The Abdus Salam
International Centre
for Theoretical Physics

Developer School for HPC

Applications in Earth Sciences

10 Nov. 2014

Development strategies for the MITgcm, a versatile ocean model

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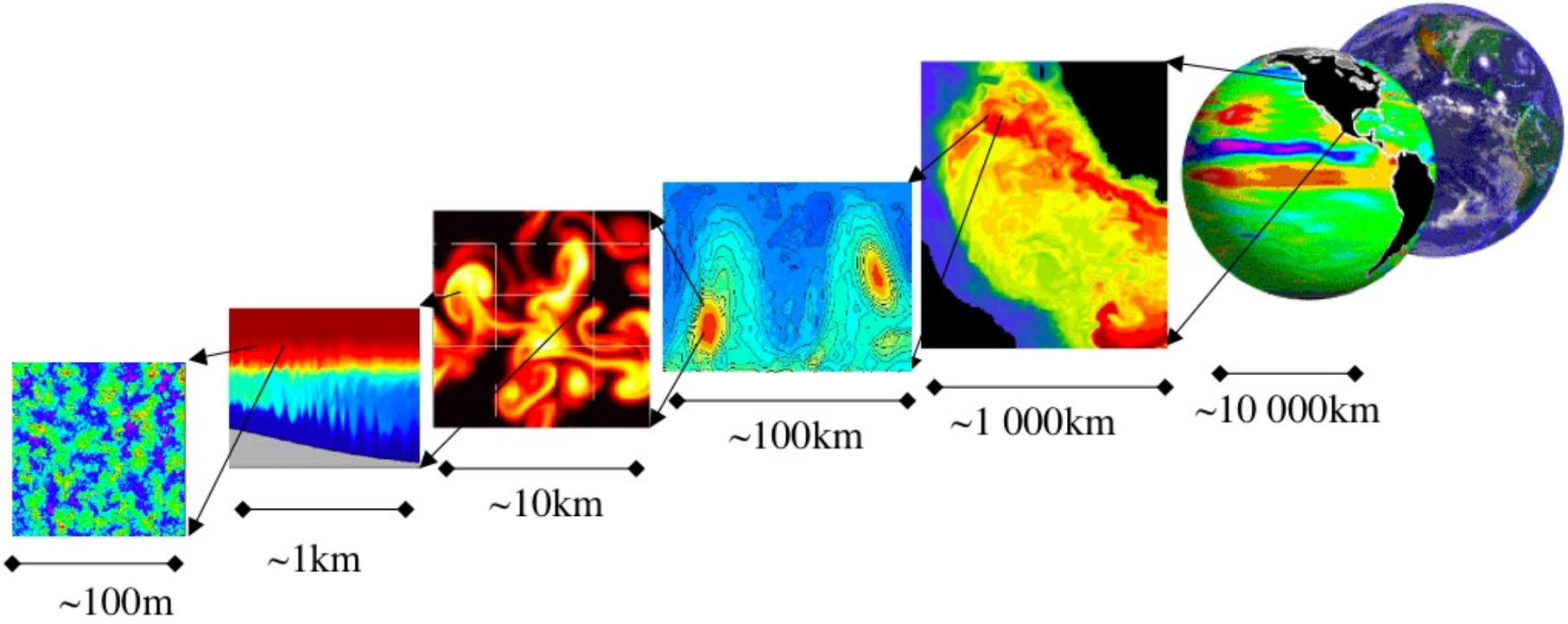
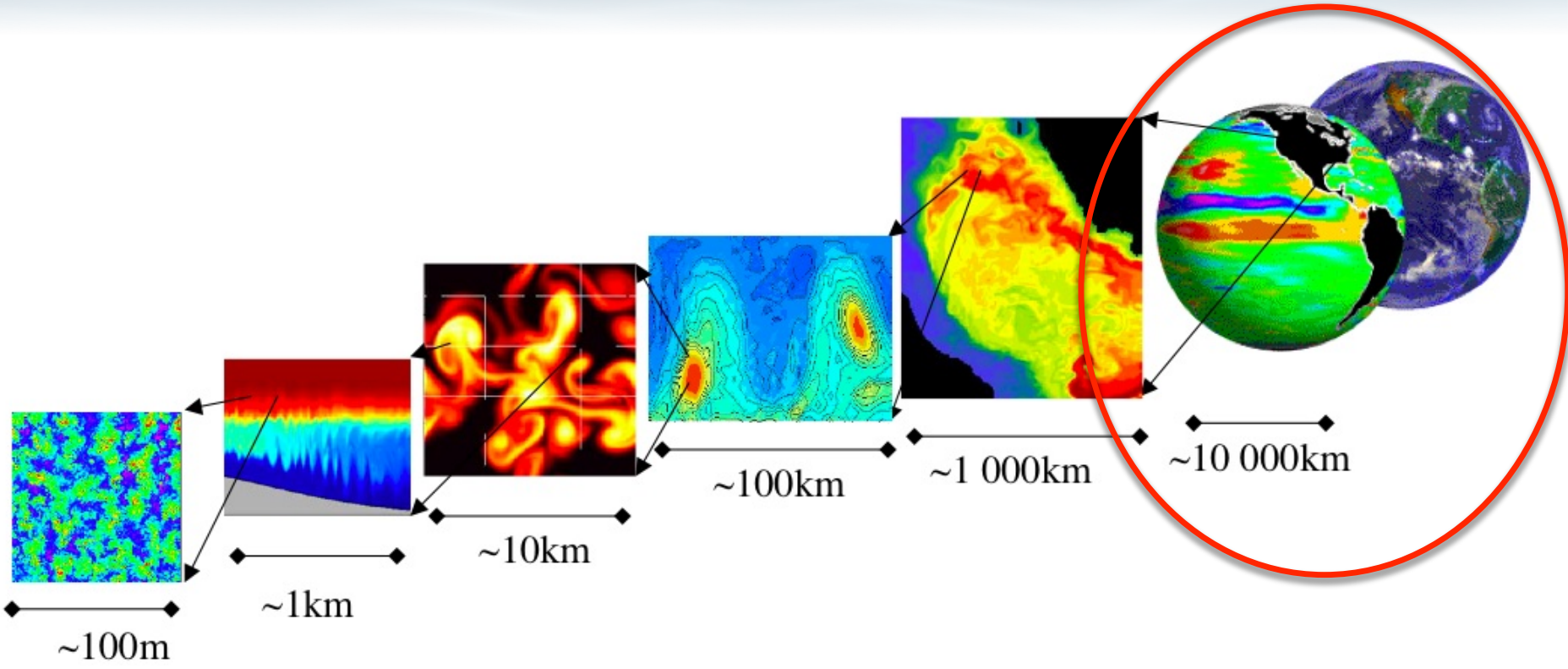
Which ocean model?



