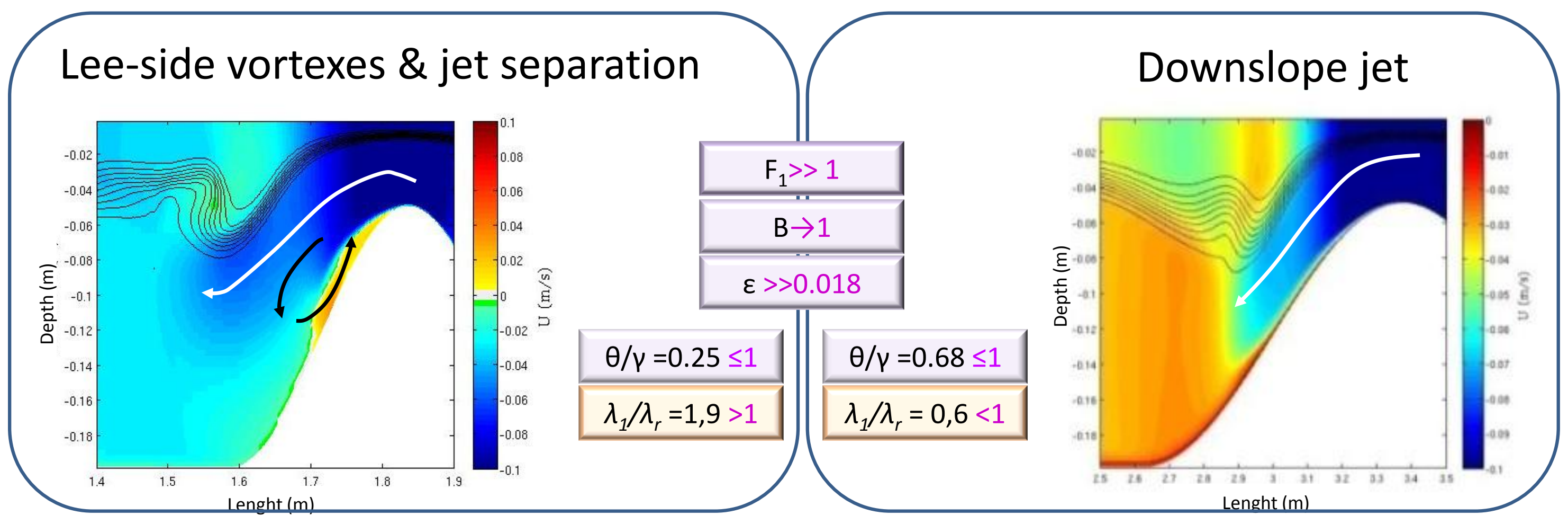
Mode 2 ISW train:
$\lambda_1/\lambda_r = 3.2 \geq 1$
$\lambda_2/\lambda_r = 0.9 \approx 1$
$F_1=0.5 < 1$
$F_2=1.3 \geq 1$
$B=0.94 \geq 0.6$
$\theta/\gamma = 0.15 \leq 1$
$\varepsilon=0.018 = 0.018$

Fig. *Vertical section of the pycnocline (upper) and space-time diagram of the vertical isopycnal displacement (lower) for δρ =12 kg/m3 (white line on the vertical section) in **Sim3**, **Sim4** (mode1 hydraulic control) and **Sim5** (mode 2 hydraulic control). White and black contour lines locate modal Froude number of minus one and one. Horizontal bold dashed line locates temporally the vertical section of the pycnocline.*

Hydraulic & topographic control on :
⇒ISW formation (appling to all modes)
⇒Breaking event (kinematic instability)
⇒ Vertical mode propagation

5. Instabilities : vortexes and jet formation

Lee-side vortexes & jet separation | Downslope jet



$F_1 >> 1$
$B \rightarrow 1$
$\varepsilon >> 0.018$

Lee-side vortexes & jet separation:
$\theta/\gamma = 0.25 \leq 1$
$\lambda_1/\lambda_r = 1,9 > 1$

