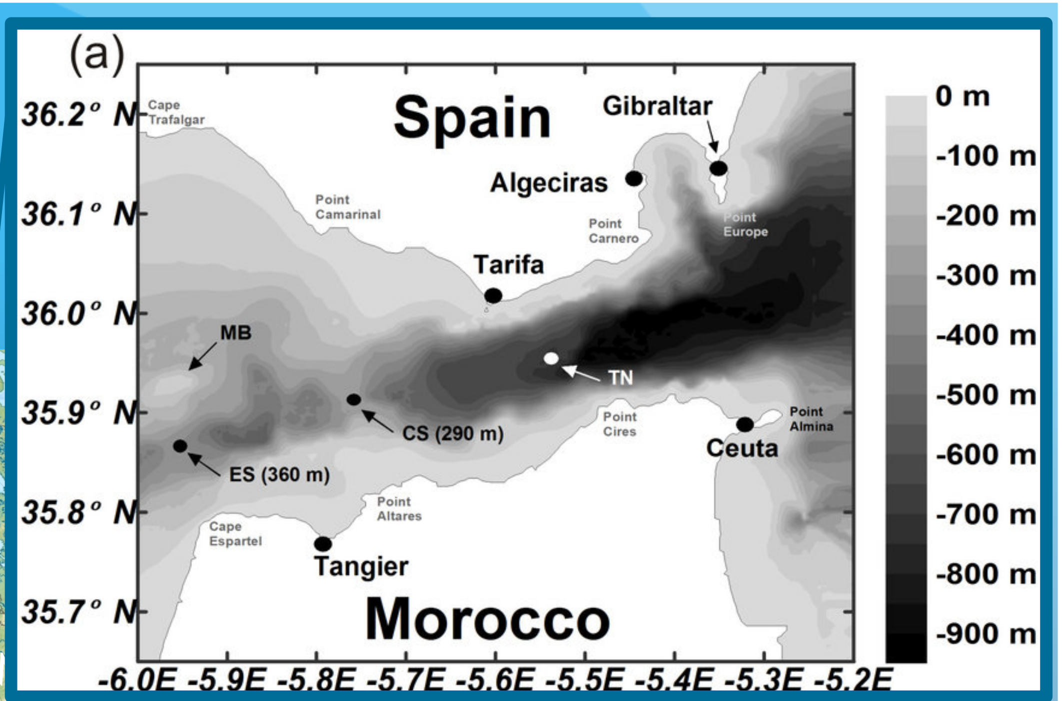
Dynamics of the strait of Gibraltar
Application of the CROCO NBQ module

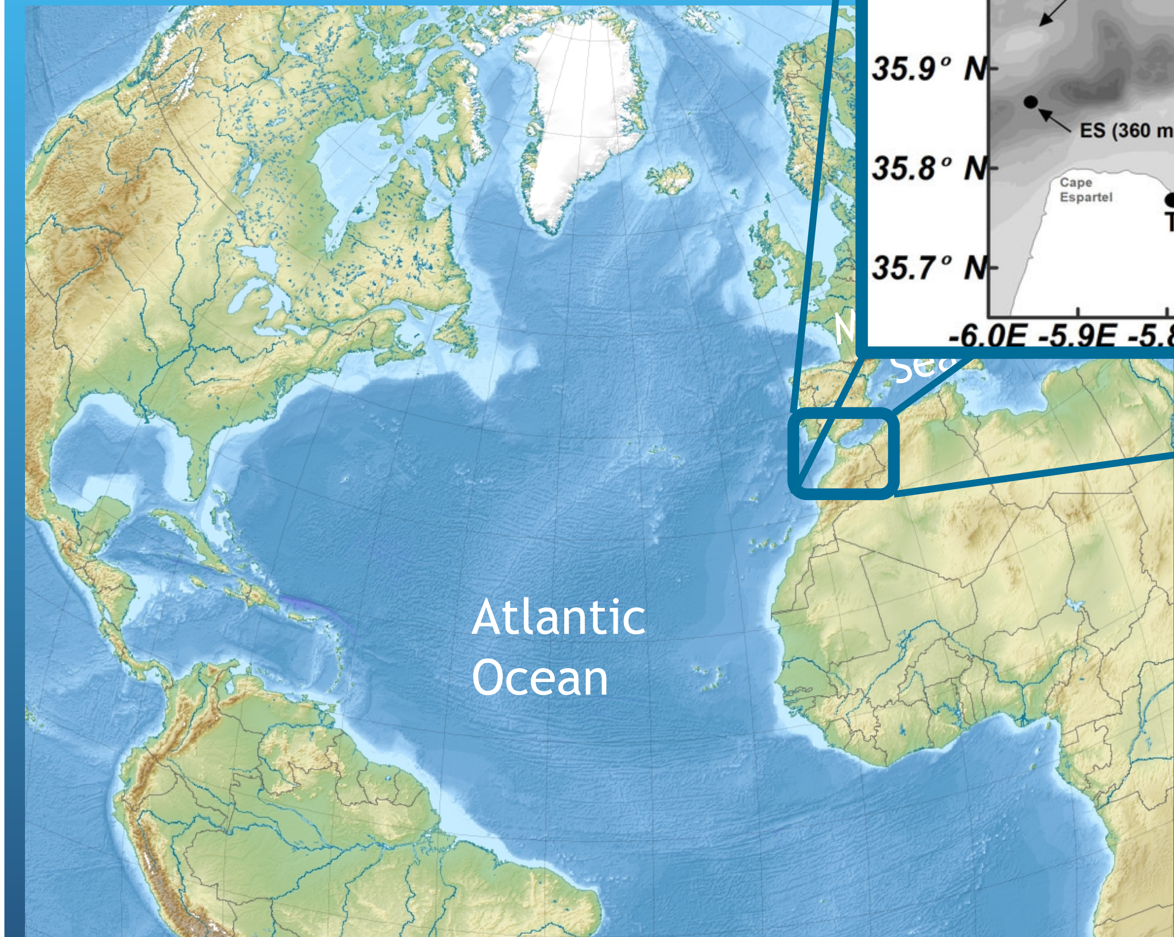
Laurent ROBLOU, F. AUCLAIR, M. HILT, C. NGUYEN, Y. SOUFFLET - LAERO
L. BORDOIS, F. DUMAS - Shom
P. MARCHESIELLO – LEGOS

Croco advanded summer School, 17-21 January 2022

Context



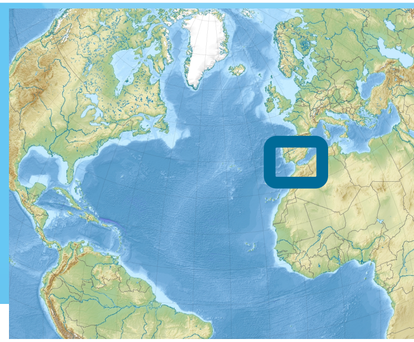
Sanchez-Roman et al., 2018

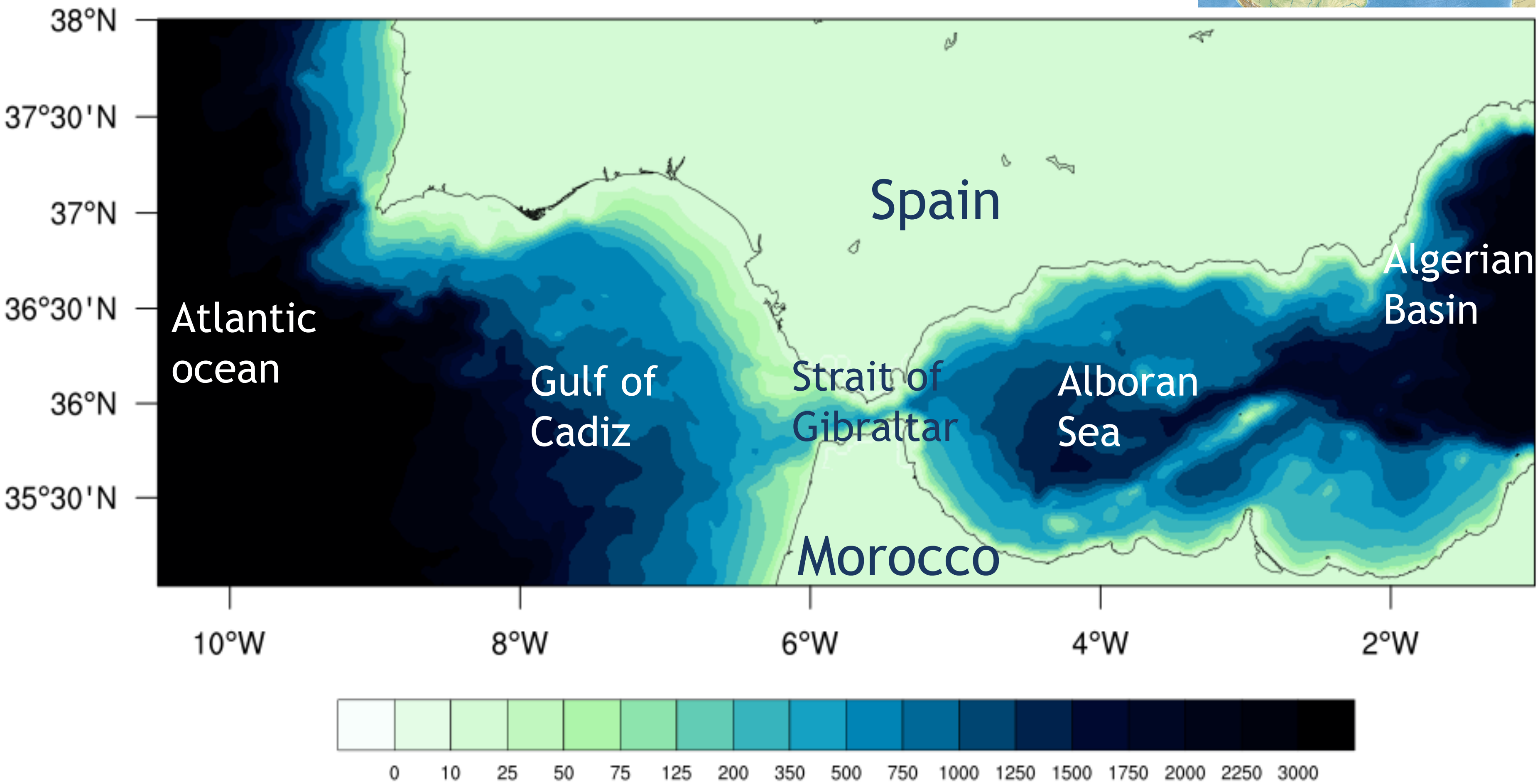


Credits: Uwe Dedering - Own work, CC BY-SA 3.0

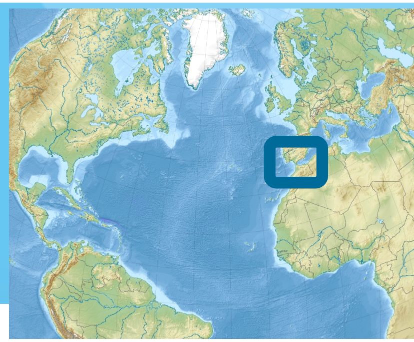
- Unique entrance of the Mediterranean Sea
- Important activities
- Narrow water passage

