Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

JONSMOD Latest modeling techniques for shallow seas

Florence - October 17-19, 2018

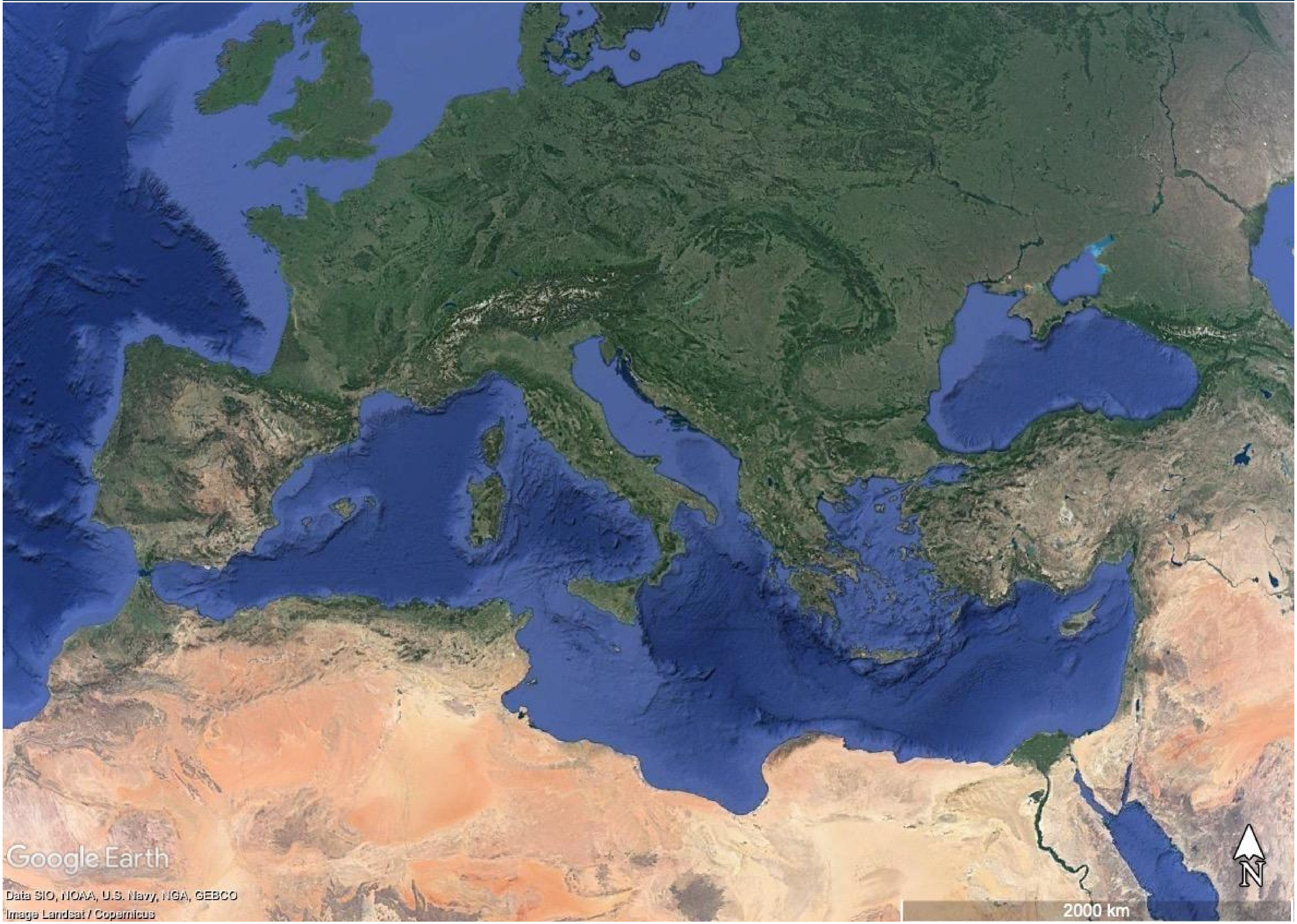
CONSORZIO LaMMA

The State-of-the-art in modelling the Mediterranean-Black Sea system

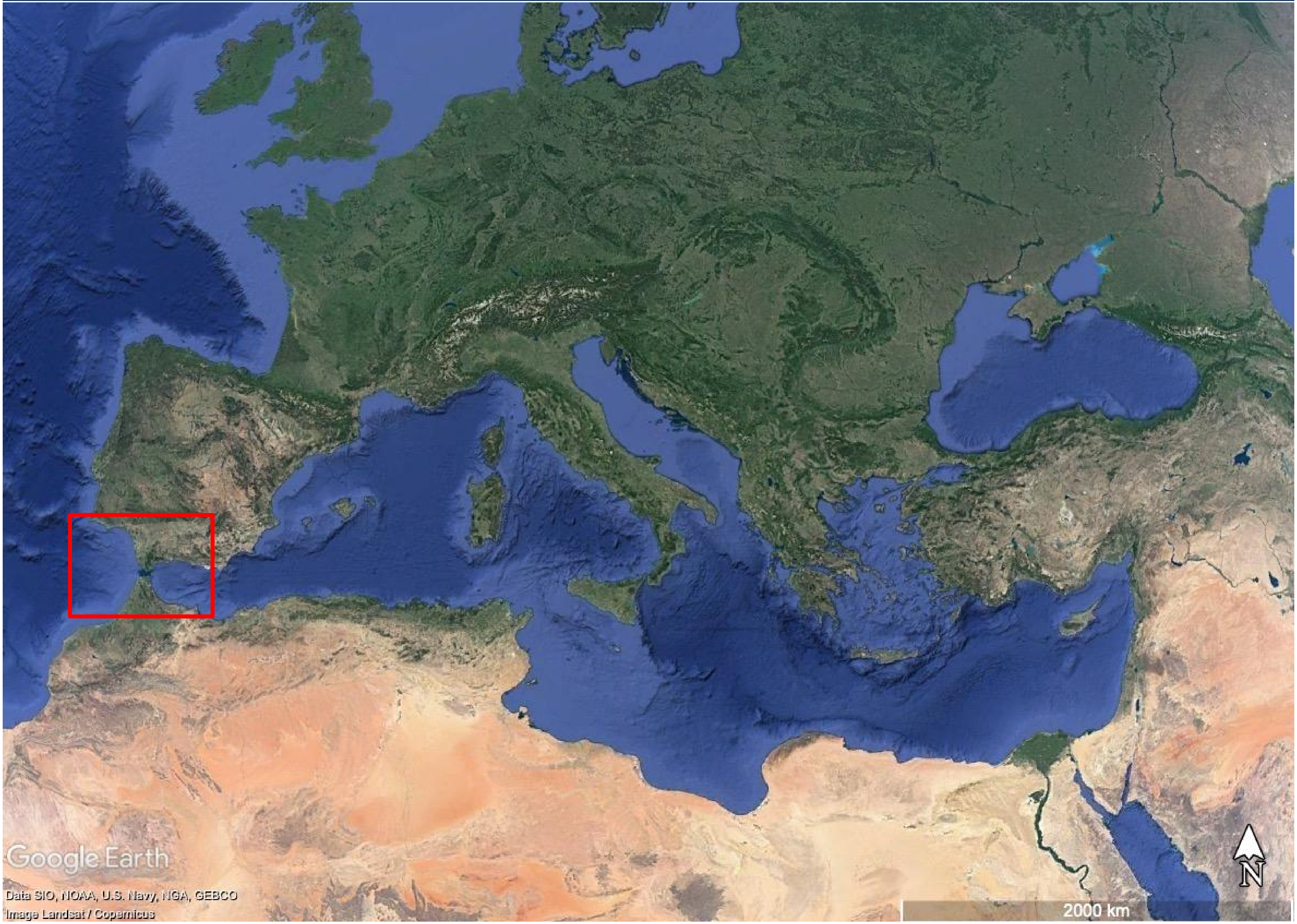
Florence October 17th 2018

Gianmaria Sannino / Climate Modelling and Impacts Laboratory @ ENEA

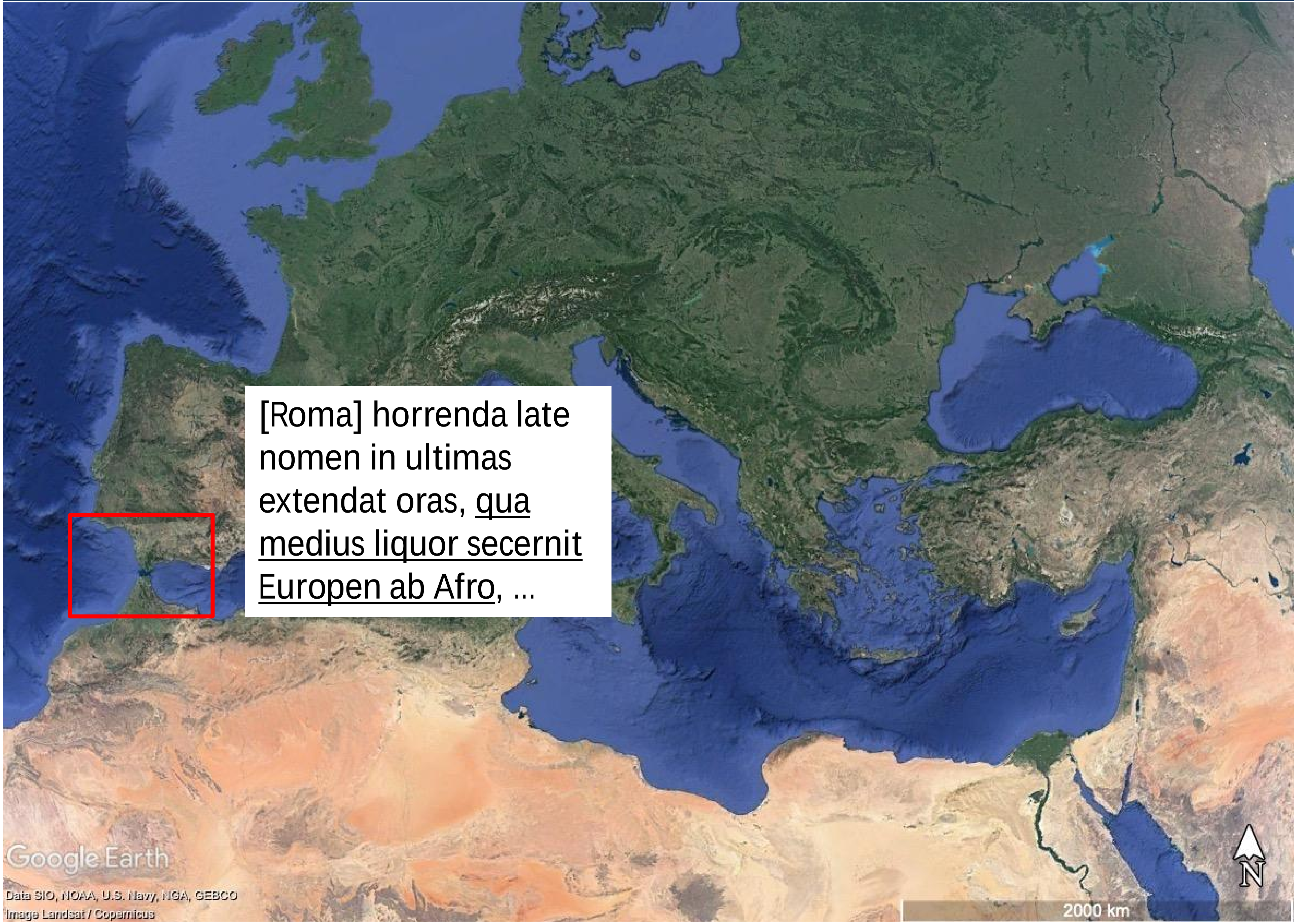
Background geography



Background geography



Background geography and history (Horace, Odes III)



[Roma] horrenda late nomen in ultimas extendat oras, <u>qua medius liquor secernit Europen ab Afro</u>, ...

Background geography and history (Horace, Odes III)

Quinto Orazio Flacco (latin: *Quintus Horatius Flaccus*; Venosa, 8 December 65 B.C. – Roma, 27 November 8 B.C.), known as Orazio (Horace), was a Roman poet.

[Roma] horrenda late nomen in ultimas extendat oras, qua medius liquor secernit Europen ab Afro, ...

[Rome] Feared far and wide, may she spread her name to the most distant shores, where the straits intervene to separate Europe from Africa, ...

Background geography

Strait of Gibraltar Background

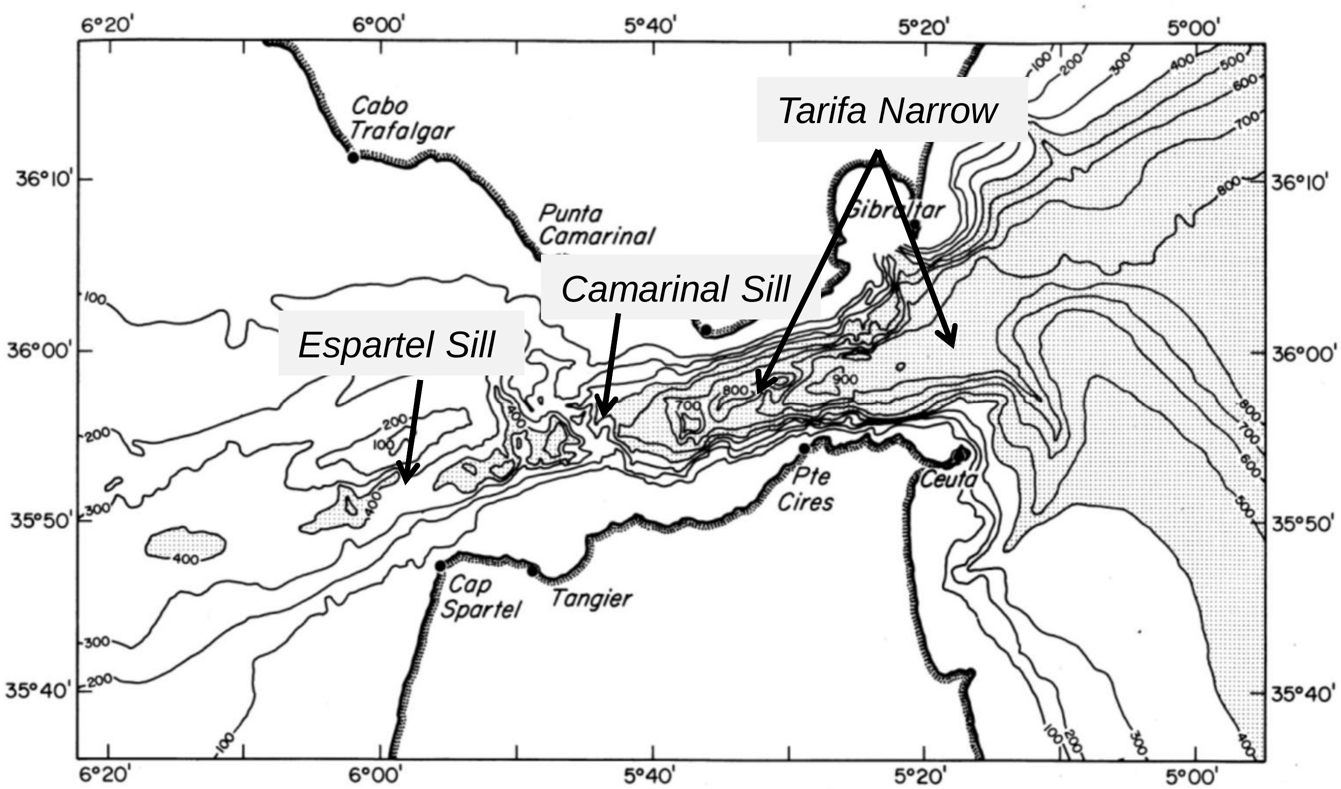
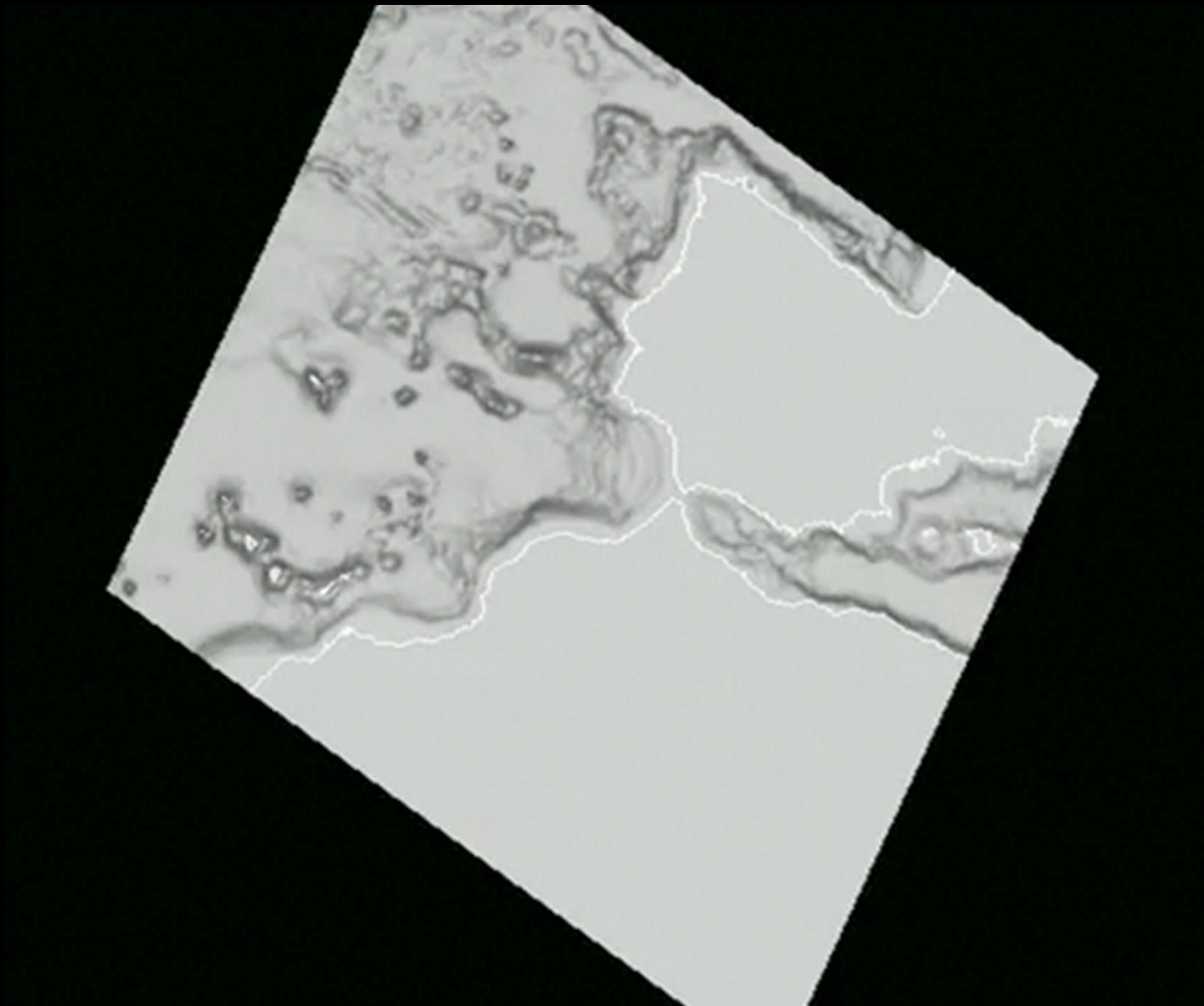


Chart of the Strait of Gibraltar, adapted from Armi & Farmer (1988), showing the principal geographic features referred to in the text.

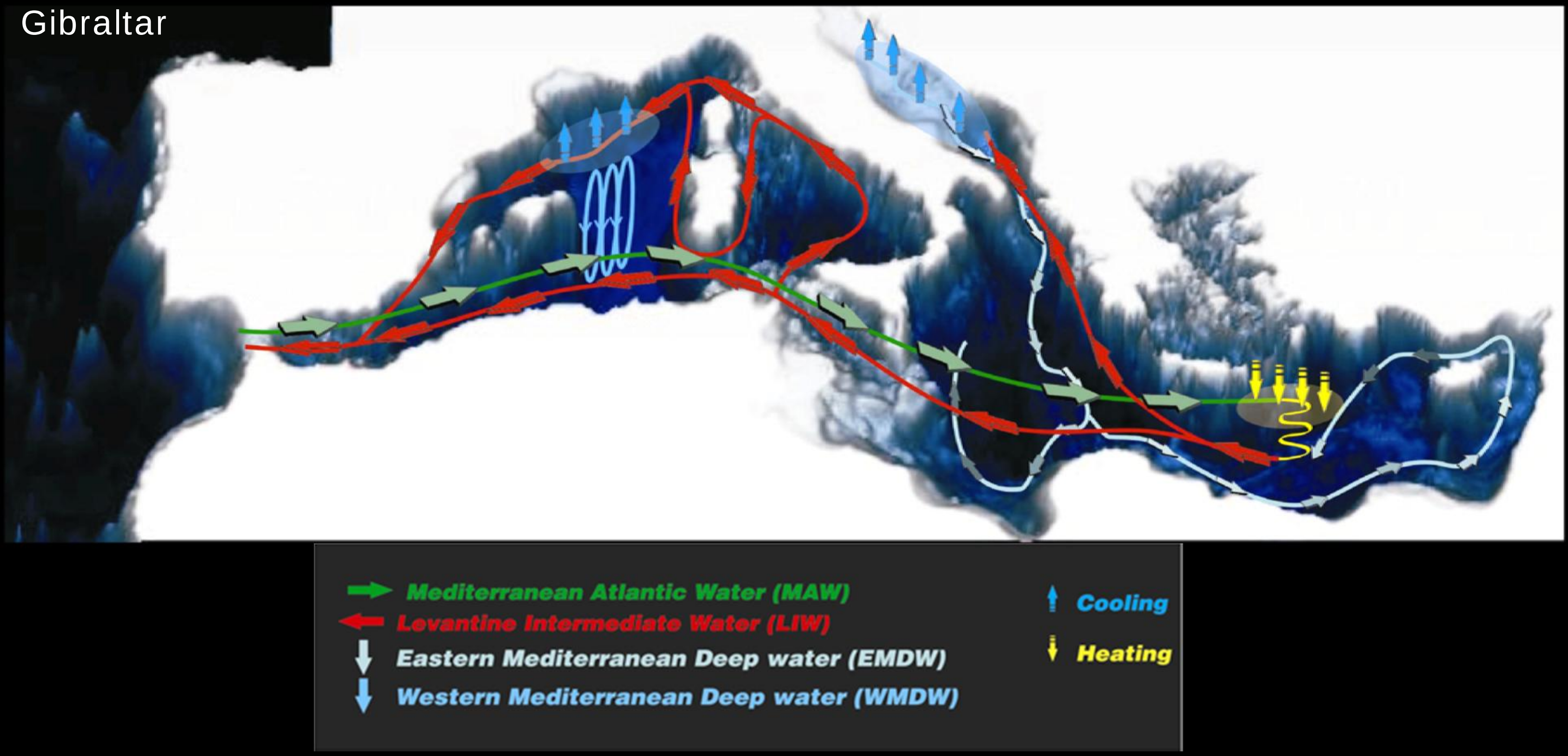
Areas deeper than 400 m are shaded

Strait of Gibraltar Background: 3D Bathymetry



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: Physics

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

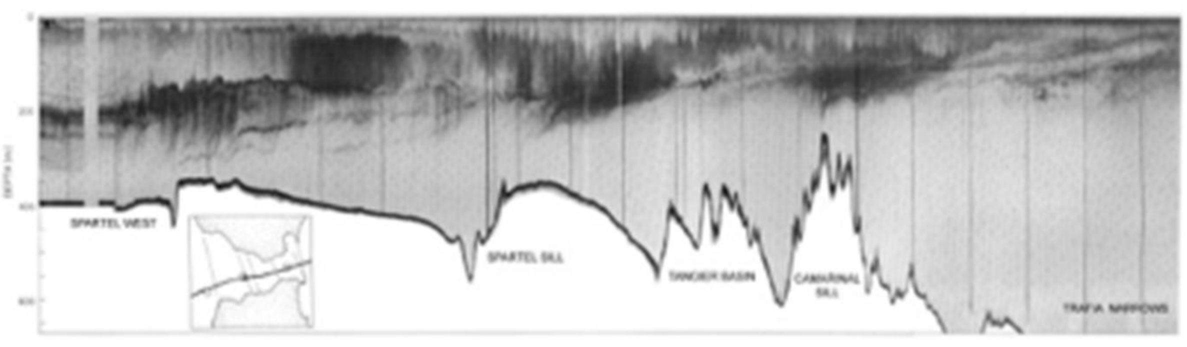


Figure 2. Transect of the Strait [From Armi and Farmer, Farmer and Armi.1988]

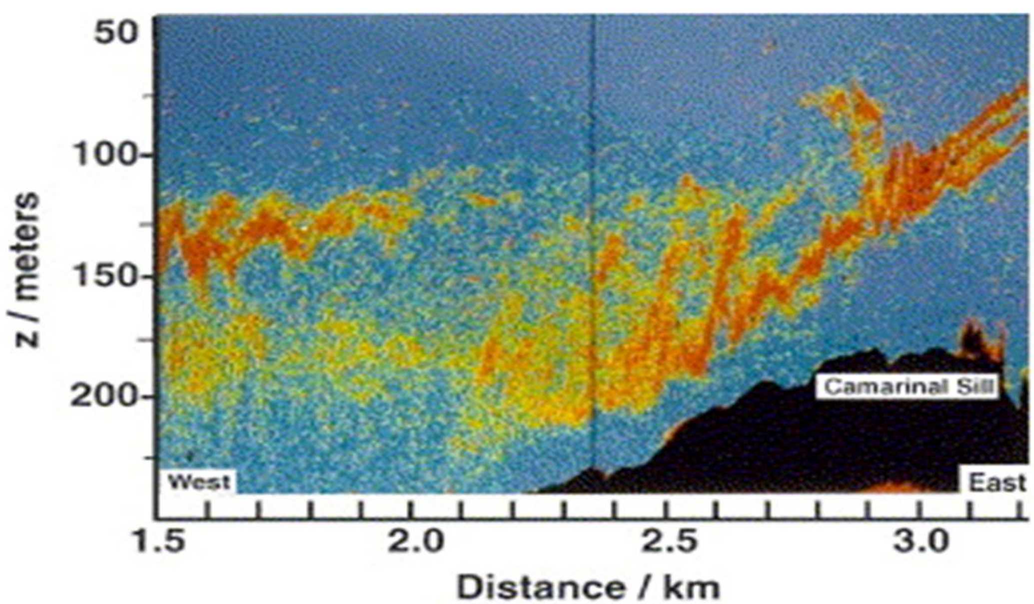
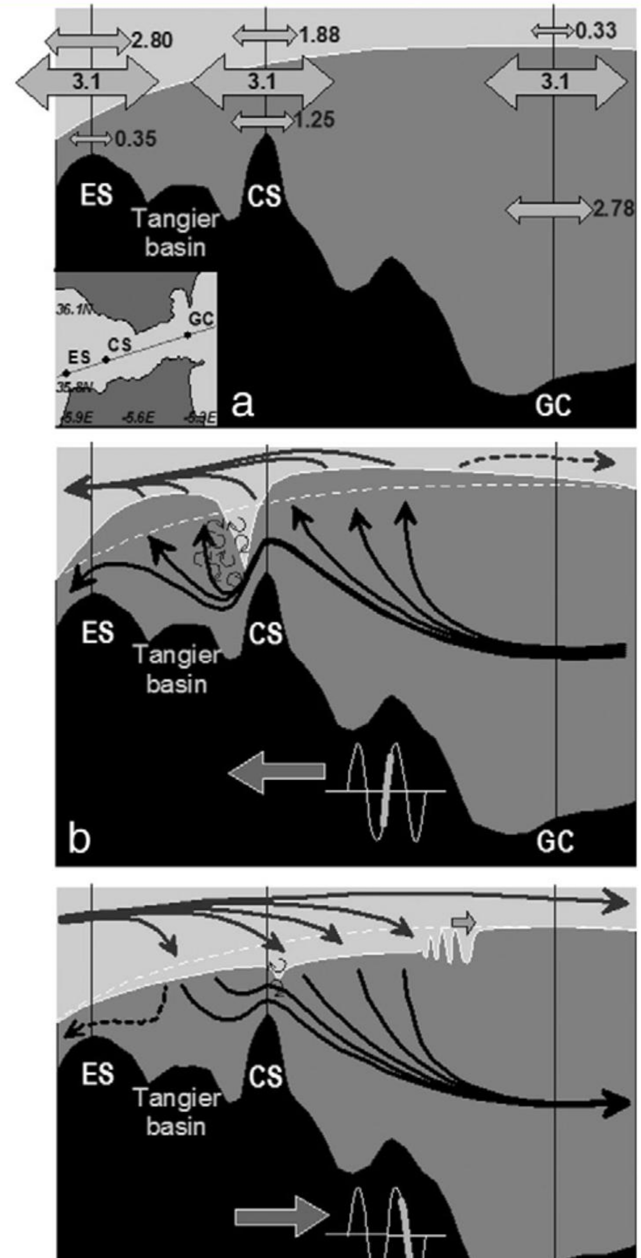


Image of acoustic backscatter during ebb tide over Camarinal Sill in the Strait of Gibraltar (Wesson and Gregg, 1994)



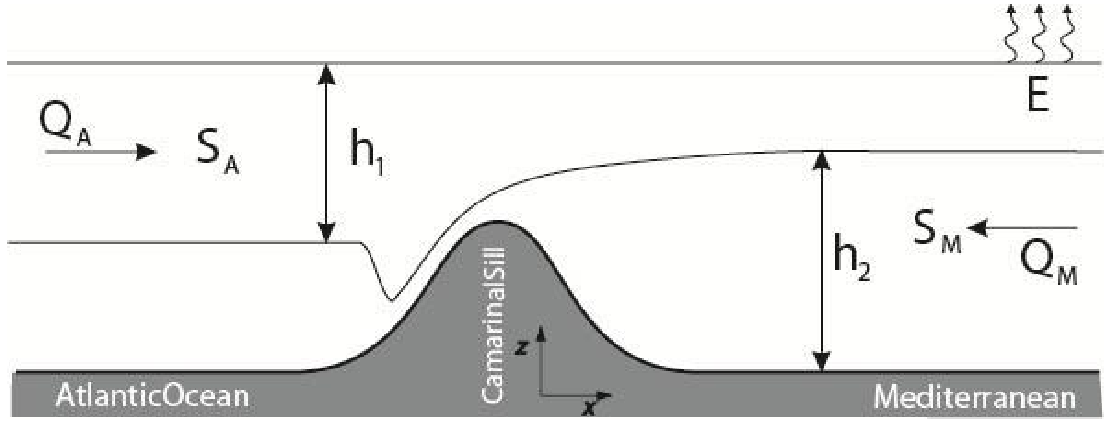
A. Sánchez-Román et al, JGR 2012

Strait of Gibraltar Background: Hydraulics

Mass Conservation

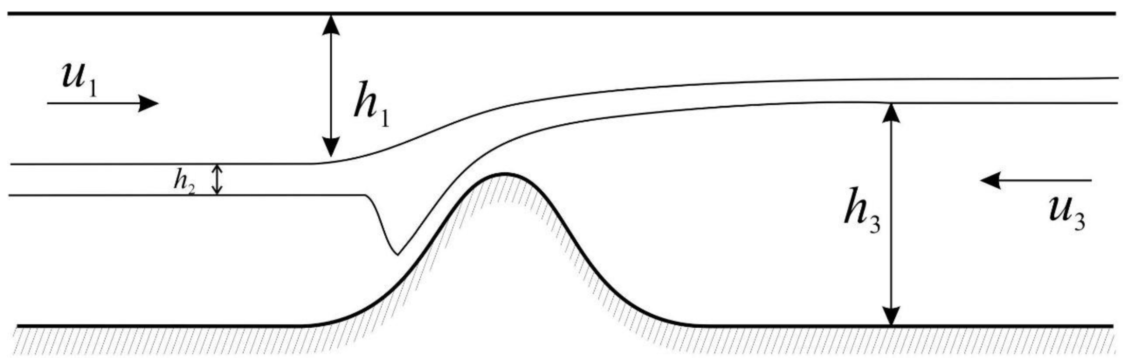
$$\begin{cases} Q_A + Q_M = E - P - R \\ Q_A S_A + Q_M S_M = 0 \end{cases}$$

Salt Conservation



Knudsen equations (1899)

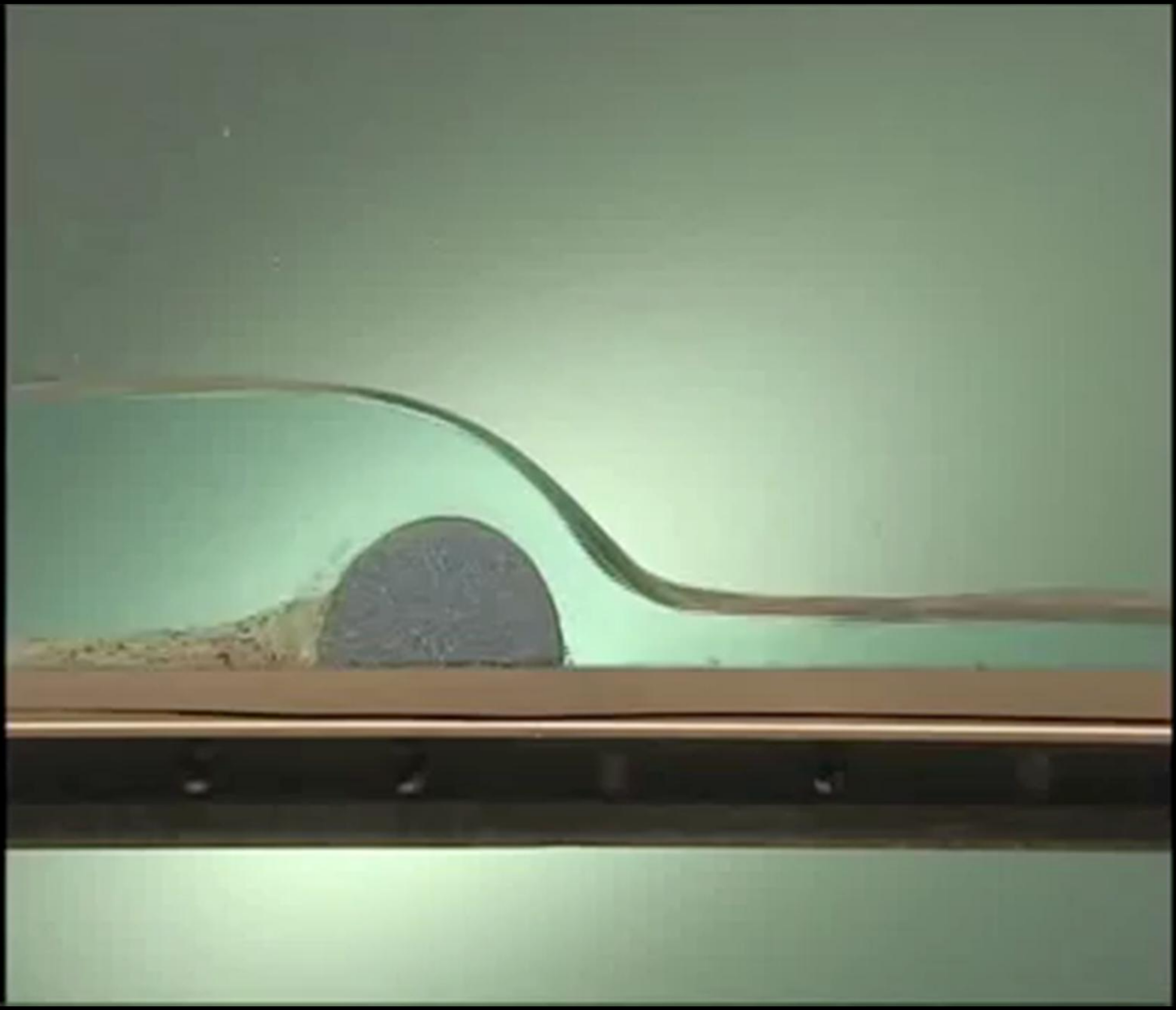
$$\begin{cases} Q_A = \frac{S_M E_{net}}{S_M - S_A} \\ Q_M = -\left[\frac{S_A E_{net}}{S_M - S_A}\right] \end{cases}$$



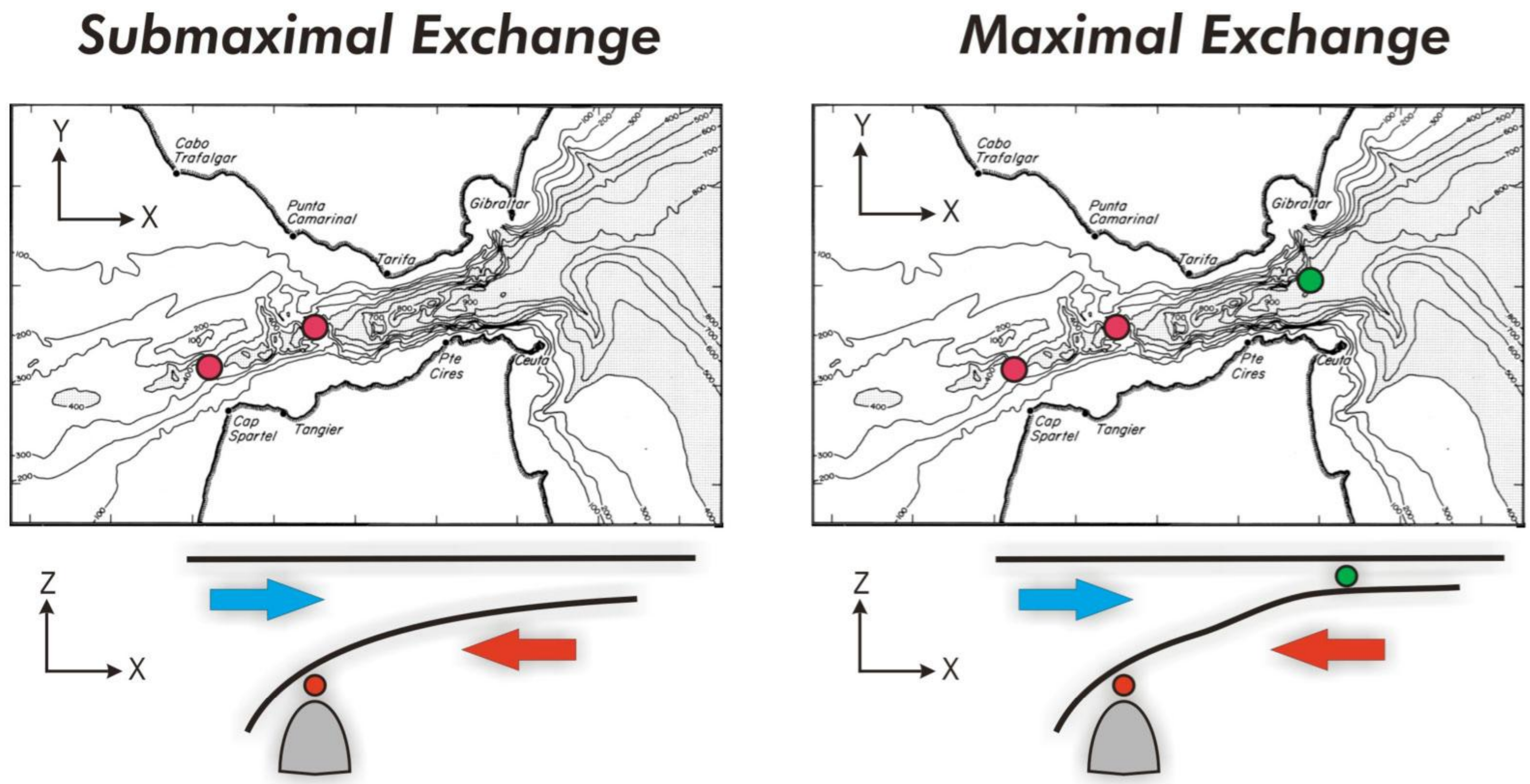
$$F_1^2 = \frac{u_1^2}{h_1 g (1 - r_{1,2})} \qquad F_2^2 = \frac{u_2^2 (1 - r_{1,3})}{h_2 g (1 - r_{1,2})(1 - r_{2,3})} \qquad F_3^2 = \frac{u_3^2}{h_3 g (1 - r_{2,3})} \qquad r_{i,j} = \frac{\rho_i}{\rho_j}$$

