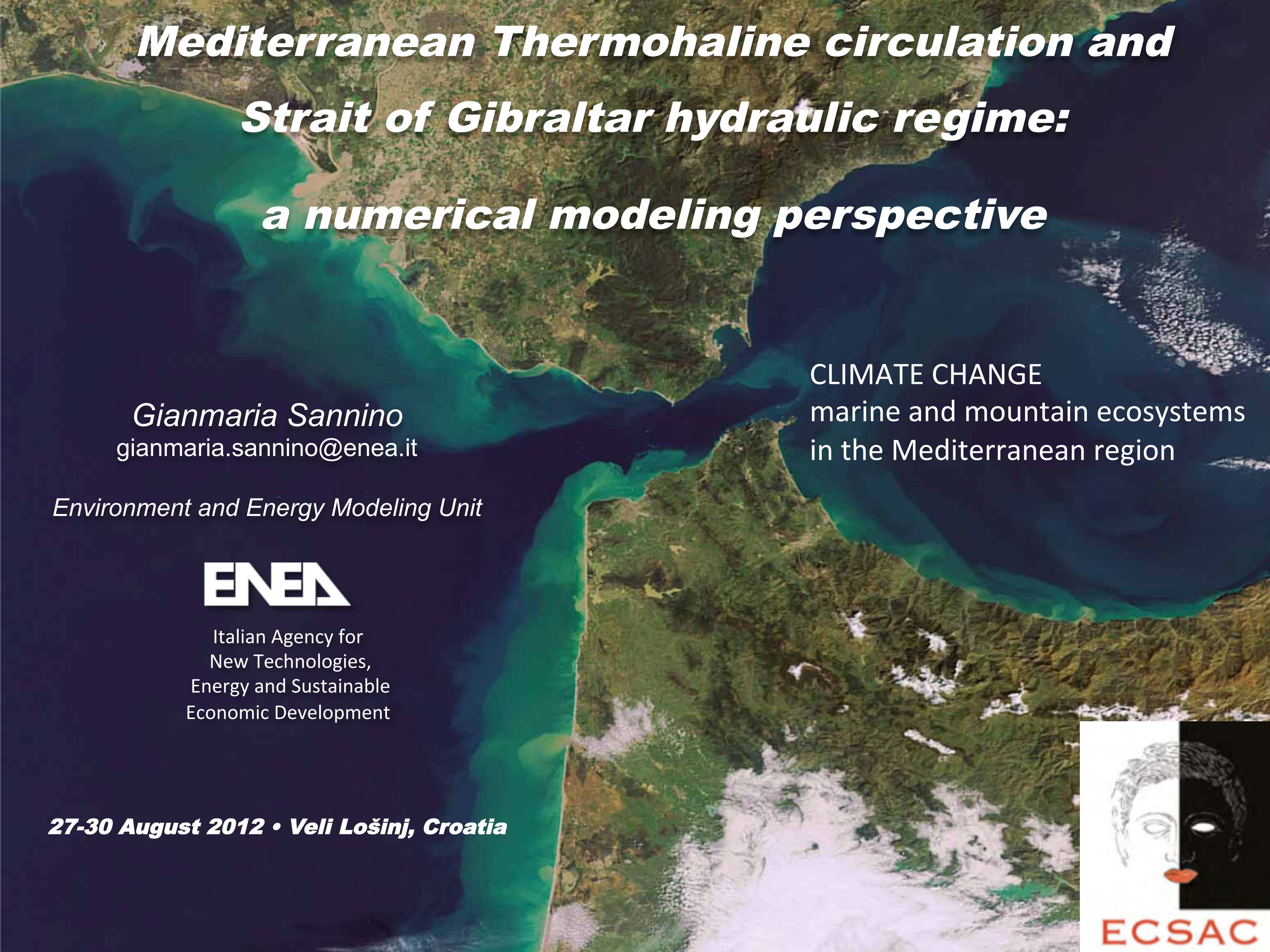

Mediterranean Thermohaline circulation and Strait of Gibraltar hydraulic regime: a numerical modeling perspective

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ENEA

Italian Agency for
New Technologies,
Energy and Sustainable
Economic Development

CLIMATE CHANGE
marine and mountain ecosystems
in the Mediterranean region

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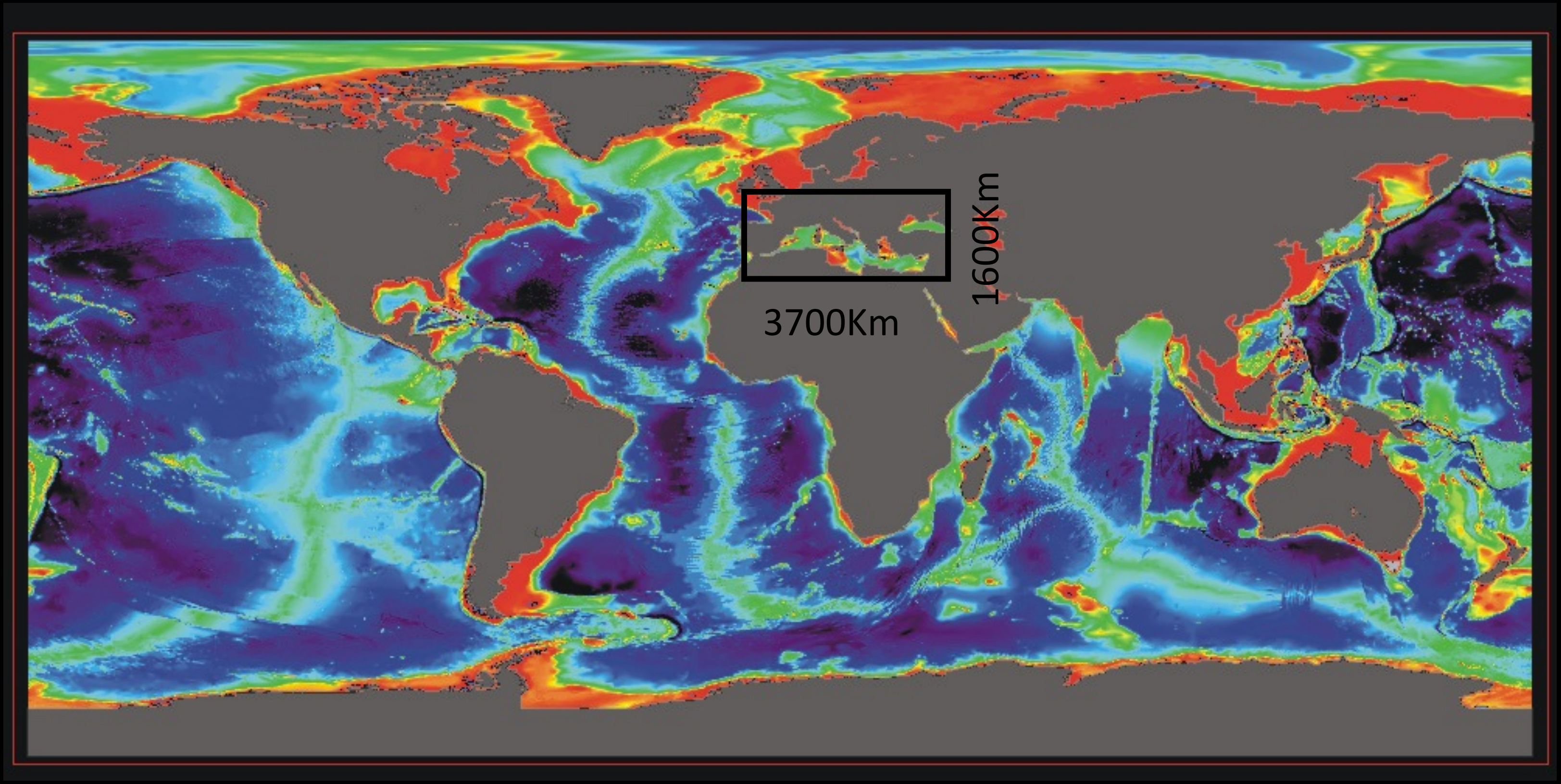
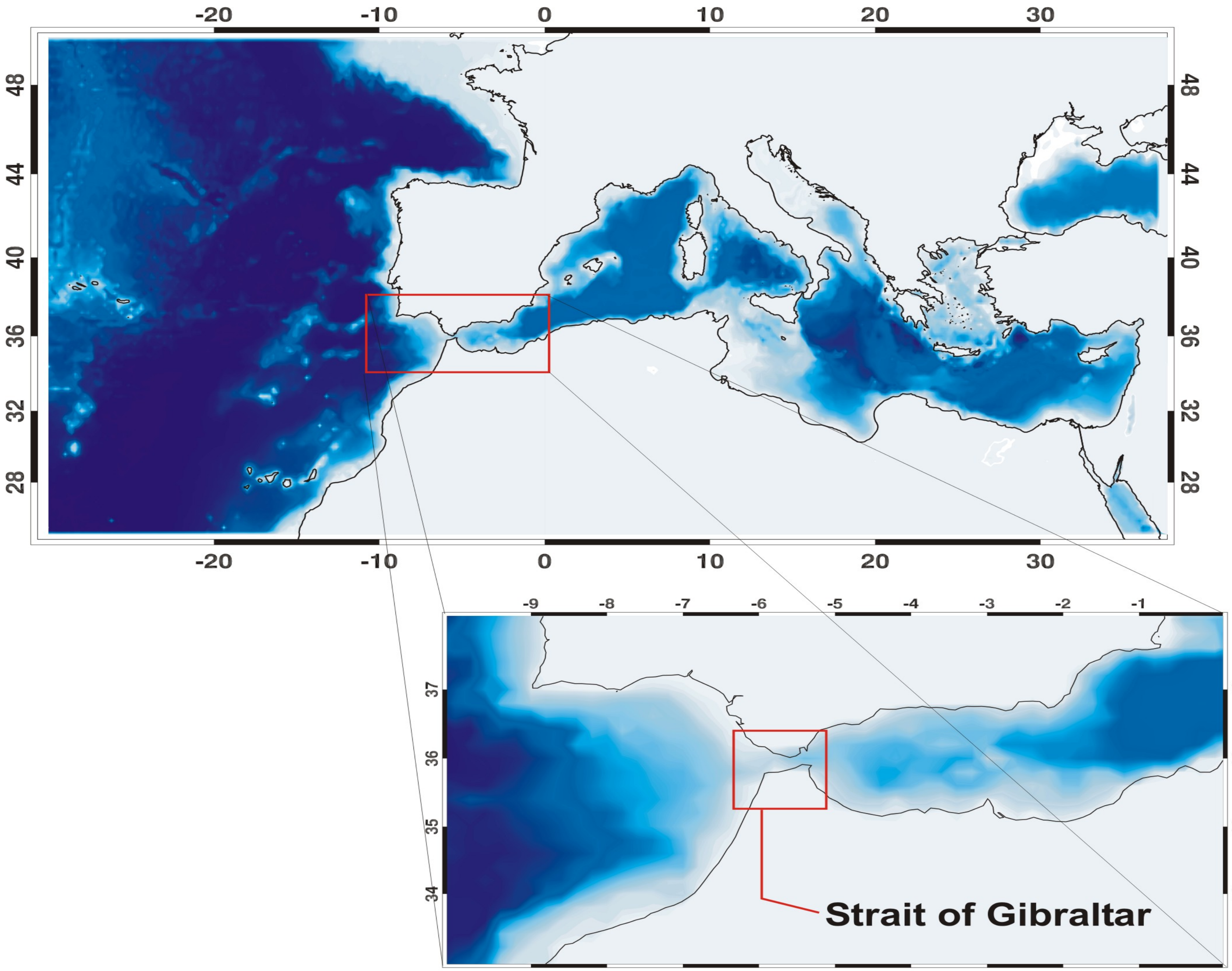
Mediterranean Thermohaline Circulation: Geography

The Mediterranean basin is a semi-enclosed sea connected to the open ocean by a narrow and shallow strait.

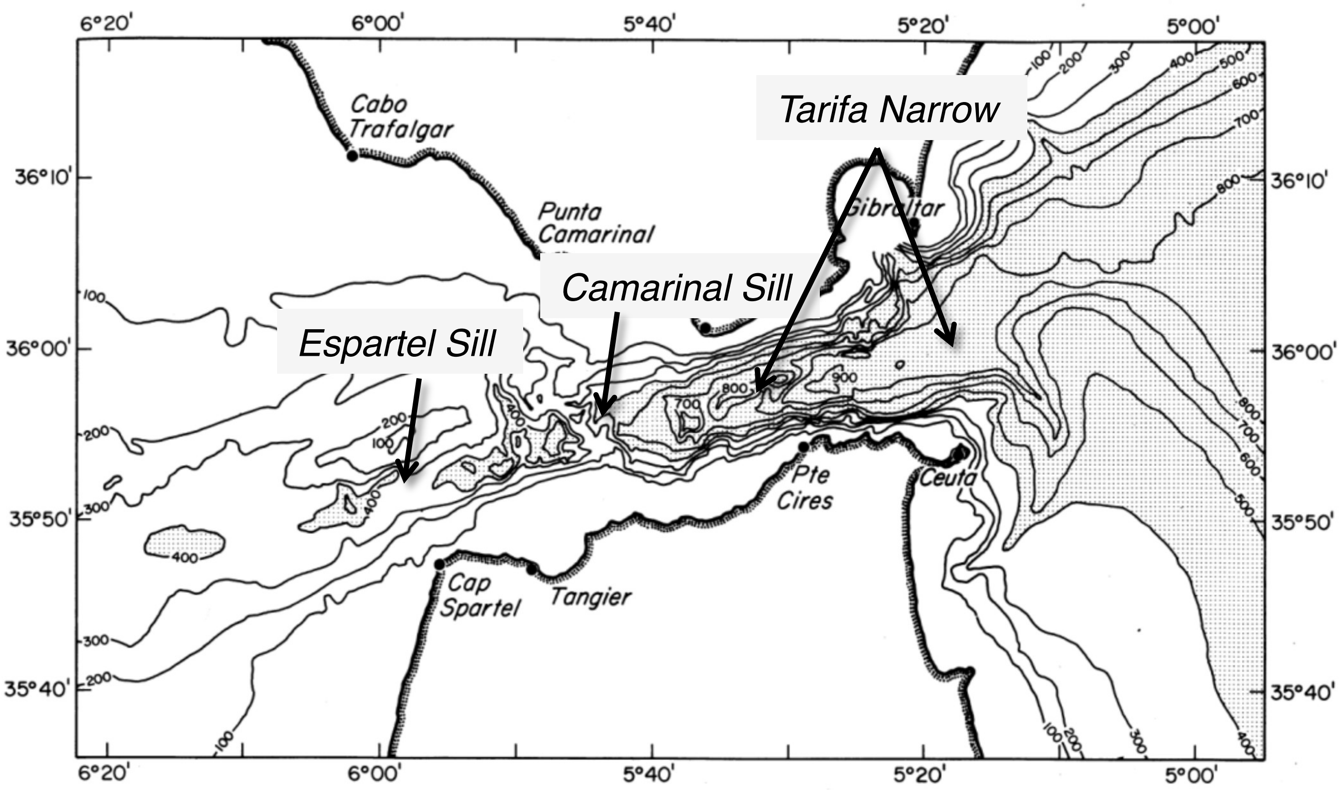


The Mediterranean is the classic example of a semi-enclosed sea

Mediterranean Thermohaline Circulation: Geography



Strait of Gibraltar Background



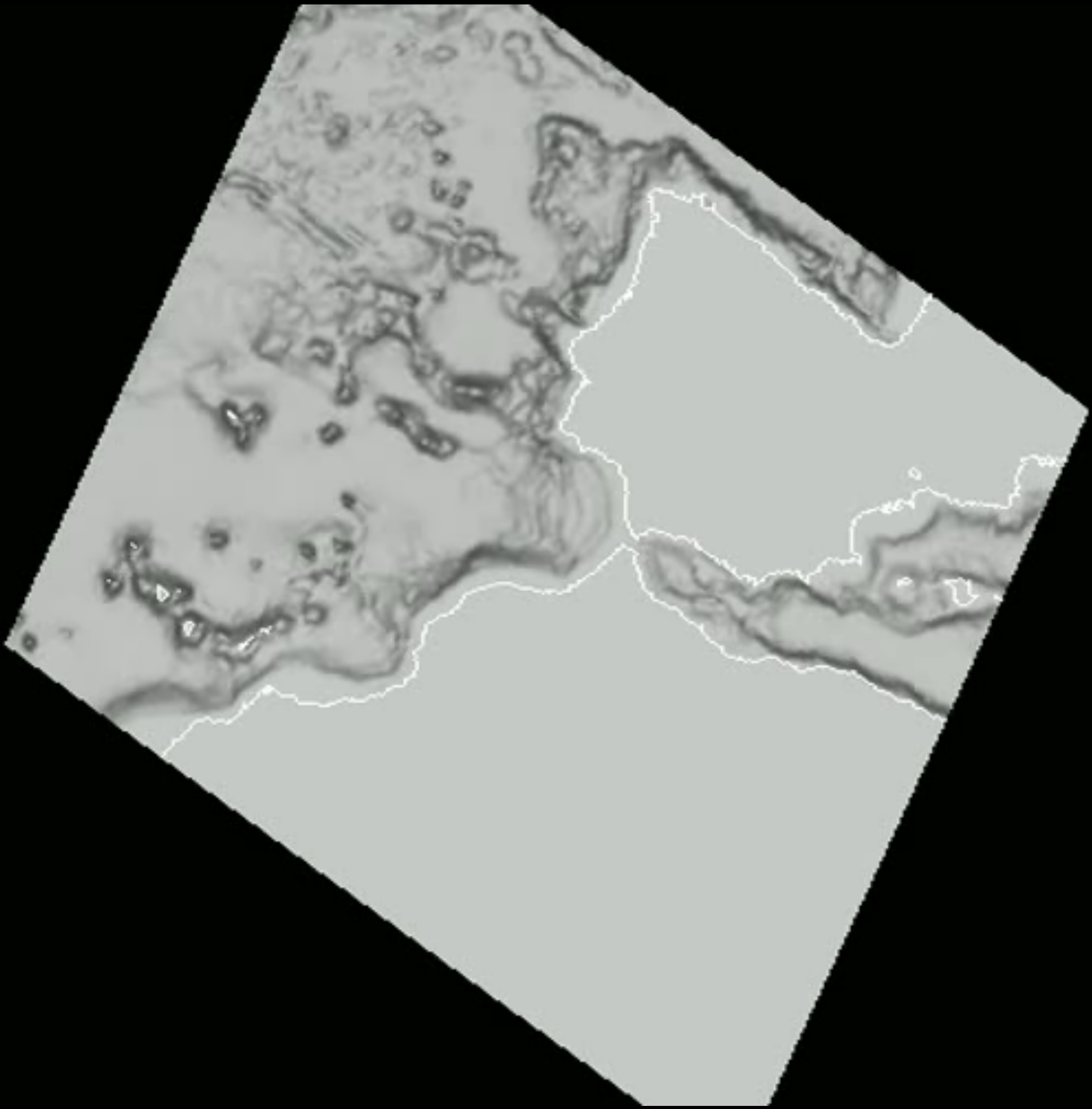
Tarifa Narrow

Camarinal Sill

Espartel Sill

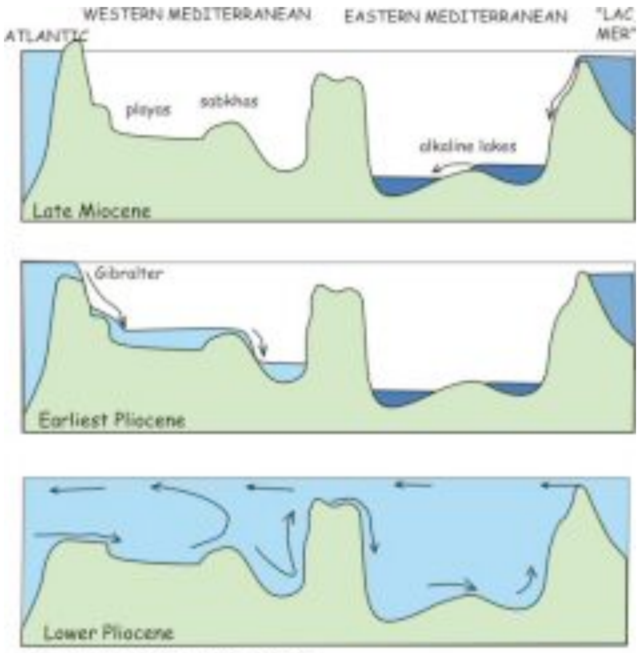
Chart of the Strait of Gibraltar, adapted from Armi & Farmer (1988), showing the principal geographic features referred to in the text. Areas deeper than 400 m are shaded

Strait of Gibraltar Background: 3D Bathymetry

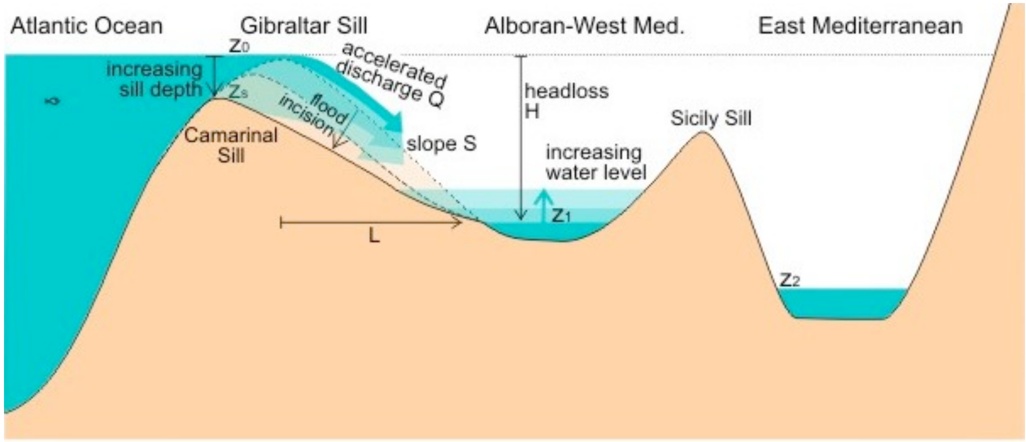


Strait of Gibraltar & Mediterranean circulation Background

Between 5.96 Ma and 5.33 Ma, during the Miocene, the strait was topographically blocked. This triggered the desiccation of the Mediterranean, inducing the so-called *Messinian Salinity Crisis* (Hsü et al. (1973)) characterized by a dramatic sealevel drop that has been estimated up to 1500 m below the current sea-level. The opening of the Strait of Gibraltar in the Early Pliocene allowed restoring the water exchange between the Atlantic and Mediterranean waters. It was an event of biblical proportions which filled the Mediterranean in less than two years. At peak times, the sea level rose by up to ten meters a day - the largest known flood in Earth's history.



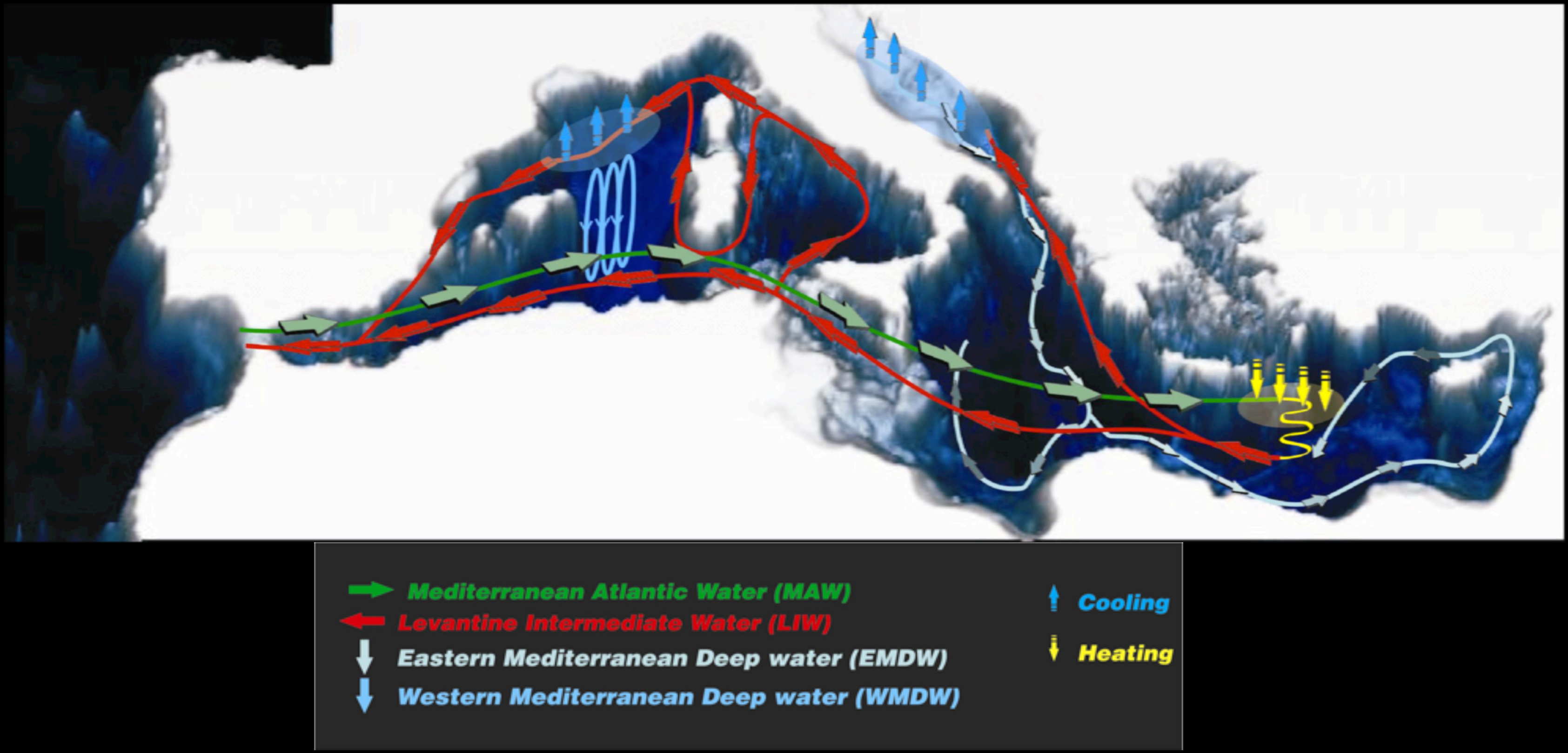
Hsu, Cita and others: late 1970s



About the opening of the Strait of Gibraltar the most recent theory proposes that it is the result of the regressive erosion of a stream that was flowing from the Atlantic toward the desiccated Mediterranean basin.

Mediterranean Thermohaline Circulation (MTHC)

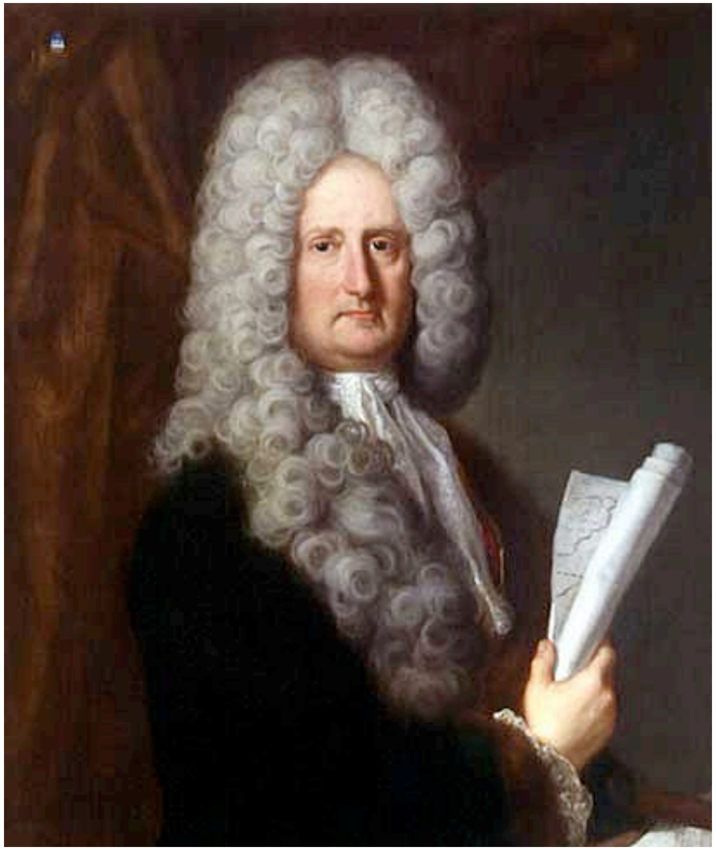
The Mediterranean Sea is a semi-enclosed basin displaying an active thermohaline circulation that is sustained by the atmospheric forcing and controlled by the narrow and shallow Strait of Gibraltar



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: History

Marsigli’s (1681) experiments in Bosporus suggested there must be a two-layer exchange through the Strait of Gibraltar.