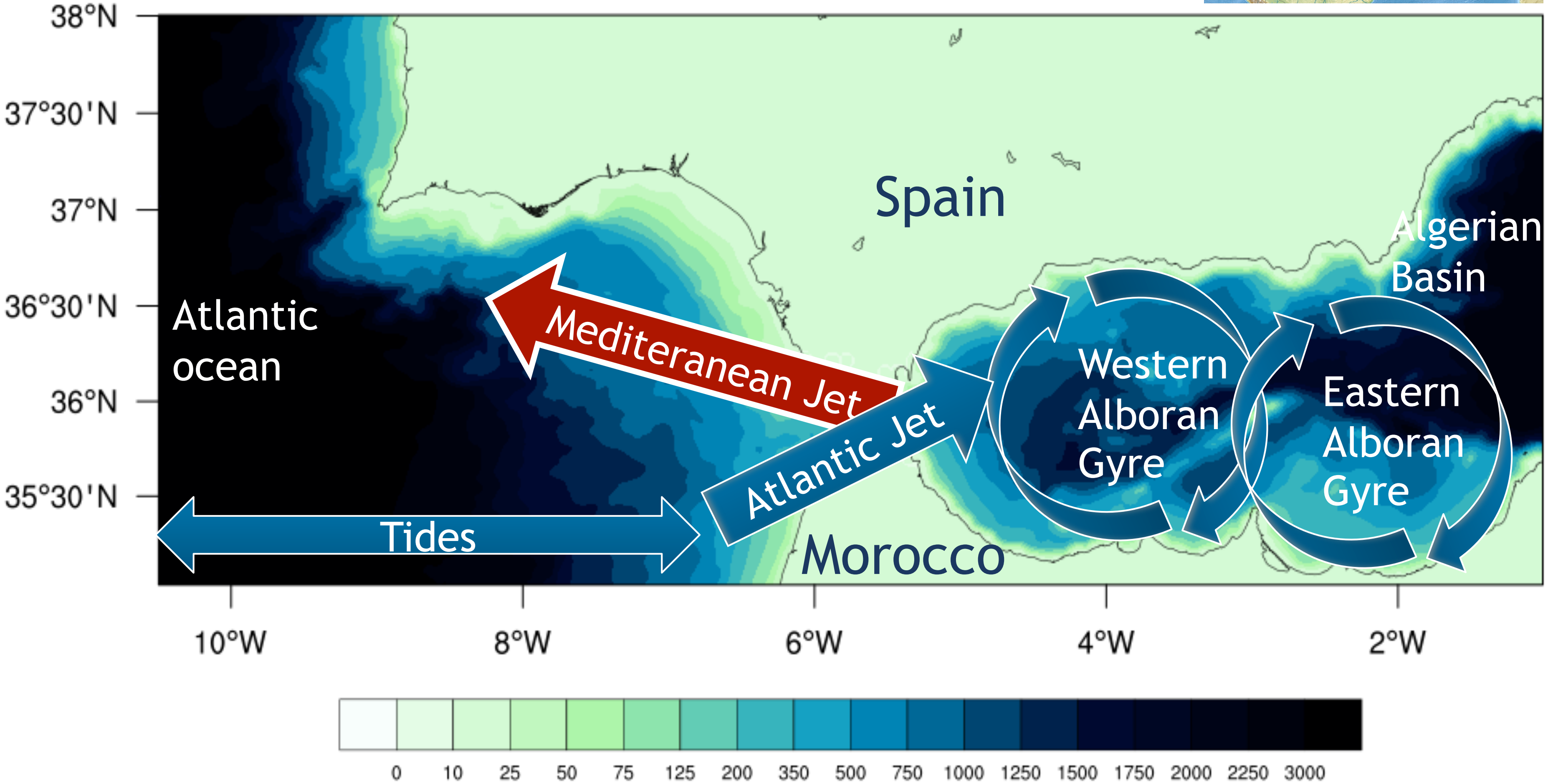
Regional ocean circulation





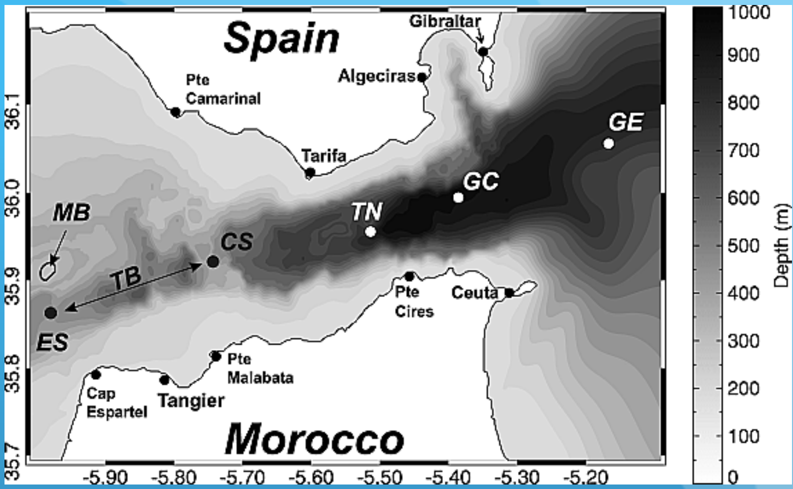
Reional ocean circulation



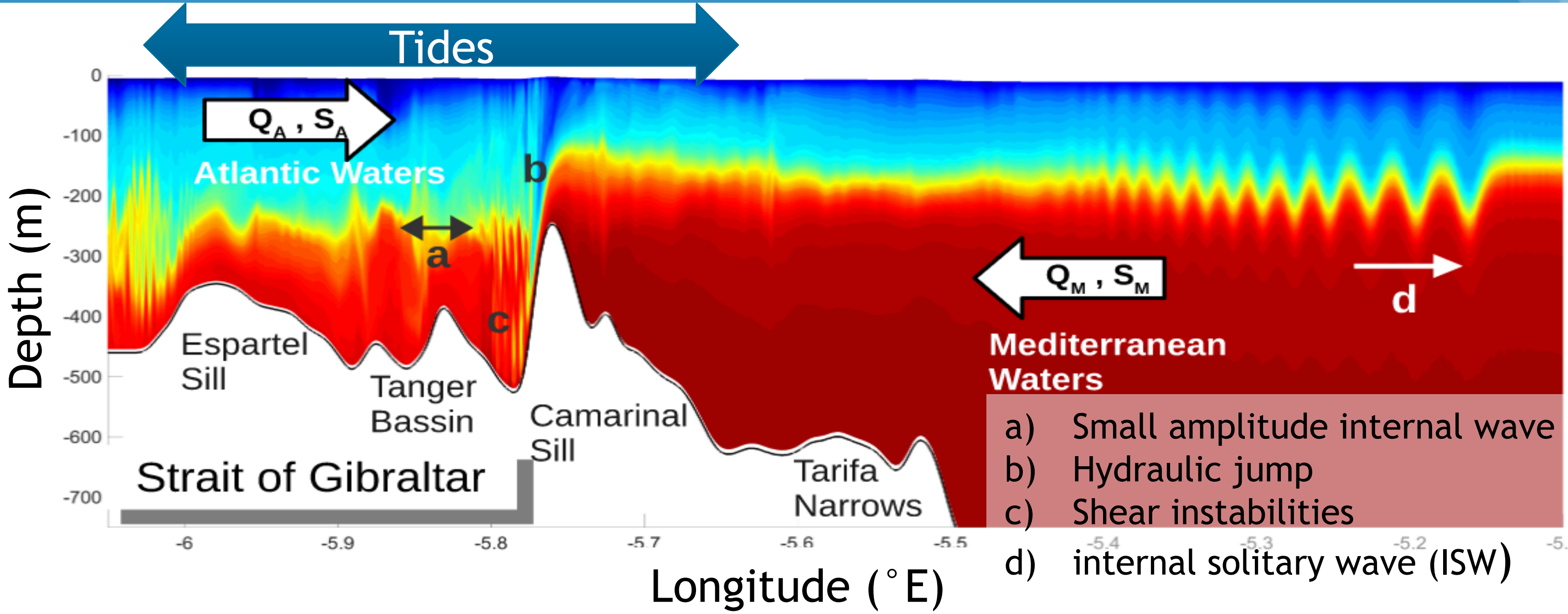


Strait NH dynamics

- Shear flow
- Tides dynamics
- Small-scale dynamics



Sanchez-Roman et al., 2009

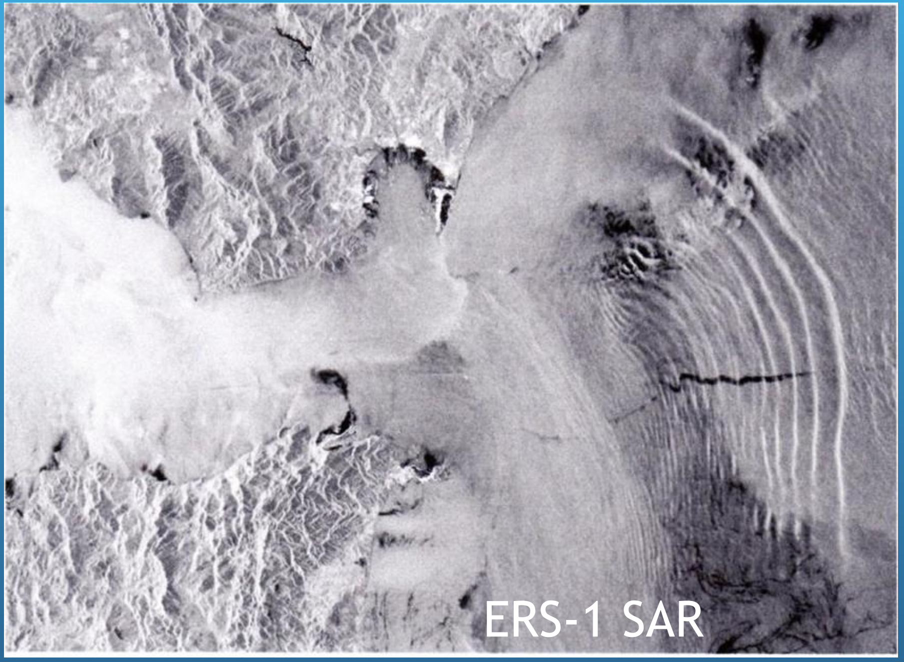


a) Small amplitude internal wave
b) Hydraulic jump
c) Shear instabilities
d) internal solitary wave (ISW)