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

Strait of Gibraltar Background: Hydraulics ...an example



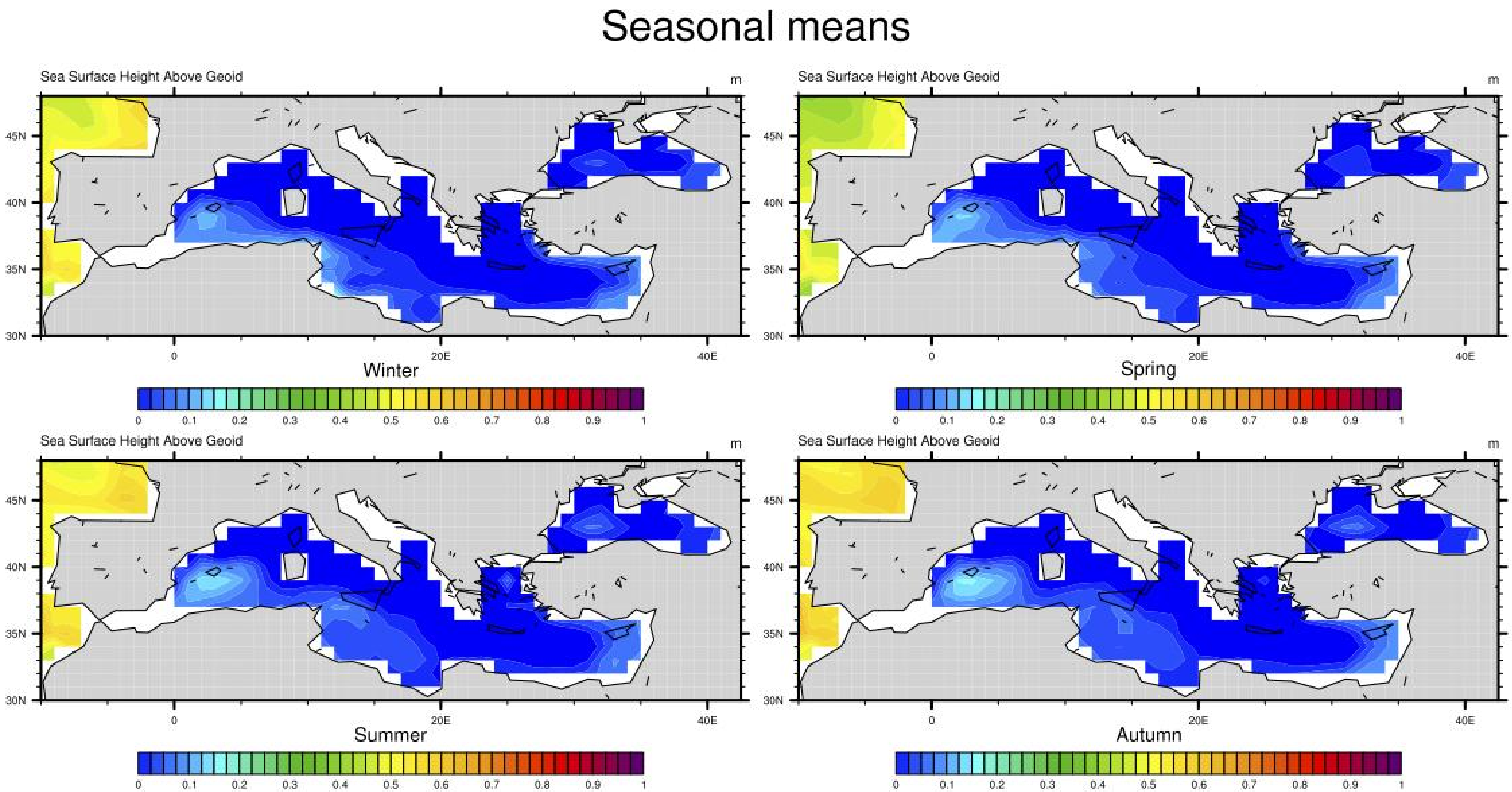
Strait of Gibraltar Background: Hydraulics



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.

Global climate models

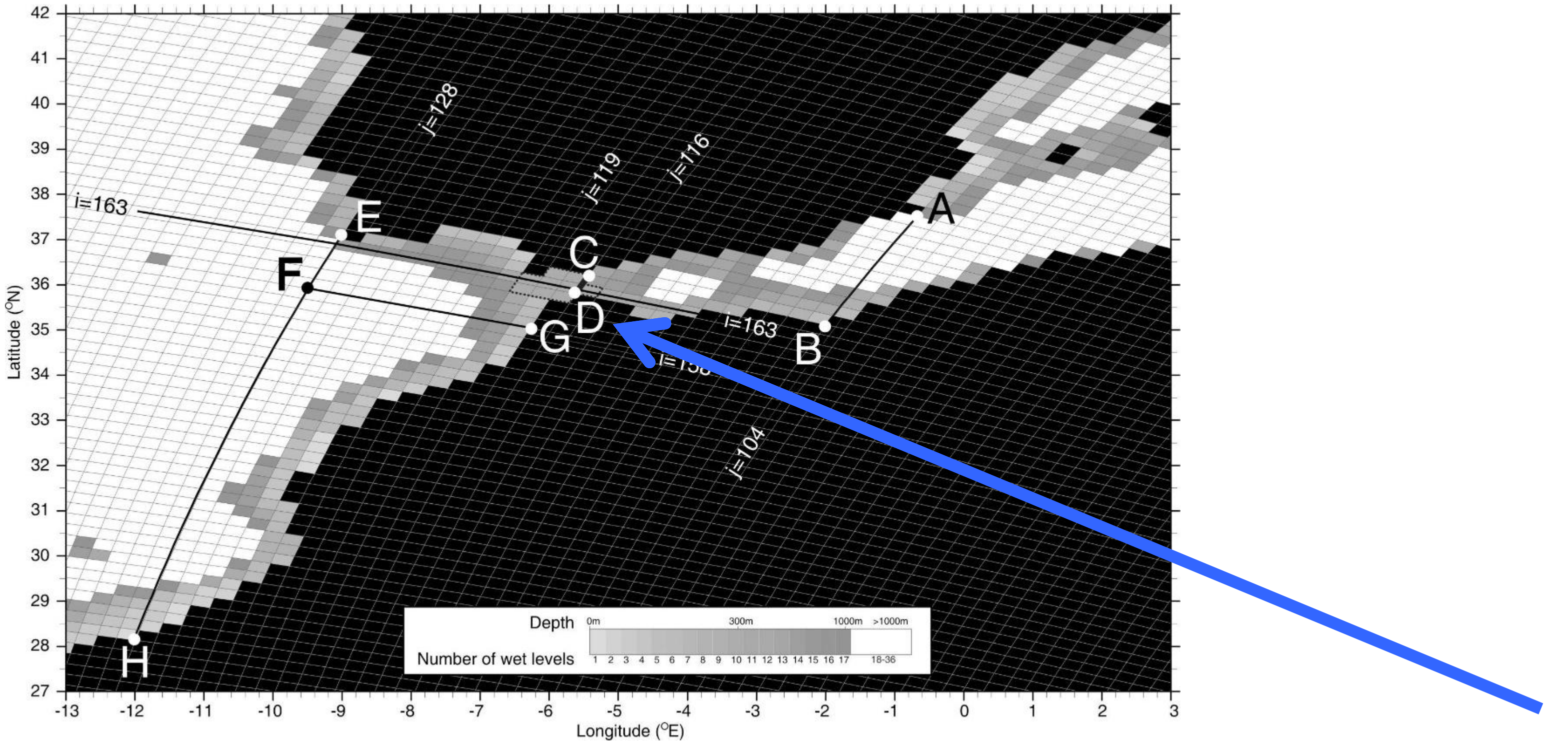


Mediterranean sea level reproduced by CMIP5* global models (present climate)

*Coupled Model Intercomparison Project - https://cmip.llnl.gov/cmip5/

Climate models, both at global and regional scale, represent the Strait of Gibraltar like a

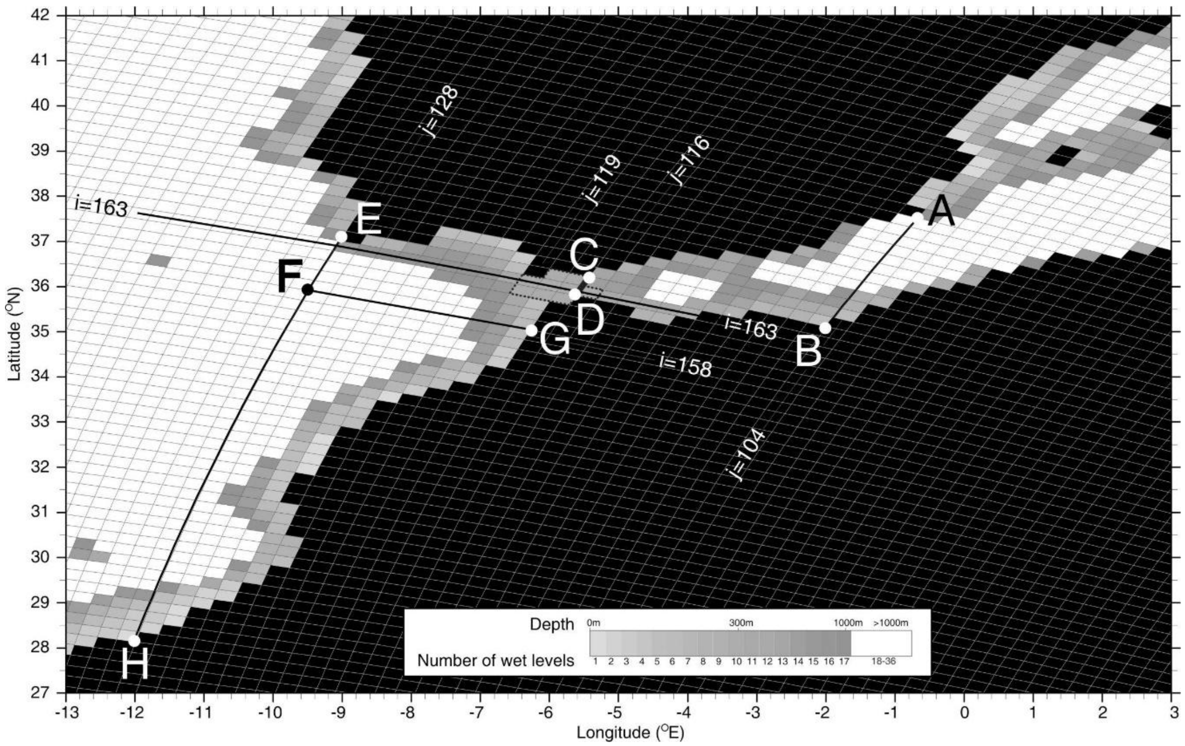
rectangular pipe



Strait of Gibraltar

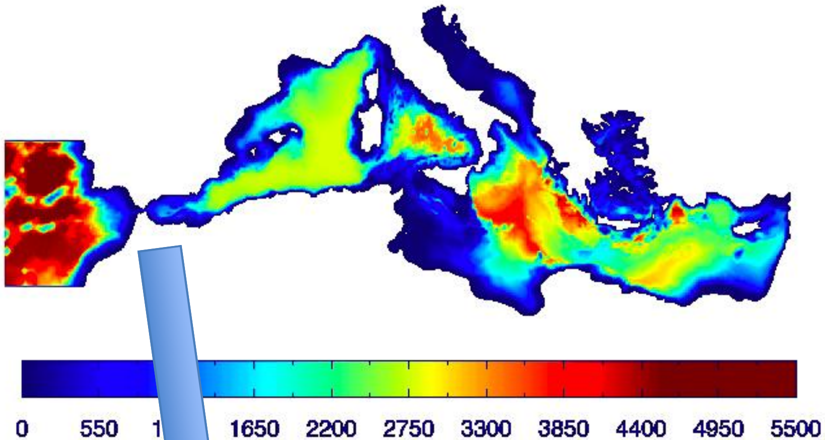
Climate models, both at global and regional scale, represent the Strait of Gibraltar like a

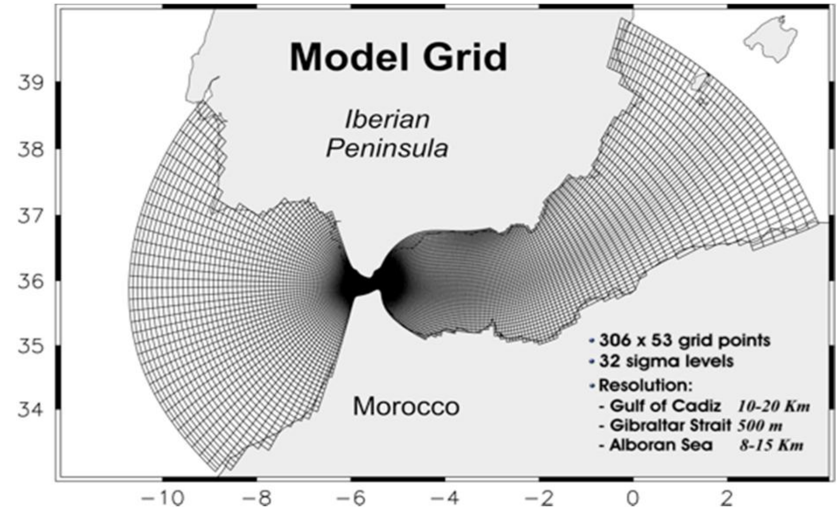
rectangular pipe

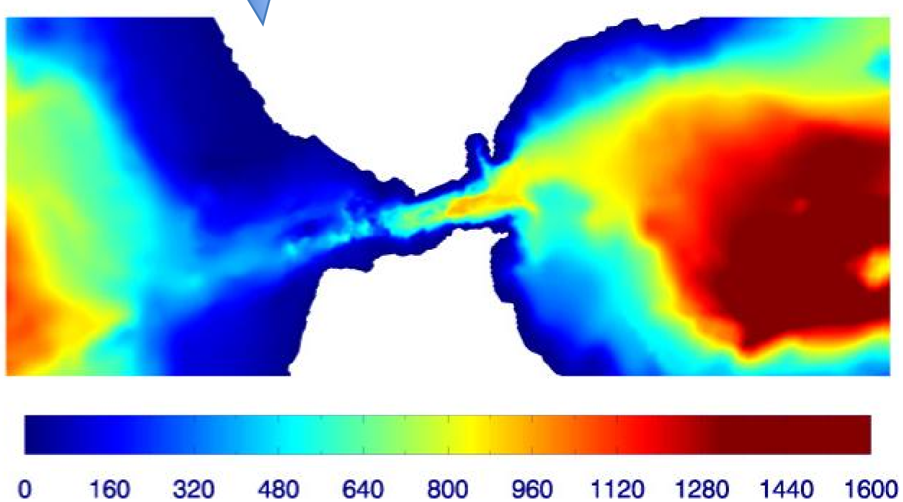


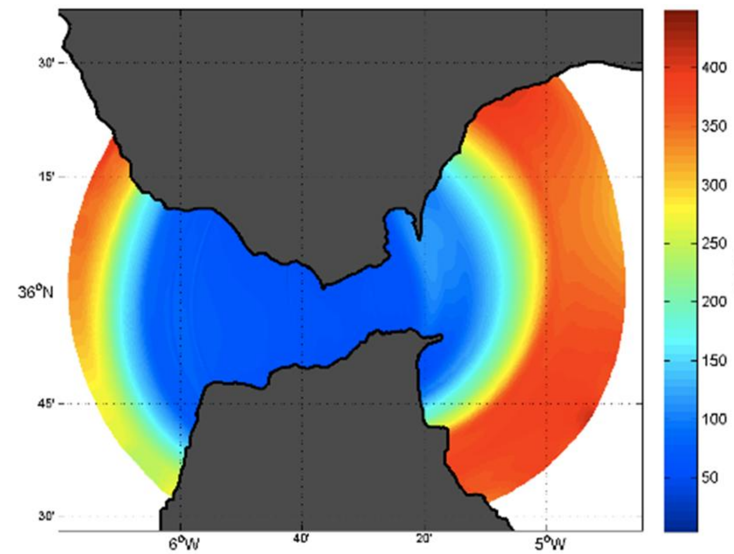
- Is it reasonable?
- If NOT, what are these models neglecting?
- If NOT, what is the minimum resolution to adopt for the Strait?

Answer: Direct simulation of the Strait at high resolution

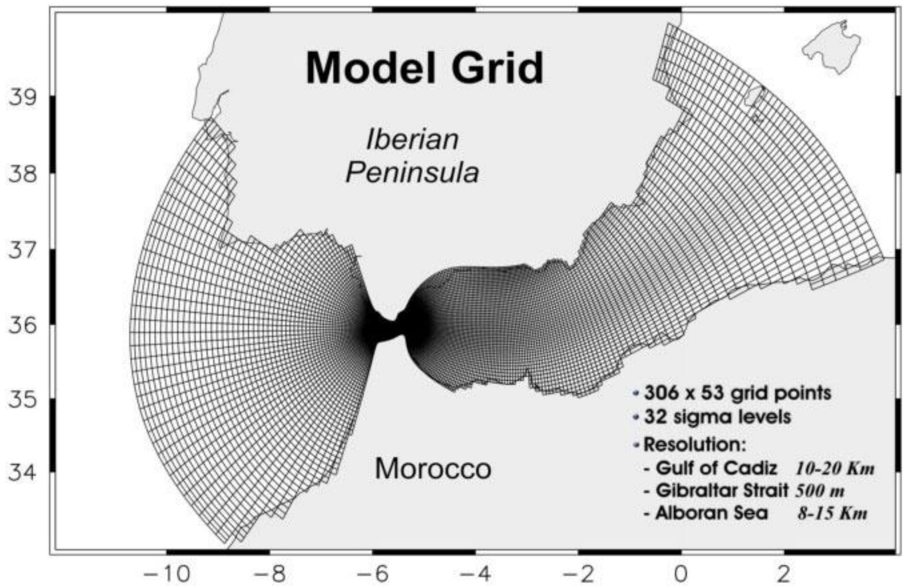


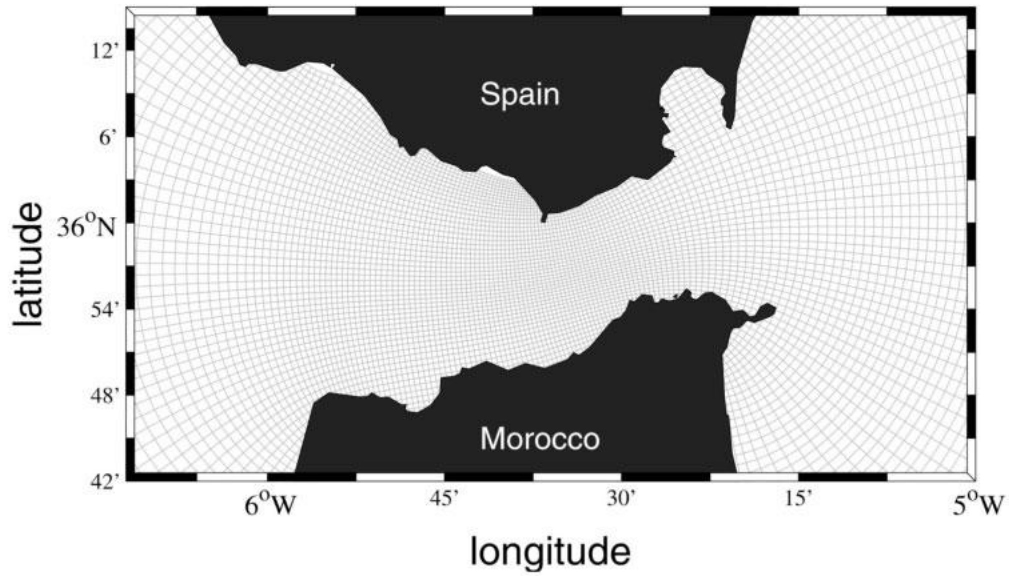






Sub-basin Model: Cadiz – Gibraltar - Alboran





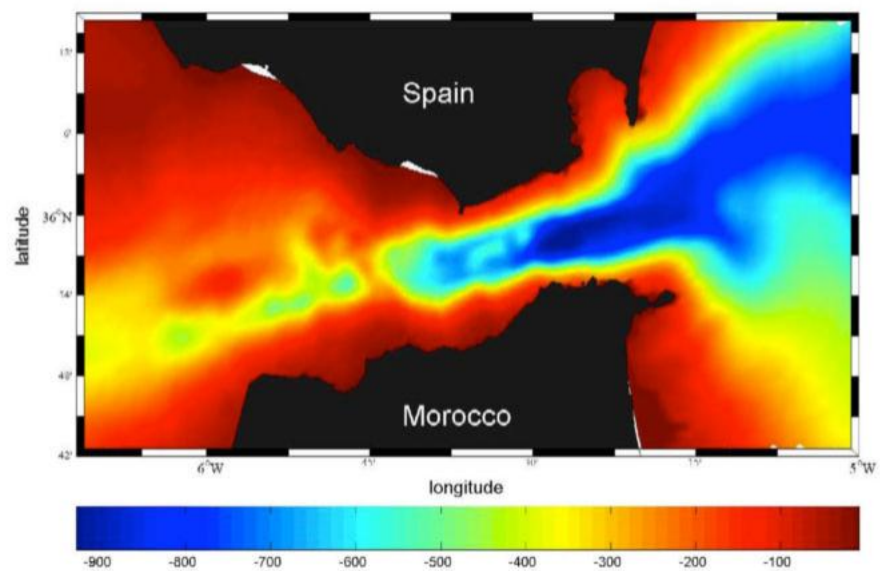
Modified POM

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

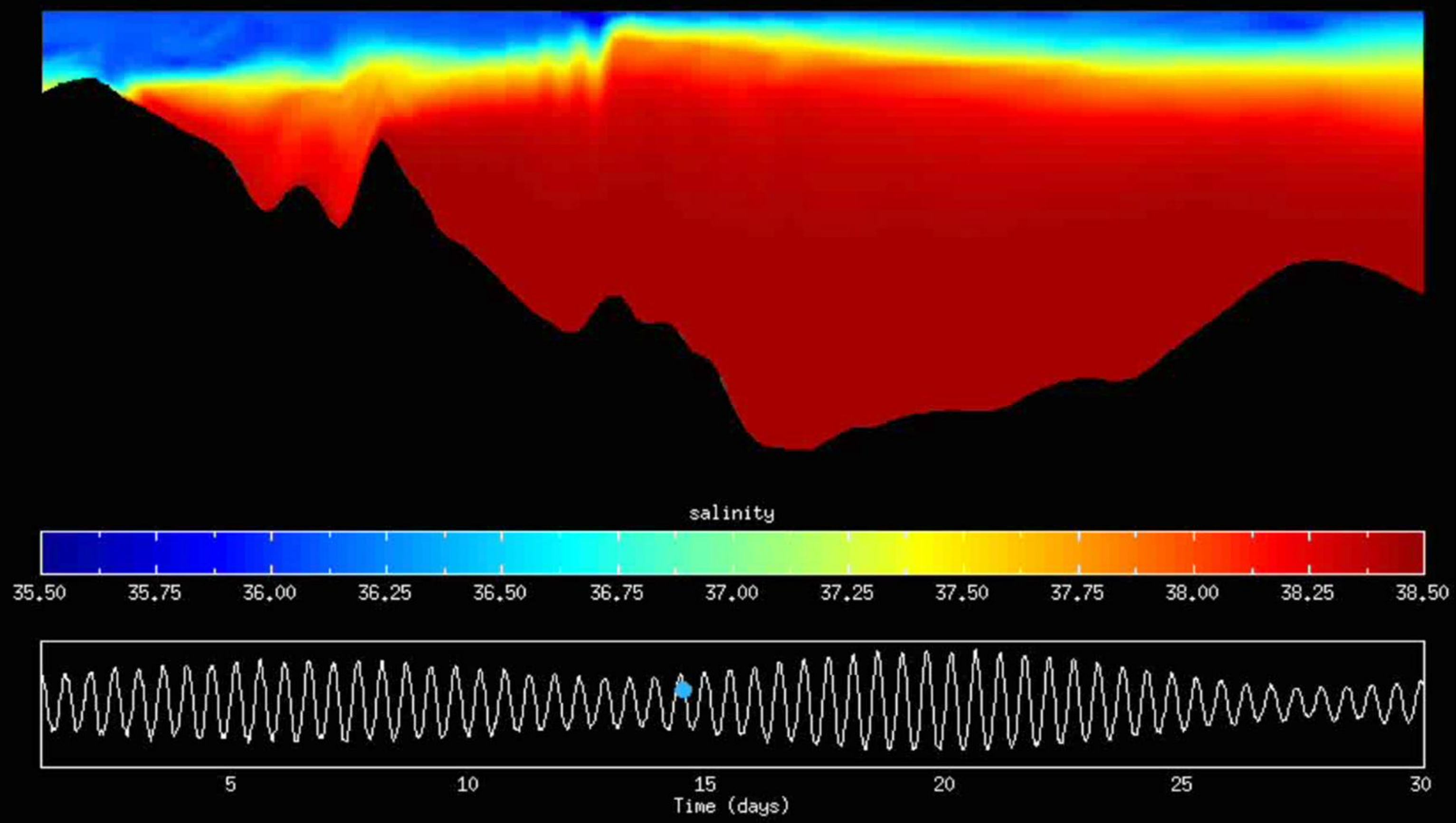
•Sannino et al, JGR, 2007

•Sannino et al , NC, 2005

•Sannino et al, JGR, 2004

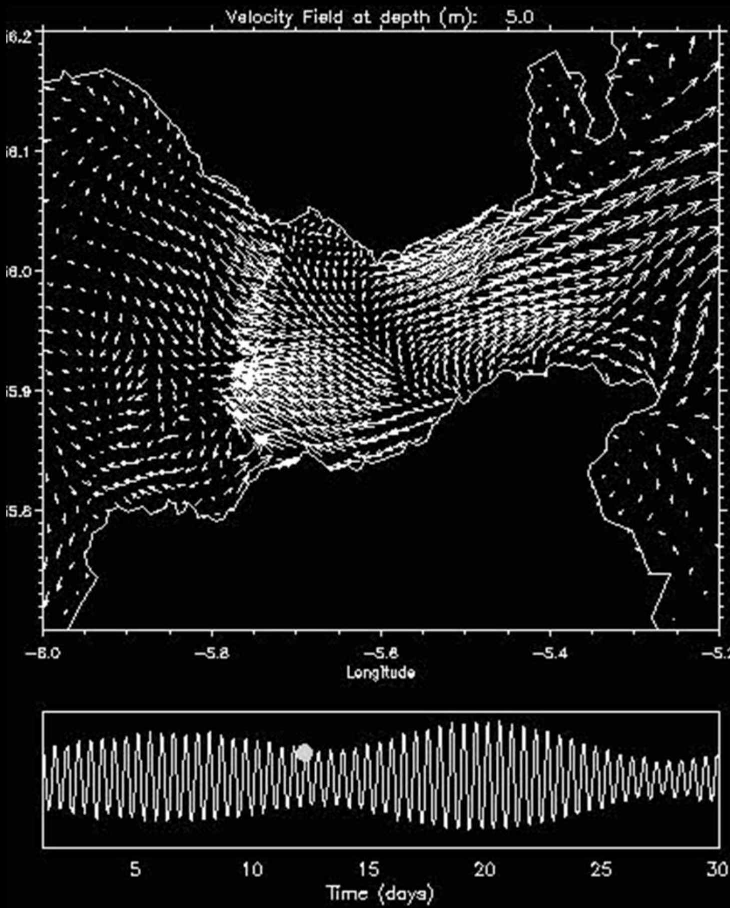
•Sannino et al, JGR, 2002

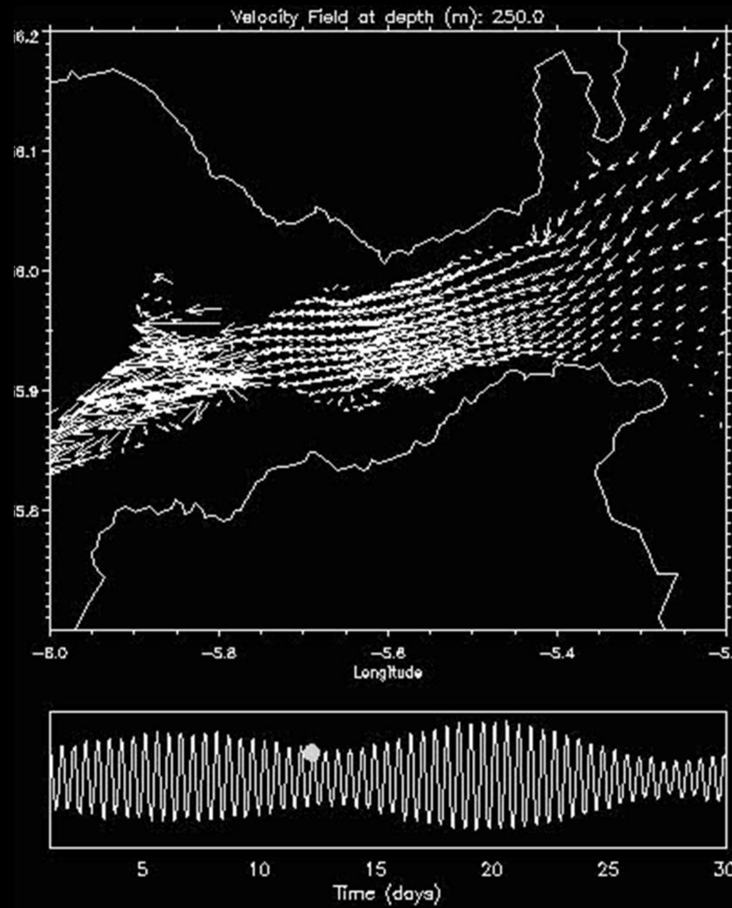
Sub-basin Model: Cadiz – Gibraltar - Alboran



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

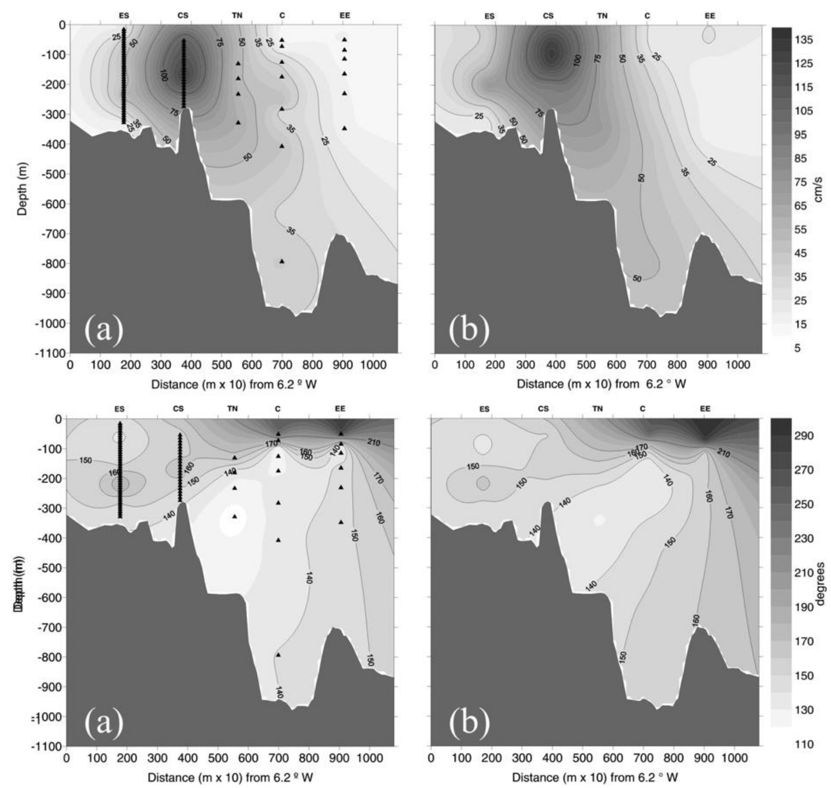
Tidal Components comparison
Along-strait velocity

(a) Data

(b) Model

(a) Data

(b) Model



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

Sánchez-Román et al., JGR, 2009

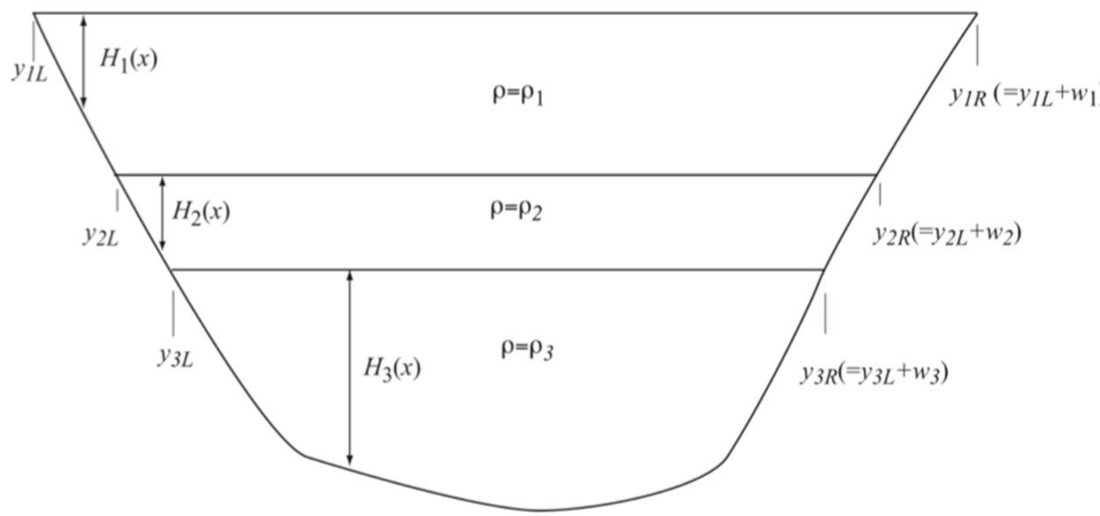
Strait of Gibraltar: new 3Layer Hydraulic Theory

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

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

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

(b)



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

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

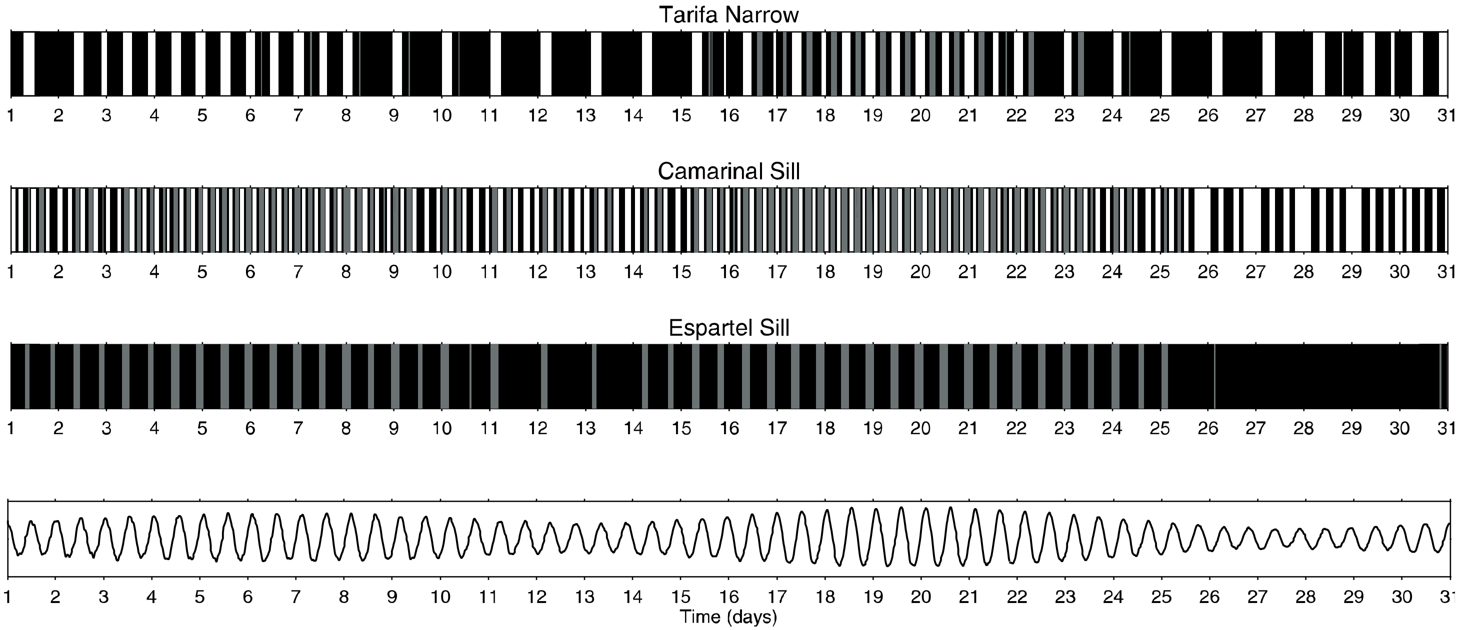
In order to determine whether a particular state is subcritical, supercritical, or critical, it is helpful to rewrite this equation as:

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

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

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.