Downslope jet:
$\theta/\gamma = 0.68 \leq 1$
$\lambda_1/\lambda_r = 0,6 < 1$

Fig. *Vertical section of two highly non-linear simulations, at t=34.5 s. The tidal flow is leftward. Color bar represents horizontal velocity output highlighting hydraulic control regions ($u<c_1$= - 0.025 m/s). Contour lines represent isopycnal lines.*

6. Gibraltar strait configuration

Ocean scale (LES)

2.5 D vertical
Earth's rotation
Tidal forcing : at lateral boundaries (M2)
Resolution : 50<dx<150 m, 20 σ levels
Numerical diffusion and viscosity :
$\nu = 2.10^{-6}$ m²/s, $K_p = 10^{-6}$ m²/s

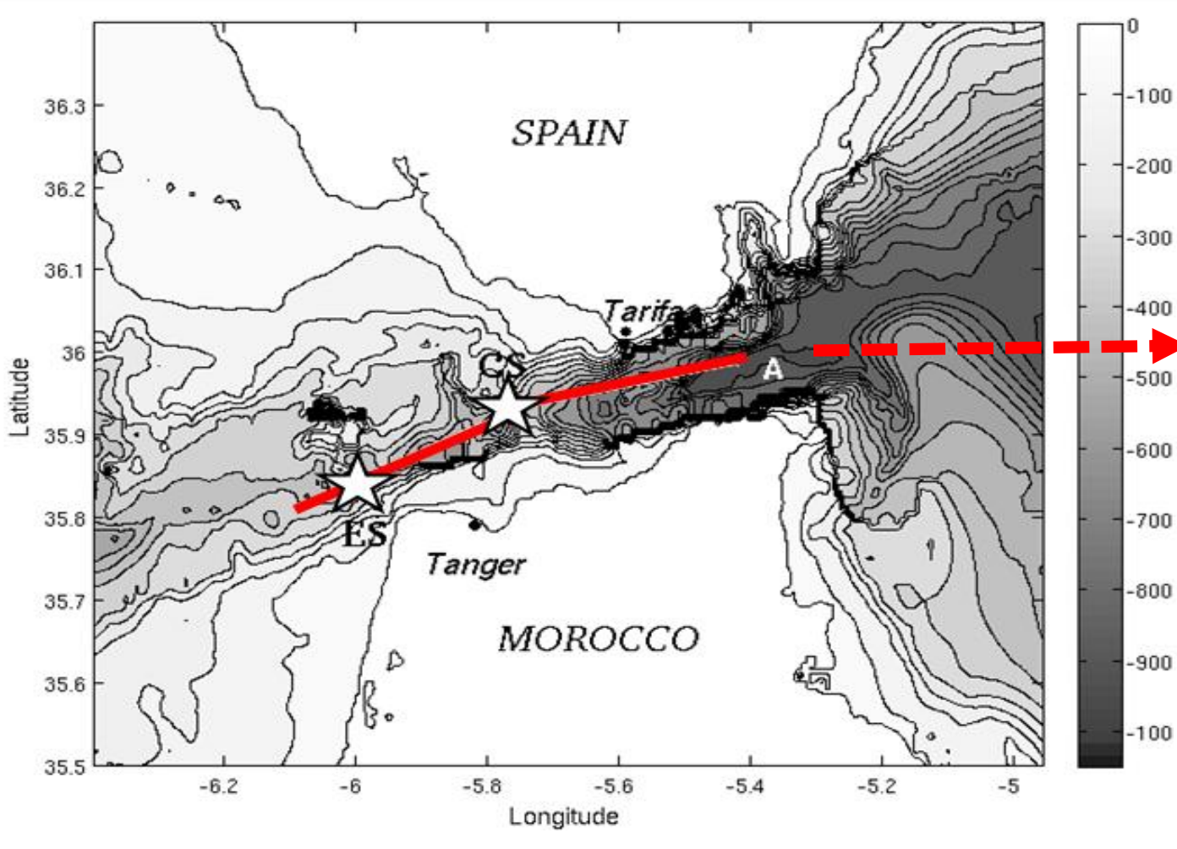


Fig. *Bathymetry of the strait of Gibraltar, location of the transect A used in **SimGBR0** and location of Camarinal Sill (CS), Espartel Sill (ES)*

