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## **LES Modelling of the Impact of the Topography on Large-scale Exchange Flow in the Strait of Gibraltar**

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## Small-Scale dynamics of the Strait of Gibraltar

The Strait of Gibraltar connects the North Atlantic and the Mediterranean Sea. It is a narrow and shallow area where **intense mixing** changes the characteristics of Mediterranean and Atlantic waters<sup>1</sup>. Several small-scale (< 1 km) phenomena contribute to this mixing :

- Small amplitude internal gravity waves at the interface of Atlantic and Mediterranean waters.
- Hydraulic control at Camarinal Sill (and other locations) caused by tidal currents : an **hydraulic jump** is formed<sup>2</sup>.
- Shear instabilities in the Mediterranean vein<sup>3</sup>.
- The hydraulic jump is released during inflowing conditions and propagates eastward as a train of **Internal Solitary Waves (ISWs)**<sup>2</sup>.

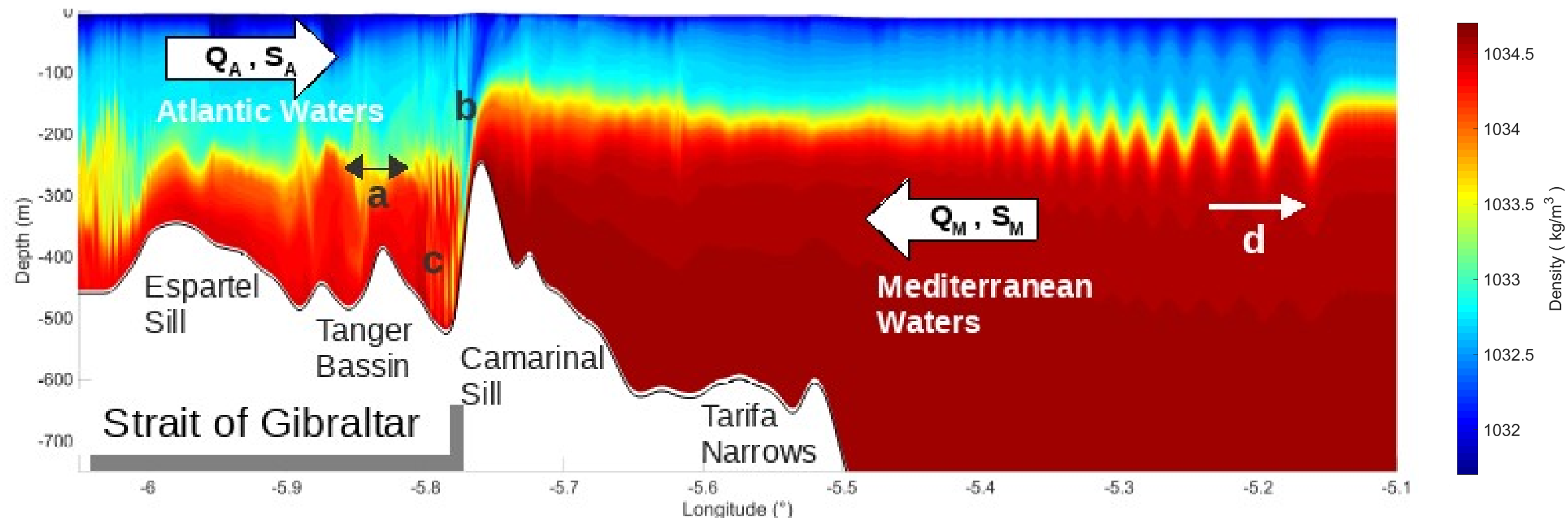


Fig. 1 : Vertical section of density in the longitudinal direction along the Strait of Gibraltar.

## Numerical Model : CROCO-NBQ

- CROCO is a free-surface, compressible, NH ocean model based on ROMS-AGRIF.
- NH pressure computed in "Fast Mode"<sup>4,5</sup>.
- Configuration based on a SHOM HR bathymetry.
- Initialization and lateral forcing from the ENEA Mediterranean and black Sea forecasting system<sup>6</sup>.