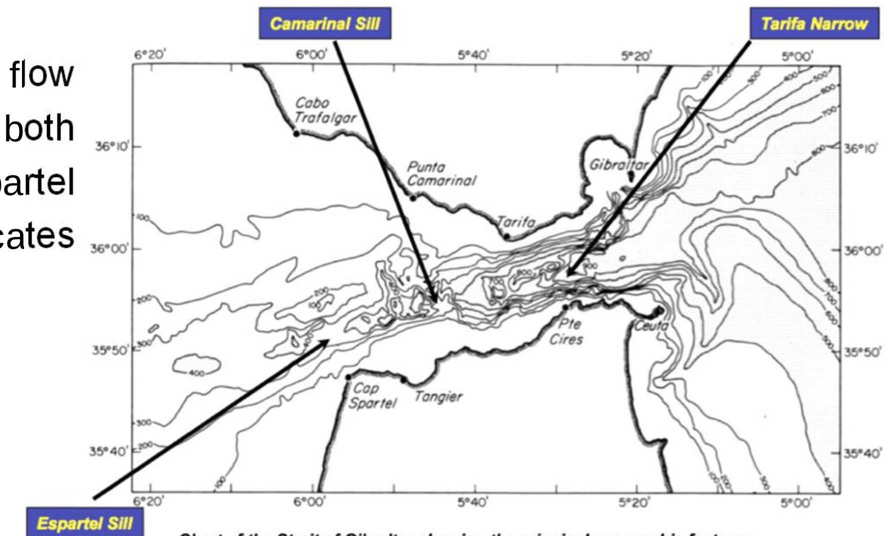
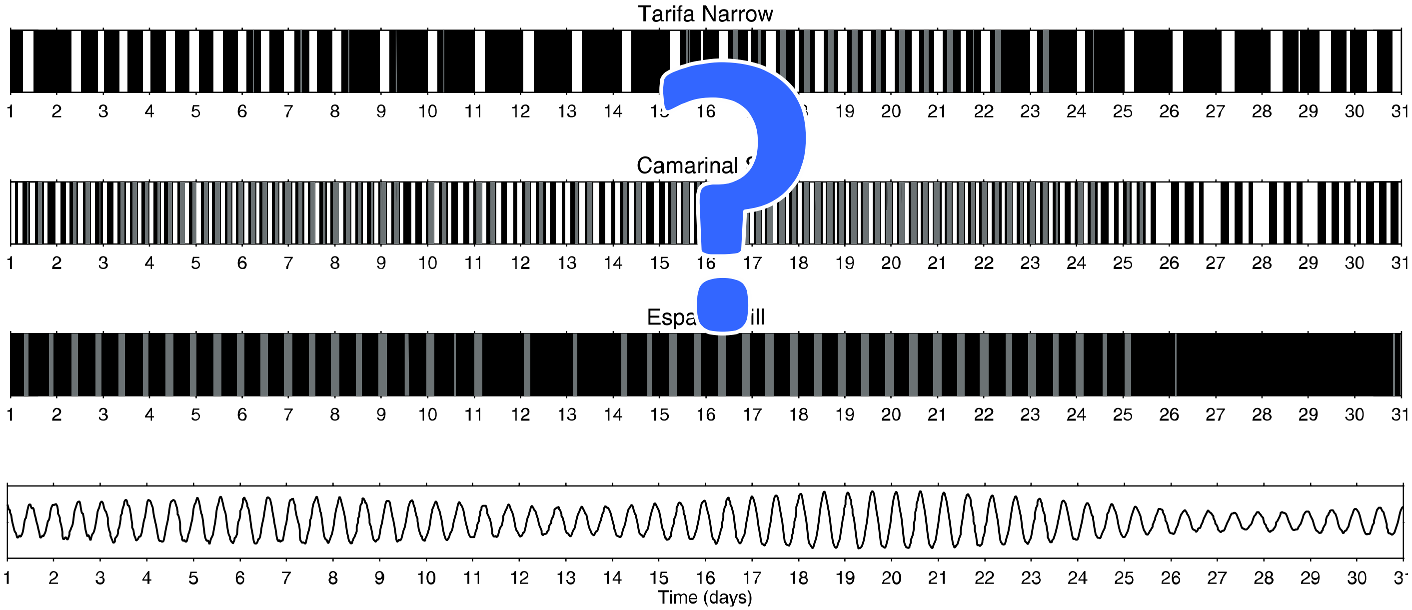


Chart of the Strait of Gibraltar showing the principal geographic features. Areas deeper than 400 m are shaded

POM model and hydraulics

Are the hydraulic results model depended?

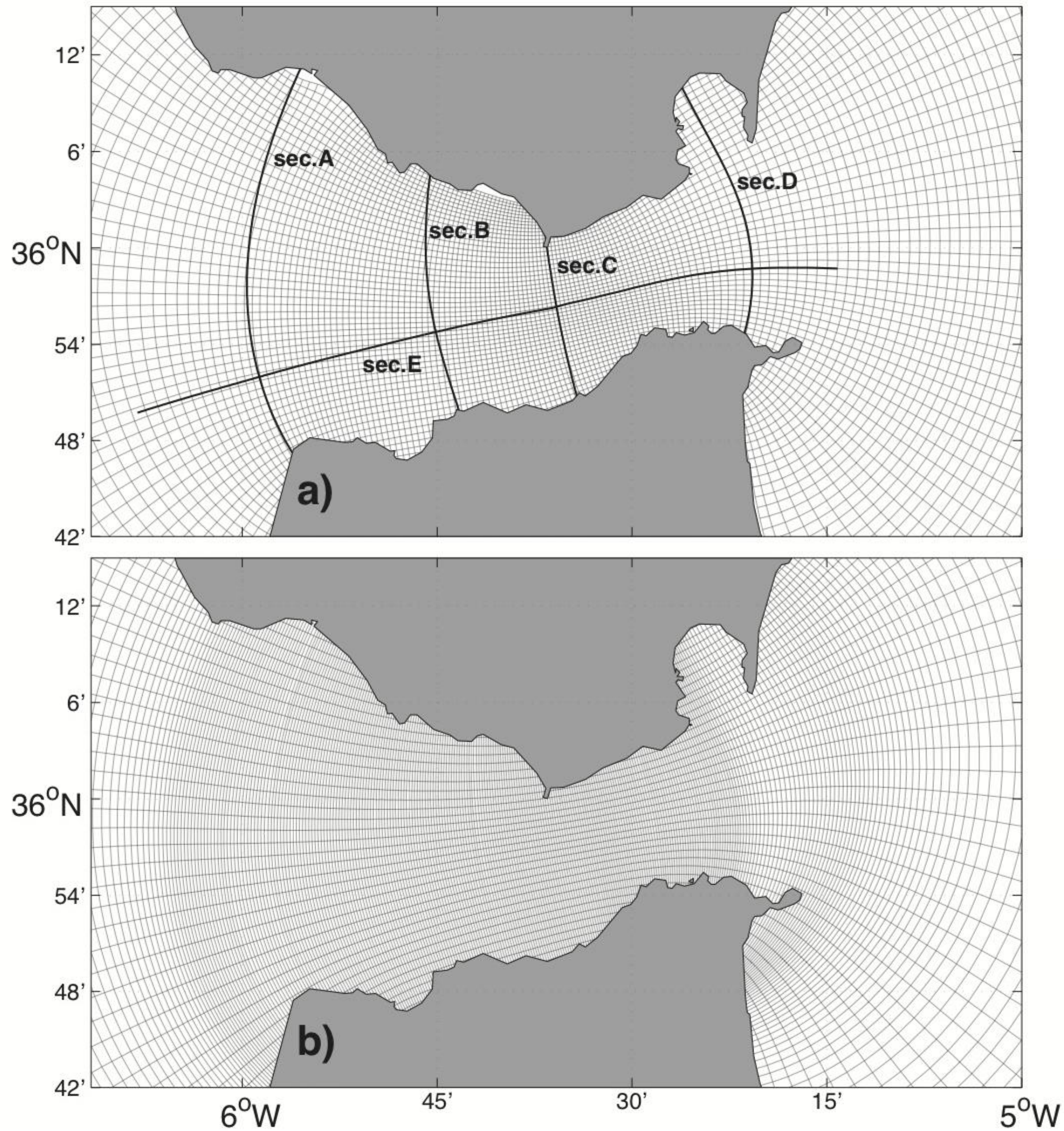


To answer the question the exchange flow simulated by POM has been compared with the exchange flow simulated by a very high resolution non-hydrostatic model implemented for the Strait region.

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)



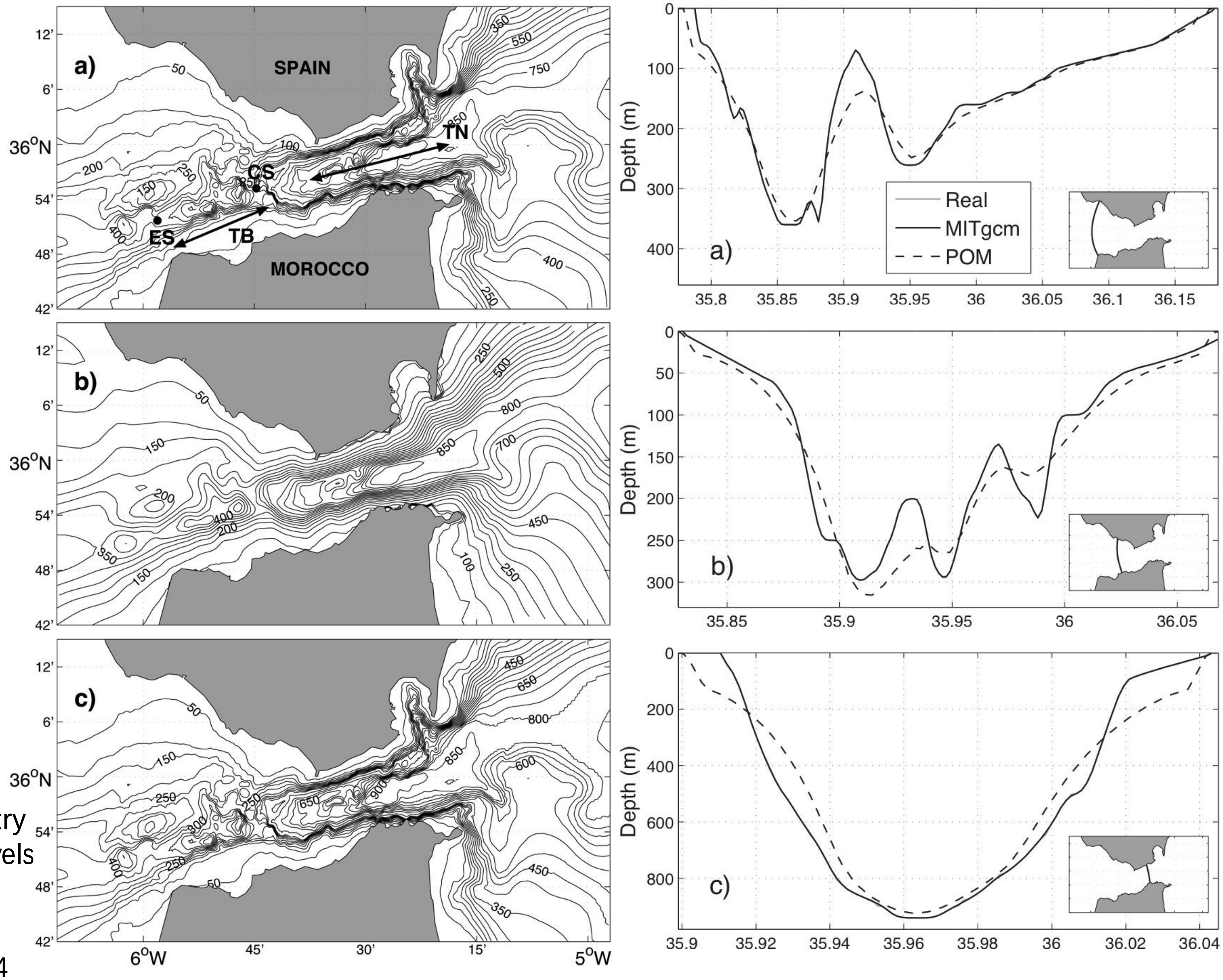
Sannino et al 2014

MITgcm vs POM : model bathymetry

Real bathymetry

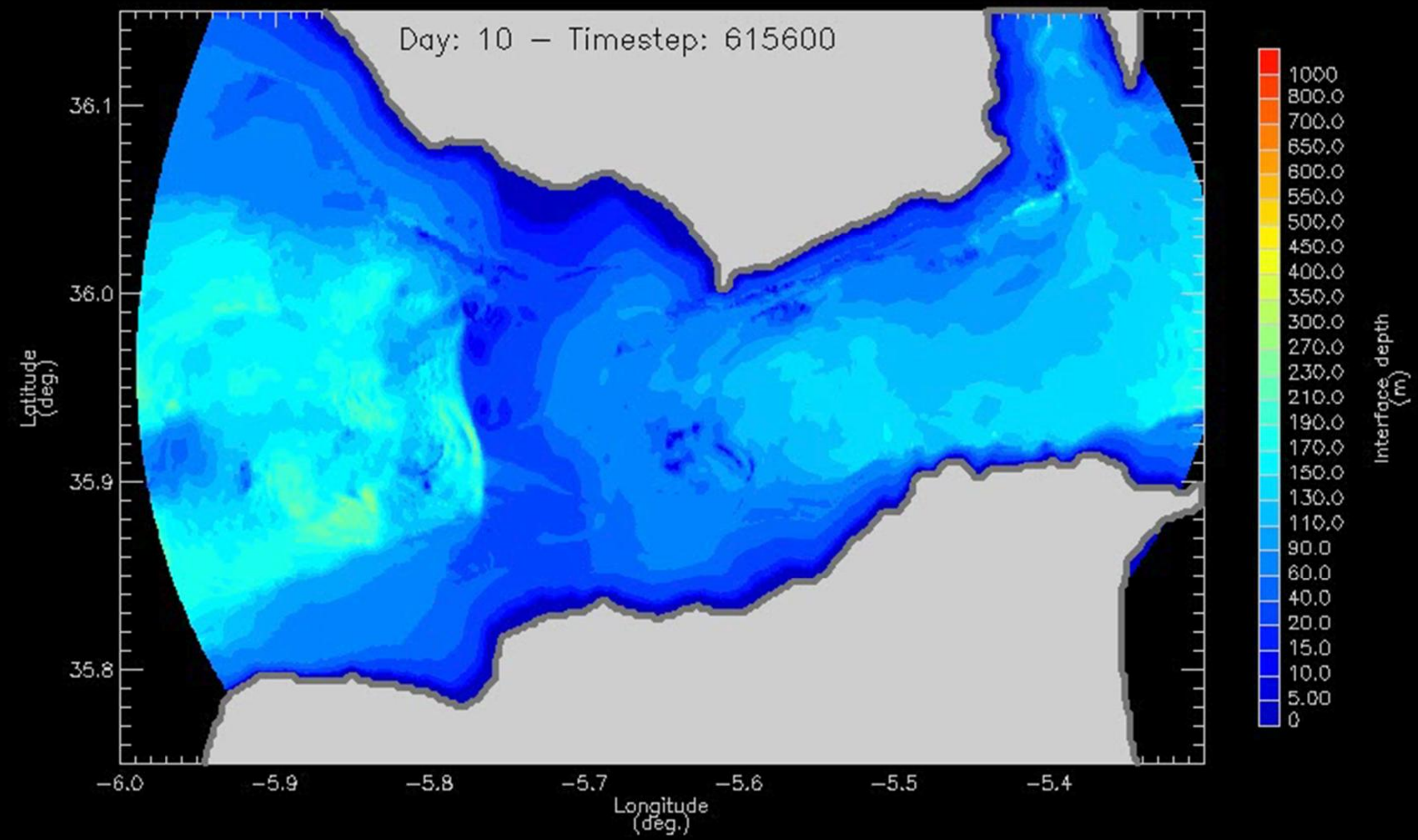
POM bathymetry
32 sigma-levels

MITgcm bathymetry
53 vertical zeta-levels
(partial cell)



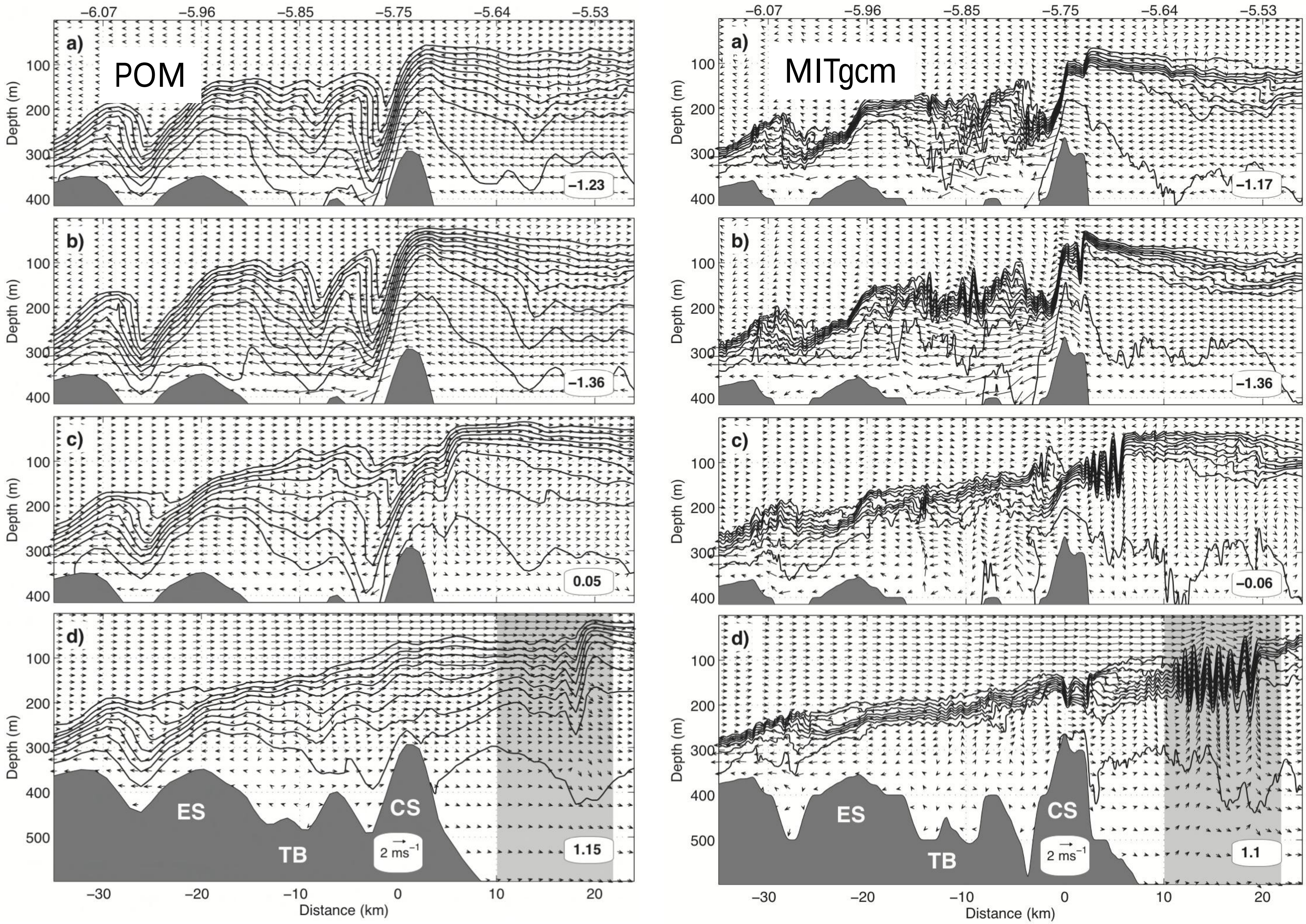
Sannino et al 2014

MITgcm model simulation



Interface depth evolution

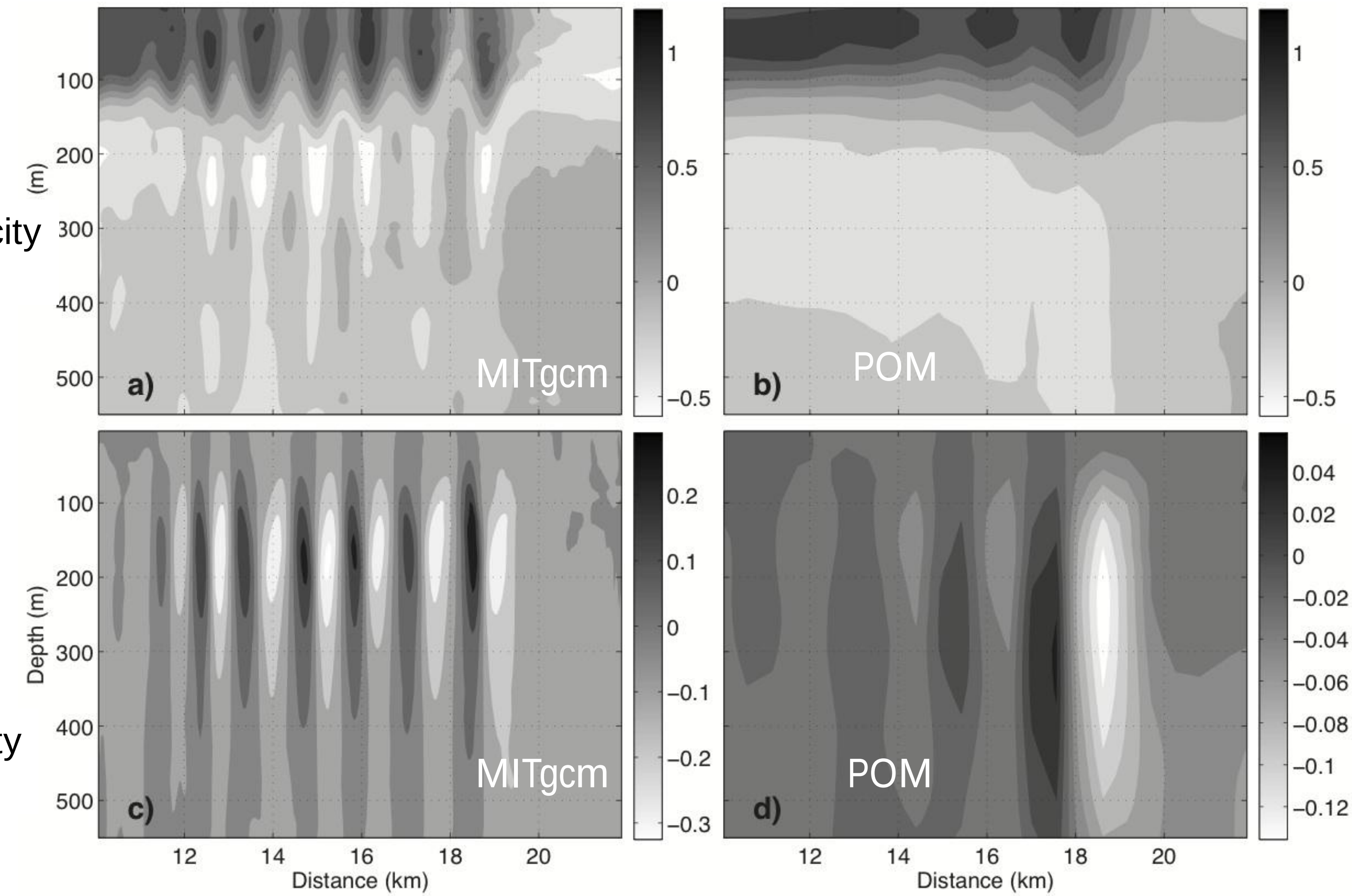
MITgcm vs POM – Internal bore evolution



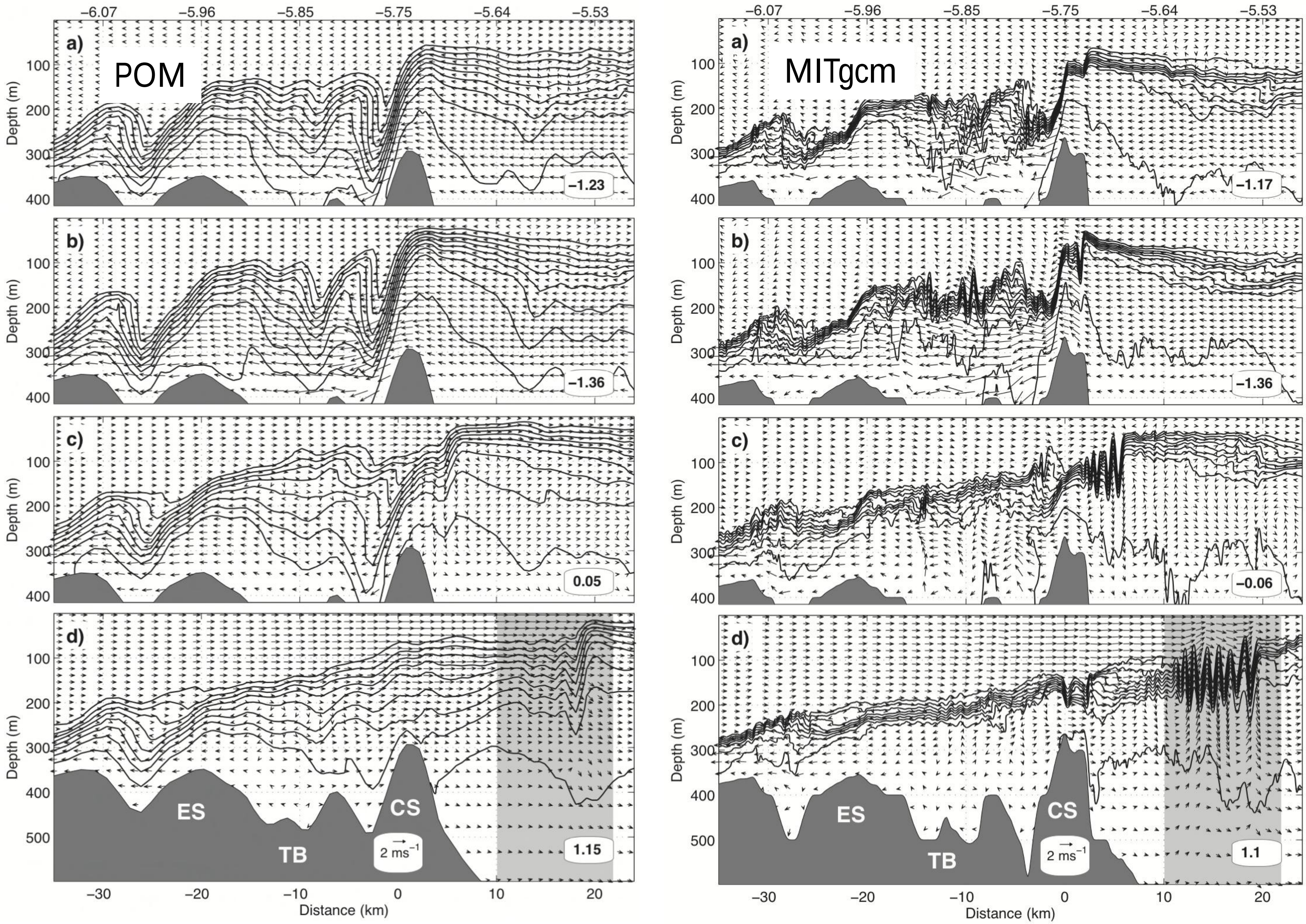
MITgcm vs POM – Internal bore evolution

Horizontal velocity (m/s)

Vertical velocity (m/s)



MITgcm vs POM – Internal bore evolution



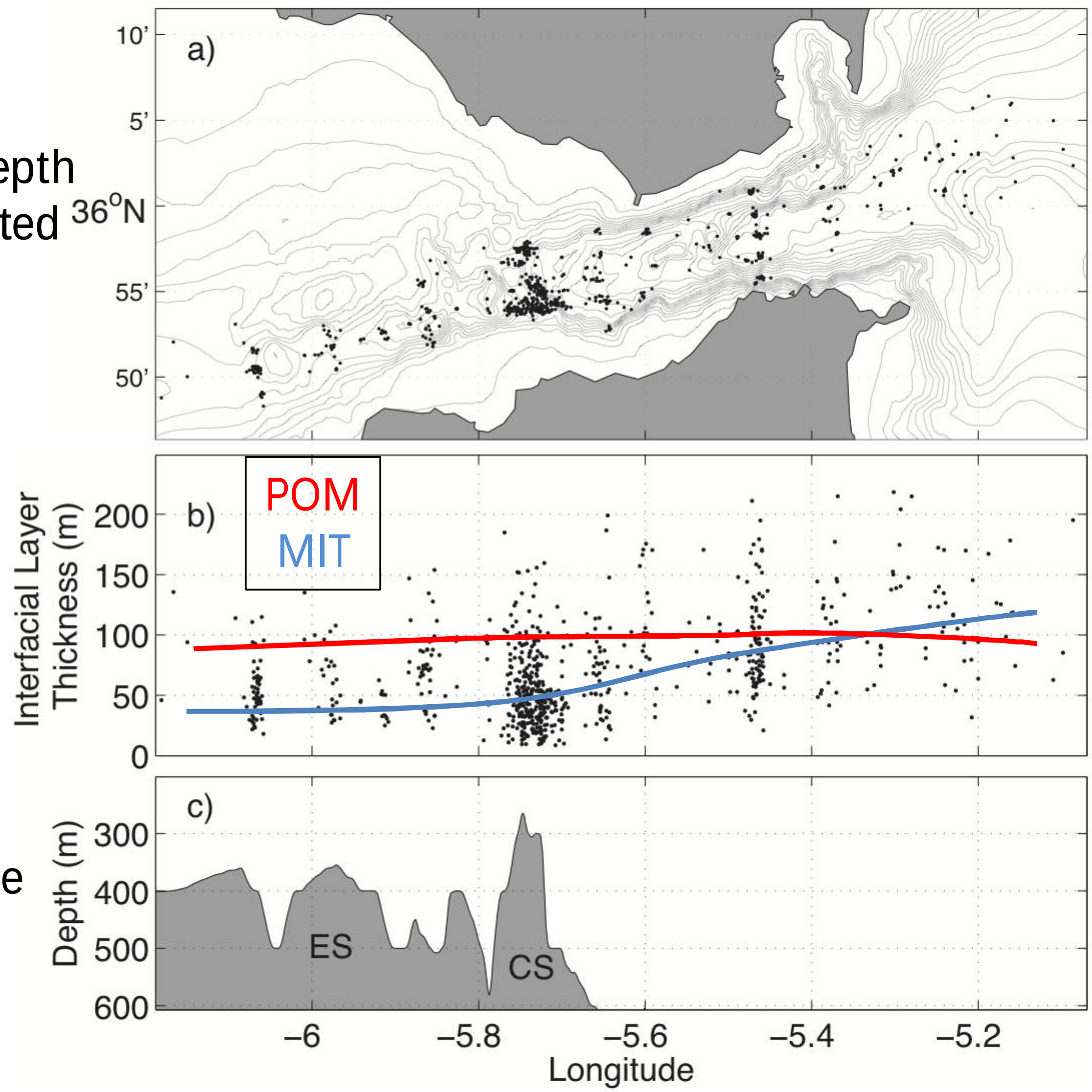
Garrido et al. jgr 2011

Observed 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.

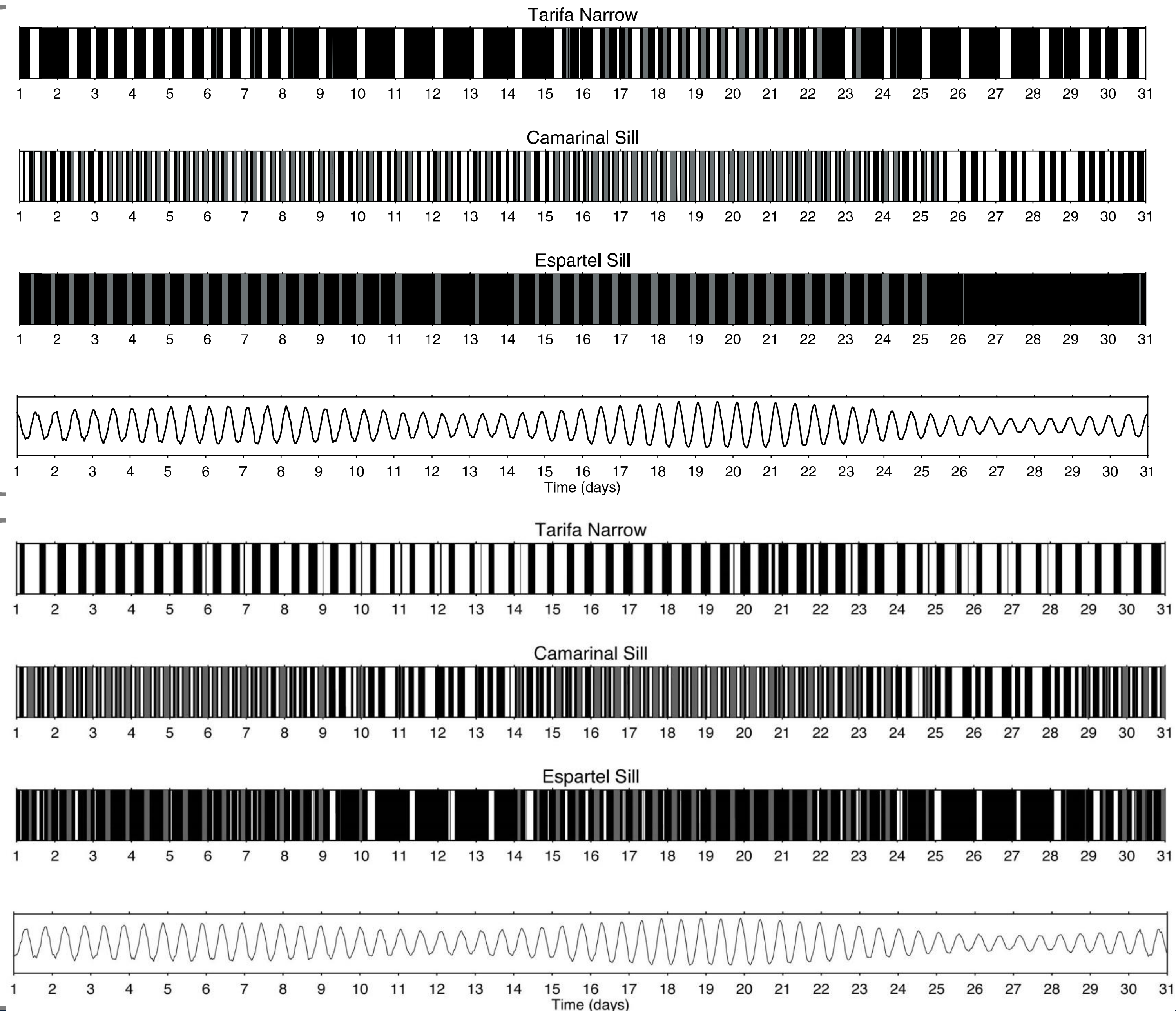


ENEA

MITgcm vs POM alongstrait hydraulics

POM

MITgcm



Strait of Gibraltar Background

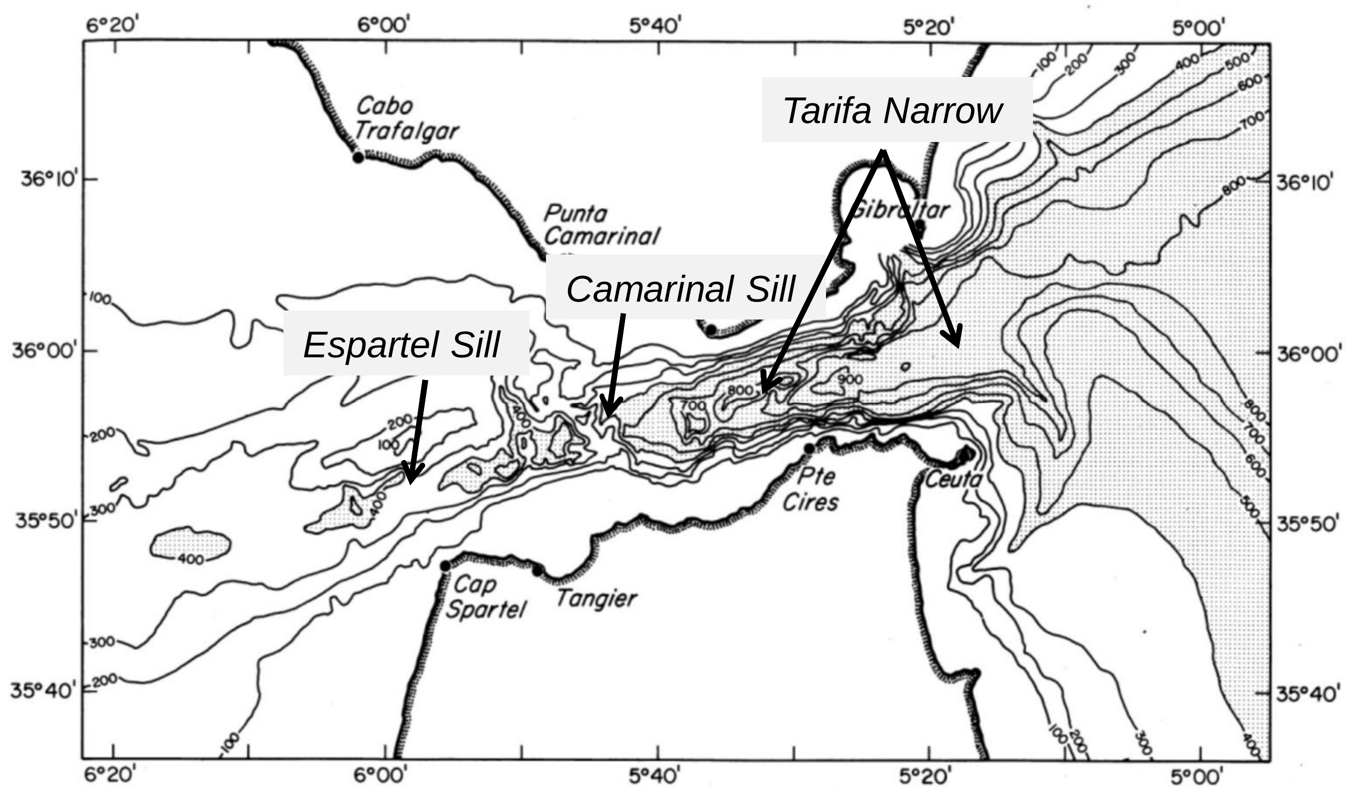
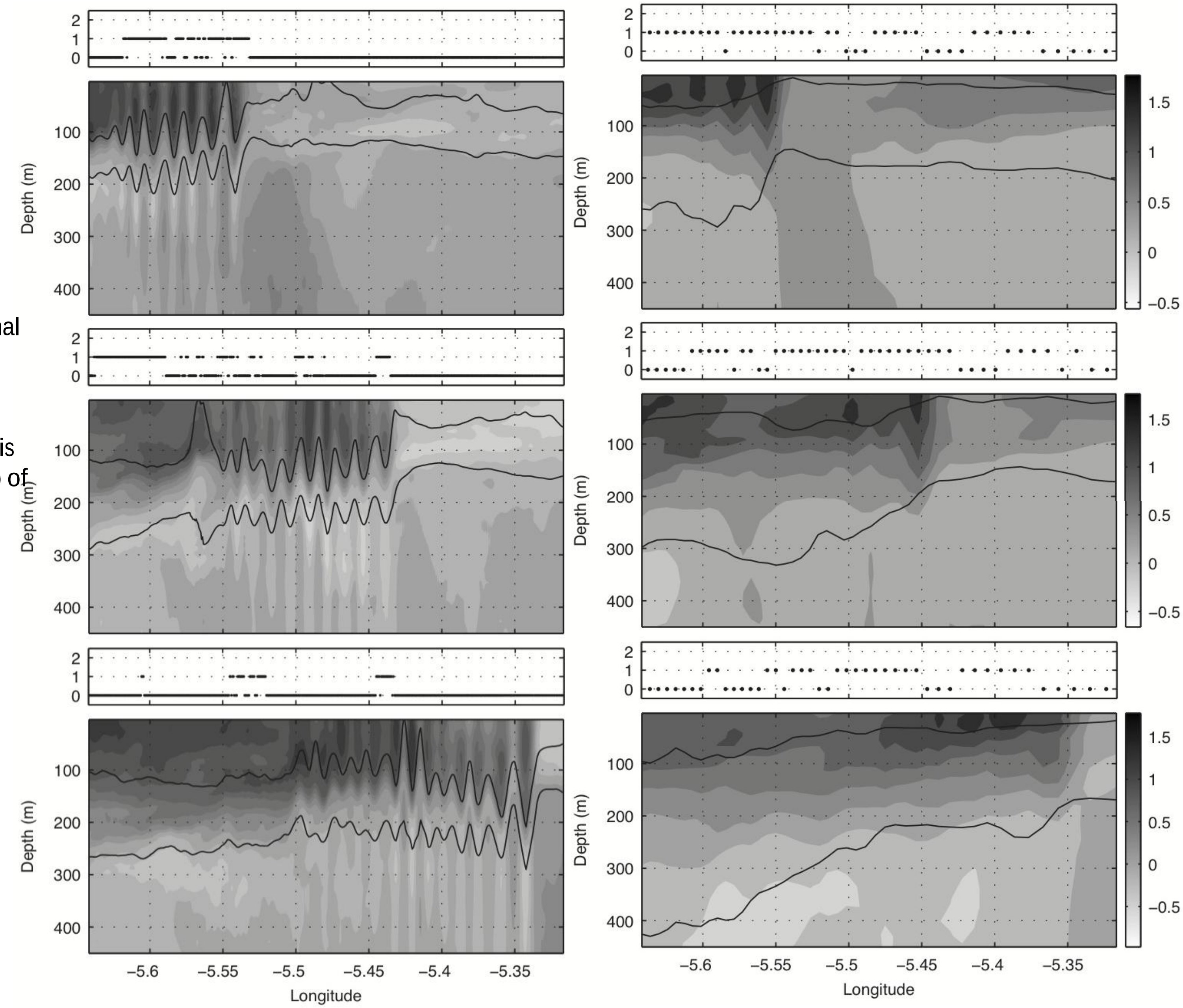


Chart of the Strait of Gibraltar, adapted from Armi & Farmer (1988), showing the principal geographic features referred to in the text.