Ship trajectory (Gibraltar Experiment[6], Avril 1986)

« Lock exchange » initialization[7]

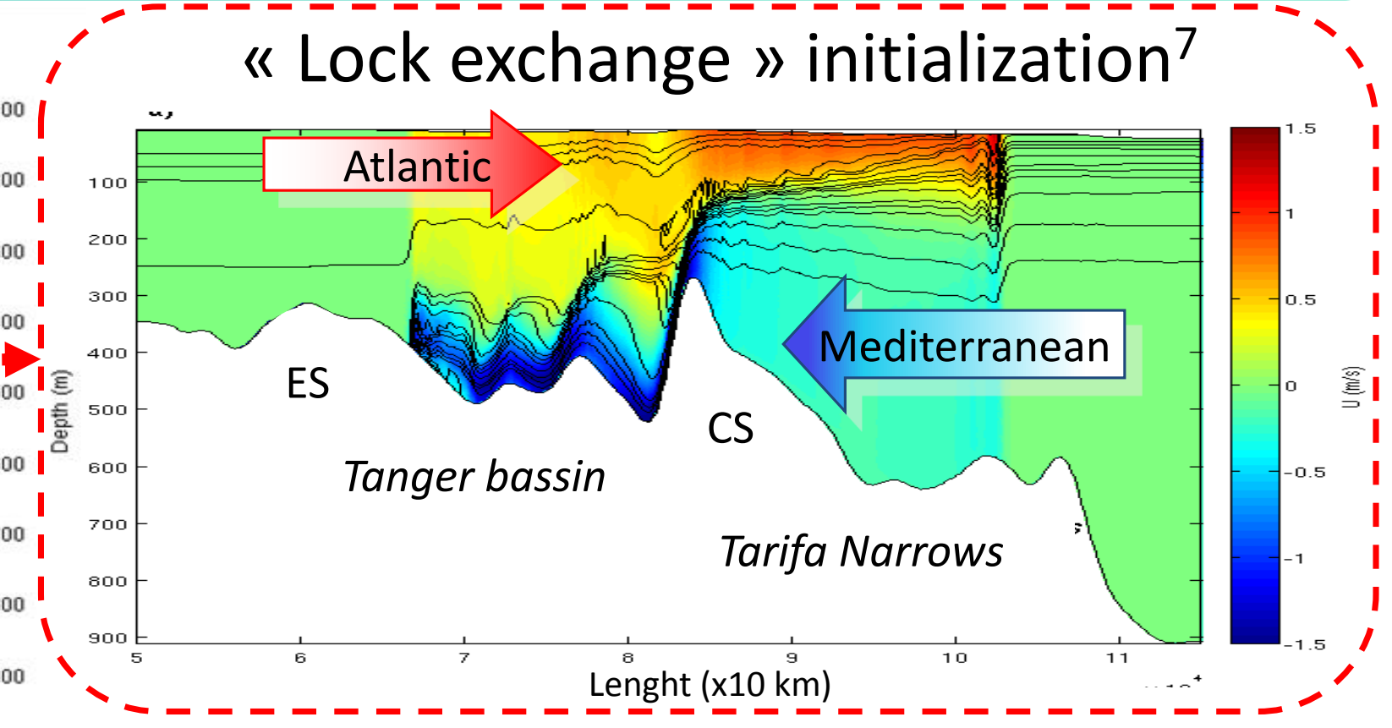


Fig. *Vertical section of the density at t=4h during the spin-up phase (no tidal forcing) and model bathymetry in **SimGBR0**. Color bar represents horizontal velocity output highlighting gravity currents and fronts induced by the lock exchange initialization.*

7. Internal tide dynamics at Gibraltar strait : a supercritical region

Above CS

$\lambda_3/\lambda_r \in [0.8;1,4] \approx 1$
$\lambda_2/\lambda_r \in [1,4;2,3] > 1$
$\lambda_1/\lambda_r \in [3.8;5.2] > 1$