Domain	6°4.8'W 5°3.4'W ; 35°23.8'N 36°27.4'N	
Number of horizontal grid points ( $\Delta t_s, N_t, C_s$ )	2049 x 2621 (1 s, 11, 400 m/s)	
Number of vertical sigma levels	40	
Horizontal resolution dx	45 m	
Depth	Minimum	Maximum
	26 m	960 m
Vertical resolution	0.7 m	
Advection scheme	WENO-5	
Tidal components	M <sub>2</sub> , S <sub>2</sub> , H <sub>1</sub> , O <sub>1</sub>	
Turbulent closure scheme	Smagorinski or k-ε or no-closure scheme ( $K_p = \nu = 10^{-6} \text{ m}^2/\text{s}$ )	
Simulation period	September 2017 (2 days)	

Table 1 : Main parameters of simulations.

## Detection of coherent turbulent structures

Billows of primary shear instabilities are detected for positive values of **Q-parameter**, second invariant of velocity gradient<sup>7</sup> :

$$Q = -\frac{1}{2} \frac{\partial u_i \partial u_j}{\partial x_j \partial x_i} = \frac{1}{2} (\Omega_{ij} \Omega_{ij} - S_{ij} S_{ij})$$

In outflowing conditions, patches of  $Q > Q_{\min}$  appear west of Camarinal Sill at the shear interface and are characterised by a roll-up of salinity. They are advected westward by the Mediterranean outflow.

## Detection of Hydraulic Jump

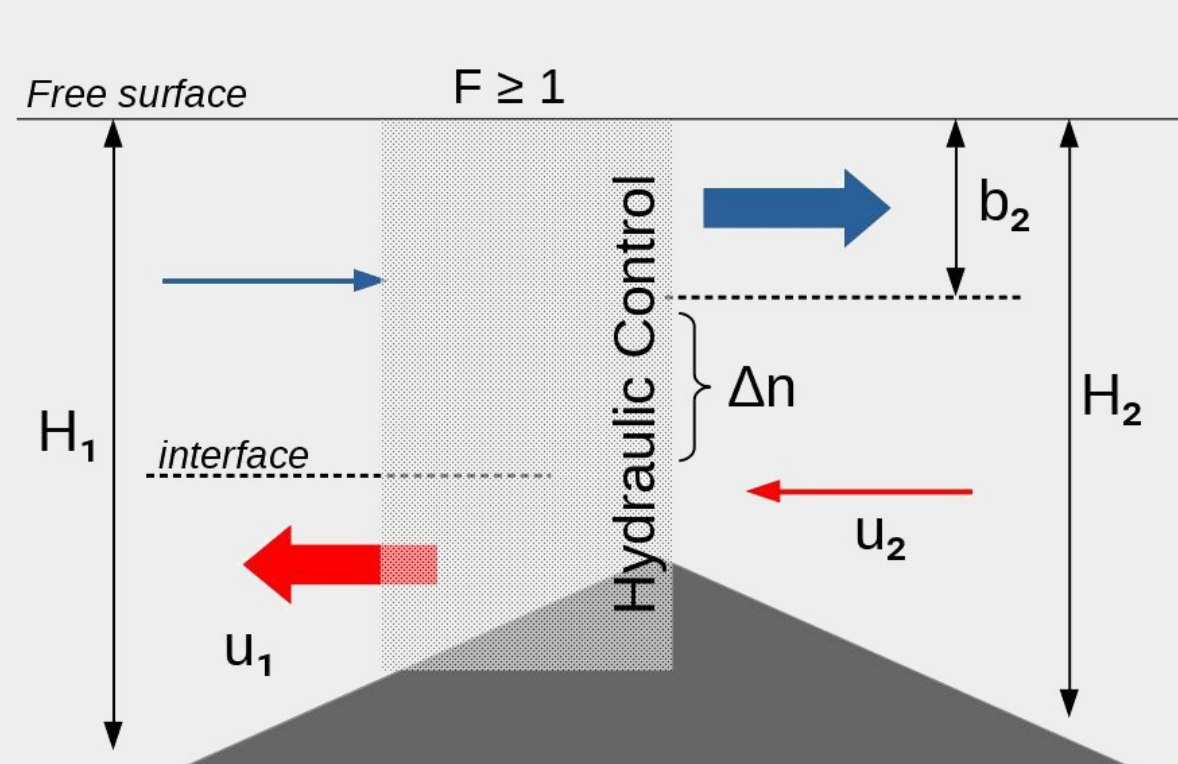


Fig. 2 : Schematic of hydraulic control over Camarinal Sill.