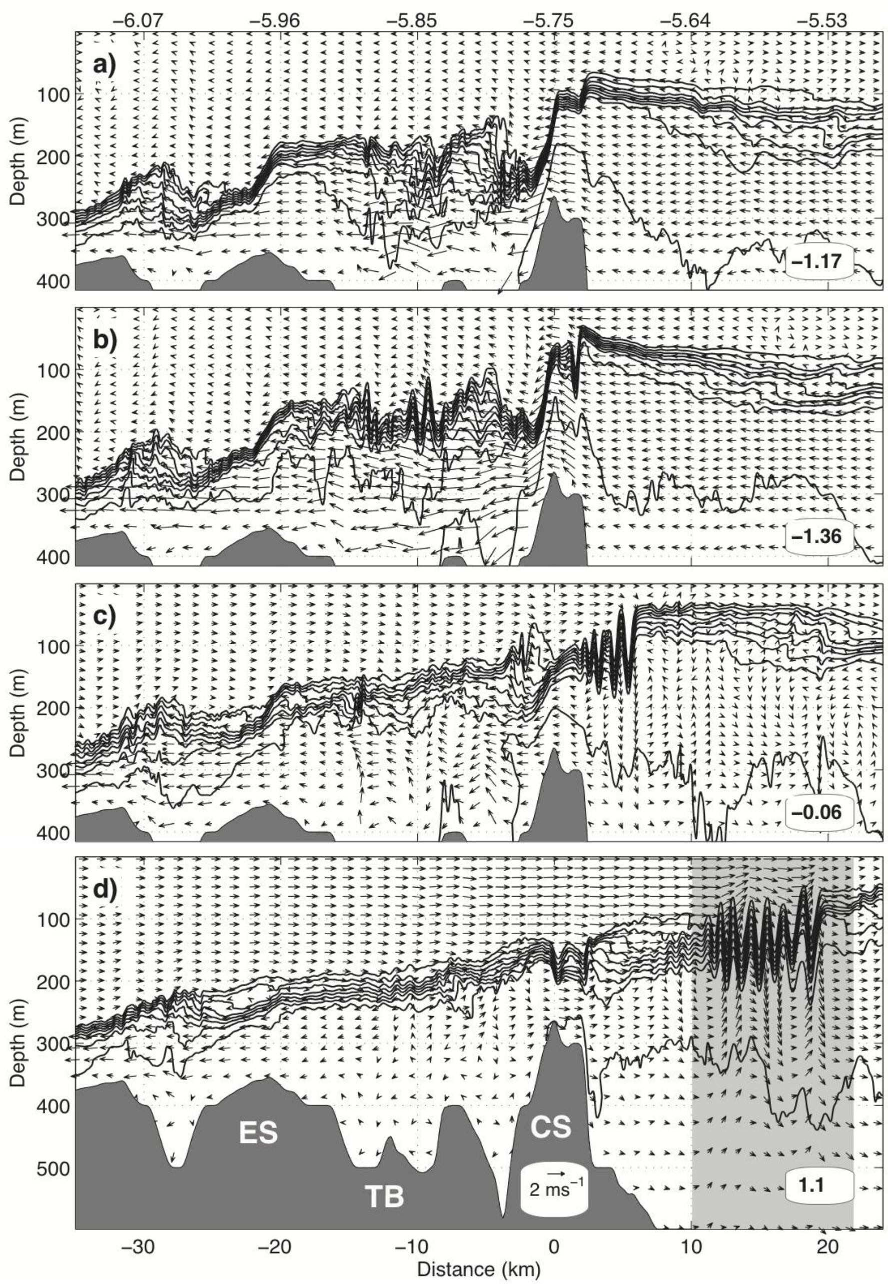
Areas deeper than 400 m are shaded

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.

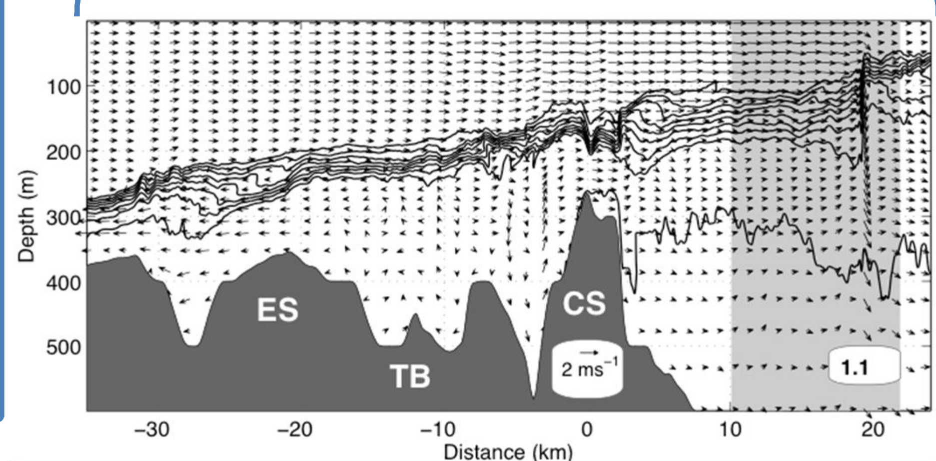


MITgcm sensitivity to non-hydrostaticity

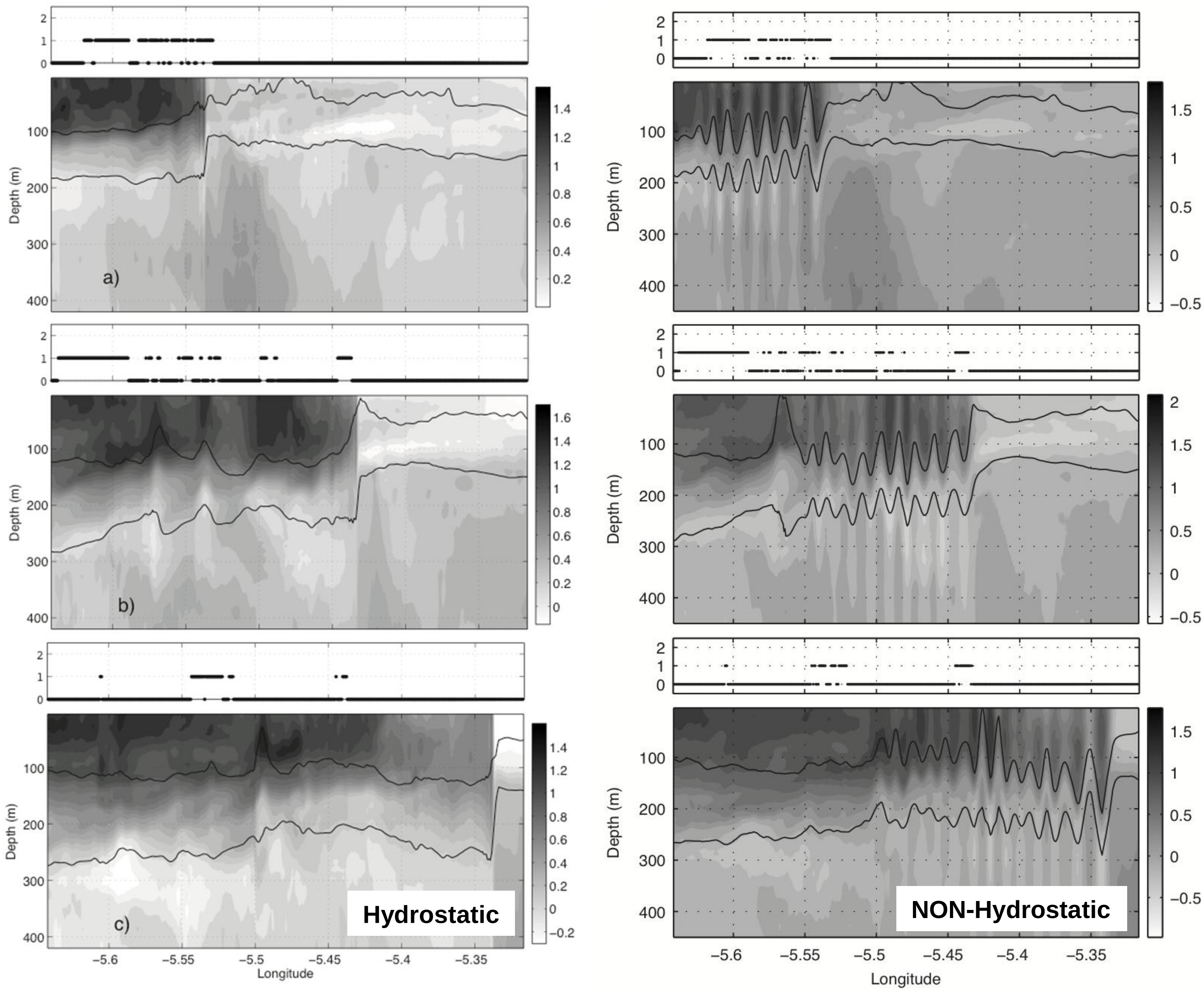


MITgcm NON Hydrostatic

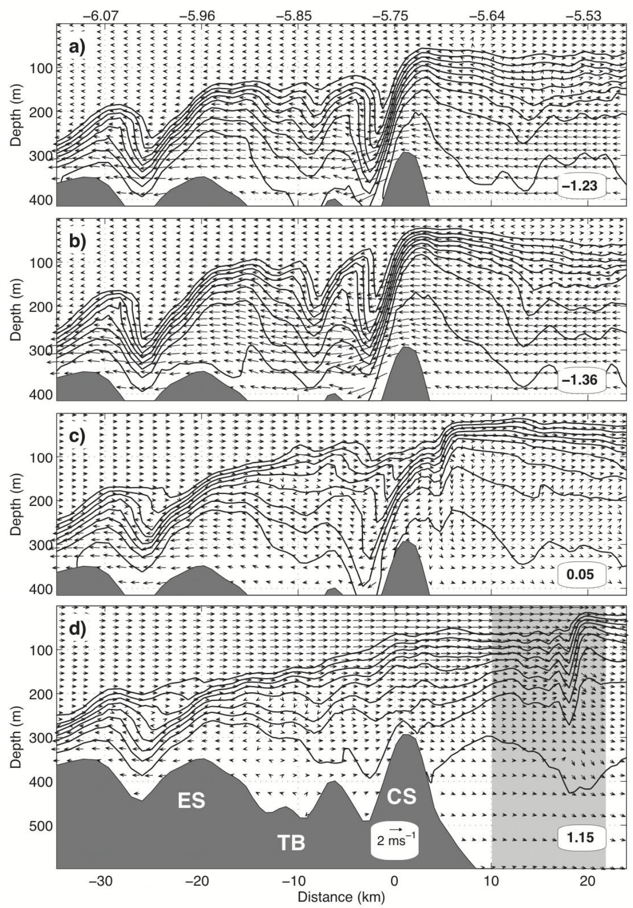
MITgcm Hydrostatic



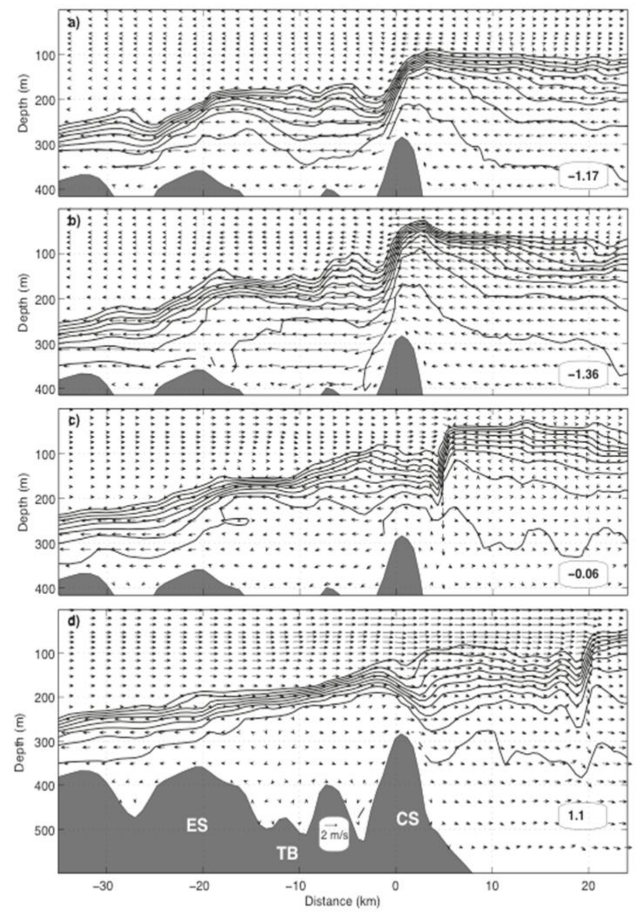
MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



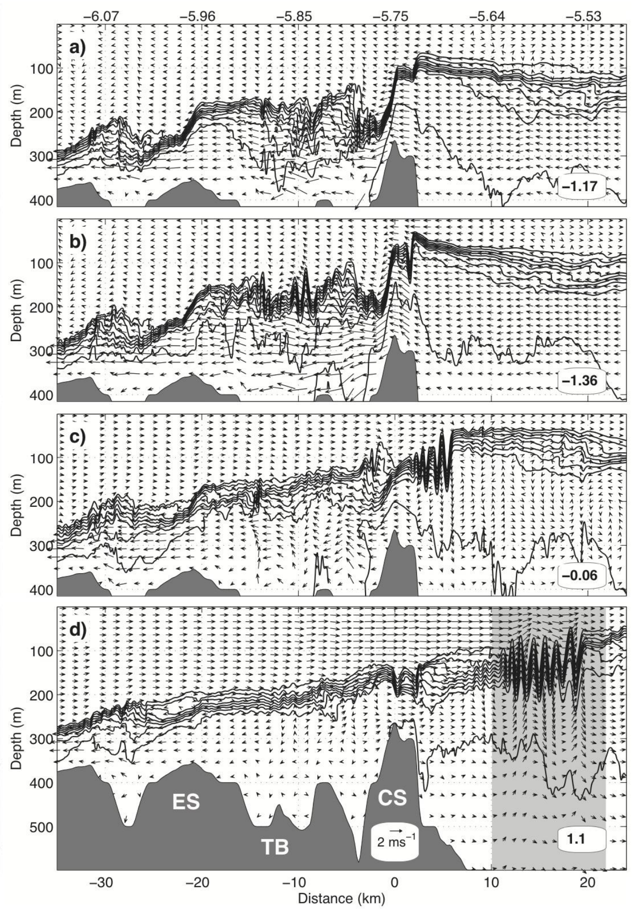
MITgcm alongstrait hydraulics & bore propagation-Hydrostatic



POM
Original simulation

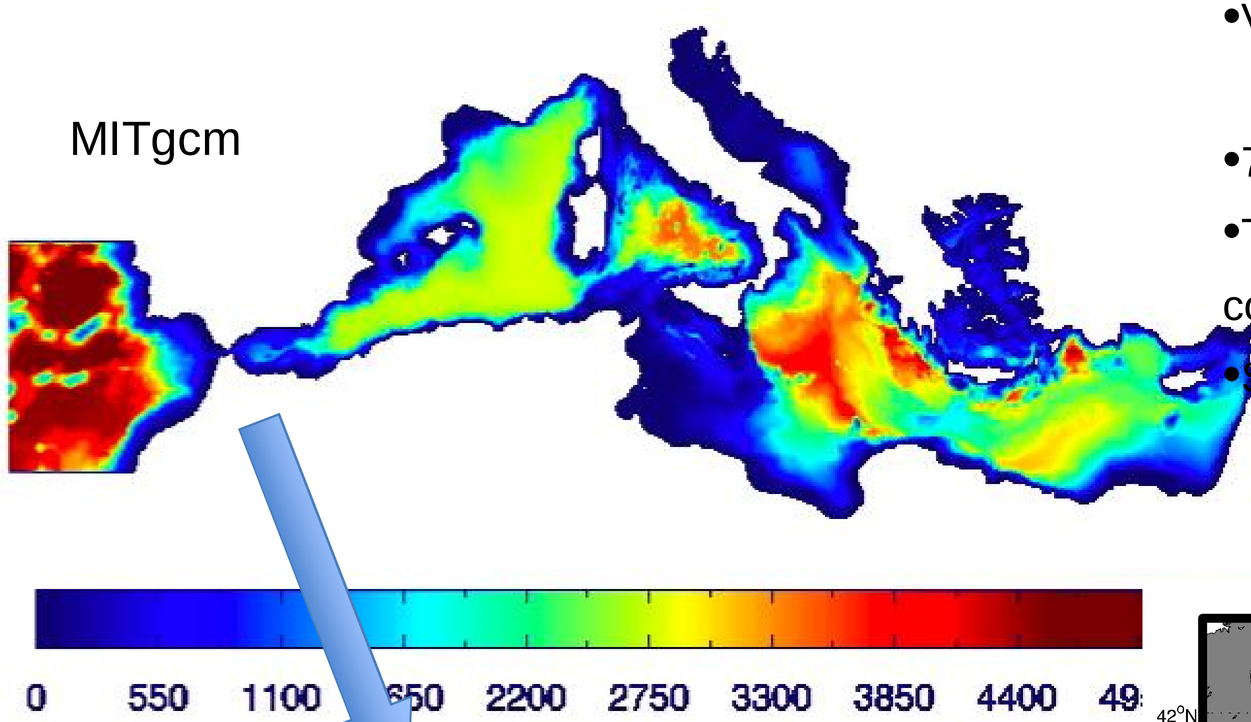


MITgcm
hydrostatic
Model grid as POM

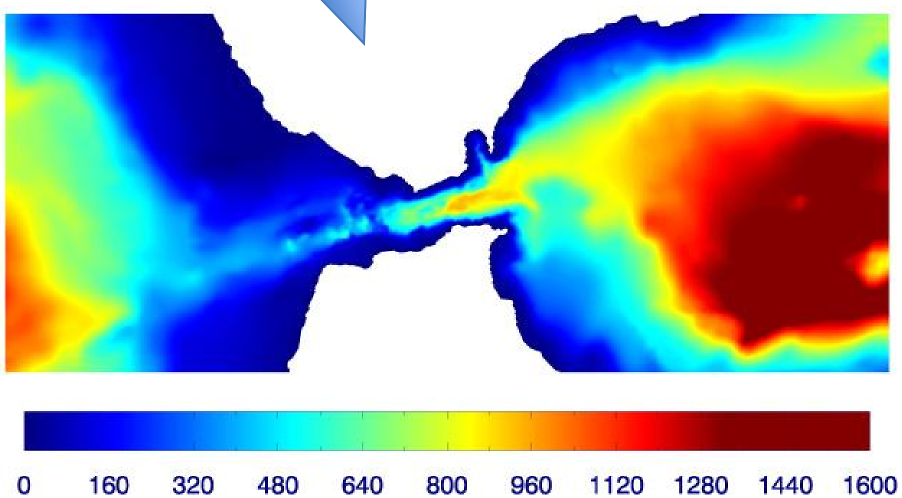


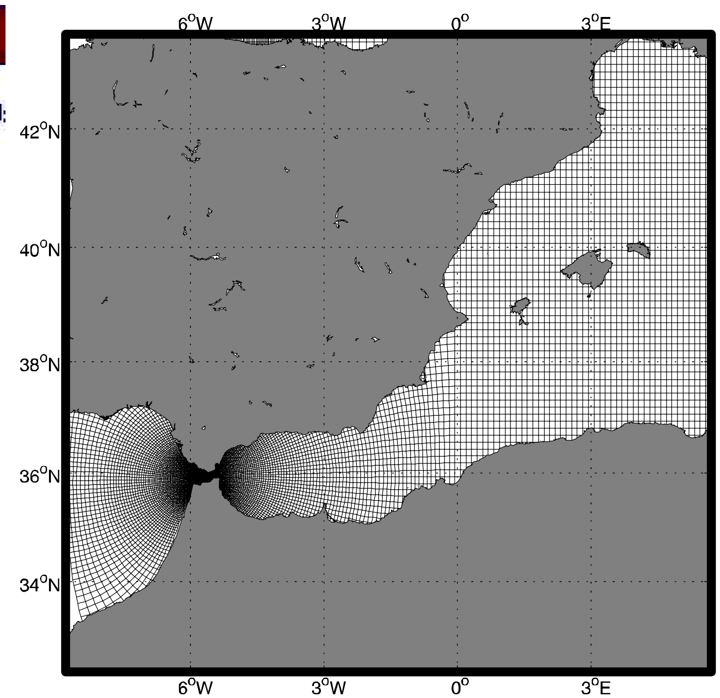
MITgcm
NON-Hydrostatic
Original grid

New modeling strategy for the Mediterranean

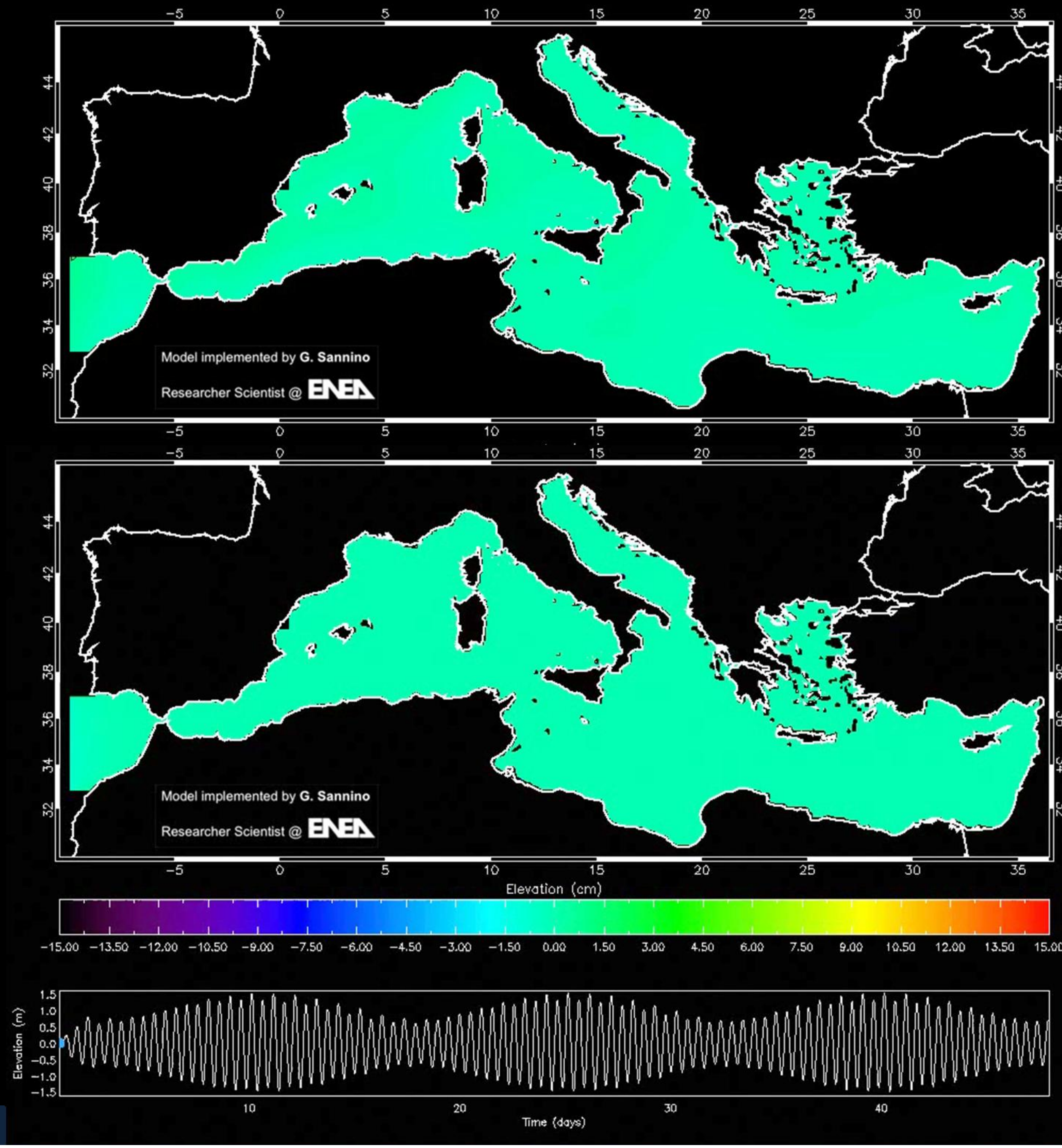


- Variable horizontal resolution (1/16 ° up to 1/200 °)
- 72 vertical levels
- Tidal forcing (main 4 components)
- Surface atmospheric pressure



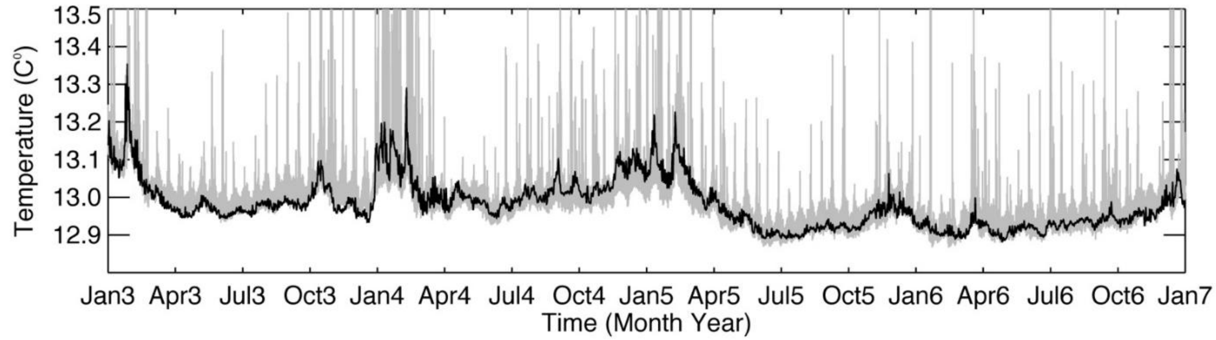


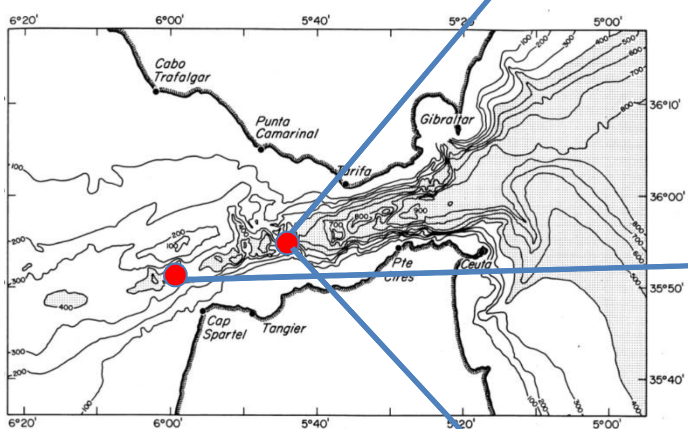
New modeling strategy for the Mediterranean

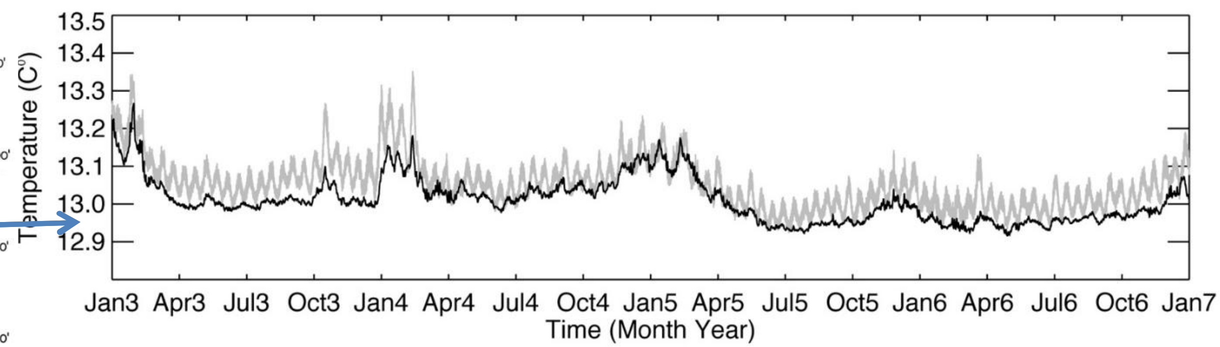


Results: temperature in the Strait

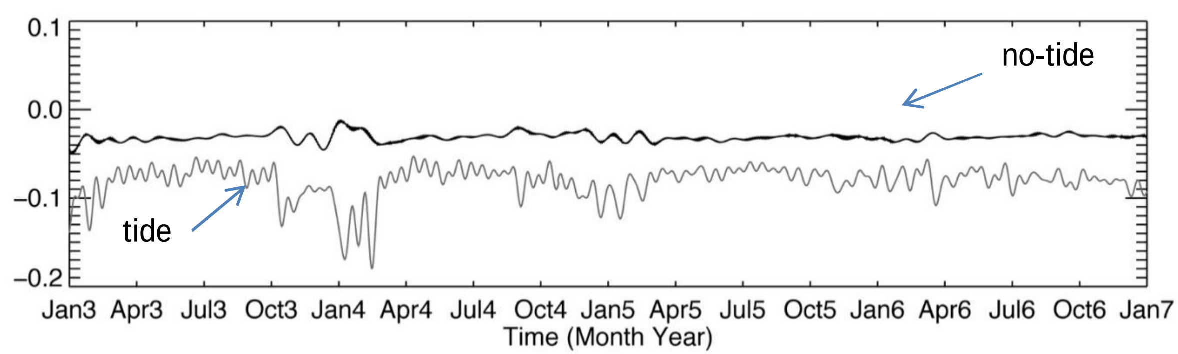
Time series of the vertical minimum temperature for the years 1963-1967. Upper panel for the CS and lower panel for ES. ExpT in grey, ExpNT in black







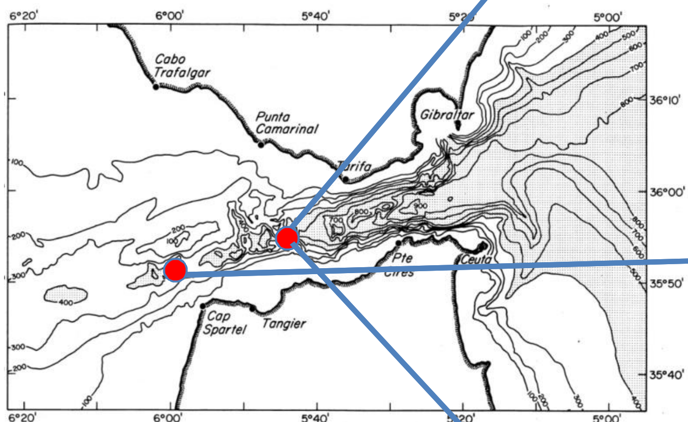
Time series of the difference between daily minimum temperature in CS and in ES filtered off frequencies higher than 30 days. ExpT in grey, ExpNT in black.

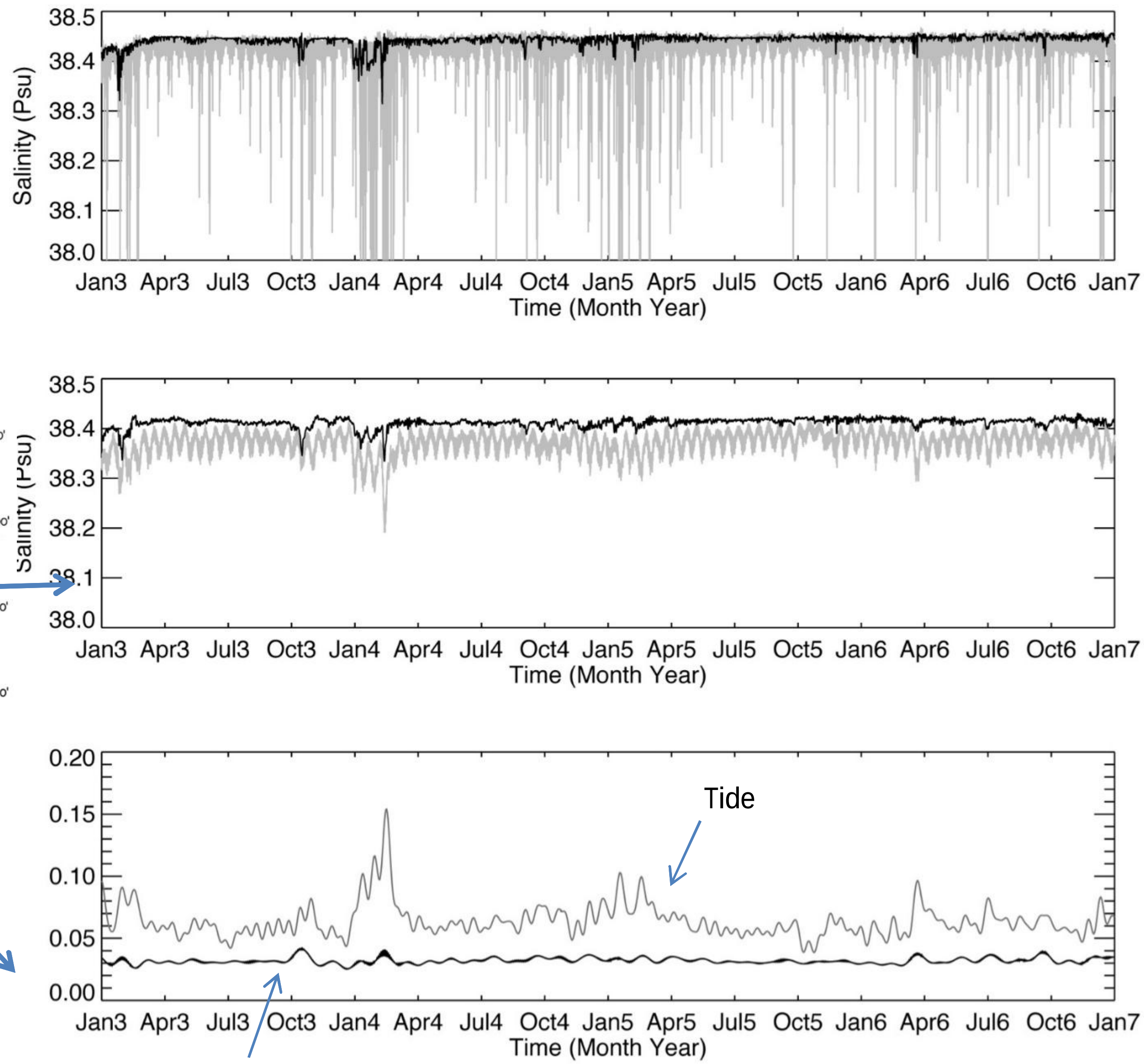


Sannino et al. 2015
Progress in Ocean.