$Max(F_1) = 1.1 \geq 1$
$Max(F_2) \approx 2.8 \geq 1$

$B \approx 0.75 \geq 0.6$

$\theta/\gamma \in [0.14;0.5] \leq 1$

$\varepsilon \approx 0.1 \geq 0.018$

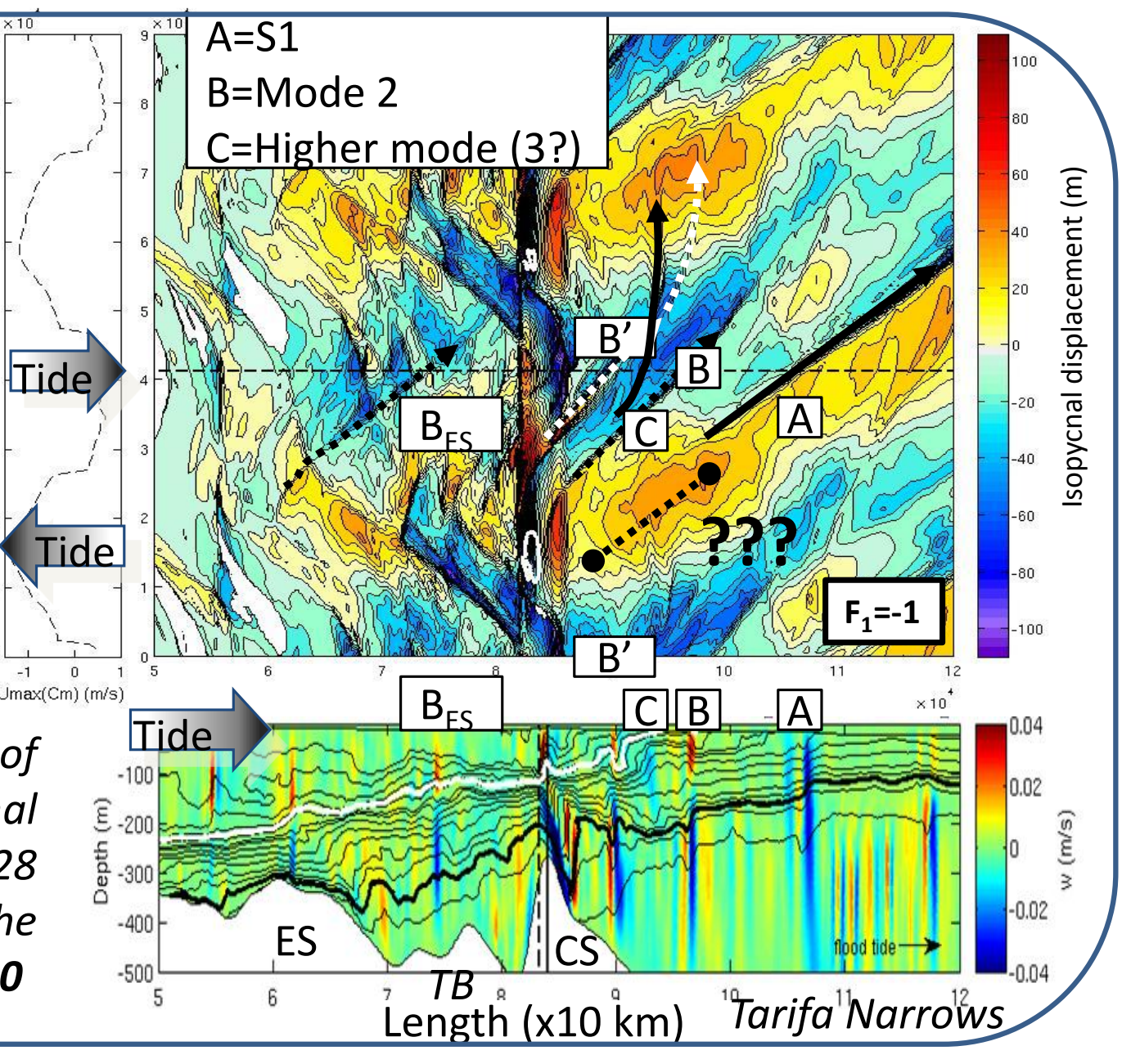


Fig. *Space-time diagram of the vertical isopycnal displacement for ρ=1028 kg/m3 (black line on the vertical section) in **SimGBR0***