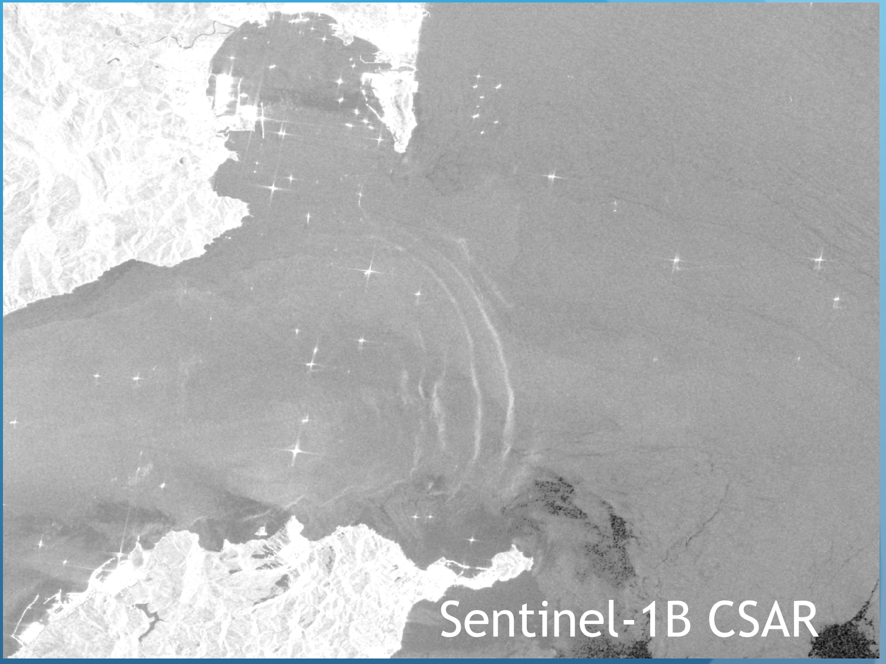
Hilt et al., 2020

Small scale dynamics surface signature

Internal solitary waves by Synthetic Aperture Radar



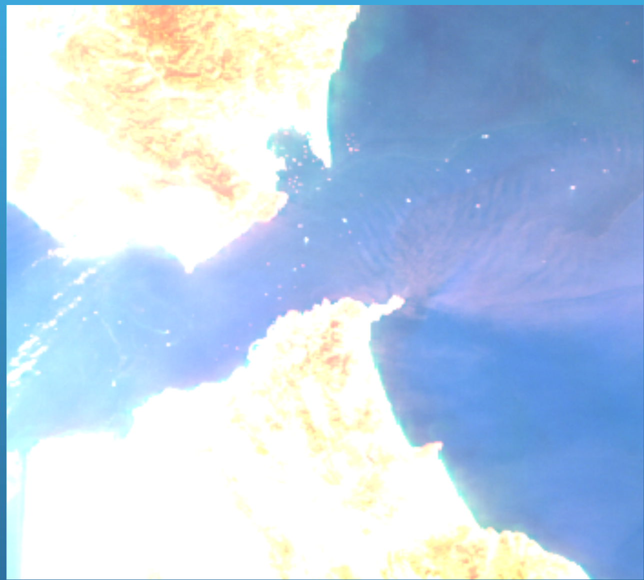
Alpers et al, 19961



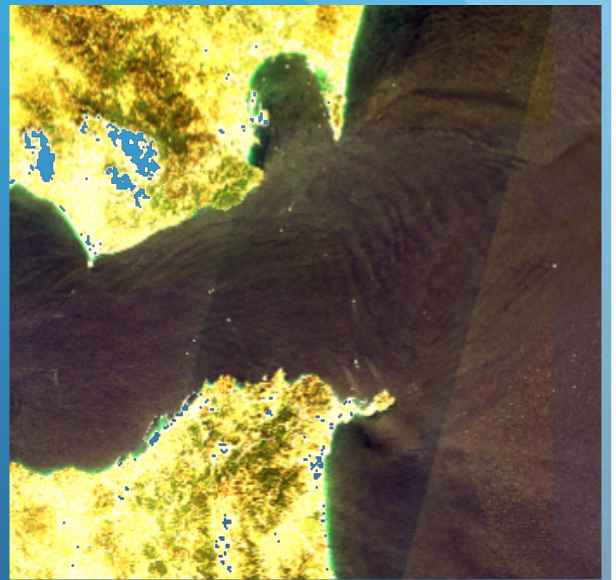
Small scale dynamics surface signature

Internal solitary waves by multispectral imagery

Terra (EOS-AM-1) MODIS
Courtesy: EUMETSAT, Credit: NASA



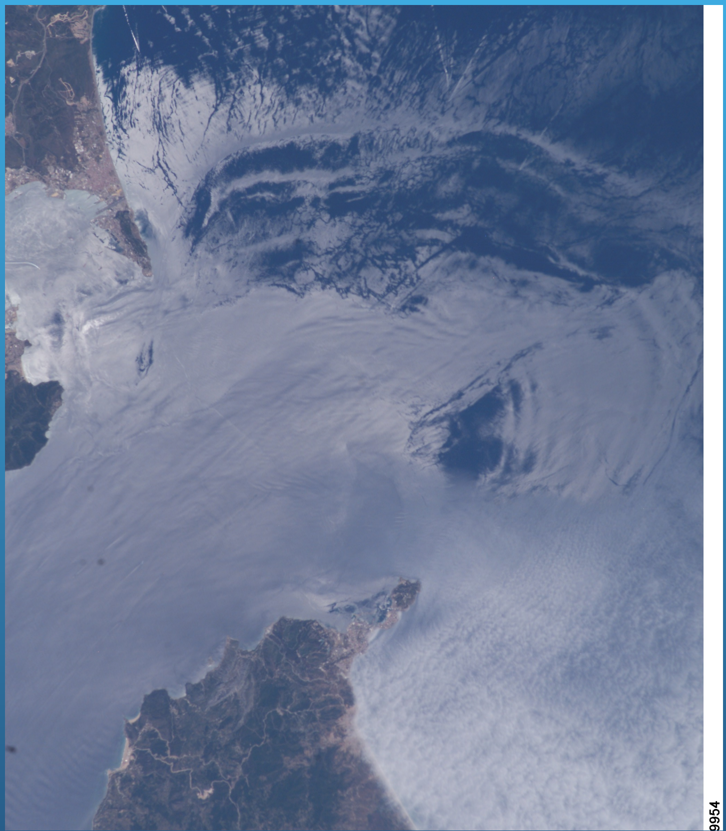
Sentinel3A OLCI



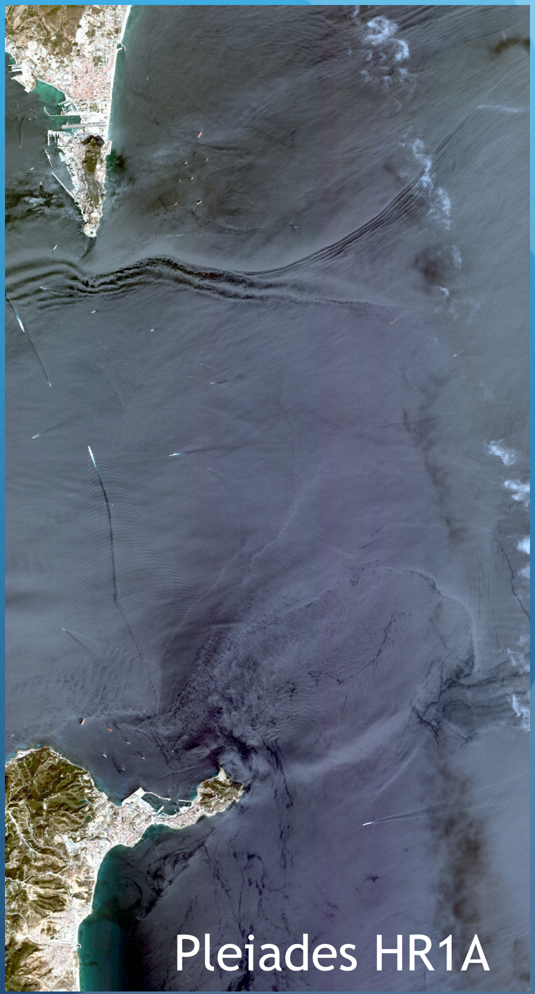
Sentinel-2A MSI

Small scale dynamics surface signature

Internal solitary waves by optical imagers

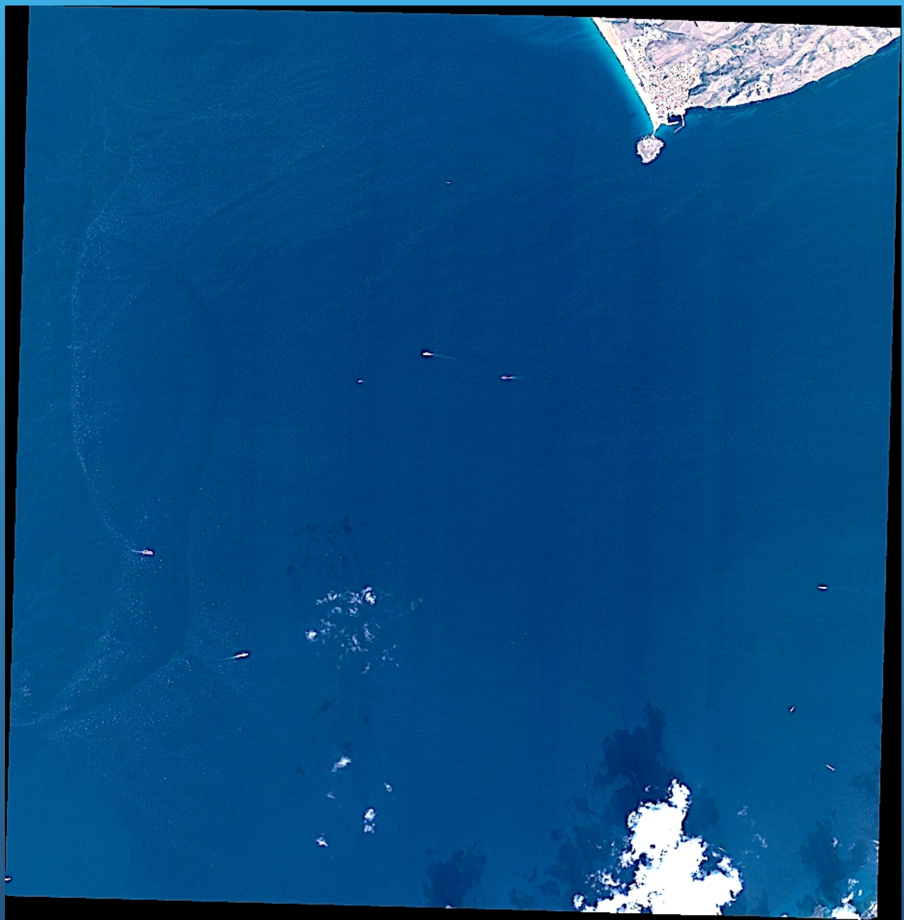


ISS camera,
Courtesy: Eumetsat, credit: NASA



Small scale dynamics surface signature

Hydraulic jump from optical imagers



Pleiades HR1A

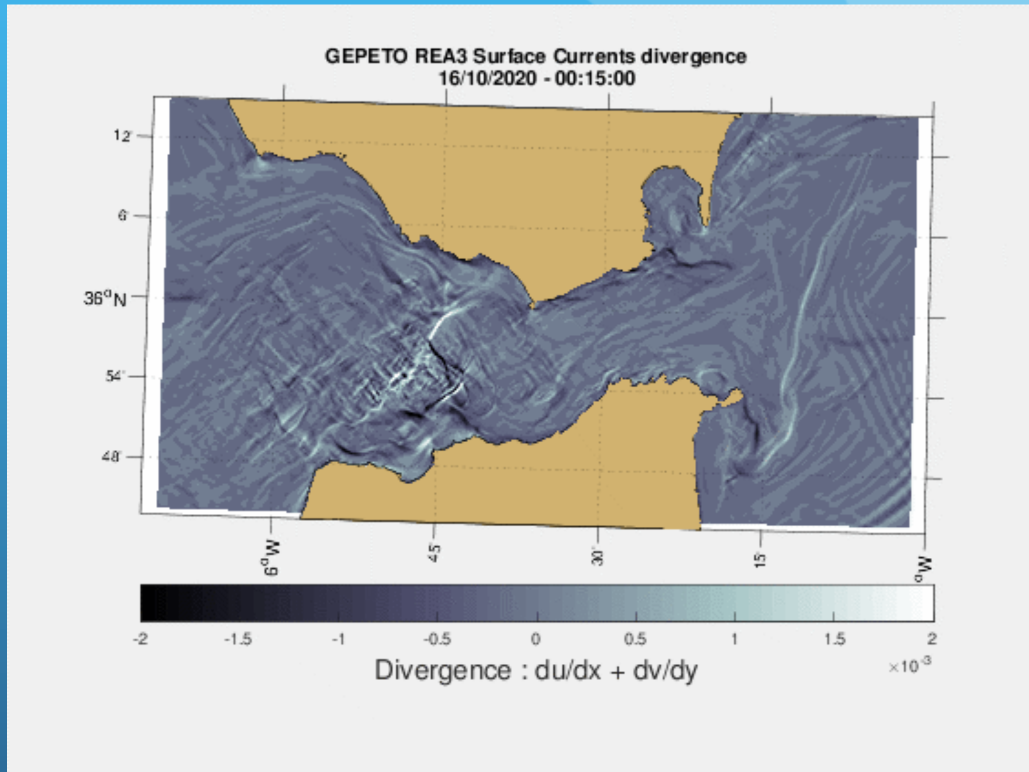
Franck Dumas's personnal camera

Numerical modelling

- Two-layer models (eg. Brandt et al., 1996; Izquierdo et al., 2001)
- 3D modelling (eg. Sannino et al., 2004)
- Non hydrostatic modelling (eg. Sanchez Garrido et al., 2011; Sannino et al., 2014)
- State-of-the-art Croco-NH model, NBQ module (eg. Hilt et al., 2020; Marchesiello et al., 2021; Auclair et al. in prep.)
  - No Boussinesq approximation
  - LES or DNS problems
  - Monotonic schemes (WENO5, TVD)
  - 3D turbulence closure
  - Grid refinement (AGRIF)

Outlines

- Introduction
- Croco-NH NBQ module
  - S2DV capability
  - 3D capability
  - AGRIF refinement



2D vertical model pre-preprocessing

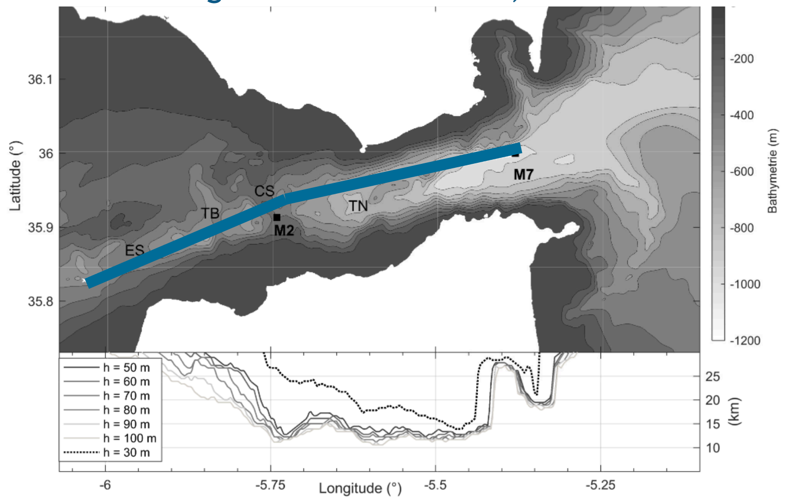
- Grid configuration dx = 50m;
NX = 2662, NY = 5, NZ = 40

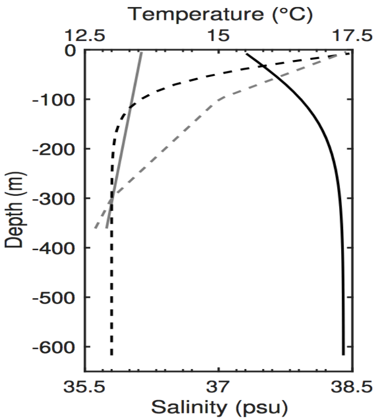
- Realistic bathymetry 100m-resolution (Biscara et al, 2016)
- Stratification: lock-exchange
- Tides adjusted from TPXO8 (clm_tides.F)
- No atmospheric forcing

