Symposium on HPC And Data-Intensive Applications

In Earth Sciences: Challenges and Opportunities

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The Abdus Salam International Centre for Theoretical Physics

Modeling the Mediterranean region under the PRACE NEMERTE Project: towards enhanced resolution, accurate Strait of Gibraltar description and tidal forcing effects

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NEMERTE – Numerical Experiment on the Mediterranean model response to Enhanced Resolution and TidE

Project leader: Gianmaria Sannino, ENEA, ITALY

Collaborators:

Patrick Heimbach, Massachusetts Institute of Technology (MIT), UNITED STATES
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MariaVittoria Struglia, ENEA, Italy

FERMI@CINECA

NEMERTE Resource Awarded:
18 Million core hours on FERMI

Architecture: 10 BGQ Frames
Model: IBM-BG/Q
Processor type: IBM PowerA2 @1.6 GHz
Computing Cores: 163840
Computing Nodes: 10240
RAM: 1GByte / core (163 PByte total)
Internal Network: 5D Torus
Disk Space: 2PByte of scratch space
Peak Performance: 2PFlop/s

N. 7 in Top 500 rank (June 2012)

National and PRACE Tier-0 calls

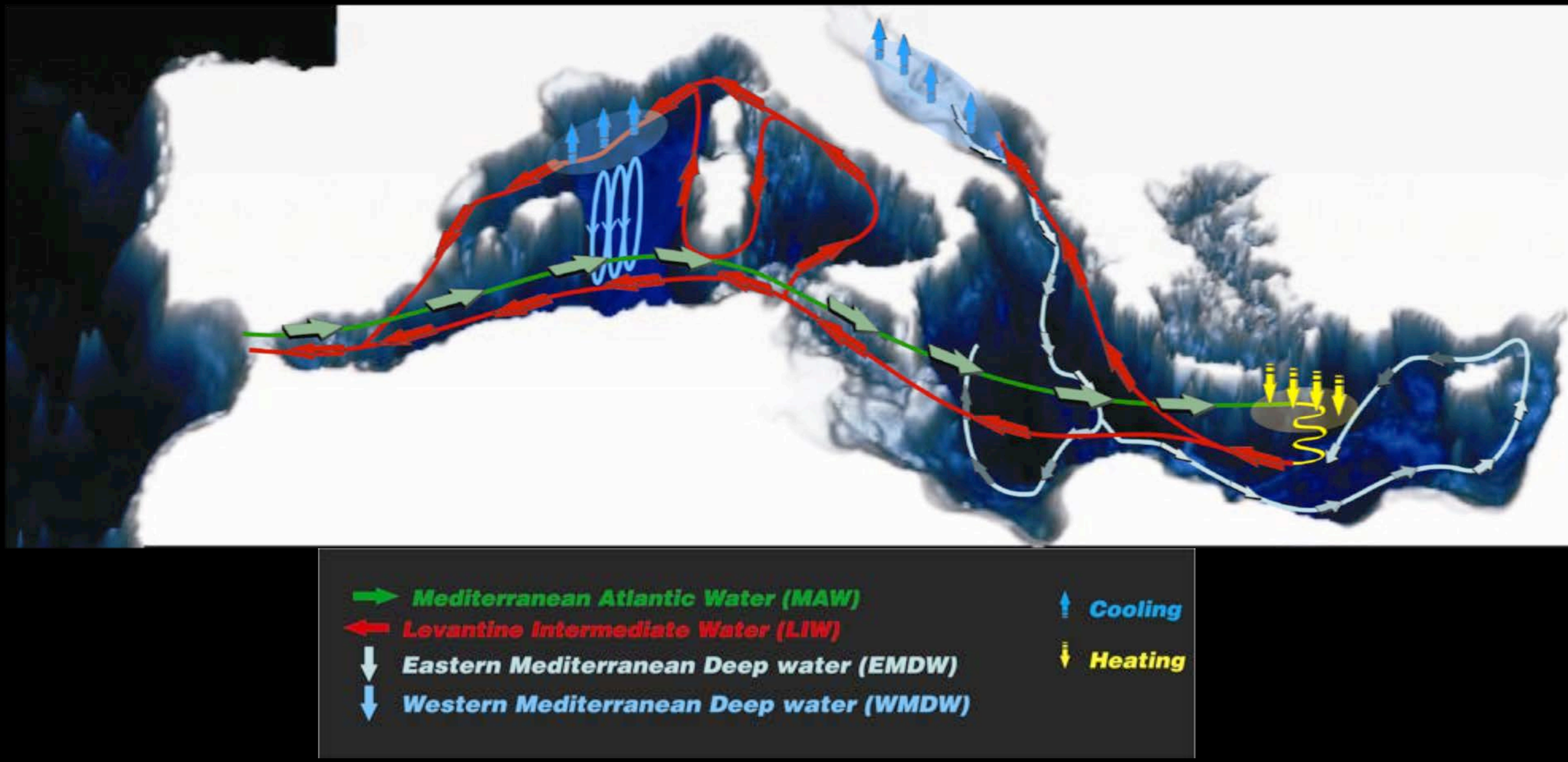
The mission of **PRACE** (Partnership for Advanced Computing in Europe) is to enable high impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society. PRACE seeks to realize this mission by offering world class computing and data management resources and services through a peer review process.

HOW DID NEMERTE BEGIN?

A fascinating story involving ocean models and HPC

Mediterranean Thermohaline Circulation (MTHC)

The Mediterranean Sea is a semi-enclosed basin displaying an active thermohaline circulation that is sustained by the atmospheric forcing and controlled by the narrow and shallow Strait of Gibraltar



The atmospheric forcing drives the Mediterranean basin toward a negative budget of water and heat, and toward a positive budget of salt. Over the basin, evaporation exceeds the sum of precipitation and rivers discharge, while through the surface a net heat flux is transferred to the overlying atmosphere. Mass conservation in the basin represents the last ingredient necessary to activate the MTHC

Strait of Gibraltar Background

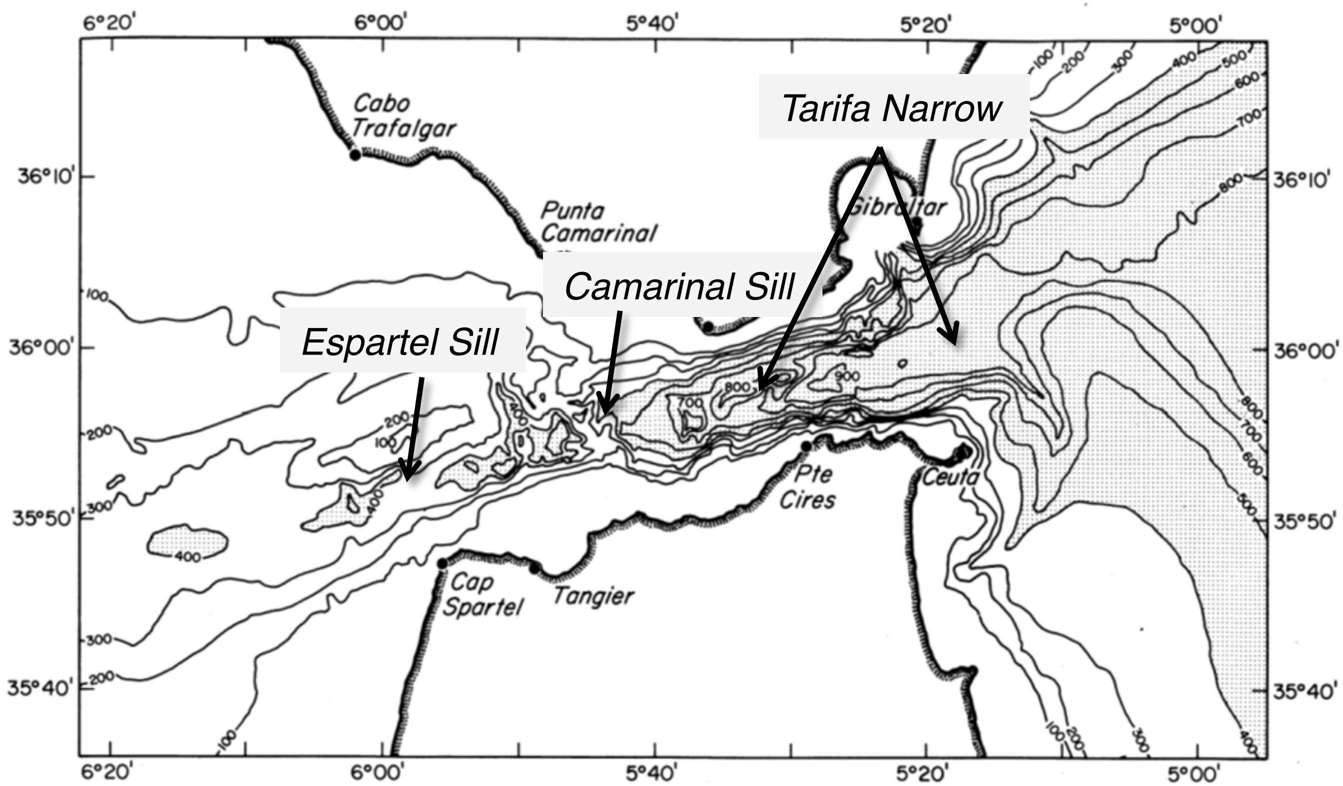
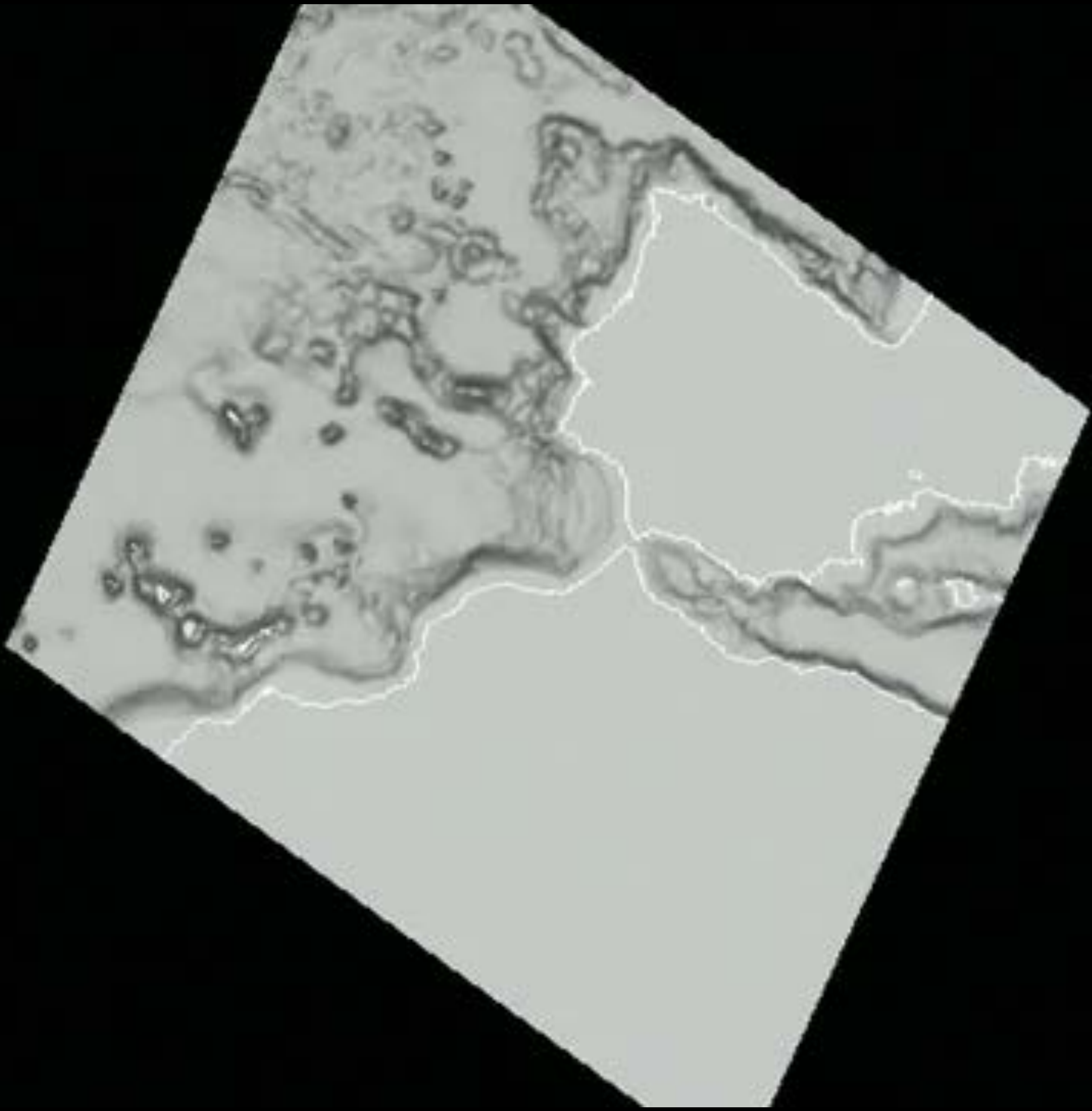


Chart of the Strait of Gibraltar, adapted from Armi & Farmer (1988), showing the principal geographic features referred to in the text. Areas deeper than 400 m are shaded

Strait of Gibraltar Background: 3D Bathymetry



Strait of Gibraltar Background: Physics

Strong mixing and entrainment mainly driven by the very intense tides.

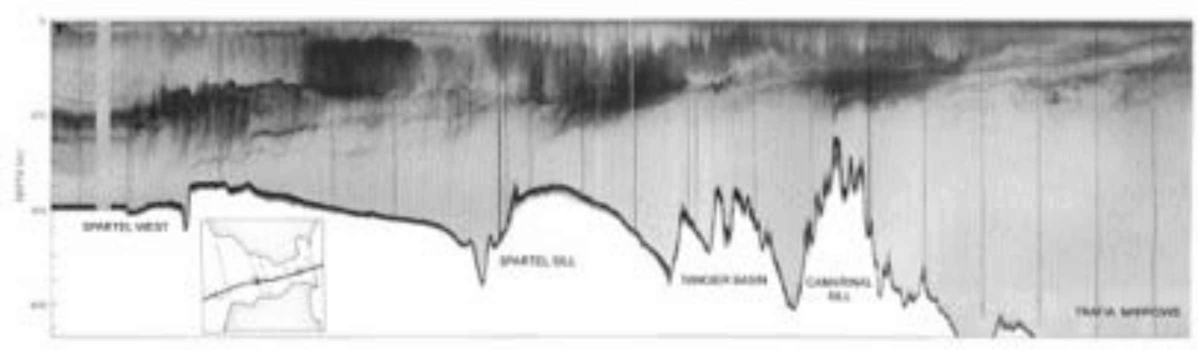


Figure 2. Transect of the Strait [From Armi and Farmer, Farmer and Armi.1988]

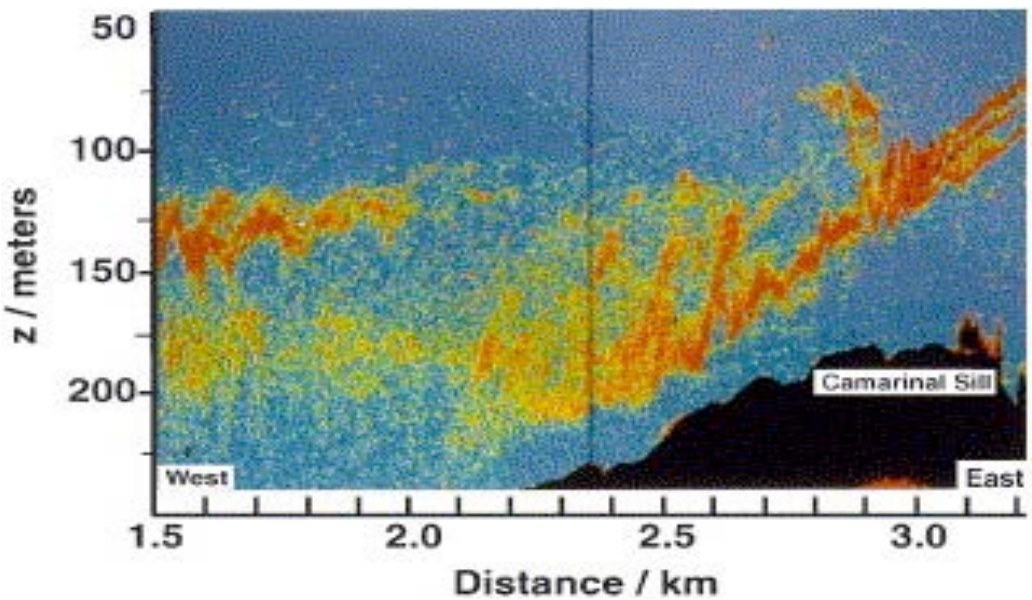
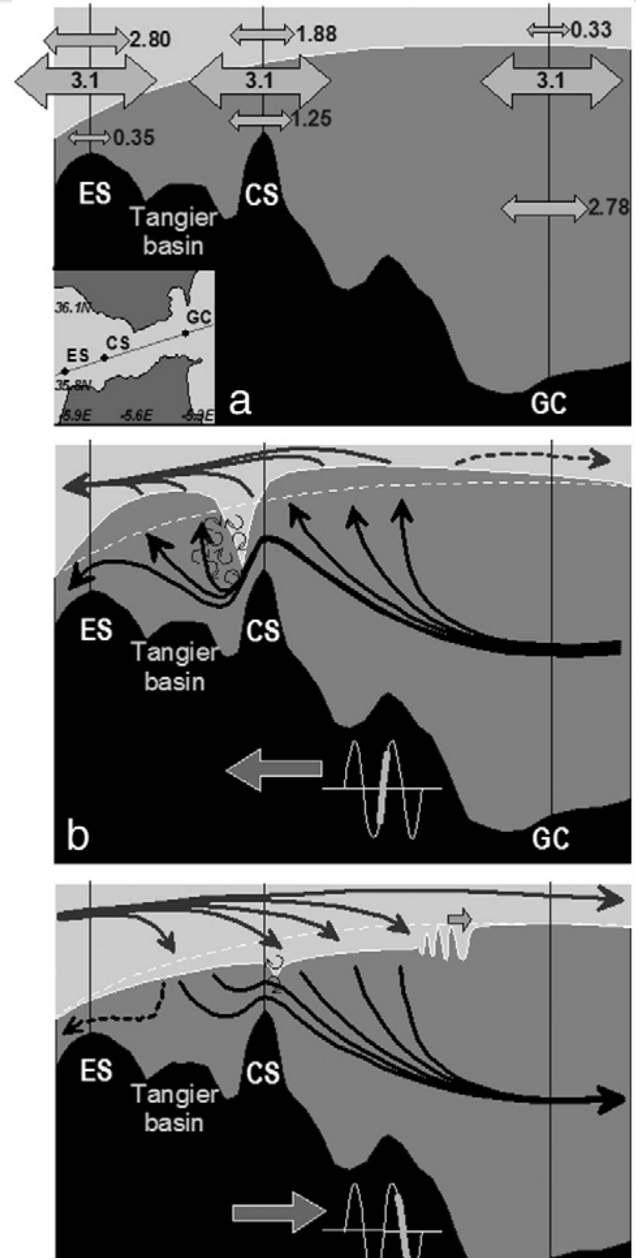


Image of acoustic backscatter during ebb tide over Camarinal Sill in the Strait of Gibraltar (Wesson and Gregg, 1994)



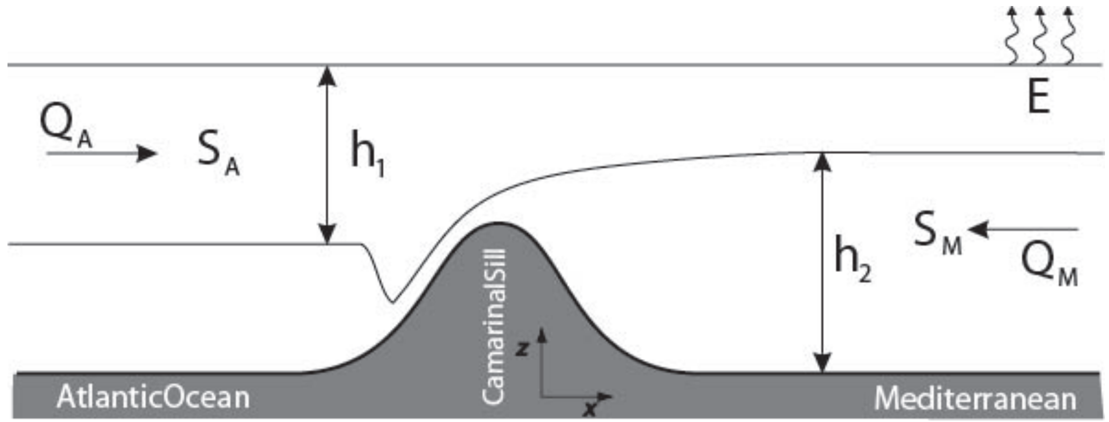
A. Sánchez-Román et al, JGR 2012

Strait of Gibraltar Background: Hydraulics

Mass Conservation

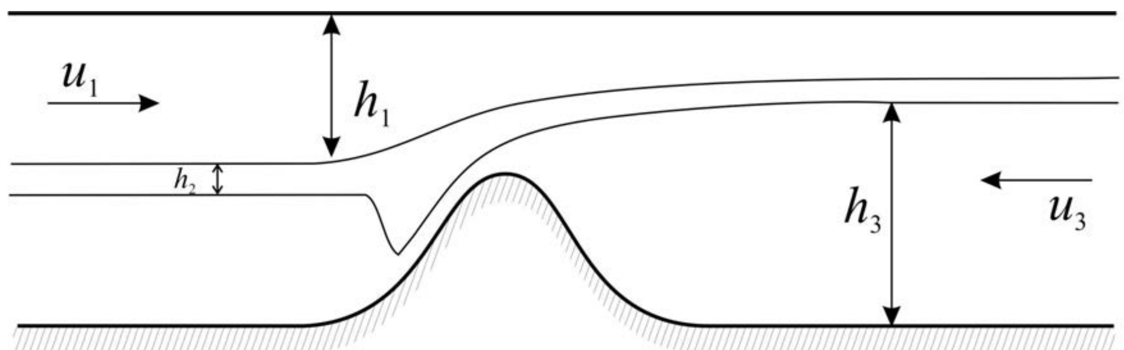
$$\begin{cases} Q_A + Q_M = E - P - R \\ Q_A S_A + Q_M S_M = 0 \end{cases}$$

Salt Conservation



Knudsen equations (1899)

$$\begin{cases} Q_A = \frac{S_M E_{net}}{S_M - S_A} \\ Q_M = -\left[\frac{S_A E_{net}}{S_M - S_A}\right] \end{cases}$$

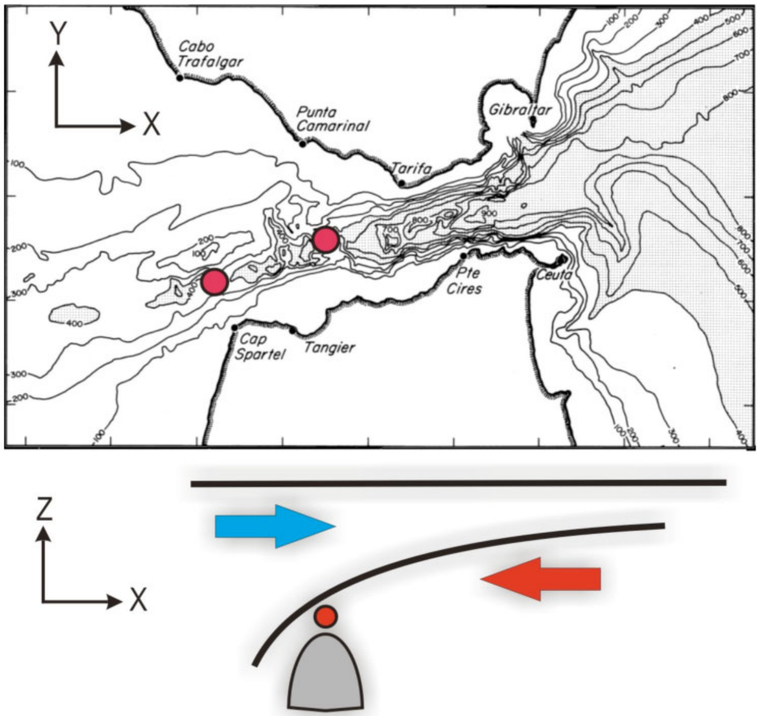


$$F_1^2 = \frac{u_1^2}{h_1 g\left(1 - r_{1,2}\right)} \qquad F_2^2 = \frac{u_2^2\left(1 - r_{1,3}\right)}{h_2 g\left(1 - r_{1,2}\right)\left(1 - r_{2,3}\right)} \qquad F_3^2 = \frac{u_3^2}{h_3 g\left(1 - r_{2,3}\right)} \qquad r_{i,j} = \frac{\rho_i}{\rho_j}$$