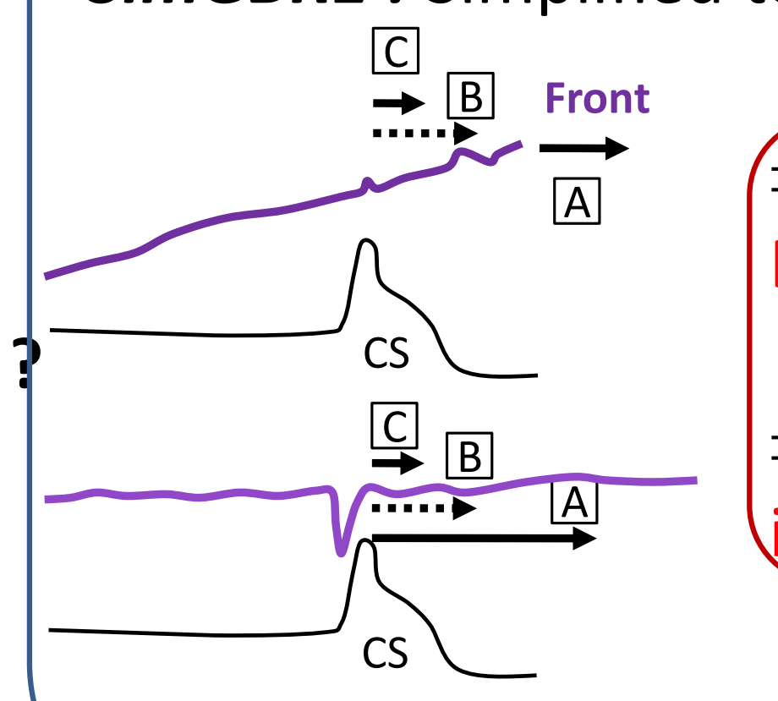
⇒Mode 1 soliton train [A] above TN
⇒Two modes 2 [B] & [B'] above TN
⇒Mode 2 [B_{ES}] generated above ES

Why two modes 2 [B] & [B'] above TN ?

Where and how is generated [A] ?

Two simplified configurations

SimGBR1 : Simplified topography



⇒Generation of B' related to ES (B_{ES})