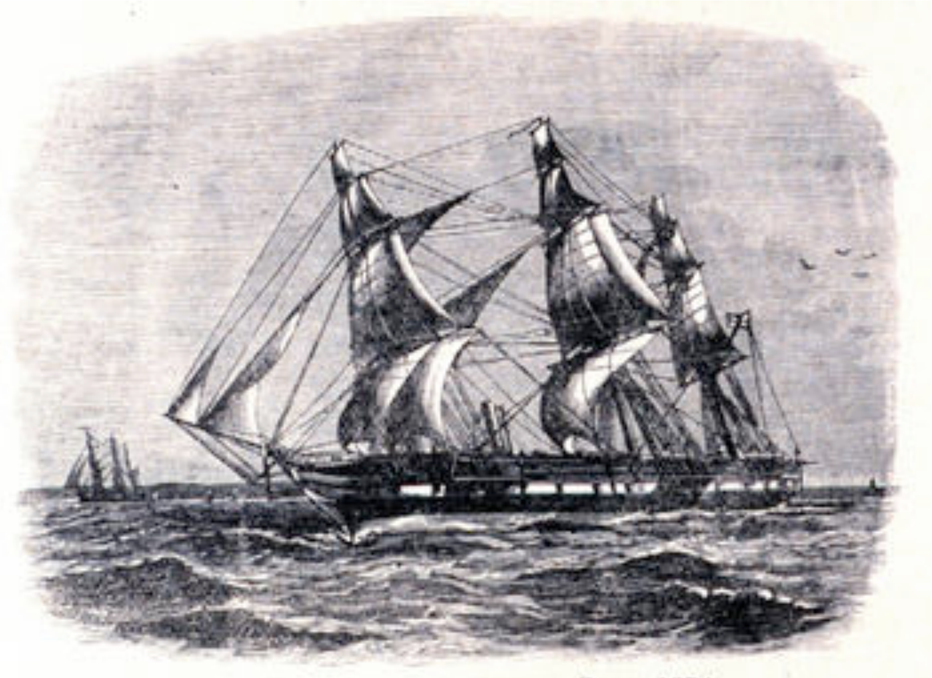
Bologna, July 10th - 1658 –
Bologna, November 1st 1730).

Marsigli was born in Bologna. He was a member of an old patrician family and was educated in accordance with his rank. He was a mathematician, physicist, geologist, naturalist..

His principal works are the following: *Osservazioni interne al Bosforo Tracio* (Rome, 1681); *Histoire physique de la mer*, translated by Leclerc (Amsterdam, 1725);

Strait of Gibraltar Background: History

Carpenter and Jeffreys (1871) observed the undercurrent toward the Atlantic by deploying a parachute drogue at 300 m depth beneath a small boat south of Gibraltar.

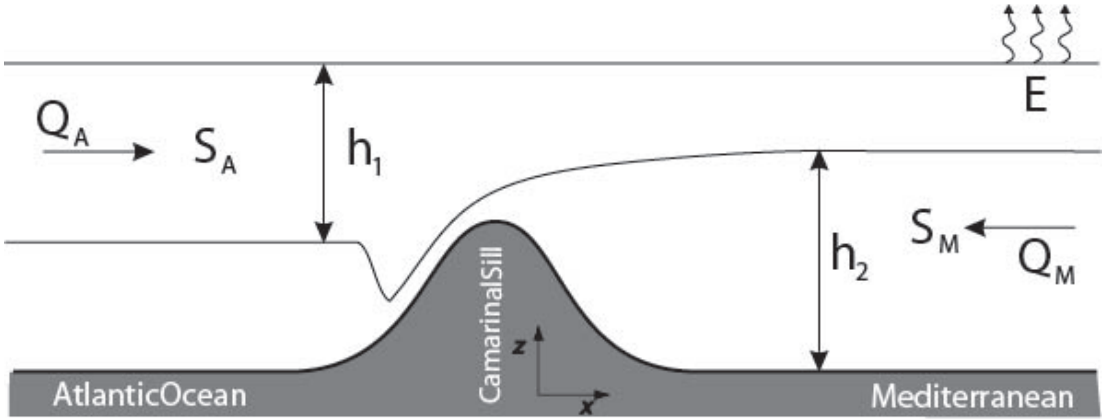


H.M.S. CHALLENGER UNDER SAIL, 1874.

The Challenger expedition of 1872–76

Strait of Gibraltar Background: flux estimation

A key issue is to quantify the exchange: how much water coming in and out through the Strait?



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

Mass Conservation

Salt Conservation

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

Knudsen equations (1899)

Strait of Gibraltar Background: flux estimation

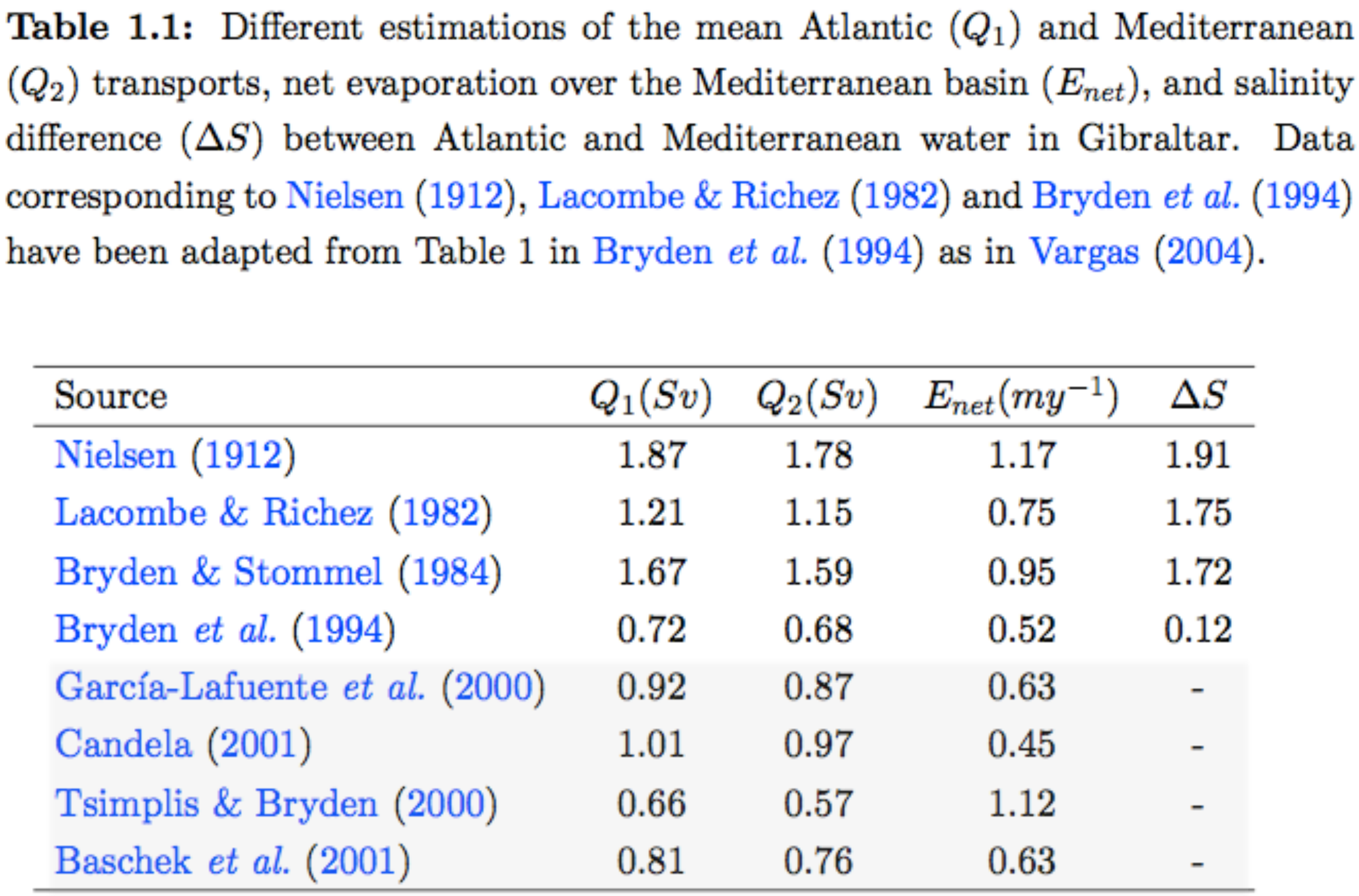


Table 1.1: Different estimations of the mean Atlantic (Q_1) and Mediterranean (Q_2) transports, net evaporation over the Mediterranean basin (E_{net}), and salinity difference (ΔS) between Atlantic and Mediterranean water in Gibraltar. Data corresponding to Nielsen (1912), Lacombe & Richez (1982) and Bryden *et al.* (1994) have been adapted from Table 1 in Bryden *et al.* (1994) as in Vargas (2004).

Source	$Q_1(Sv)$	$Q_2(Sv)$	$E_{net}(my^{-1})$	ΔS
Nielsen (1912)	1.87	1.78	1.17	1.91
Lacombe & Richez (1982)	1.21	1.15	0.75	1.75
Bryden & Stommel (1984)	1.67	1.59	0.95	1.72
Bryden *et al.* (1994)	0.72	0.68	0.52	0.12
García-Lafuente *et al.* (2000)	0.92	0.87	0.63	-
Candela (2001)	1.01	0.97	0.45	-
Tsimplis & Bryden (2000)	0.66	0.57	1.12	-
Baschek *et al.* (2001)	0.81	0.76	0.63	-

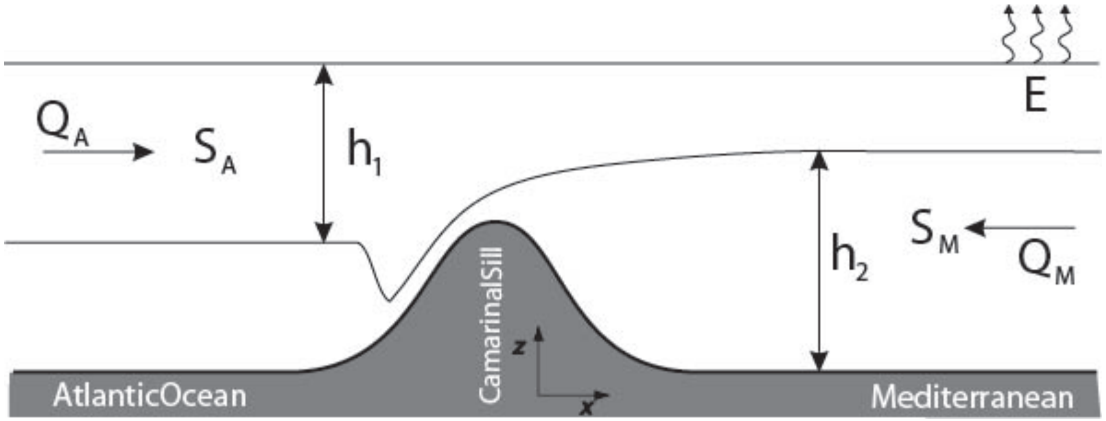
$$\begin{cases} Q_A = \frac{S_M E_{net}}{S_M - S_A} \\ \\ Q_M = -\left[\frac{S_A E_{net}}{S_M - S_A}\right] \end{cases}$$

Strait of Gibraltar Background: Hydraulics

Mass Conservation

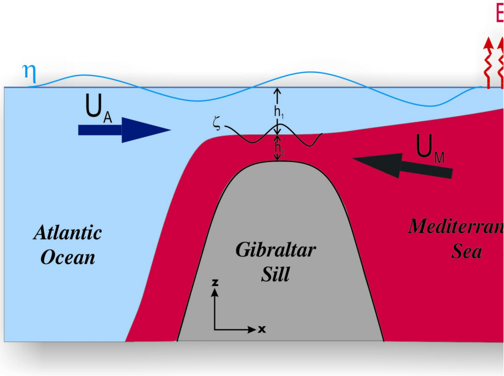
$$\begin{cases} Q_A + Q_M = E - P - R \\ Q_A S_A + Q_M S_M = 0 \end{cases}$$

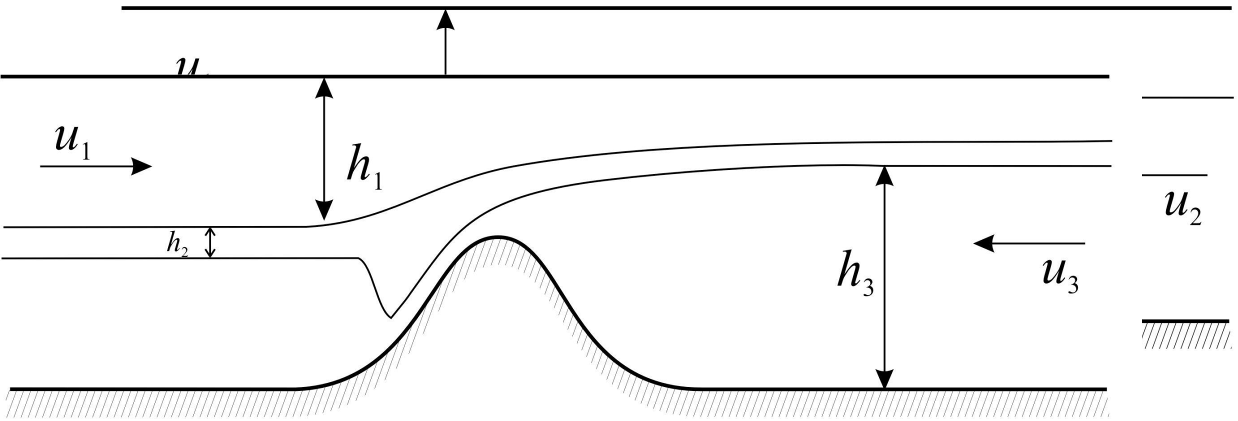
Salt Conservation



Knudsen equations (1899)

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



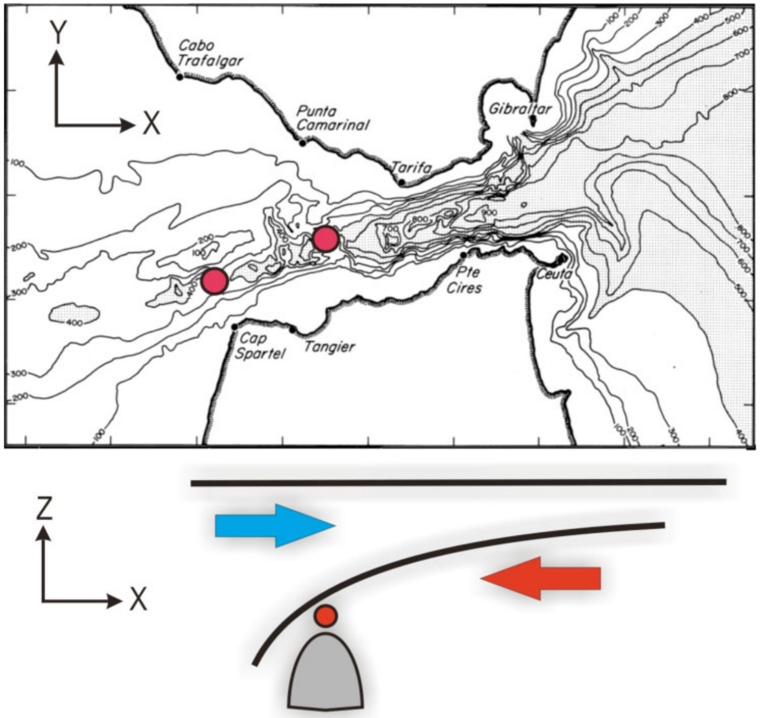


$$F_1^2 = \frac{u_1^2}{h_1 g\left(1 - r_{1,2}\right)} \qquad F_2^2 = \frac{u_2^2\left(1 - r_{1,3}\right)}{h_2 g\left(1 - r_{1,2}\right)\left(1 - r_{2,3}\right)} \qquad F_3^2 = \frac{u_3^2}{h_3 g\left(1 - r_{2,3}\right)} \qquad r_{i,j} = \frac{\rho_i}{\rho_j}$$

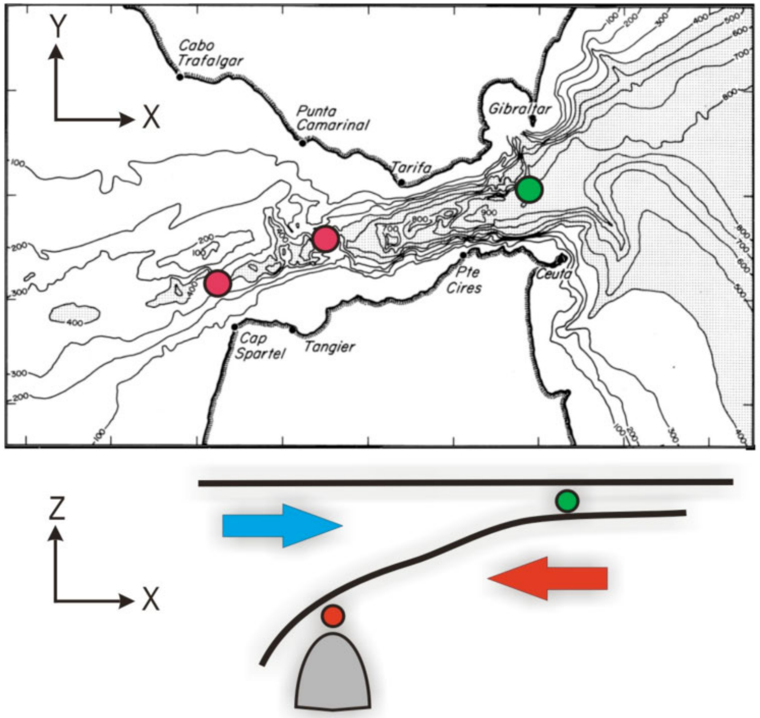
$$G^2 = F_1^2 + F_2^2 + F_3^2$$

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.

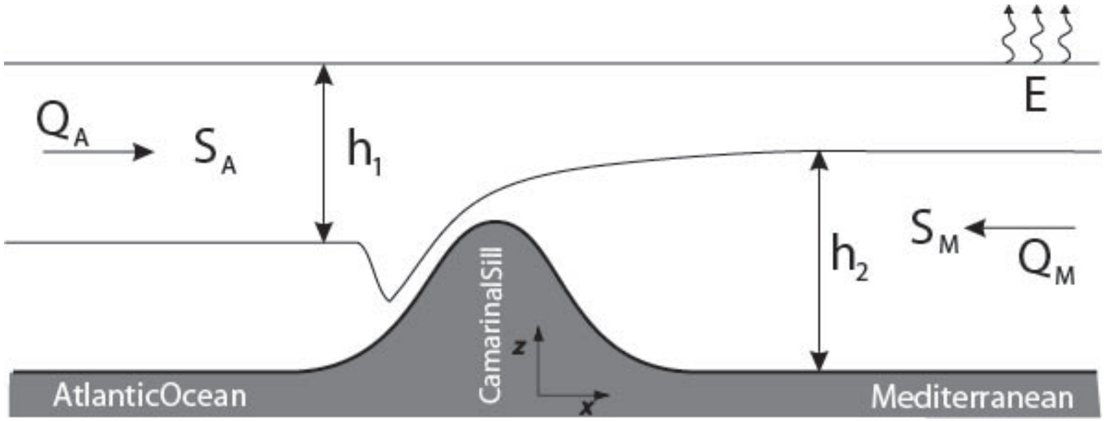
The maximal regime can be expected to have larger heat, salt, and mass fluxes and to respond more slowly to changes in stratification and thermohaline forcing within the Mediterranean Sea and the North Atlantic Ocean.

Strait of Gibraltar Background: Hydraulics

Mass Conservation

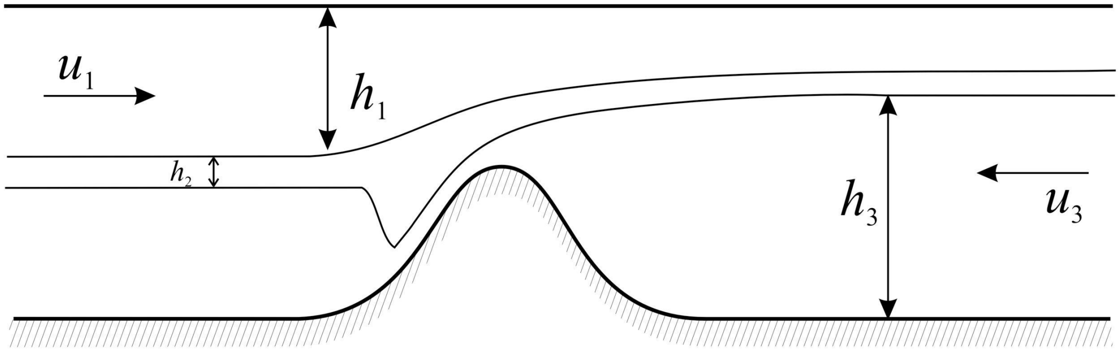
$$\begin{cases} Q_A + Q_M = E - P - R \\ Q_A S_A + Q_M S_M = 0 \end{cases}$$

Salt Conservation



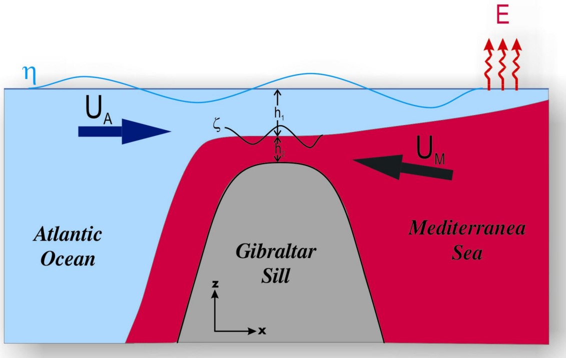
Knudsen equations (1899)

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



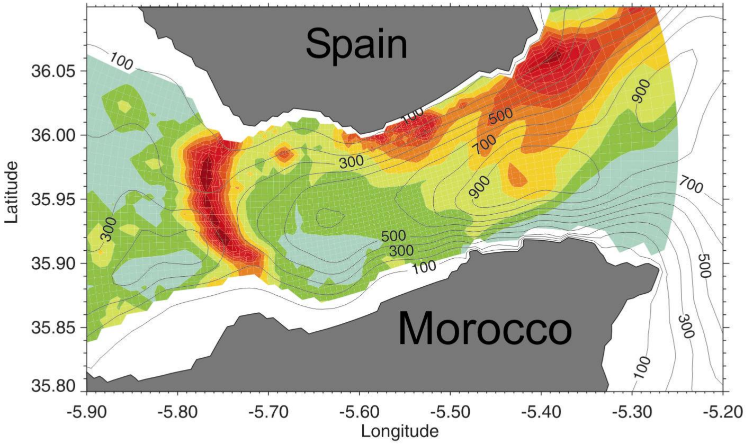
$$F_1^2 = \frac{u_1^2}{h_1 g\left(1 - r_{1,2}\right)} \qquad F_2^2 = \frac{u_2^2\left(1 - r_{1,3}\right)}{h_2 g\left(1 - r_{1,2}\right)\left(1 - r_{2,3}\right)} \qquad F_3^2 = \frac{u_3^2}{h_3 g\left(1 - r_{2,3}\right)} \qquad r_{i,j} = \frac{\rho_i}{\rho_j}$$

$$\boxed{G^2 = F_1^2 + F_2^2 + F_3^2}$$

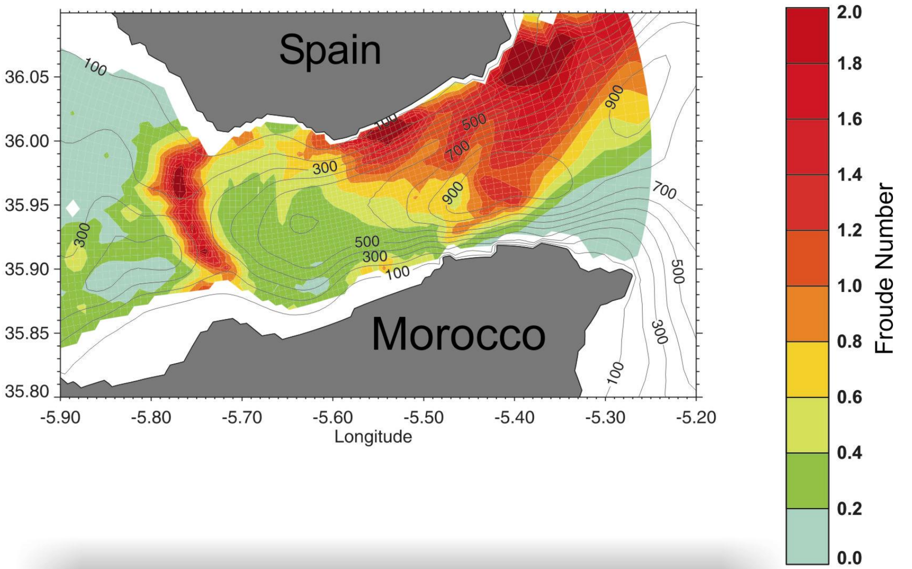


Strait of Gibraltar Background: Hydraulics

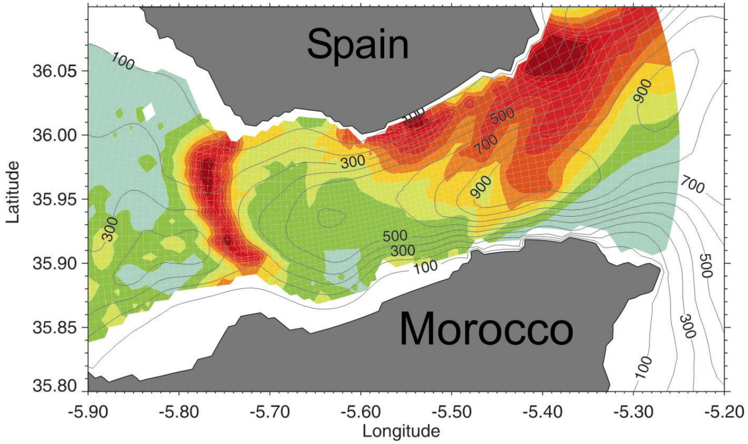
$\Delta S = 2.0$

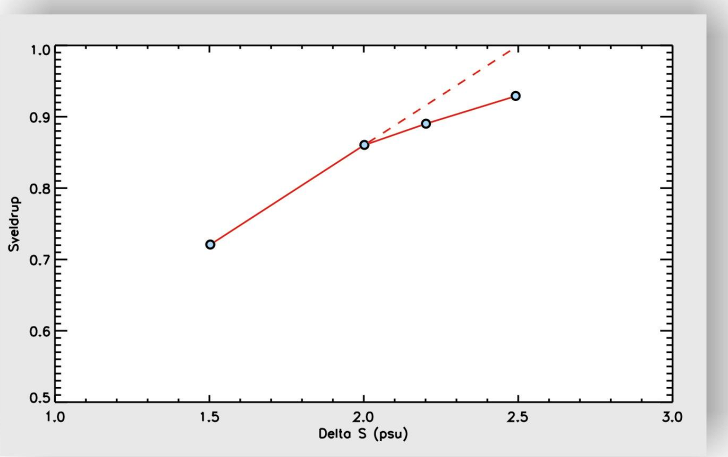


$\Delta S = 2.5$



$\Delta S = 2.2$





Question

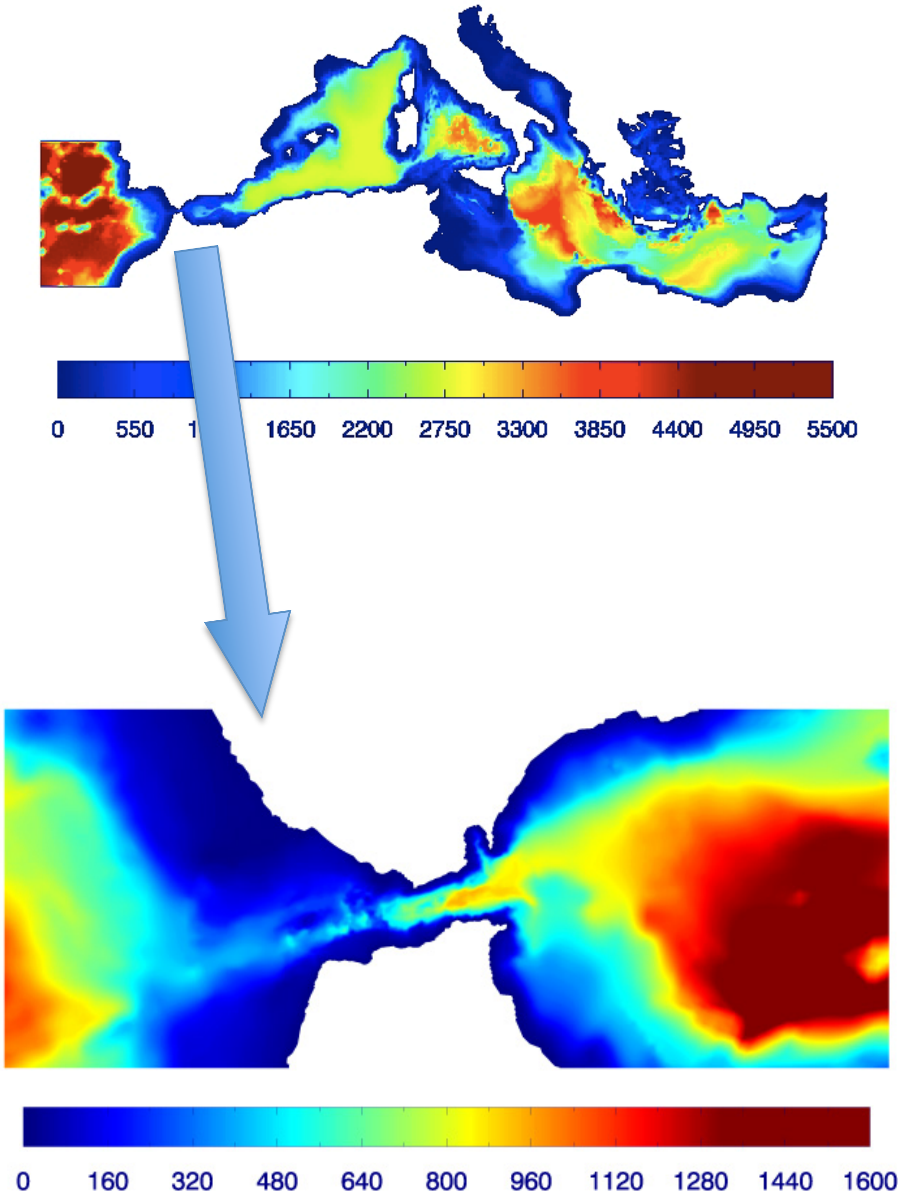
Climate models represent the

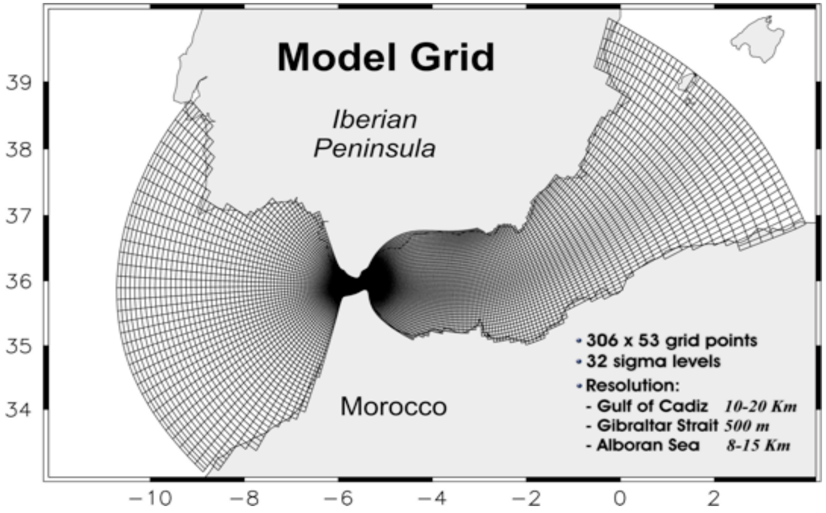
Strait of Gibraltar like a rectangular pipe & notides

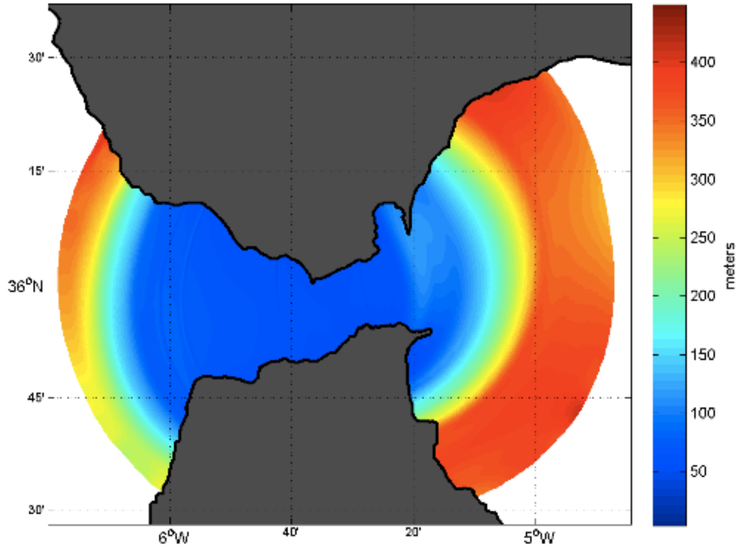
- Is it reasonable?