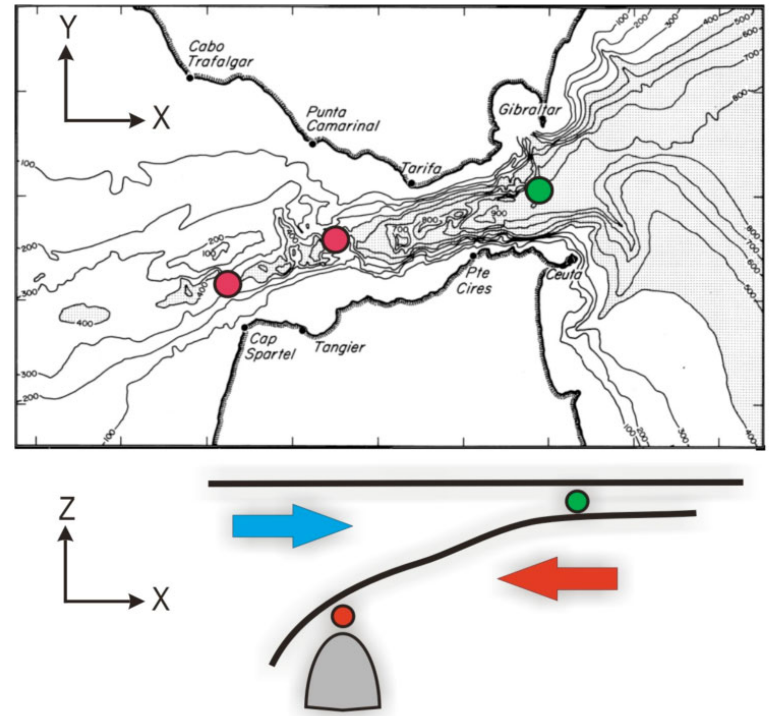
$$G^2 = F_1^2 + F_2^2 + F_3^2$$

Strait of Gibraltar Background: Hydraulics

Submaximal Exchange



Maximal Exchange

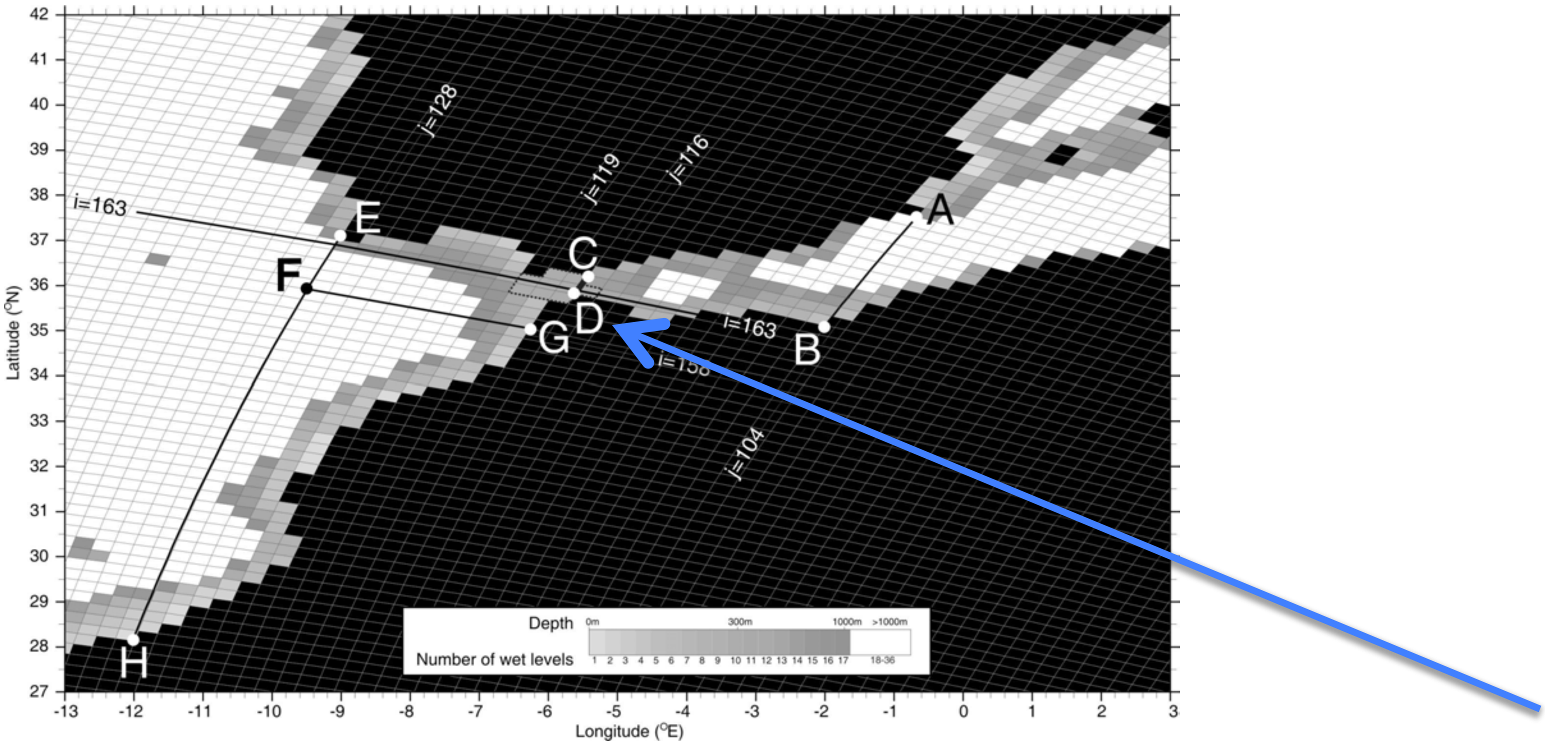


If the exchange is subject to one hydraulic control in the western part of the Strait, the regime is called submaximal, while if the flow exchange is also controlled in the eastern part of the Strait along TN, the regime is called maximal.

The maximal regime can be expected to have larger heat, salt, and mass fluxes and to respond more slowly to changes in stratification and thermohaline forcing within the Mediterranean Sea and the North Atlantic Ocean.

Climate models, both global and regional, represent the

Strait of Gibraltar like a rectangular pipe & notides

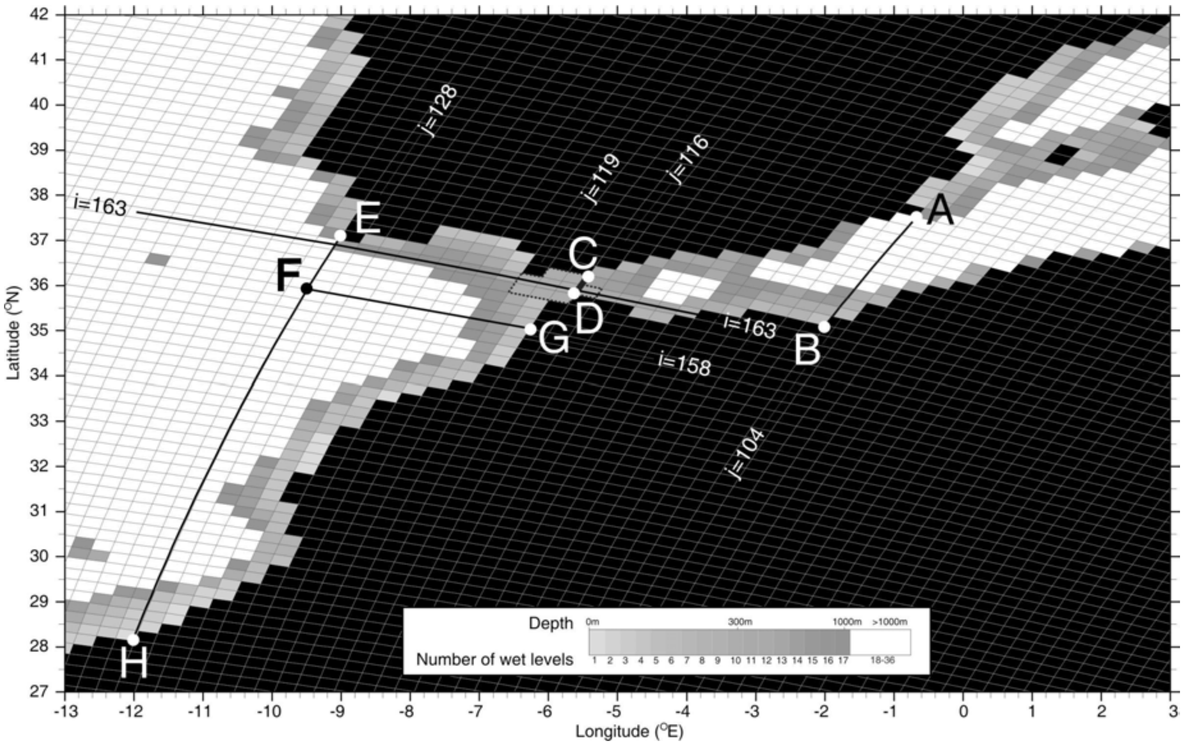


Strait of Gibraltar

Question & Motivation in the NEMERTE project

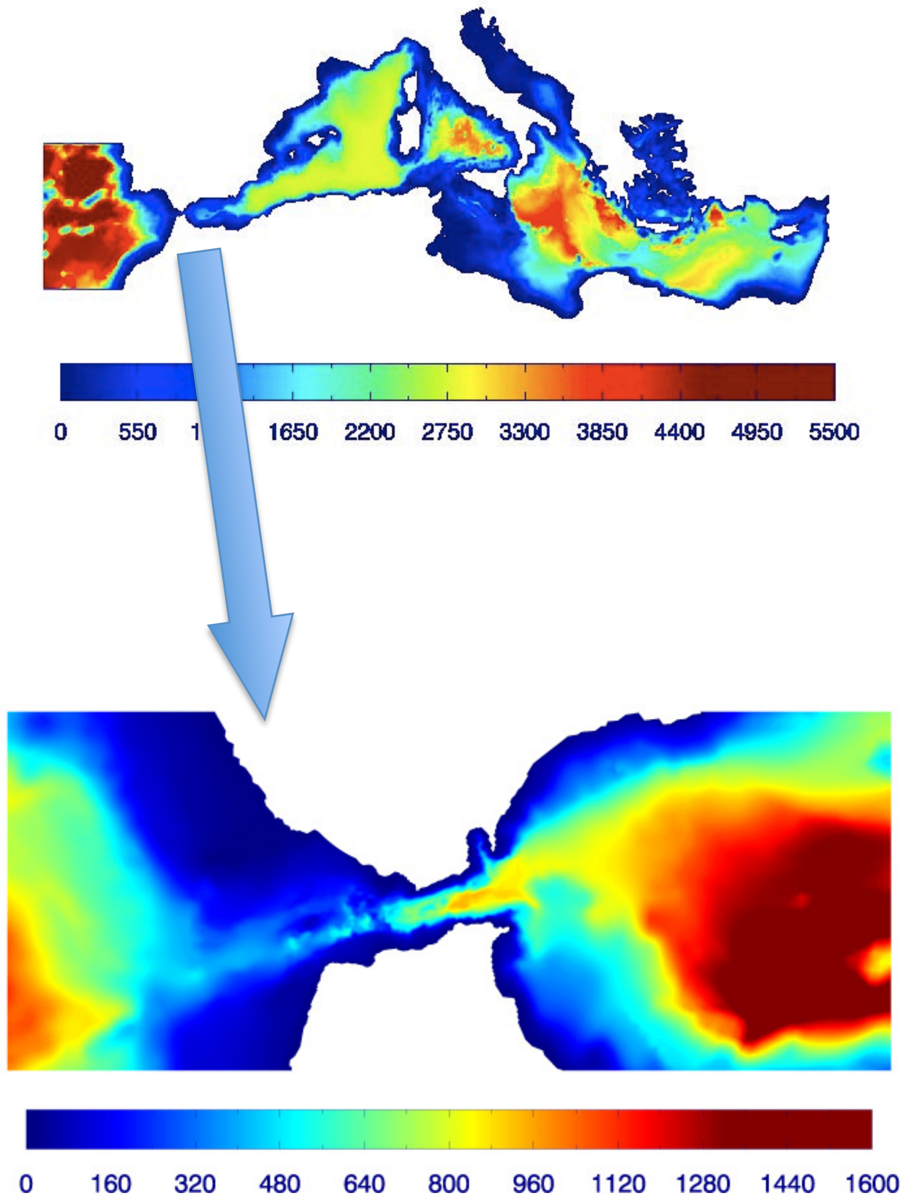
Climate models, both global and regional, represent the

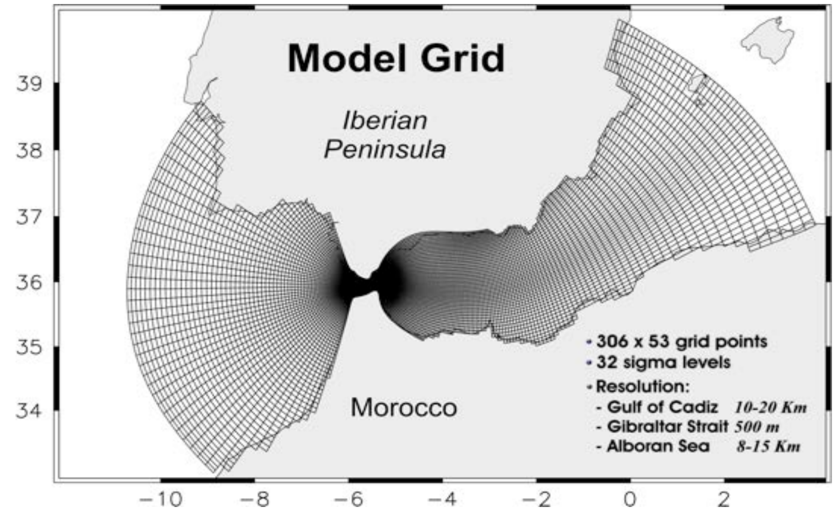
Strait of Gibraltar like a rectangular pipe & notides

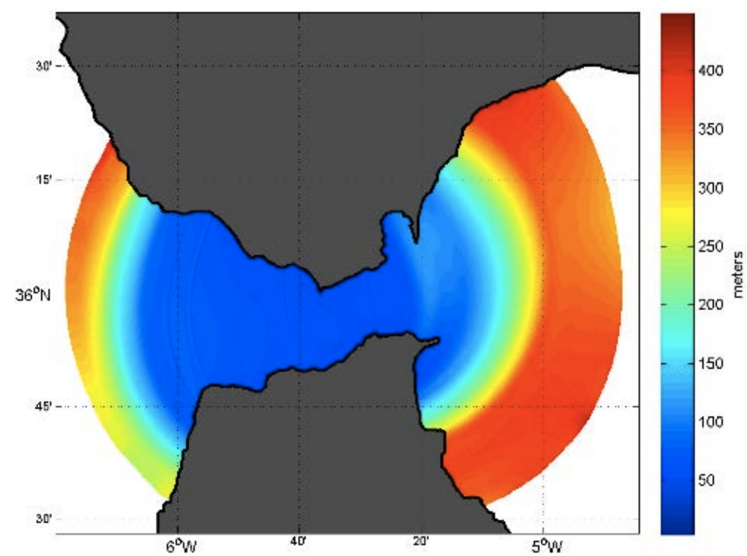


- Is it reasonable?
- If NOT, what are these models neglecting?
- If NOT, what is the minimum resolution to adopt for the Strait?

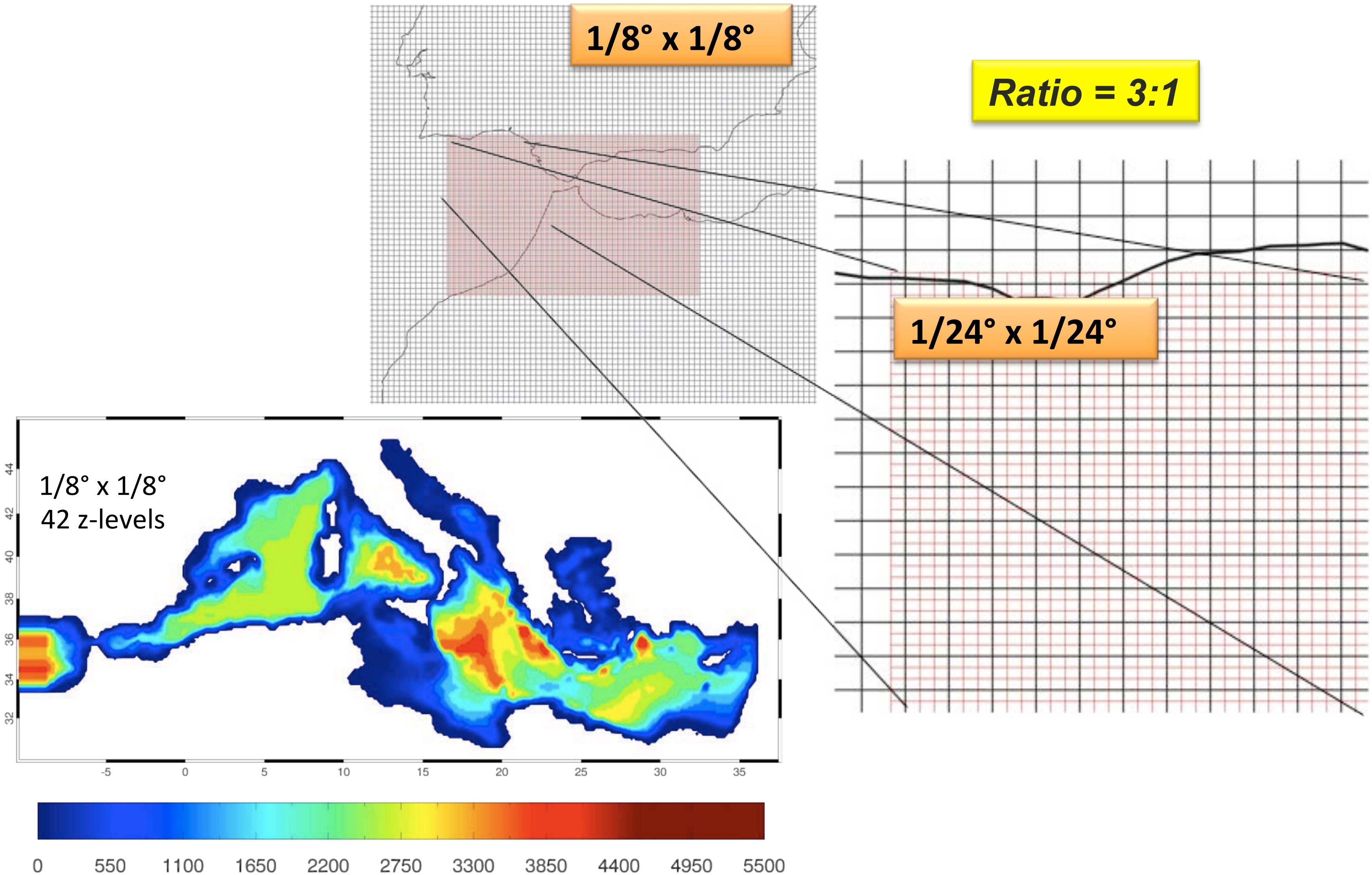
Answer: Direct simulation of the Strait at high resolution





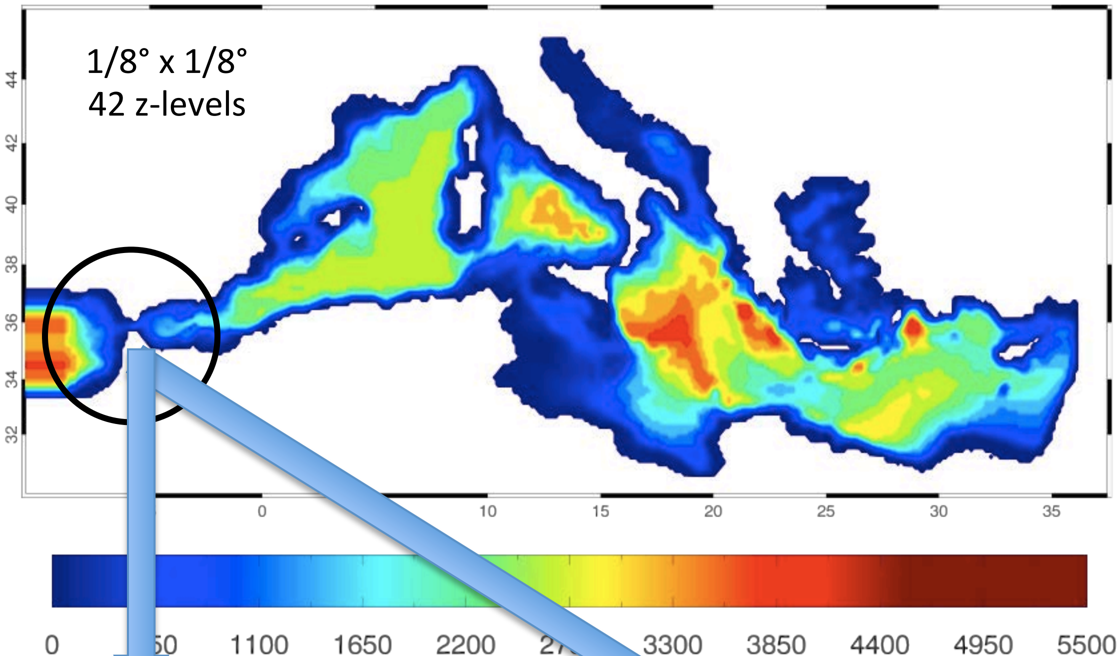


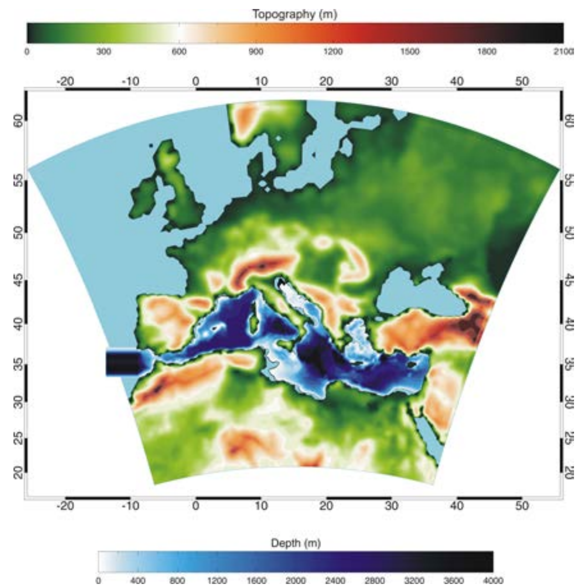
Effects of high resolution at Gibraltar in a 1/8° Mediter. model



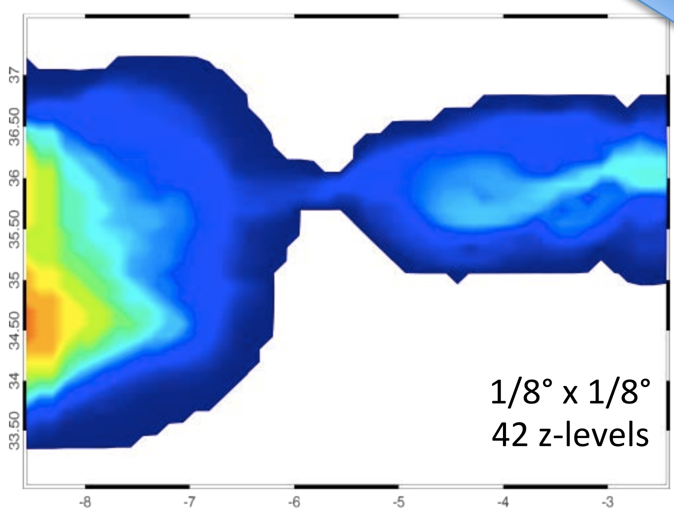
Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean. Modeling

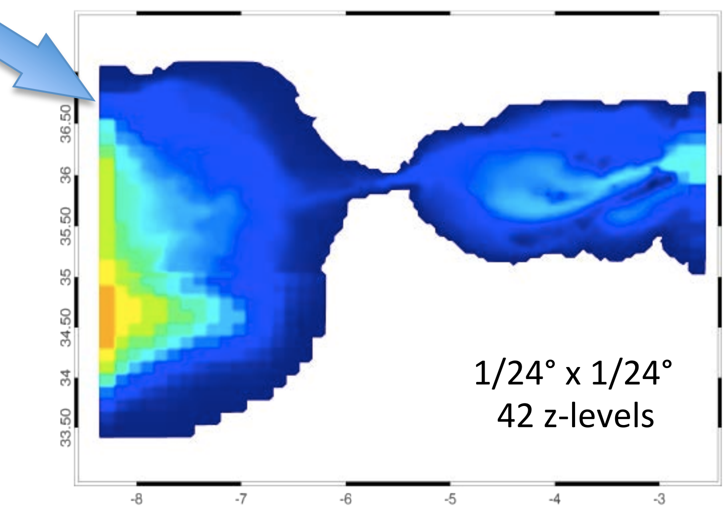
Effects of high resolution at Gibraltar in a 1/8° Mediter. model