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



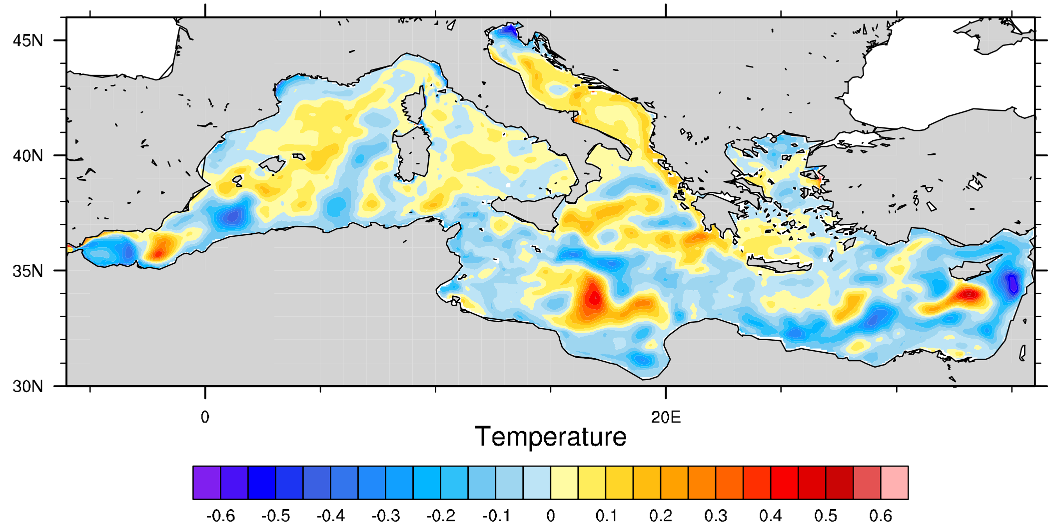


Time series of the difference between daily maximum salinity in CS and in ES filtered off frequencies higher than 30 days. ExpT in grey, ExpNT in black.

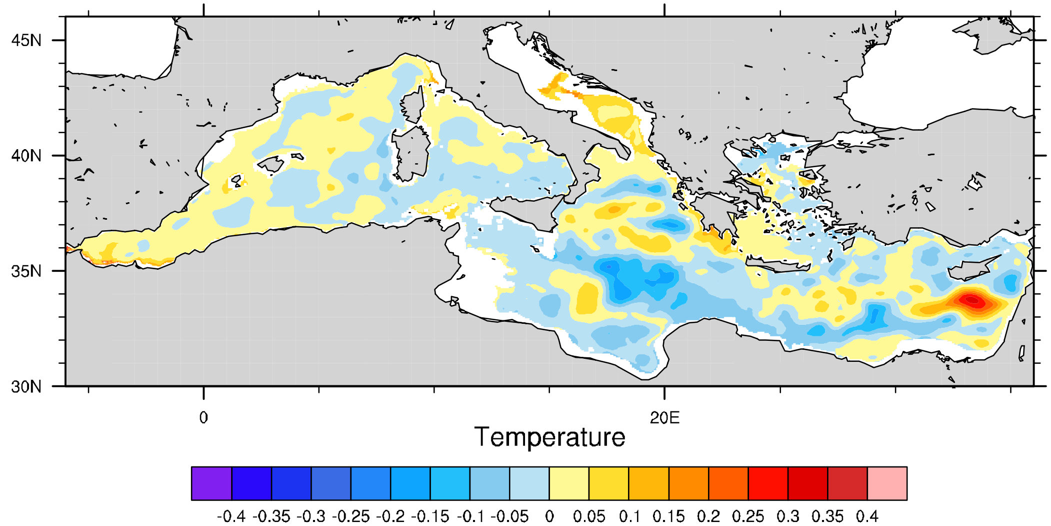
Sannino et al. 2015
Progress in Ocean.

Results: temperature difference

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



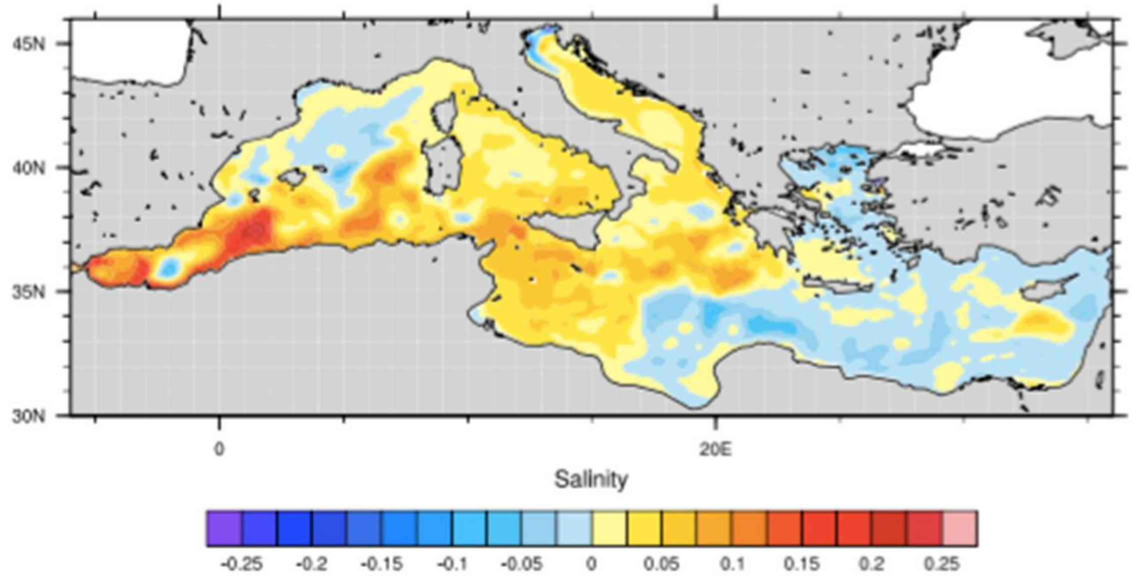
Temperature difference between the ExpT and ExpNT. Data are vertically averaged between 150 m and 500m. Time-averaged over the entire simulated period



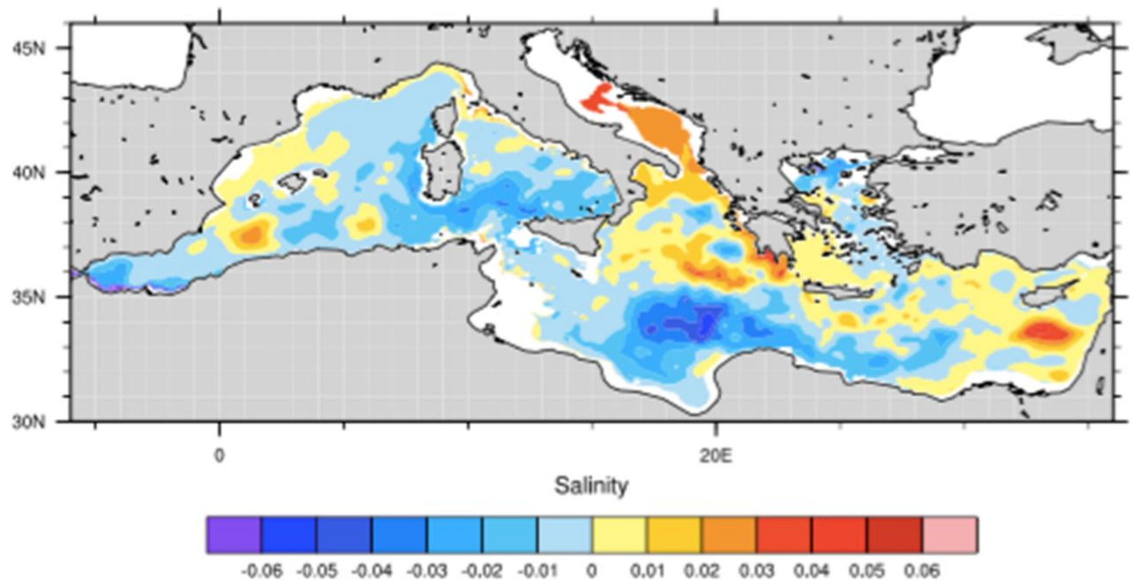
Sannino et al. 2015
Progress in Ocean.

Results: salinity difference

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



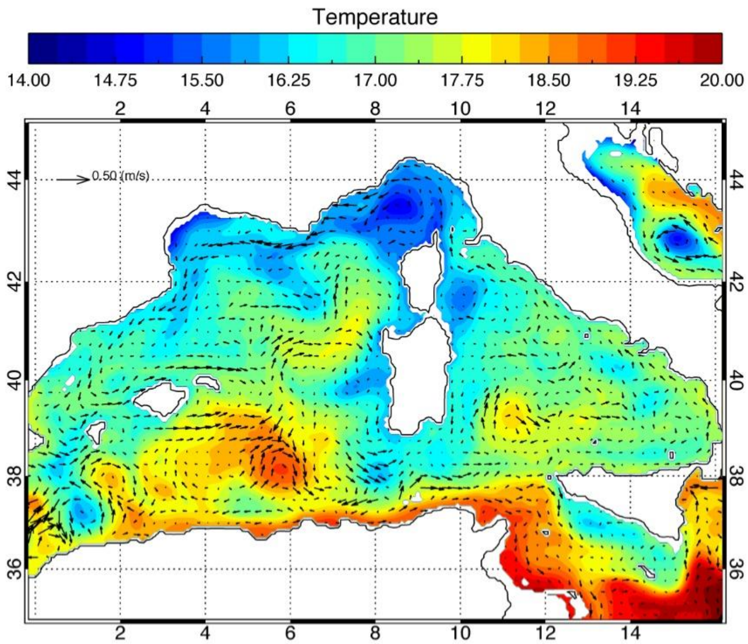
Salinity difference between the ExpT and ExpNT. Data are vertically averaged between 150 m and 500m. Time-averaged over the entire simulated period



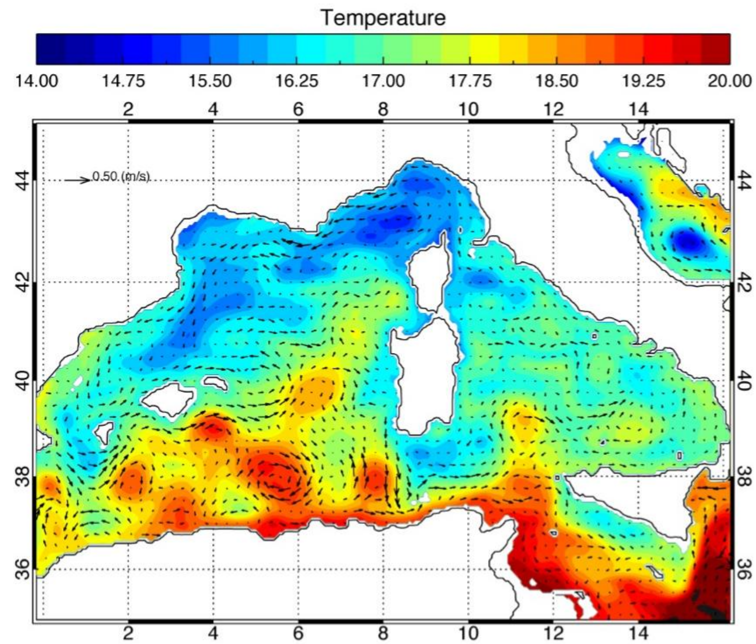
Sannino et al. 2015
Progress in Ocean.

Results: surface circulation

ExpTD

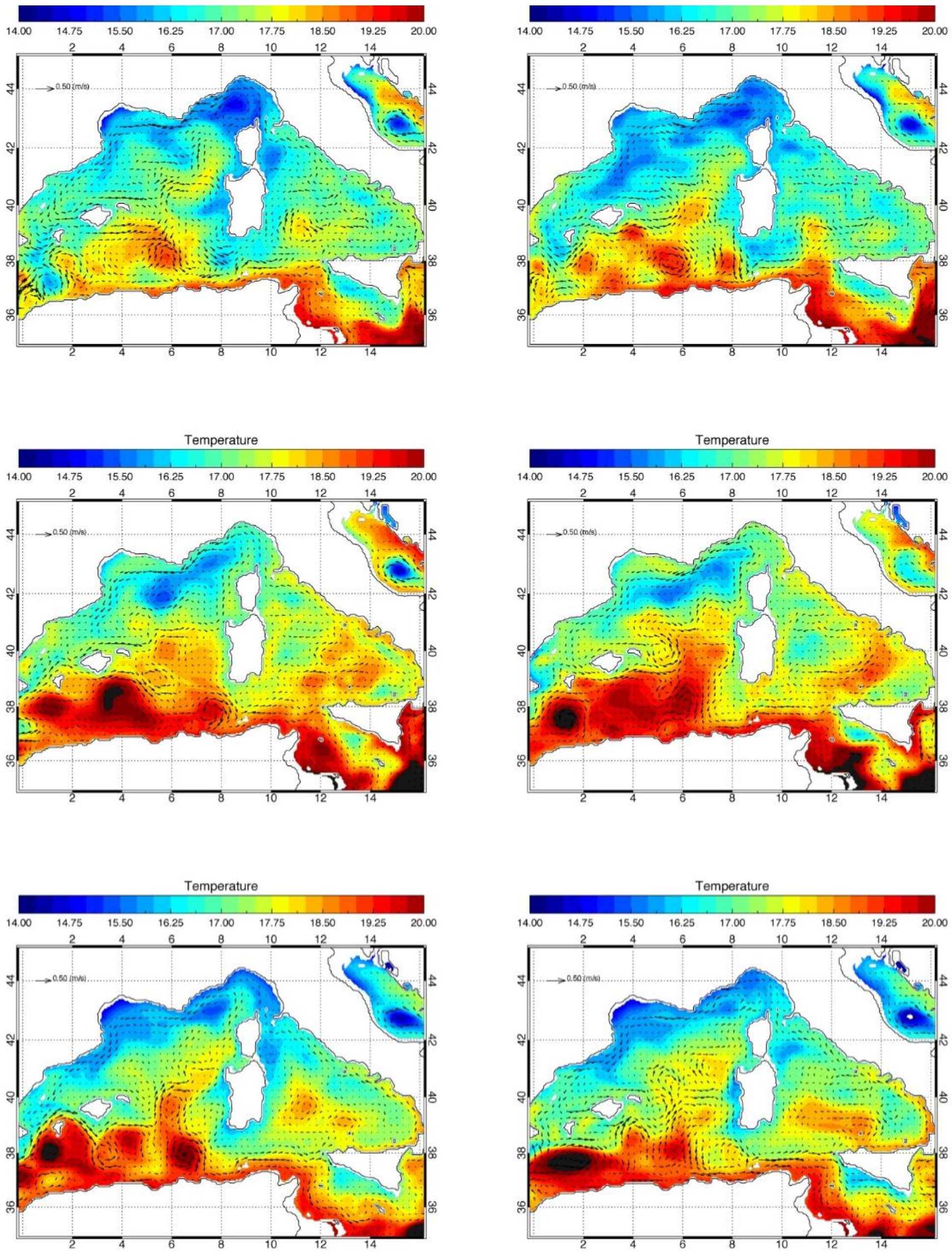


ExpNoTD



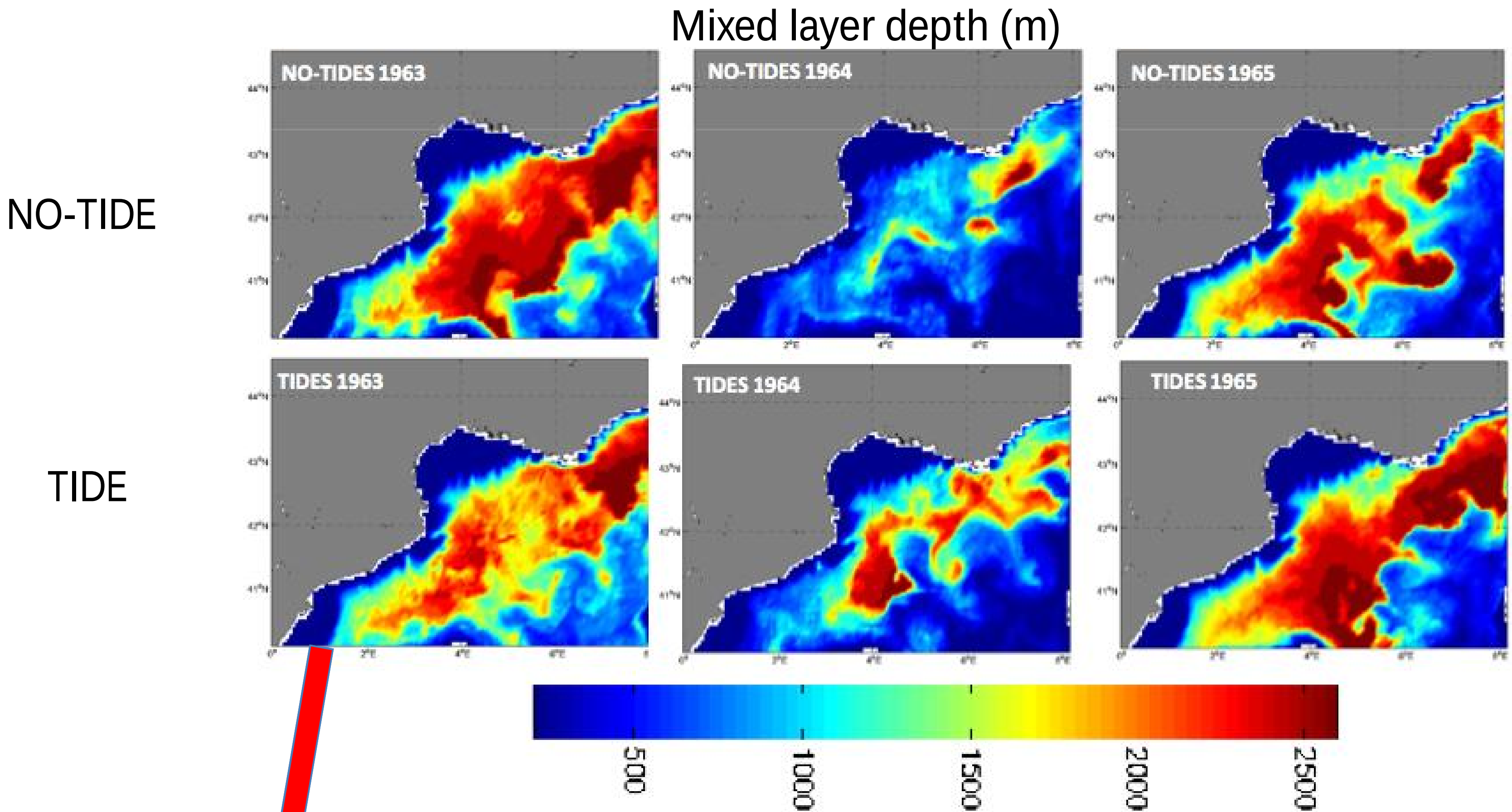
Temperature at 50m time-averaged over the period October-December 1962

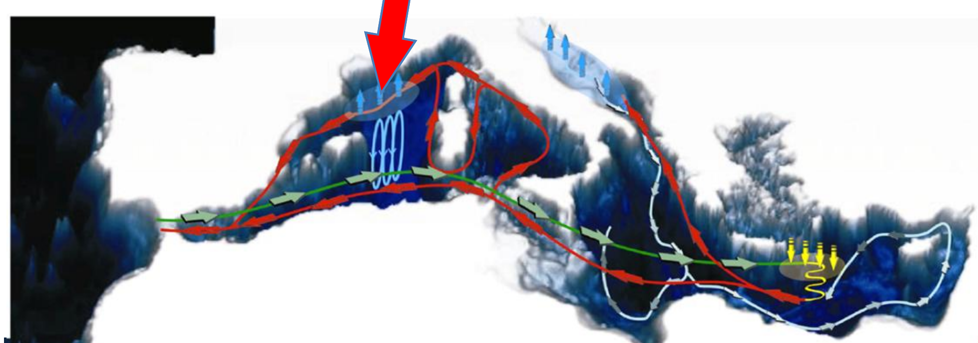
Results: surface circulation



Temperature at 50m time-averaged over the period October-December 1962 (upper panel) October-December 1963 (middle panel), and October-December 1964 (lower panel). One of three values of velocity are plotted. Left ExpT, right ExpNT

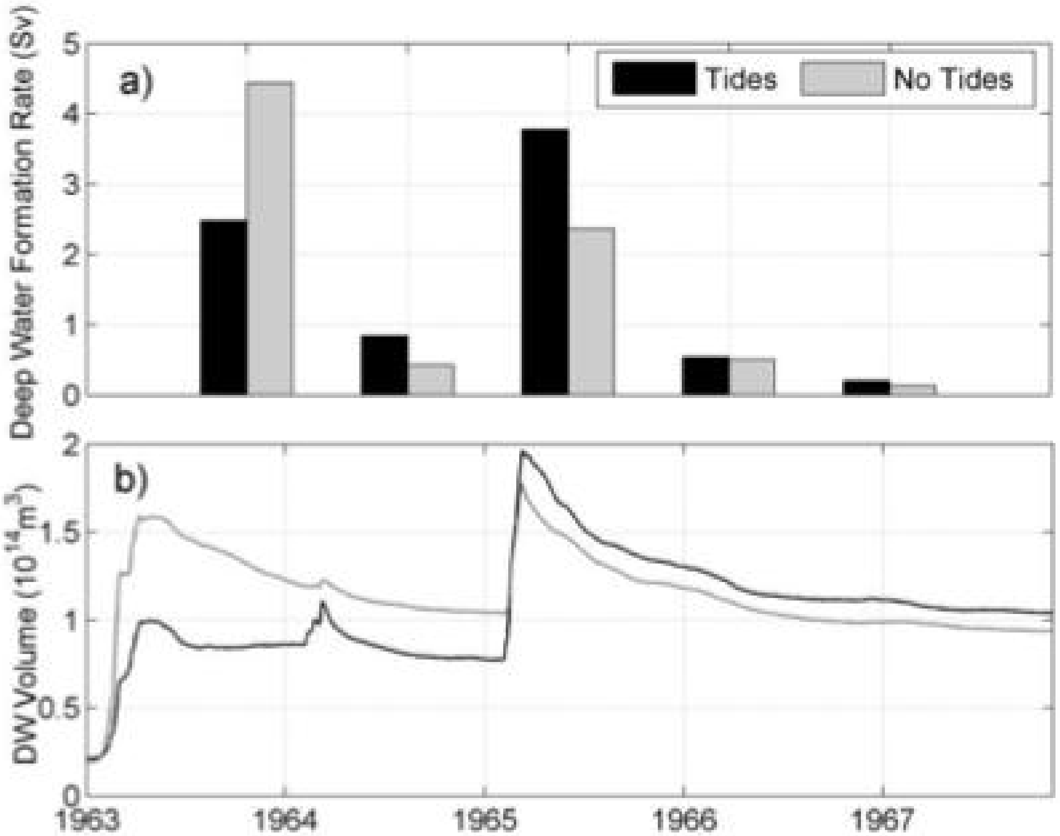
Results: Mixed Layer Depth





Naranjo et al . Progress in Oceanography (2014)

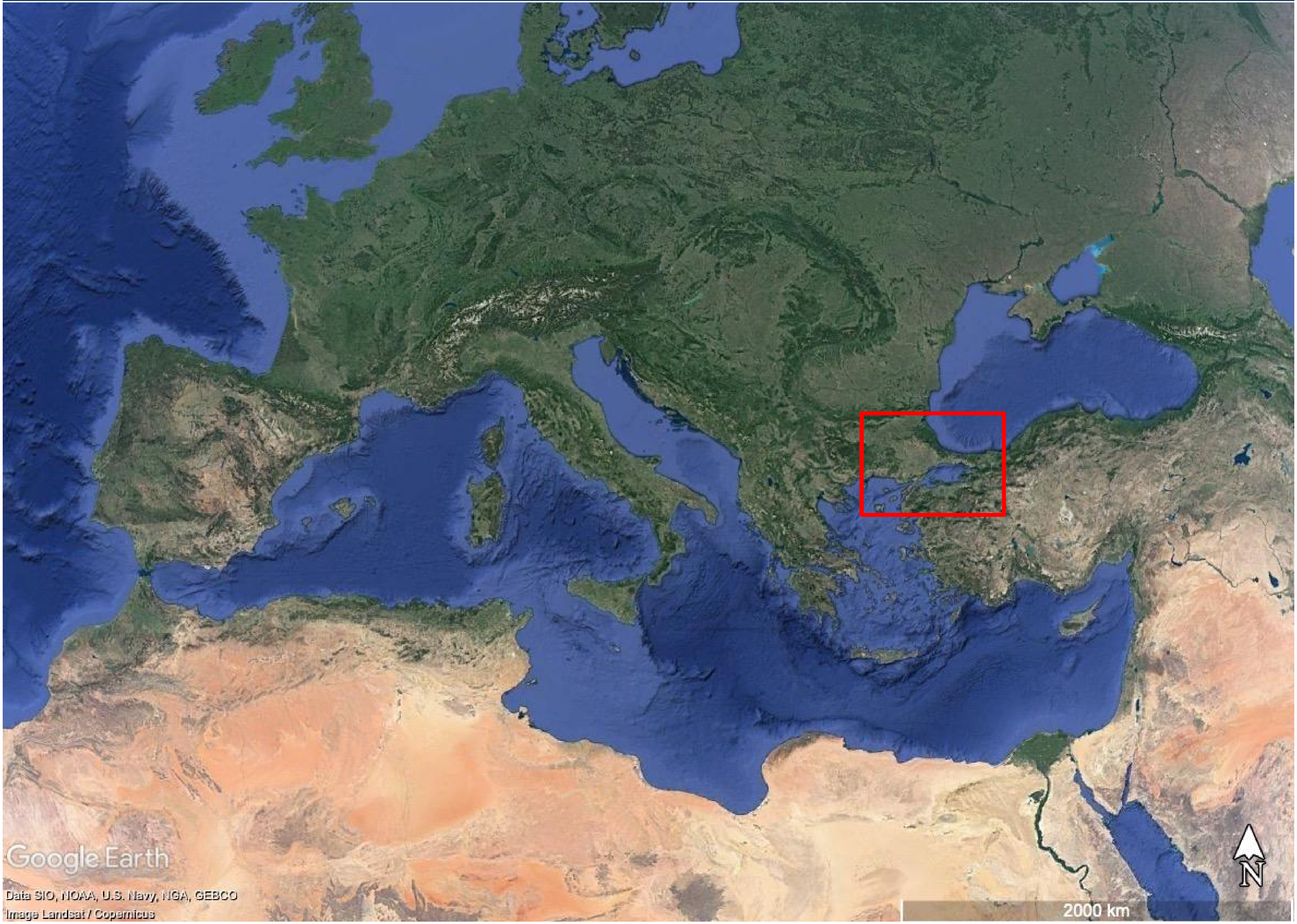
Results: Water formation rate in the Gulf of Lion



Deep Water formation rate (in Sv)

A longer simulation
is on the way

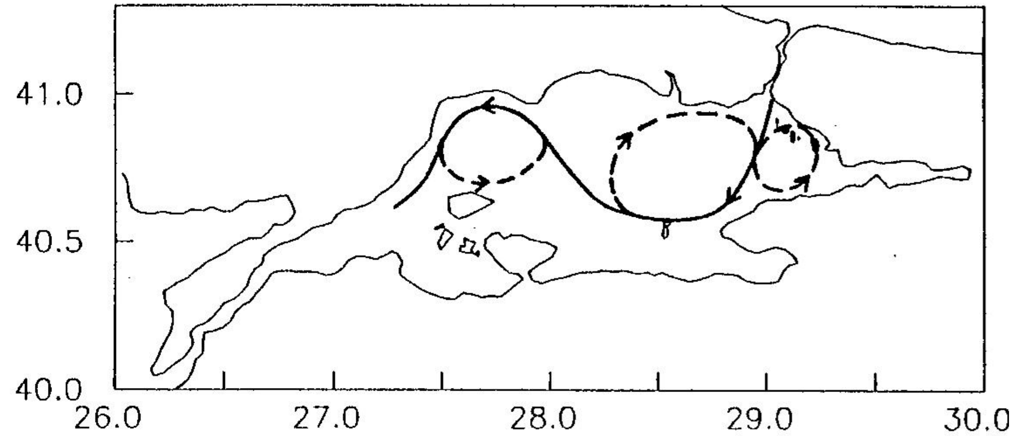
Background geography



Turkish Strait System Background

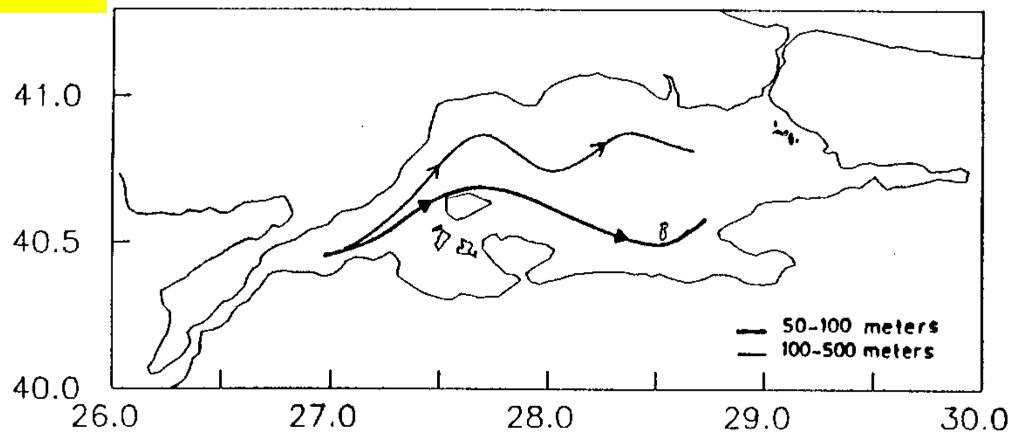
Turkish Strait System Background: 2-layer circulation

upper layer circulation



Dardanelles Strait | **Marmara Sea** | **Bosphorus Strait** | **Black Sea**

lower layer circulation



Beşiktepe et al. 1994

Turkish Strait System Background: surface circulation

29 April 2013

Turkish Strait System Background: surface circulation

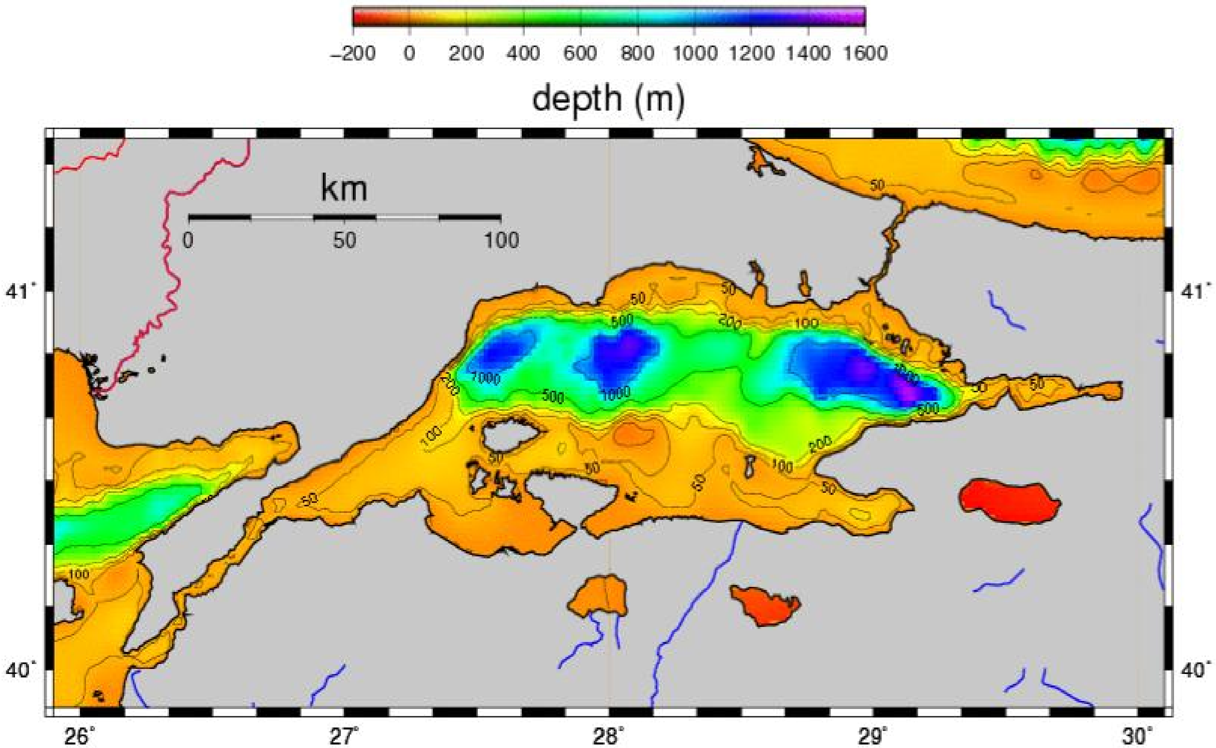
26 April 2013

27 April 2013

Turkish Strait System Background: Previous modeling attempts

The Turkish straits system is a complex environment characterized by highly contrasting properties in a region of high climatic variability.

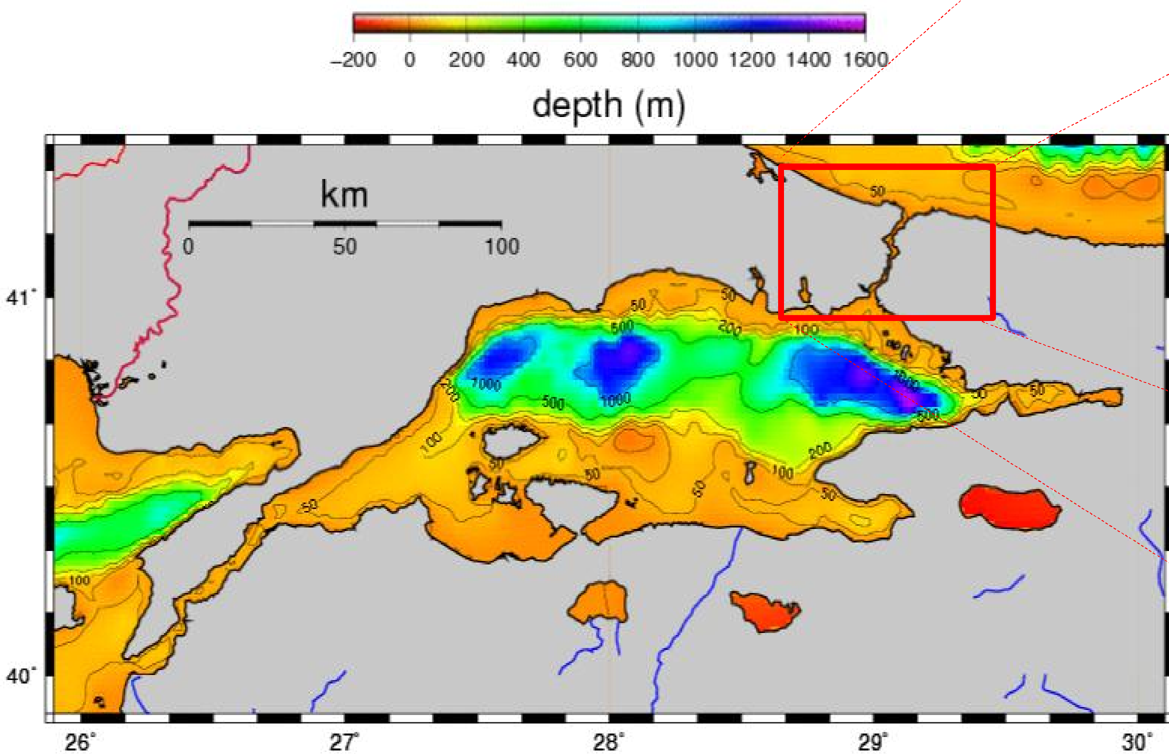
An all time challenge is the modeling of the entire system: Dardanelles – Maramara Sea – Bosphorous.

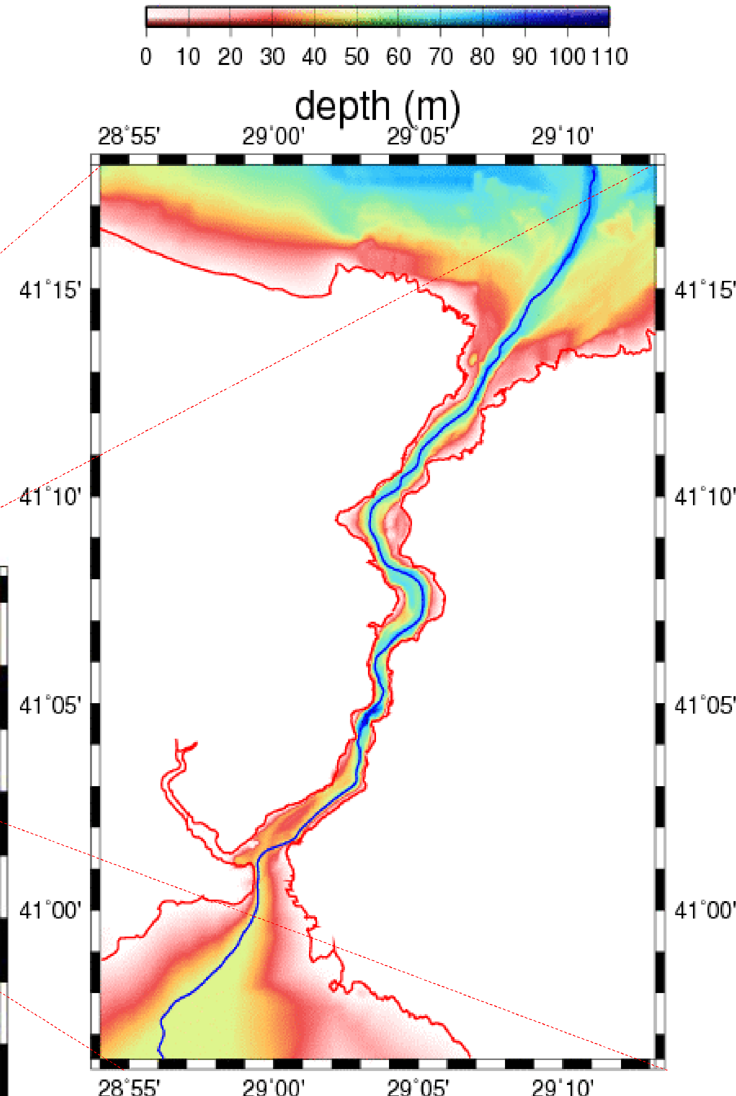


<u>Question</u>:

can we use state-of-art finite difference model to reproduce correctly the TSS circulation?