- If NO, what are they neglecting?

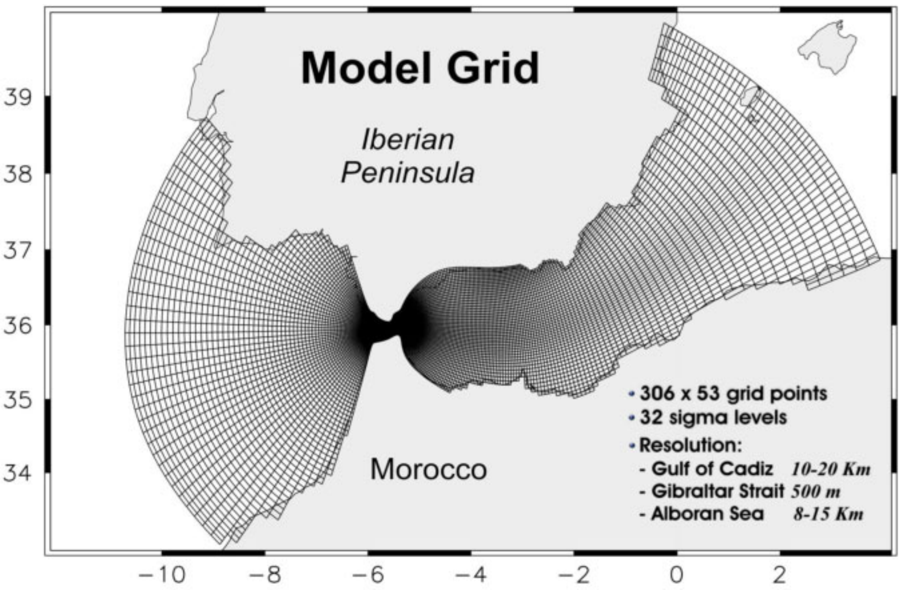
Answer: Direct simulation

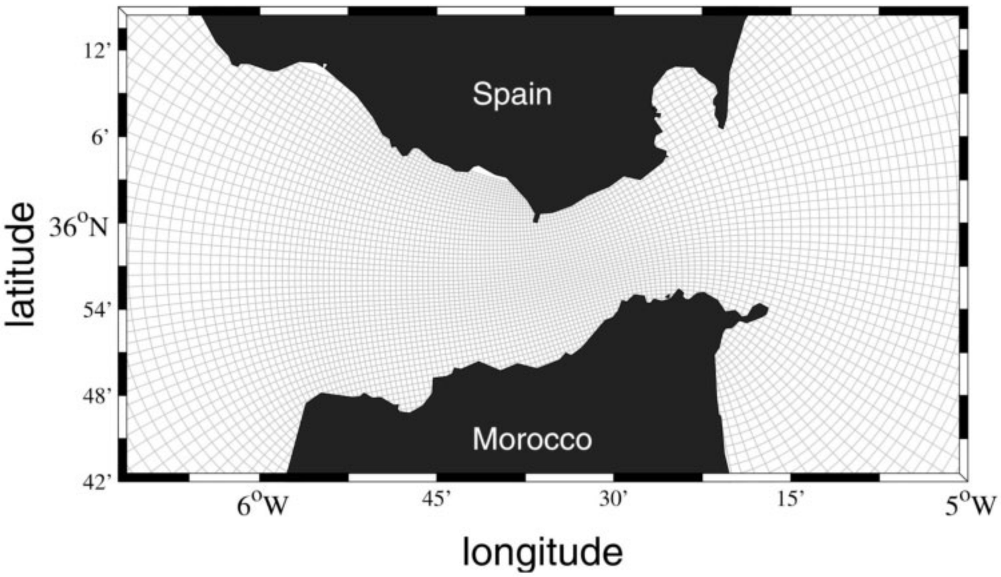






Sub-basin Model: Cadiz – Gibraltar - Alboran





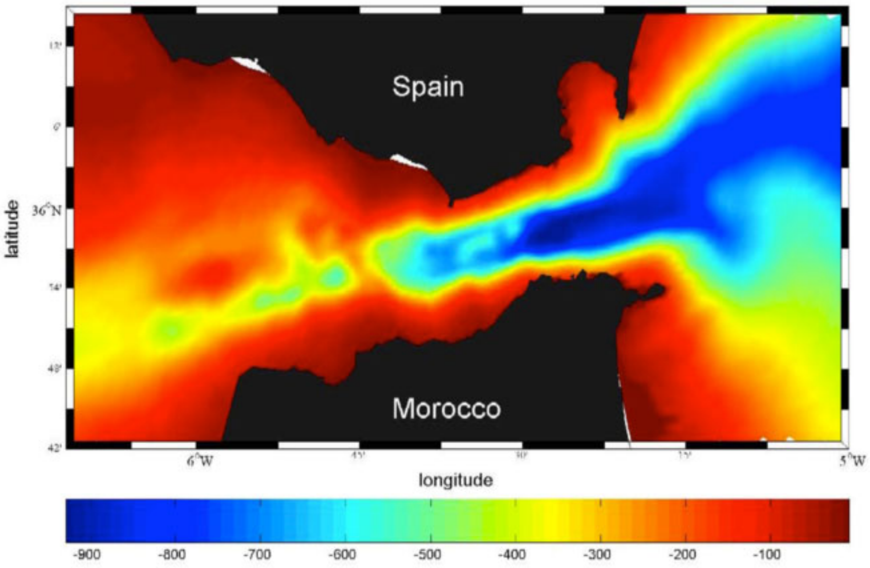
Modified POM

Minimal Hor. Resolution: < 500 m

External Time-Step: 0.1 sec

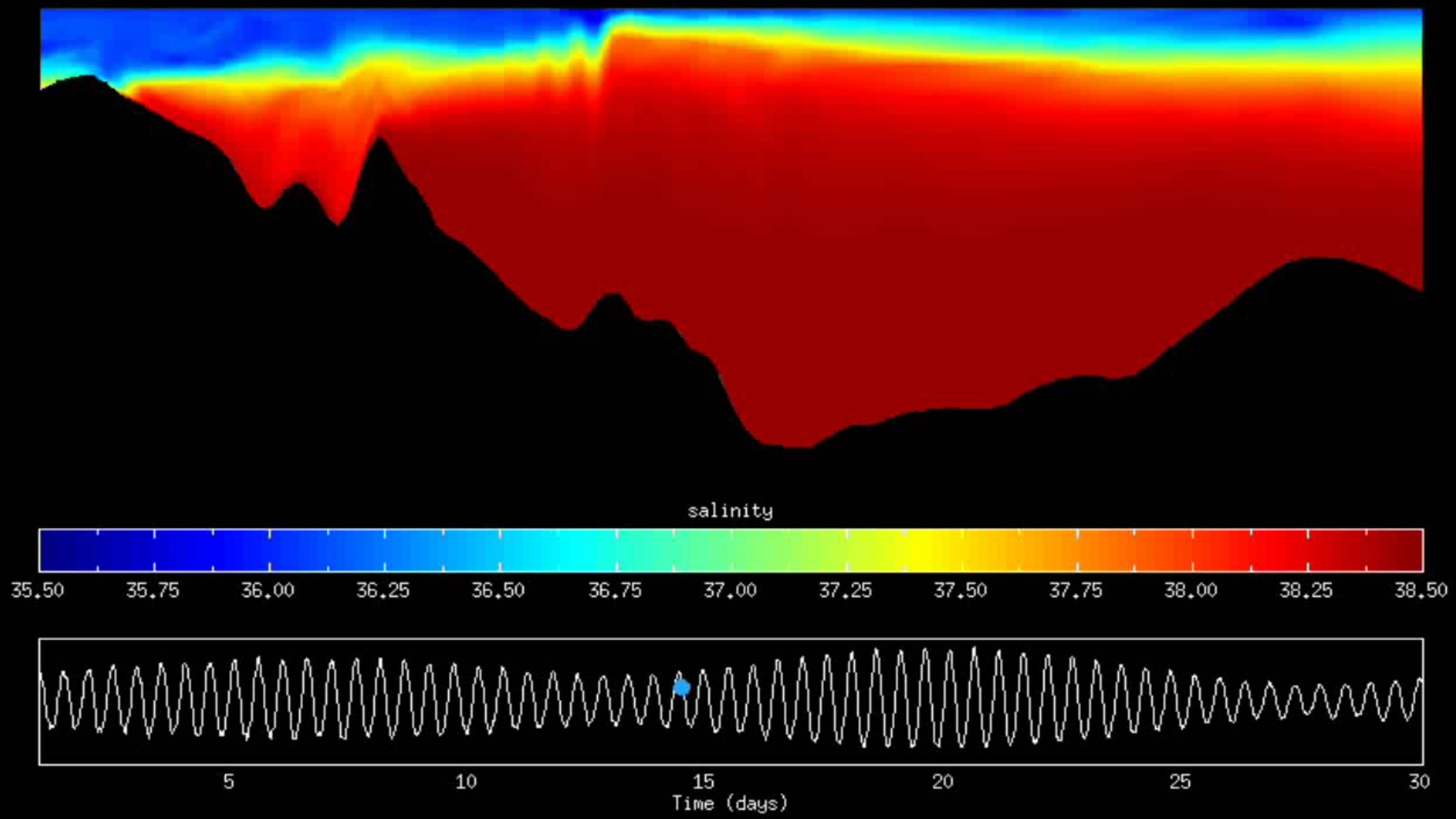
O_1 K_1 diurnal tidal component

M_2 S_2 diurnal tidal component



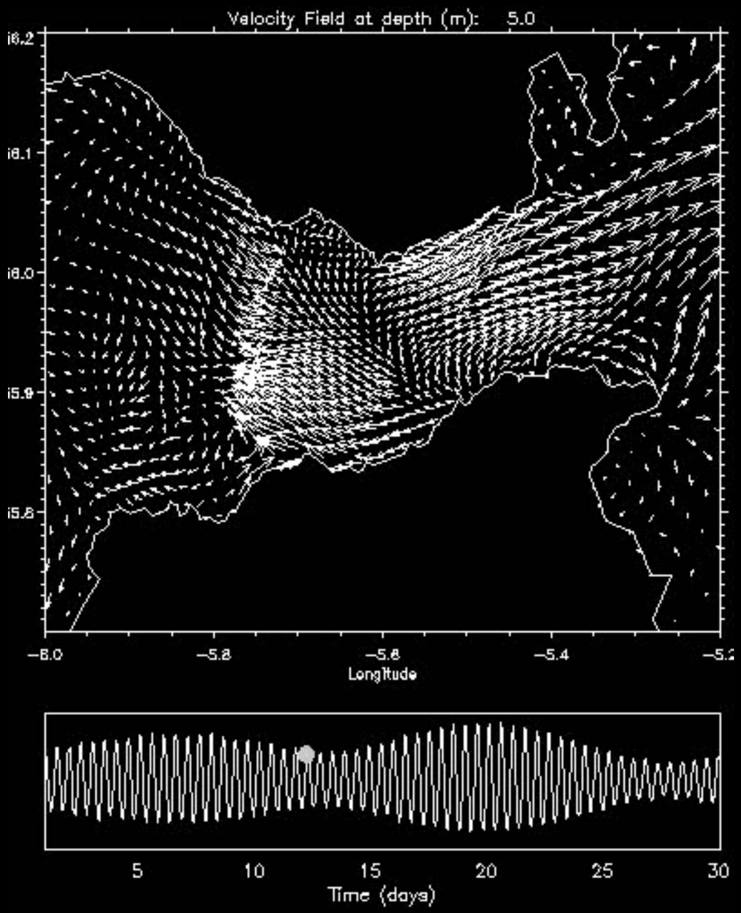
- Sannino et al, JGR, 2012 sub.
- Sannino et al, JPO, 2009
- Sanchez et al, JGR, 2009
- Garrido et al, JGR, 2008
- Garcia-Lafuente et al, JGR, 2007
- Sannino et al, JGR, 2007
- Sannino et al , NC, 2005
- Sannino et al, JGR, 2004
- Sannino et al, JGR, 2002

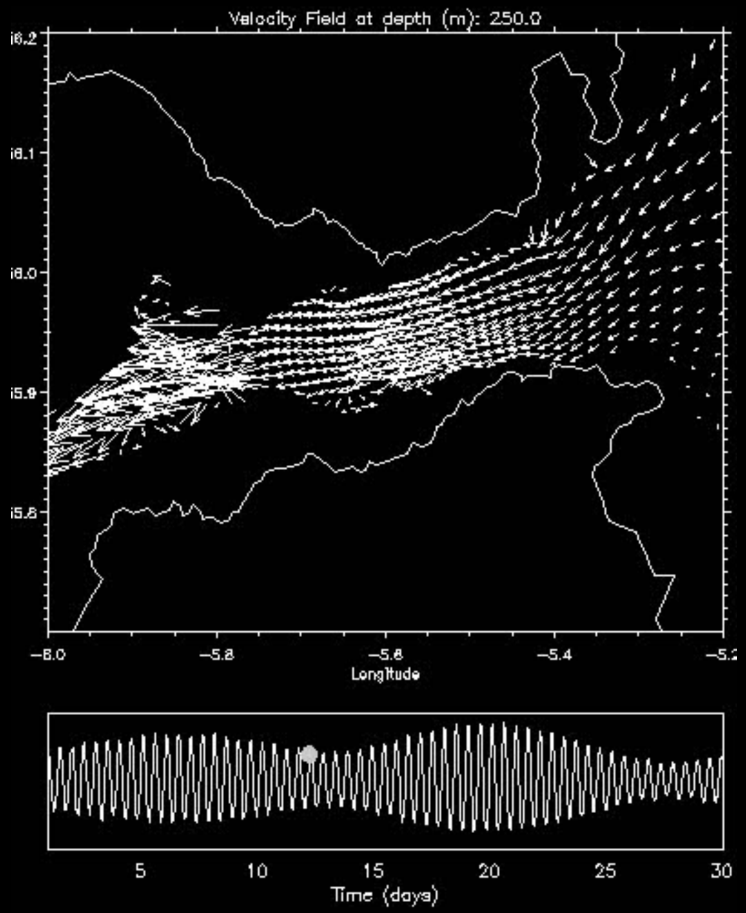
Sub-basin Model: Cadiz – Gibraltar - Alboran



salinity along-strait section

Sub-basin Model: Cadiz – Gibraltar - Alboran





Sub-basin Model: Cadiz – Gibraltar - Alboran

Tidal Components comparison
Surface elevation

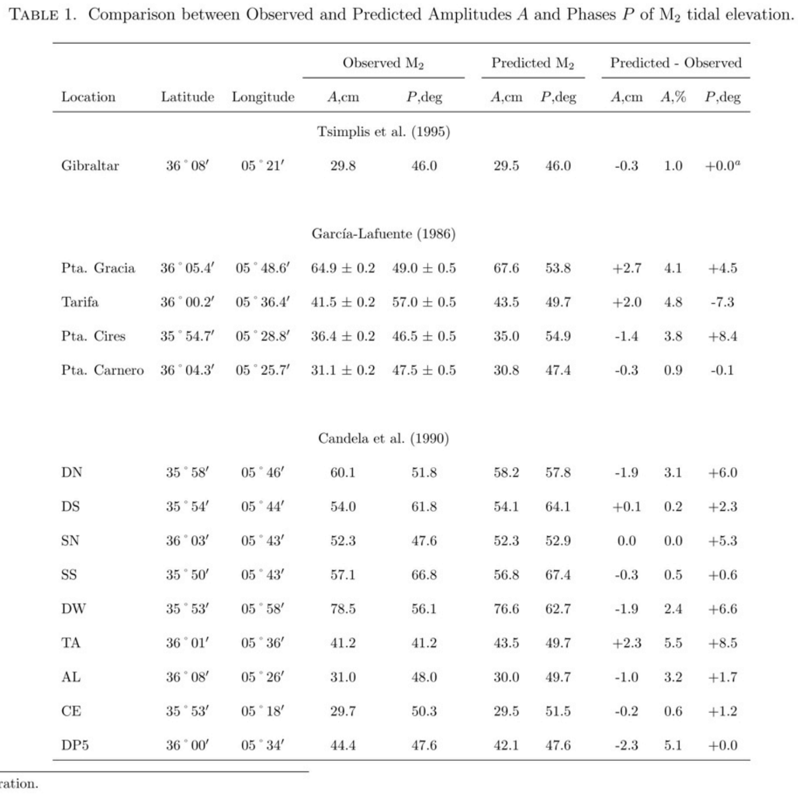


TABLE 1. Comparison between Observed and Predicted Amplitudes A and Phases P of M_2 tidal elevation.

Location	Latitude	Longitude	Observed M_2 A,cm	Observed M_2 P,deg	Predicted M_2 A,cm	Predicted M_2 P,deg	Predicted - Observed A,cm	Predicted - Observed A,%	Predicted - Observed 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

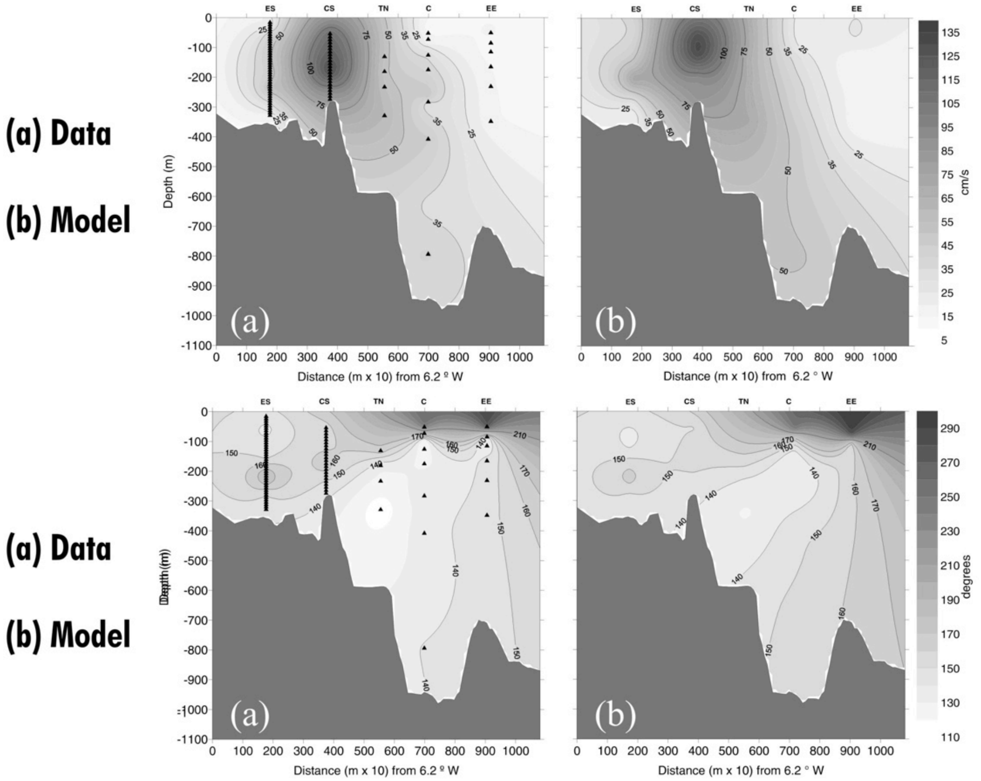
---

[a] Calibration.

Max Differences:
Amp: 3.6 cm
Pha: 11°

Sannino et al.,JPO, 2009

Tidal Components comparison
Along-strait velocity



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

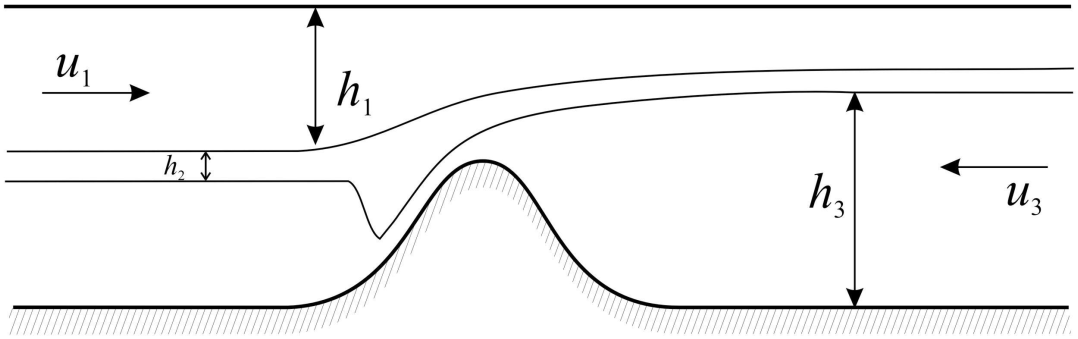
Sánchez-Román et al., JGR, 2009

Strait of Gibraltar: new 3Layer Hydraulic Theory

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

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

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



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

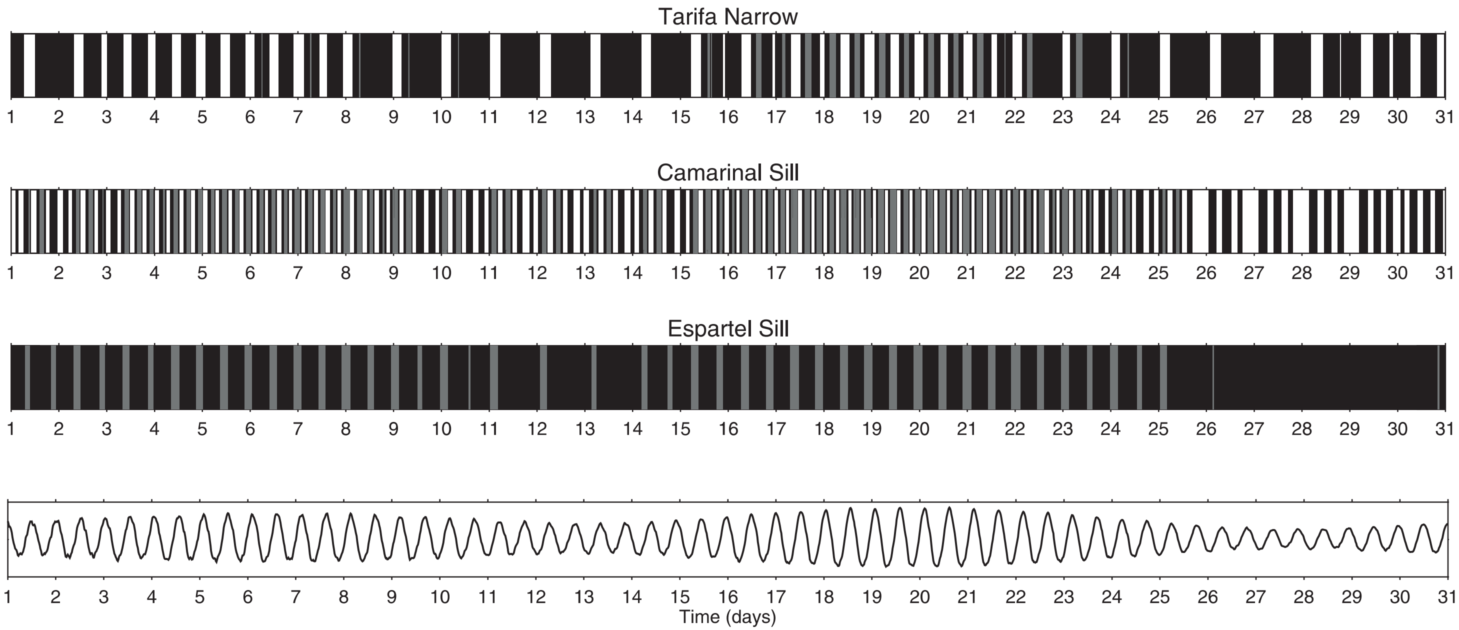
$$\tilde{F}_1^2 + \left(\frac{1-r}{r} + \frac{w_3}{w_2} \right) \tilde{F}_2^2 + \tilde{F}_3^2 - \frac{w_3}{w_2} \tilde{F}_1^2 \tilde{F}_2^2 - \tilde{F}_1^2 \tilde{F}_3^2 - \frac{1-r}{r} \tilde{F}_2^2 \tilde{F}_3^2 = 1$$

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

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

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.