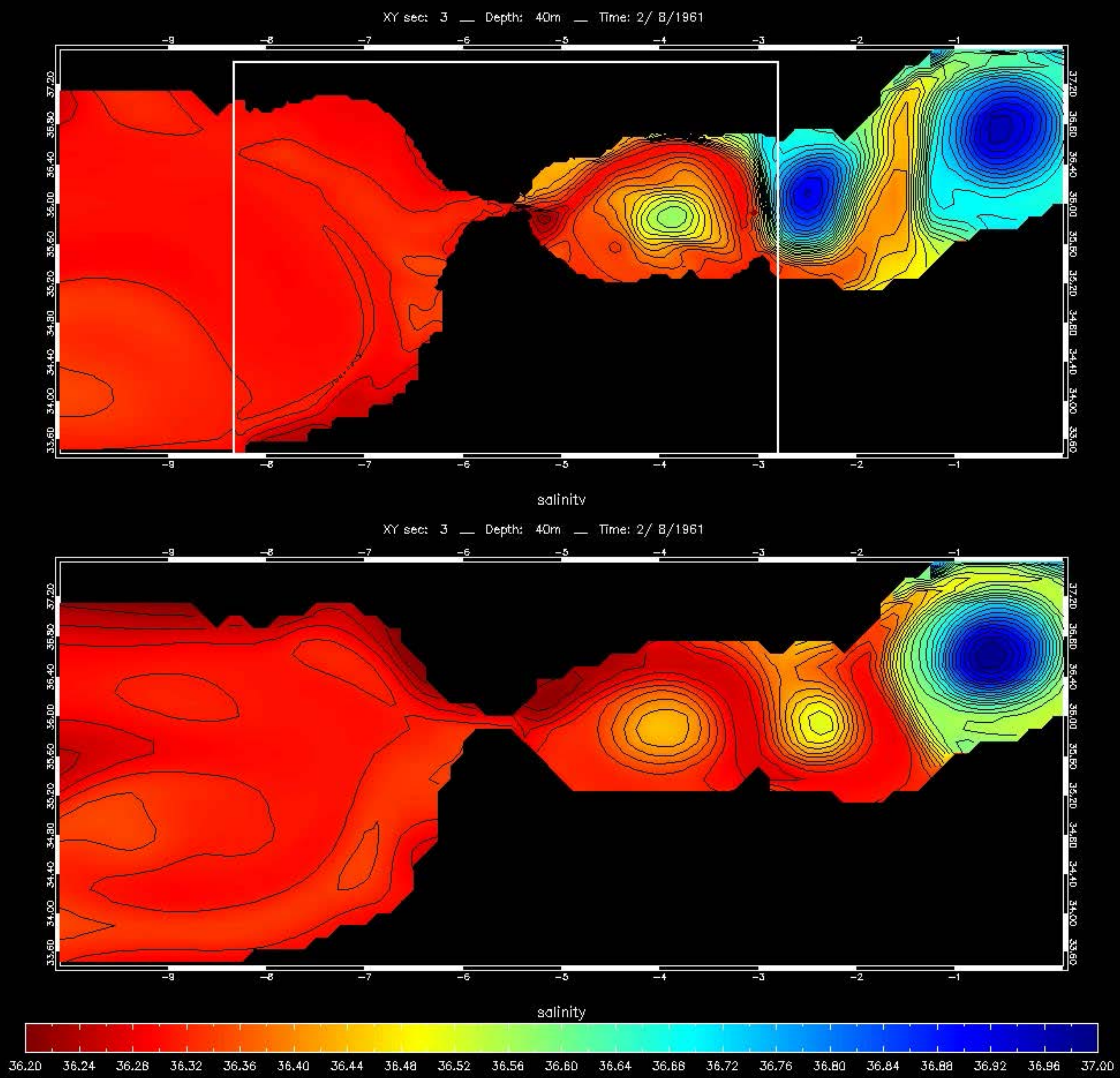


Oceanic component in the **PROTHEUS** *regional climate system*

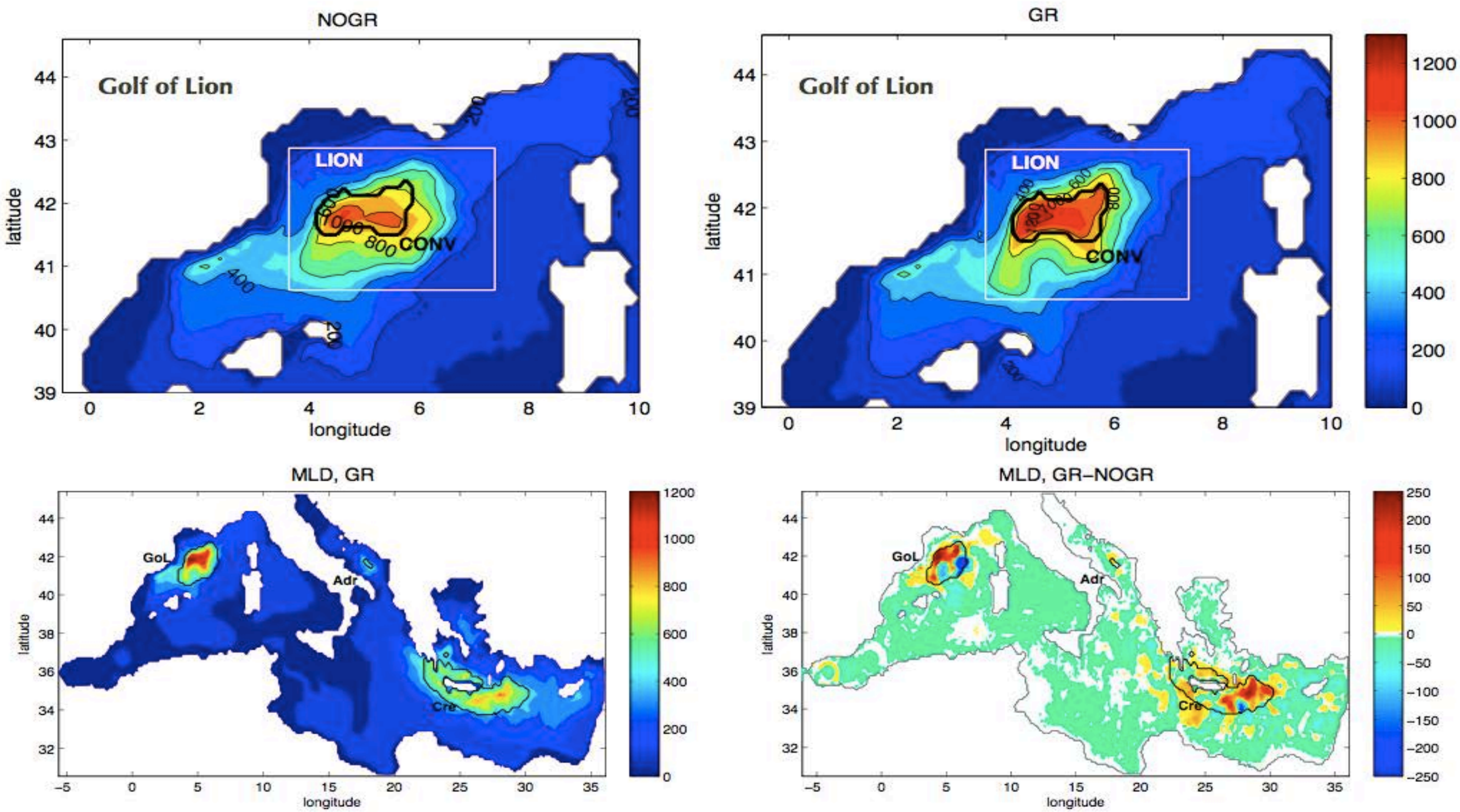




Effects of high resolution at Gibraltar in a 1/8° Mediter. model



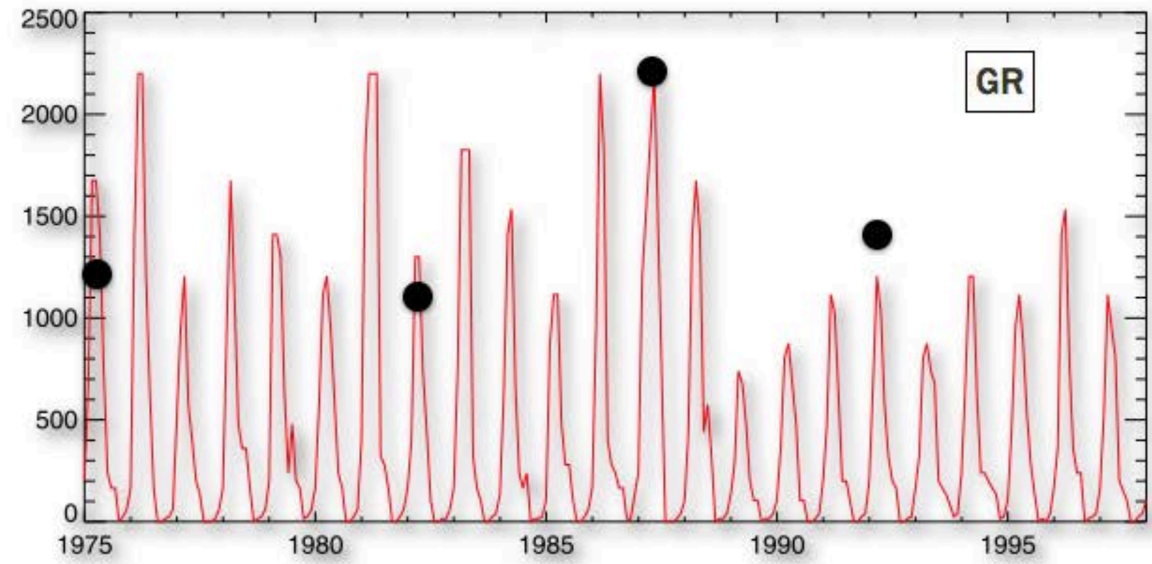
Effects of high resolution at Gibraltar in a 1/8° Mediter. model

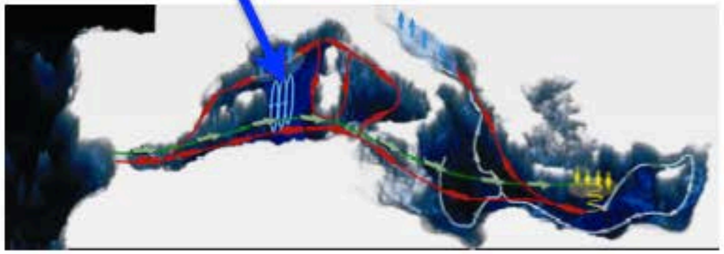


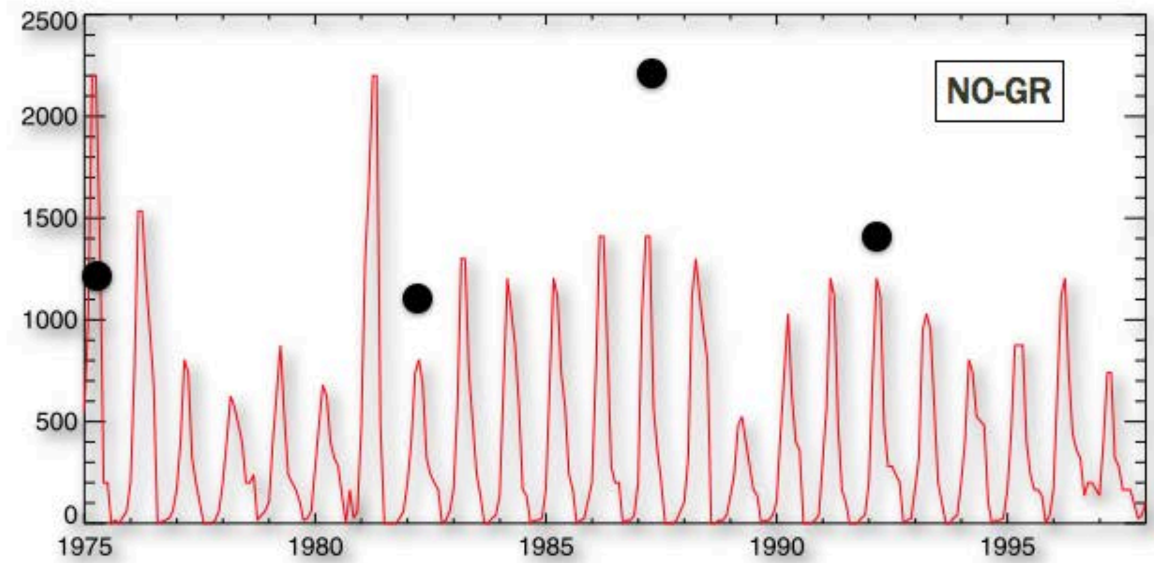
Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean Modeling

Effects of high resolution at Gibraltar in a 1/8° Mediter. model

Convection depth in the Gulf of

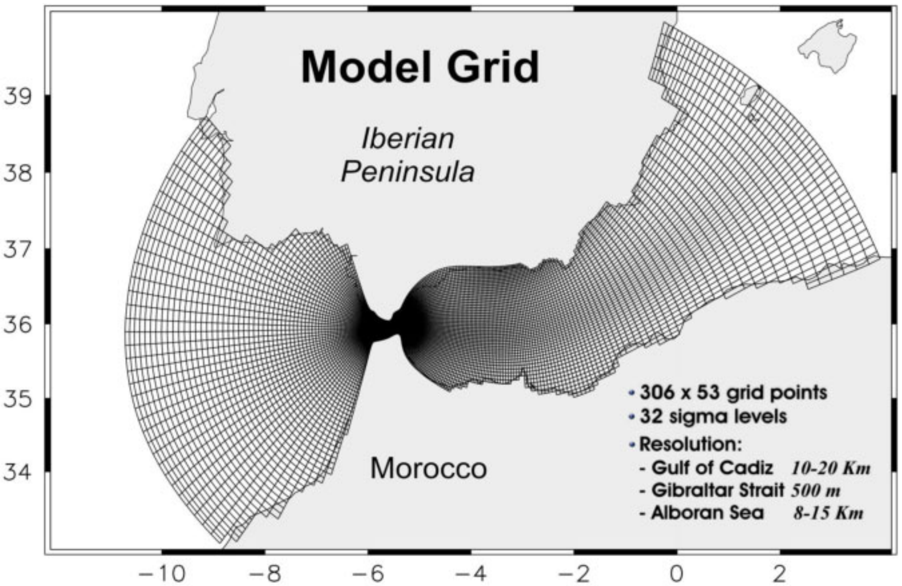


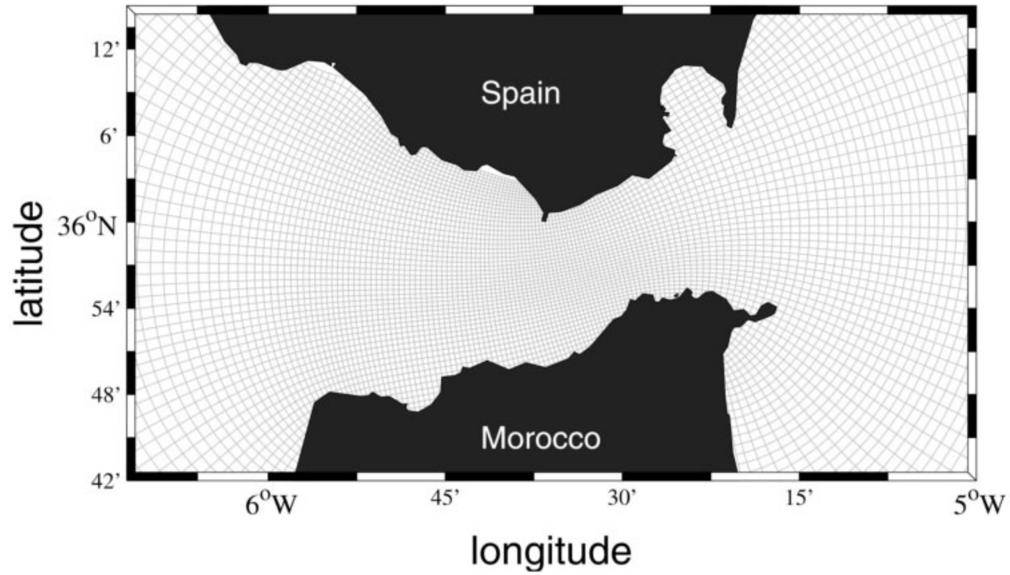




Black circles mark the experimentally observed convection depth (Mertens and Schott, 1998).

Sub-basin Model: Cadiz – Gibraltar - Alboran





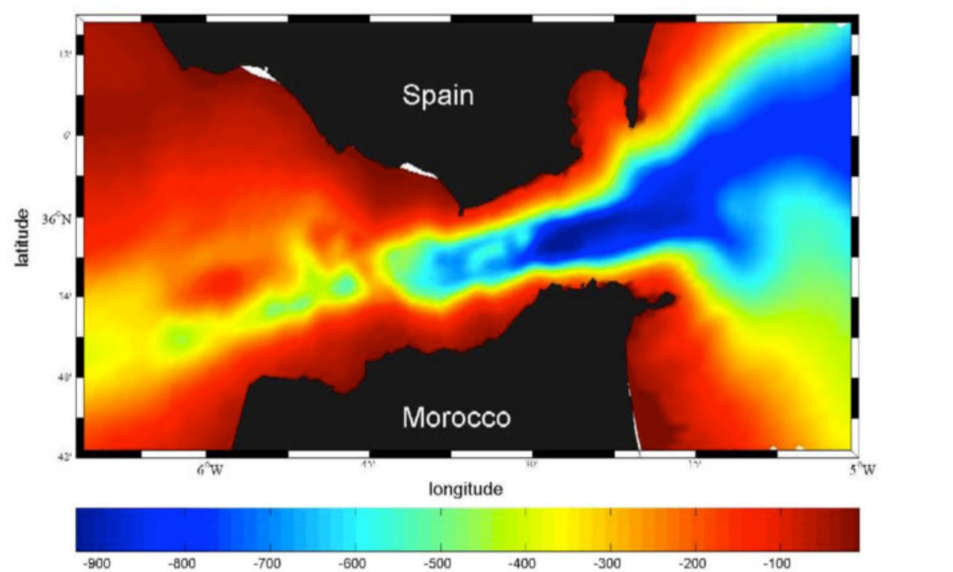
Modified POM

Minimal Hor. Resolution: < 500 m

External Time-Step: 0.1 sec

O_1 K_1 diurnal tidal component

M_2 S_2 diurnal tidal component



•Sannino et al, JGR-Book, 2013

•Sannino et al, JPO, 2009

•Sanchez et al, JGR, 2009

•Garrido et al, JGR, 2008

•Garcia-Lafuente et al, JGR, 2007

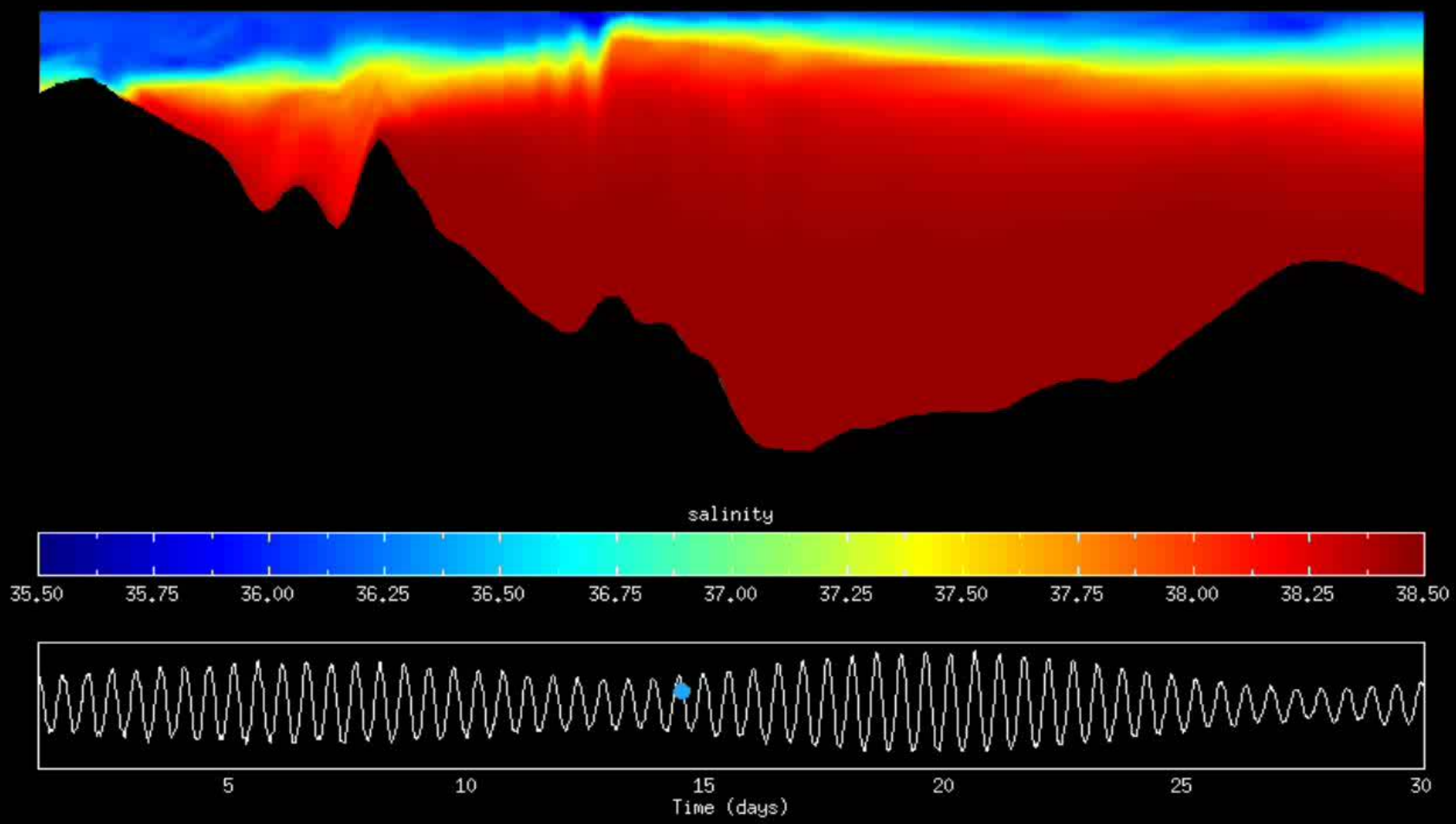
•Sannino et al, JGR, 2007

•Sannino et al , NC, 2005

•Sannino et al, JGR, 2004

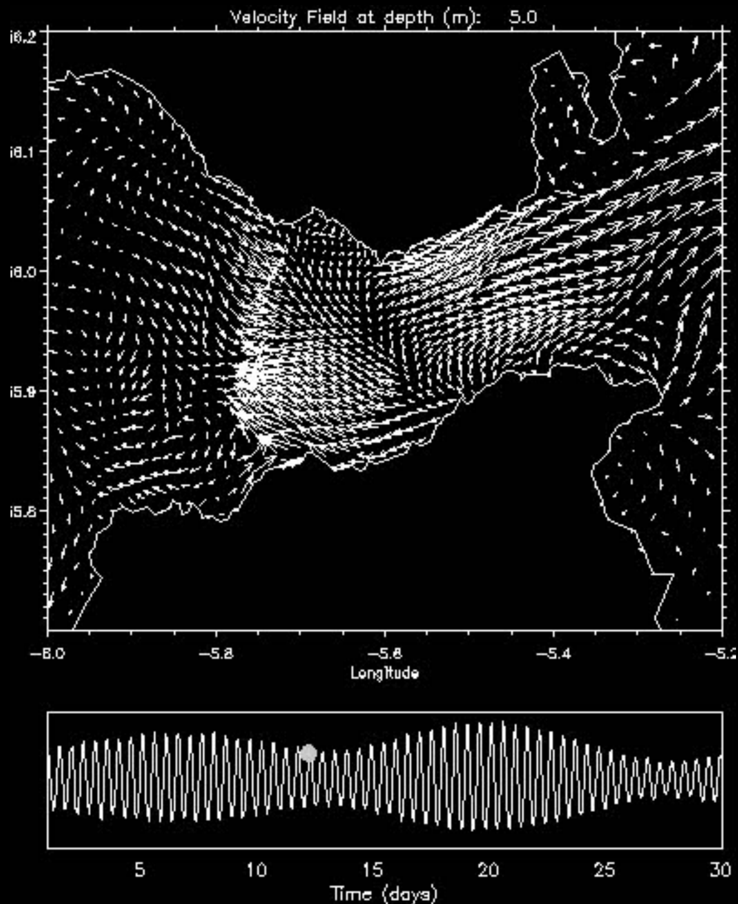
•Sannino et al, JGR, 2002

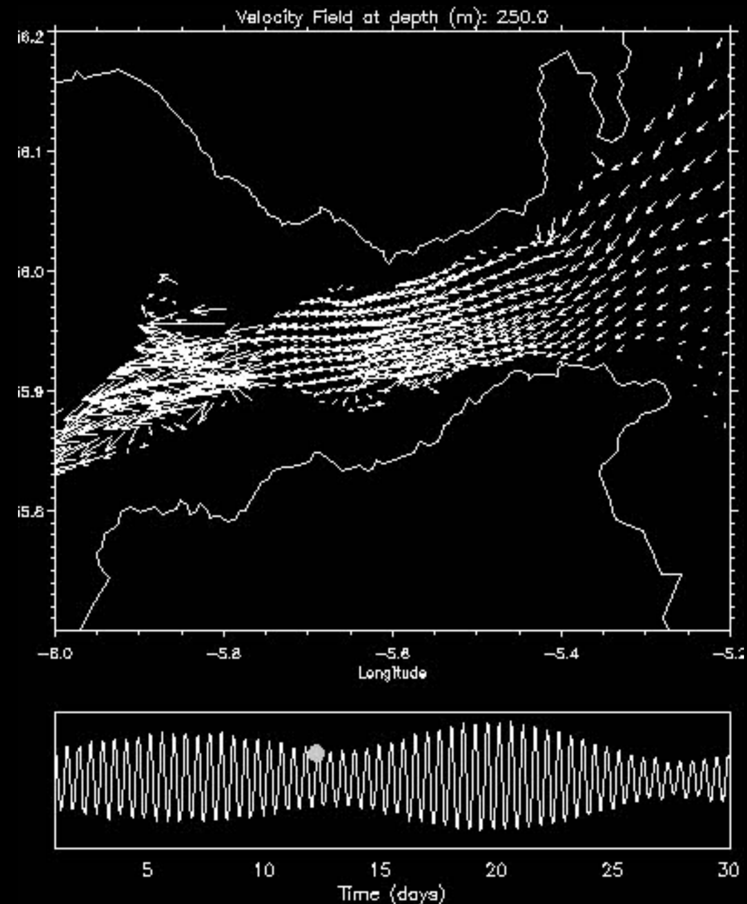
Sub-basin Model: Cadiz – Gibraltar - Alboran



salinity along-strait section

Sub-basin Model: Cadiz – Gibraltar - Alboran





Sub-basin Model: Cadiz – Gibraltar - Alboran

Tidal Components comparison
Surface elevation

TABLE 1. Comparison between Observed and Predicted Amplitudes A and Phases P of M_2 tidal elevation.