⇒A propagation or generation impacted by the frontal area

SimGBR2 : Simplified topography & stratification

A complex multimodal structure

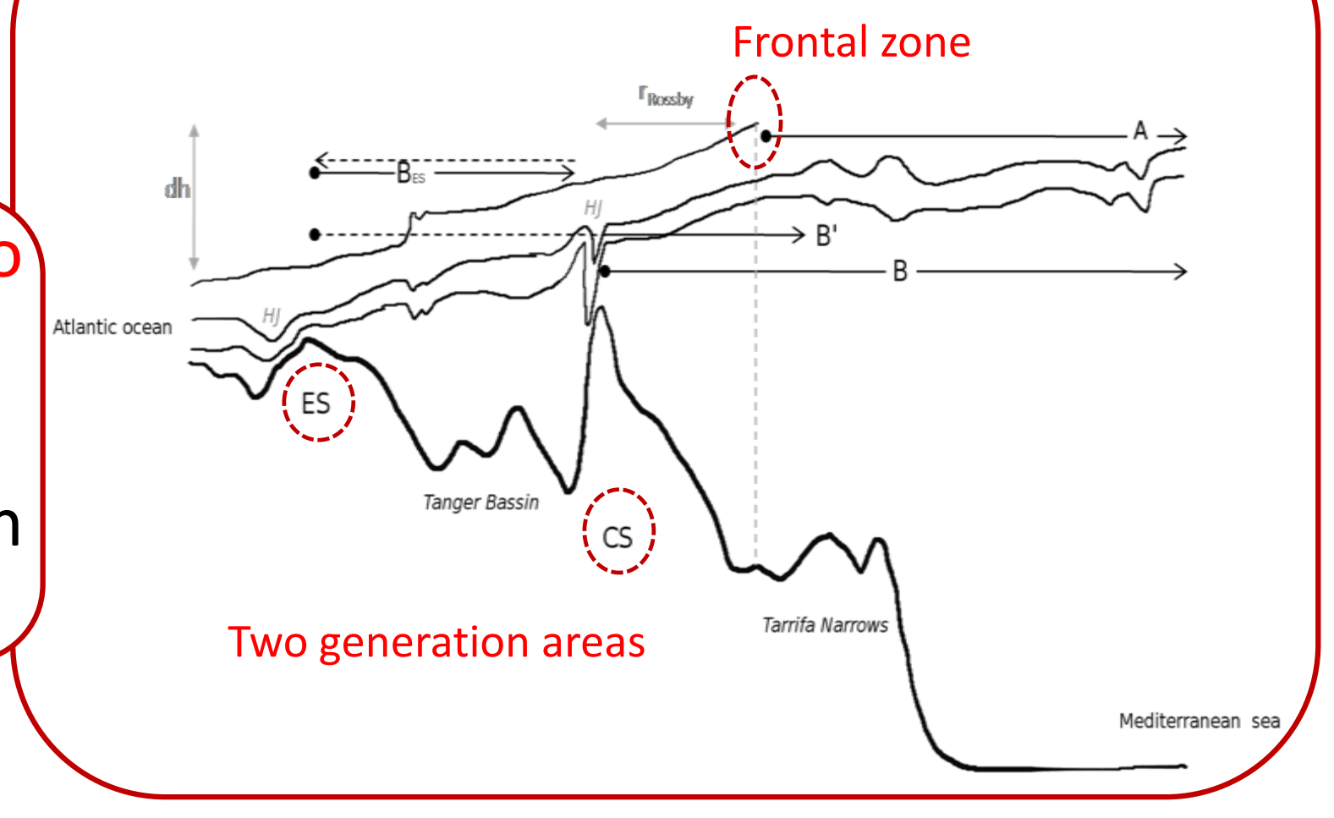


Fig. *Schematic of internal wave dynamics above Gibraltar strait (transect A) for a moderate tidal forcing*

Conclusions

⇒Identification and adaptation of key parameters for supercritical region dynamics
⇒Regions caracterised by a complex multimodal structure
⇒Strong interactions between internal tides – topography and tidal current above supercritical regions : hydraulic and topographic controls on vertical mode generation, propagation, ISW formation and instabilities.

References

[1] F. Auclair, C. Estournel, J.W. Floor, M. Herrmann, C. Nguyen, and P. Marsaleix, "A Non-Hydrostatic Algorithm for Free-Surface Ocean Modelling", Ocean Model., **36, 49 (2011).**
[2] F. Auclair, L. Bordois, Y. Dossmann, T. Duhaut, A. Paci, C. Ulses, and C. Nguyen, "A Non-Hydrostatic Non-Boussinesq Algorithm for Free-Surface Ocean Modelling", Ocean Model., in revision, (First submitted 2014).
[3] F. Auclair, L. Bordois, Y. Dossmann, T. Duhaut, C. Estournel, J.W. Floor, P. Marsaleix, C. Nguyen, A. Paci, and C. Ulses, "Implementation of a Time-Dependent Bathymetry in a Free-Surface Ocean Model: Application to Internal Wave Generation", Ocean Model., **80, 1 (2014).**
[4] V. Vlasenko, N. Stashchuk, and K. Hutter, *Baroclinic Tides: Theoretical Modeling and Observational Evidence (Cambridge University Press, 2005).*
[5] Y. Dossmann, F. Auclair, and A. Paci, "Topographically Induced Internal Solitary Waves in a Pycnocline: Primary Generation and Topographic Control", Phys. Fluids, **25, 066601 (2013).**
[6] D.M. Farmer, L. Armi, L. Armi, and D.M. Farmer, "The Flow of Atlantic Water through the Strait of Gibraltar", Prog. Oceanogr., **21, 1 (1988).**
[7] Sannino, G., Bargagli, A. & Artale, V. "Numerical modeling of the mean exchange through the Strait of Gibraltar. *J," Geophys. Res. Oceans* ***107, 9–1 (2002).***

NewWave : New challenges in internal wave dynamics
14-16 Oct 2015 Lyon (France)