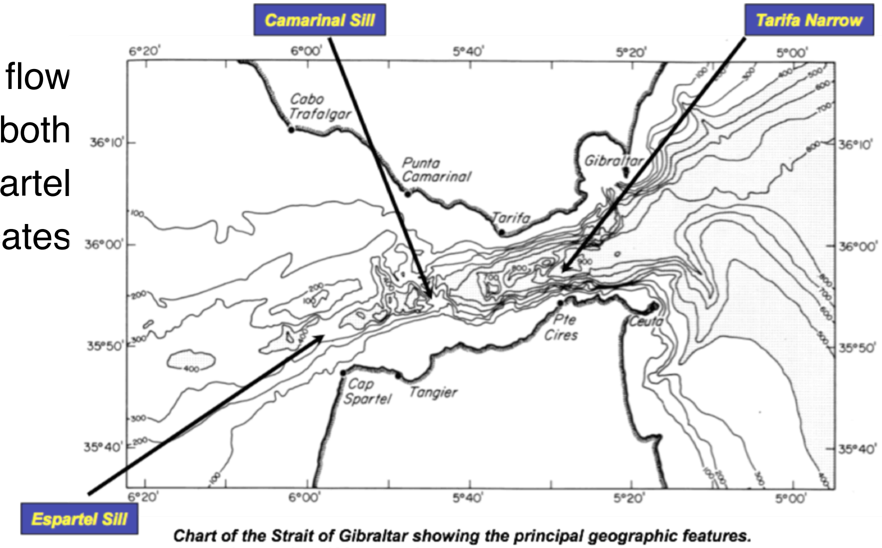
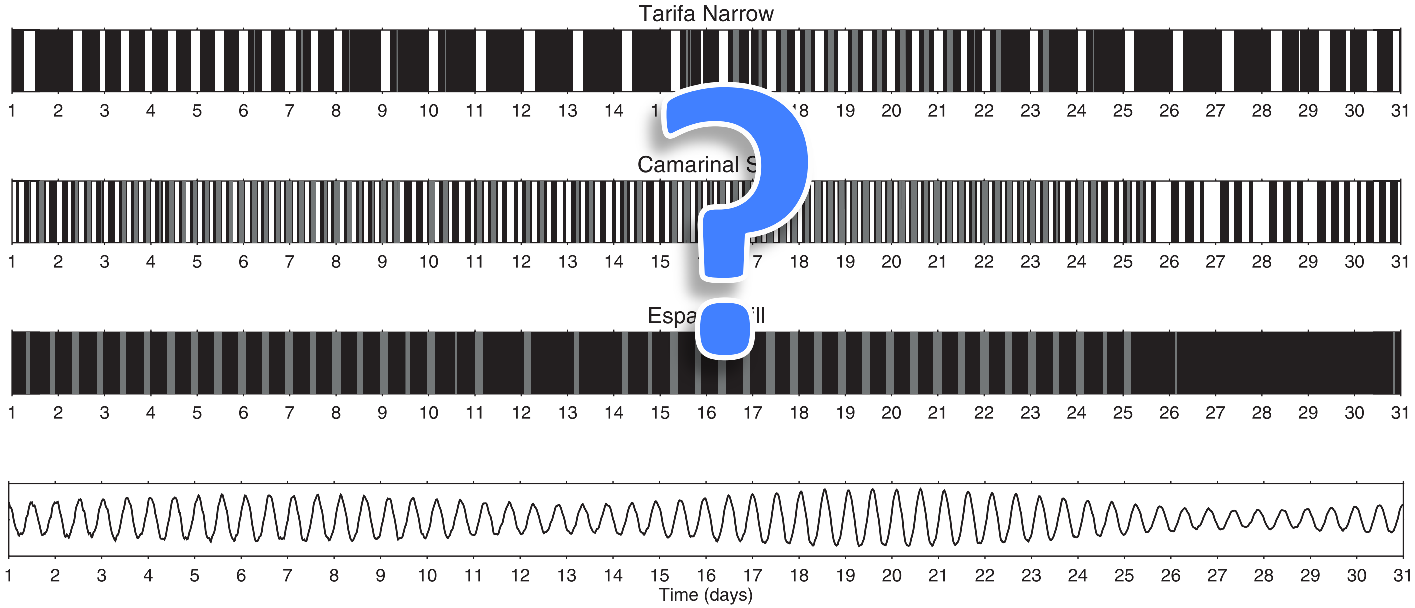


Chart of the Strait of Gibraltar showing the principal geographic features. Areas deeper than 400 m are shaded

Are the hydraulic results model depended?

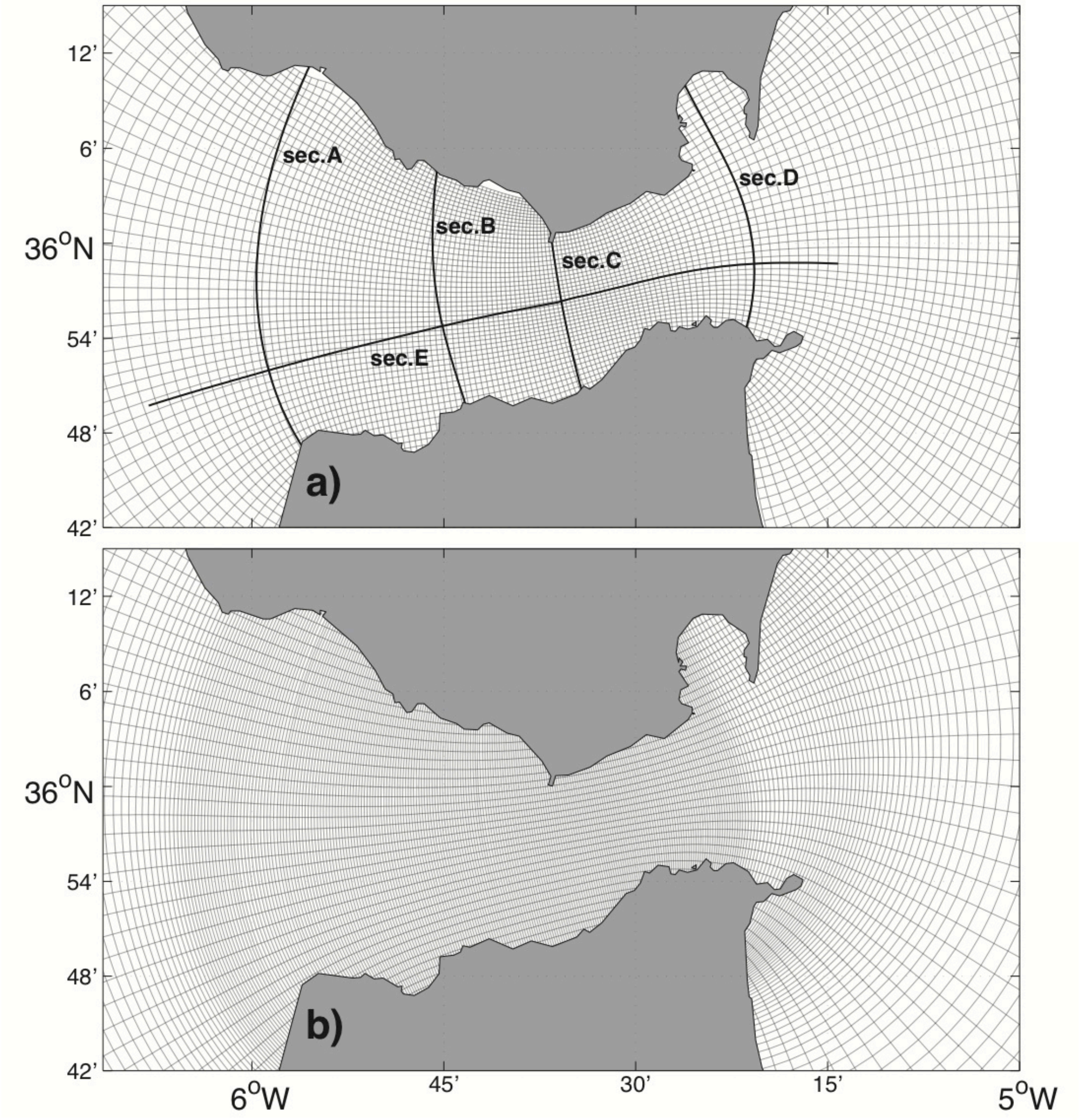


To answer the question the exchange flow simulated by POM has been compared with the exchange flow simulated by a very high resolution non-hydrostatic model implemented for the Strait region.

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)

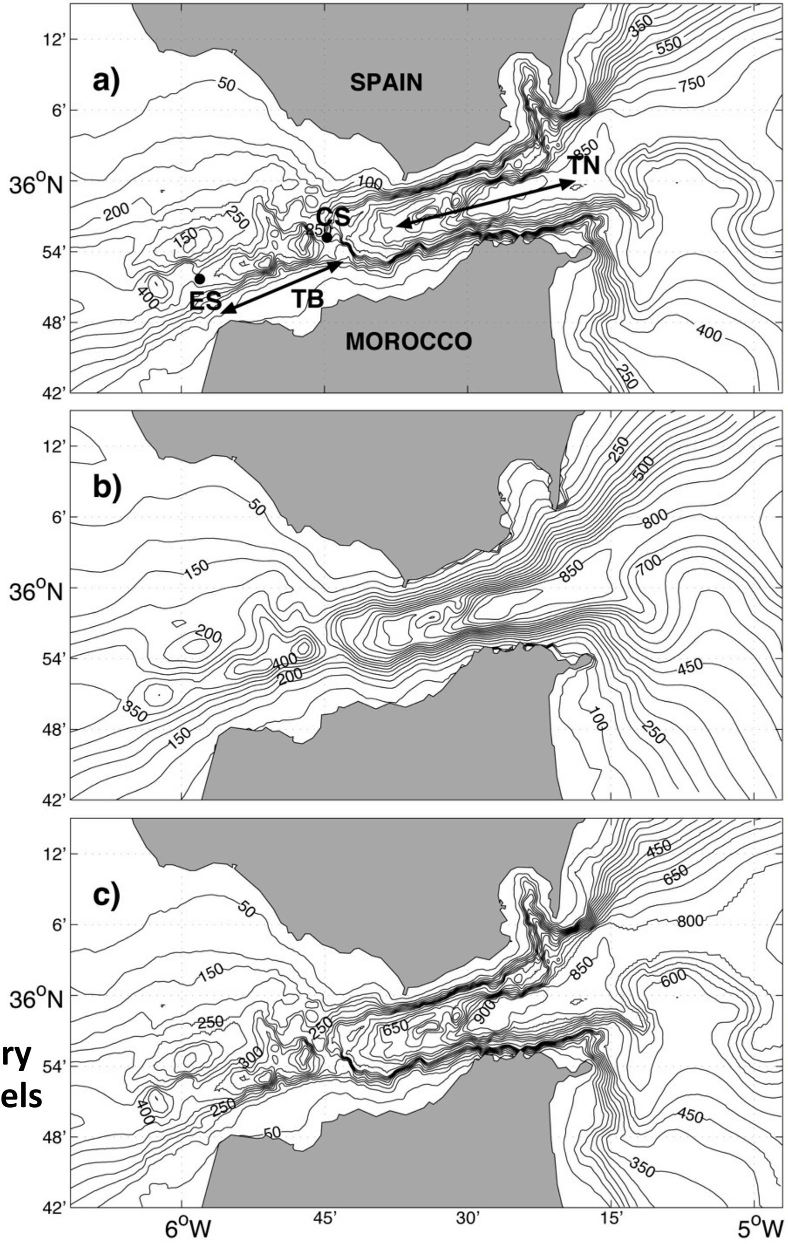


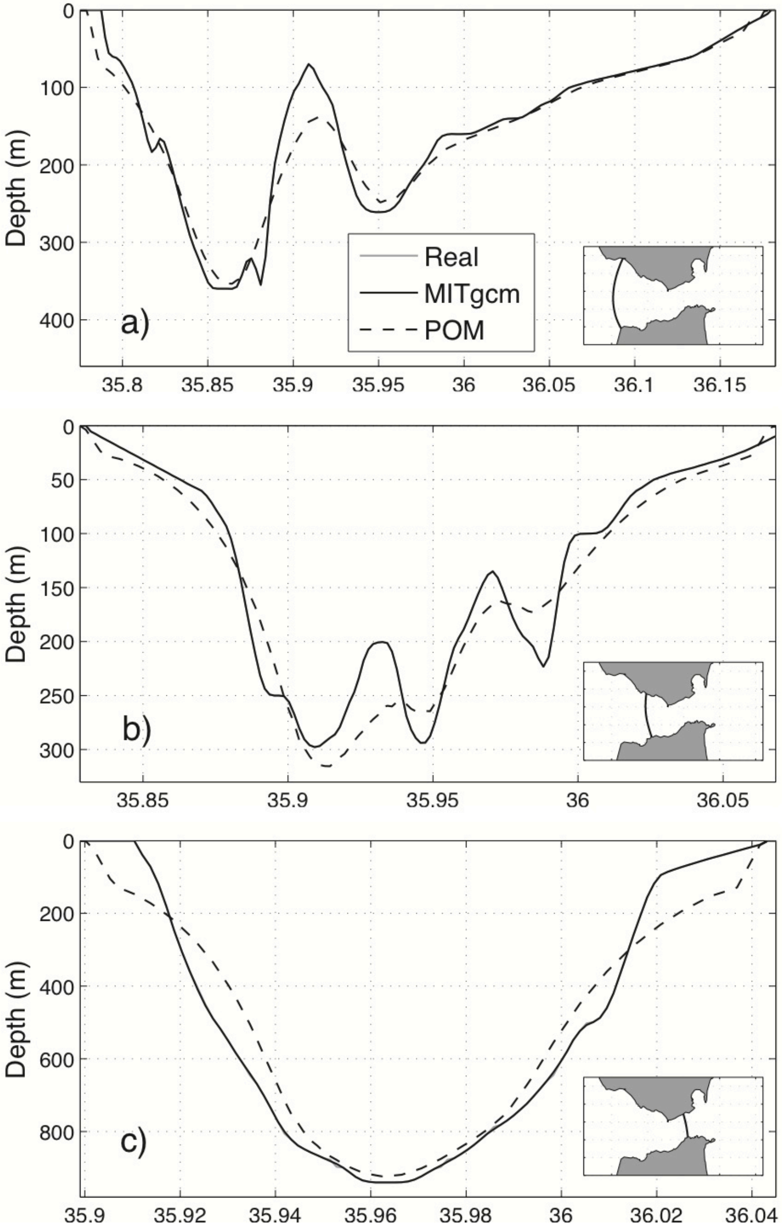
MITgcm vs POM : model bathymetry

Real bathymetry

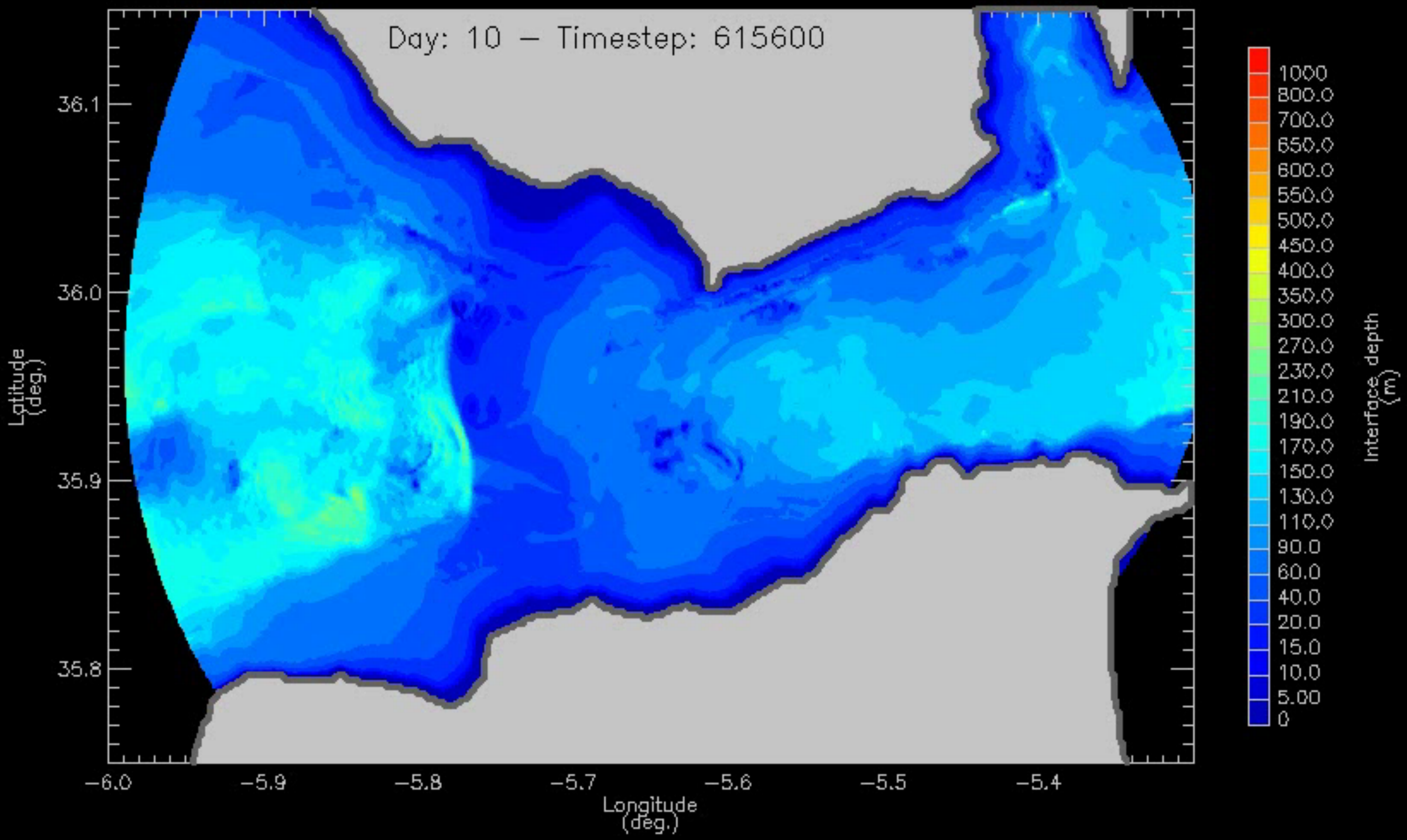
POM bathymetry
32 sigma-levels

MITgcm bathymetry
53 vertical zeta-levels
(partial cell)