Location	Latitude	Longitude	Observed M_2		Predicted M_2		Predicted - Observed		
			A,cm	P,deg	A,cm	P,deg	A,cm	A,%	P,deg
			Tsimplis et al. (1995)						
Gibraltar	36°08′	05°21′	29.8	46.0	29.5	46.0	-0.3	1.0	+0.0[a]
			García-Lafuente (1986)						
Pta. Gracia	36°05.4′	05°48.6′	64.9 ± 0.2	49.0 ± 0.5	67.6	53.8	+2.7	4.1	+4.5
Tarifa	36°00.2′	05°36.4′	41.5 ± 0.2	57.0 ± 0.5	43.5	49.7	+2.0	4.8	-7.3
Pta. Cires	35°54.7′	05°28.8′	36.4 ± 0.2	46.5 ± 0.5	35.0	54.9	-1.4	3.8	+8.4
Pta. Carnero	36°04.3′	05°25.7′	31.1 ± 0.2	47.5 ± 0.5	30.8	47.4	-0.3	0.9	-0.1
			Candela et al. (1990)						
DN	35°58′	05°46′	60.1	51.8	58.2	57.8	-1.9	3.1	+6.0
DS	35°54′	05°44′	54.0	61.8	54.1	64.1	+0.1	0.2	+2.3
SN	36°03′	05°43′	52.3	47.6	52.3	52.9	0.0	0.0	+5.3
SS	35°50′	05°43′	57.1	66.8	56.8	67.4	-0.3	0.5	+0.6
DW	35°53′	05°58′	78.5	56.1	76.6	62.7	-1.9	2.4	+6.6
TA	36°01′	05°36′	41.2	41.2	43.5	49.7	+2.3	5.5	+8.5
AL	36°08′	05°26′	31.0	48.0	30.0	49.7	-1.0	3.2	+1.7
CE	35°53′	05°18′	29.7	50.3	29.5	51.5	-0.2	0.6	+1.2
DP5	36°00′	05°34′	44.4	47.6	42.1	47.6	-2.3	5.1	+0.0

[a]Calibration.

Max Differences:
Amp: 3.6 cm
Pha: 11°

Sannino et al.,JPO, 2009

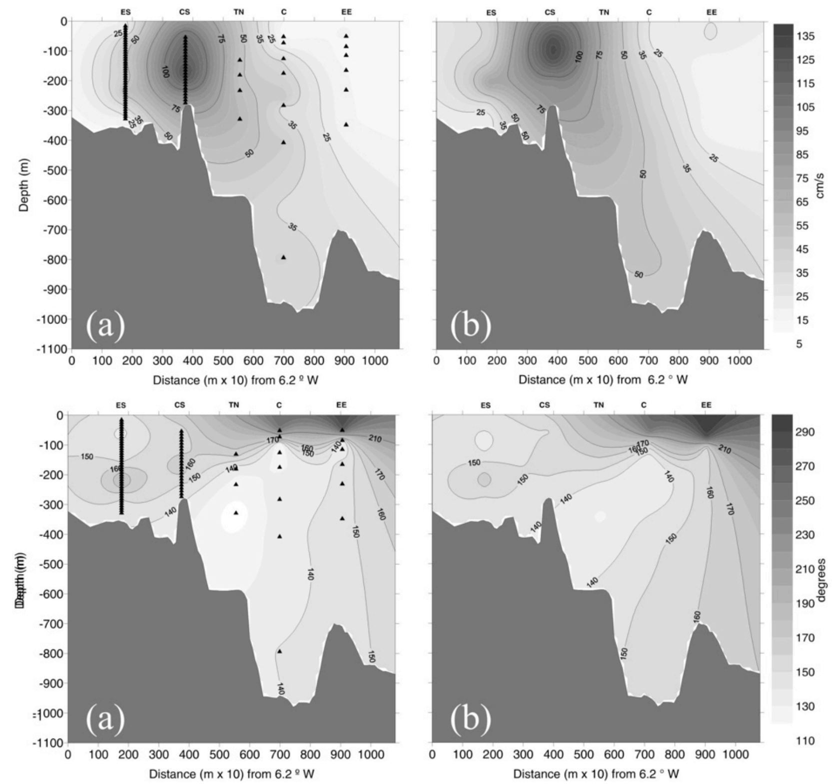
Tidal Components comparison
Along-strait velocity

(a) Data

(b) Model

(a) Data

(b) Model



Max Differences:
Amp: 10 cm s^{-1}
Pha: 20°

Sánchez-Román et al., JGR, 2009

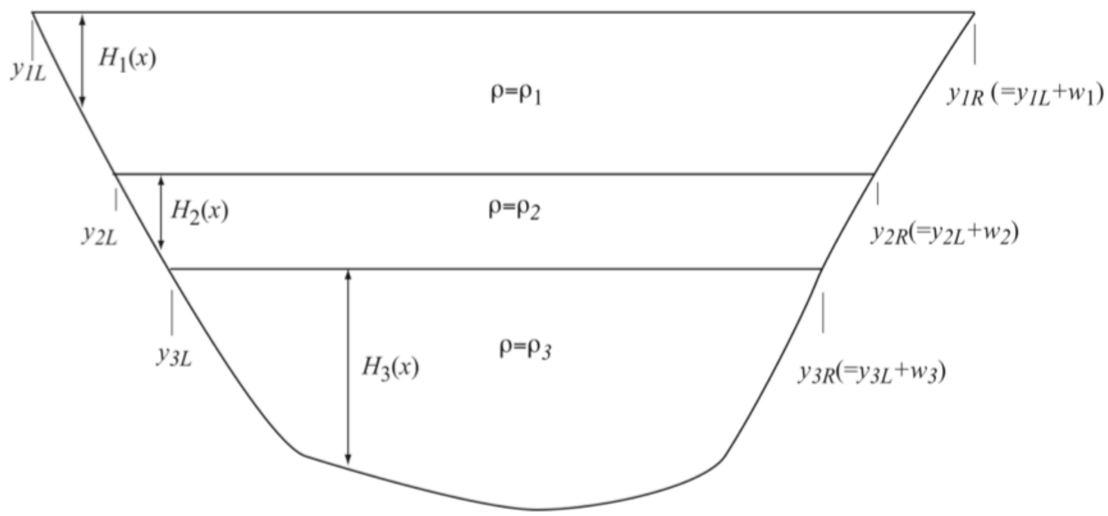
Strait of Gibraltar: new 3Layer Hydraulic Theory

$$\tilde{F}_1^2 = \left(\frac{1}{w_2} \int_{y_{1L}}^{y_{1R}} \frac{g'_{21} H_1}{u_1^2} dy_1 \right)^{-1}$$

$$\tilde{F}_2^2 = \left(\frac{1}{w_2} \int_{y_{2L}}^{y_{2R}} \frac{g'_{32} H_2}{u_2^2} dy_2 \right)^{-1}$$

$$\tilde{F}_3^2 = \left(\frac{1}{w_3} \int_{y_{3L}}^{y_{3R}} \frac{g'_{32} H_3}{u_3^2} dy_3 \right)^{-1}$$

(b)



$$g'_{21} = g(\rho_2 - \rho_1)/\bar{\rho}, \quad g'_{32} = g(\rho_3 - \rho_2)/\bar{\rho}, \quad r = \frac{\rho_2 - \rho_1}{\rho_3 - \rho_1}$$

$$\tilde{F}_1^2 + \left(\frac{1-r}{r} + \frac{w_3}{w_2} \right) \tilde{F}_2^2 + \tilde{F}_3^2 - \frac{w_3}{w_2} \tilde{F}_1^2 \tilde{F}_2^2 - \tilde{F}_1^2 \tilde{F}_3^2 - \frac{1-r}{r} \tilde{F}_2^2 \tilde{F}_3^2 = 1$$

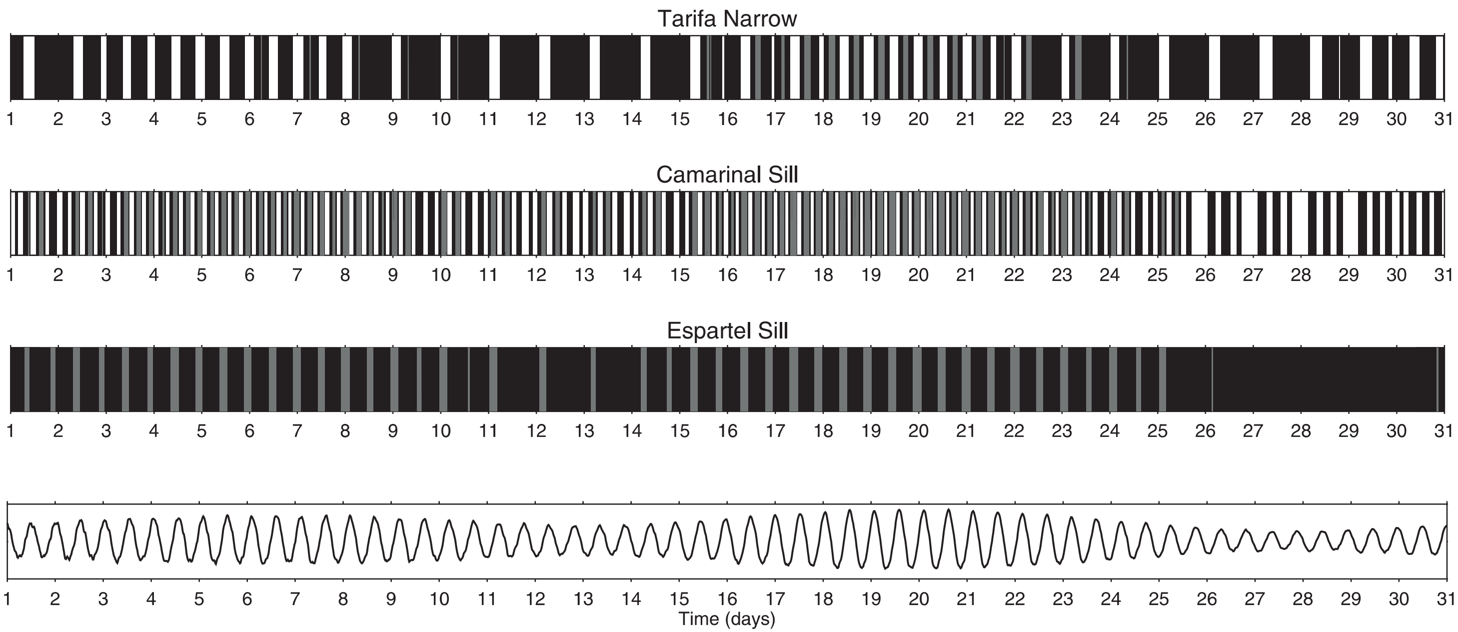
In order to determine whether a particular state is subcritical, supercritical, or critical, it is helpful to rewrite this equation as:

$$\frac{w_3}{w_2} \tilde{F}_2^2 = - \frac{(\tilde{F}_1^2 - 1)(\tilde{F}_3^2 - 1)}{(\tilde{F}_1^2 - 1) + \beta (\tilde{F}_3^2 - 1)}$$

$$\beta = \frac{w_2(1-r)}{w_3 r}$$

Sannino et al, JPO, 2009

POM model and hydraulics



Bars indicating the presence of provisional supercritical flow with respect to one mode (black) and with respect to both modes (grey) in the three main regions of the Strait: Espartel Sill, Camarinal Sill and Tarifa Narrow. Lower panel indicates tidal elevation at Tarifa.

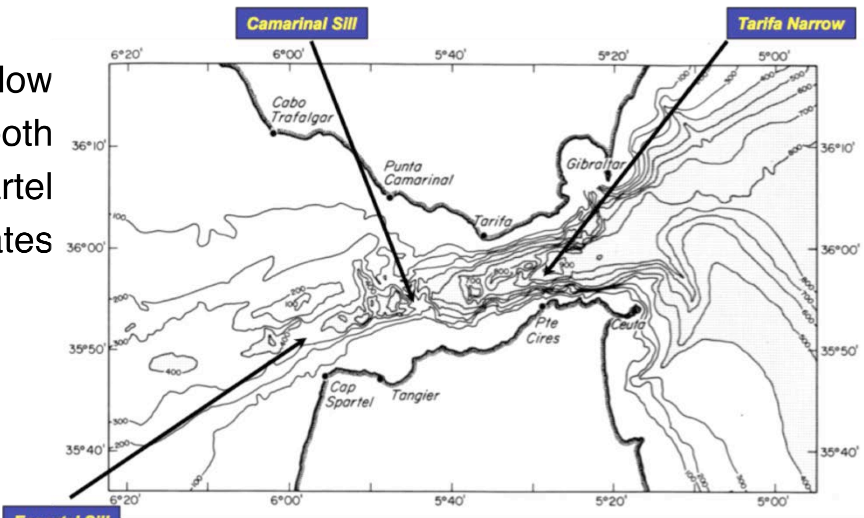


Chart of the Strait of Gibraltar showing the principal geographic features. Areas deeper than 400 m are shaded

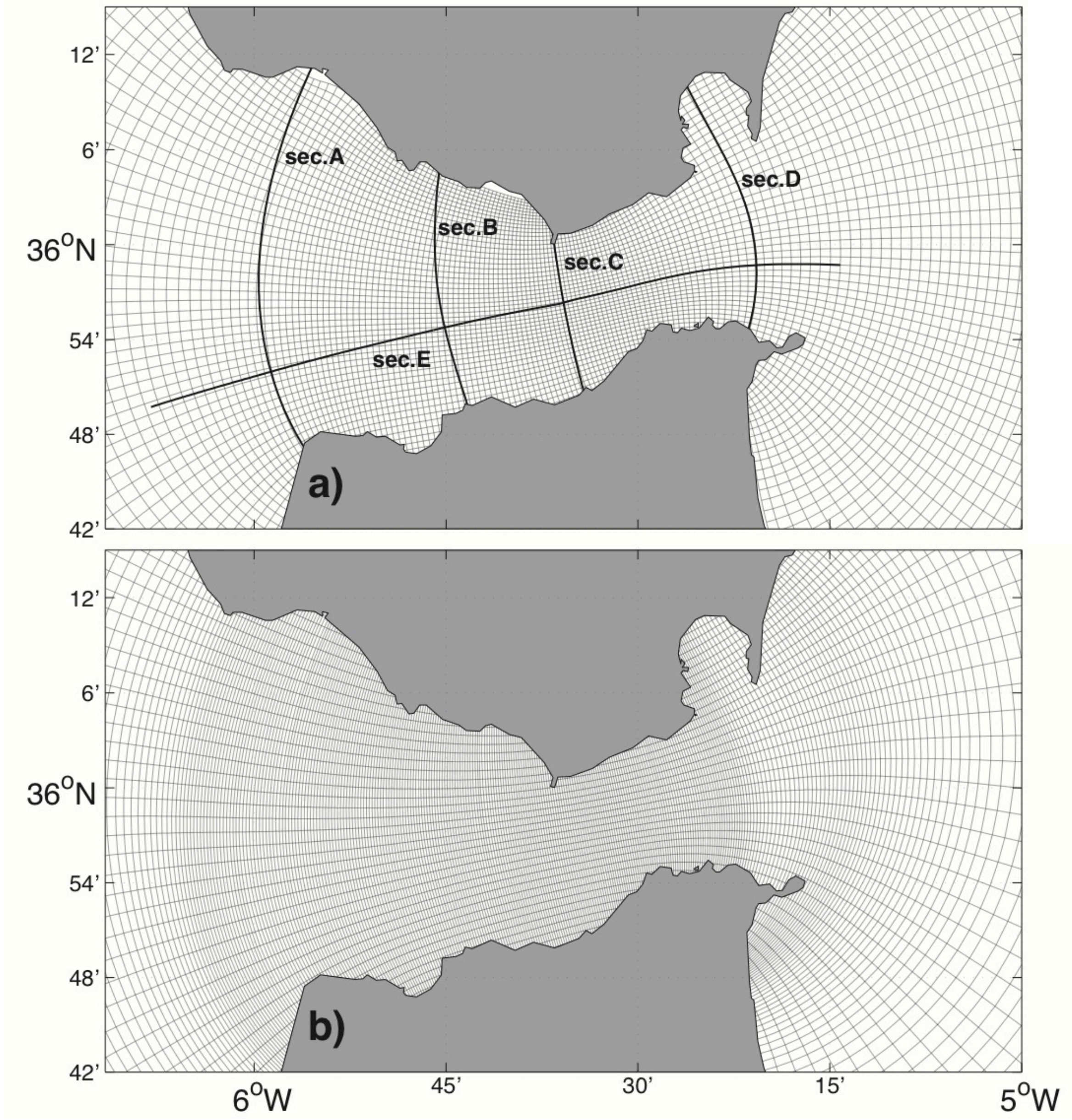
Are the hydraulic results model depended?

To answer the question the exchange flow simulated by POM has been compared with the exchange flow simulated by a very high resolution non-hydrostatic model implemented for the Strait region.

MITgcm vs POM : model grids

POM grid
Max resolution
300 m

MITgcm grid
Max resolution
25 m
(only 25% of the
actual grid is shown)

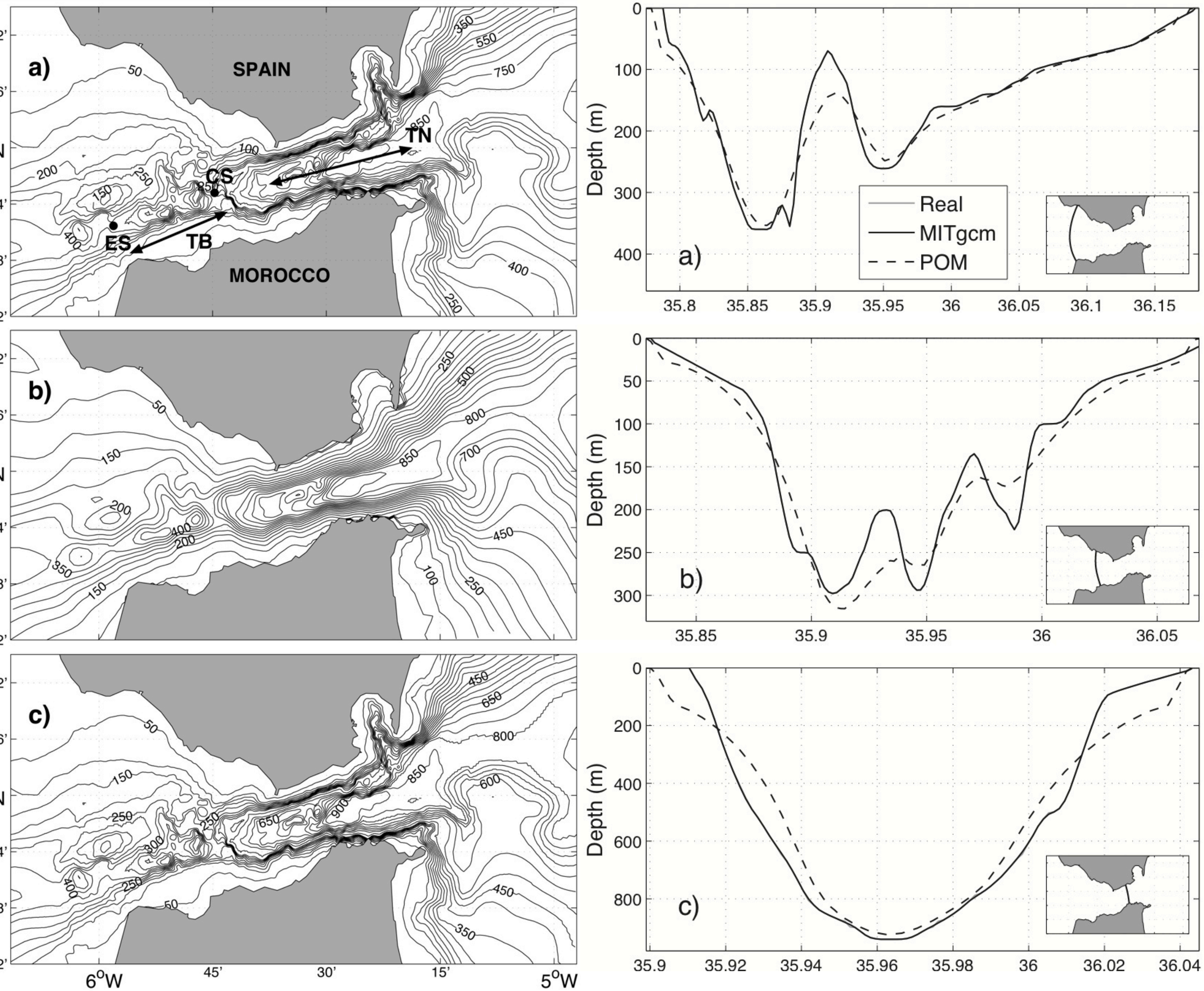


MITgcm vs POM : model bathymetry

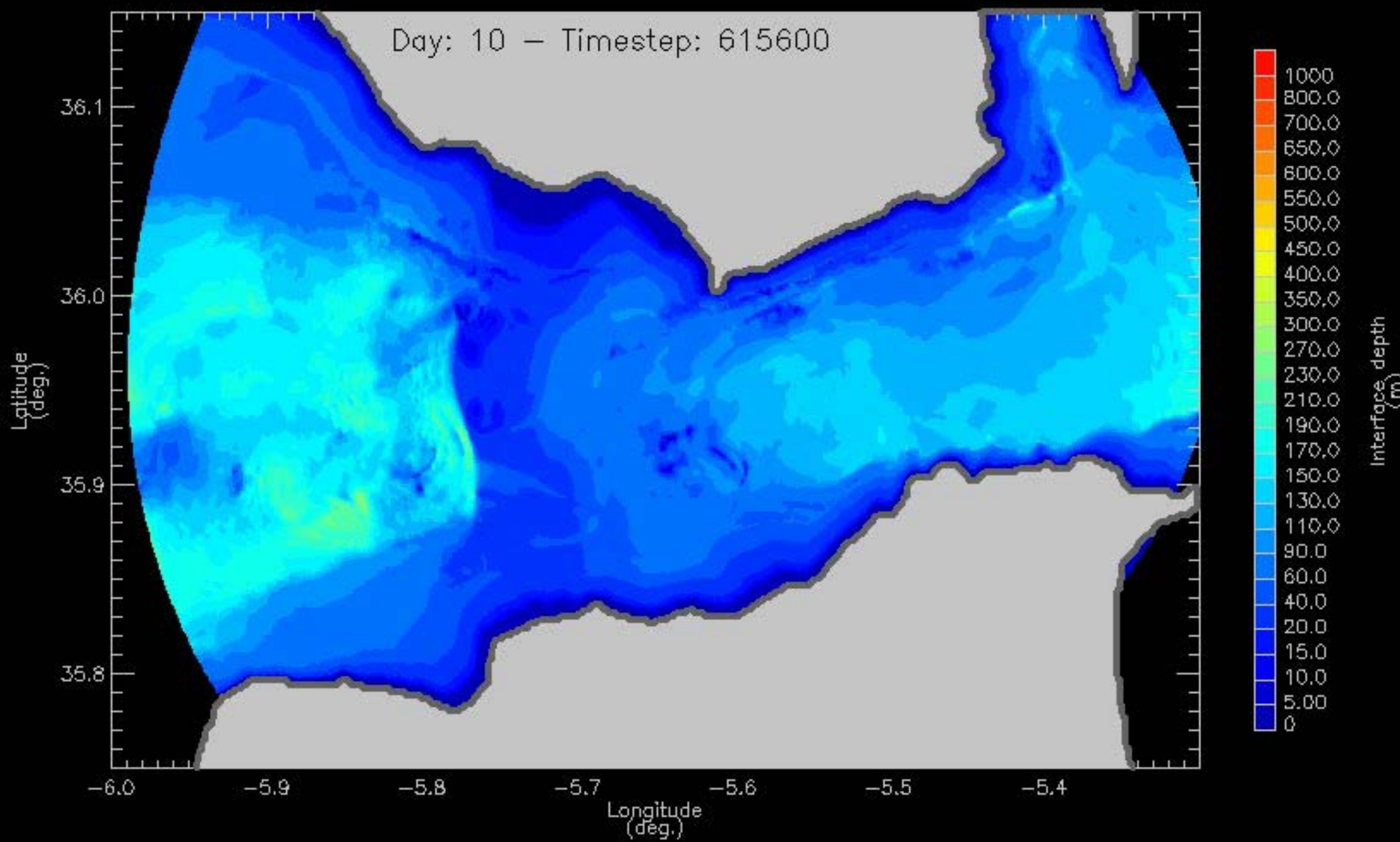
Real bathymetry

POM bathymetry
32 sigma-levels

MITgcm bathymetry
53 vertical zeta-levels
(partial cell)