- Adaptation of some croco_tools routines
  - ✓ make_bathygrid.m

- Run
  - ✓ 3-day spinup
  - ✓ 10 M2-periods (~5days)
  - ✓ time step 1s / ndtfast = 8

Transect design: Farmer and Armi, 1988





Lock-exchange

Configuration adapted from Saninno *et al*, 2012
T/S profiles adapted from Bryden *et al*, 1994

Hilt et al., 2020

2D vertical model setup

- CROCO NBQ module

```
#define NBQ
#define NBQ_PERF
```

- 2D vertical grid

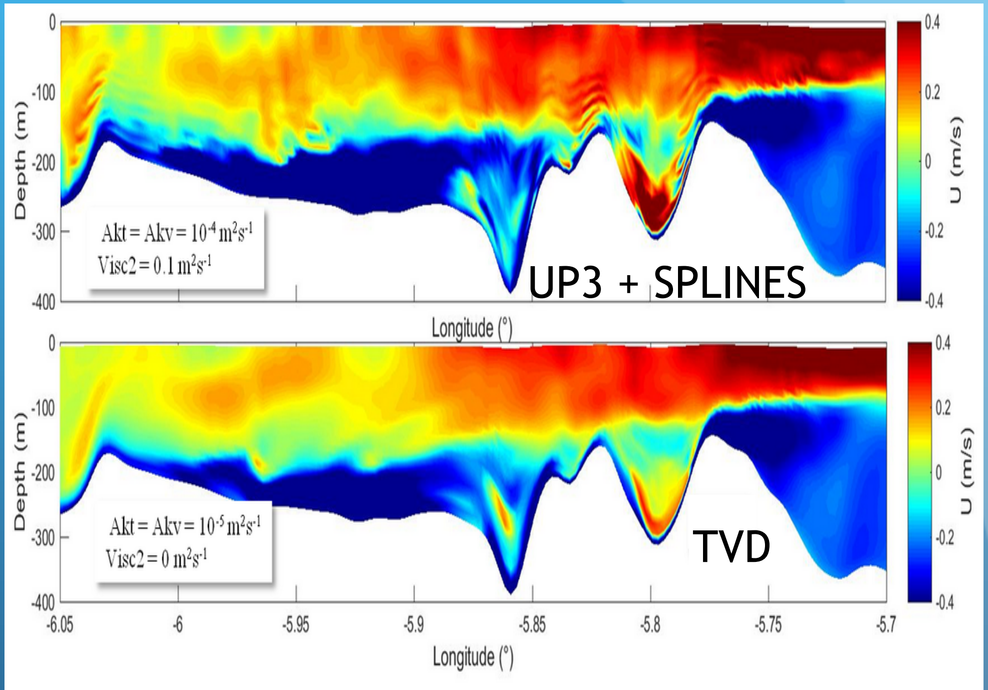
```
#define S2DV
#define NEW_S_COORD
#define MASKING
```

- M2 Tidal forcing (no make_tides.m)

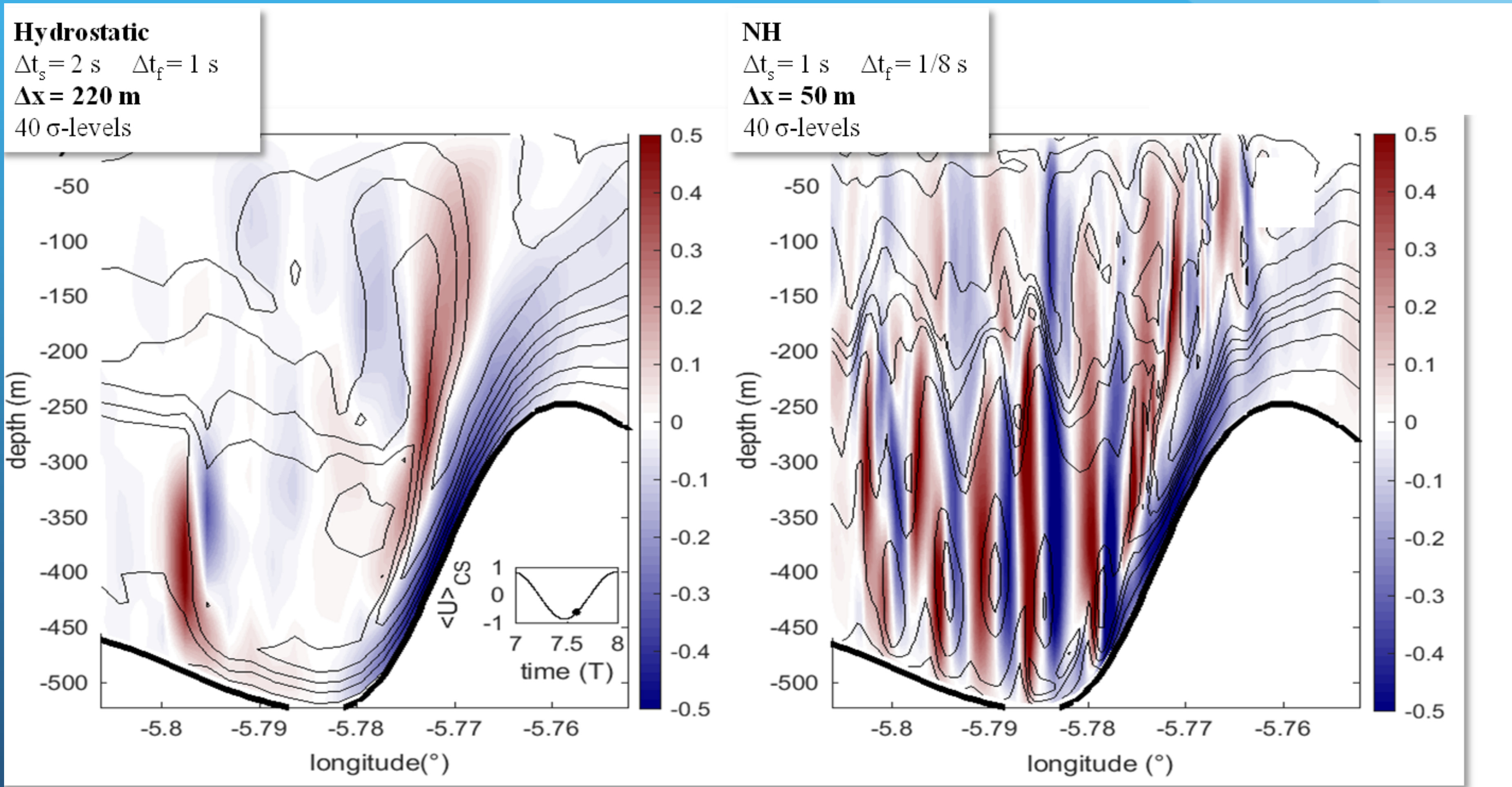
```
#define TIDES
#define OBC_NBQORLANSKI
#define NS_PERIODIC
```

- Advection

```
#define UV_HADV_TVD,UV_VADV_TVD
#define W_HADV_TVD, W_VADV_TVD
#define TS_HADV_WENO5
```