Turkish Strait System Background: Bathymetry





Length 35 km
Min. width 0.7 km

Turkish Strait System: our finite difference modeling approach

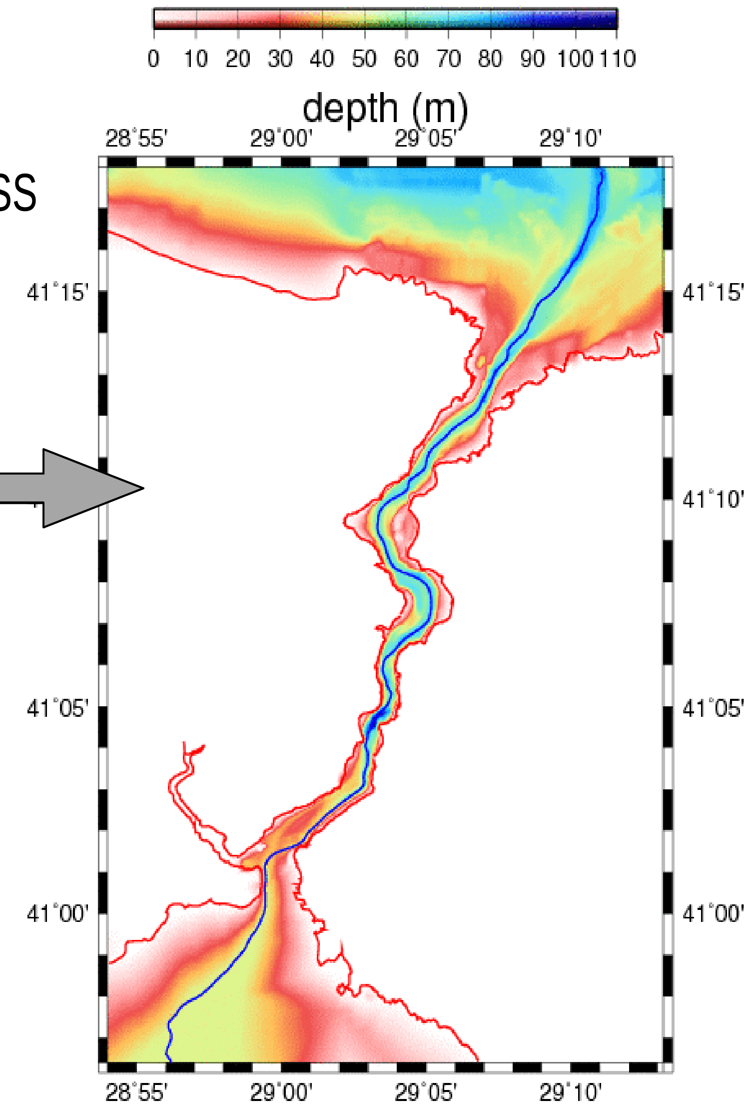
Model choice

Application to the most challenging place of the TSS

z-level σ-level

MITgcm ROMS

Performances Comparison



Bosphorus Strait

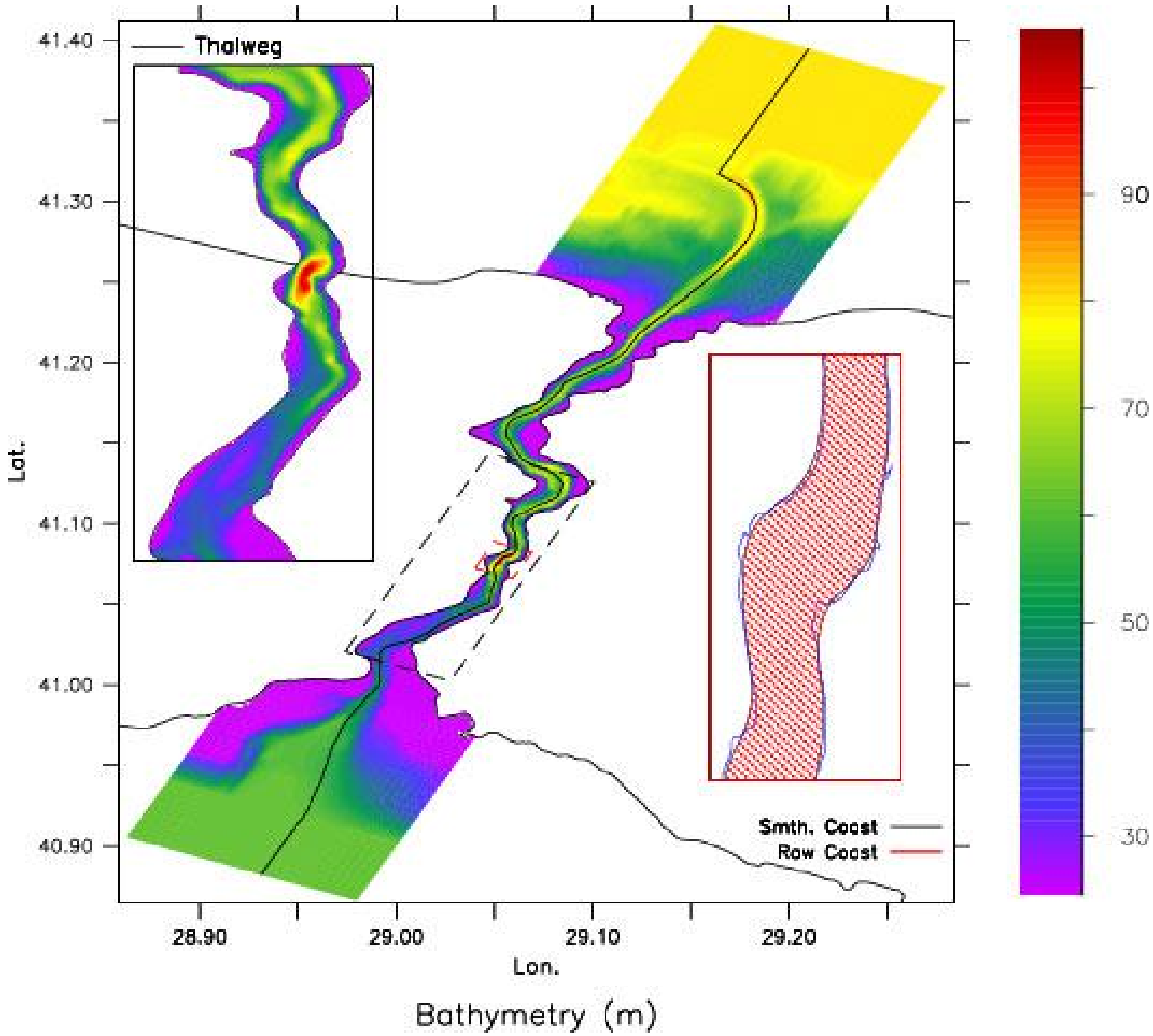
Bosphorus Modeling: Two Models – One Model configuration

Model Grid

Dx = 50-200m
Dy = 50-325m
L = 11,500m
M = 61,475m
Min Depth=25m

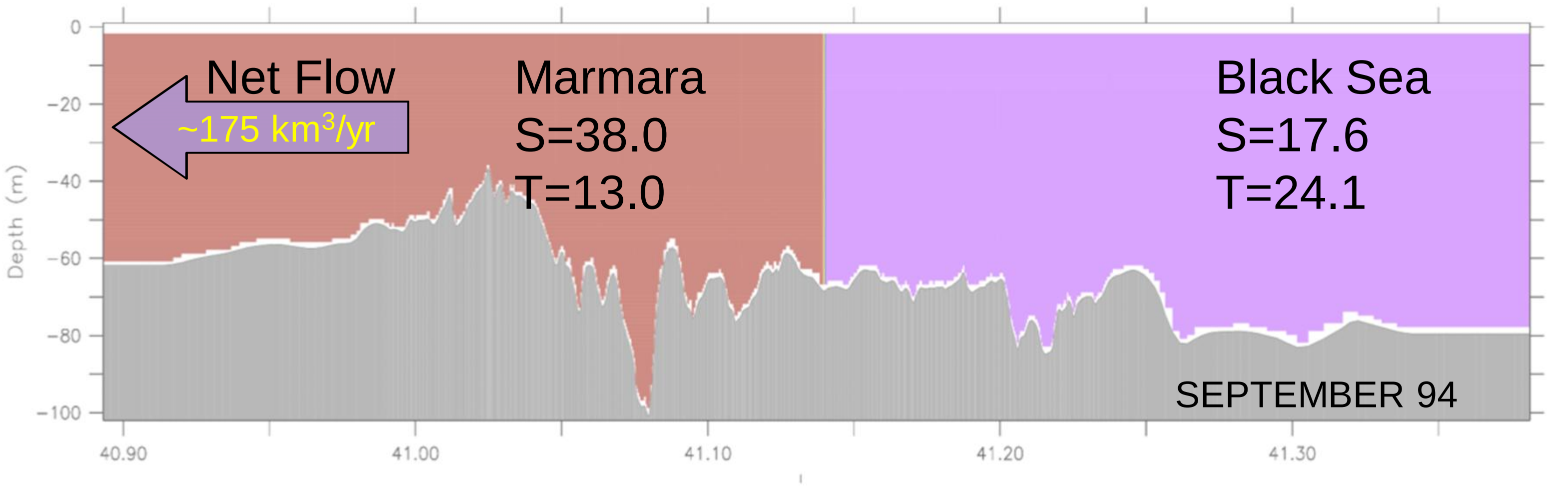
ROMS
Dz=0.7-2.9m
Grid Size=163x716x35

MITgcm
Dz=1.4m
Grid Size=163x716x70

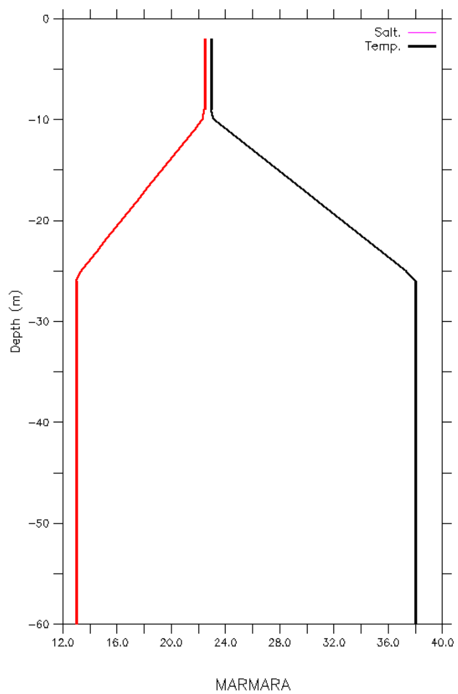


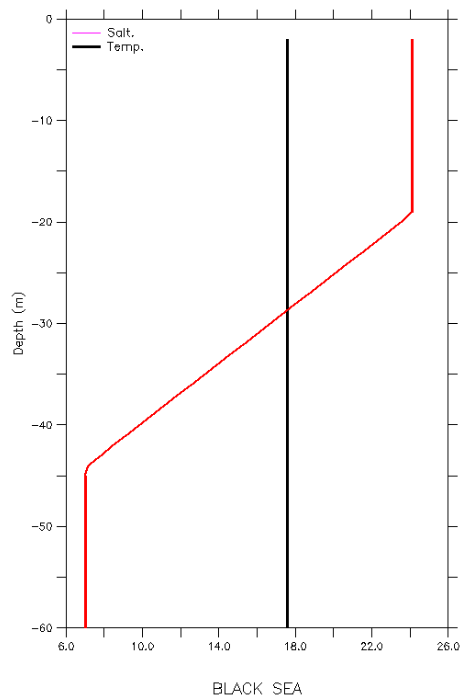
Bosphorus Modeling: Two Models – One setup

Orlanski Radiation

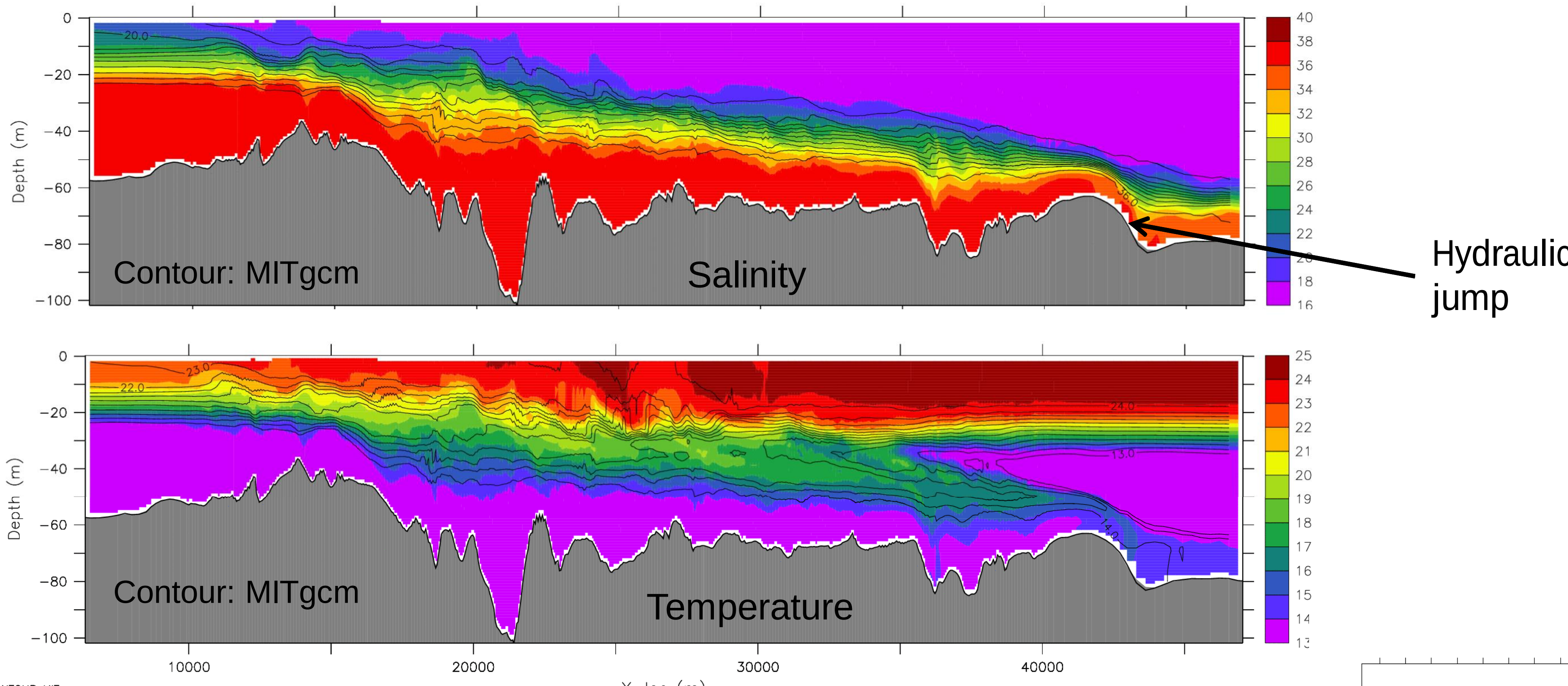


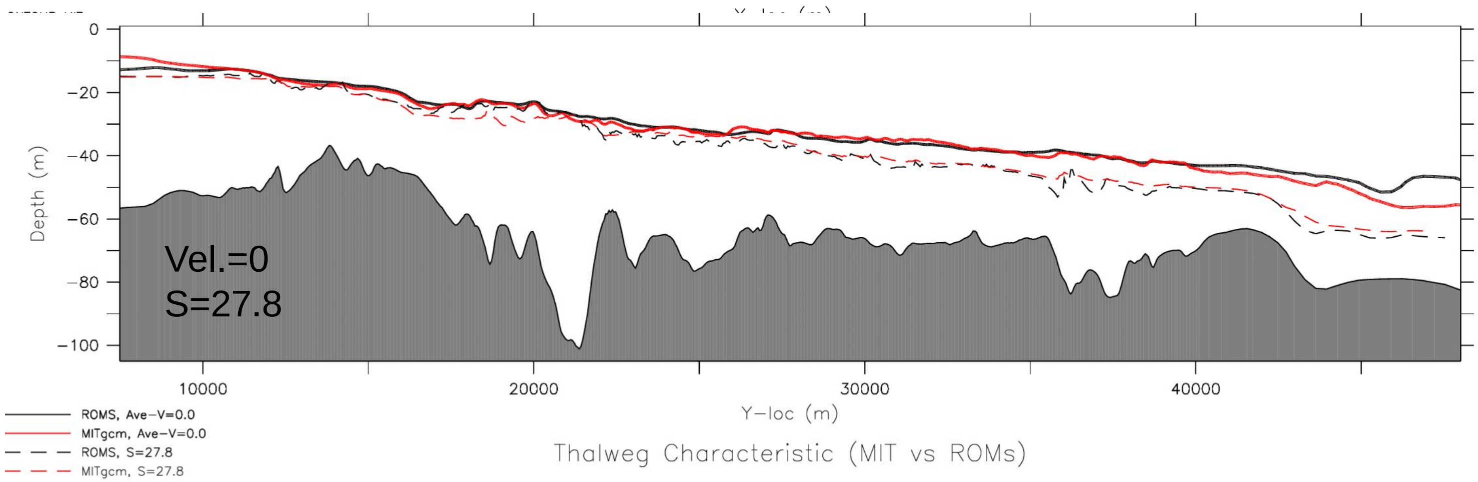
Orlanski Radiation

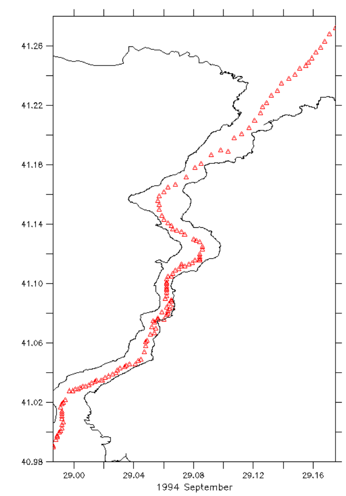




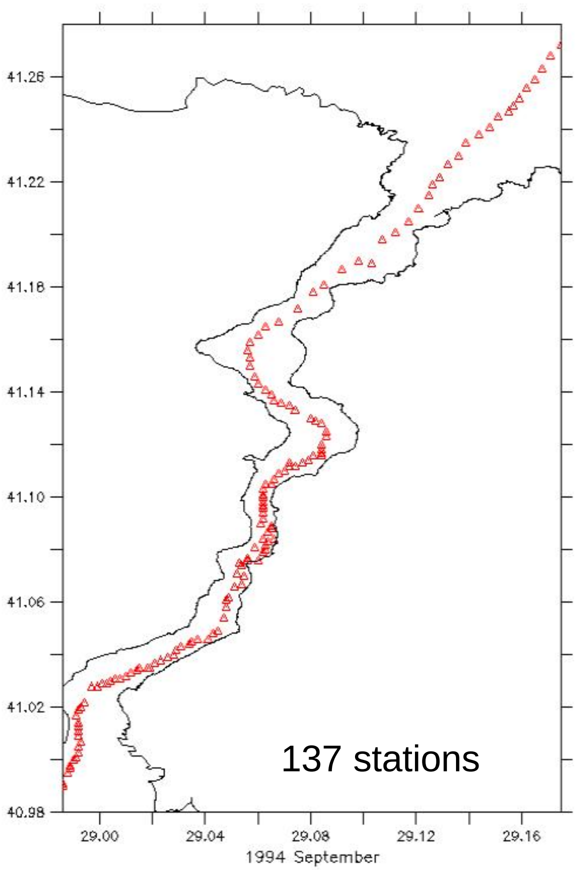
Bosphorus Modeling: Results & Model inter-comparison

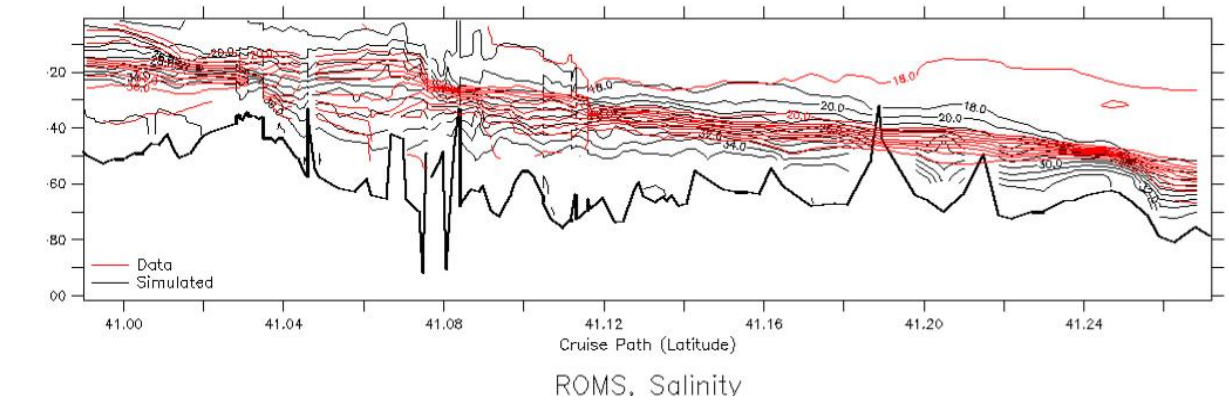


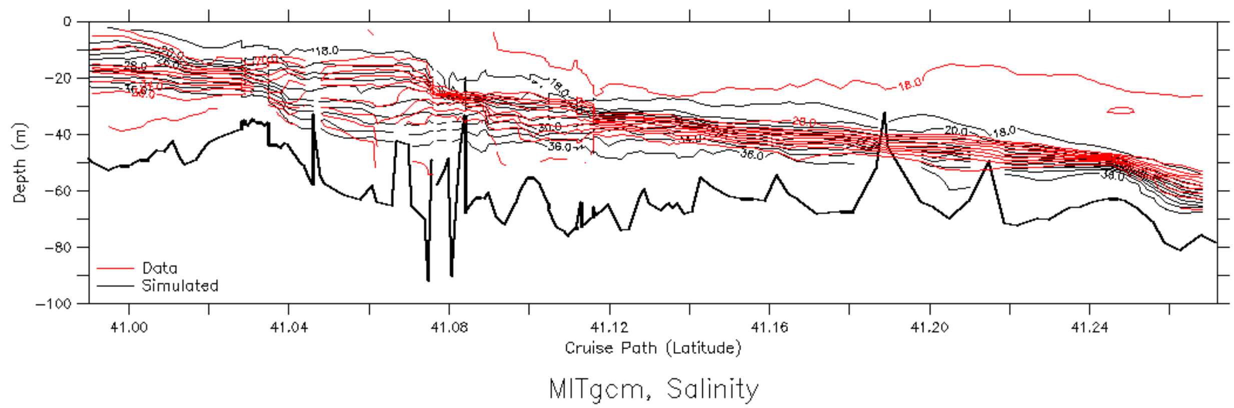




COMPARISON with OBS. DATA



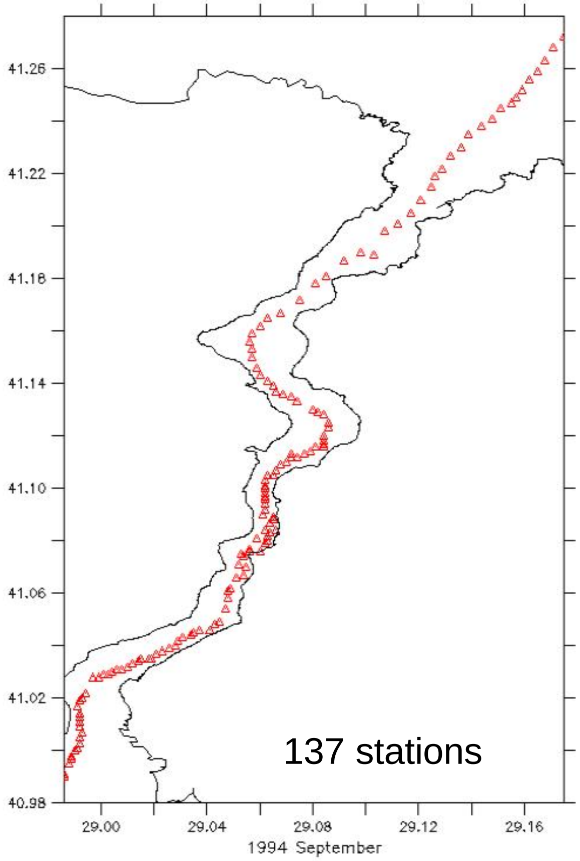




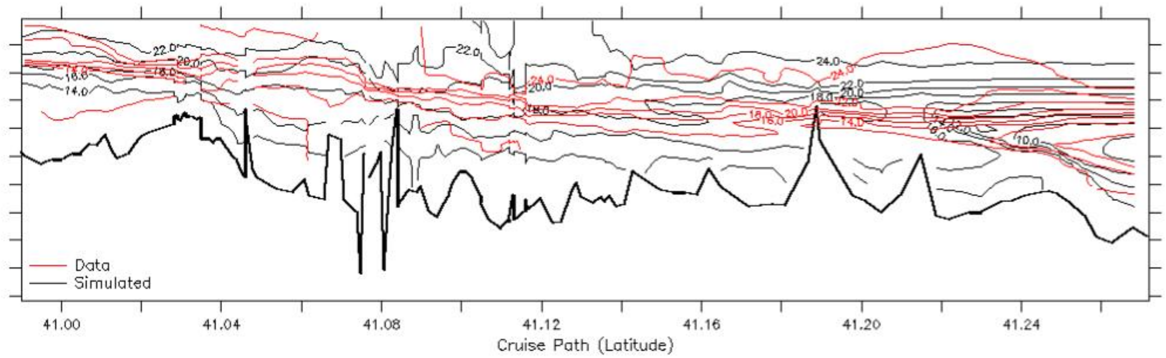
7-9 September 1994

Bosphorus Modeling: ROMS and MITgcm validation

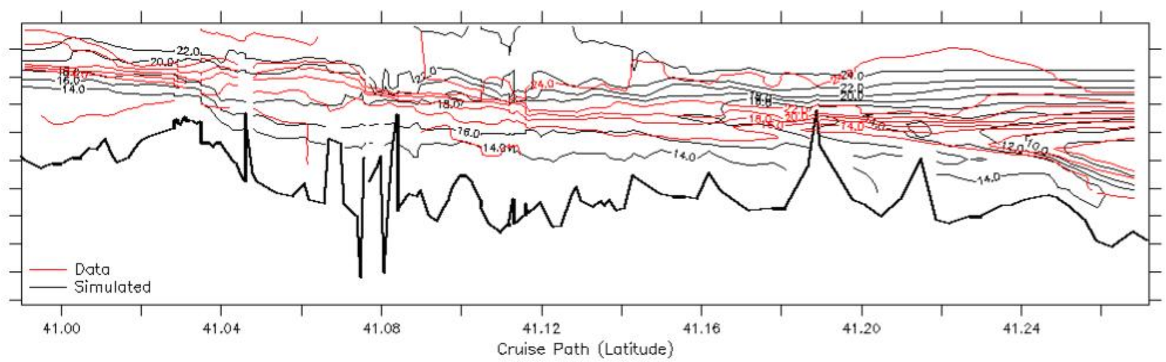
COMPARISON with OBS. DATA



7-9 September 1994



ROMS, Temperature



MITgcm, Temperature

Model choice

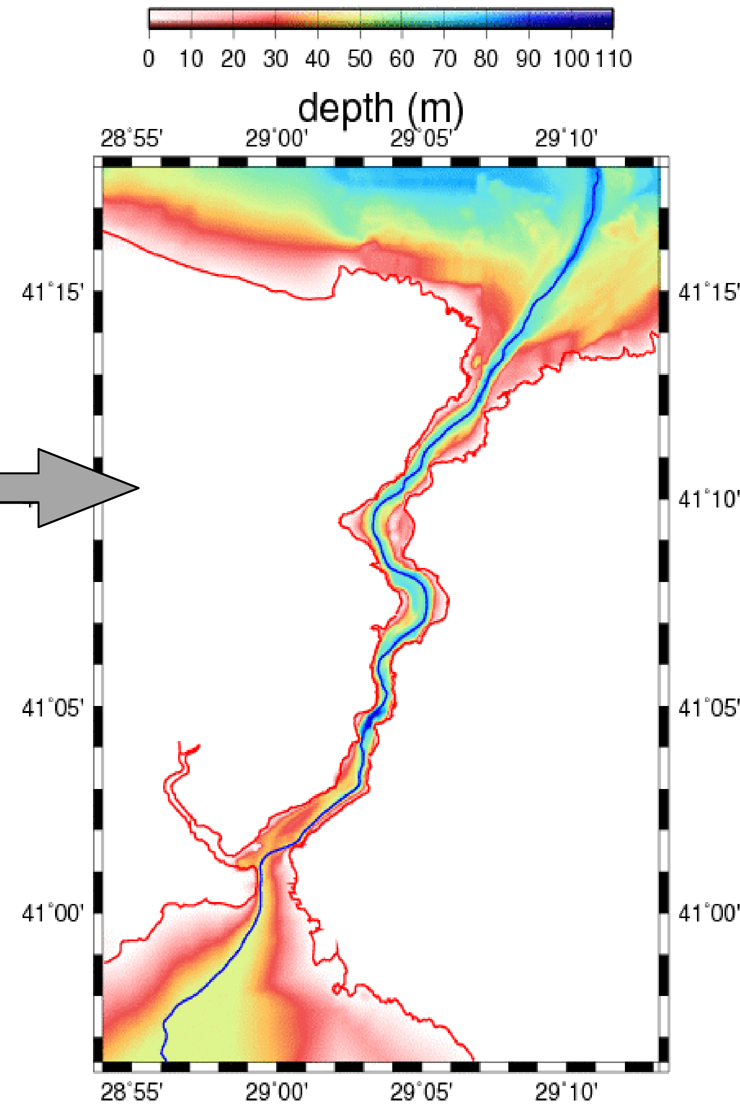
Application to the most challenging place of TSS

z-level MITgcm

σ-level ROMS

Performances Comparison

Similar results (slightly better MITgcm)

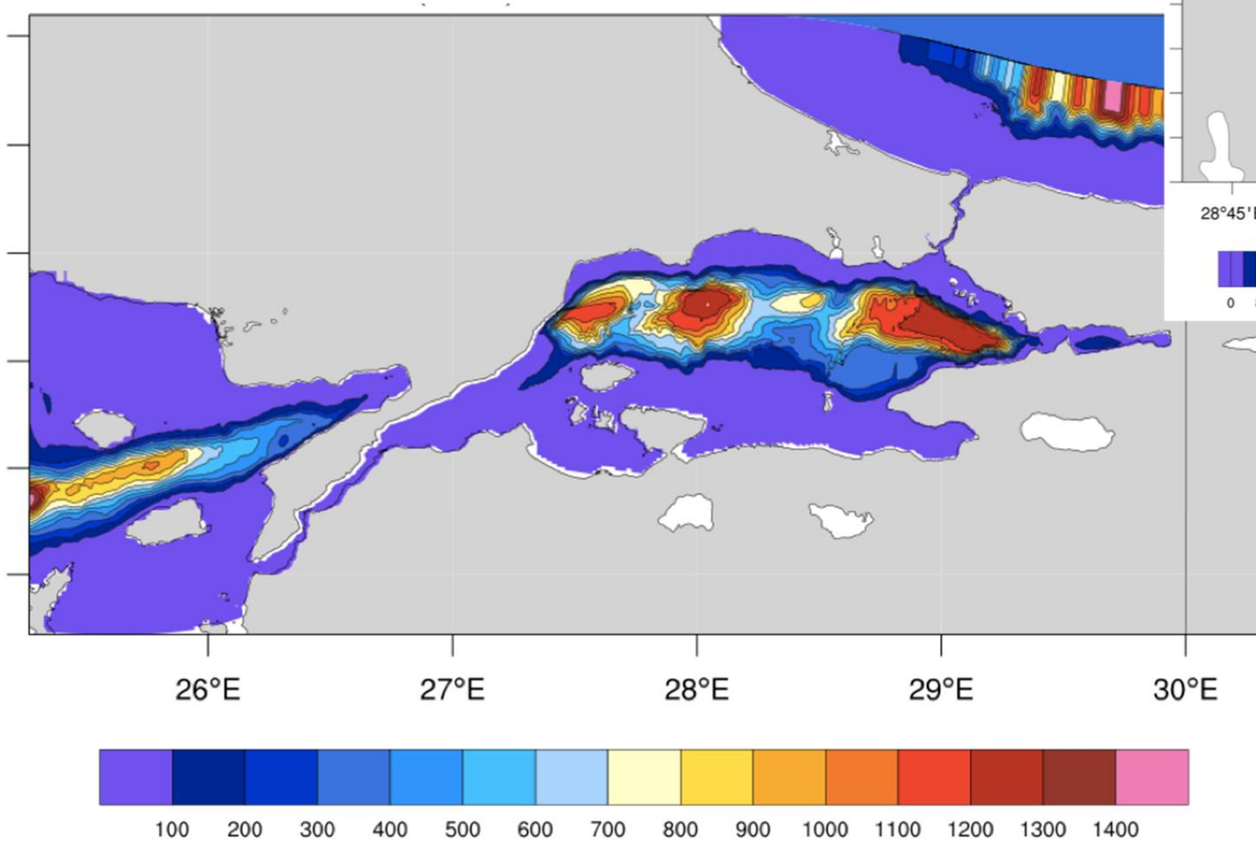


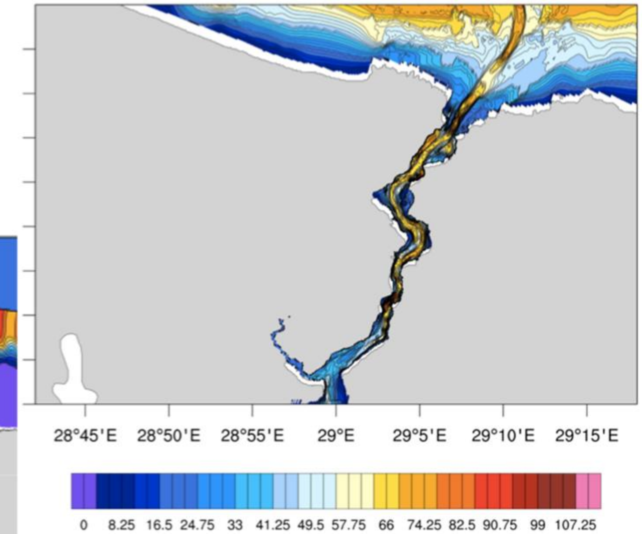
Bosphorus Strait

Turkish Strait System (TSS) model: unique grid – variable resolution

MITgcm

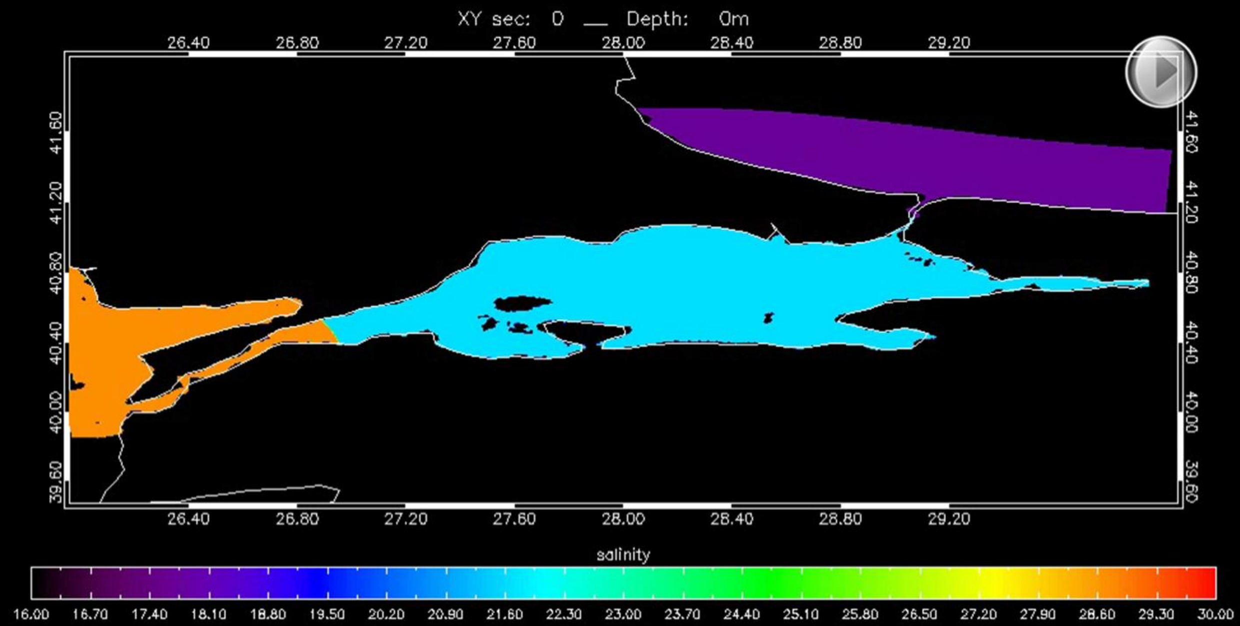
Dx= 35m-500m
Dy =60m-1000m
Grid Size=1728x648x100



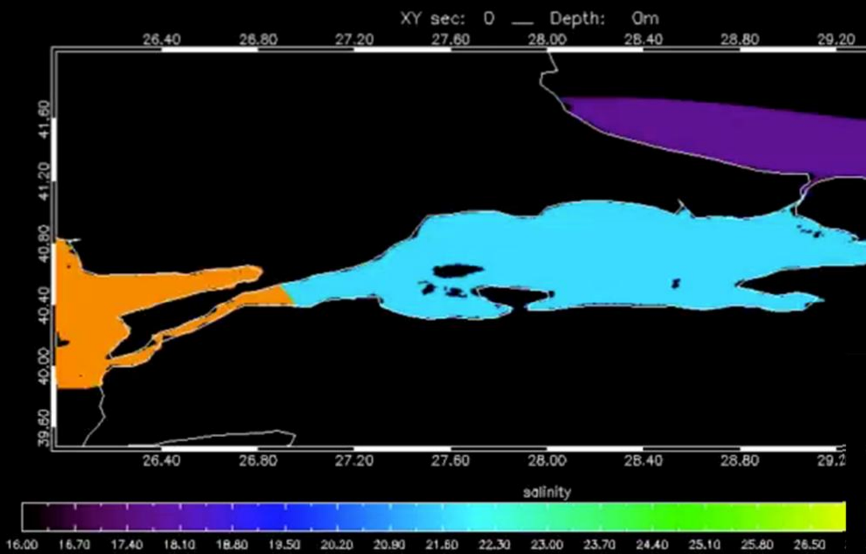


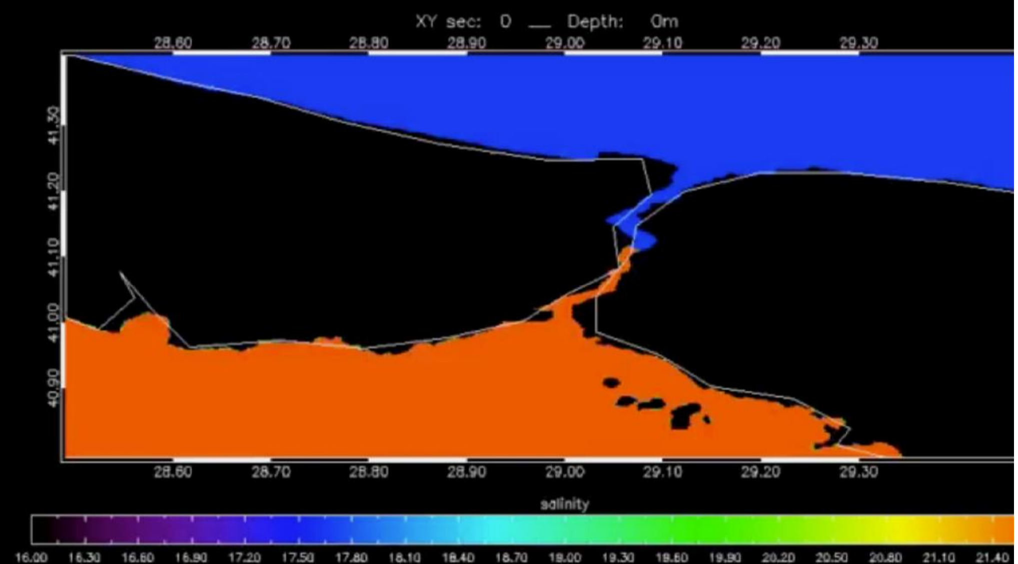
The extreme environment has been represented as a whole and with the full details of its highly contrasting properties. The huge computing resources needed to run such an ambitious model have been provided by the EU initiative PRACE (Partnership for Advanced Computing in Europe).