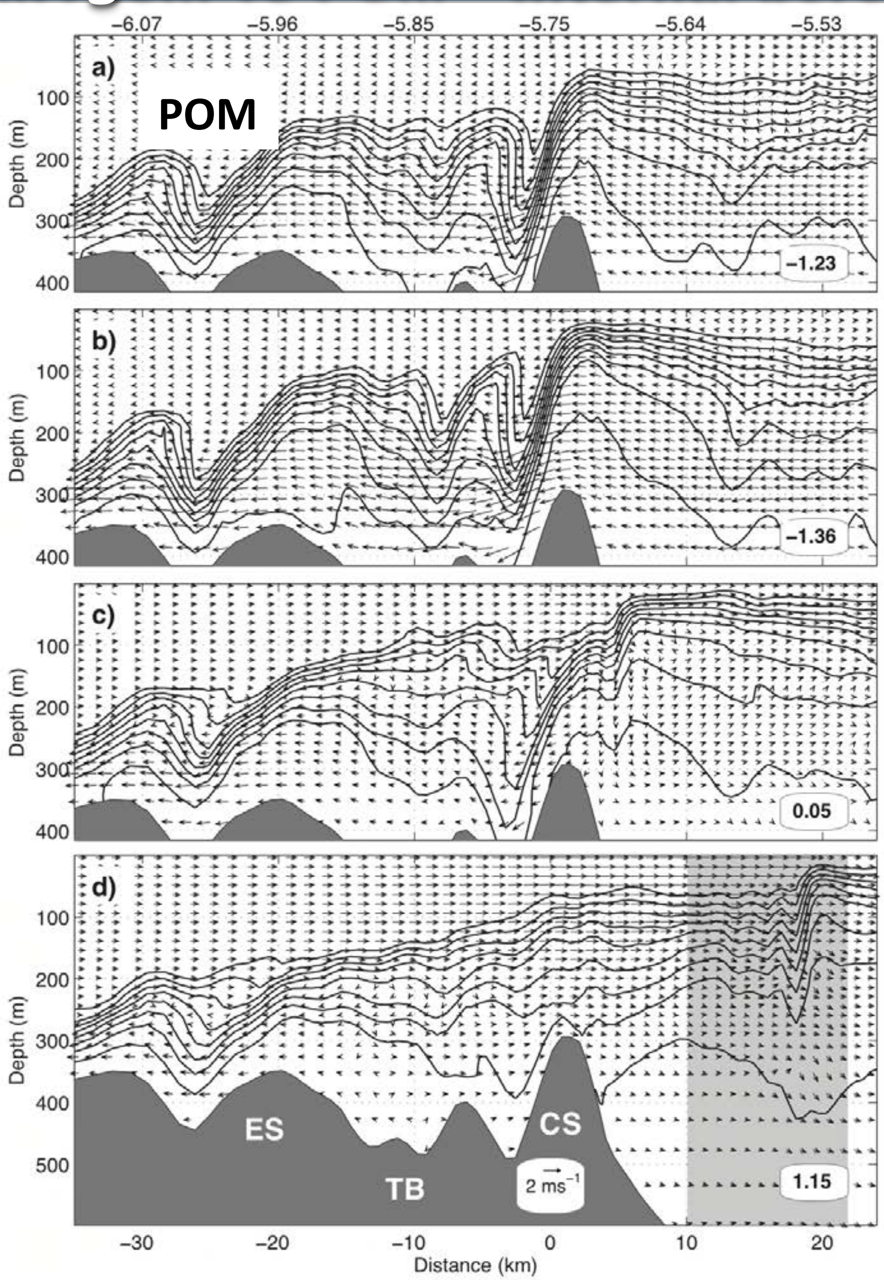
MITgcm model simulation

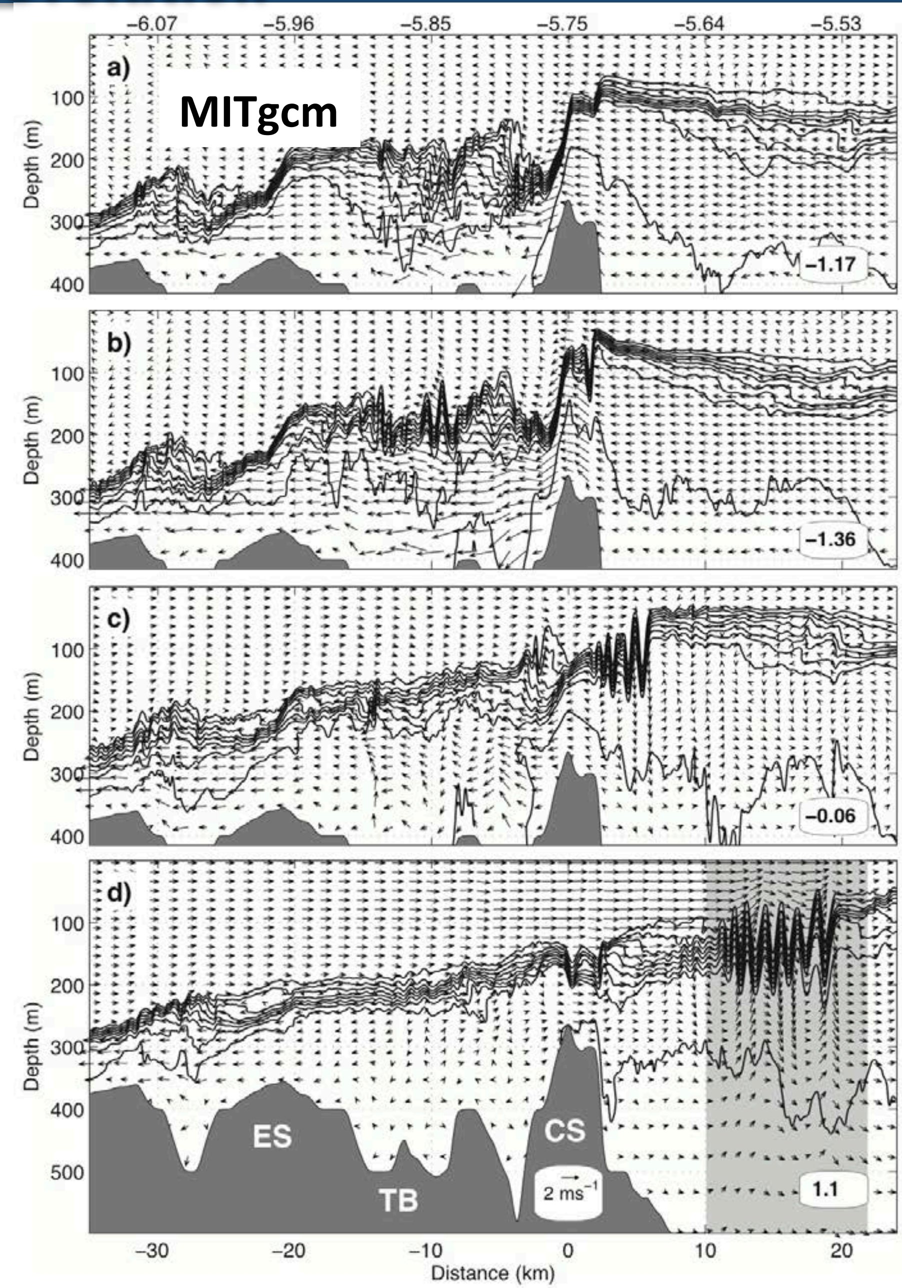


Garrido et al. jgr 2011

Interface depth evolution

MITgcm vs POM – Internal bore evolution



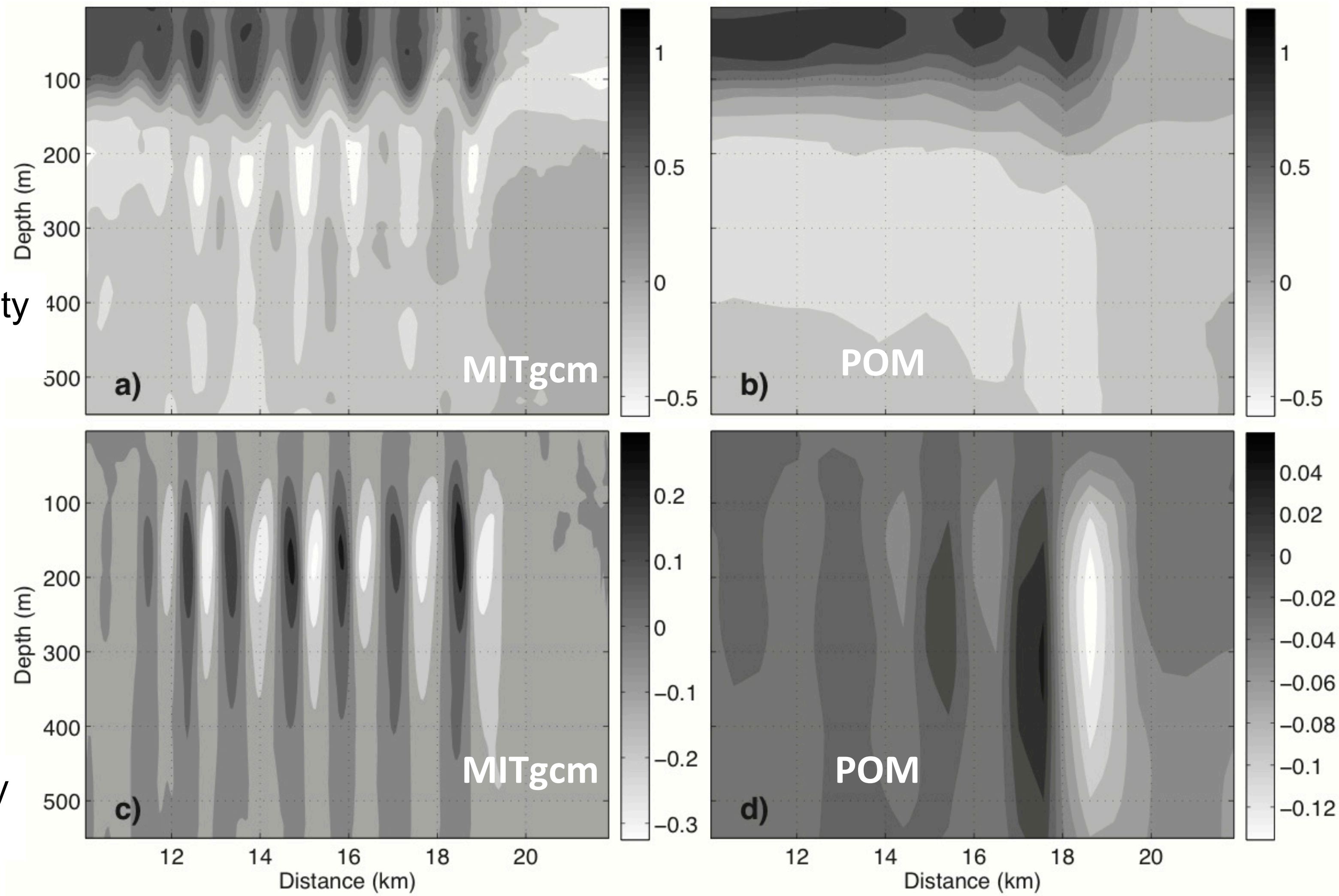


Garrido et al. jgr 2011

MITgcm vs POM – Internal bore evolution

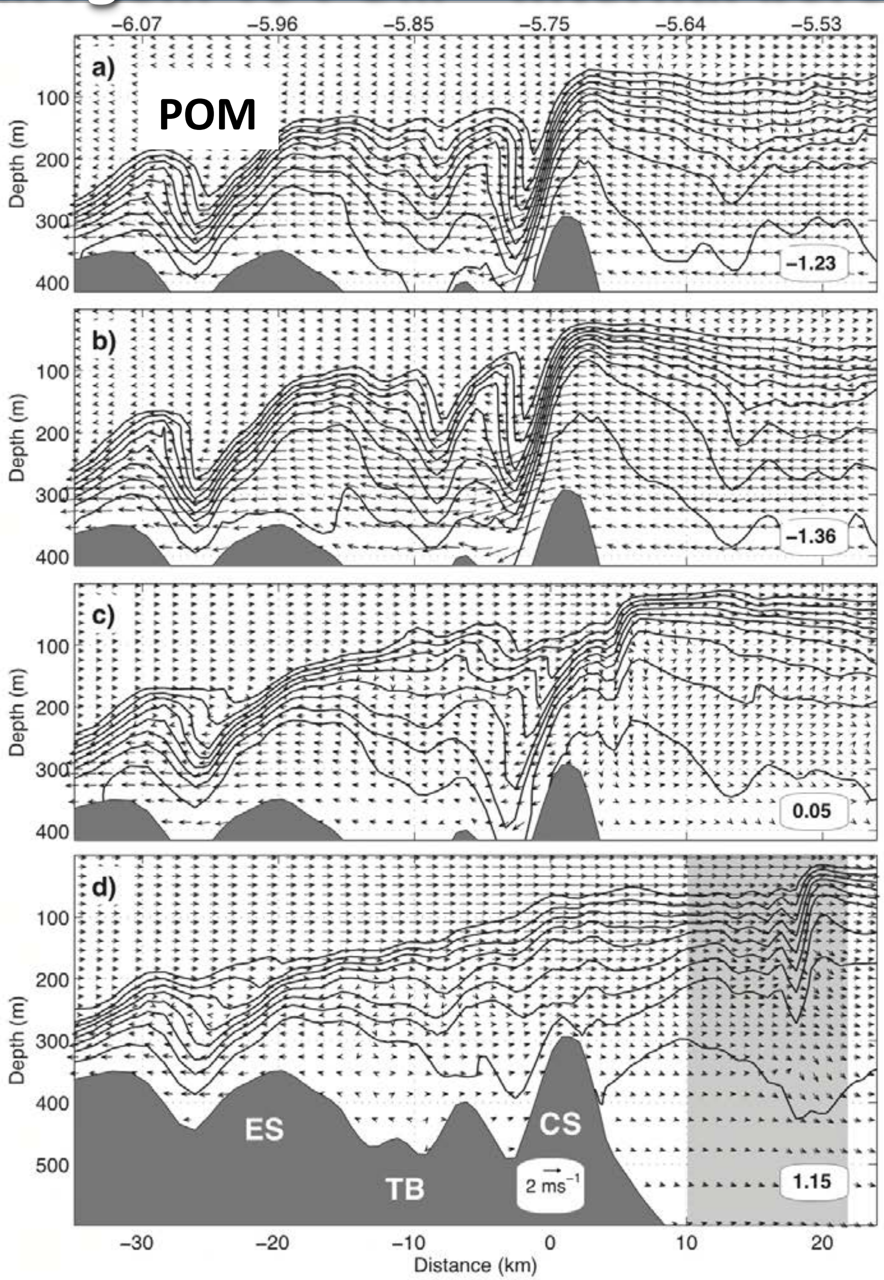
Horizontal velocity (m/s)

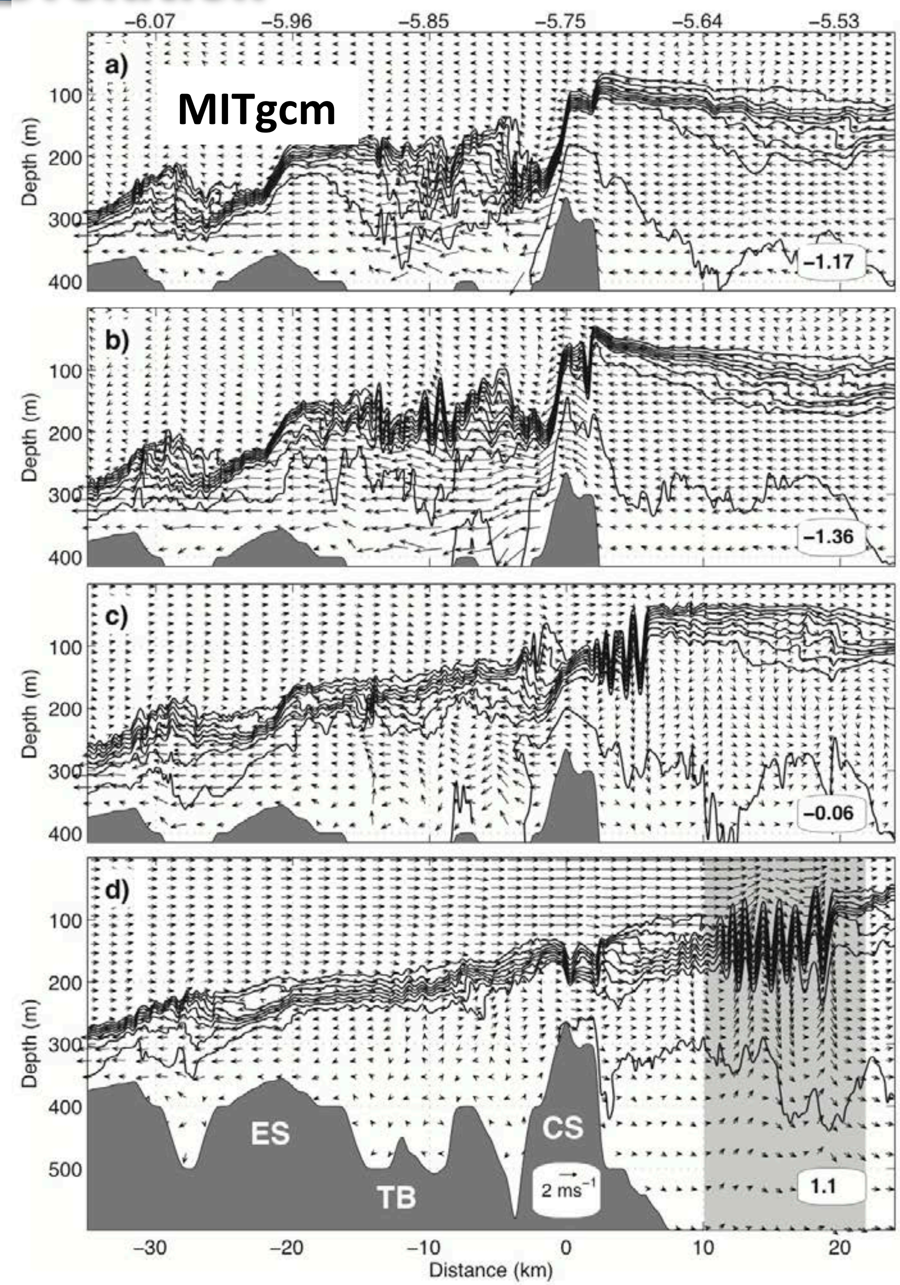
Vertical velocity (m/s)



Horizontal current velocity simulated by MITgcm during the arrival of an internal waves train at TN. (b) Same as (a) simulated by POM. (c) Vertical current simulated by MITgcm during the same instant of (a). (d) Same as c) simulated by POM.

MITgcm vs POM – Internal bore evolution





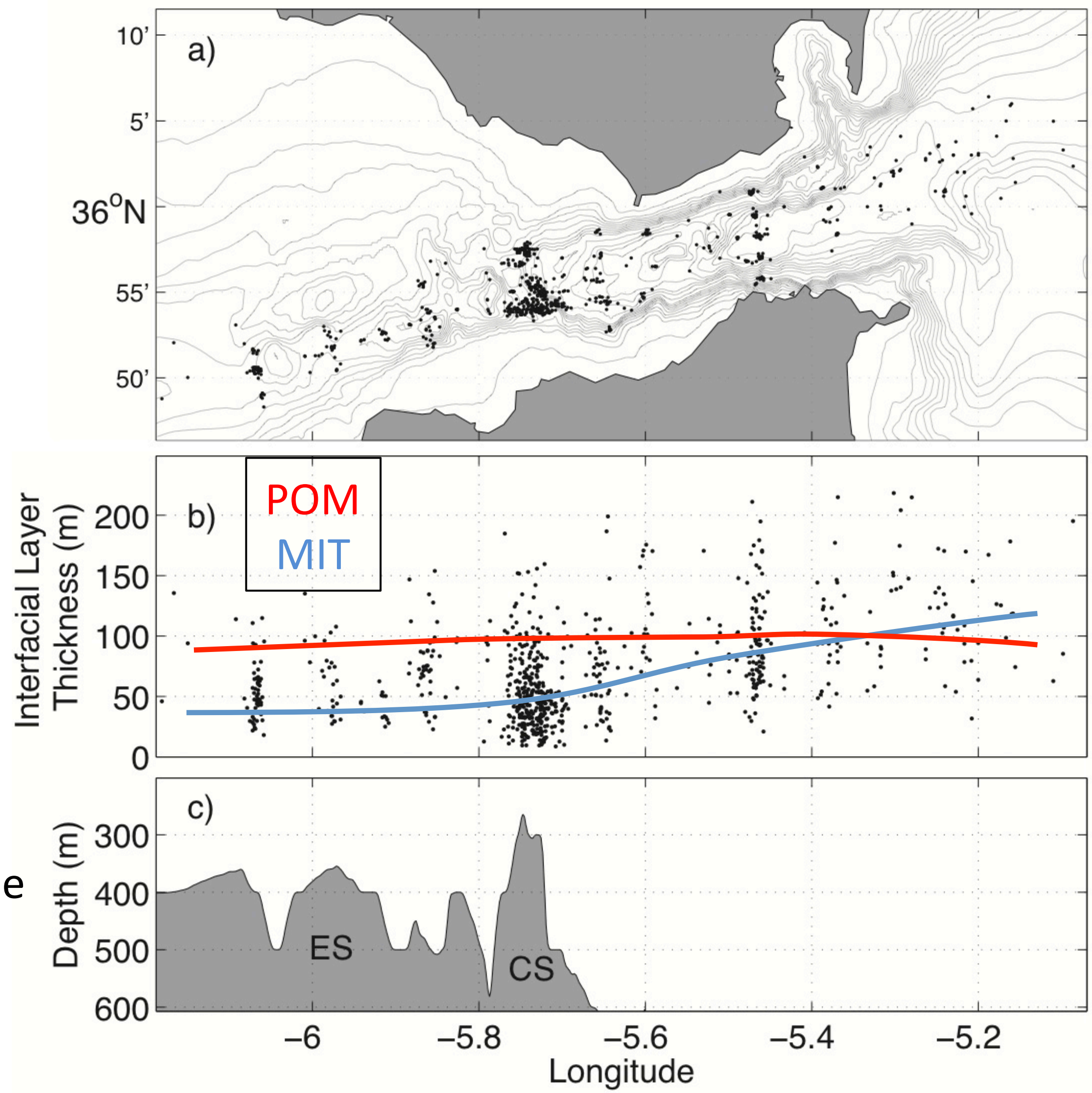
Garrido et al. jgr 2011

Observed and models interface layer thickness

a) Locations of historical conductivity-temperature-depth data (CTD, black dots) collected in the Strait.