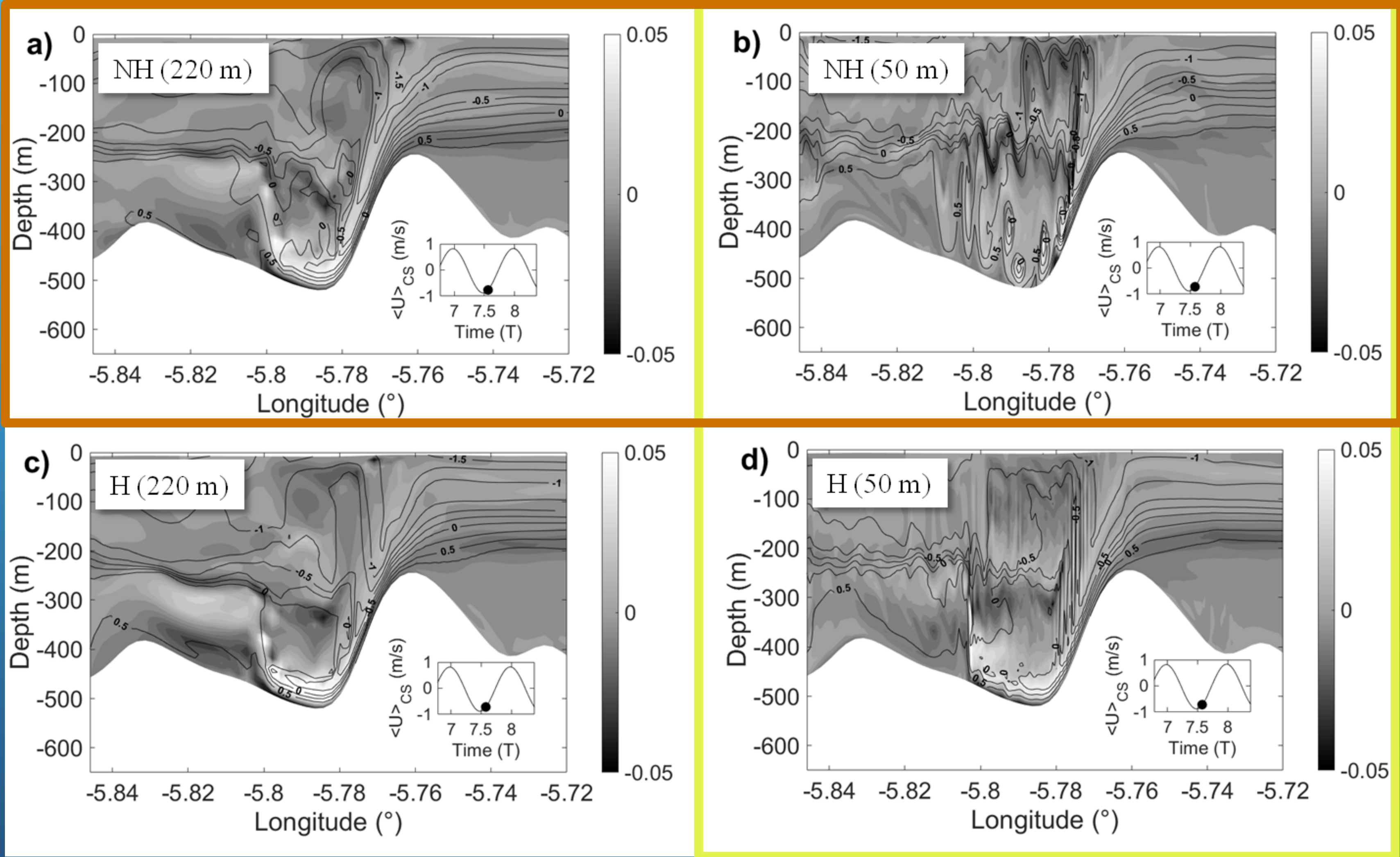


Shear instabilities



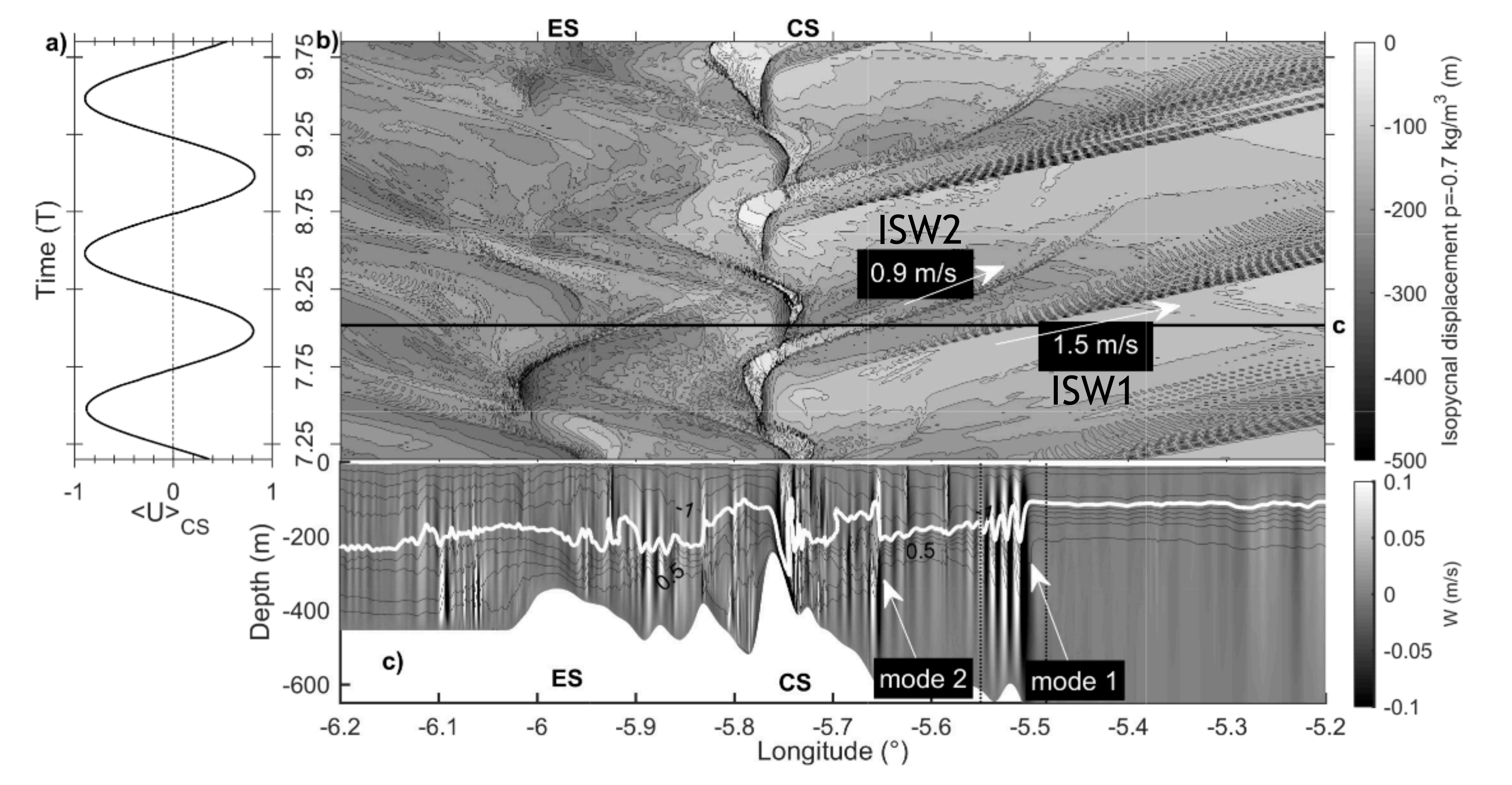
Contours of vertical velocity w (m/s) and isopycnal surfaces (kg/m^3)

Shear instabilities



Contours of vorticity (s-1) and isopycnal surfaces (kg.m-3)

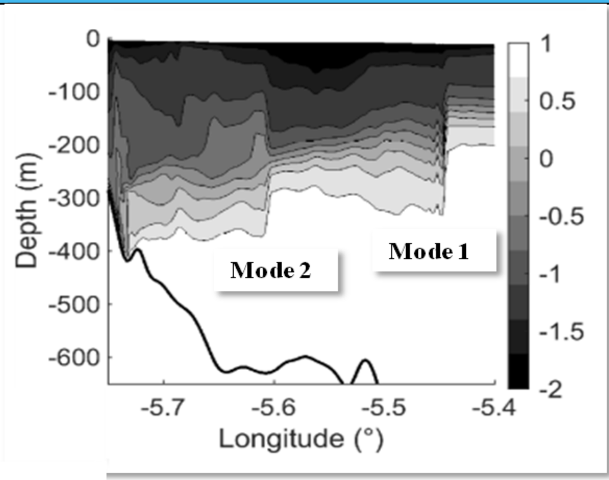
Internal solitary waves



Hilt et al, 2020

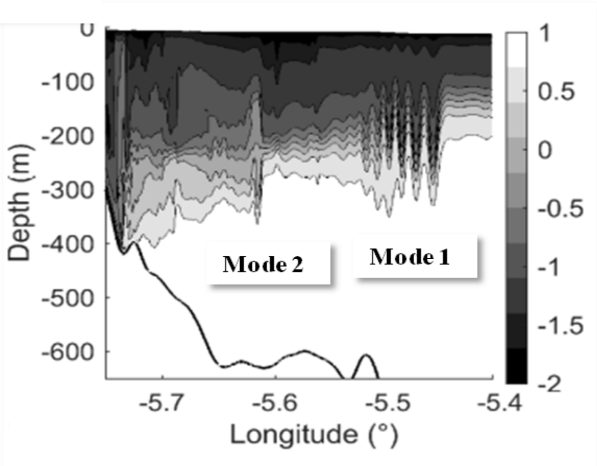
Internal solitary waves

Hydrostatic
$\Delta t_s = 2$ s $\Delta t_f = 1$ s
$\Delta x = 220$ m
40 σ-levels

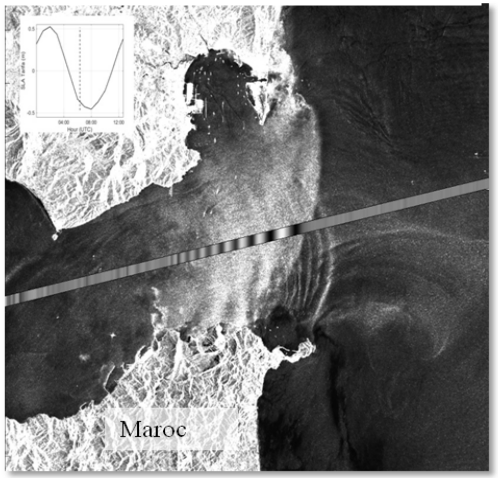


Density anomaly (kg/m3)

NH
$\Delta t_s = 1$ s $\Delta t_f = 1/8$ s
$\Delta x = 50$ m
40 σ-levels



Free surface slope



Sentinel-1A SAR
(20/04/2016 6:27 UTC)

S2DV capability – wrap up

- Simple model for one-direction flows problems
- Easy to implement, primary investigations
- CPU-efficient
- Mandatory elements: NBQ module AND high horizontal resolution
- Results
  - Shear instabilities
  - Internal solitary waves mode 1 and mode 2
  - Limitations
    - ✓ Simplified bathymetry
    - ✓ Secondary instabilities
    - ✓ ISW transverse propagation and reflections at coasts

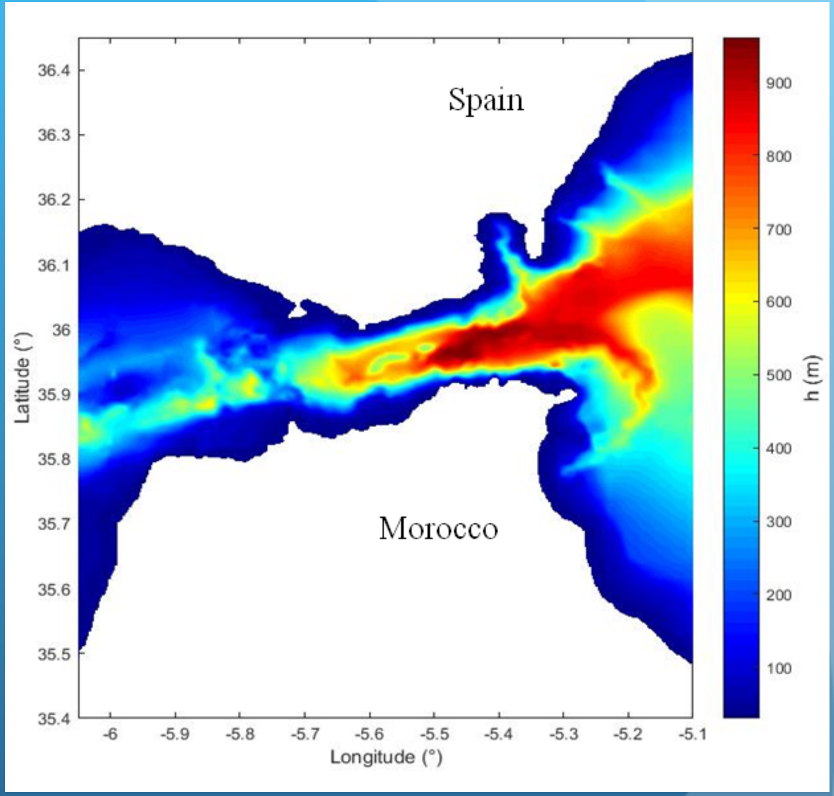
3D LES model pre processing

- Grid configuration dx = dy = 50m;
NX = 2046, NY = 2618, NZ = 40

- Realistic bathymetry 100m-resolution (Biscara et al, 2016)
- Initialization and lateral conditions: ENEA Med System (Sannino et al., 2015)
- Tides: ENEA (Sannino et al., 2015)
- No atmospheric forcing or fluxes

- Adaptation of some Matlab routines
  - ✓ large grids
  - ✓ interpolation/masking issues

- Run
  - ✓ Restart after a 2-days from Croco-H run
  - ✓ 8 M2-periods (~4 days)
  - ✓ time step 1s / ndtfast = 11



3D LES model setup

- CRCO NBQ module

```
#define NBQ
#define NBQ_PERF
```

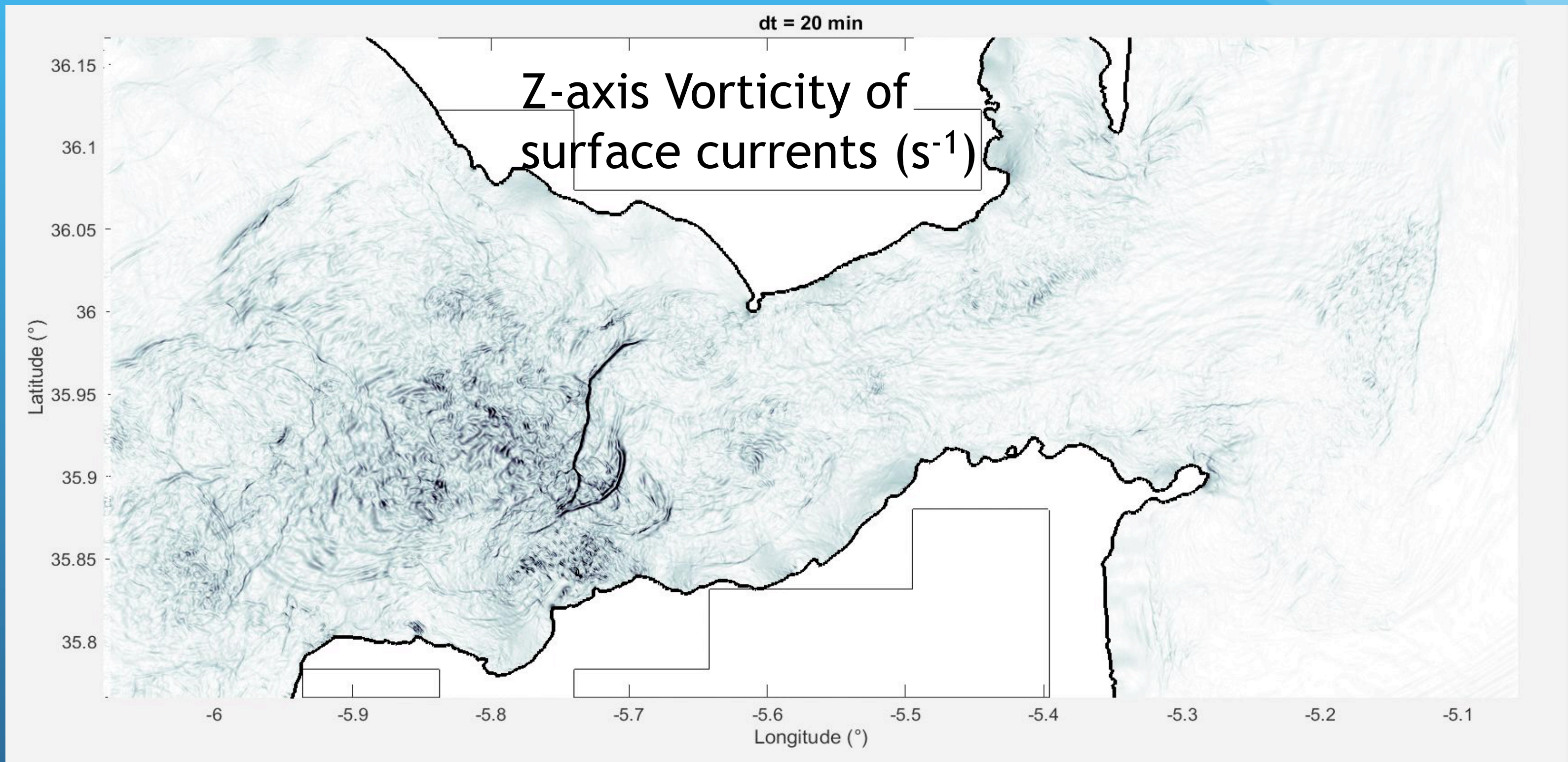
- Advection

```
#define UV_HADV_TVD,UV_VADV_TVD
#define W_HADV_TVD, W_VADV_TVD
#define TS_HADV_WENO5
```

- Tidal forcing (M_2, S_2, K_1, O_1)