MITgcm TSS model: Initial Conditions

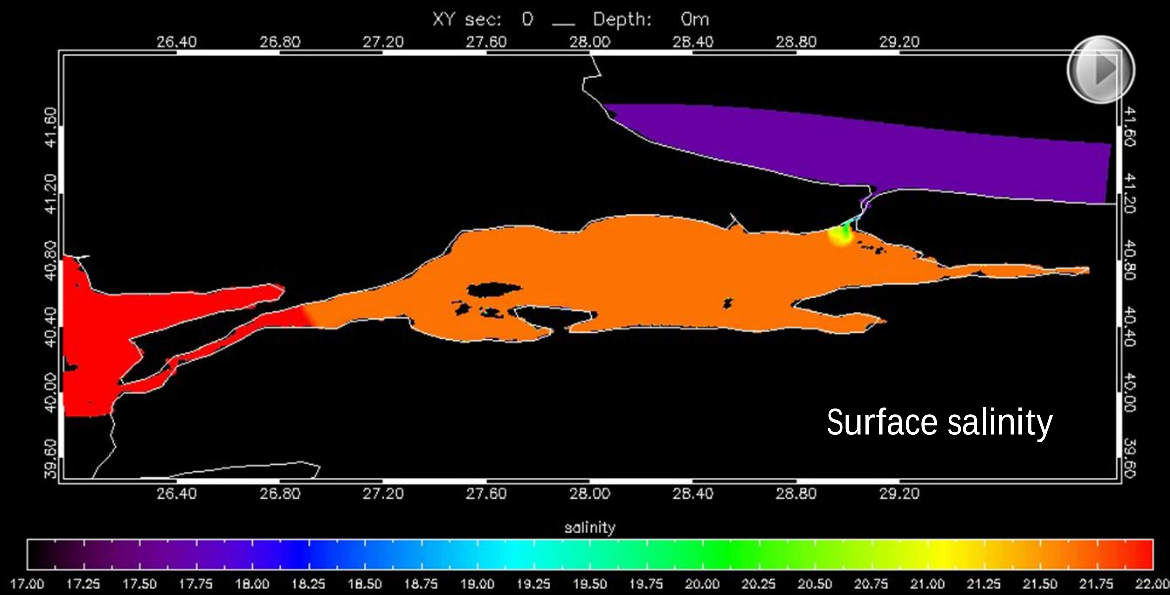


The model is initialized with three different water masses filling the western part of the domain, the Marmara Sea and the eastern side of the domain respectively, with vertical profiles selected from CTD casts obtained during the cruise of the R/V BİLİM of the Institute of Marine Sciences in June-July 2013. With the initial condition specified as lock-exchanges at the two straits, the model is left free to adjust to the expected two-way exchange.

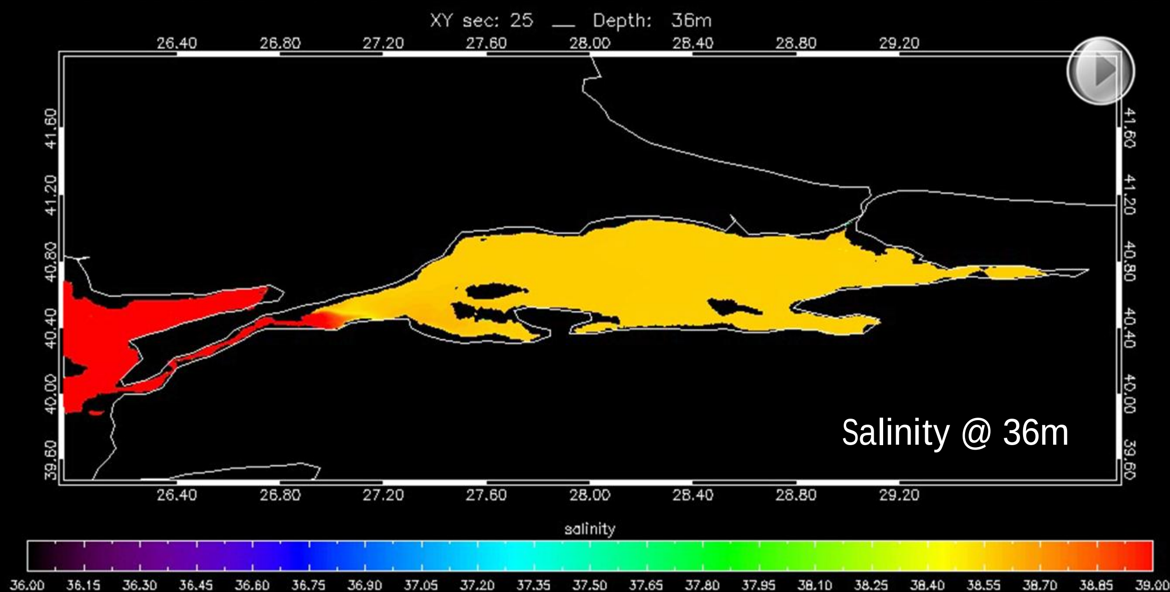




Sannino et al.
ODY 2017



Forced net barotropic flow 18000 m³/sec experiment

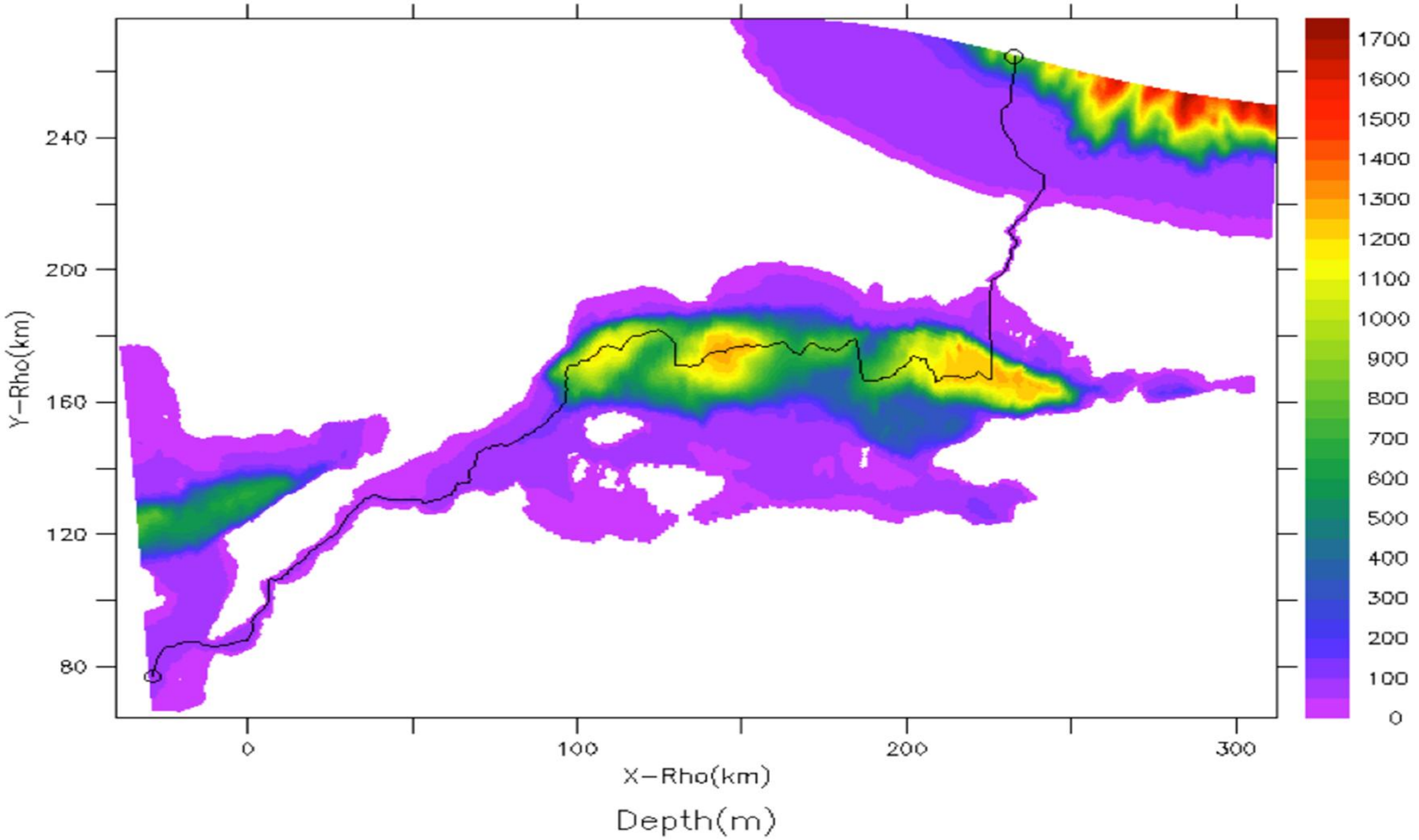


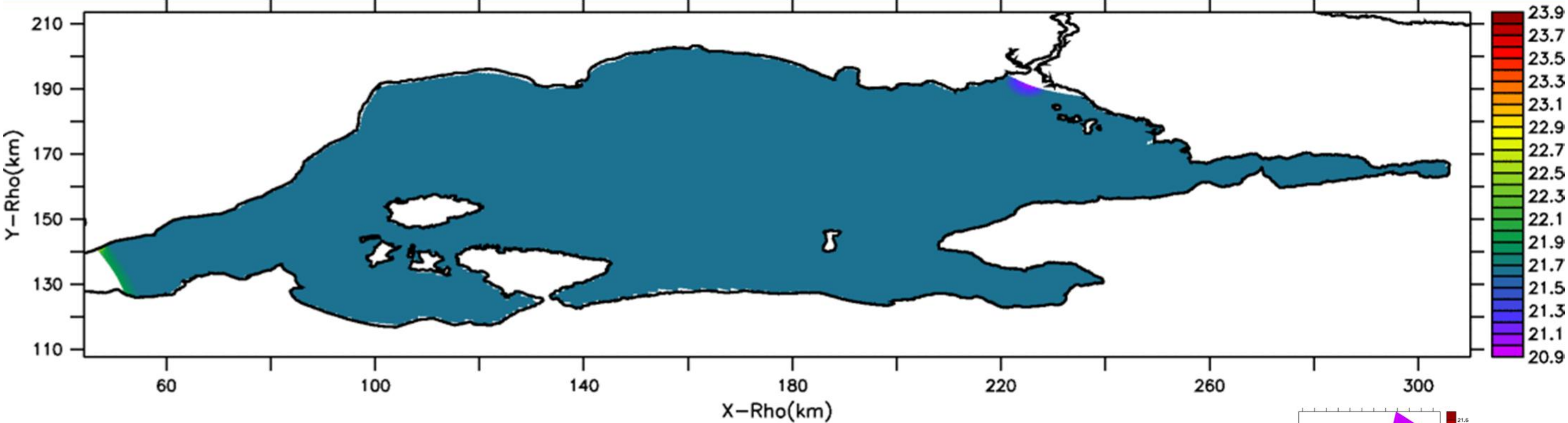
Sannino et al.
ODY 2017

Three experiments were conducted to study the sensitivity of the circulation to different net barotropic flows: 5600, 9600, 18000, and 50000 m³/sec

TSS model: along straits section

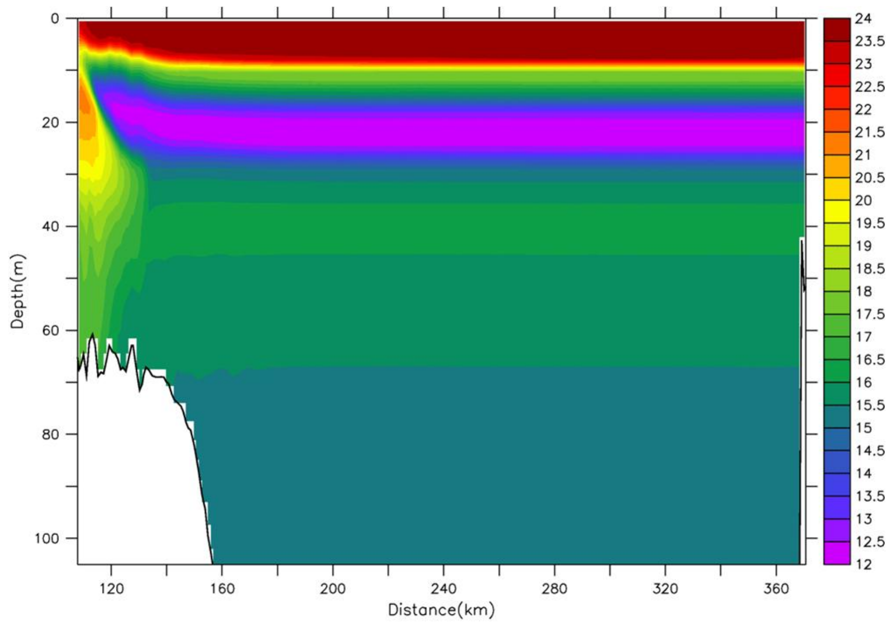
Model results will be shown along the black line indicated in the figure



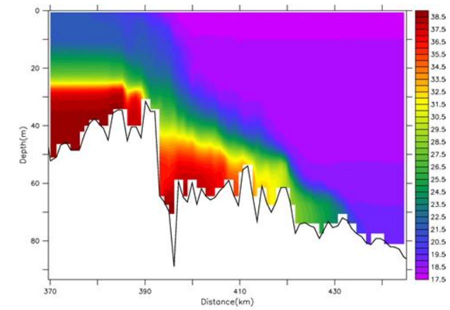


Net Flux=5600m^3/s

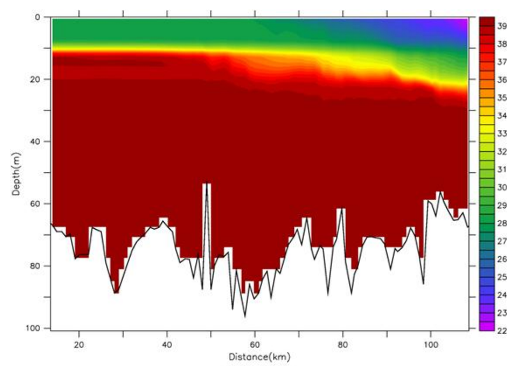
Salt, Z=−0.6m, Day=001.00



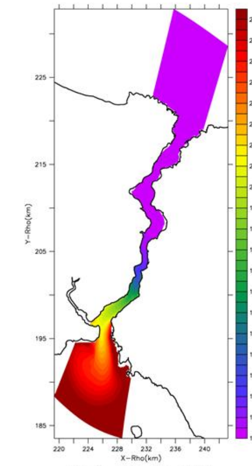
Salt, Day=1



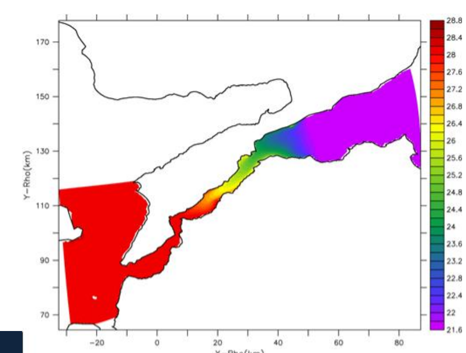
Salt, Day=1



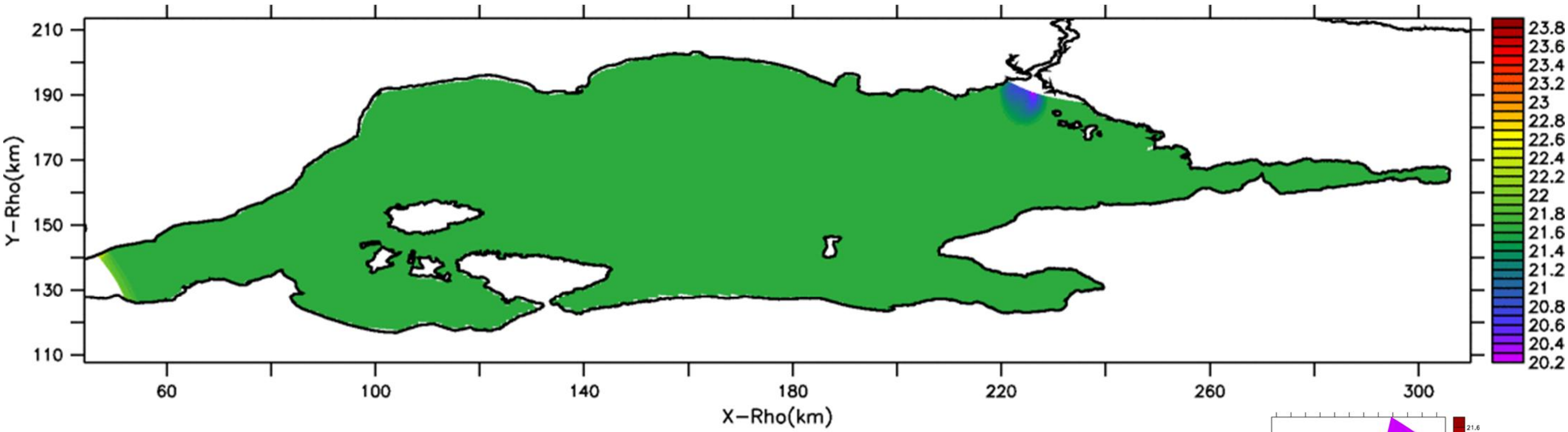
Salt, Day=1



Salt, Z=−0.6m, Day=001.00

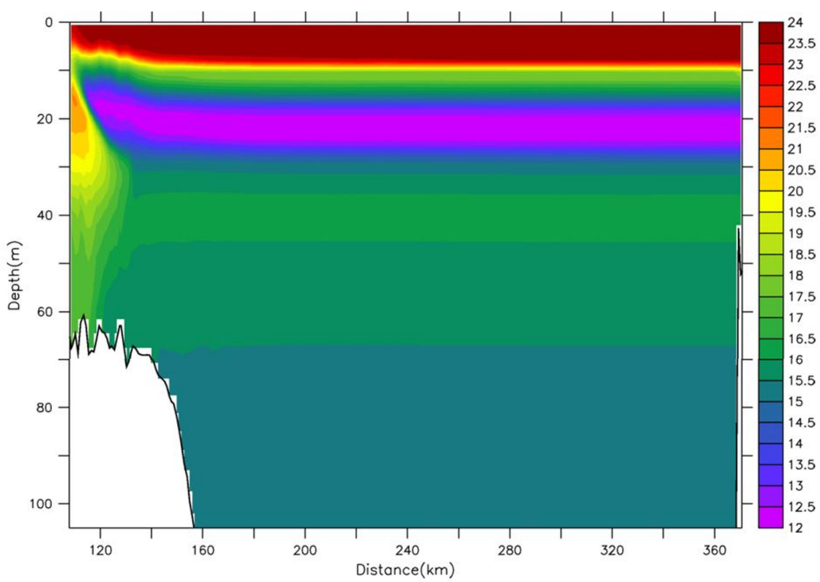


Salt, Z=−0.6m, Day=001.00

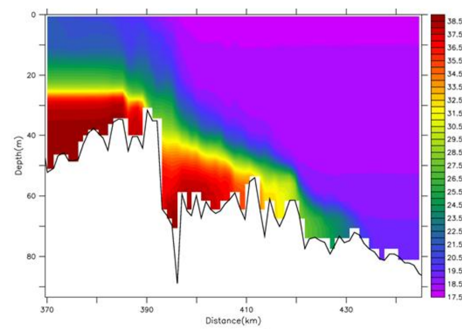


Salt, Z=−0.6m, Day=001.00

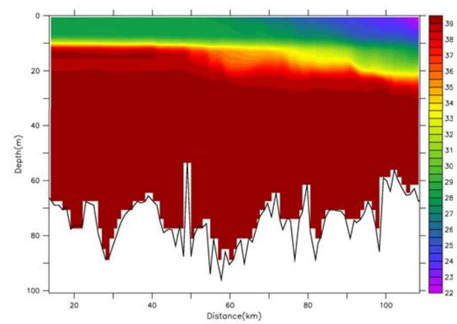
Net Flux=18000m^3/s



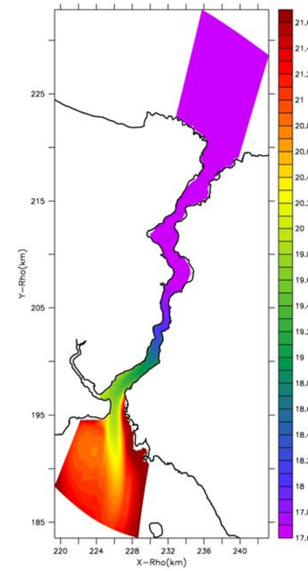
Salt, Day=1

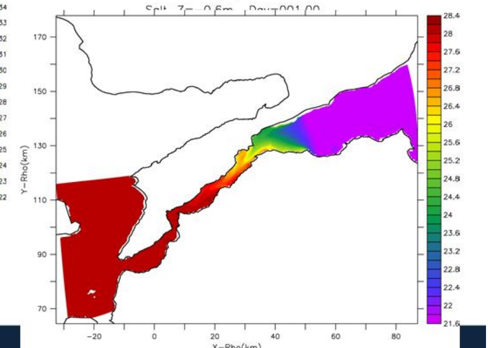


Salt, Day=1



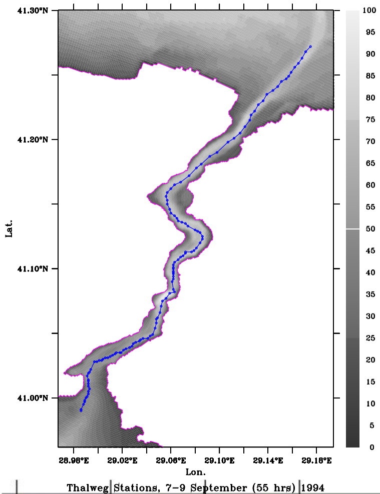
Salt, Day=1



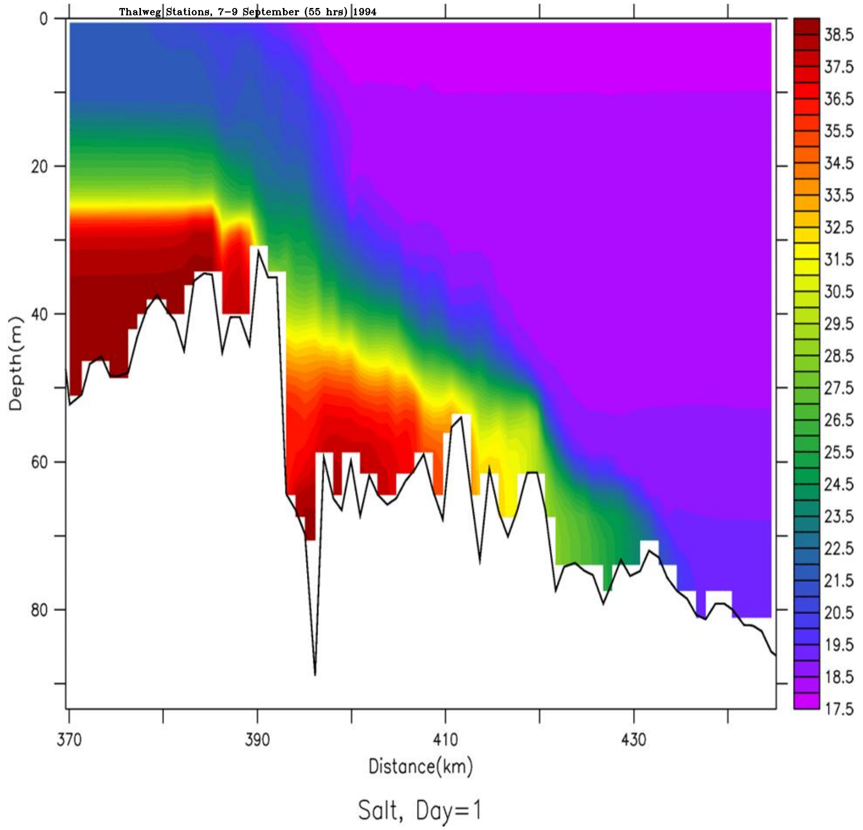


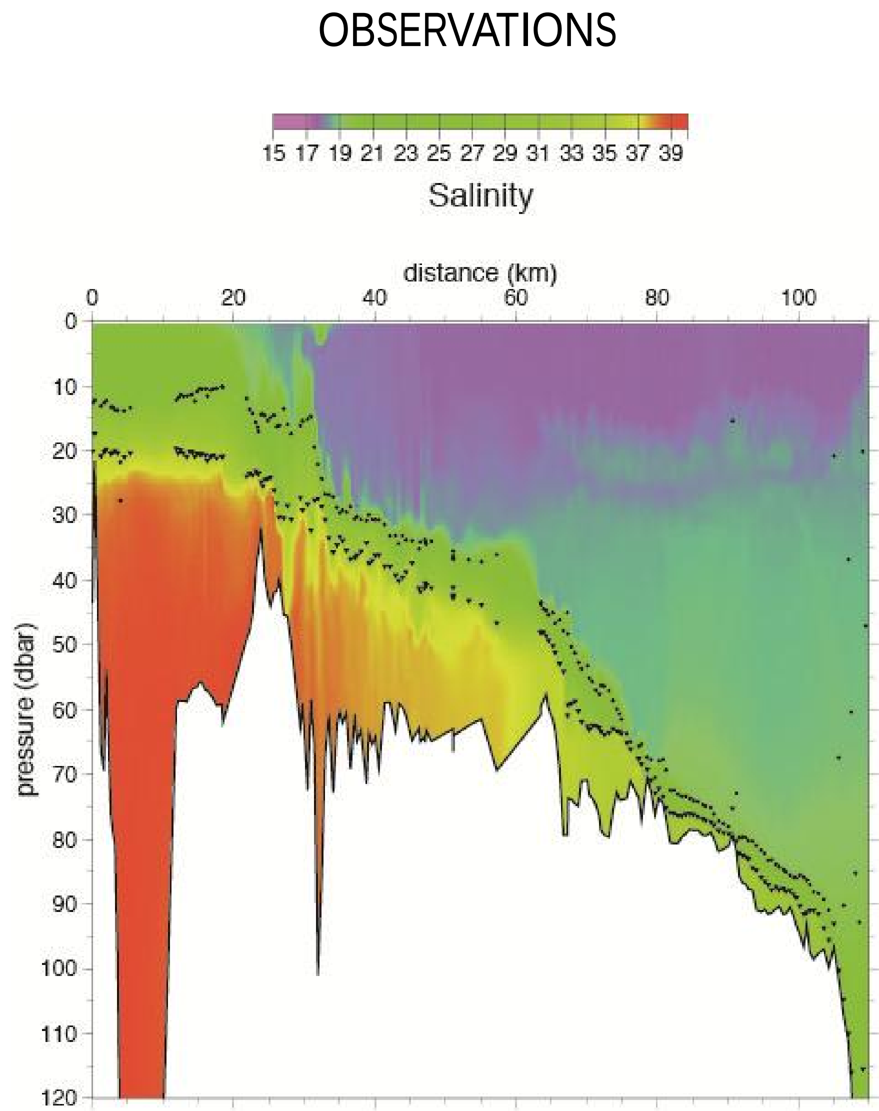
Salt, Z=−5.4m, Day=001.00

MITgcm TSS model: Bosphorus along-strait salinity field



Net Flux=-5600m^3/s

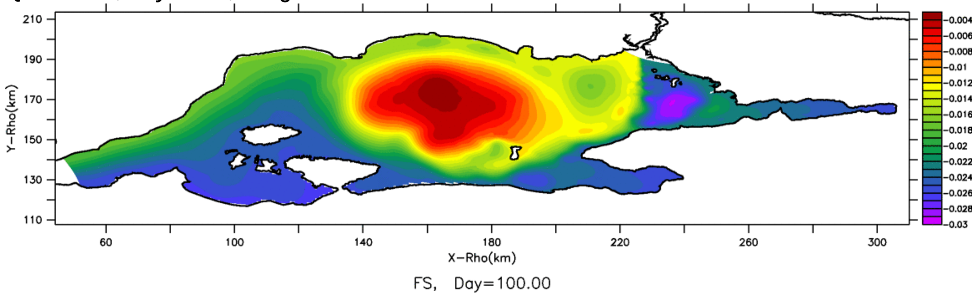




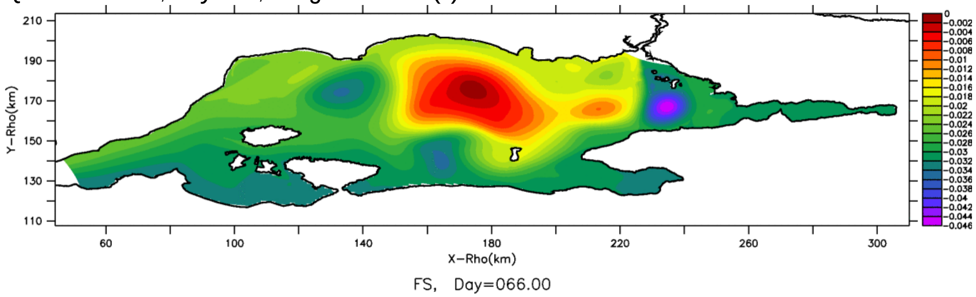
Marmara Bosphorus Black Sea

MITgcm TSS model: sea level anomaly field

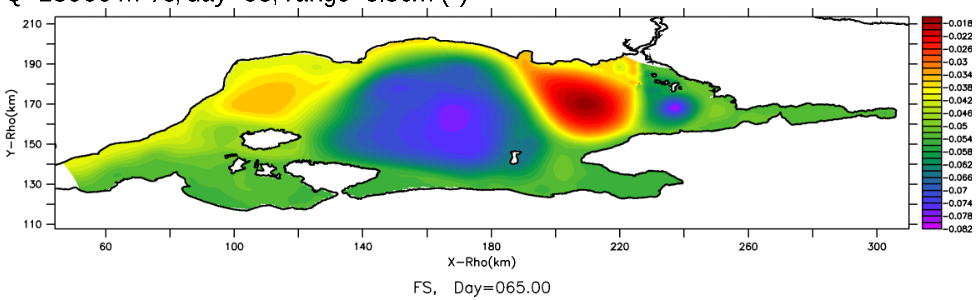
Q=0 m^3/s, day=100, range=3.5cm



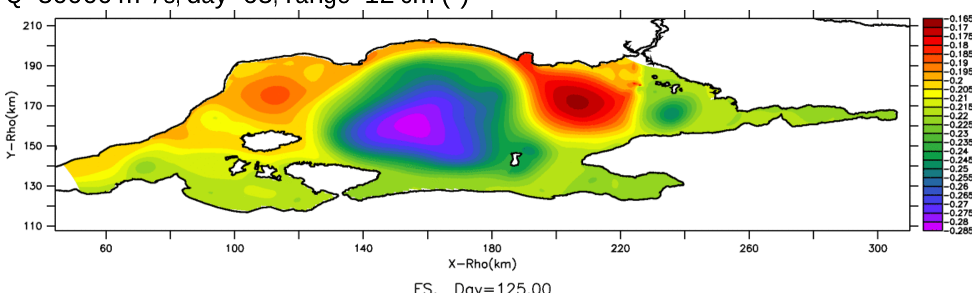
Q=5600 m^3/s, day=65, range=4.5 cm (-)



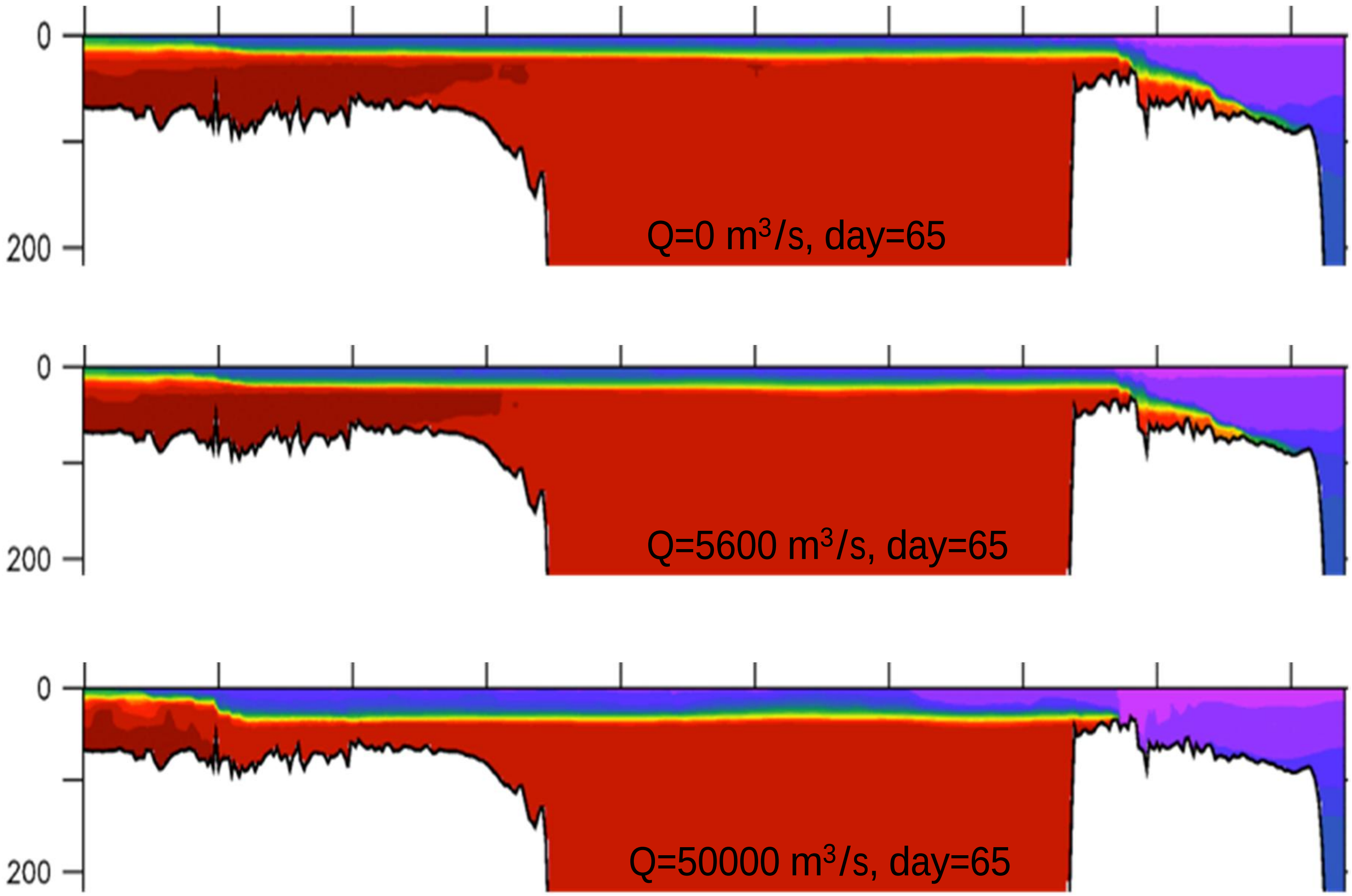
Q=18000 m^3/s, day=65, range=6.5cm (-)