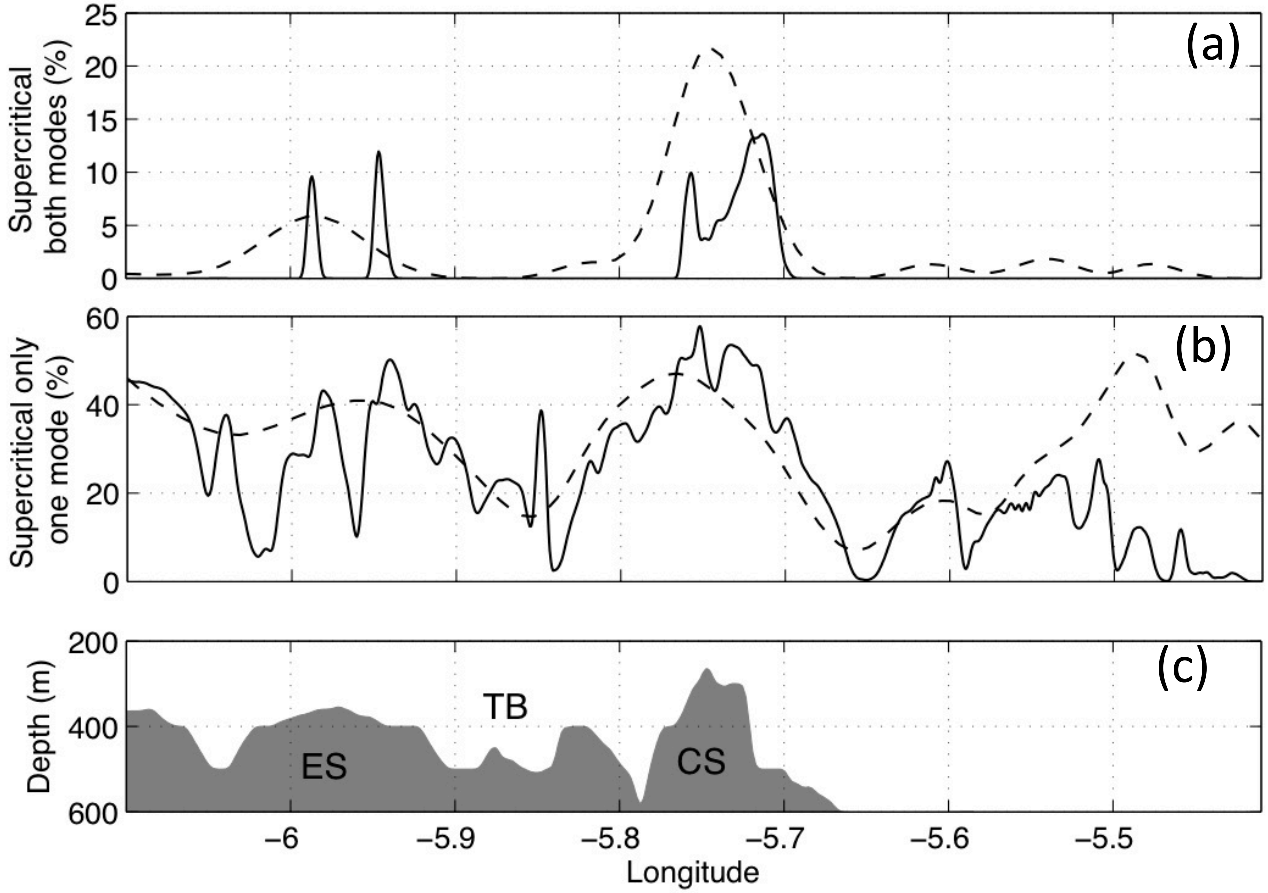
b) Interface layer thickness computed from CTD data.

c) Bottom topography along the central axis of the Strait.



MITgcm vs POM alongstrait hydraulics

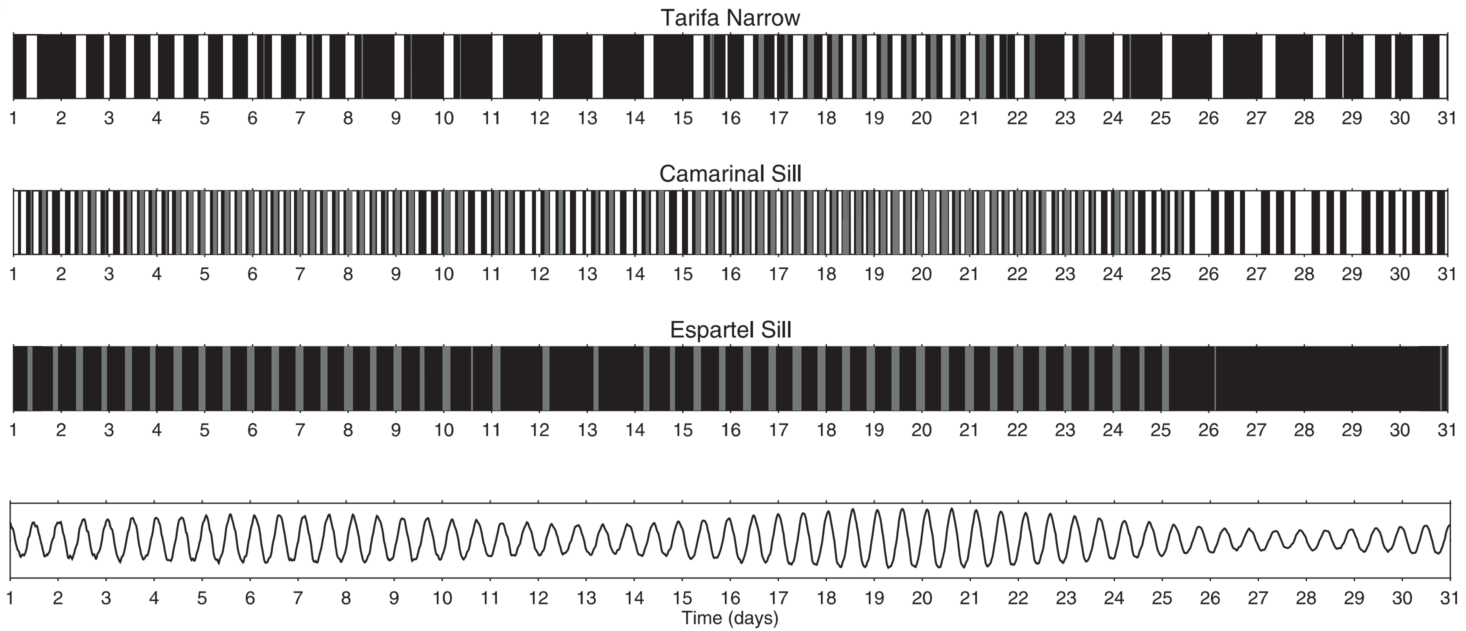
Frequency of occurrence, over the tropical month period, of supercritical flow with respect to one mode (a) and both modes (b) along the Strait as obtained by POM (dashed line) and MITgcm (solid line).



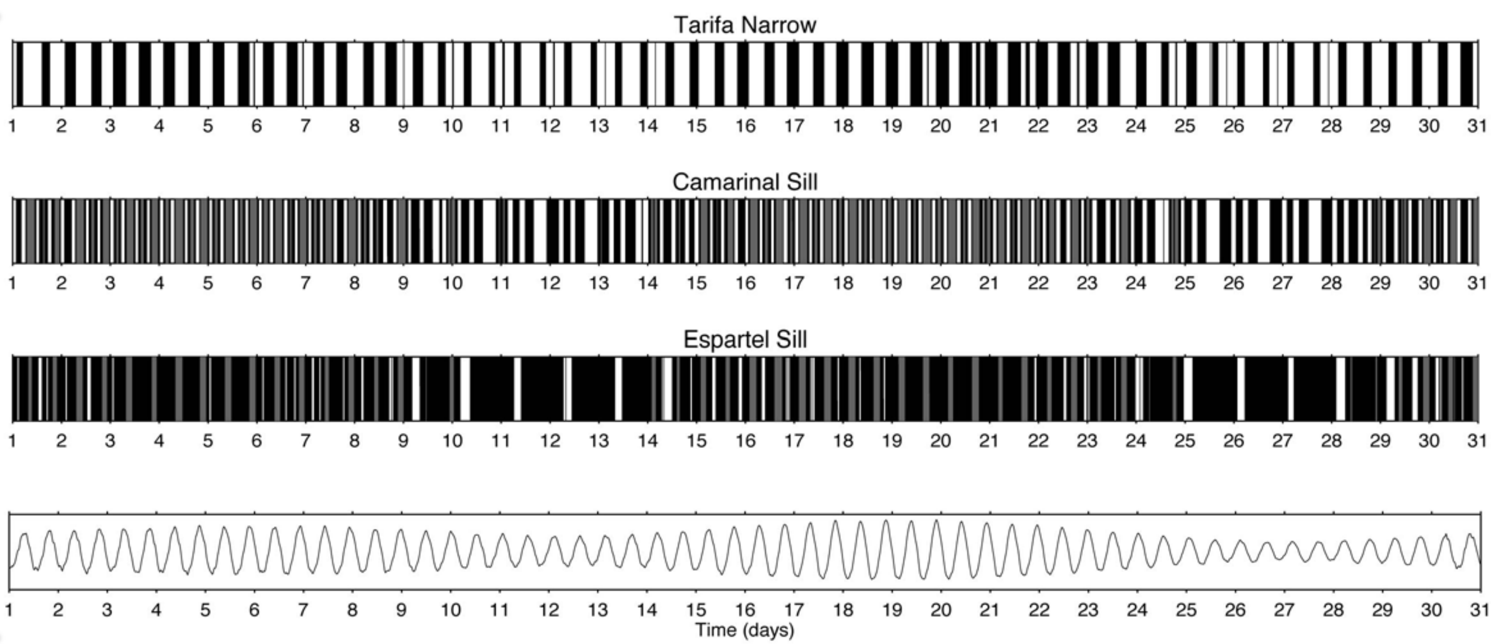
MITgcm displays a marked along-strait variability associated to the finer description of the bathymetry. Moreover when both modes are supercritical (a), MITgcm predicts lower values all along the Strait with respect to POM, except for ES where on the contrary MITgcm exceeds POM. When the flow is supercritical with respect to just one mode, the major differences are confined along TN. In particular POM predicts higher frequencies with respect to MITgcm.

MITgcm vs POM alongstrait hydraulics

POM

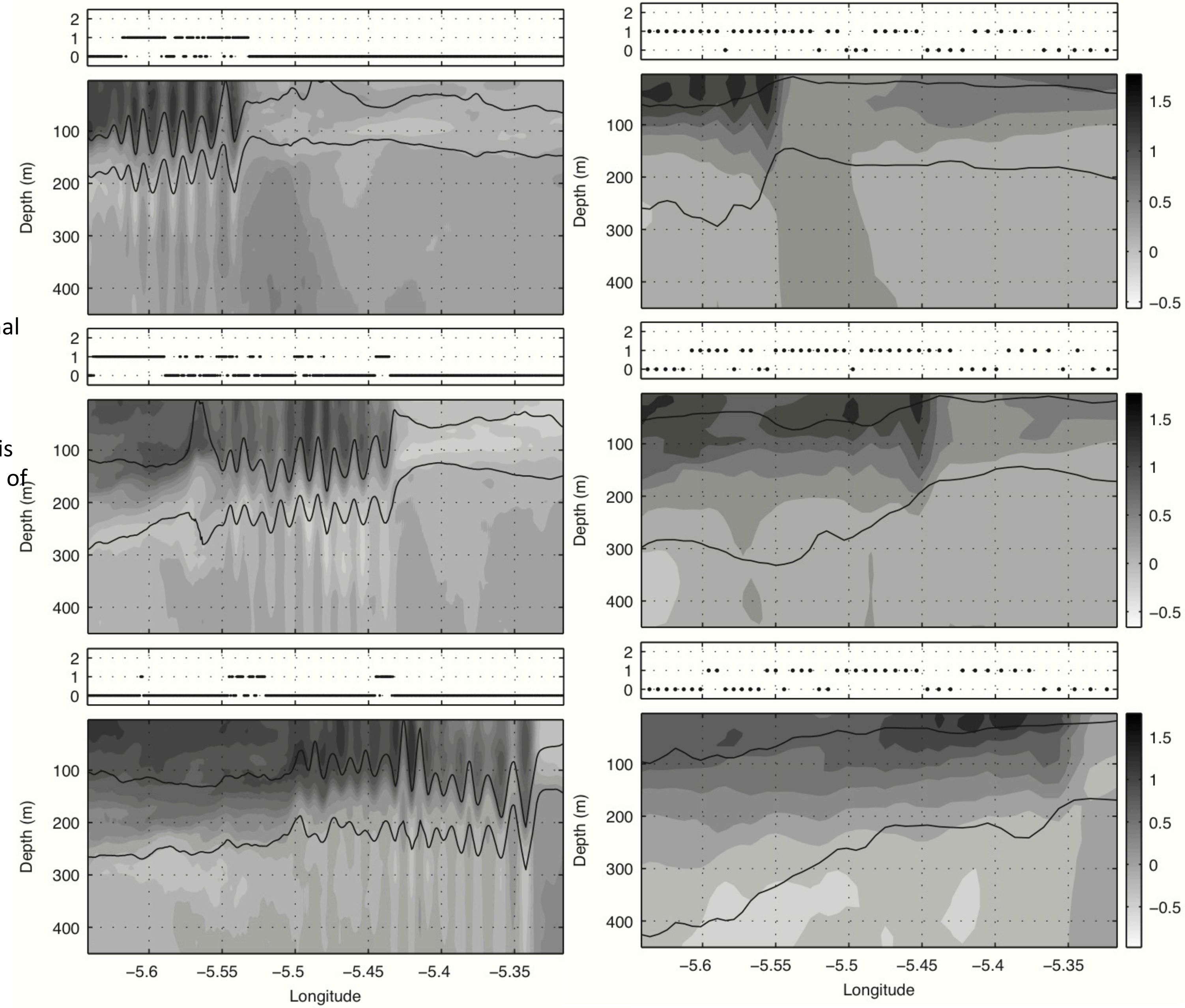


MITgcm

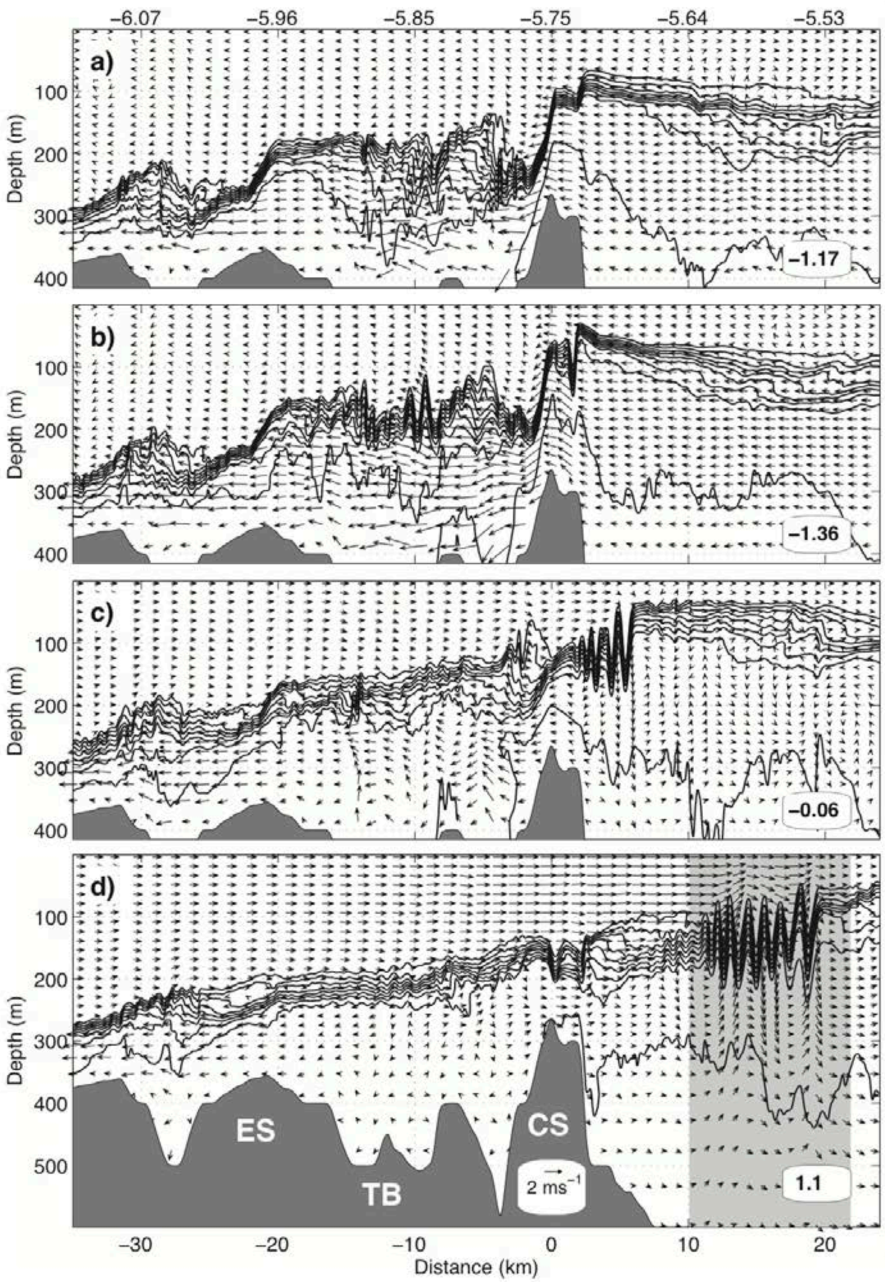


MITgcm vs POM alongstrait hydraulics & bore propagation

Evolution of the horizontal velocity field along longitudinal Sectionin the middle of the Strait during the arrival of an interval wave train to TN. Elapse time between frames is 1.33 hours. Panels on the top of each frame indicate the flow criticality; zero: subcritical flow; one: only one internal mode controlled; two: both internal modes controlled.

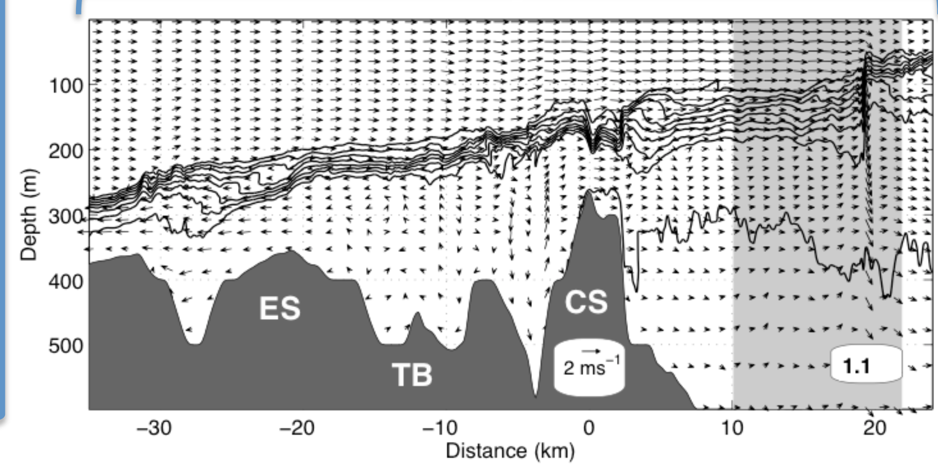


MITgcm sensitivity to non-hydrostaticity

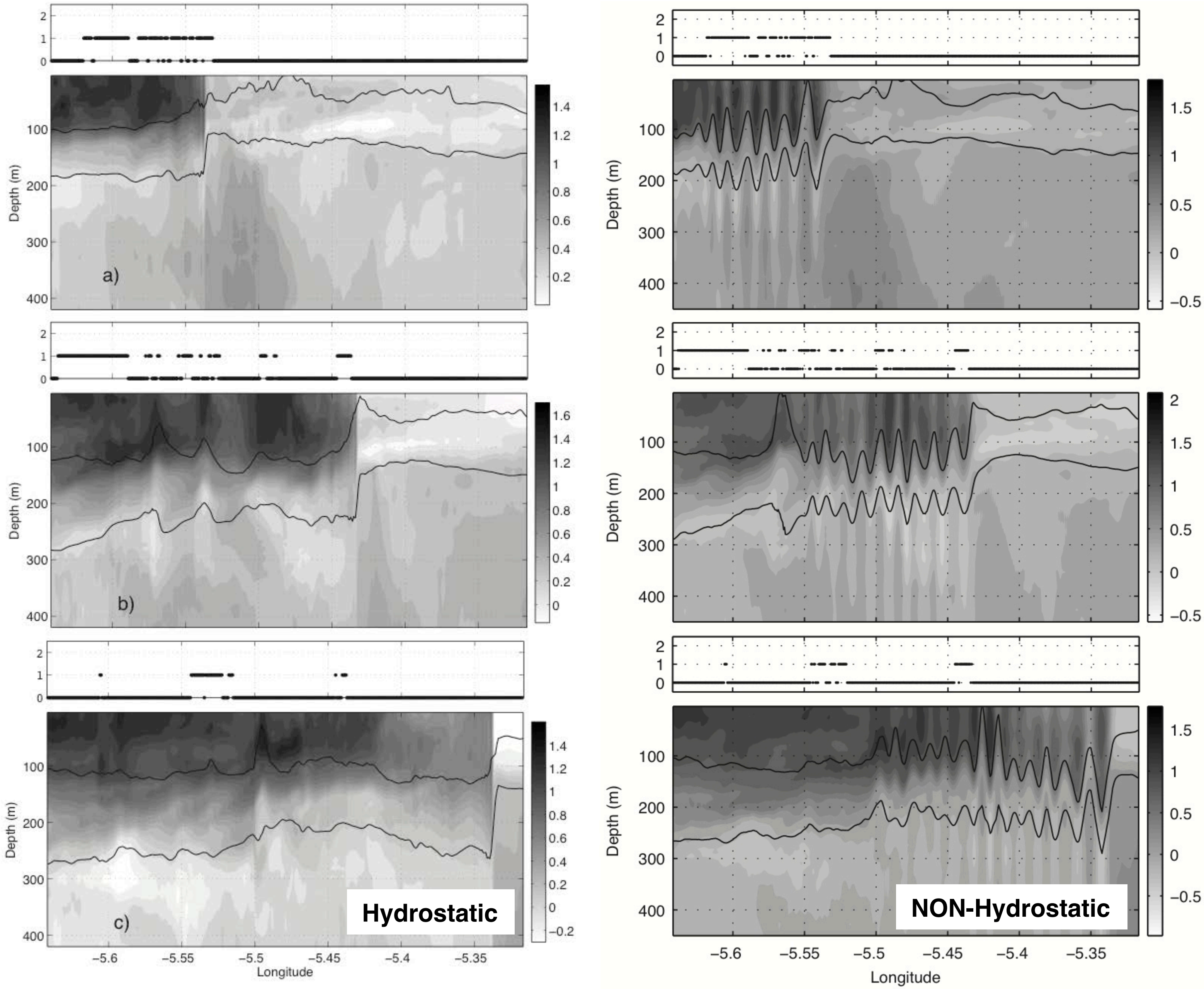


MITgcm NON Hydrostatic

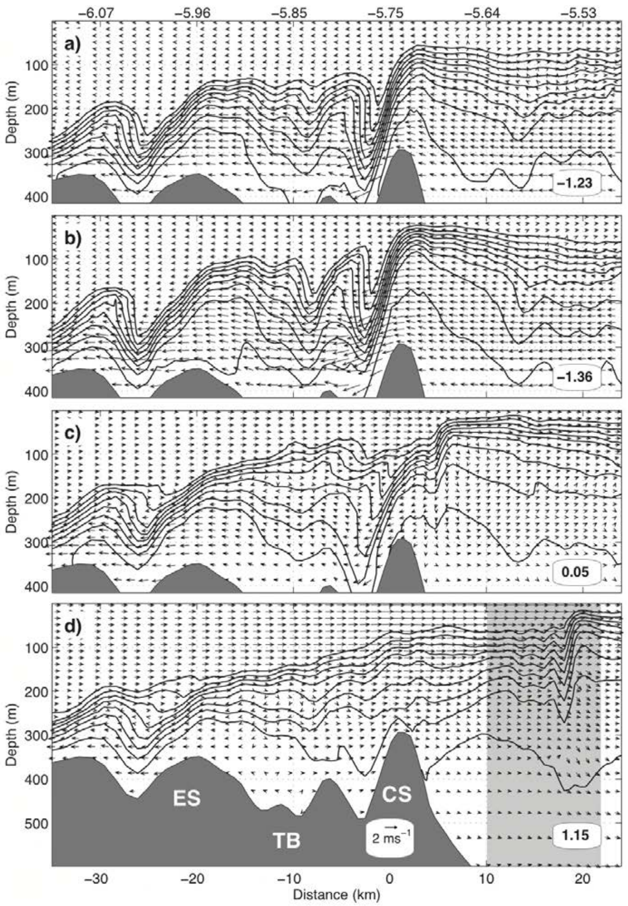
MITgcm Hydrostatic



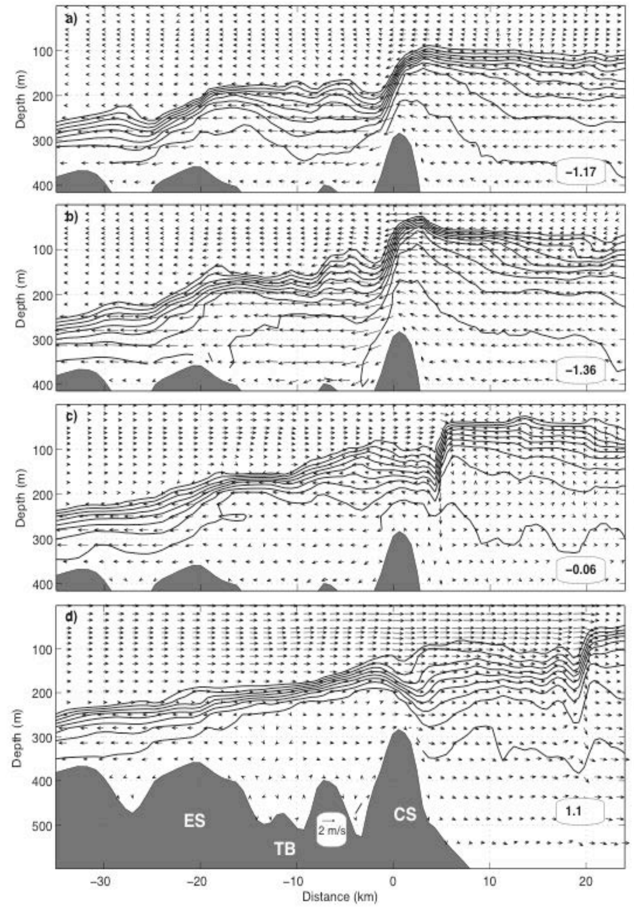
MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