Flow criticality :  $F = \frac{u_1^2}{c^2} \geq 1$

Interface discontinuity : Acceleration of surface and bottom layers: detection if  $\Delta u_{\text{croco}} \geq \Delta u_{\text{theo}}$

$$\Delta u_s = -u_1 \frac{\Delta n}{b_2}, \quad \Delta u_b = -u_1 \frac{\Delta H + \Delta n}{H_2 - b_2}$$

$$|u_1| = c = \sqrt{g' \frac{(H_1 - \Delta n - b_2)(\Delta n + b_2)}{H_1}}$$

$b_2 \sim 50 \text{ m}, \Delta n \sim 20 \text{ m}, g' \approx 0.02 \text{ m/s}^2$

## Hydraulic Jump variability

LES of hydraulic control of large-scale circulation at Camarinal Sill.

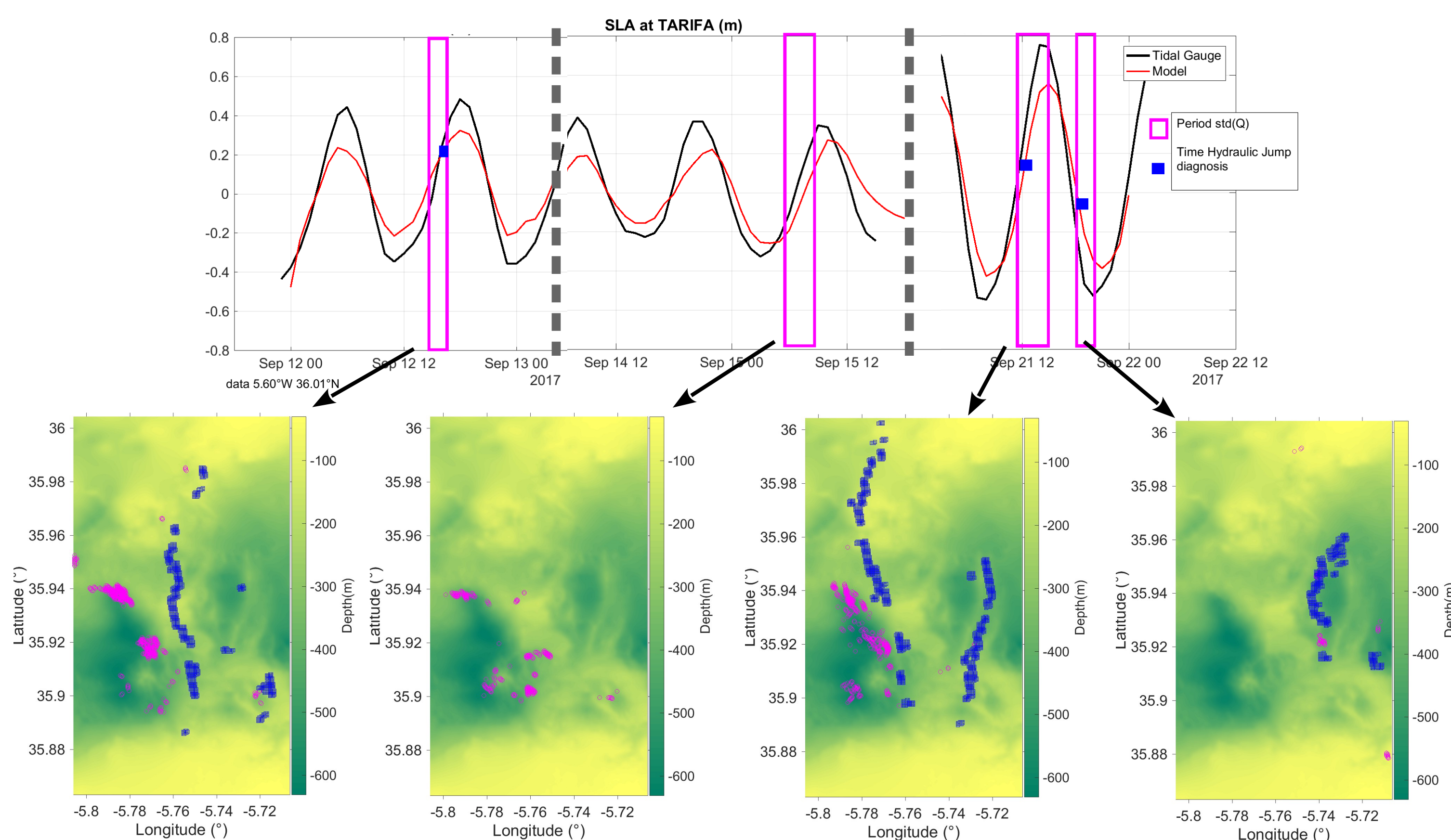


Fig. 4 : Tracking of hydraulic jumps and shear instabilities for several tidal regimes.