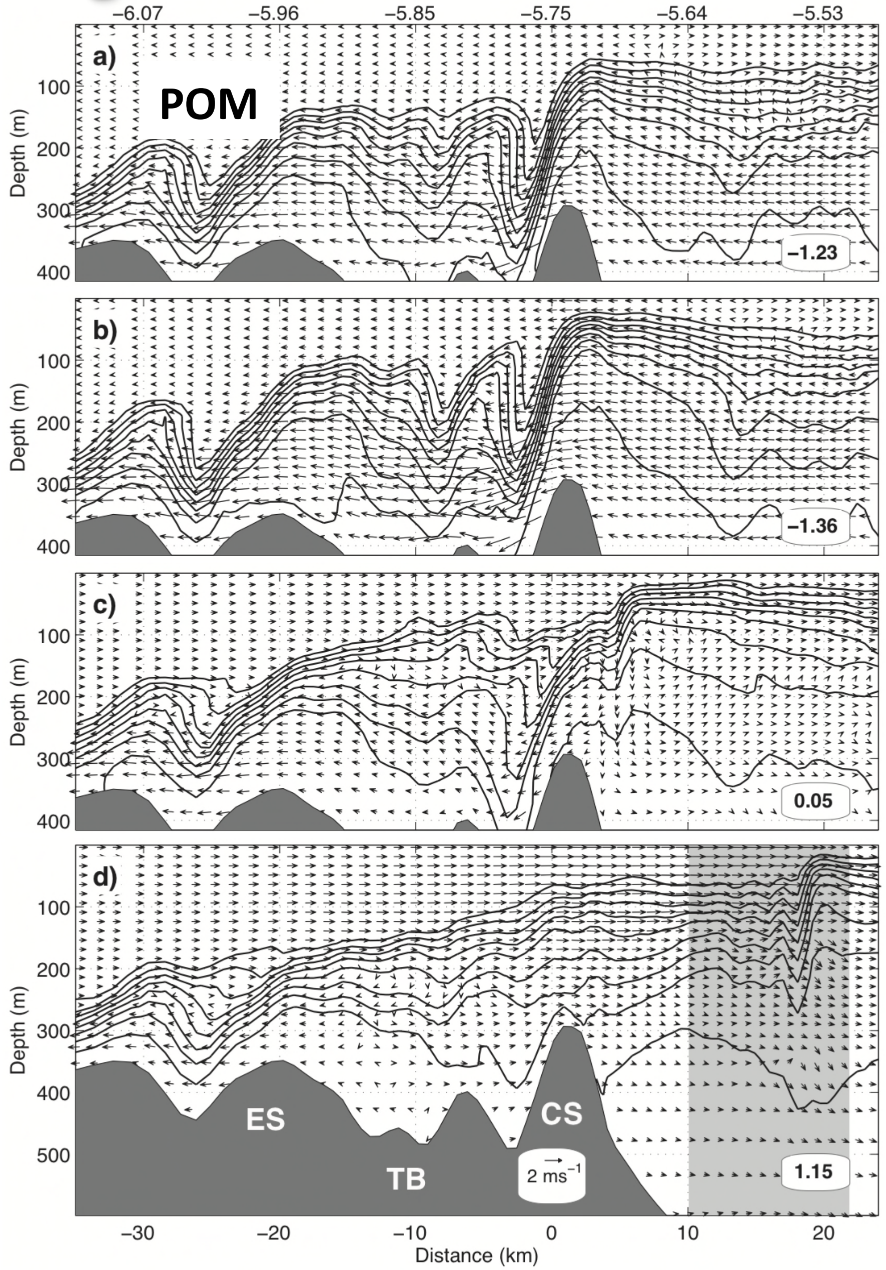
MITgcm model simulation

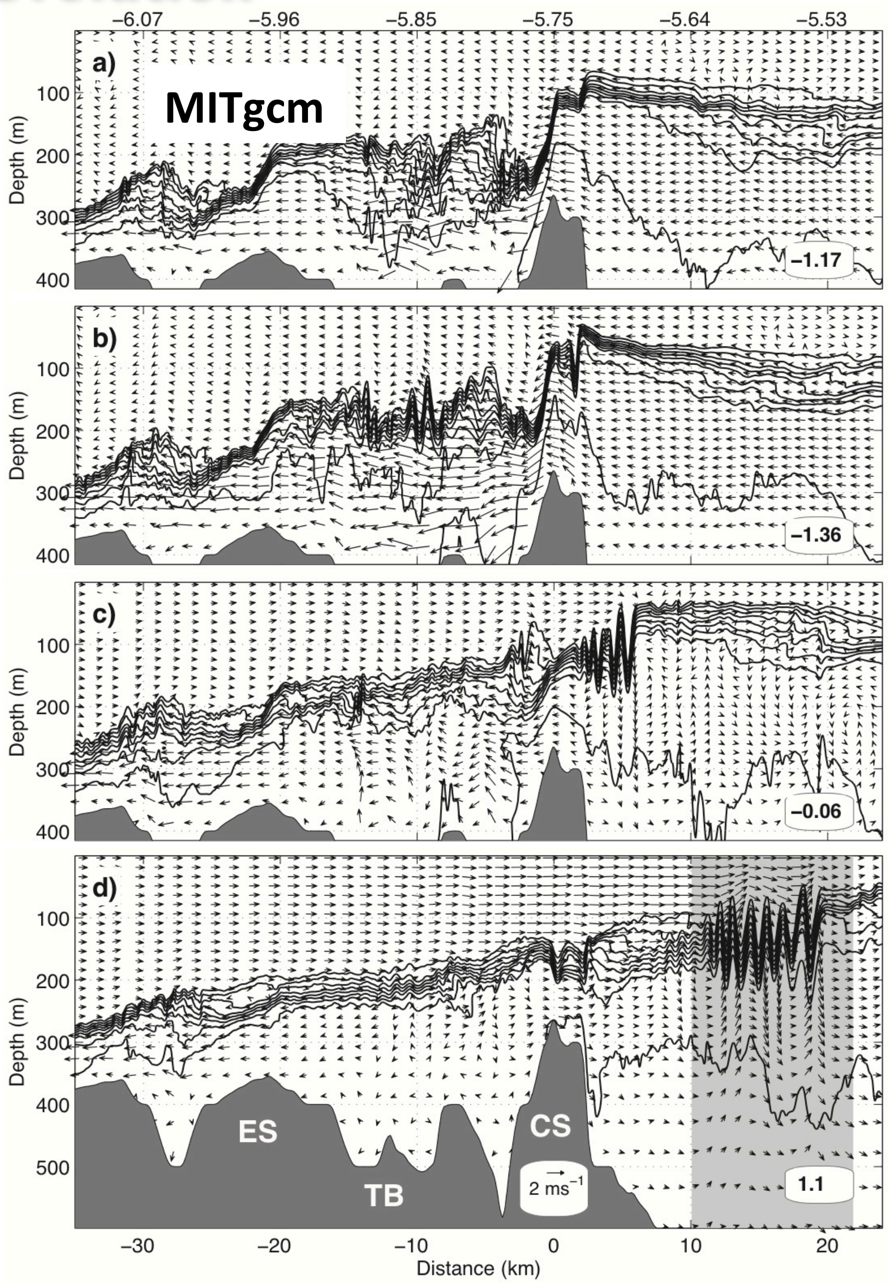


Garrido et al. jgr 2011

Interface depth evolution

MITgcm vs POM – Internal bore evolution



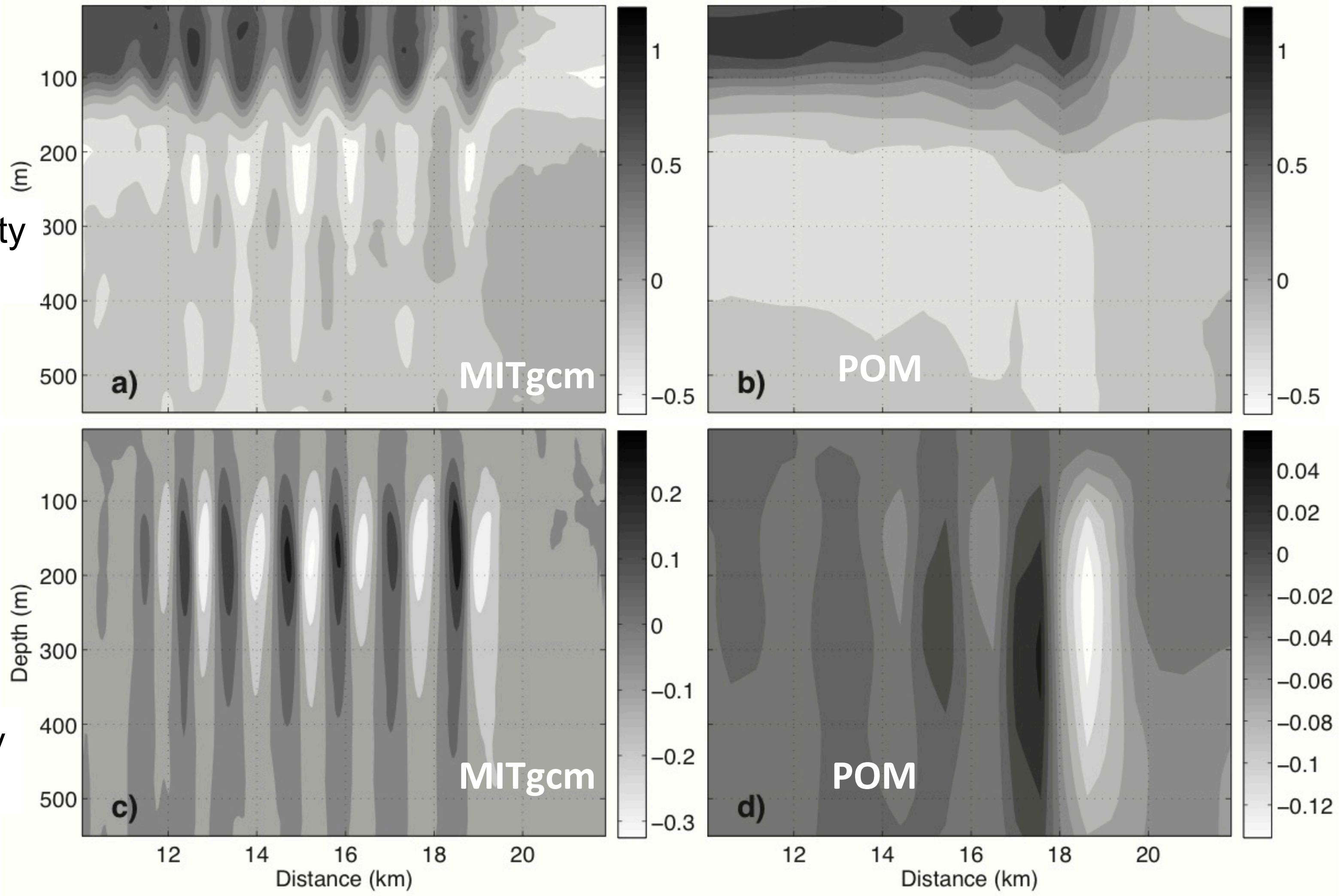


Garrido et al. jgr 2011

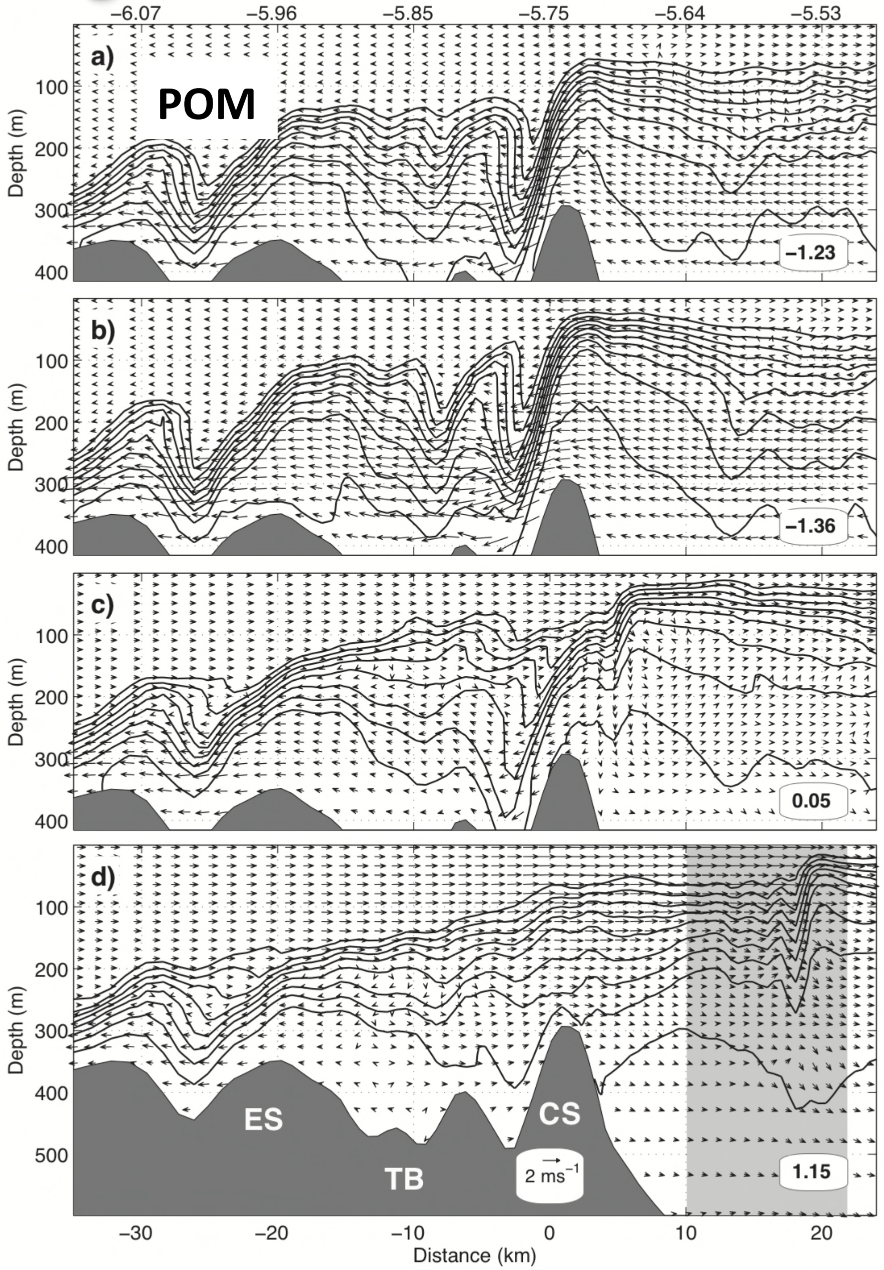
MITgcm vs POM – Internal bore evolution

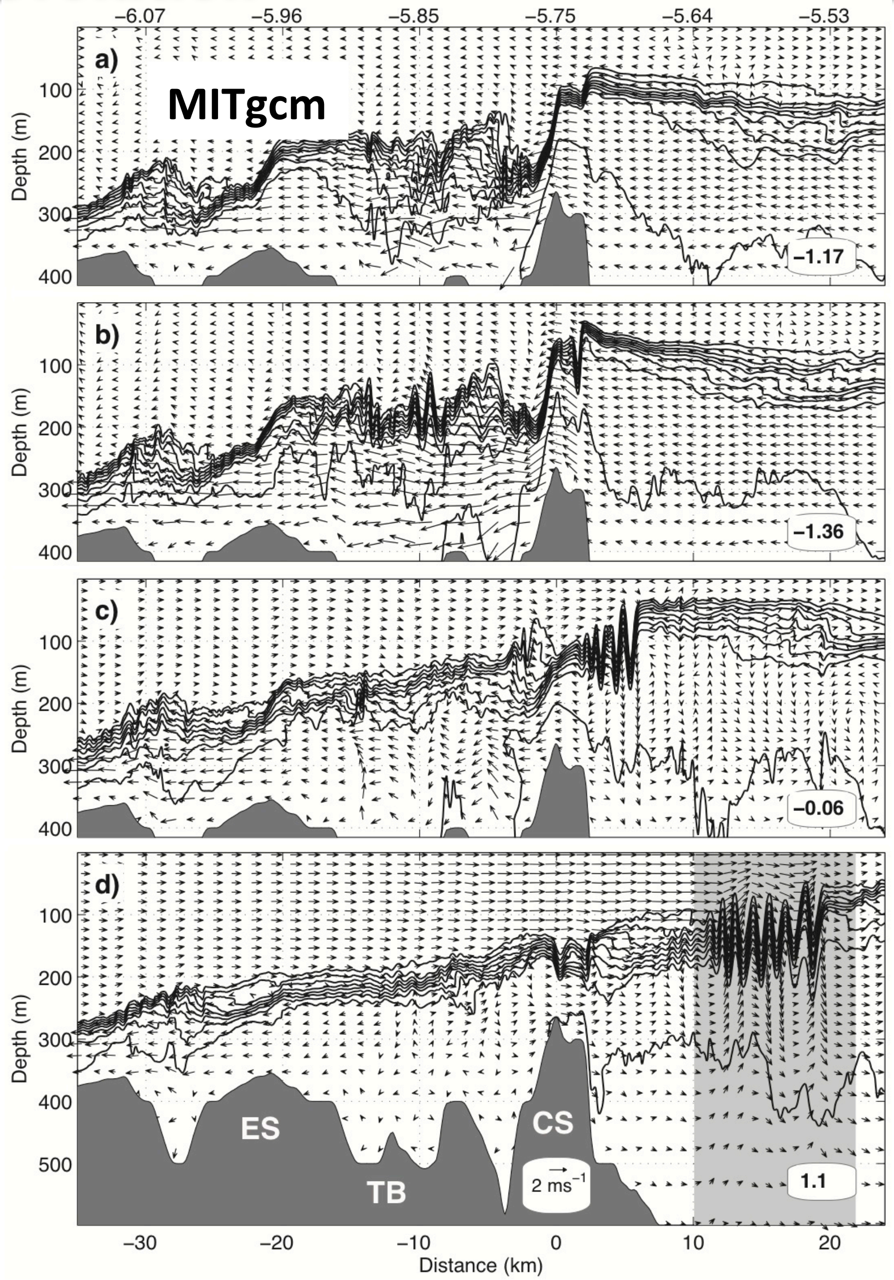
Horizontal velocity
(m/s)

Vertical velocity
(m/s)



MITgcm vs POM – Internal bore evolution





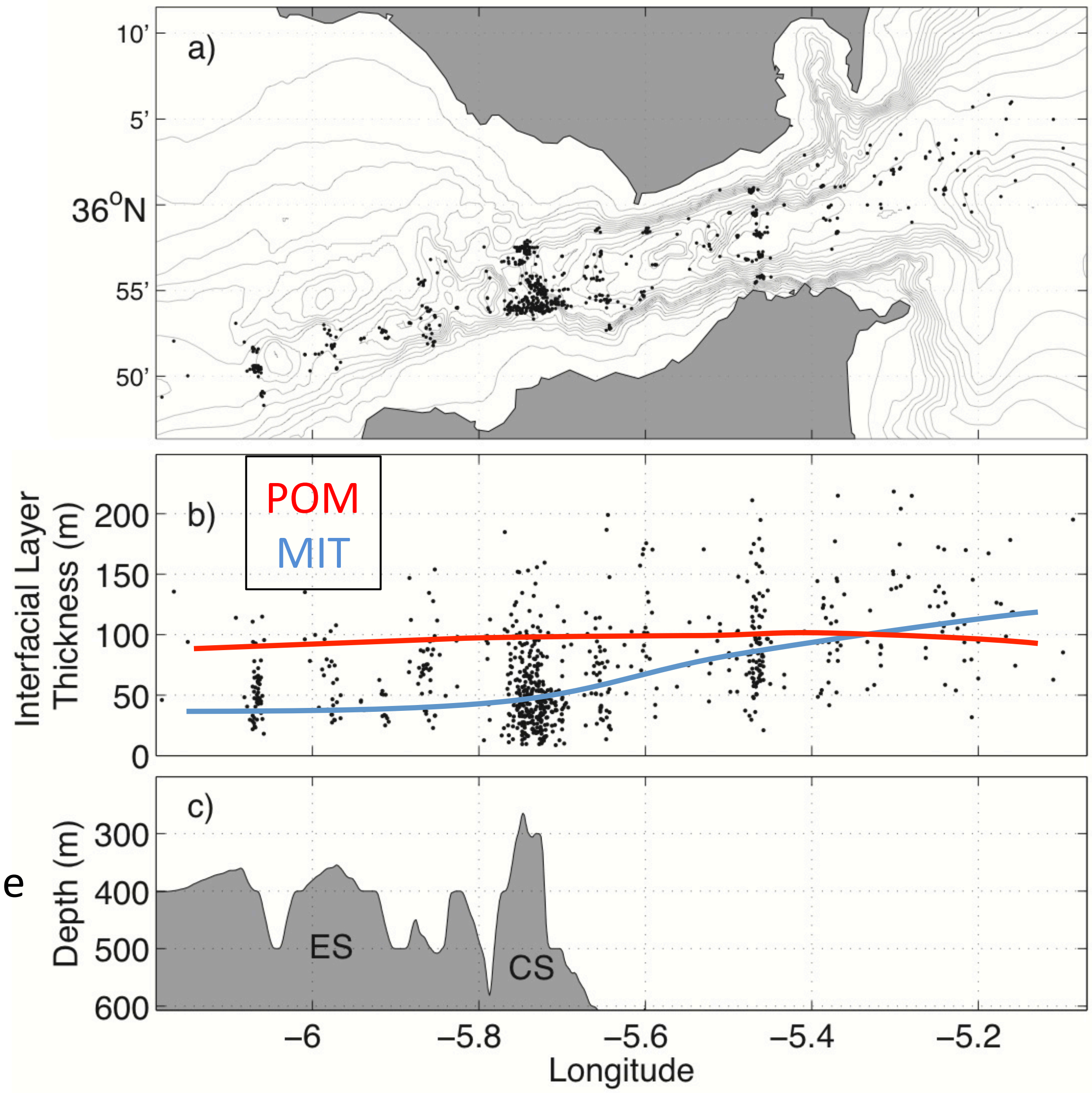
Garrido et al. jgr 2011

Observed interface layer thickness

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

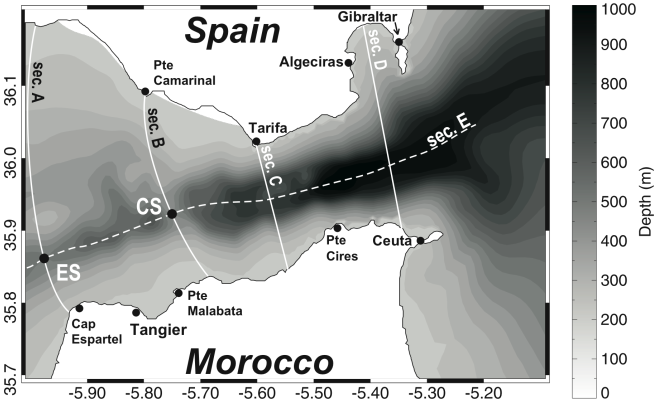
b) Interface layer thickness computed from CTD data.

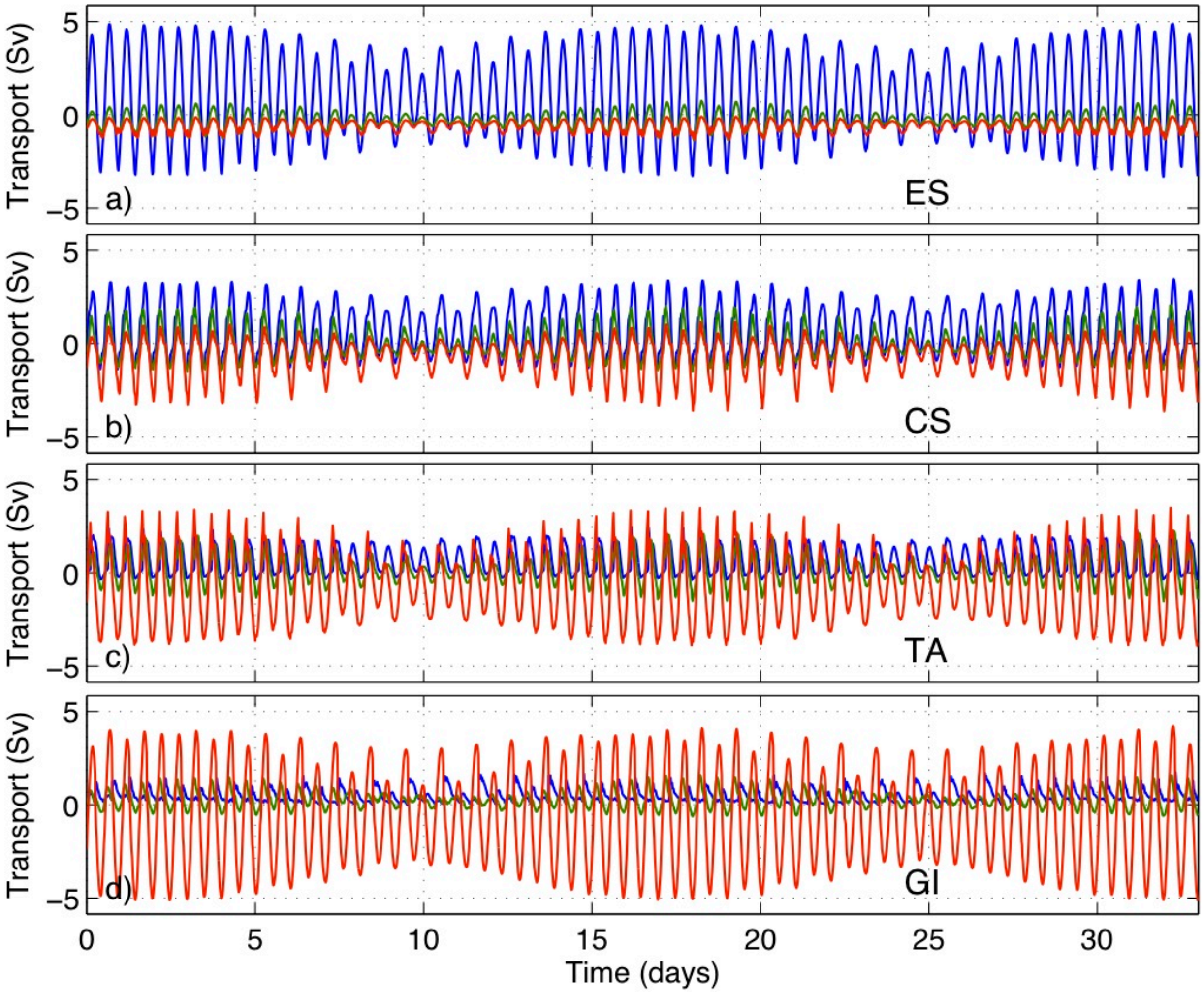
c) Bottom topography along the central axis of the Strait.



MITgcm 3-Layer transports

Atlantic layer
Interface layer
Mediterranean layer

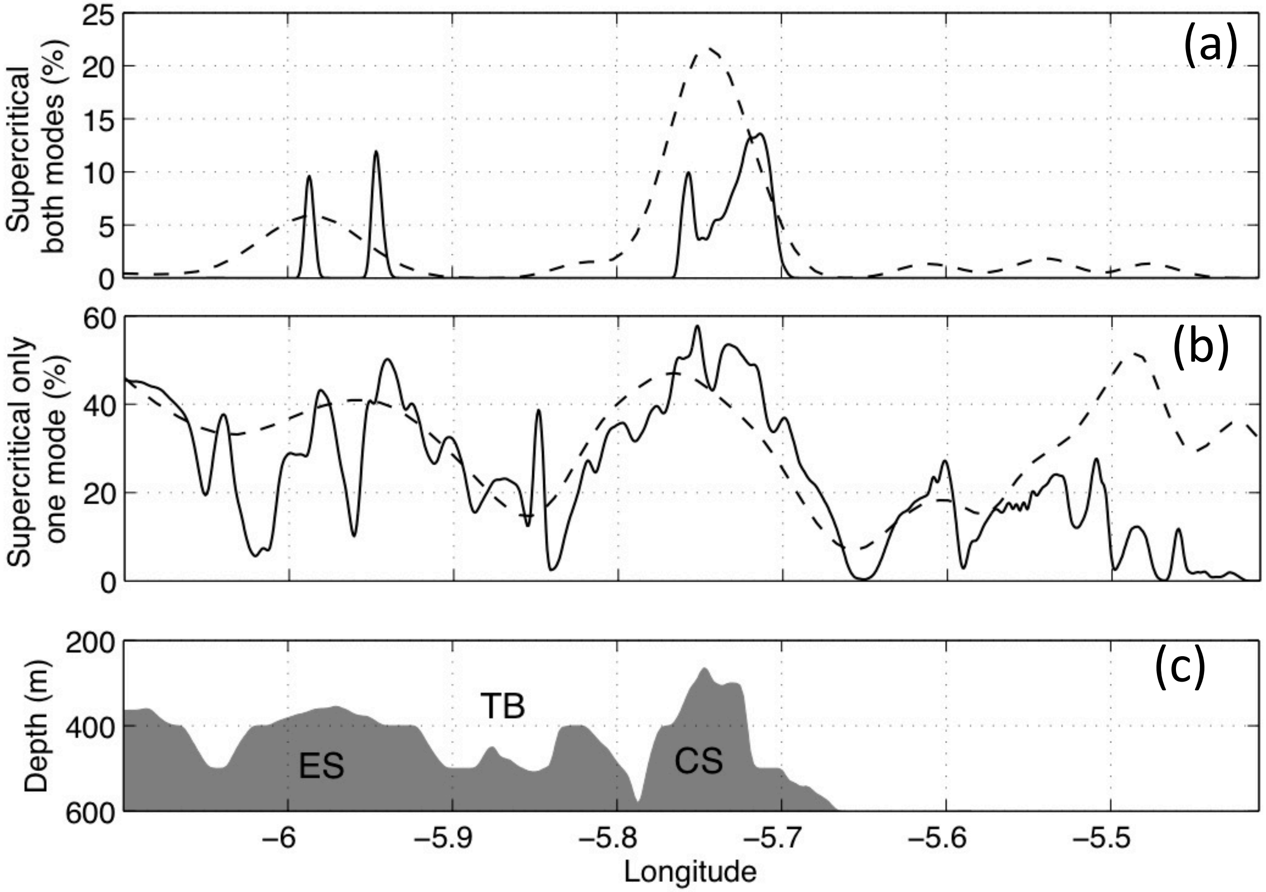




Time-dependent Atlantic layer (blue line), interfacial layer (green line), and Mediterranean layer (red line) volume transports at (a) Espartel Sill, (b) Camarinal Sill, (c) Tarifa (TA) and (d) Gibraltar (GI), respectively sec. A, sec. B, sec. C and sec. D.

MITgcm vs POM alongstrait hydraulics

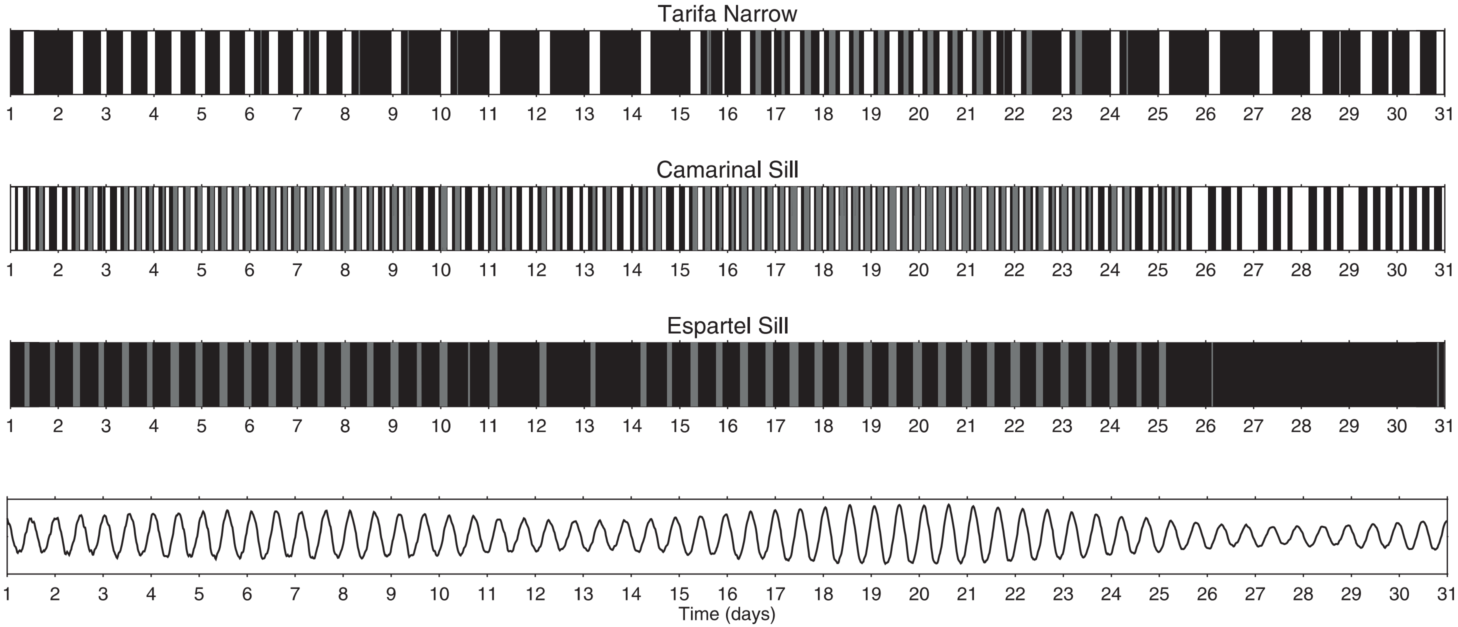
Frequency of occurrence, over the tropical month period, of supercritical flow with respect to one mode (a) and both modes (b) along the Strait as obtained by POM (dashed line) and MITgcm (solid line).



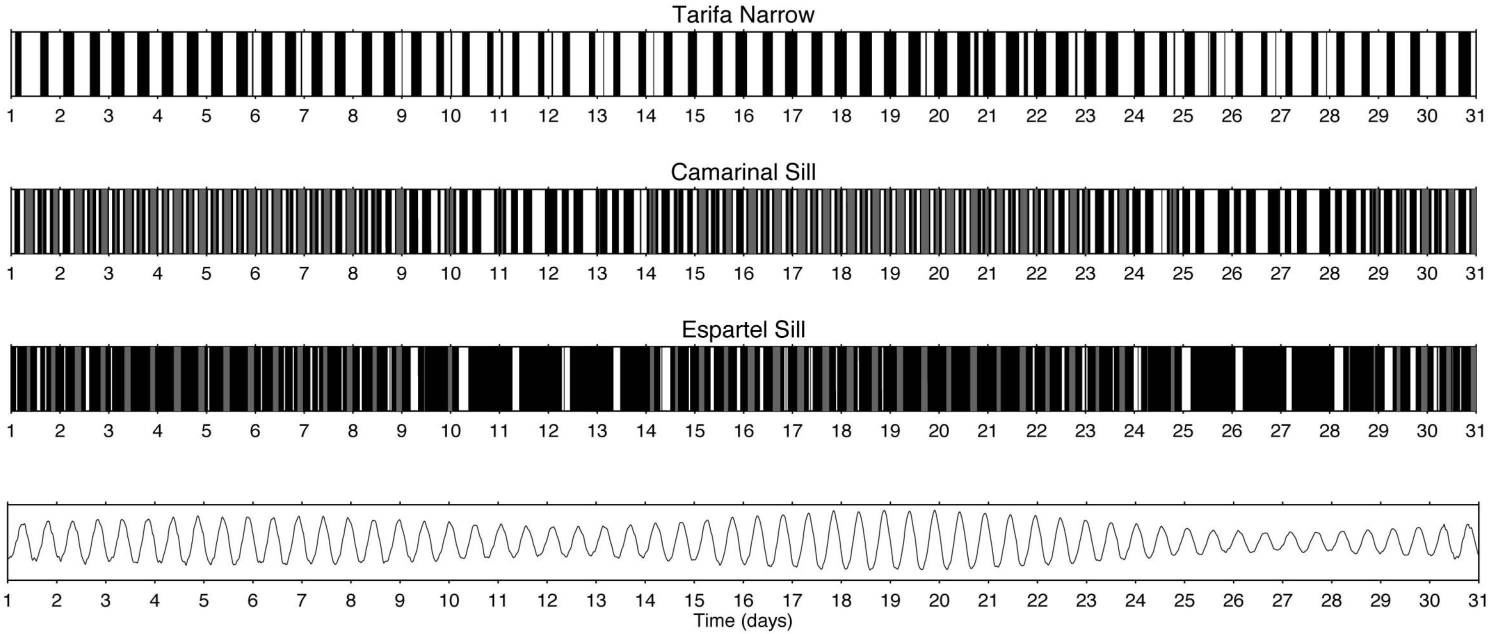
MITgcm displays a marked along-strait variability associated to the finer description of the bathymetry. Moreover when both modes are supercritical (a), MITgcm predicts lower values all along the Strait with respect to POM, except for ES where on the contrary MITgcm exceeds POM. When the flow is supercritical 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

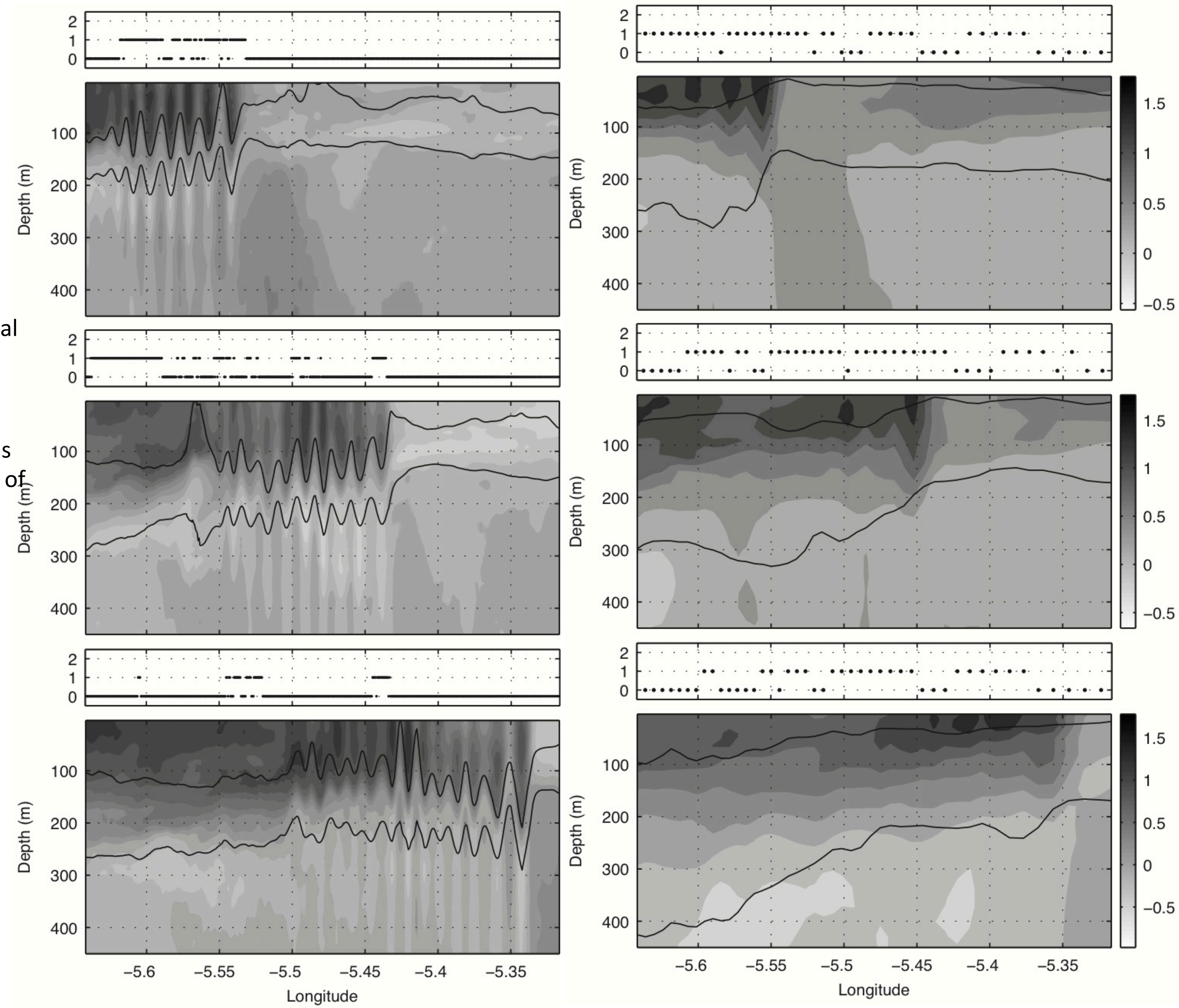


MITgcm

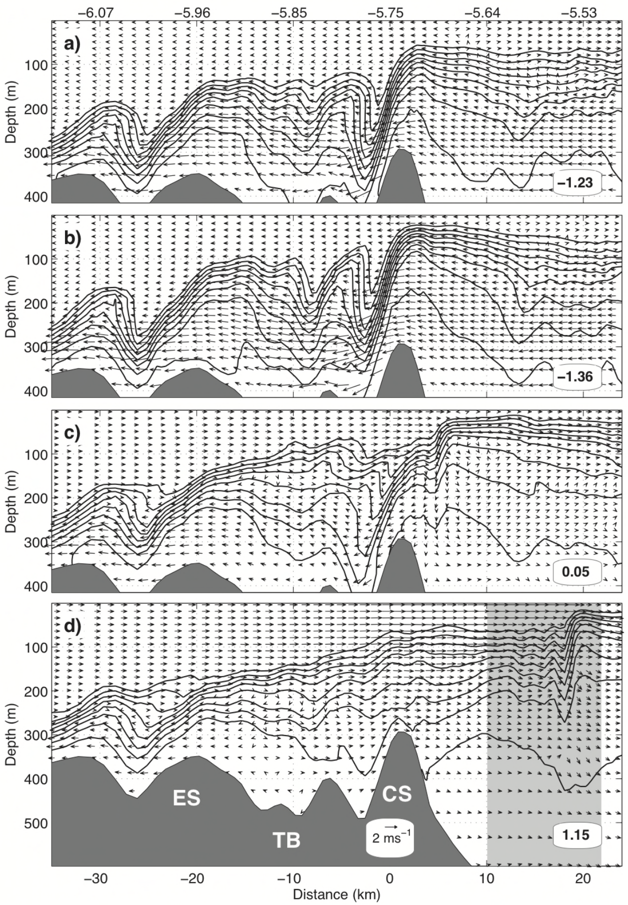


MITgcm vs POM alongstrait hydraulics & bore propagation

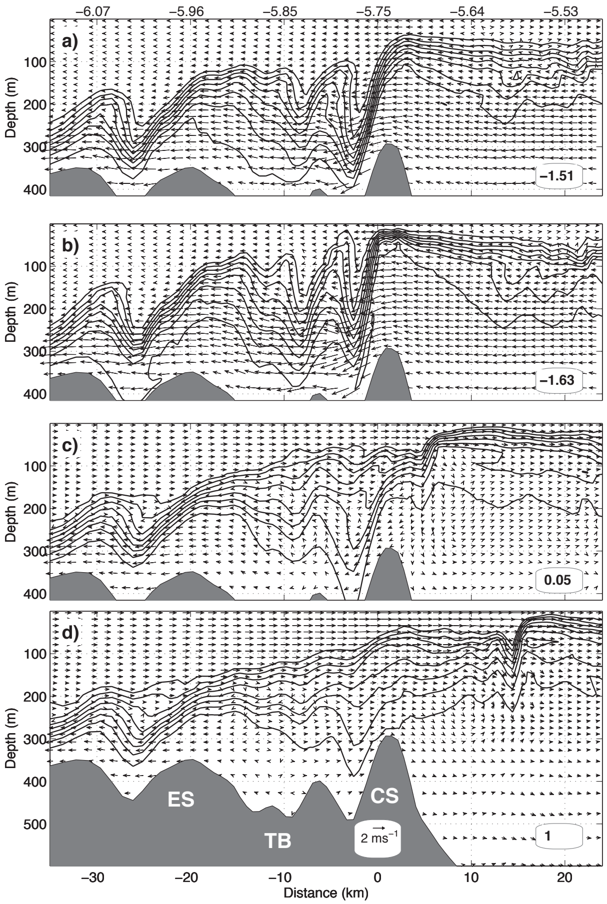
Evolution of the horizontal velocity field along longitudinal Sectionin the middle of the Strait during the arrival of an interval wave train to TN. Elapse time between frames is 1.33 hours. Panels on the top of each frame indicate the flow criticality; zero: subcritical flow; one: only one internal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