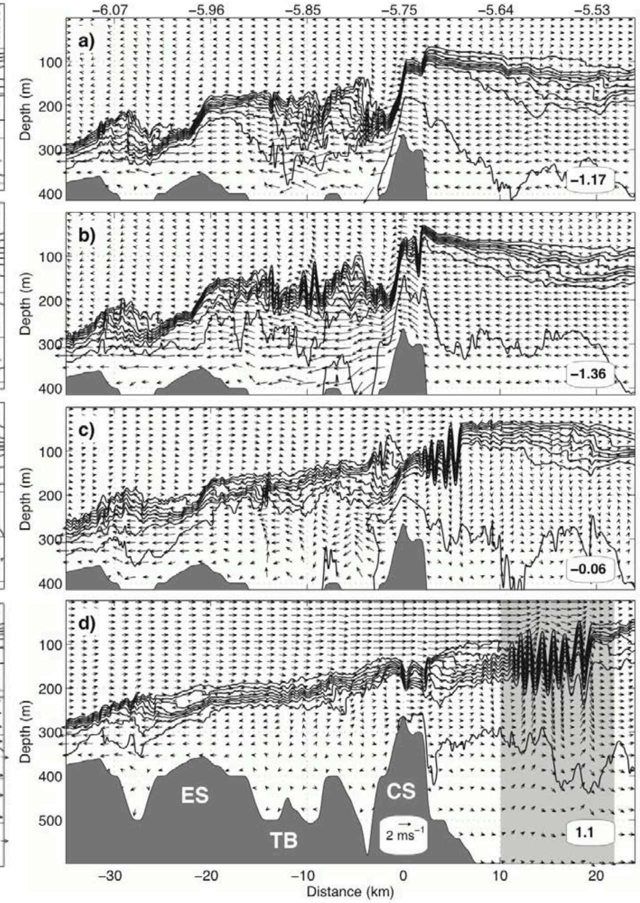
MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



POM
Original simulation



MITgcm
hydrostatic
Model grid as POM

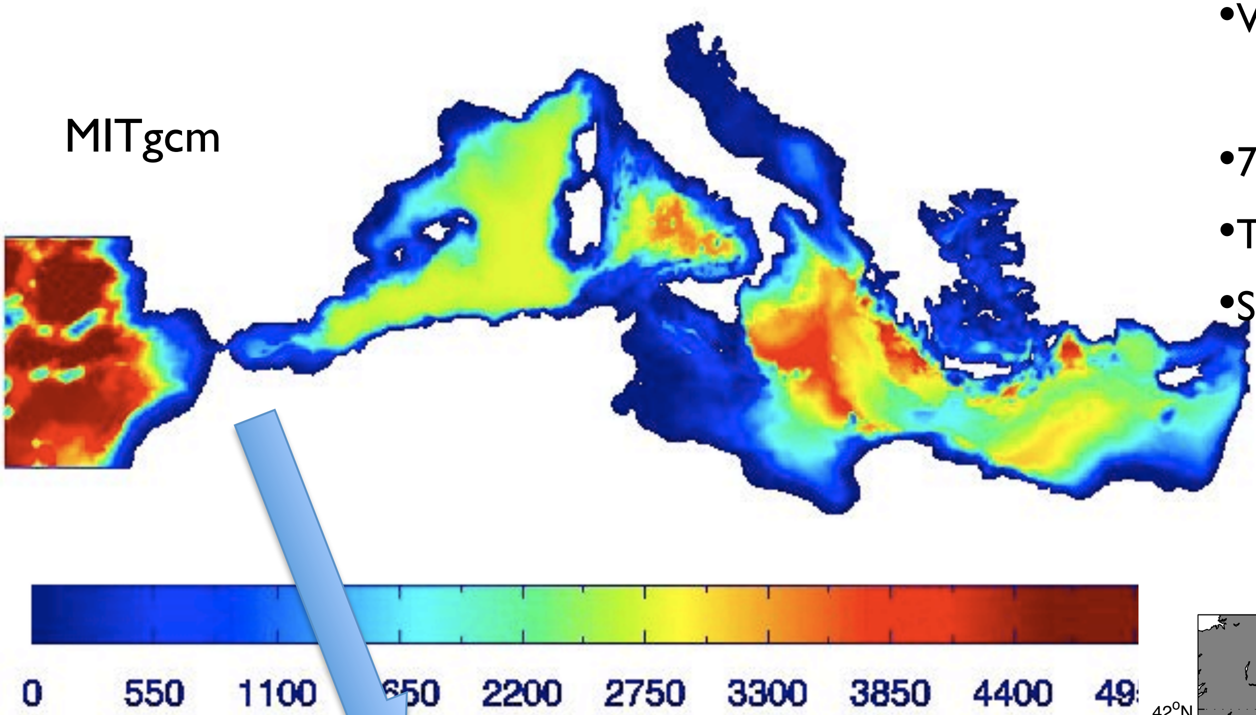


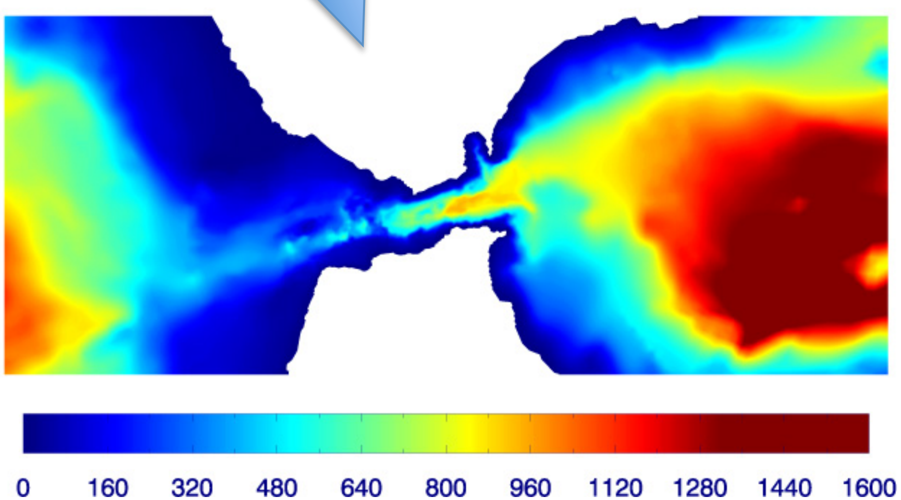
MITgcm
NON-Hydrostatic
Original grid

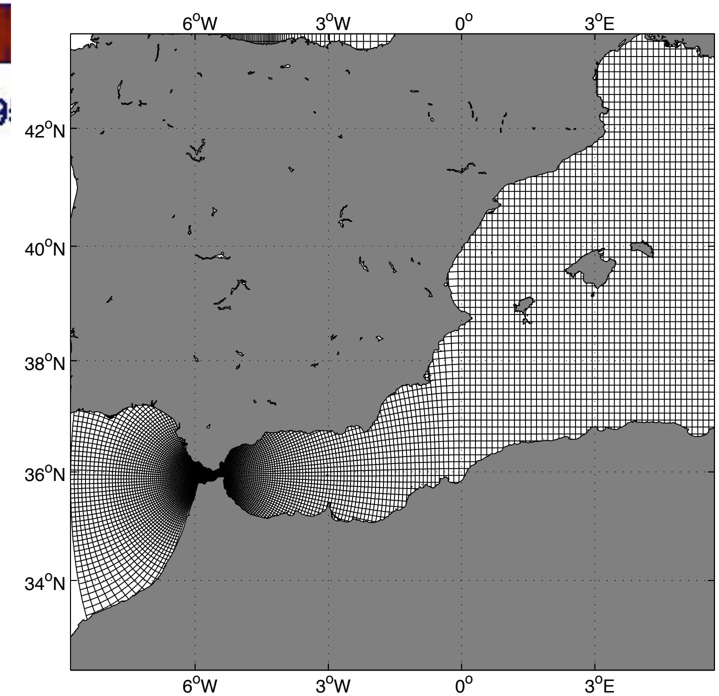
New modeling strategy for the Mediterranean

- Variable horizontal resolution (1/16° up to 1/200°)
- 72 vertical levels
- Tidal forcing (main 4 components)
- Surface atmospheric pressure

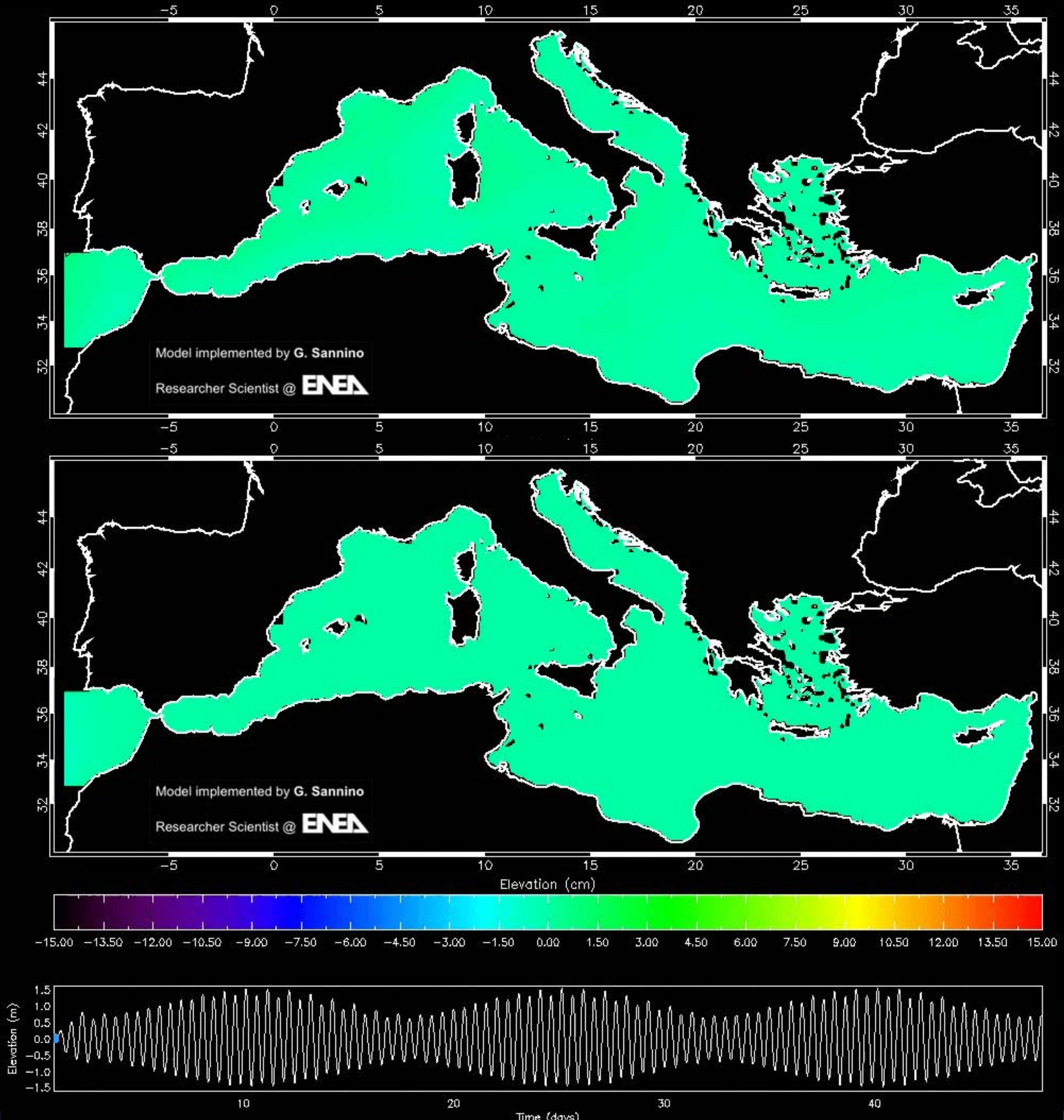
MITgcm







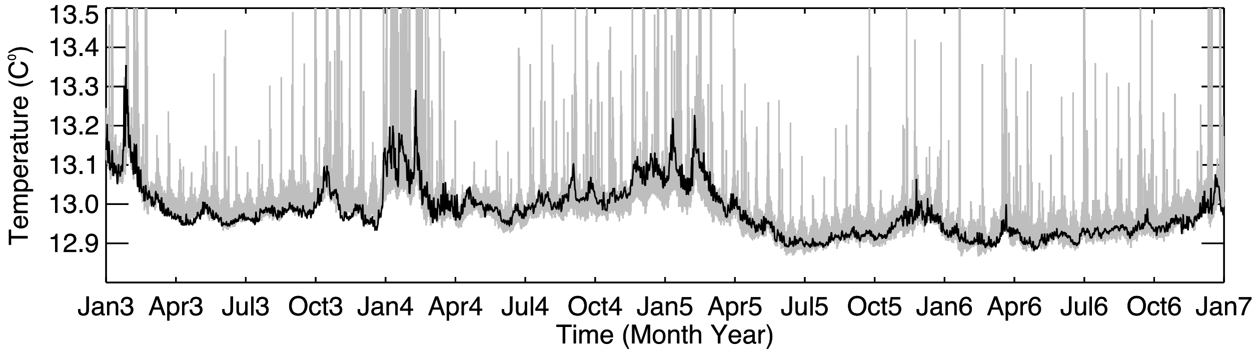
New modeling strategy for the Mediterranean

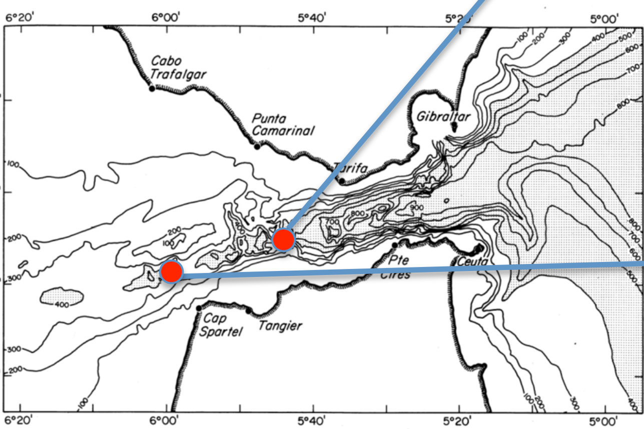


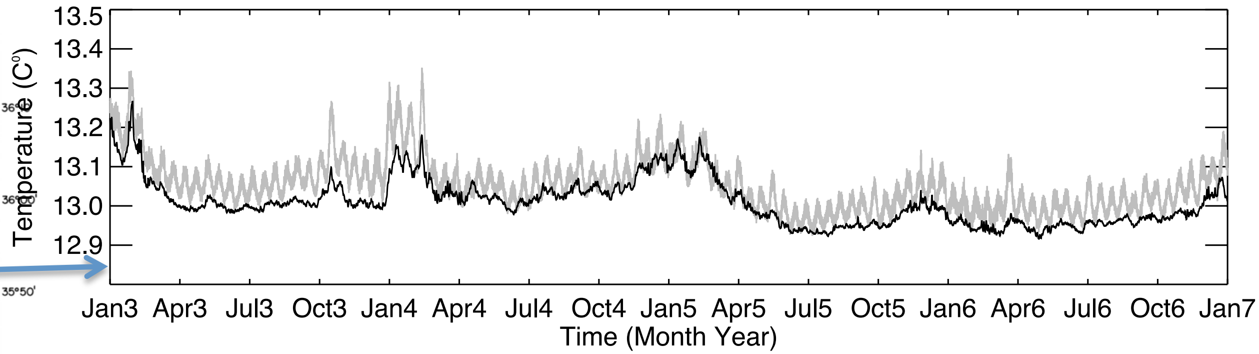
CINECA
ISCRA GRANT

Very first NEMERTE Results: temperature in the Strait

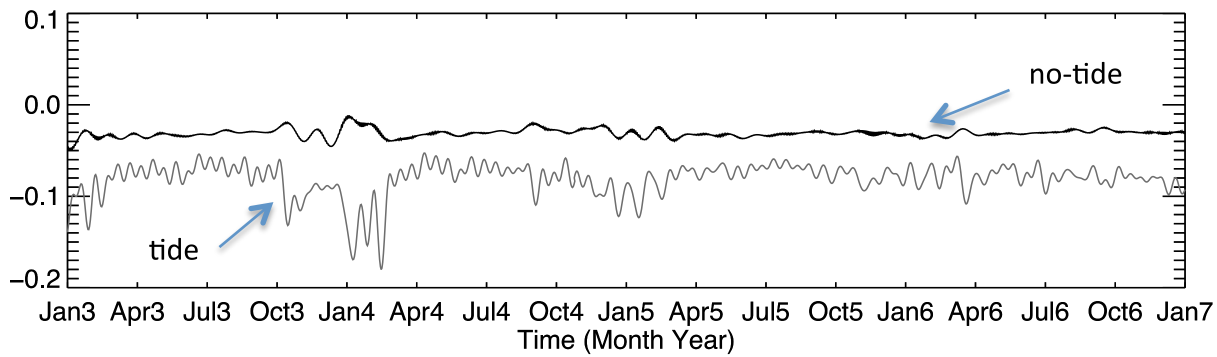
Time series of the vertical **minimum temperature** for the years 1963-1967. Upper panel for the CS and lower panel for ES. ExpT in grey, ExpNT in black







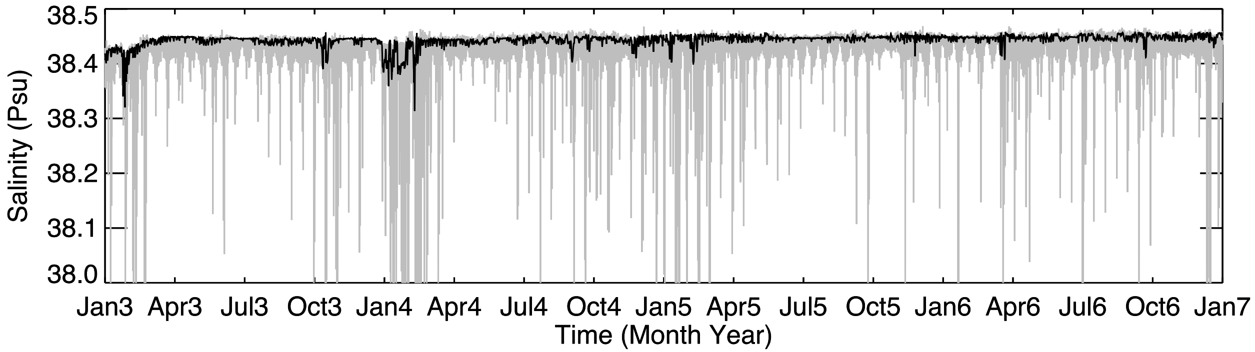
Time series of the **difference** between daily minimum temperature in **CS** and in **ES filtered** off frequencies higher than 30 days. ExpT in grey, ExpNT in black.

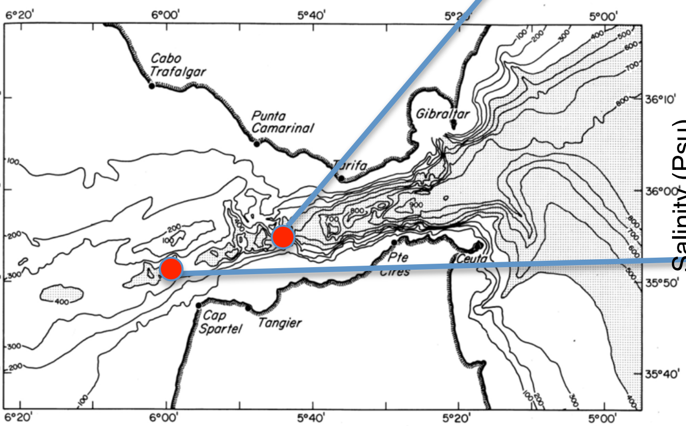


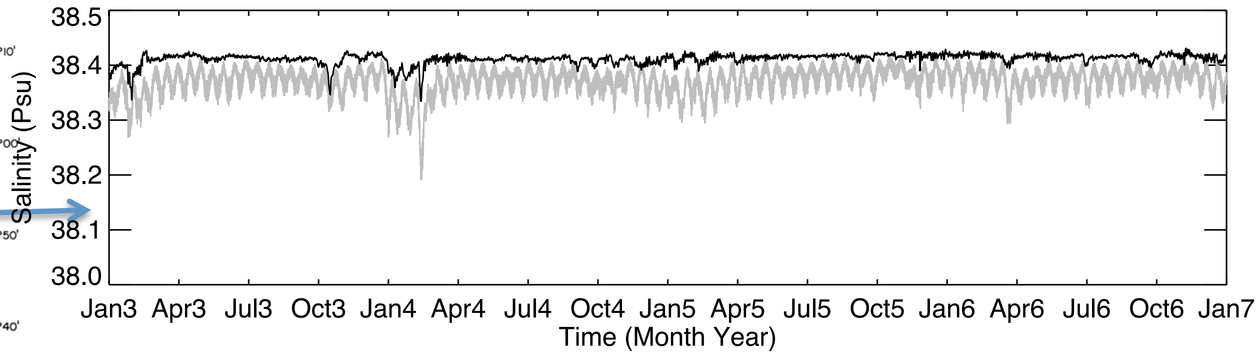
PRACE

Very first NEMERTE Results: salinity in the Strait

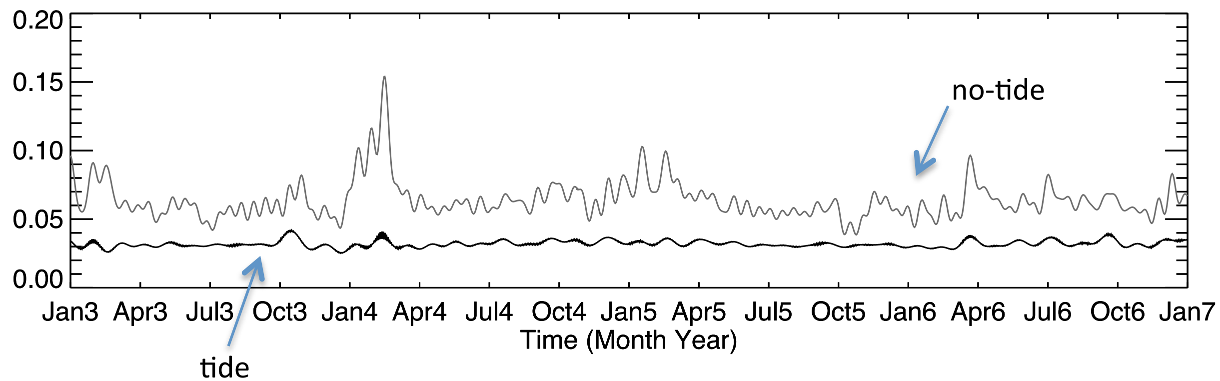
Time series of the vertical **maximum salinity** for the years 1963-1967. Upper panel for the CS and lower panel for ES. ExpT in grey, ExpNT in black





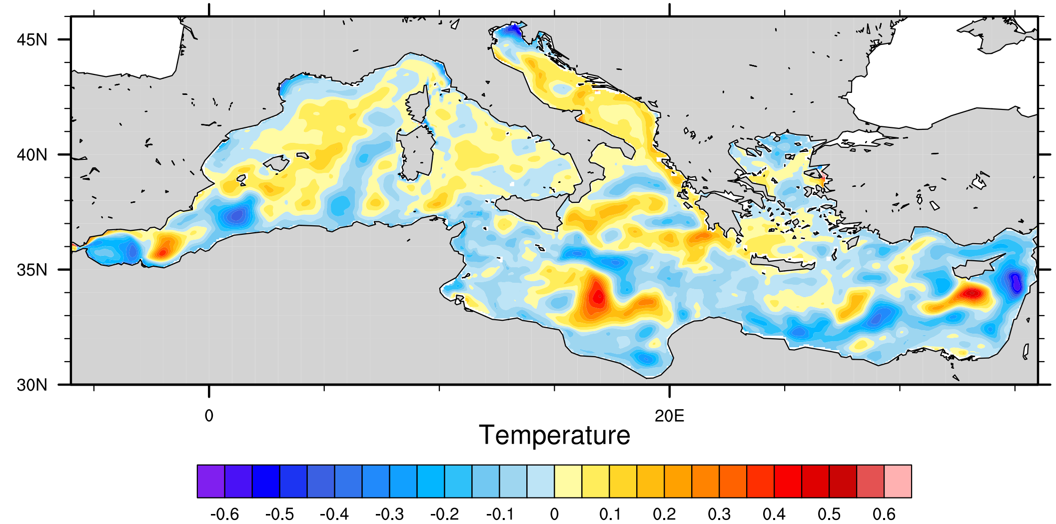


Time series of the **difference** between daily **maximum salinity** in **CS** and in **ES** **filtered** off frequencies higher than 30 days. ExpT in grey, ExpNT in black.