Upper panel : Sea level anomaly (cm) at Tarifa tidal gauge (black) and in the simulations (red). Pink rectangles : standard deviation of parameter Q. Blue squares : hydraulic jump.  
Lower panels : Bathymetry, (○) location of large values of standard deviation of Q in the water column, indicating where coherent structures propagate, and (□) position of hydraulic jumps indicated by  $\Delta u_{\text{croco}} \geq \Delta u_{\text{theo}}$  in both first and last vertical levels.

## Dynamics of coherent turbulent structures

LES of Kelvin-Helmholtz instabilities inducing mixing of water masses.

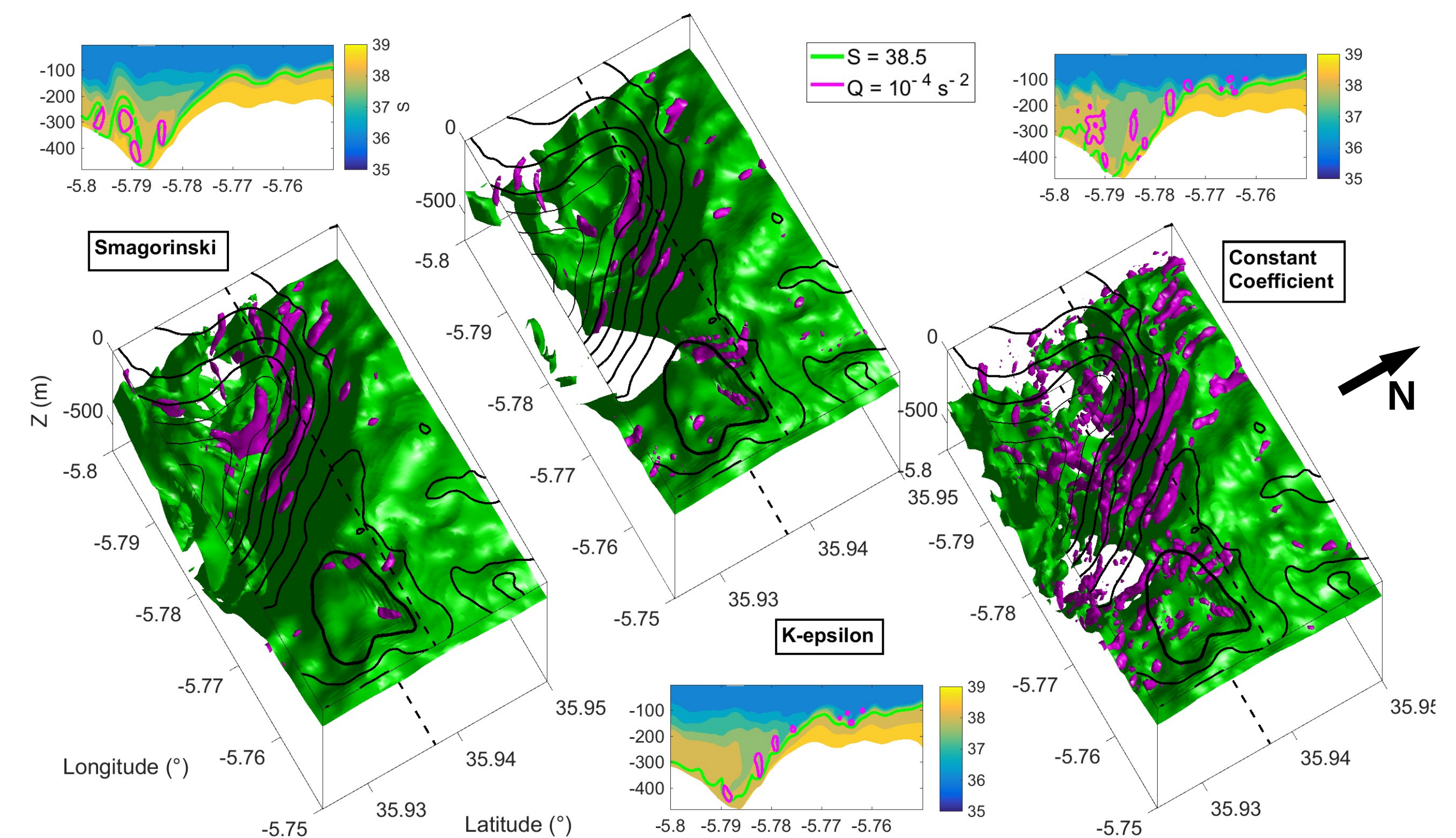


Fig. 3 : Sensitivity to turbulent closure schemes.