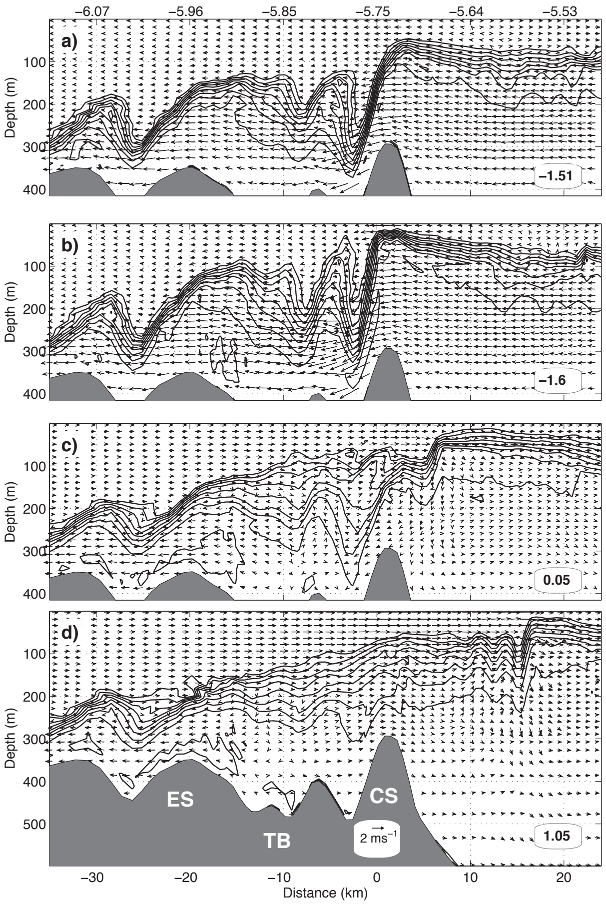
Sensitivity - POM alongstrait hydraulics & bore propagation



Original

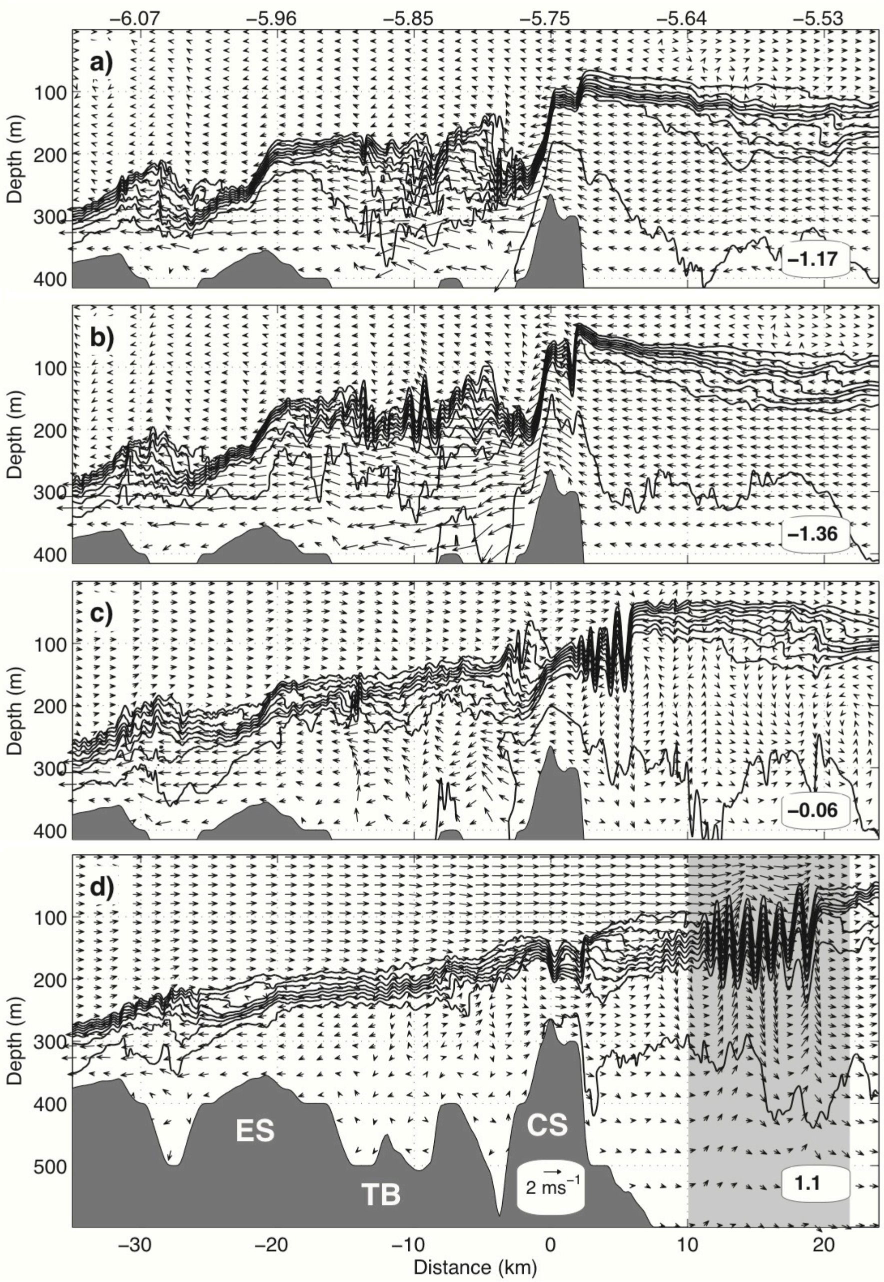


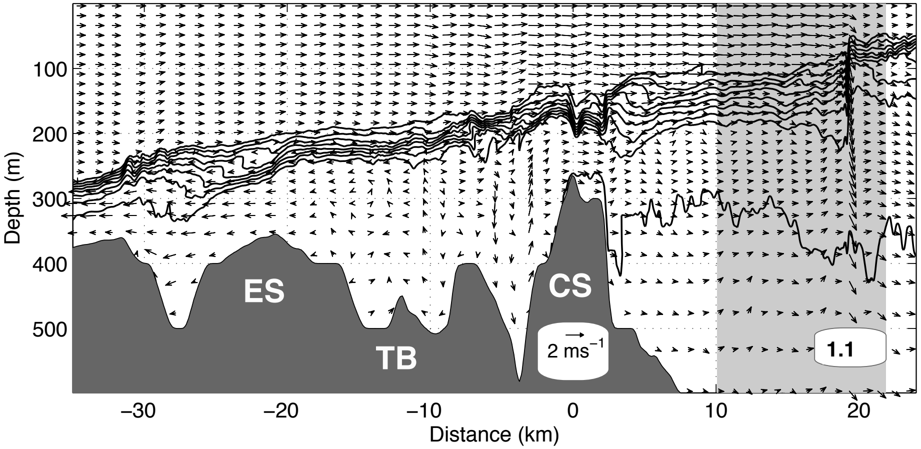
KH=0



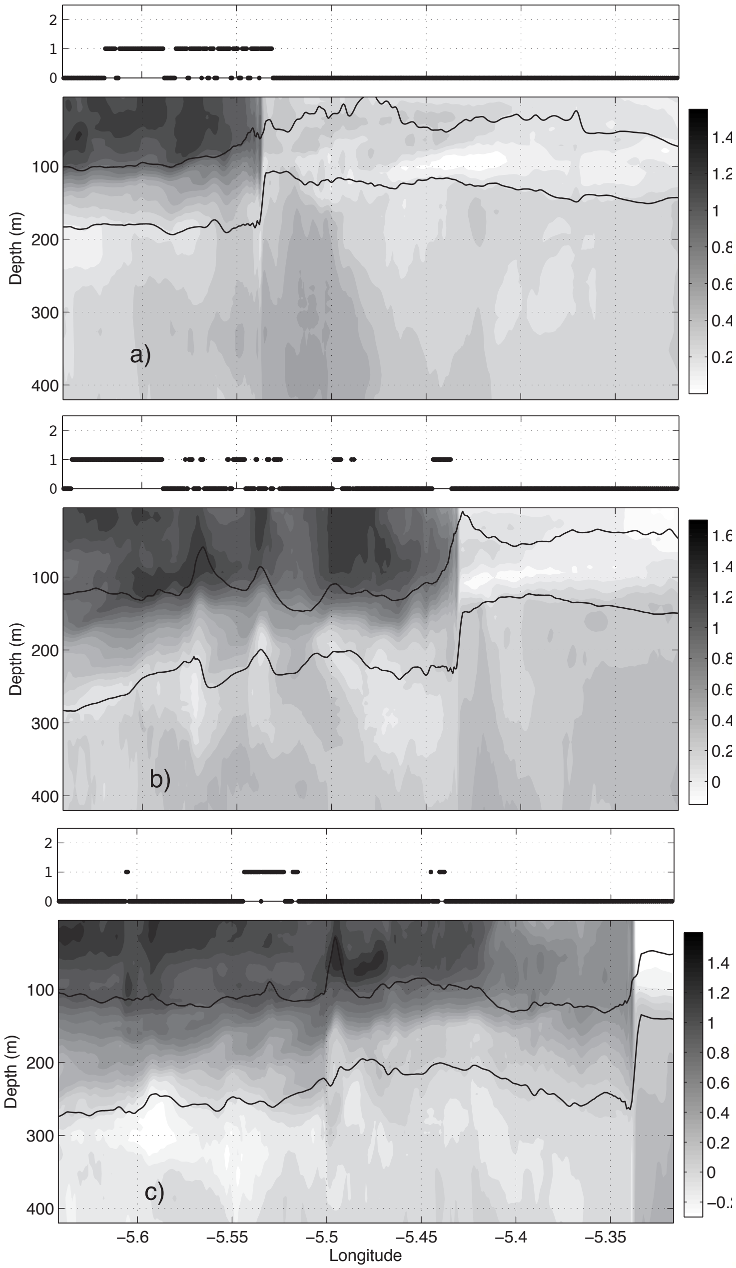
KH=0
TPRNI=0

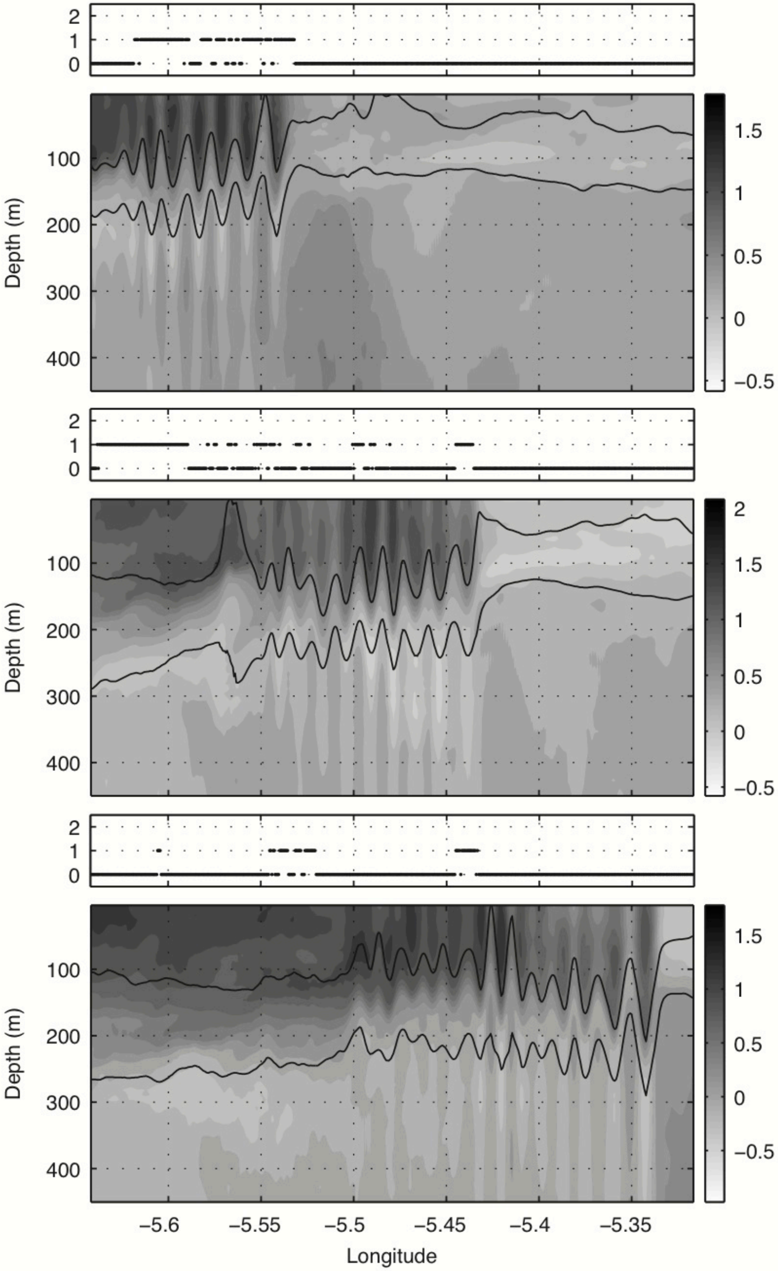
MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



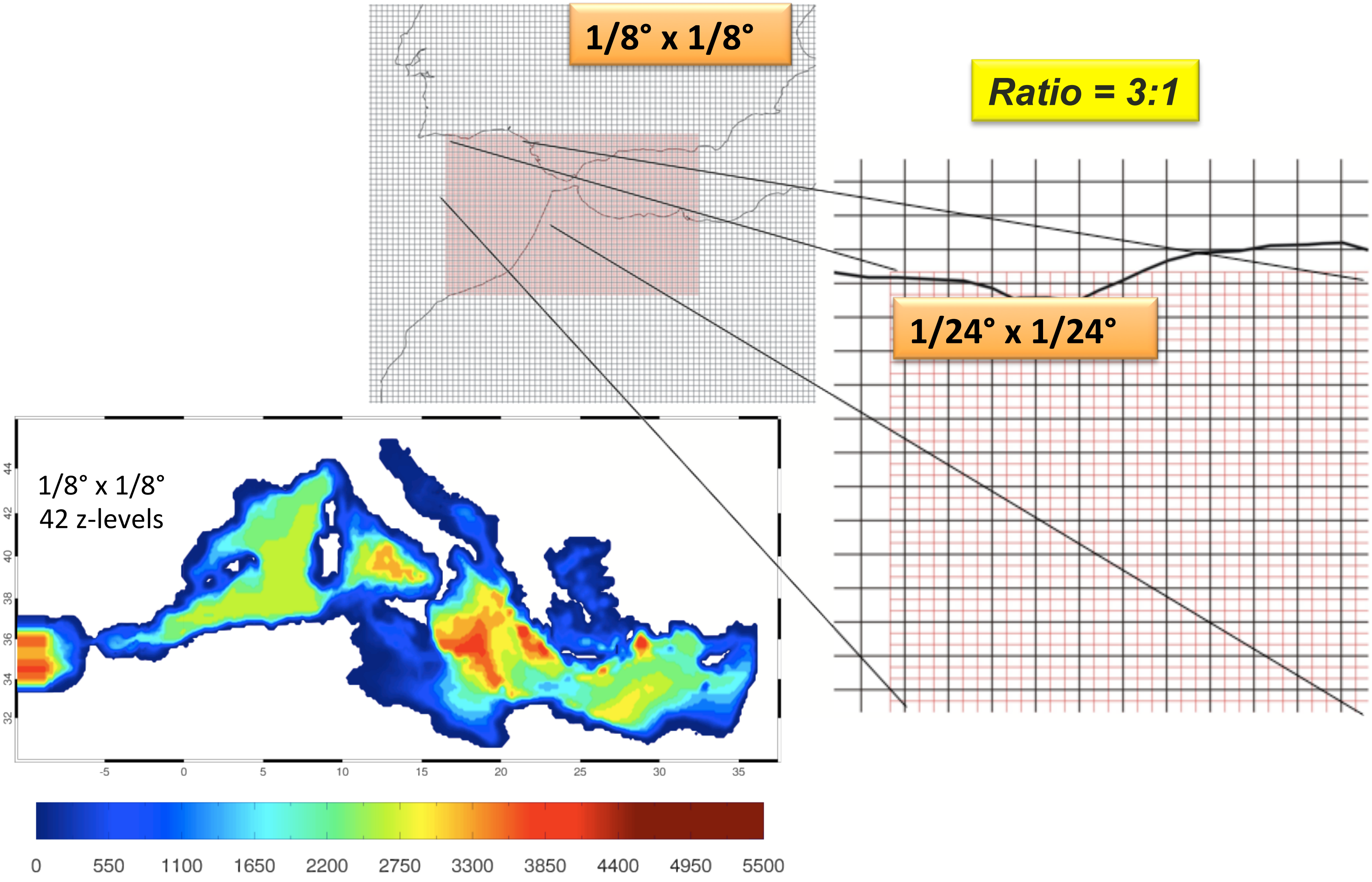


MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



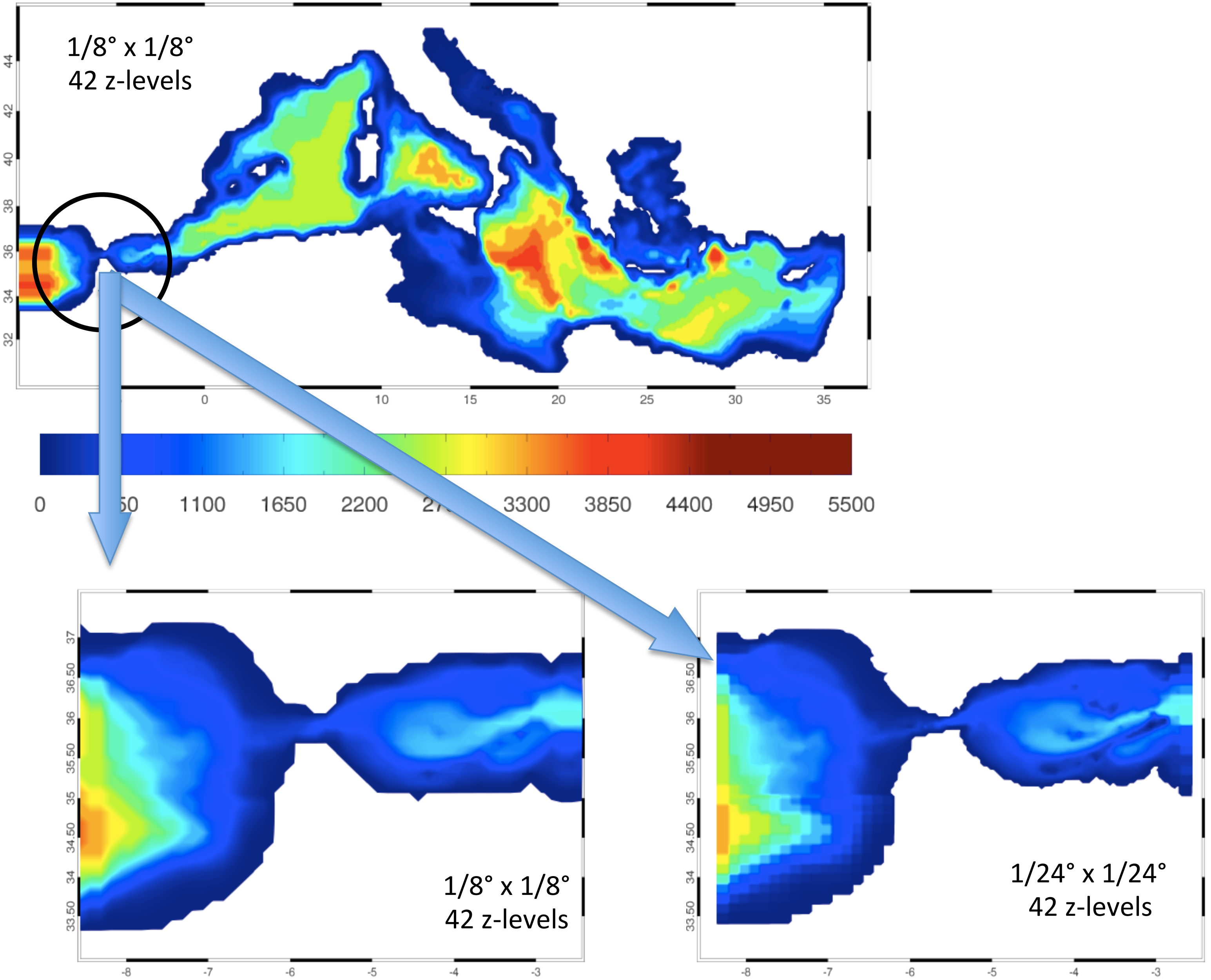


Effects of high resolution at Gibraltar in a 1/8° Mediter. model

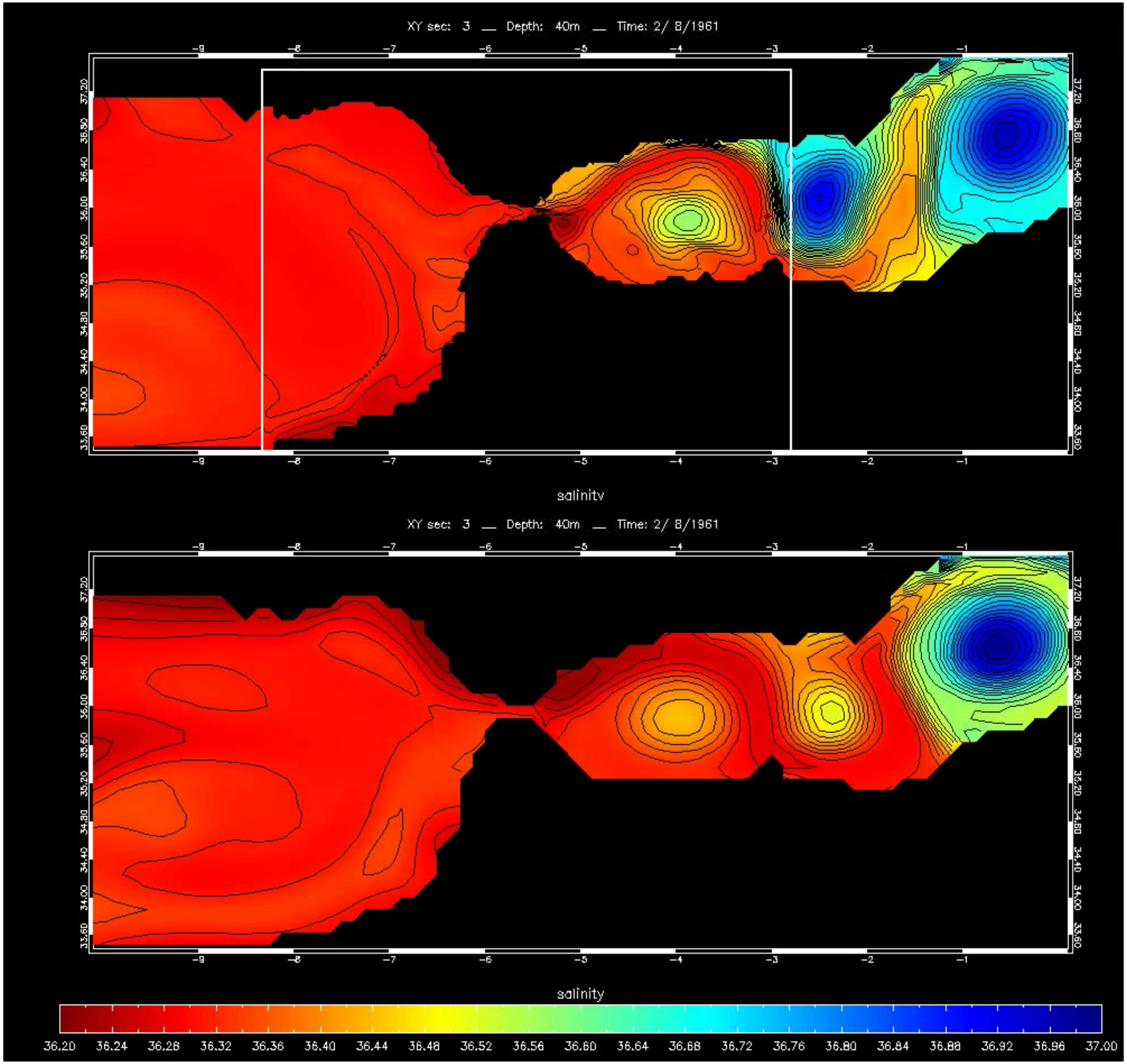


Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean. Modeling

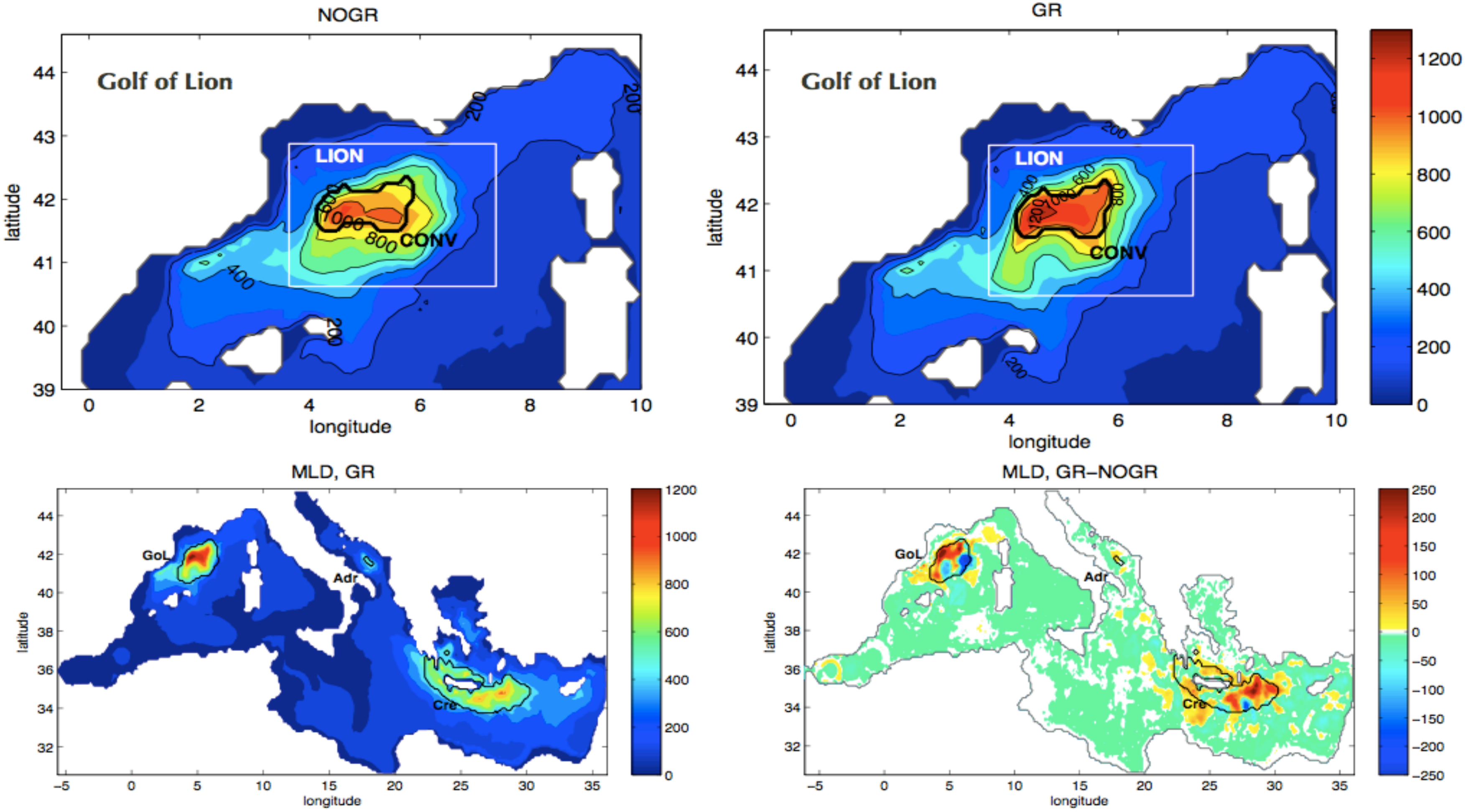
Effects of high resolution at Gibraltar in a 1/8° Mediter. model