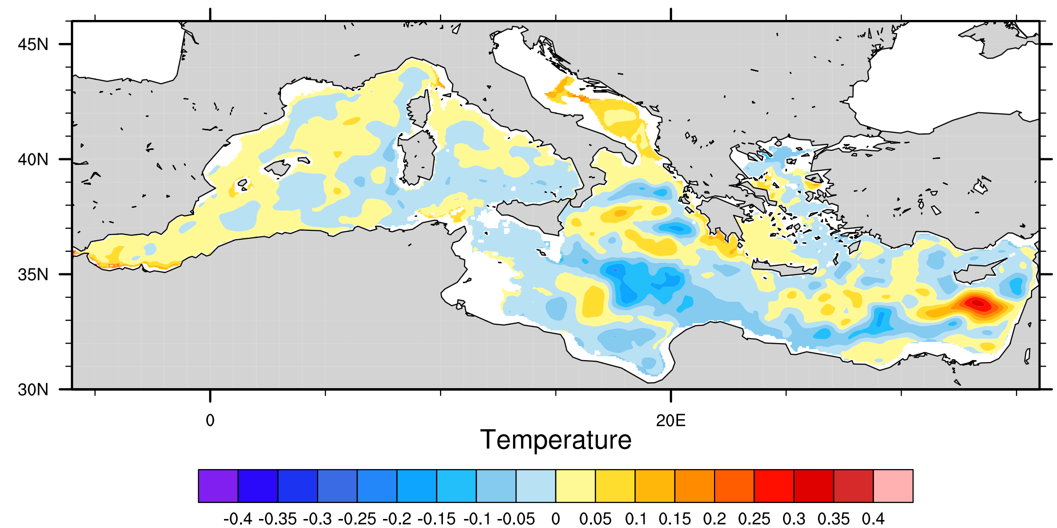


Very first NEMERTE Results

Temperature difference between the ExpT and ExpNT. Data are vertically averaged between the **upper layer and 150 m**. Time-averaged over the entire simulated period

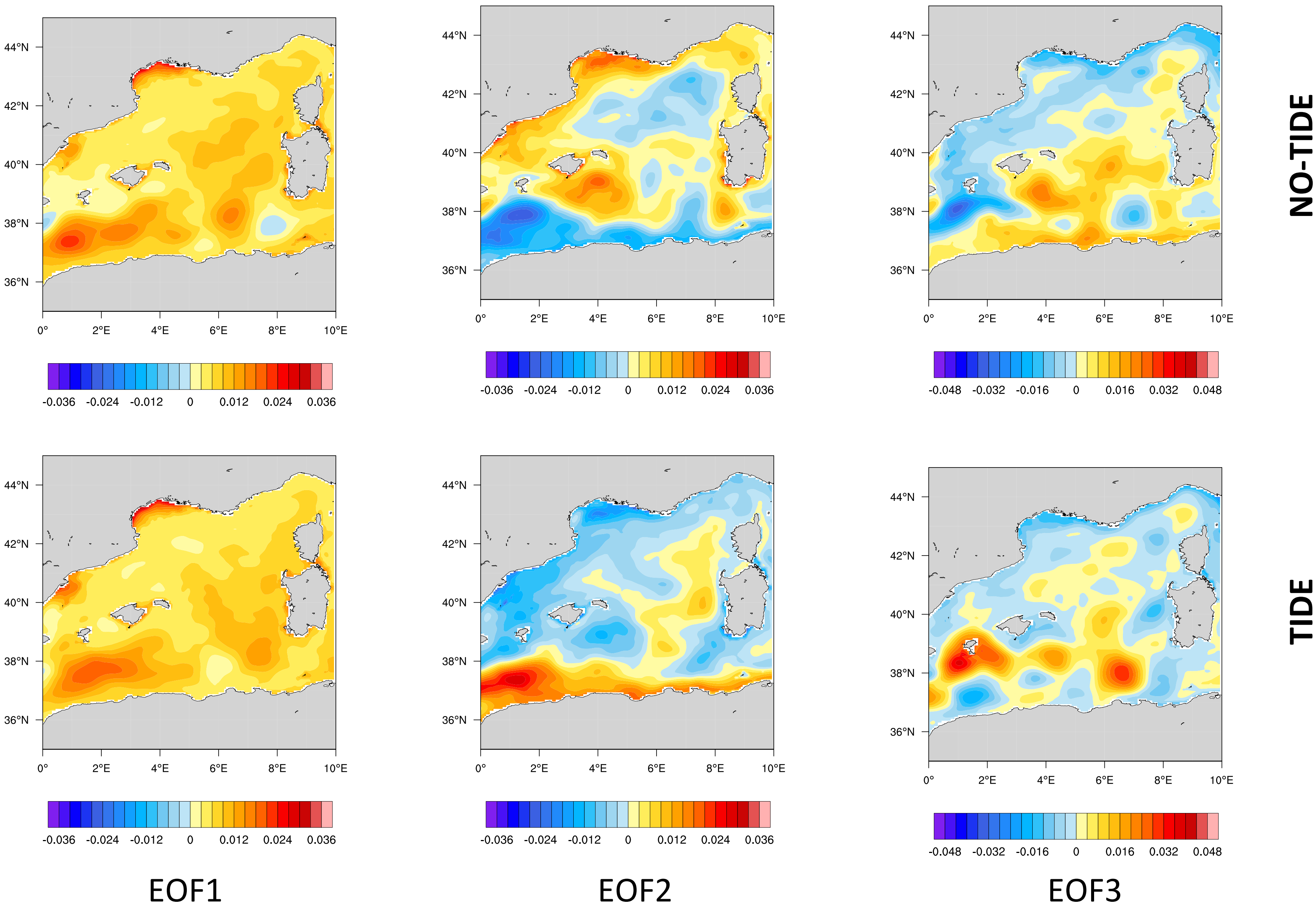


Temperature difference between the ExpT and ExpNT. Data are vertically averaged between **150 m and 500m**. Time-averaged over the entire simulated period

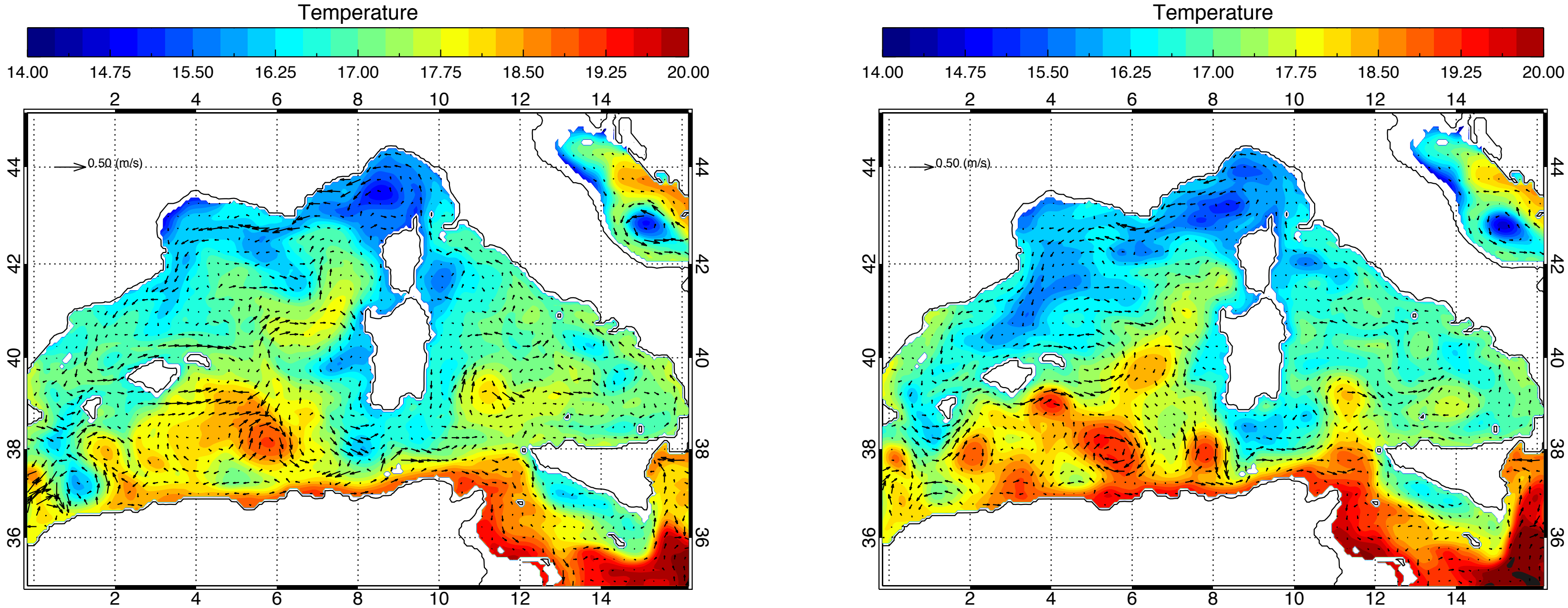


Very first NEMERTE Results

First three EOF for temperature vertically averaged over the upper 150 m



Very first NEMERTE Results



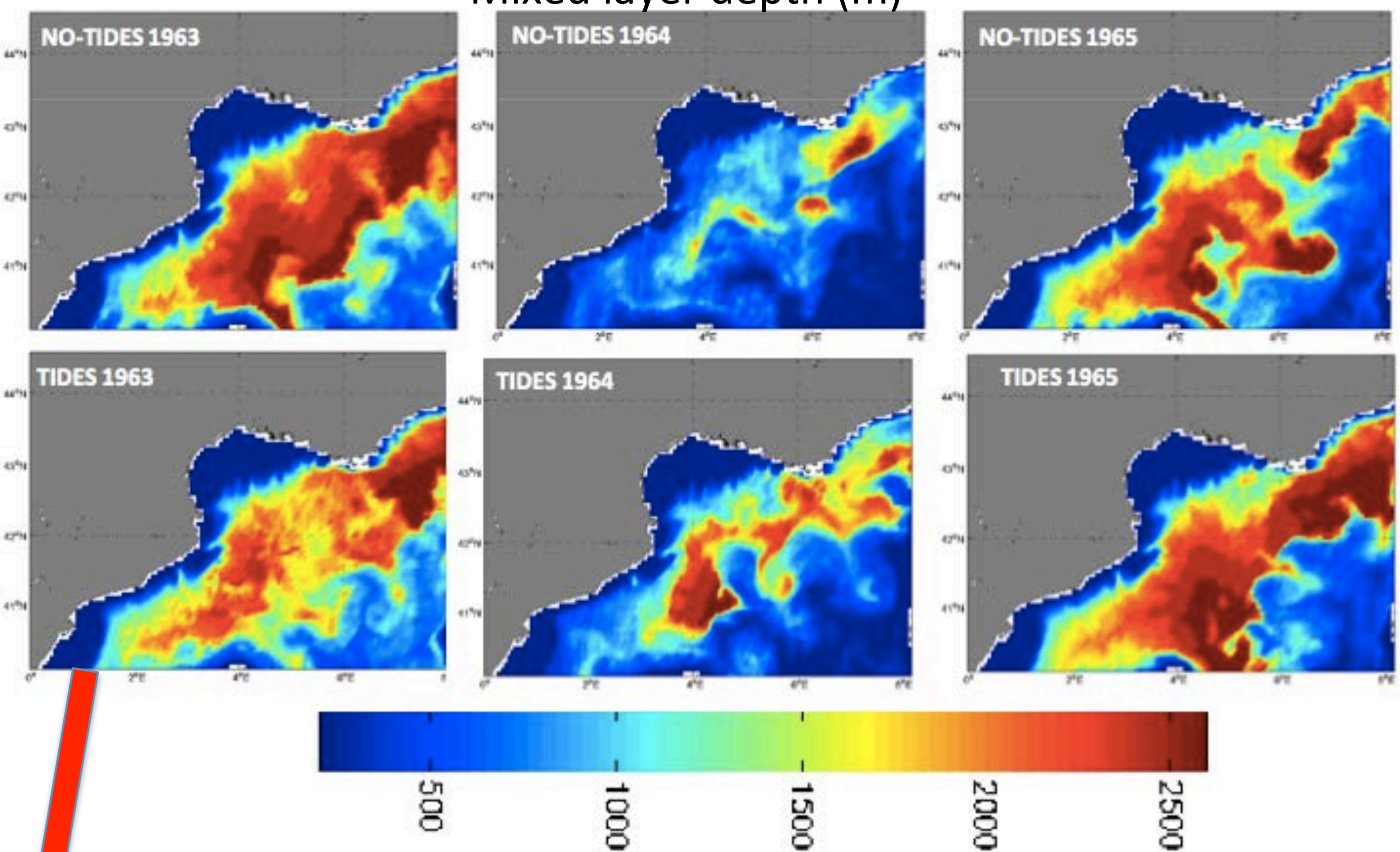
Temperature at 50m time-averaged over the period October-December 1962

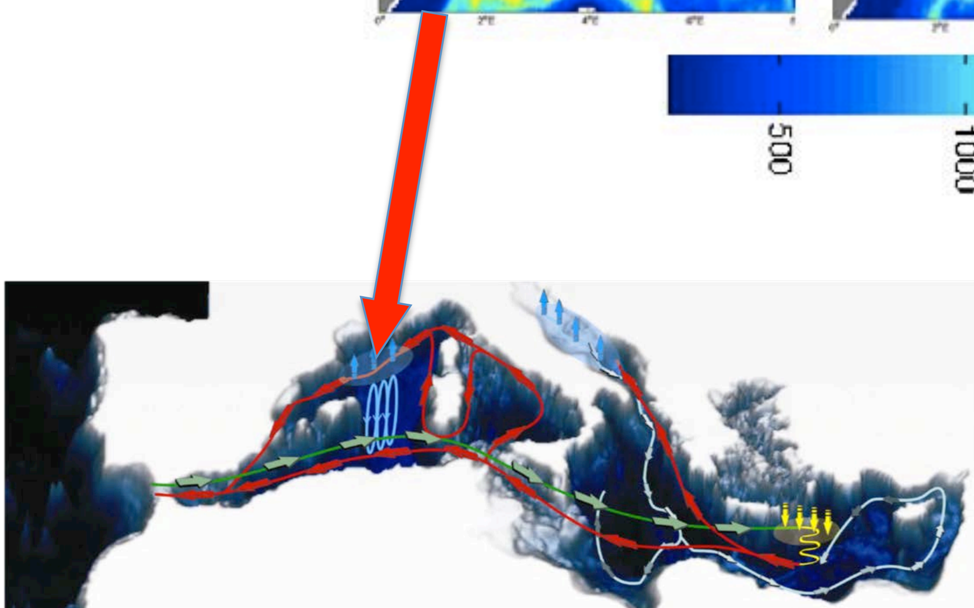
Very first NEMERTE Results: Mixed Layer Depth

Mixed layer depth (m)

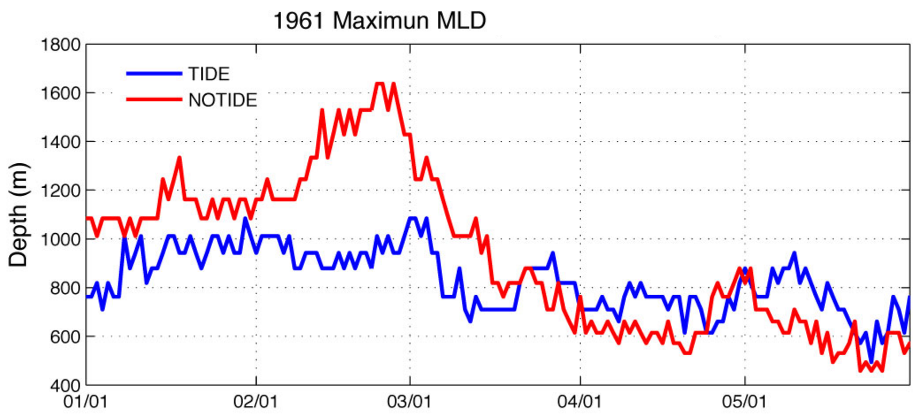
NO-TIDE

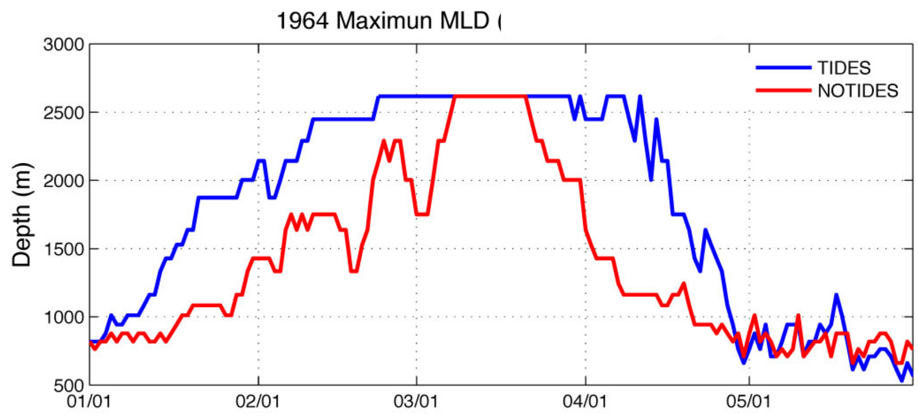
TIDE

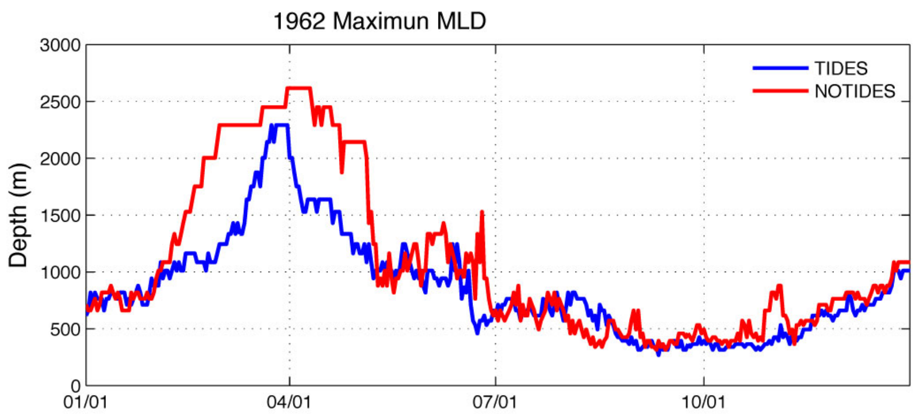


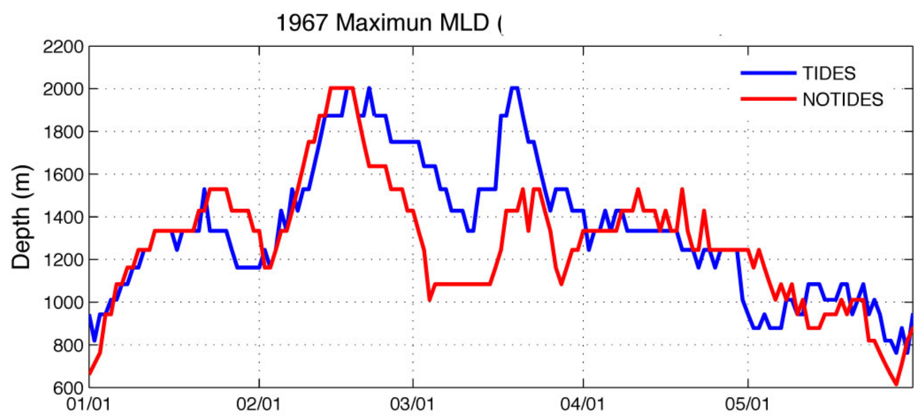


Very first NEMERTE Results





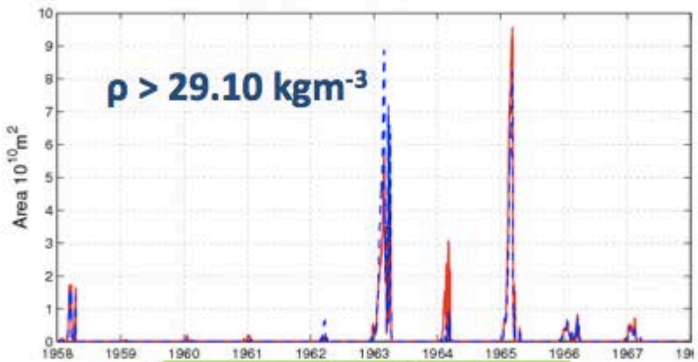


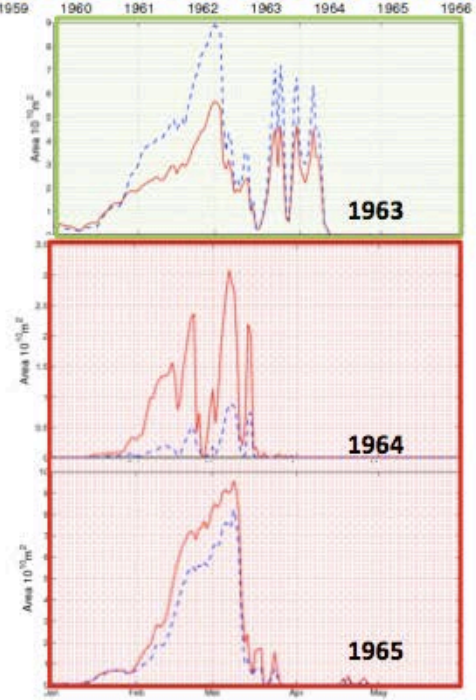


Very first NEMERTE Results

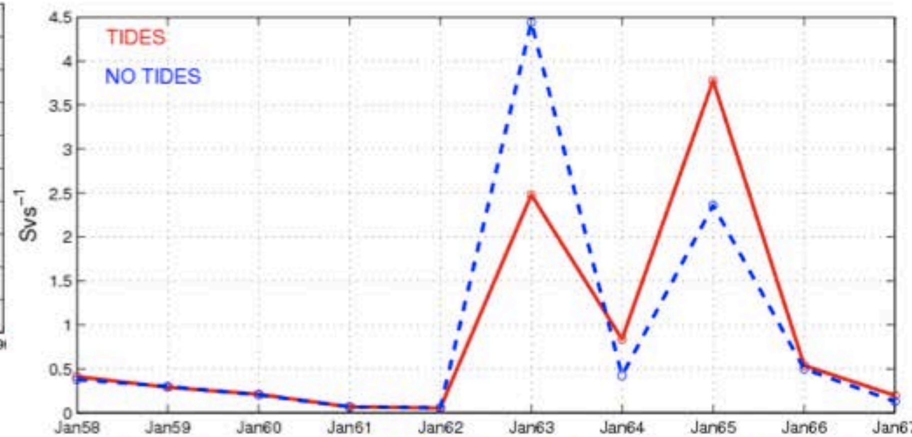
DIFERENCES IN WMDW FORMATION

SURFACE CONVECTION AREA





DEEP WATER FORMED RATE



- **1. Volume of Deep Water in the Gulf of Lion (ρ > 29.10 29.10 kgm^{-3})**
- **2. Rate of Volume of Deep formed Water before and after deep convection ocurr each year.**

$AREA_{TIDES} < AREA_{NO-TIDES}$

$AREA_{TIDES} < AREA_{NO-TIDES}$

DIFERENCES IN THE ENTIRE COLUMN OF WATER

Conclusions

- POM (in our implementation) is affected by diapycnal mixing
- Non-hydrostaticity is not needed to reproduce hydraulic controls
- POM resolution is enough (300 m) to reproduce reasonable well the SoG hydraulics
- Both tidal and high resolution at the SoG have affect the modeled MTHC

Regional Climate models represent the

Strait of Gibraltar like a simple pipe without tides

Is it still reasonable?