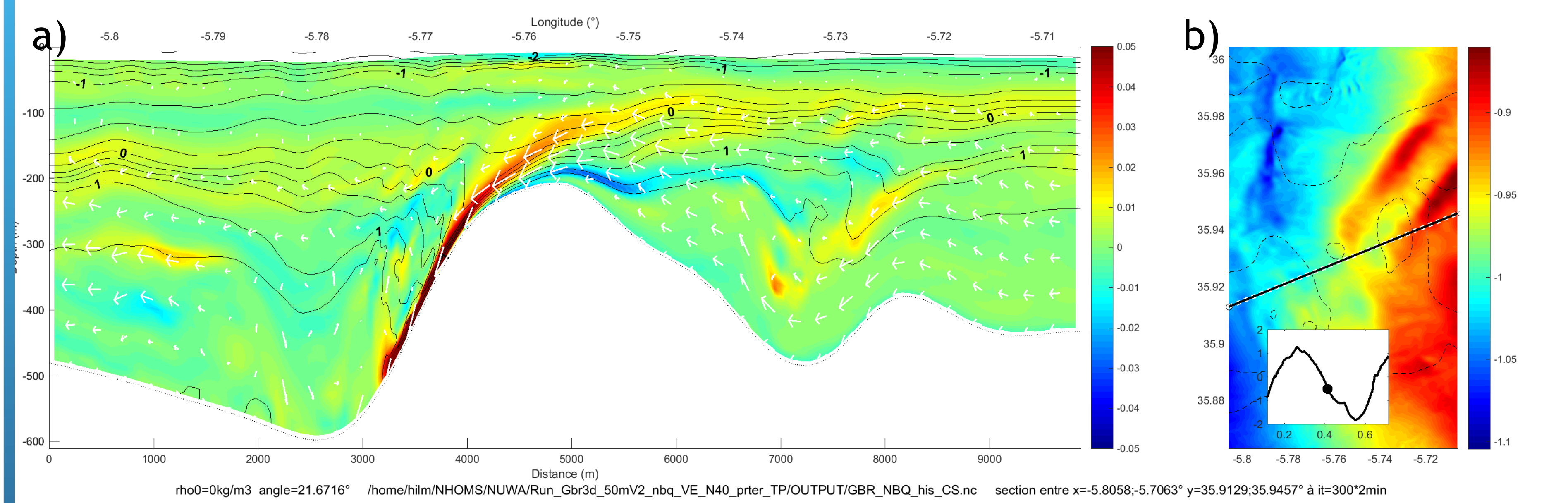
```
#define TIDES
#define OBC_NBQORLANSKI
#define NS_PERIODIC
```

Small-scale surface dynamics



- Hydraulic control and relaxation of the hydraulic jumps
- ISW generation, propagations and reflections
- ISW interactions with submesoscale vortex

Dynamics at Camarinal sill

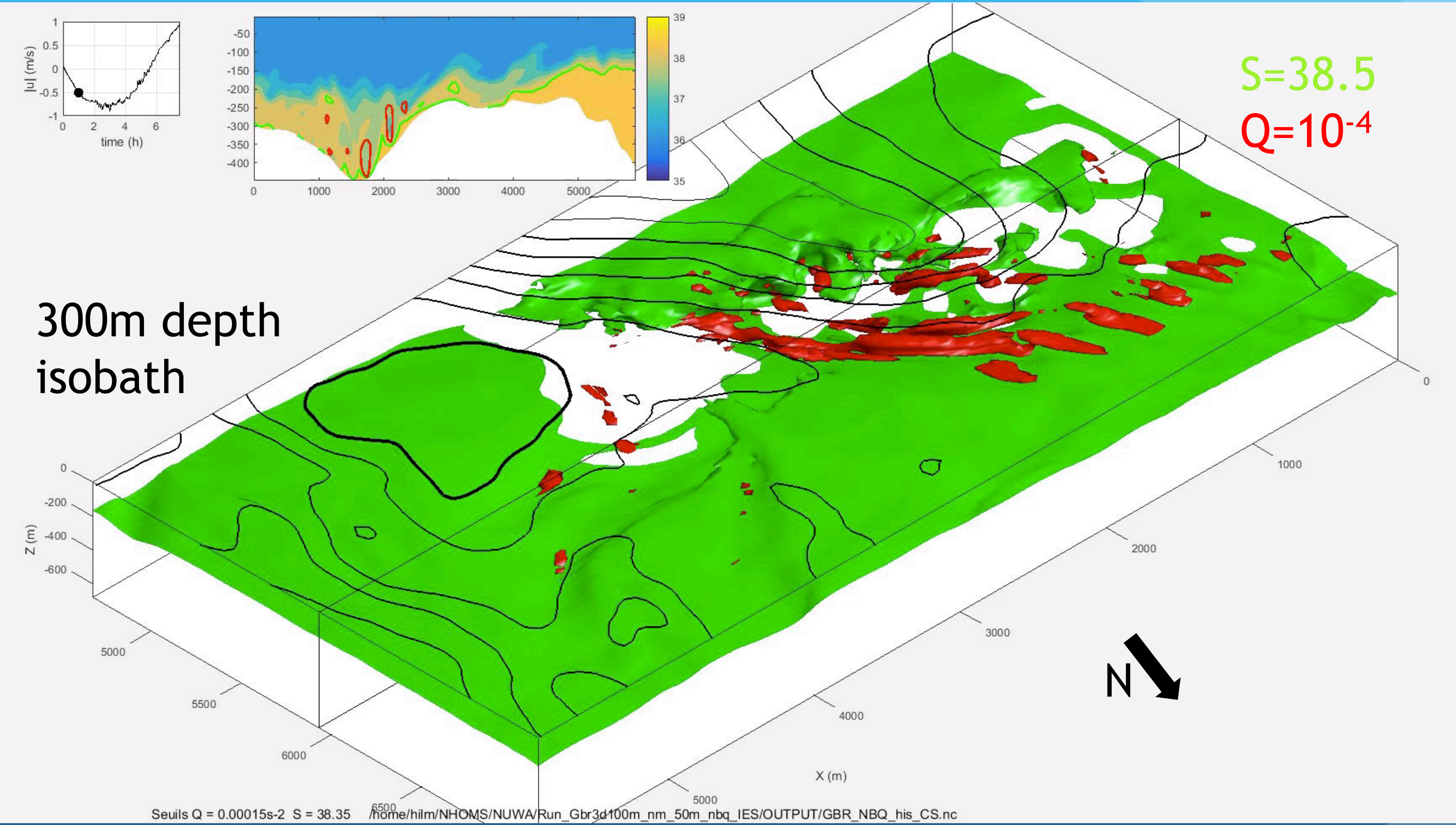


a) contours of vorticity (s-1), direction of (u,w) flow (m.s-1) and isopycnal surfaces (kg.m-3)

b) Sea surface anomaly (m)

- Shear instabilities
- Propagation of ISW
- Boiling waters

Dynamics of coherent structures



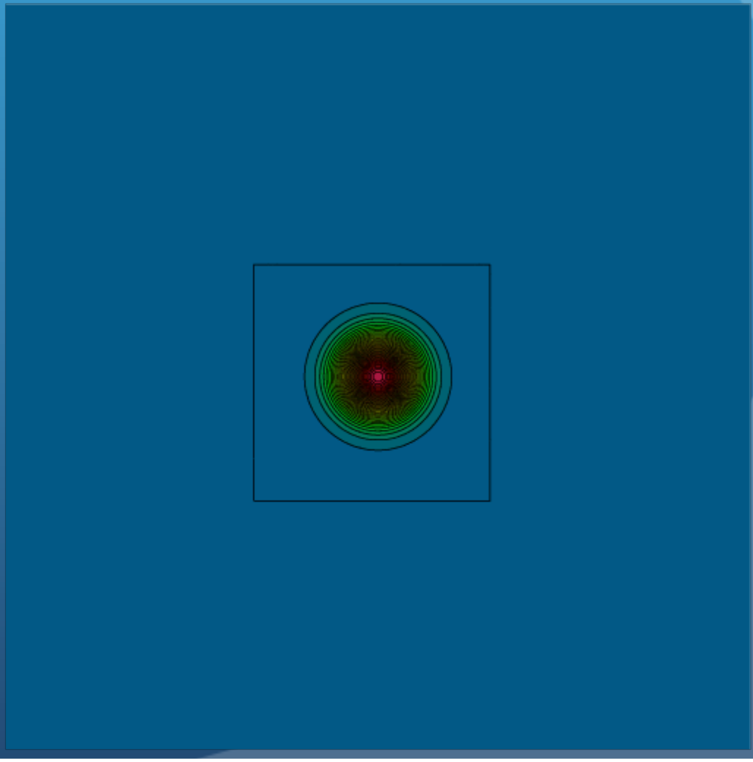
- Billows of primary shear instabilities are detected (Q-Parameter>0)
- Roll-up of salinity west of Camarinal Sill and advection westward

3D LES model capability – wrap up

- Results
  - Internal solitary waves
  - Primary shear instabilities
- Original new diagnostics for LES analysis (Hilt 2022a, b)
  - Q-parameter (detection of shear instabilities)
  - Background Potential Energy (dyapicnal mixing) – not shown

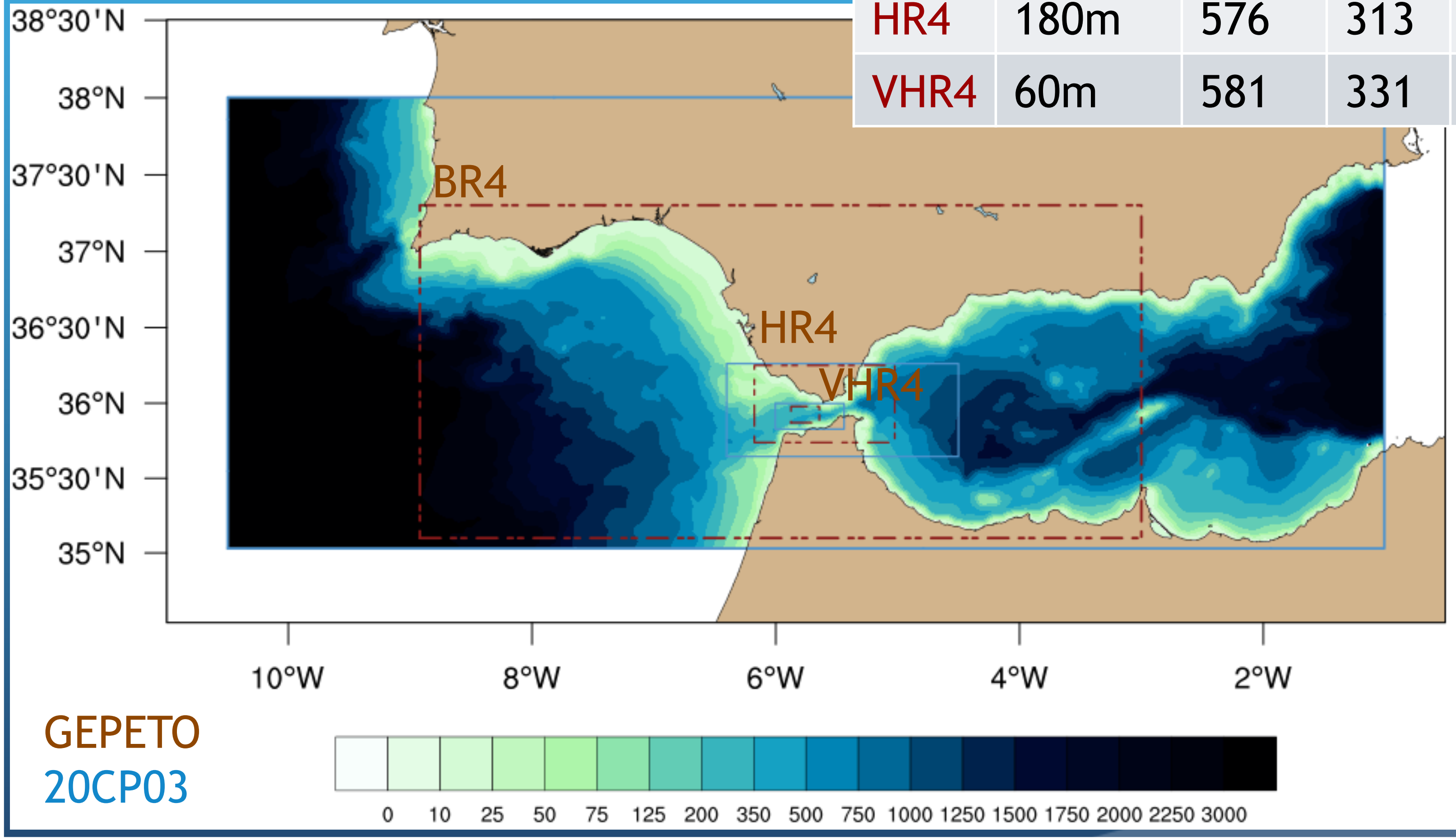
Grid Refinement implementation

- AGRIF mesh refinement (Debreu et al, 2012)
- 2-way exchange of NBQ variables (qdmu_nbq, qdmv_nbq, qdmw_nbq, rho_nbq) at fast mode
- Implementation test
  - #define VORTEX
  - #define NBQ
  - #define AGRIF
  - #define AGRIF_2WAY