Isobathes (black), surface of constant salinity (green) & Q-parameter (pink) and vertical section of salinity for simulations (12/09/2017 - 3h40am) with different turbulent closure schemes (from left to right : Smagorinski, K-ε, and constant dissipation coefficients).

## Dynamics of Internal Solitary Waves

LES of the generation, propagation and reflection of ISWs.

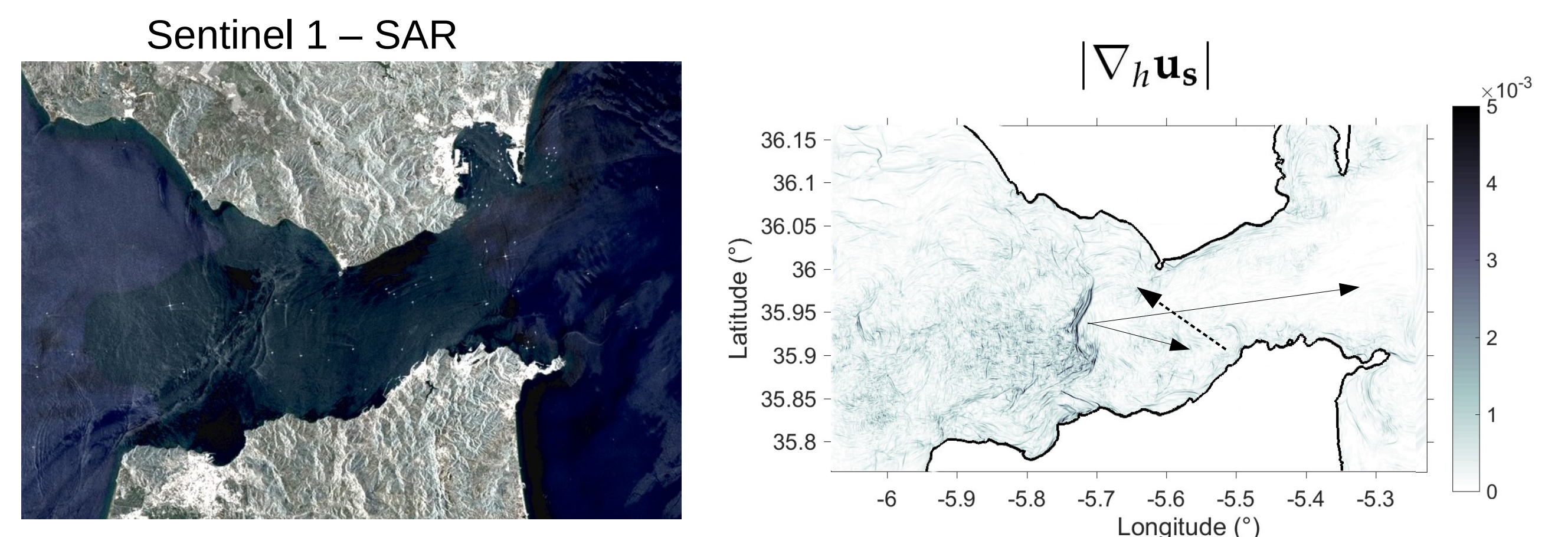


Fig. 5 : Comparison SAR / Simulation.

Left : Sentinel-1 Synthetic Aperture Radar (SAR) image (12/09/2017 - 6h18pm UTC).  
Right : Norm of the gradient of surface horizontal velocity ( $\text{s}^{-1}$ ) in the simulation (12/09/2017 - 6h30pm) and path of the ISW (reflection in dashed arrow).