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



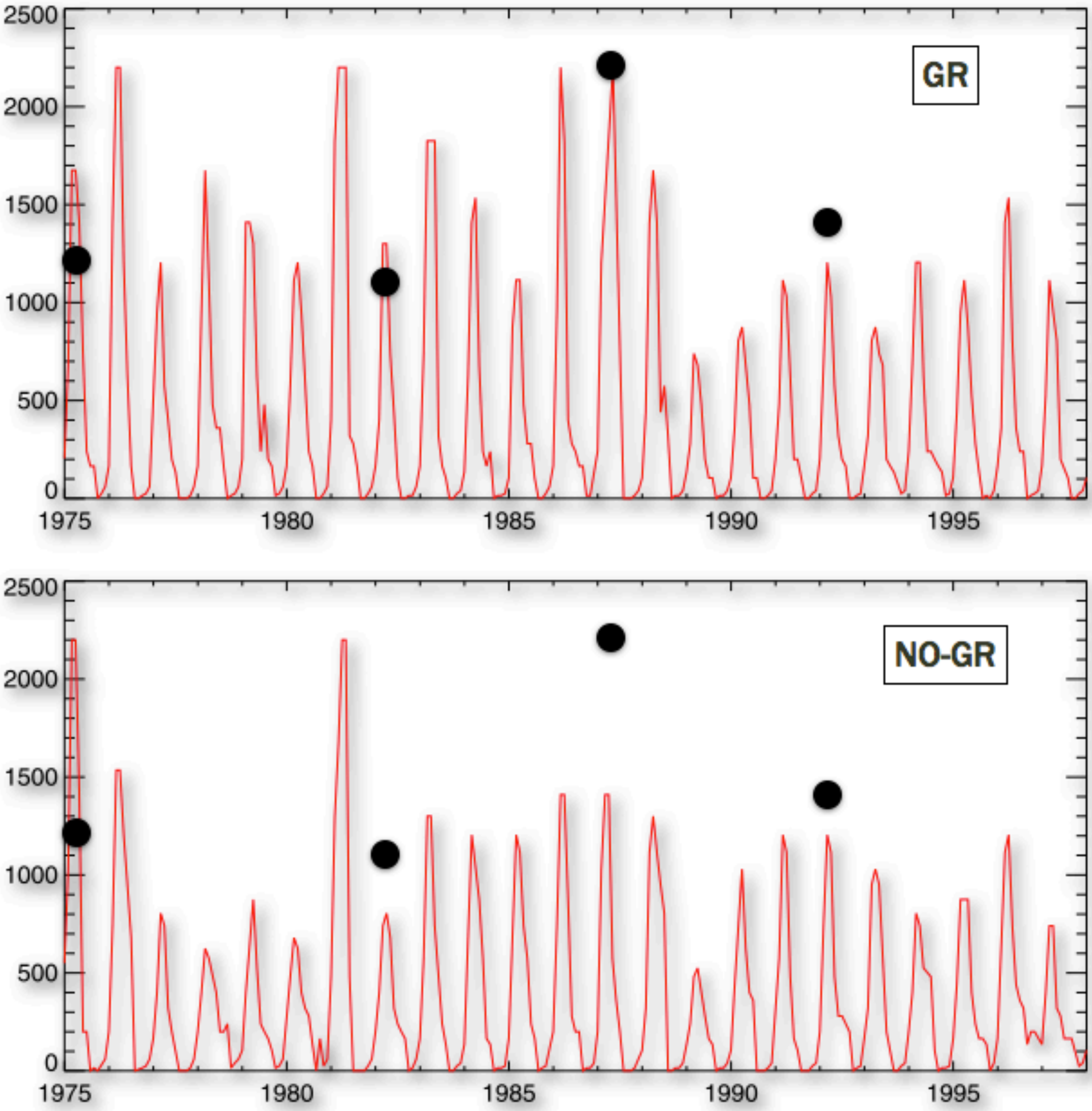
Effects of high resolution at Gibraltar in a 1/8° Mediter. model

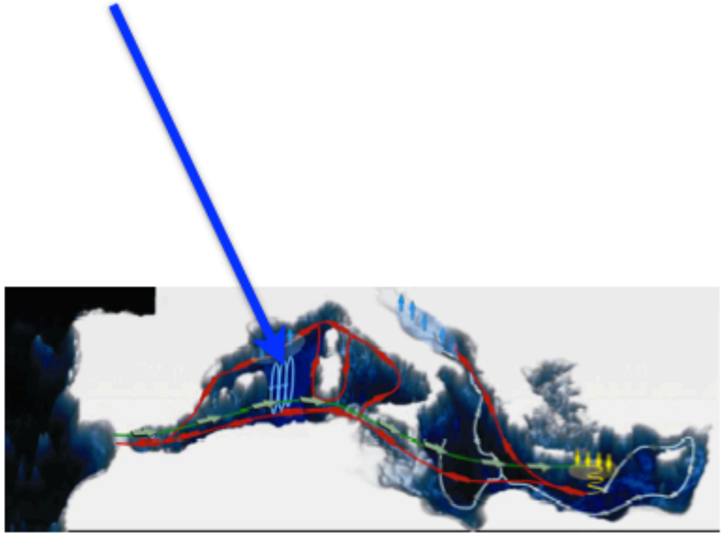


Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean Modeling

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

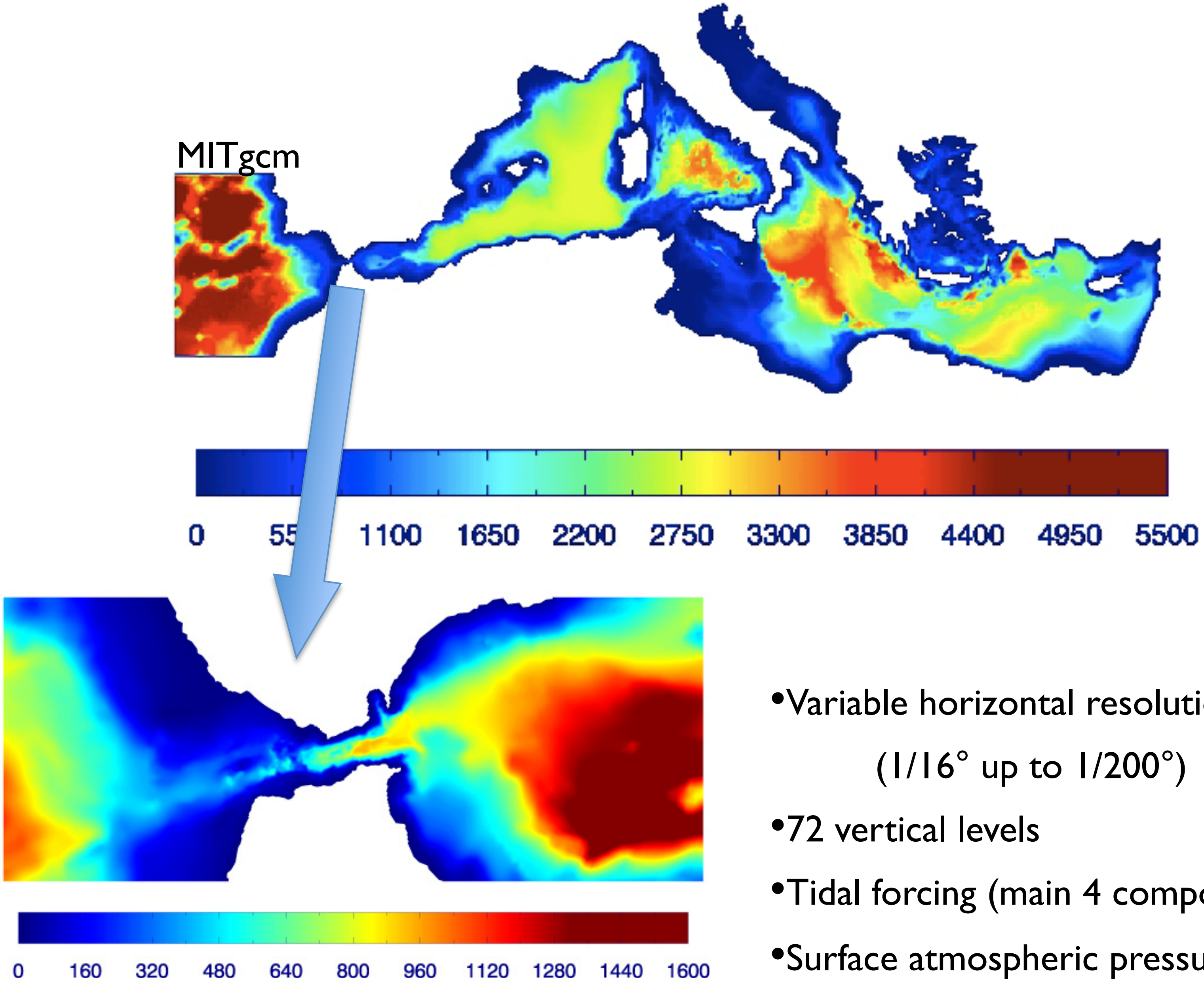
Convection depth in the Gulf of





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

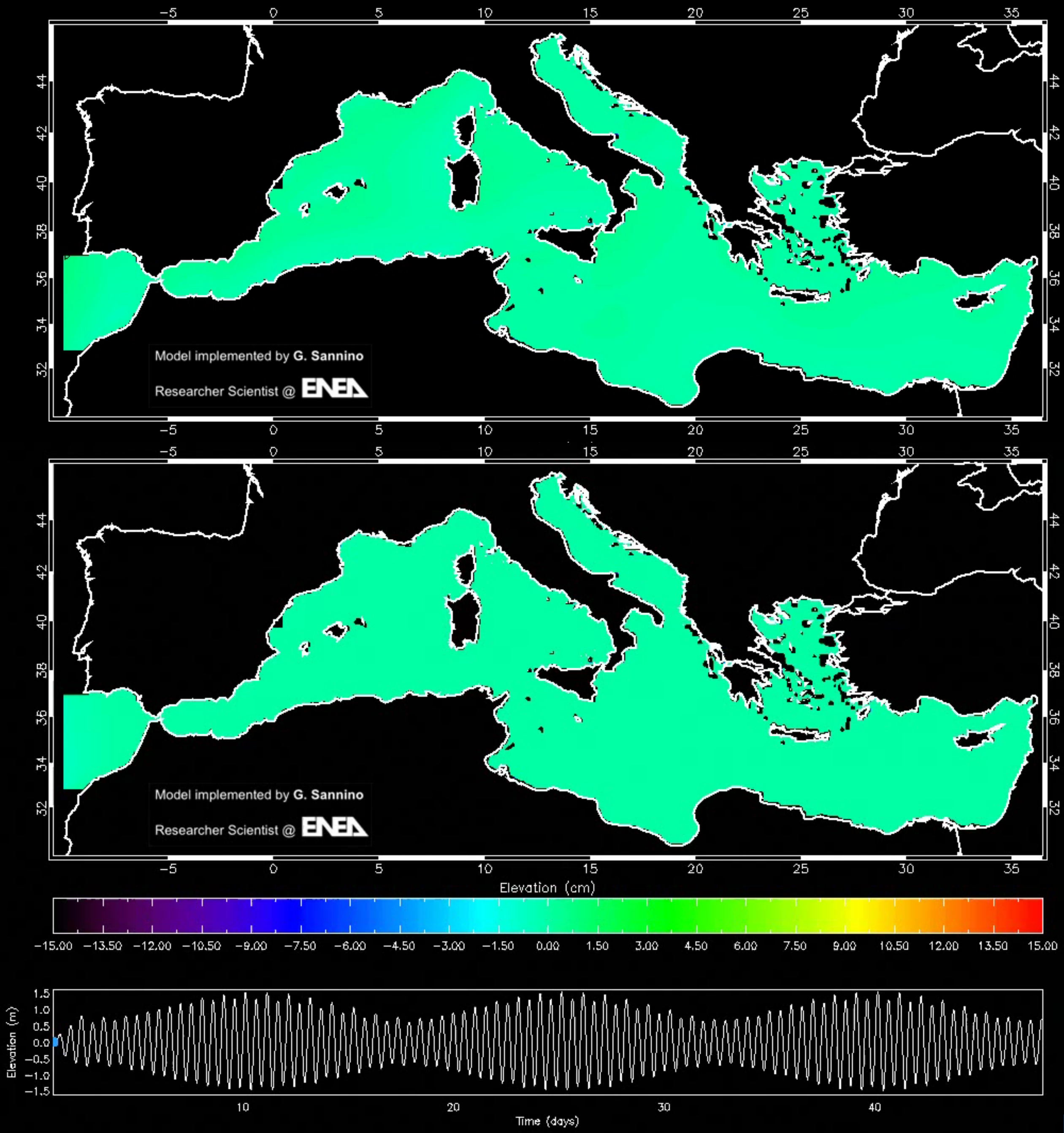
New modeling strategy for the Med.



- Variable horizontal resolution

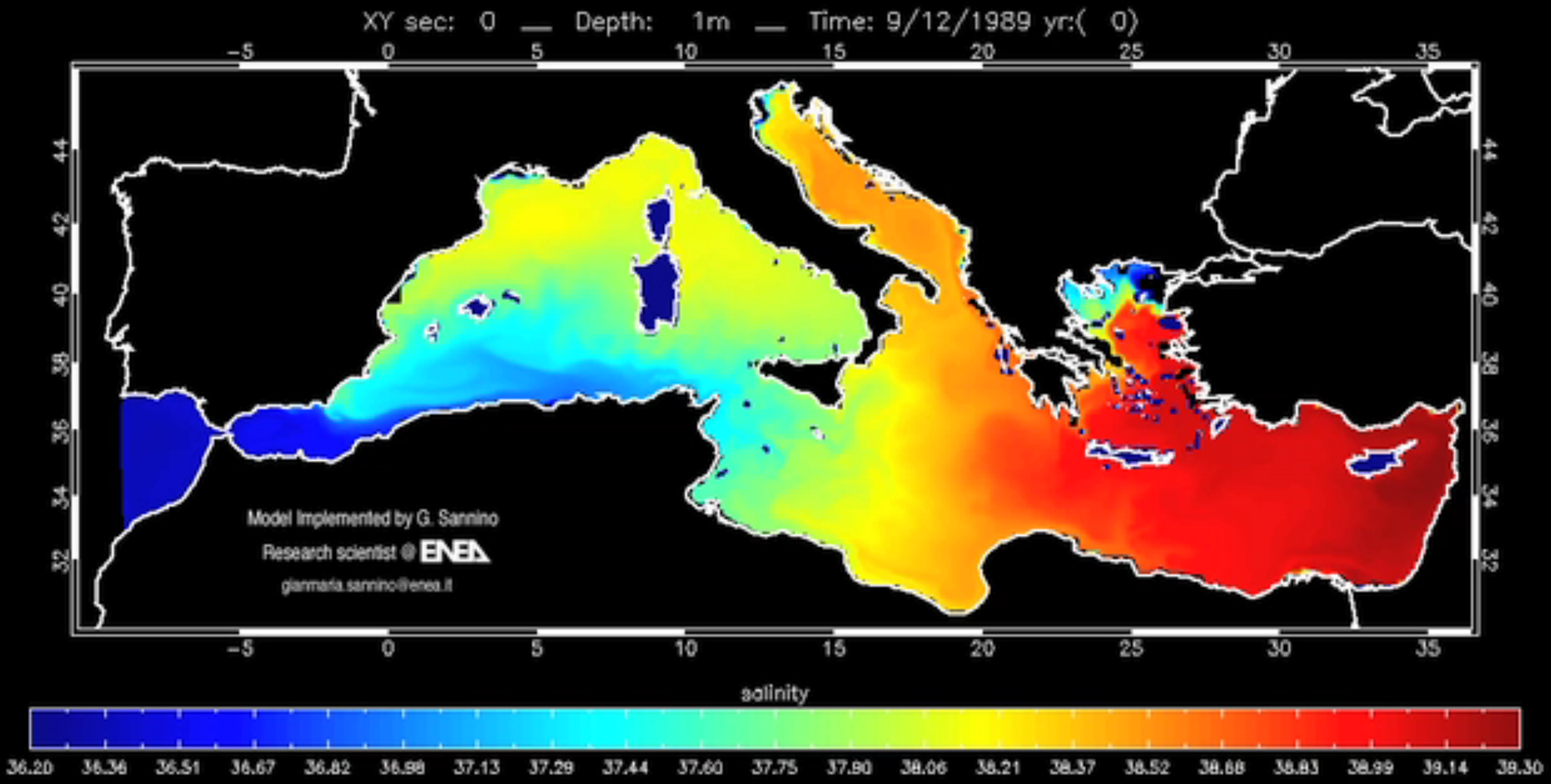
  (1/16° up to 1/200°)
- 72 vertical levels
- Tidal forcing (main 4 components)
- Surface atmospheric pressure

New modeling strategy for the Med.



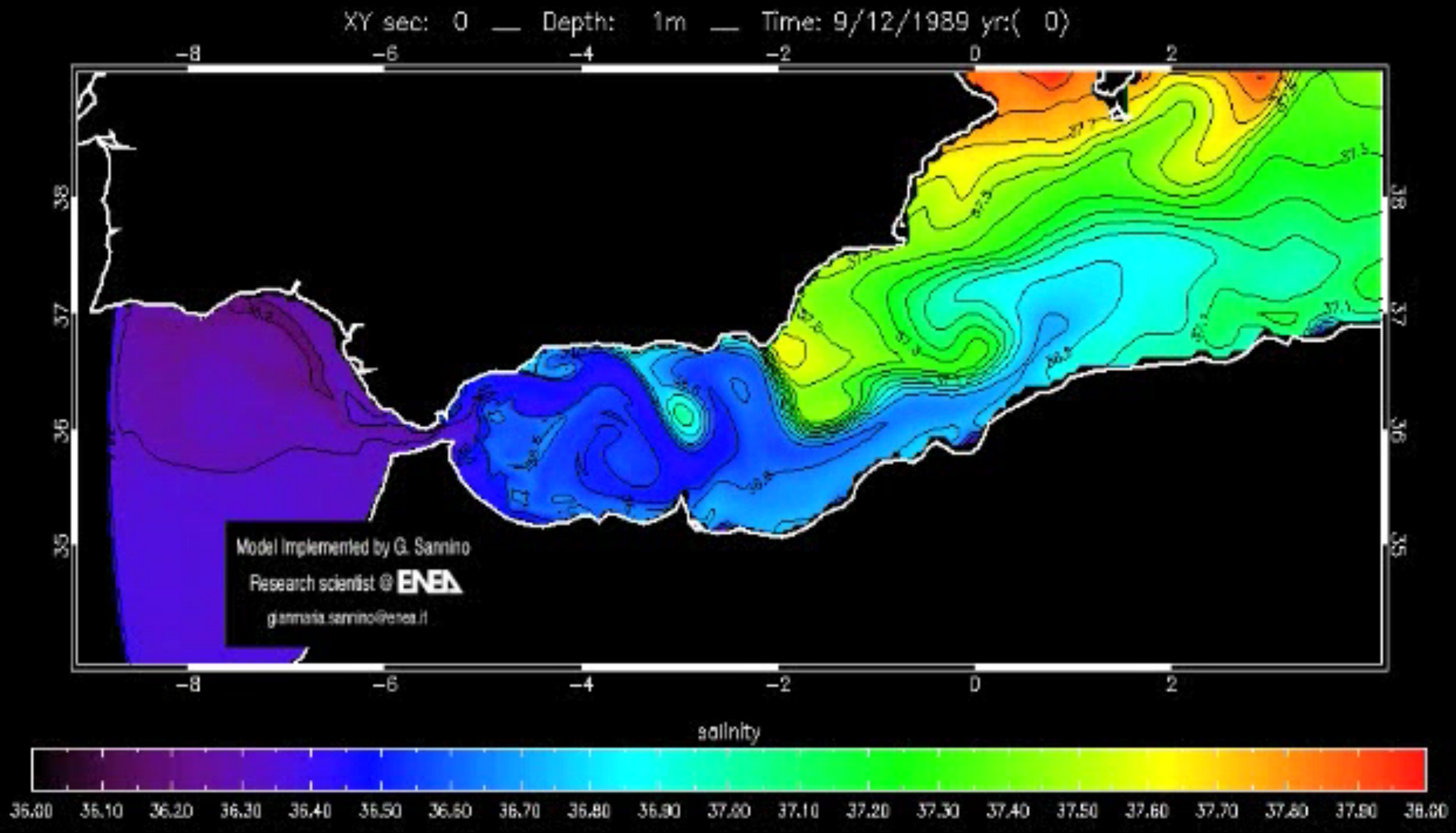
CINECA
ISCRA GRANT

New modeling strategy for the Med.



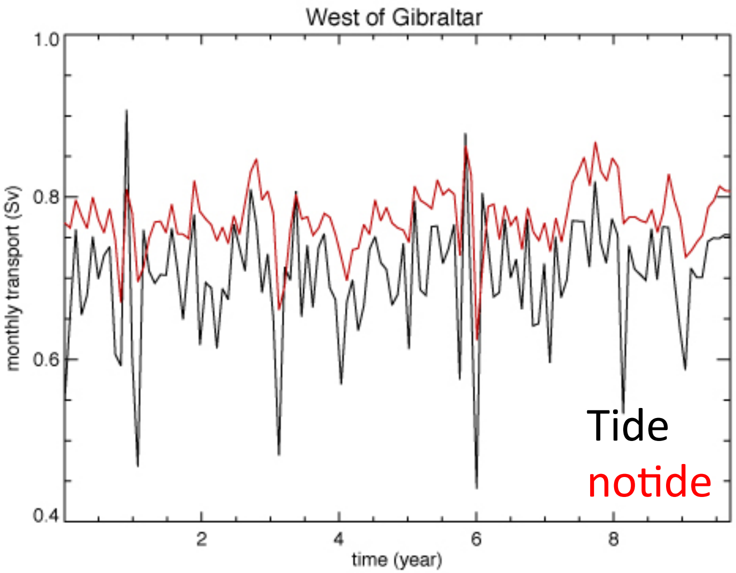
CINECA
ISCRA GRANT

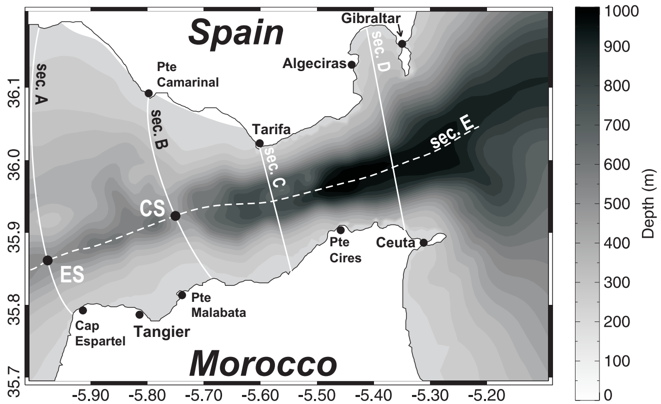
New modeling strategy for the Med.

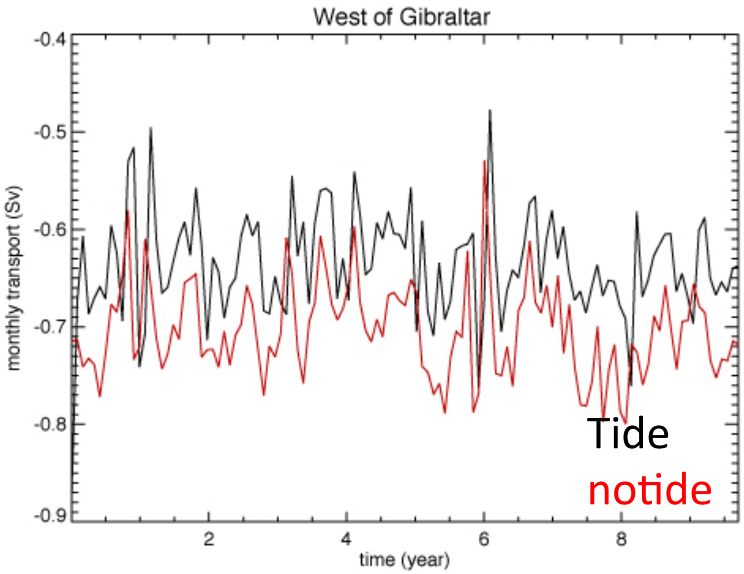


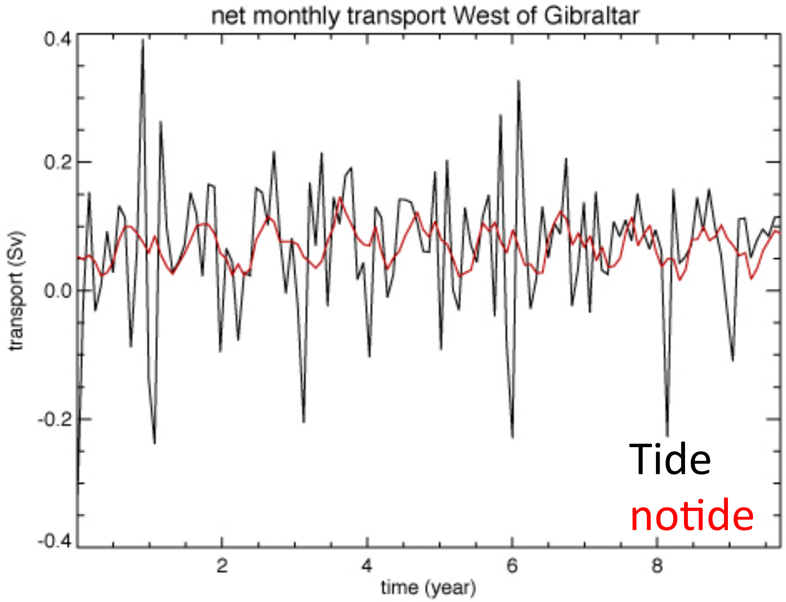
New modeling strategy for the Med.

Transports through the Strait

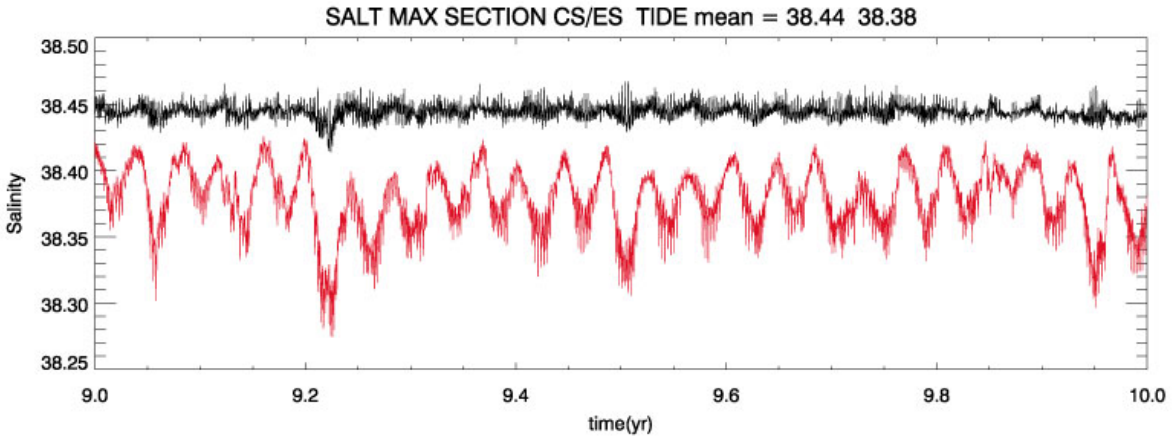


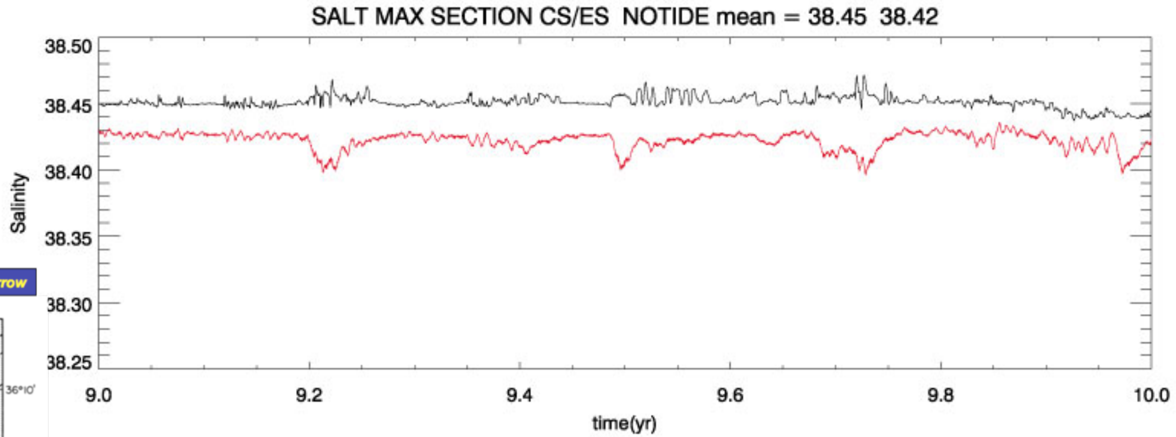






New modeling strategy for the Med.