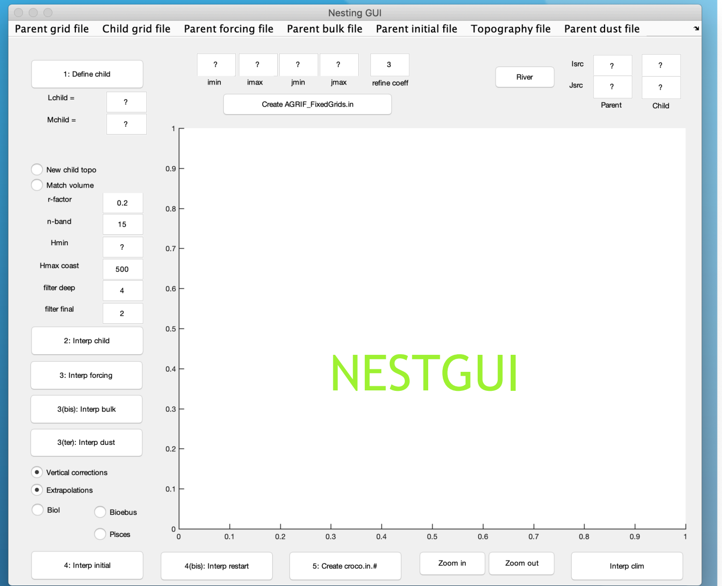
Gibraltar grid refinement

Grid	d_X	N_X	N_Y	N_Z	d_t
BR4	900m	592	273	40	15s
HR4	180m	576	313	40	3s
VHR4	60m	581	331	40	1s



Grid refinement cook book

- Same input fields for all grids
  - Realistic bathymetry (100m-resolution, Biscara et al, 2016)
  - Tides from TPXO9v1 multi-resolution atlas
  - Initial condition: Med CMEMS products (forecasts/analyses, 1/24°)
  - Lateral forcing: Med CMEMS products (forecasts/analyses, 1/24°)
  - Bulk and surface fluxes: GFS forecasts (1/4°)
  - Land/sea mask from GSHHS full resolution product (Wessel and Smith, 1996)

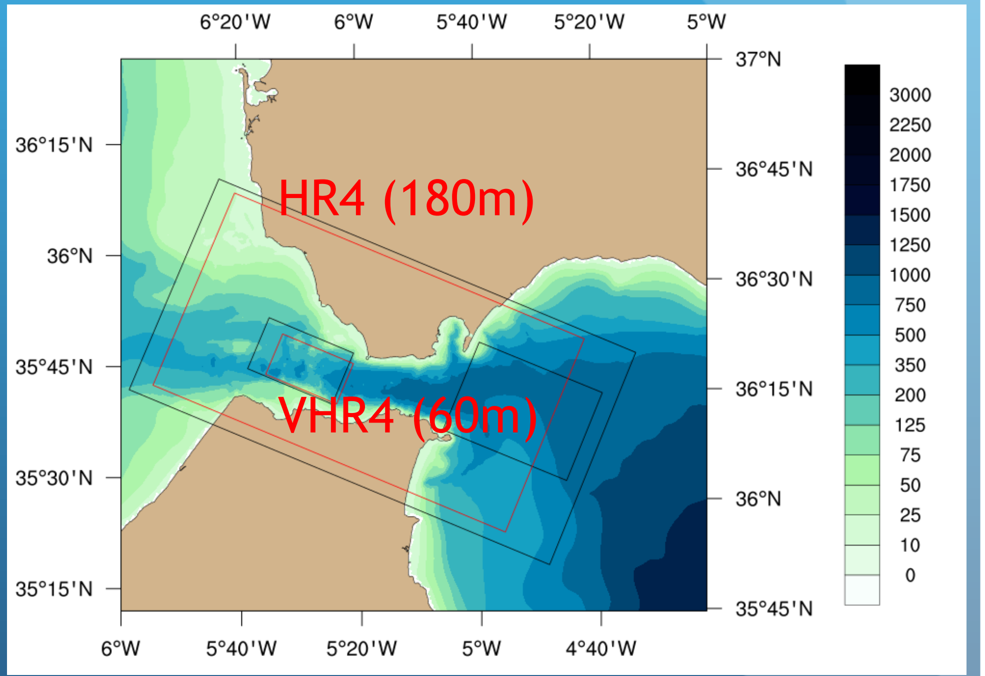


- Minor modifications to croco_tools routines (reading CMEMS, TPXO9)

- Land/sea mask
  - Creation: A. Shchepetkin Fortran code
  - Editing: edit_mask GUI (croco_tools)

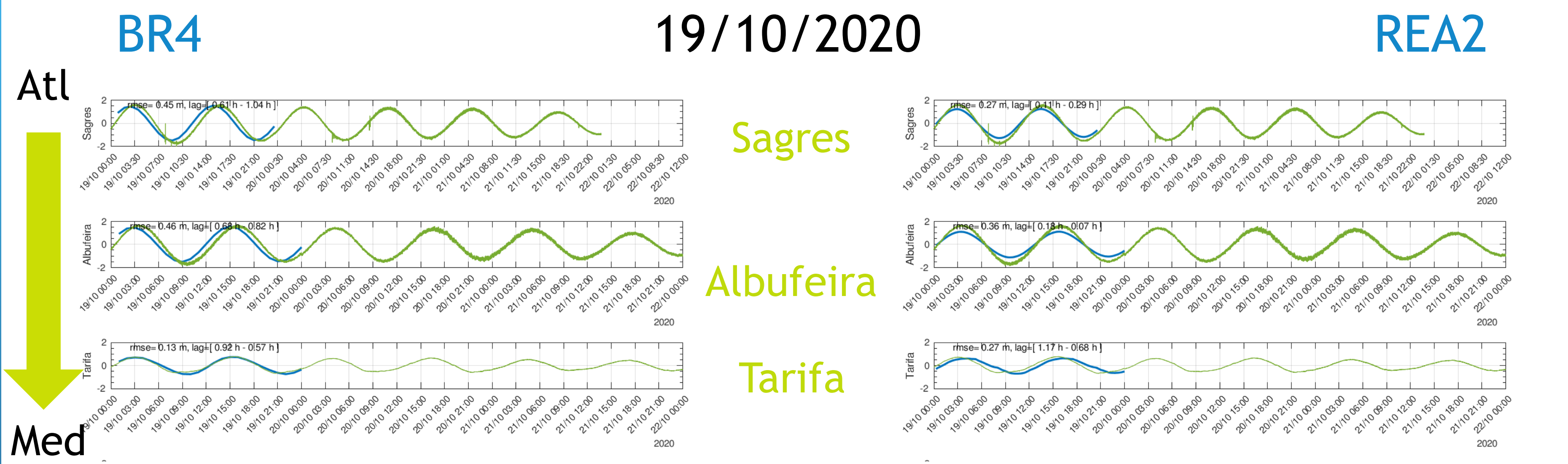
Gibraltar model

- GEPETO project (2020-2023) funded by LEFE and Mercator-Ocean
- Sensitivity experiments
  - No nesting: BR4 domain (NBQ)
  - REA2 : 2-way NBQ nesting over HR4 domain
  - REA3 : double 2-way NBQ nesting over HR4 and VHR4 domains



- Preliminary investigations
  - sea level (ISW forcing)
  - surface currents divergence (ISW surface signature)

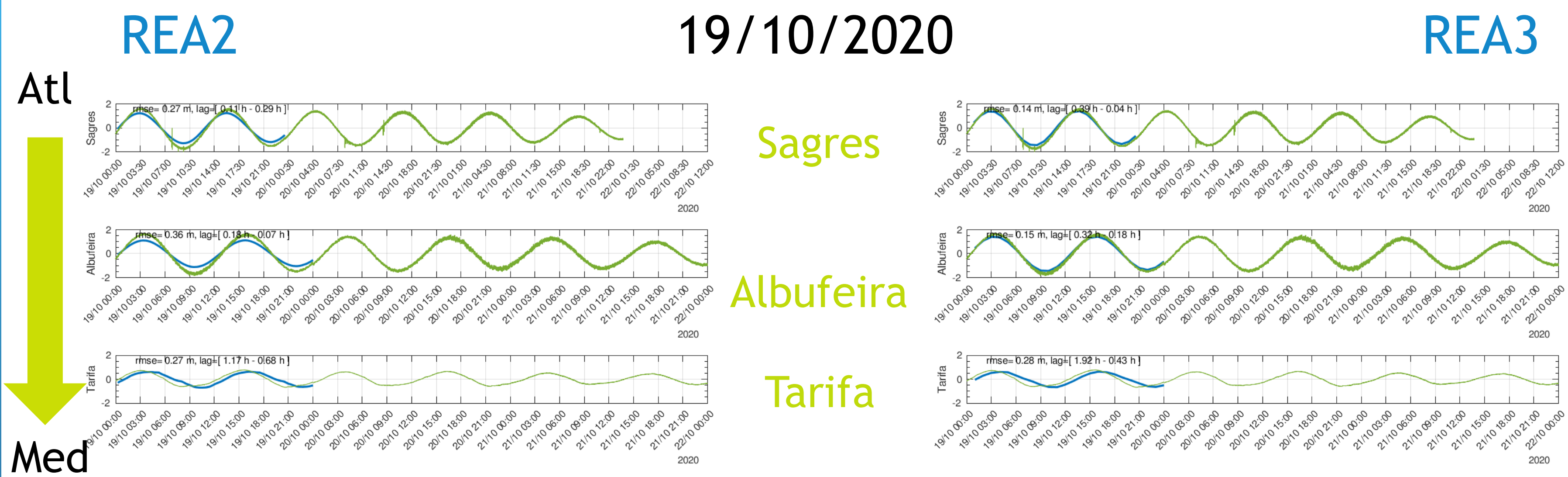
Sea level anomaly comparisons



NRT sea level observations courtesy JRC (Eu) and Puertos del Estado (Spain)

- Time lag reduction wrt NRT observations away from the strait
- Variability loss away from the strait
- Negative performances in Tarifa

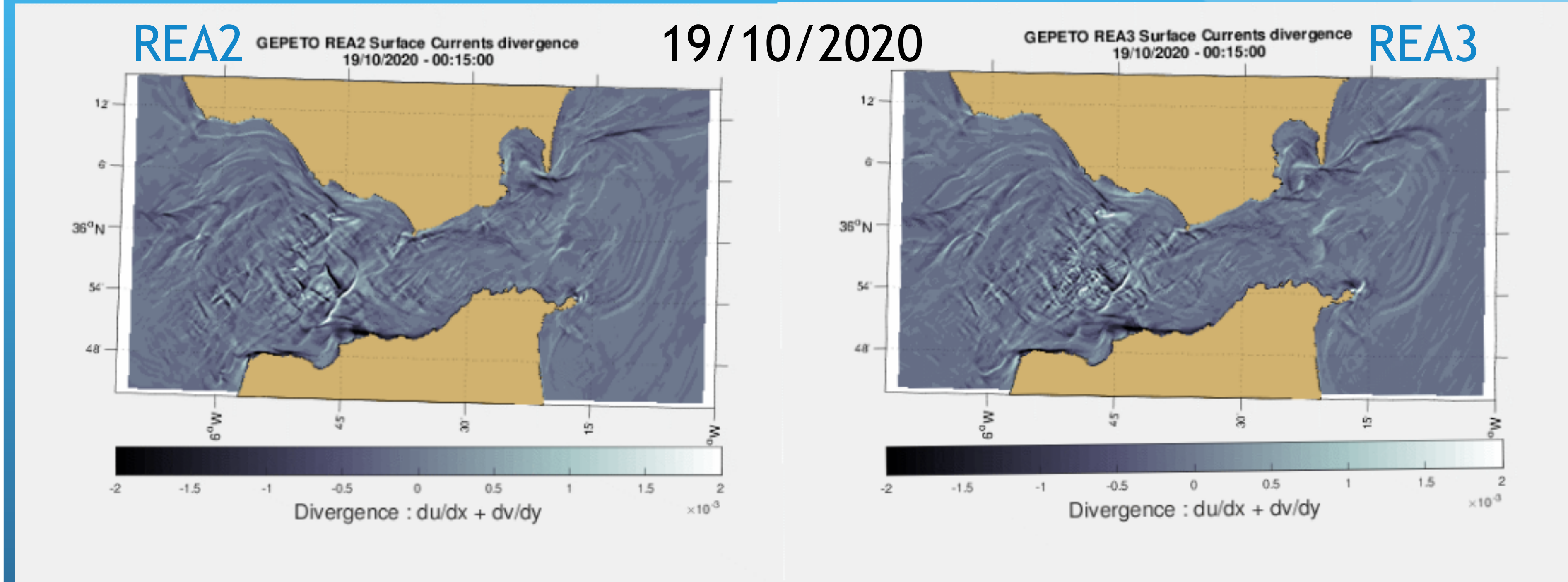
Sea level anomaly comparisons



NRT sea level observations courtesy JRC (Eu) and Puertos del Estado (Spain)