## Perspectives : Gibraltar 2020 Campaign

- Observing the small-scale physics in the Strait of Gibraltar
- Assessing the effect of different numerical schemes on mixing in the Strait

In September-October 2020, the field campaign GEPETO aims at making direct observations of hydraulic jumps, coherent mixing structures and ISWs.

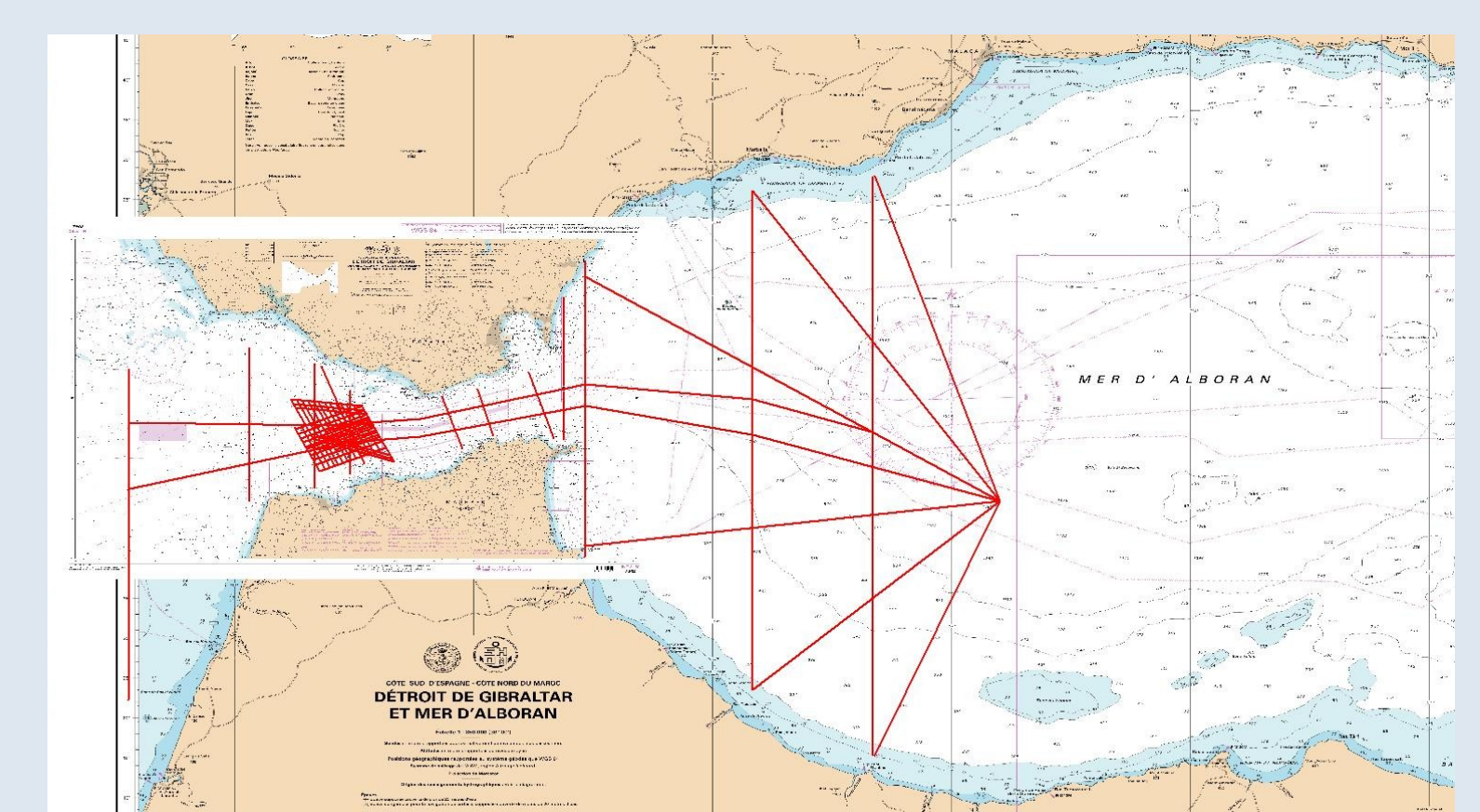


Fig. 6 : Potential radials for campaign GEPETO

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