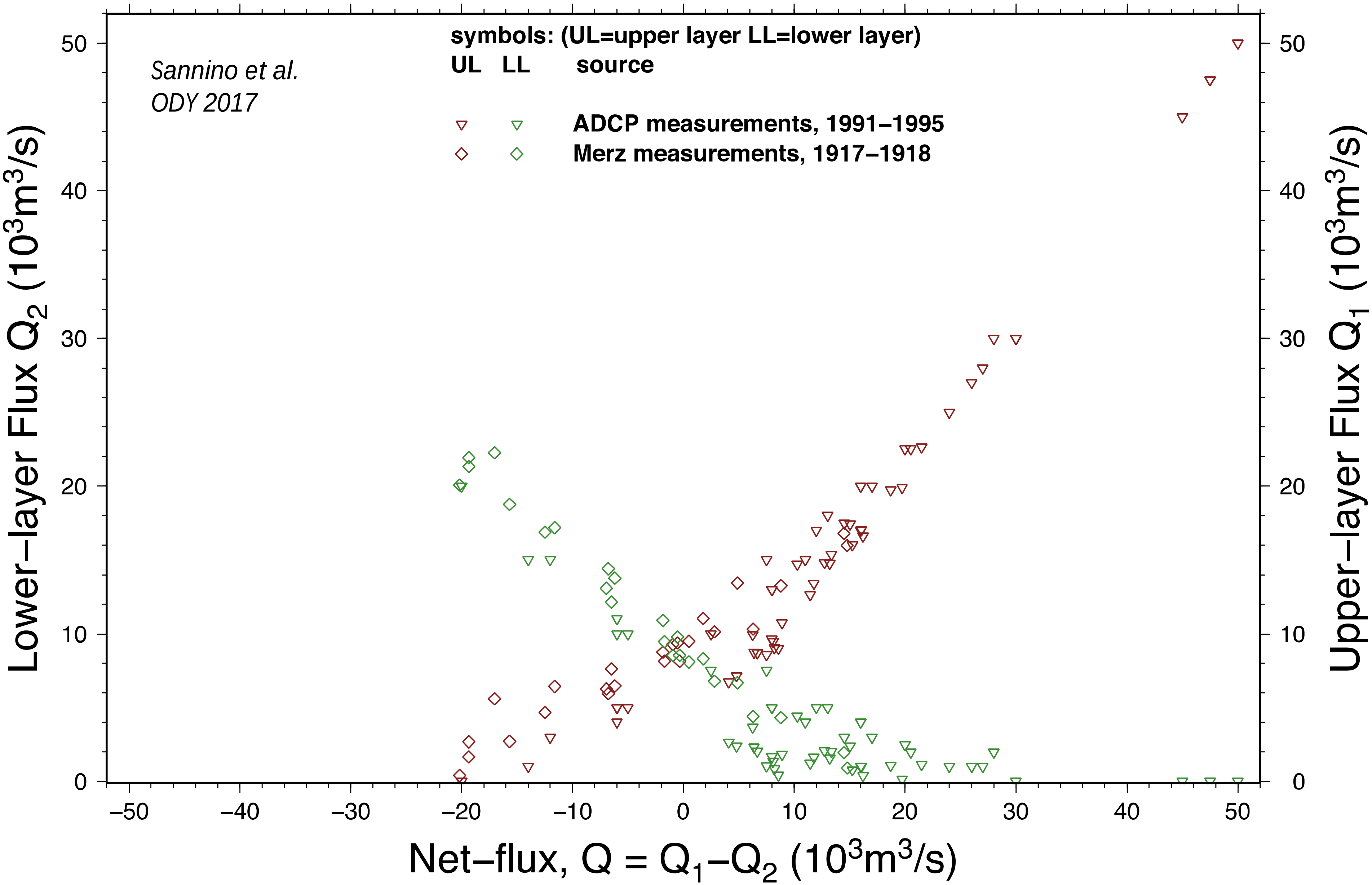
Q=50000 m^3/s, day=65, range=12 cm (-)



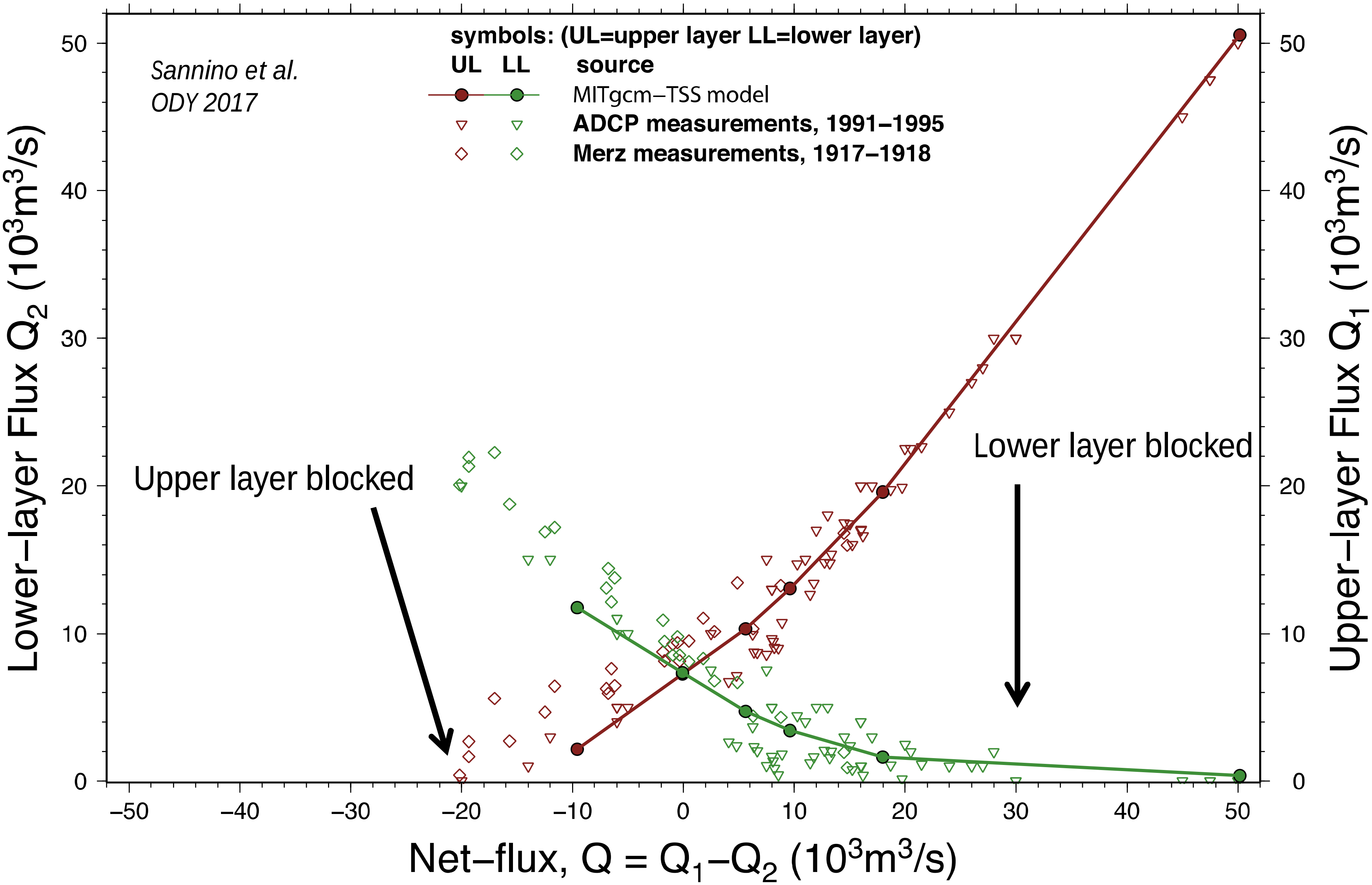
MITgcm TSS model: TSS cross-section salinity field



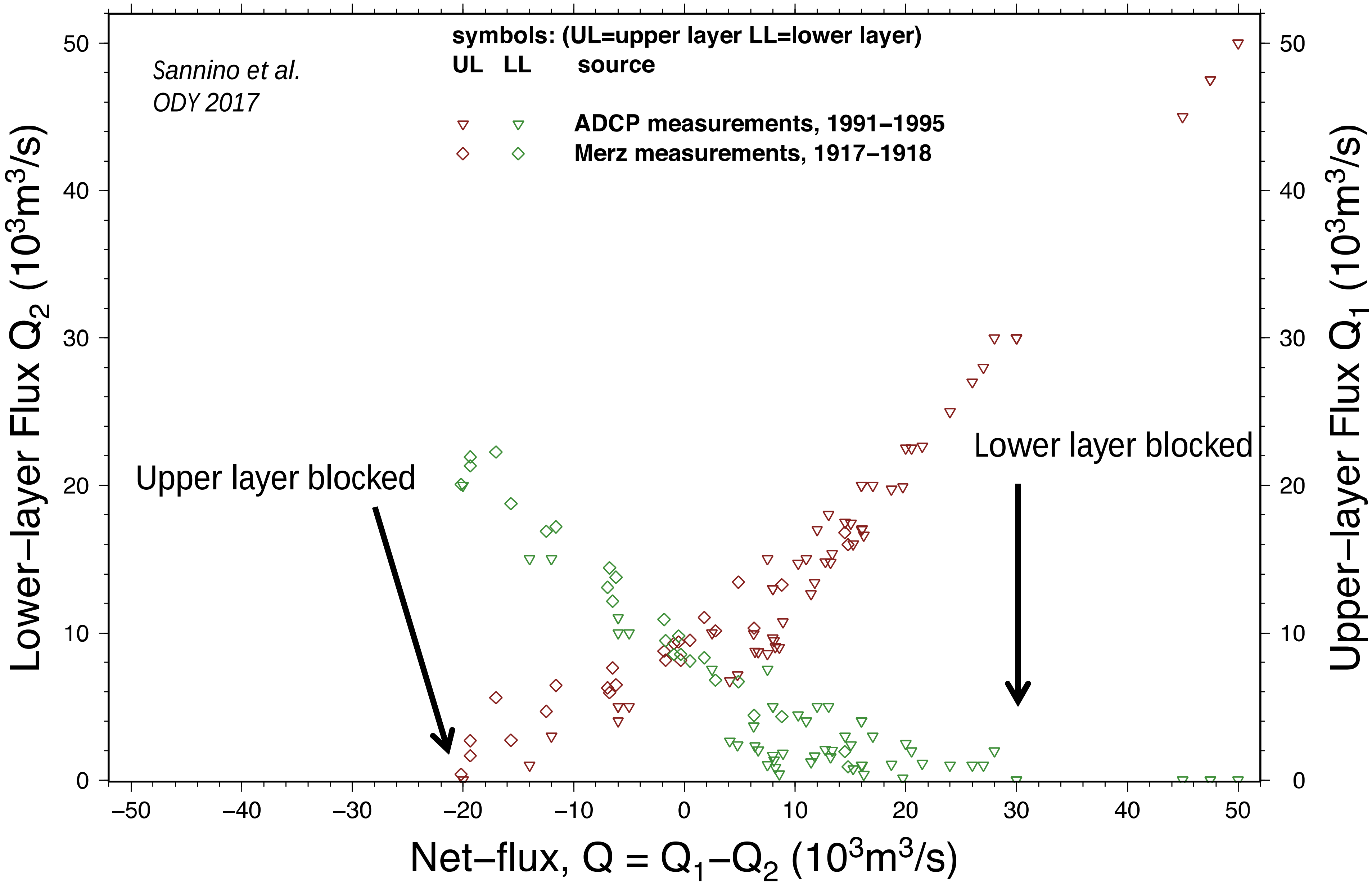
TSS model: Bosphorus transport – Model vs Observations



TSS model: Bosphorus transport – Model vs Observations



TSS model: Bosphorus transport – Model vs Observations



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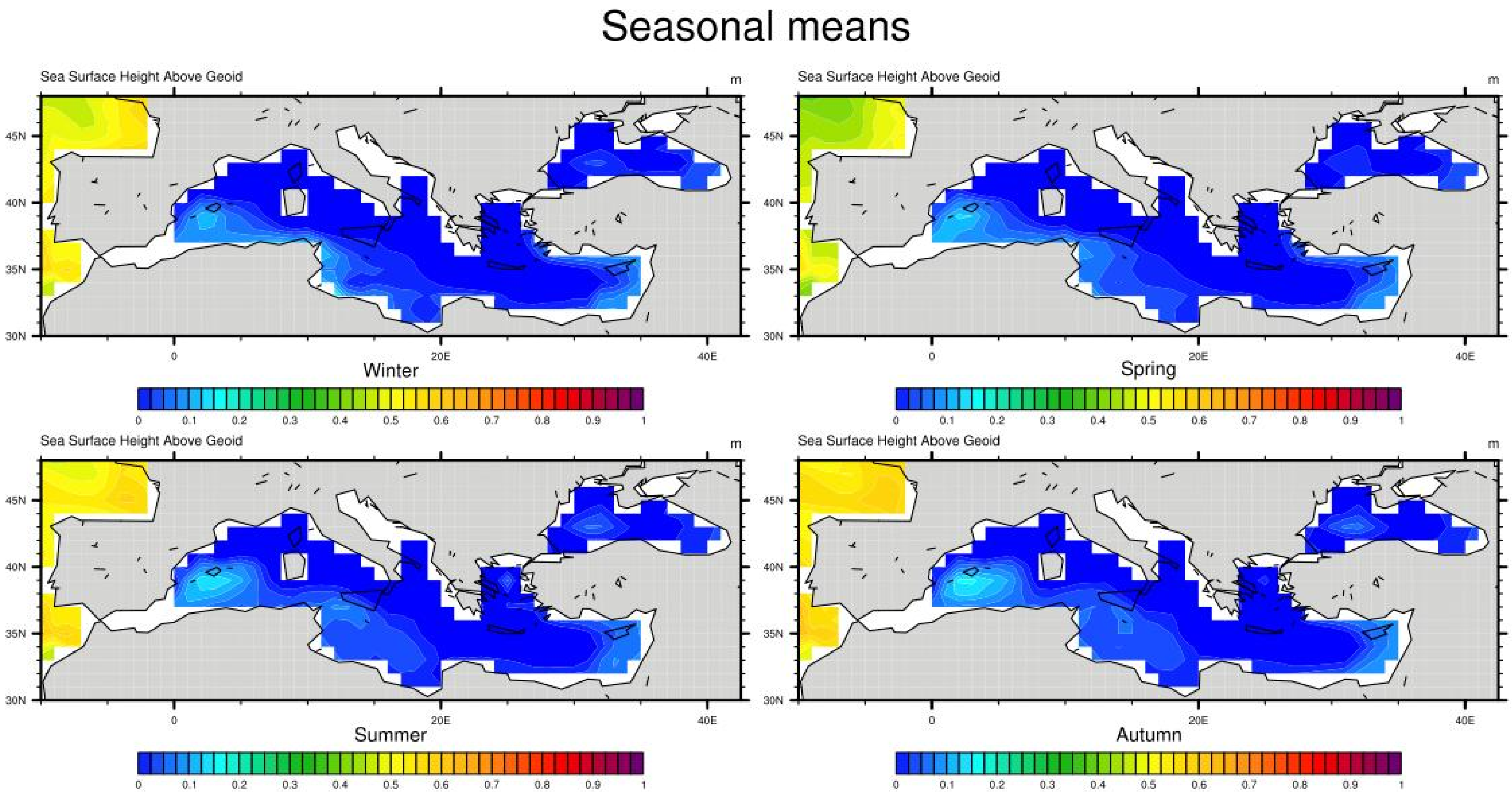
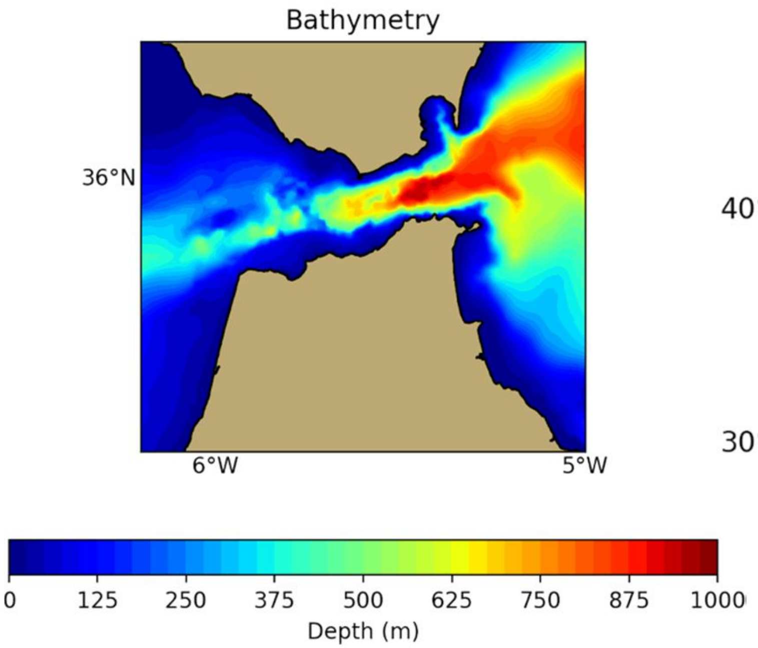
Global climate models

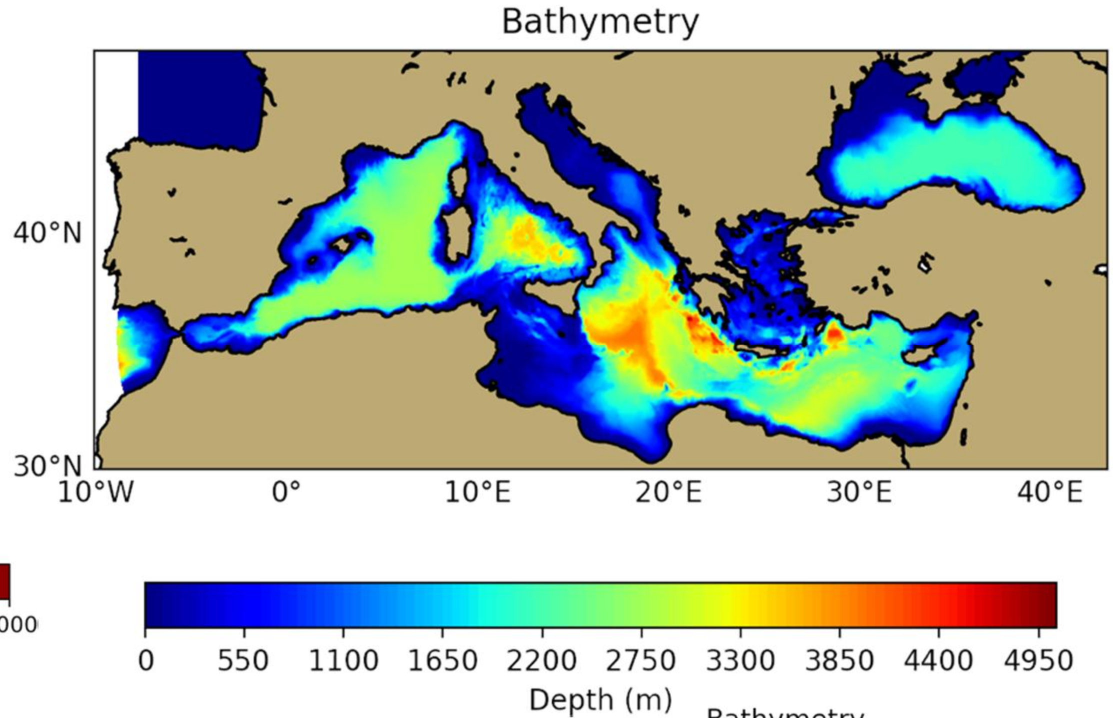


Mediterranean sea level reproduced by CMIP5* global models (present climate)

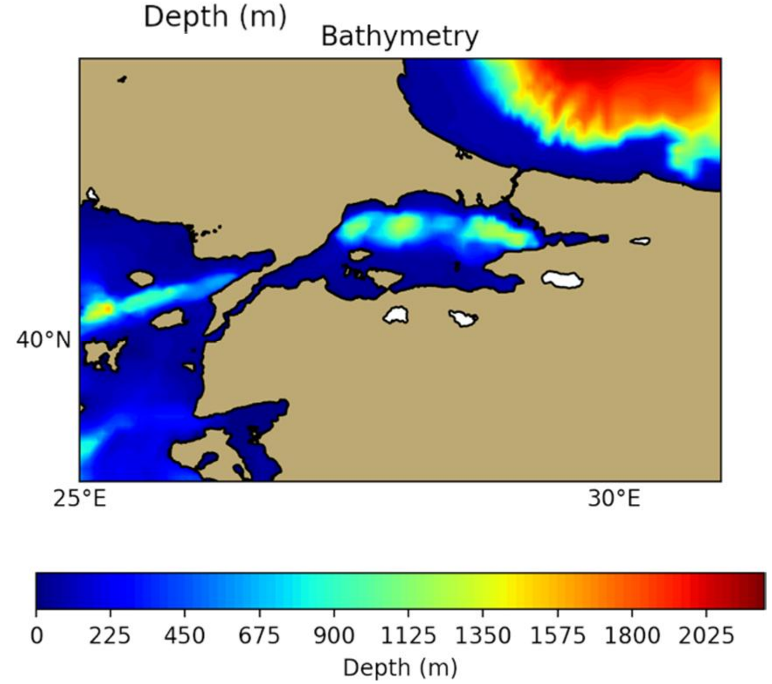
*Coupled Model Intercomparison Project - https://cmip.llnl.gov/cmip5/

First Black Sea –Mediterranean model with a ‘realistic’ connection



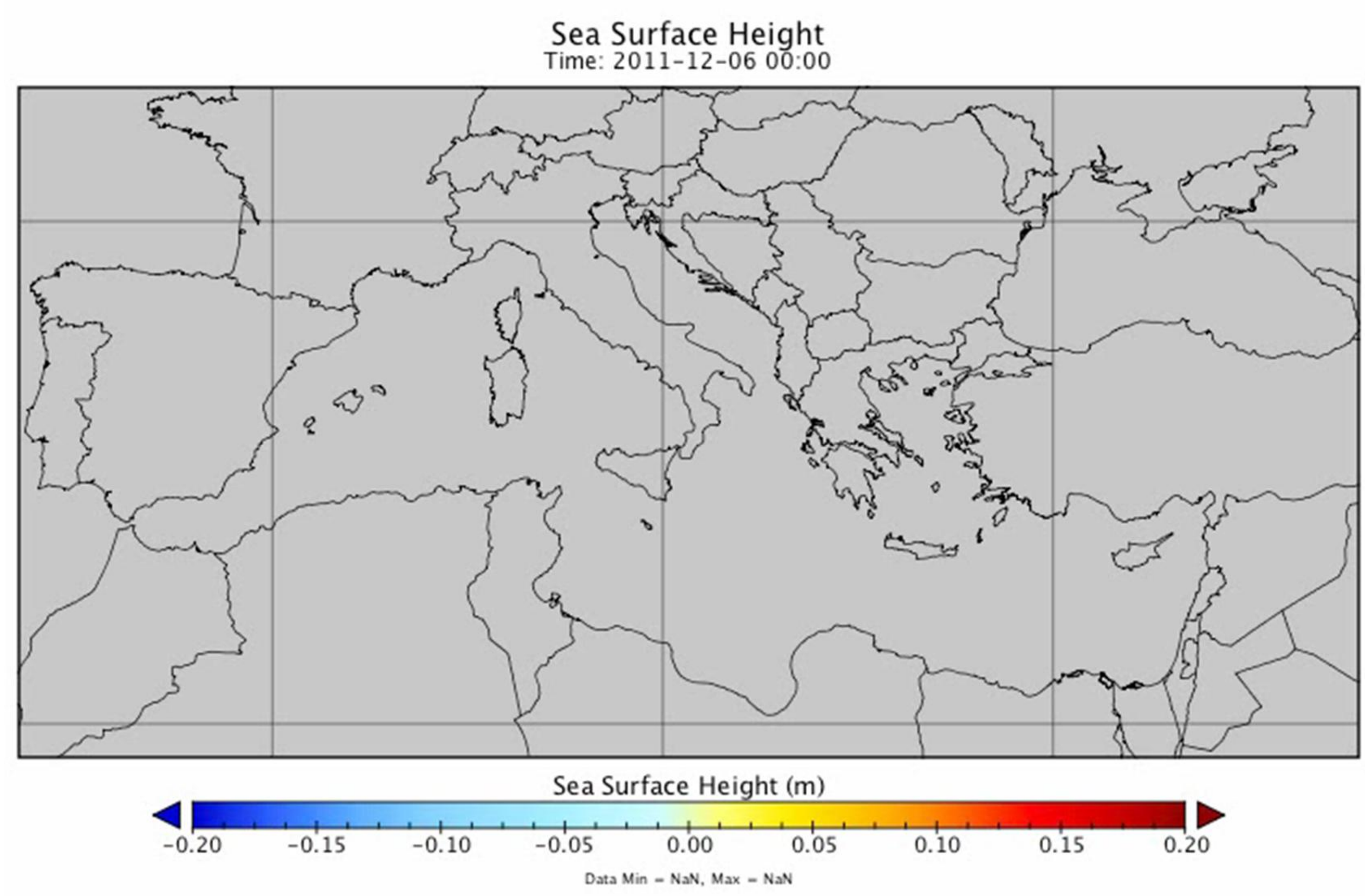


MITgcm – Explicit Tides (M2,S2, K1, O1) – Lateral Tide + Tidal Potential
Average resolution 1/16° (2.3 Km)
Minimum resolution 230m (Gibraltar and Turkish Straits)
100 Vertical Levels



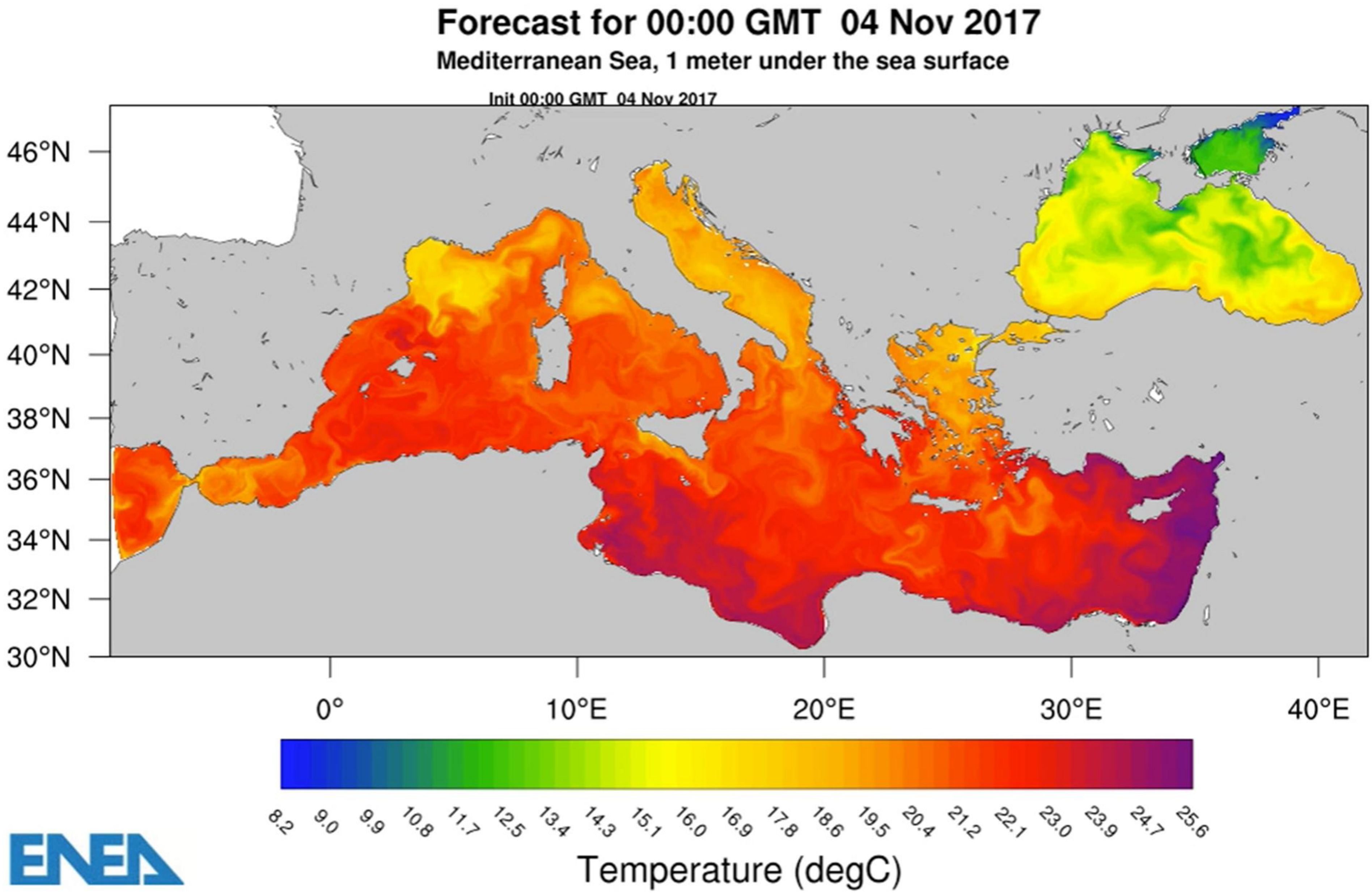
First Black Sea –Mediterranean model with a ‘realistic’ connection

Conclusions and Future Work



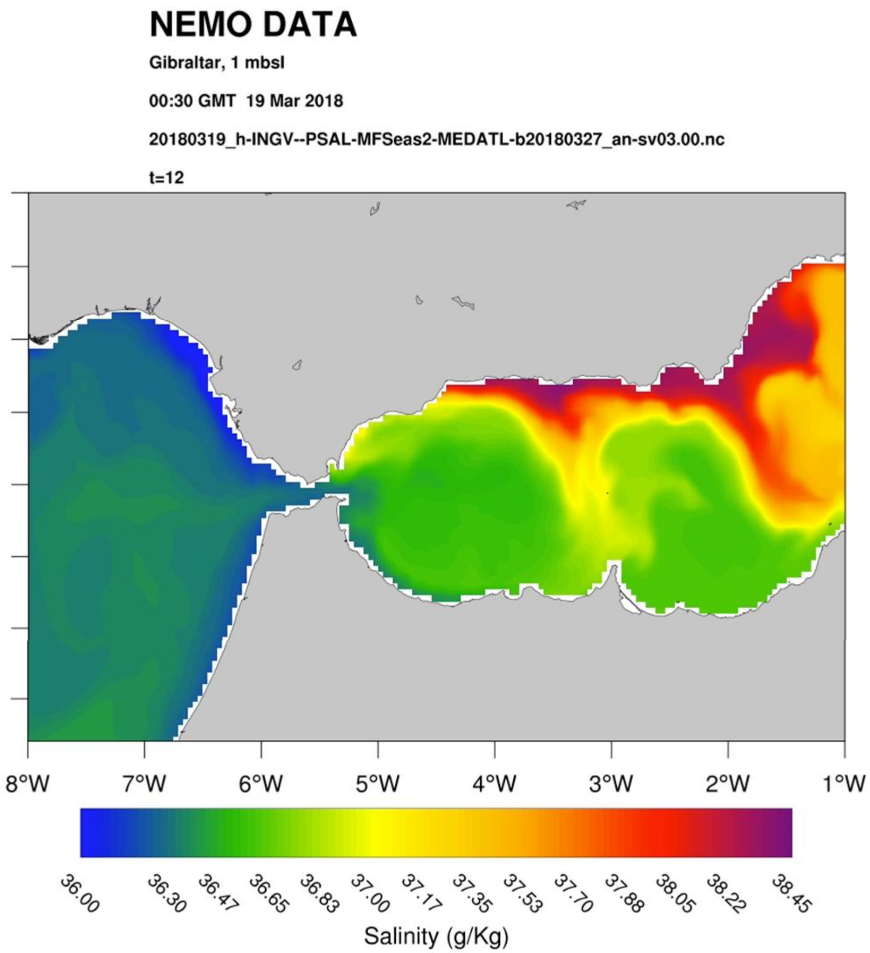
MITgcm – Explicit Tides (M2,S2, K1, O1) – Lateral Tide + Tidal Potential
Average resolution 1/48° (2.3 Km)
Minimum resolution 230m (Gibraltar and Turkish Straits)
100 Vertical Levels

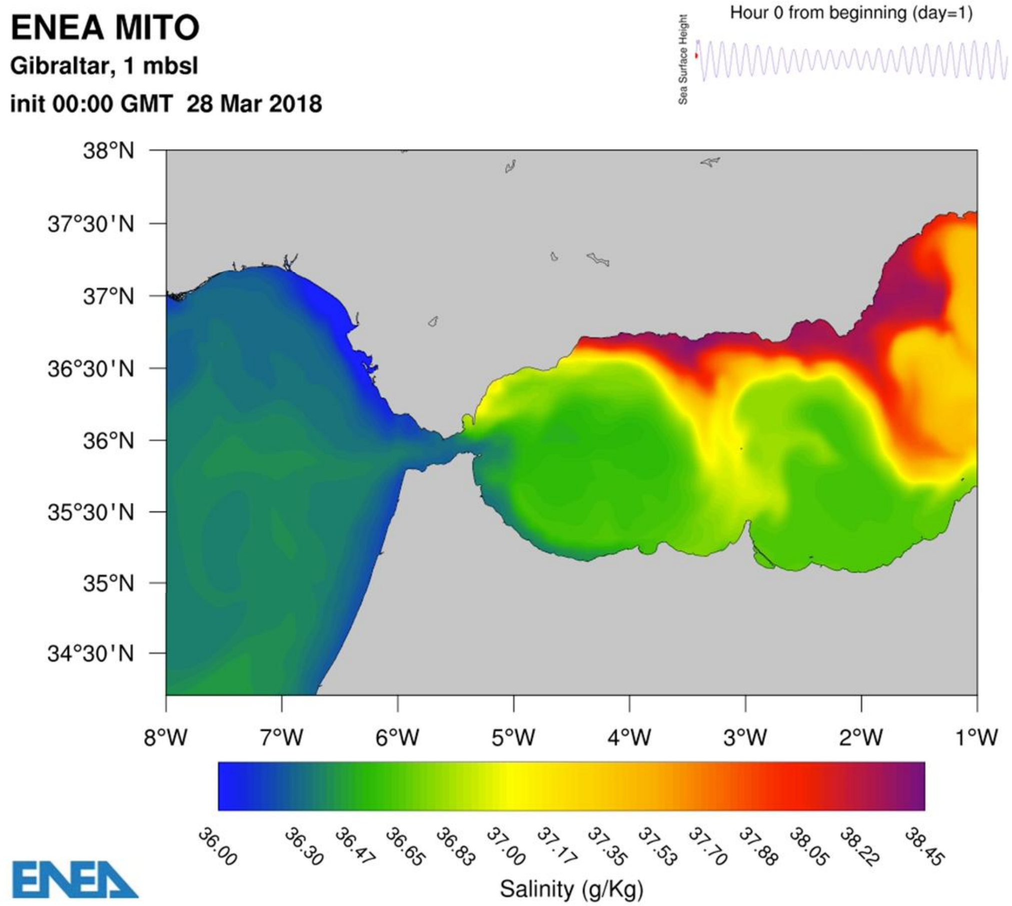
Mediterranean-Black Sea forecasting system



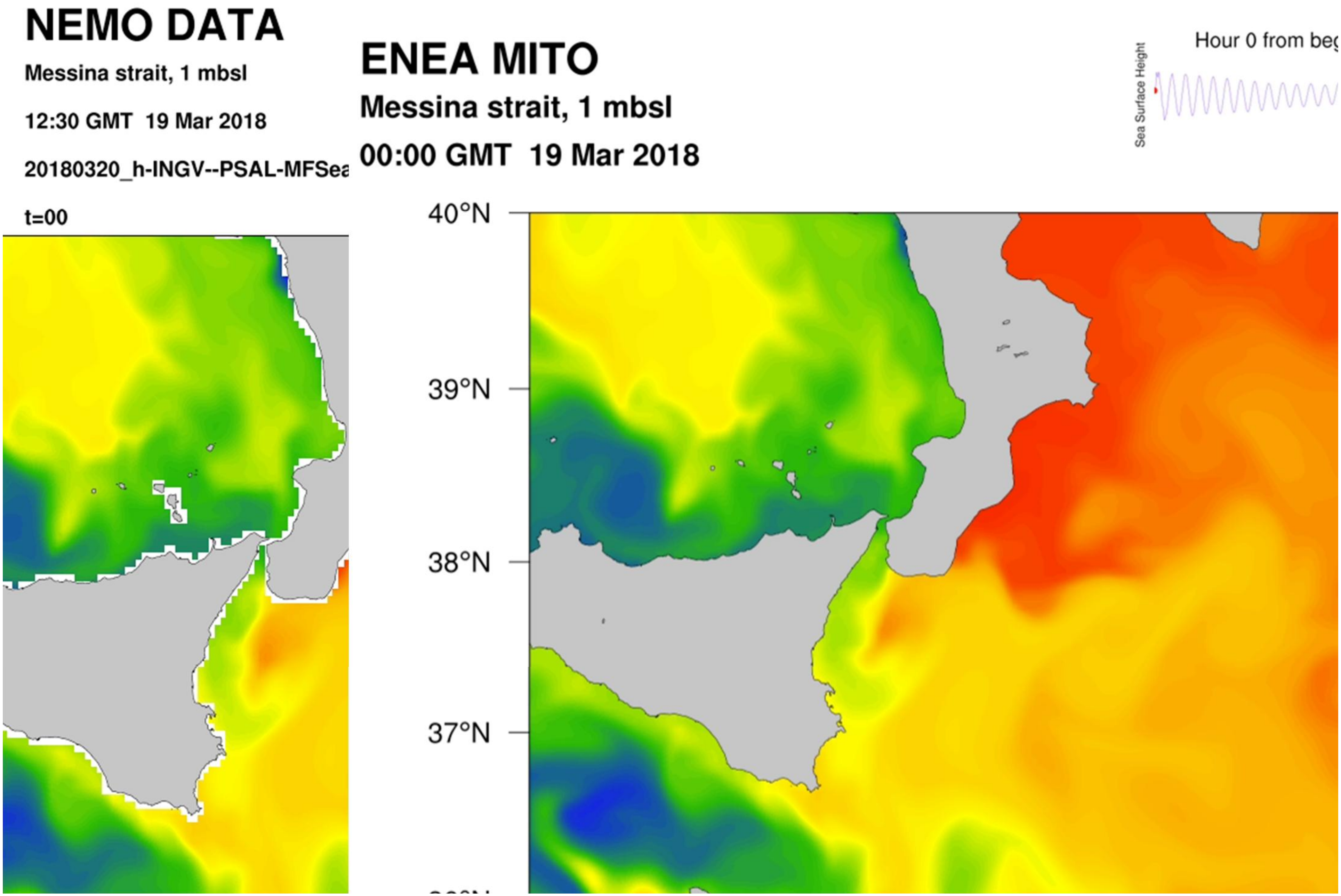
ENEA

First Black Sea –Mediterranean model with a ‘realistic’ connection





First Black Sea –Mediterranean model with a ‘realistic’ connection



THURSDAY 18 OCTOBER

12:40 - 13:00

A high-resolution, tide-including model of the Mediterranean Sea-Black Sea system

M. Palma, R. Iacono, A. Bargagli, A. Carillo, E. Lombardi, E. Napolitano, G. Pisacane,
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