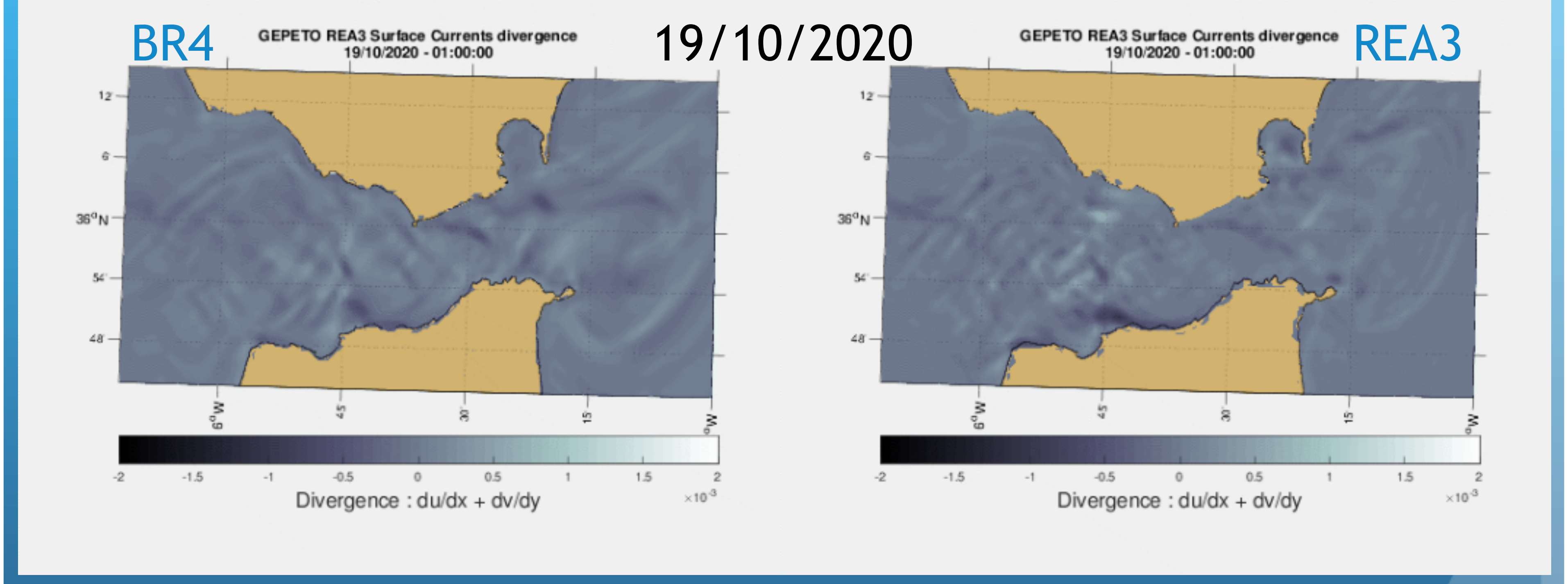
- Model variability increase, lower discrepancies
- No improvement in lag reduction wrt NRT observations
- No (positive) change in Tarifa

ISW surface signature (SAR-like)



- More fine scales, more intensity at Camarinal
- Minor differences in ISW pattern (REA3 in advance)

ISW impact on large scale (SAR-like)



- At low resolution, REA3 increases variability and update ISW pattern in agreement with 3D VHR model
- To be confirmed with ProteVs/GEPETO campaigns observations and satellite retrievals

Summary

- Croco-NH/NBQ module ready for realistic runs, even in NRT framework
  - Enhanced physics for LES and DNS problems
  - AGRIF embedding for local/regional scales interactions (soon)
  - Observation needed for accurate validation

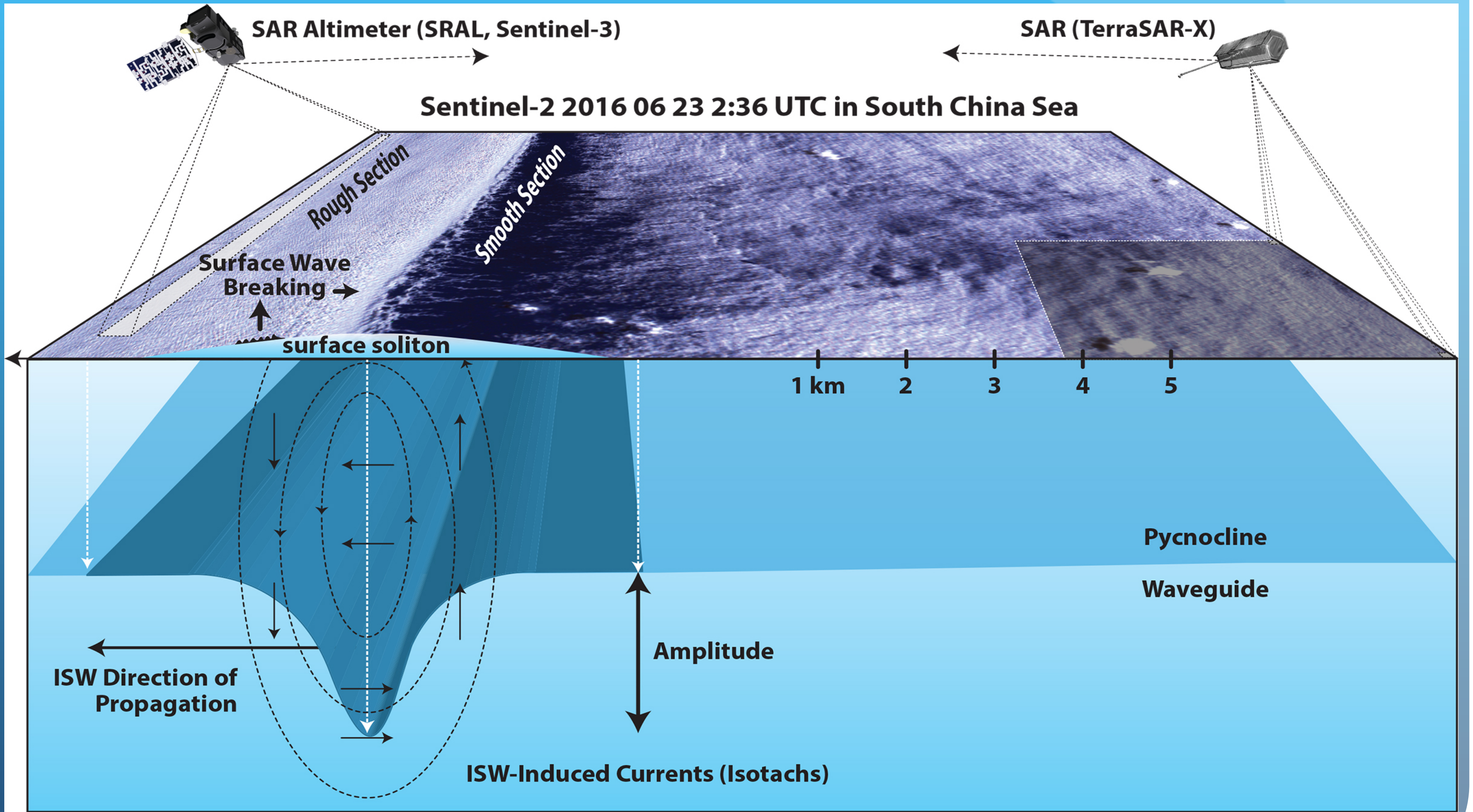
- Investigations continues over the strait of Gibraltar…
  - Large-scale upscaling (tides, Med. outflow, Atl. Jet, WAG…)
  - Mixing (location, quantification, properties, evolution…)
  - Atmosphere interactions (coupling with MesoNH weather model)

- NBQ module development continues…
  - Surface/ interior ocean, hydrodynamic/non hydrodynamic coupling
  - Acoustic gravity waves
  - Physical (CPU) and numerical (GPU) acceleration

GRACIAS A TODOS

Material

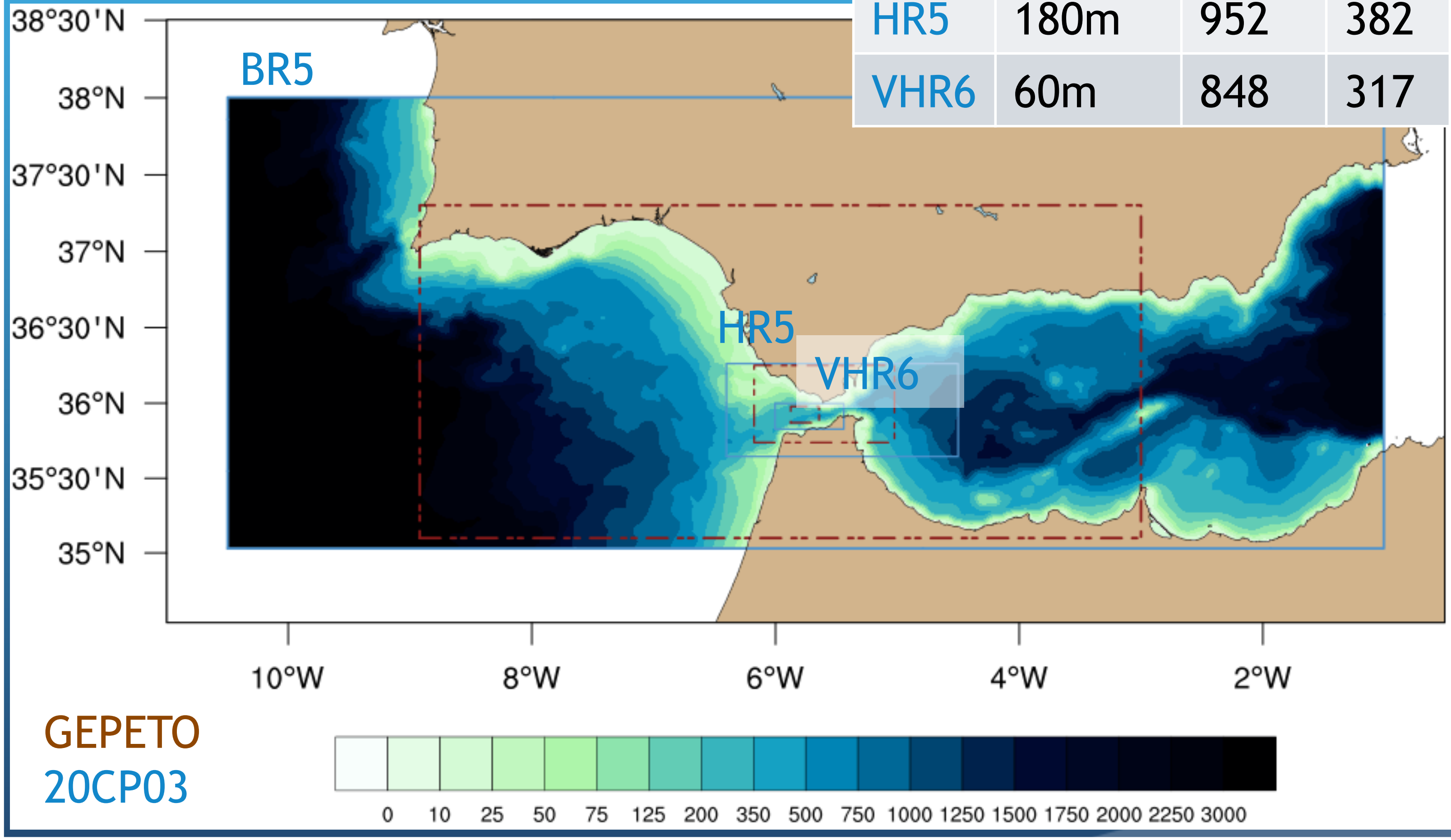
ISW by SAR altimetry



M. Magalhães et al, 2021

Gibraltar grid refinement

Grid	d_X	N_X	N_Y	N_Z	N
BR5	900m	950	371	40	x2
HR5	180m	952	382	40	x2
VHR6	60m	848	317	40	x4



GEPETO
20CP03