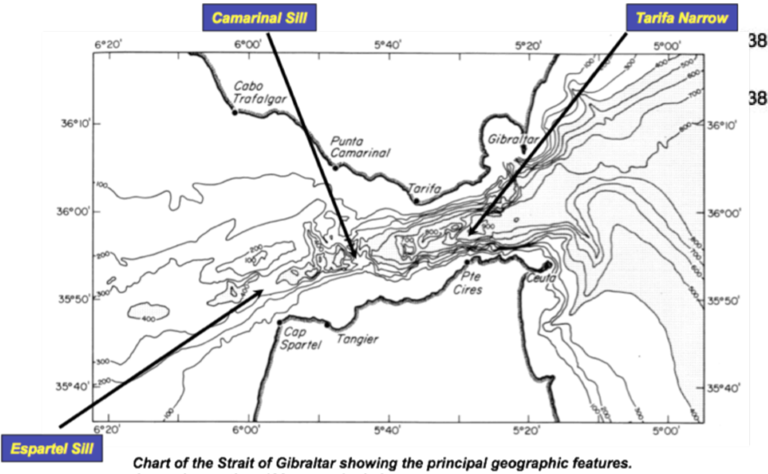
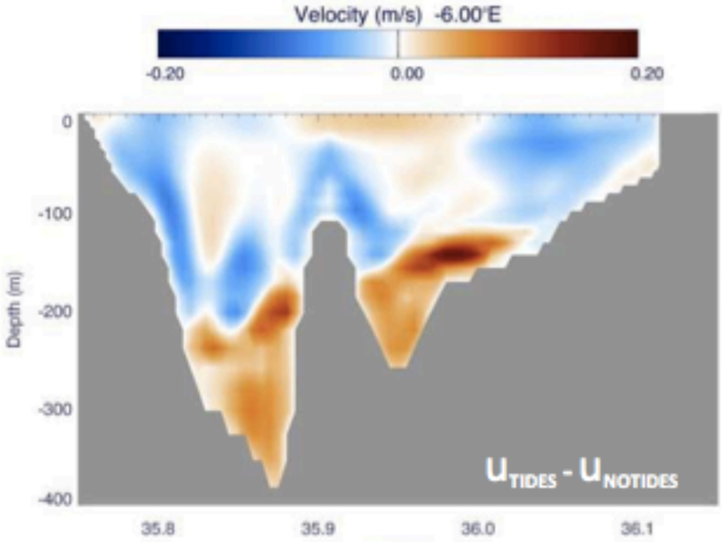
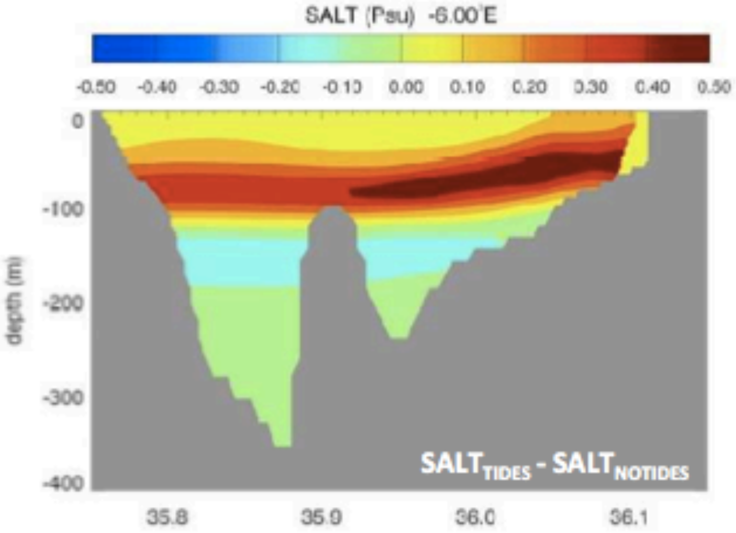
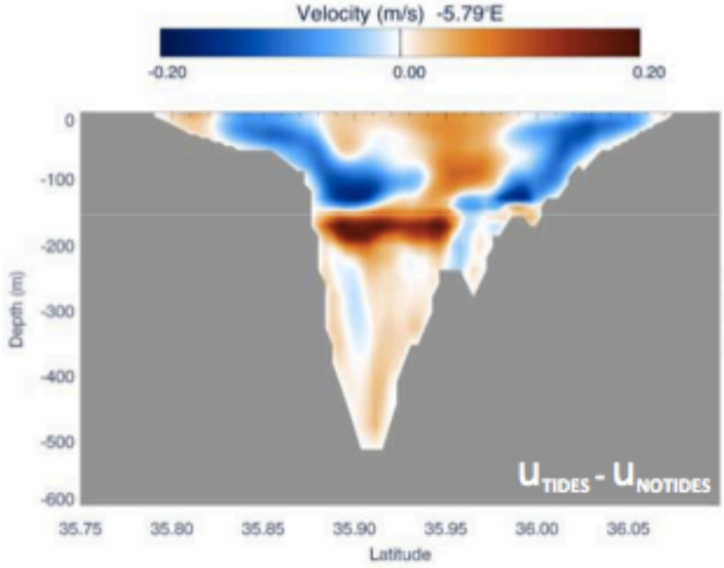


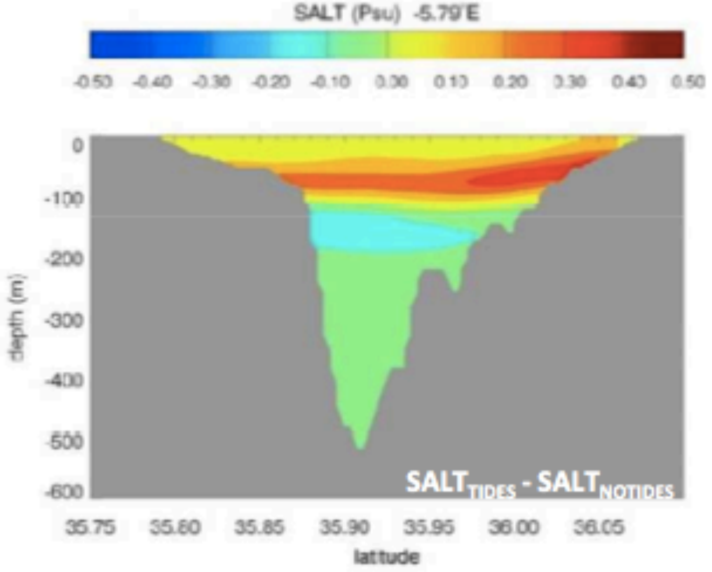
Chart of the Strait of Gibraltar showing the principal geographic features. Areas deeper than 400 m are shaded

New modeling strategy for the Med.

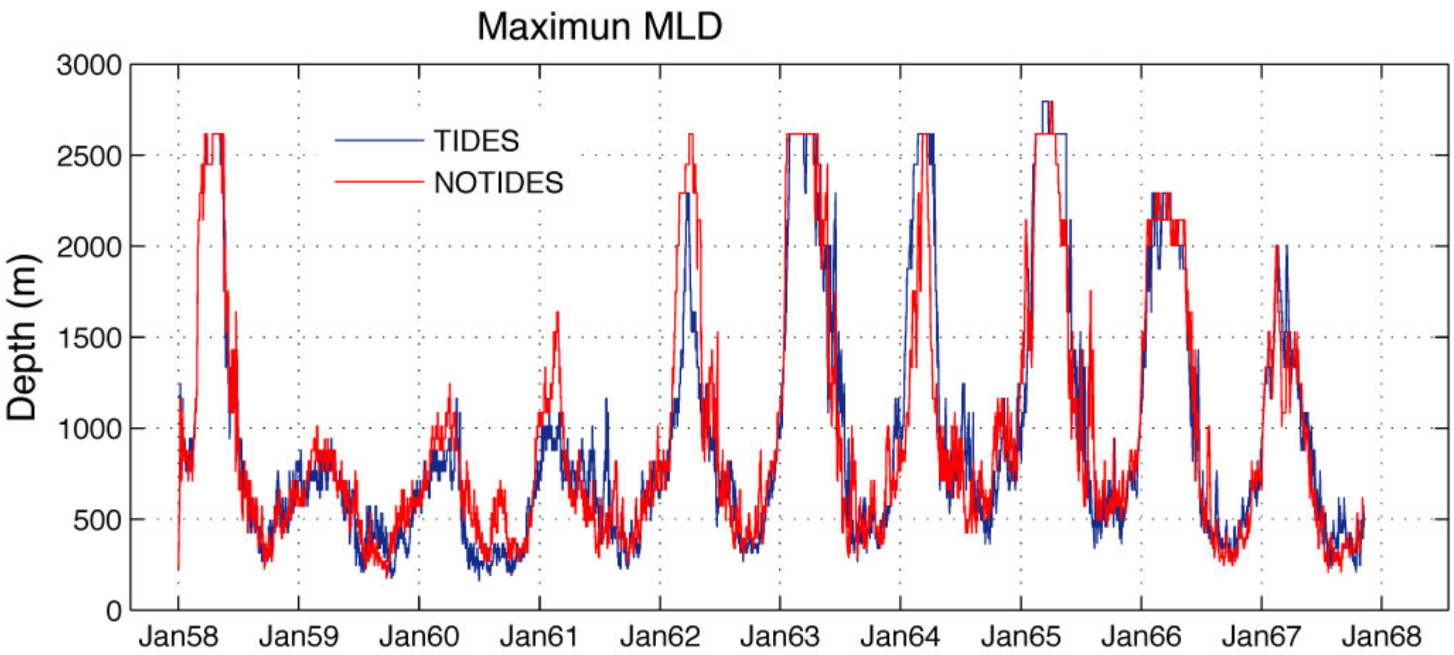


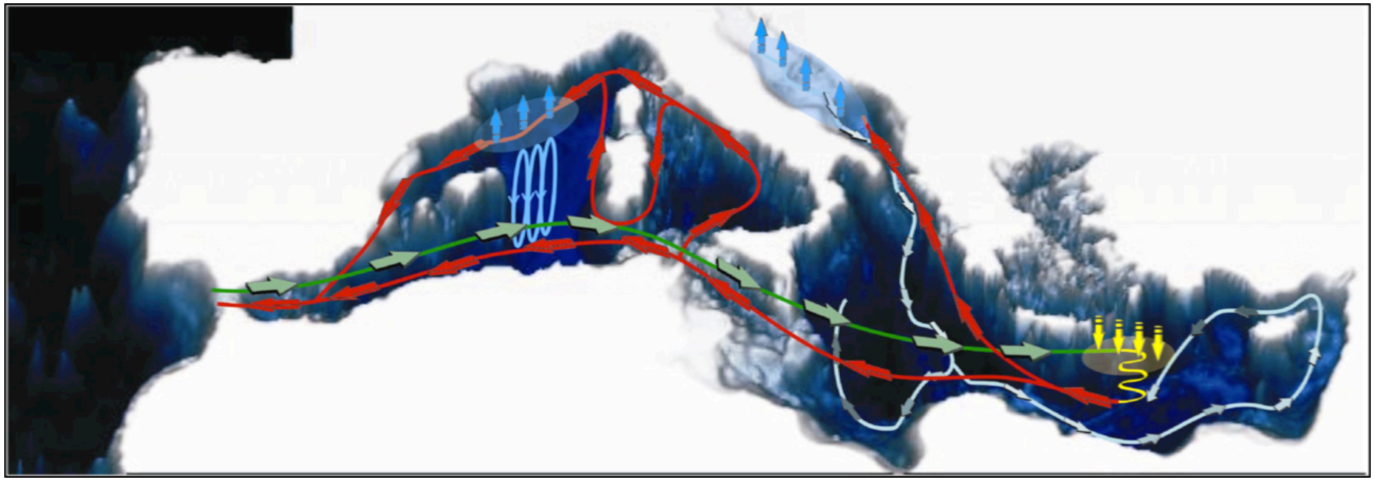


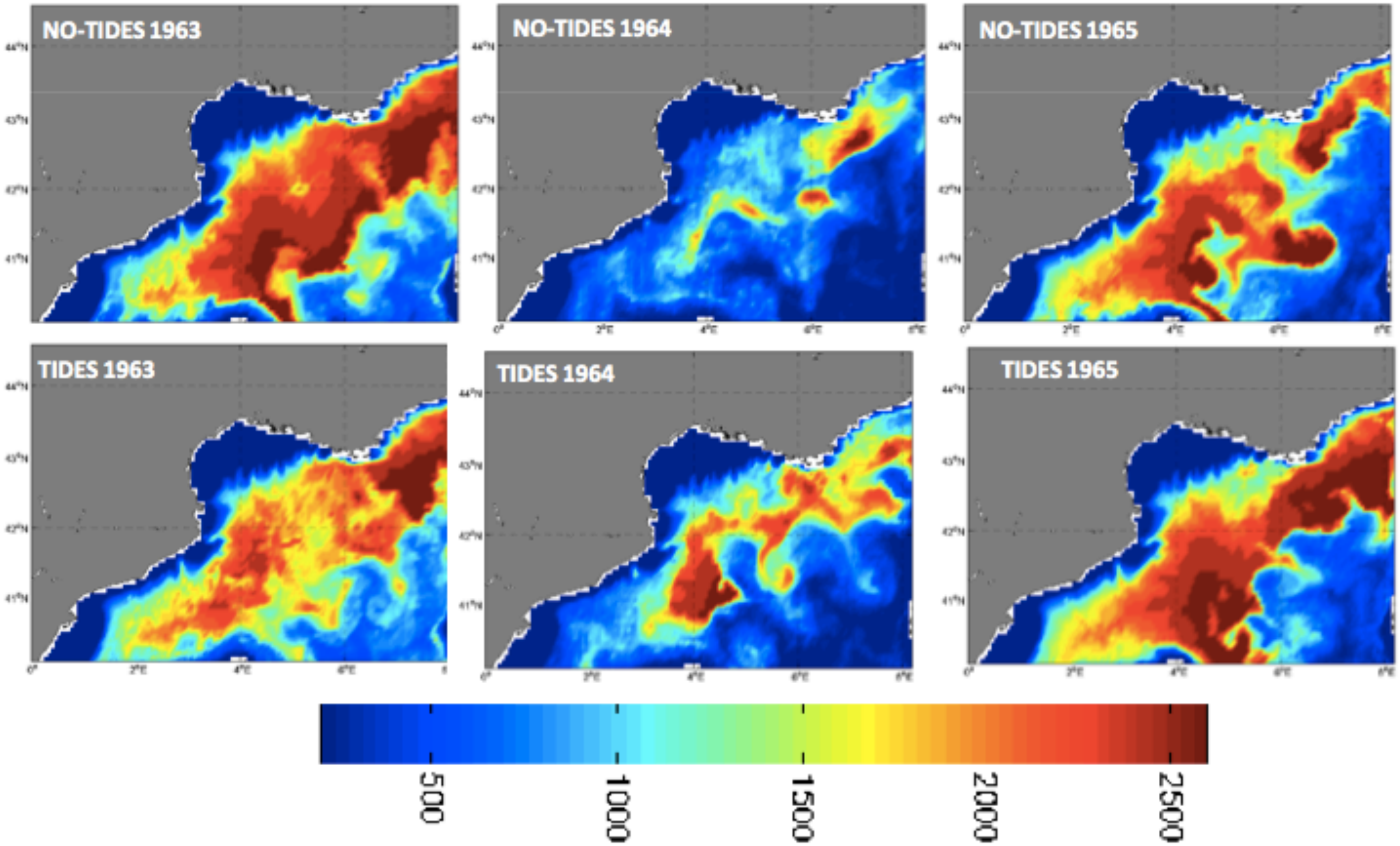




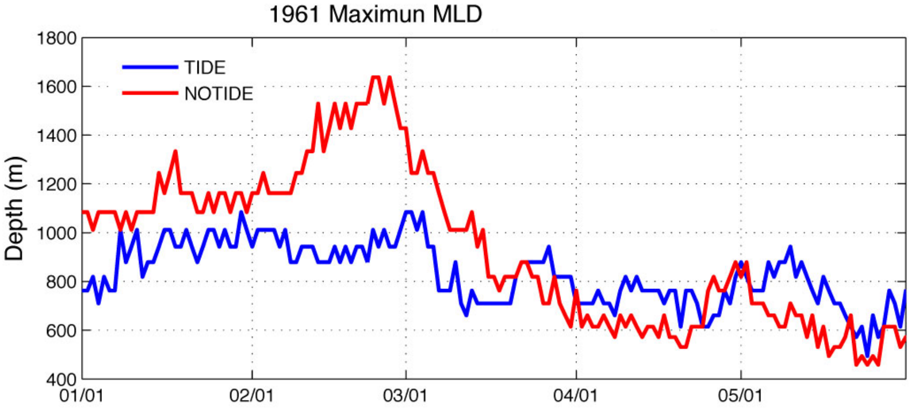
New modeling strategy for the Med.

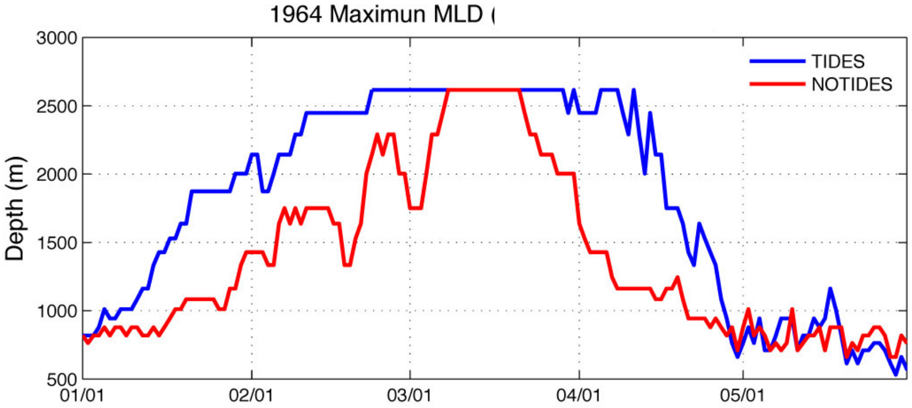


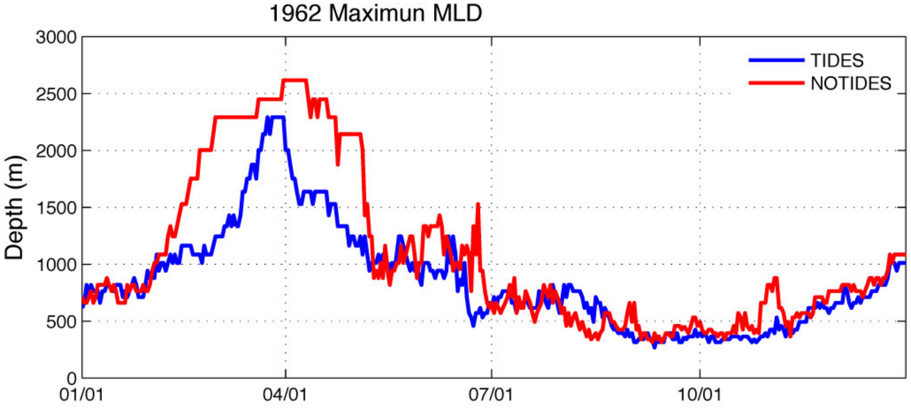


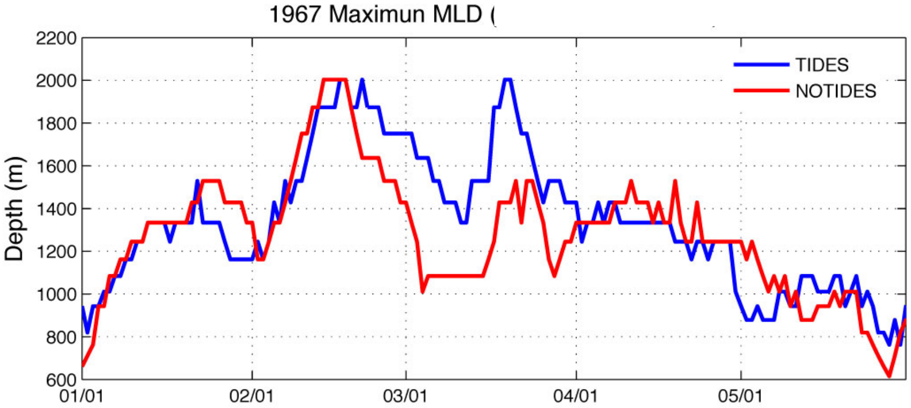

NO-TIDES 1963
NO-TIDES 1964
NO-TIDES 1965
TIDES 1963
TIDES 1964
TIDES 1965
500
1000
1500
2000
2500

New modeling strategy for the Med.


1961 Maximun MLD


1964 Maximun MLD (

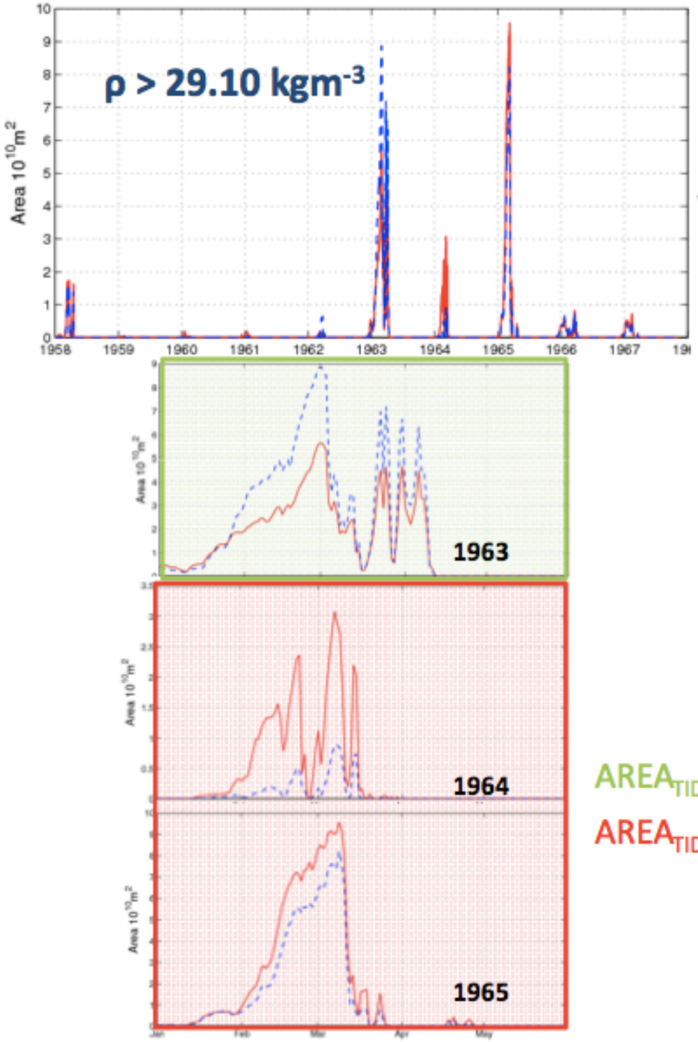

1962 Maximun MLD


1967 Maximun MLD (

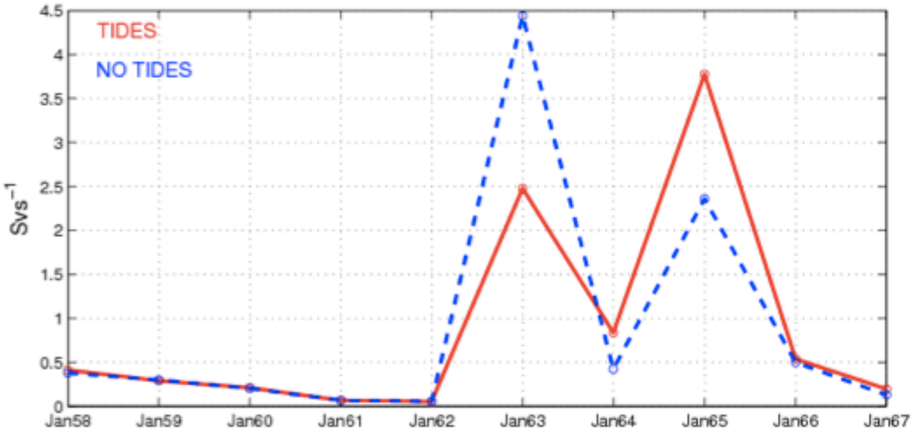
Summary and Conclusions: new modeling strategy for the Med.

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.**

$\text{AREA}_{\text{TIDES}} < \text{AREA}_{\text{NO-TIDES}}$

$\text{AREA}_{\text{TIDES}} < \text{AREA}_{\text{NO-TIDES}}$

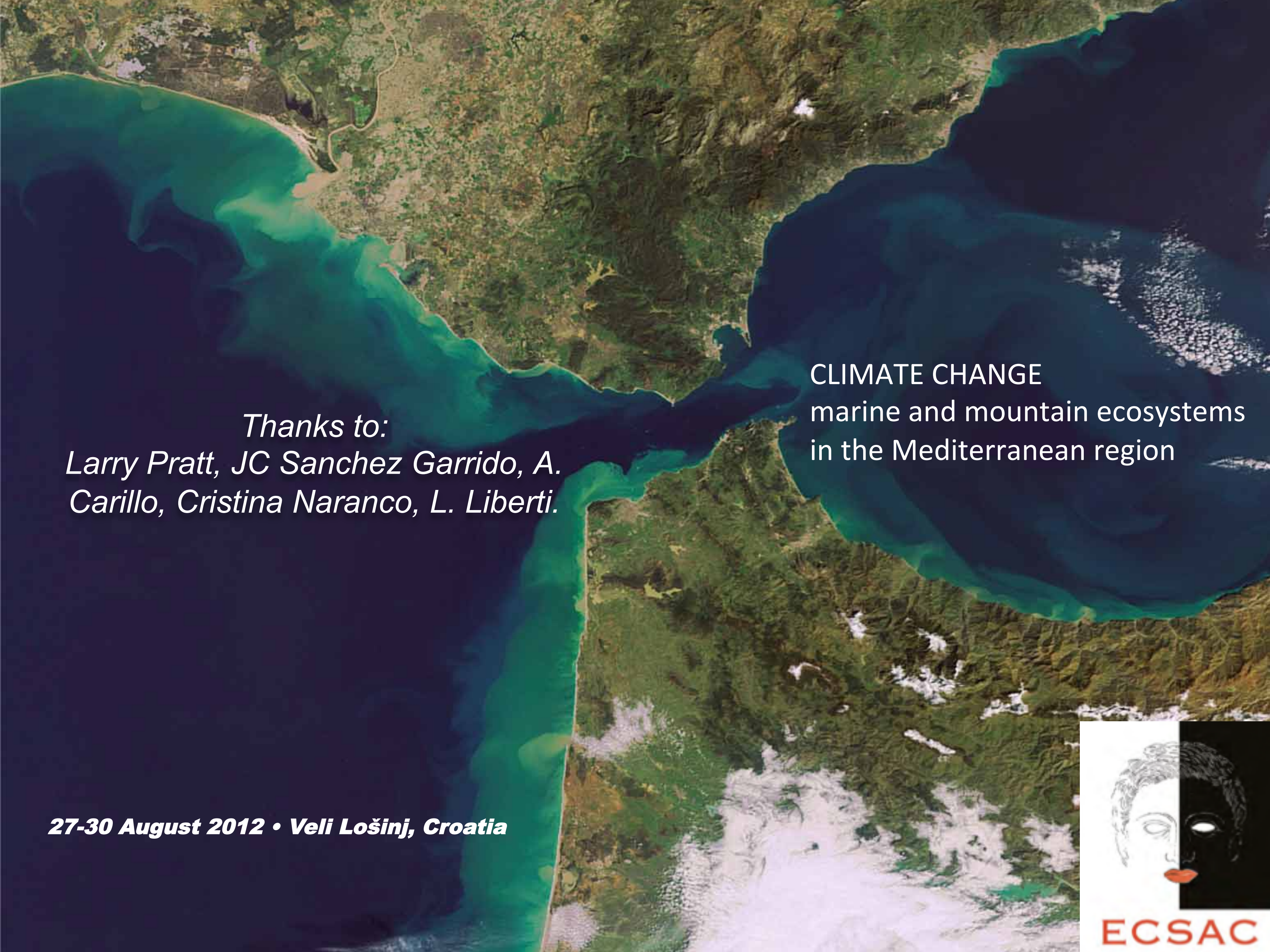
DIFERENCES IN THE ENTIRE COLUMN OF WATER

Conclusion

Climate models represent the

Strait of Gibraltar like a rectangular pipe & notides

Is it reasonable?



CLIMATE CHANGE
marine and mountain ecosystems
in the Mediterranean region

Thanks to:
Larry Pratt, JC Sanchez Garrido, A. Carillo, Cristina Naranco, L. Liberti.

27-30 August 2012 • Veli Lošinj, Croatia

ECSAC