A versatile tool for almost every ocean modeling application

Which ocean model?



A versatile tool for almost every ocean modeling application

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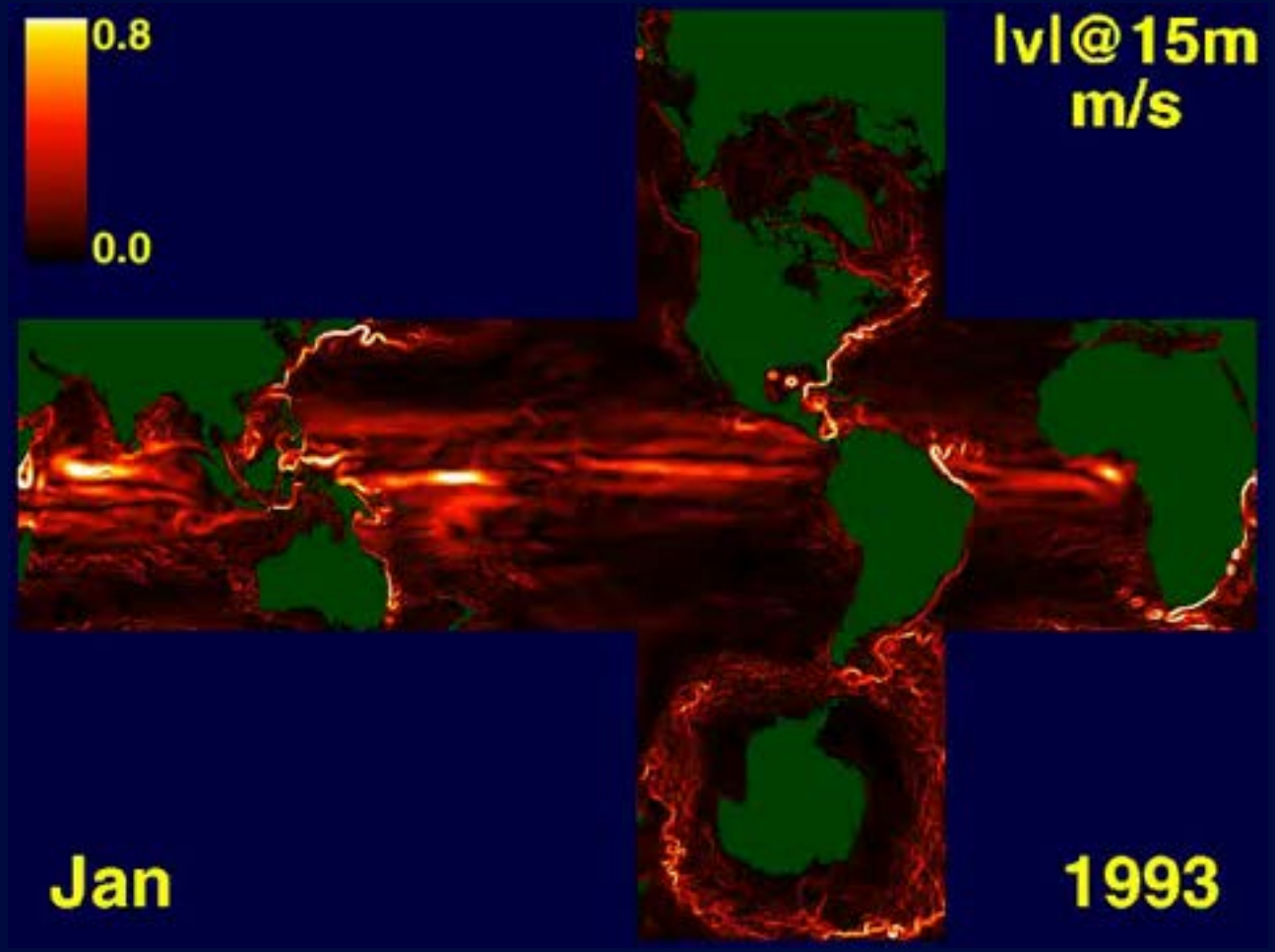
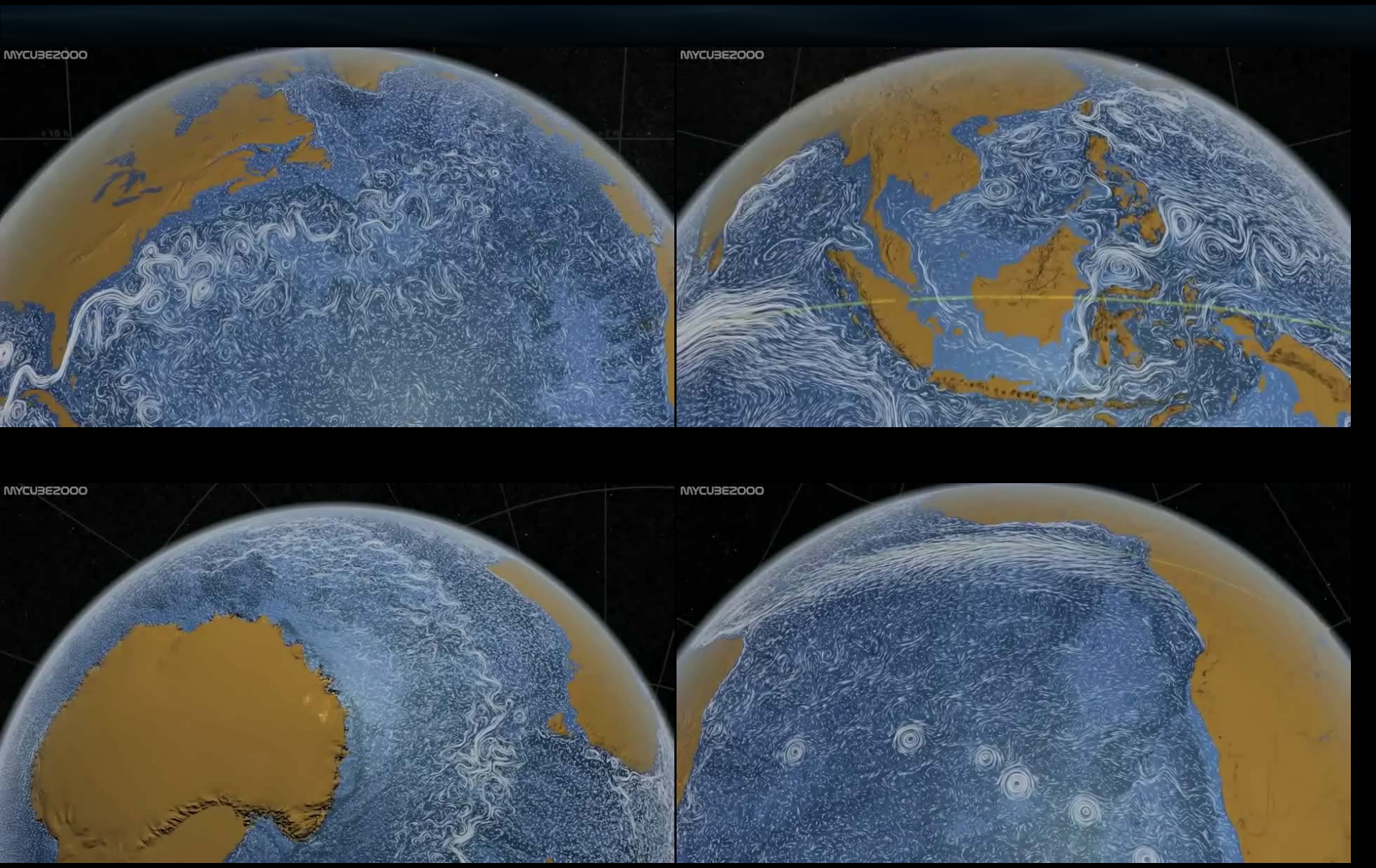


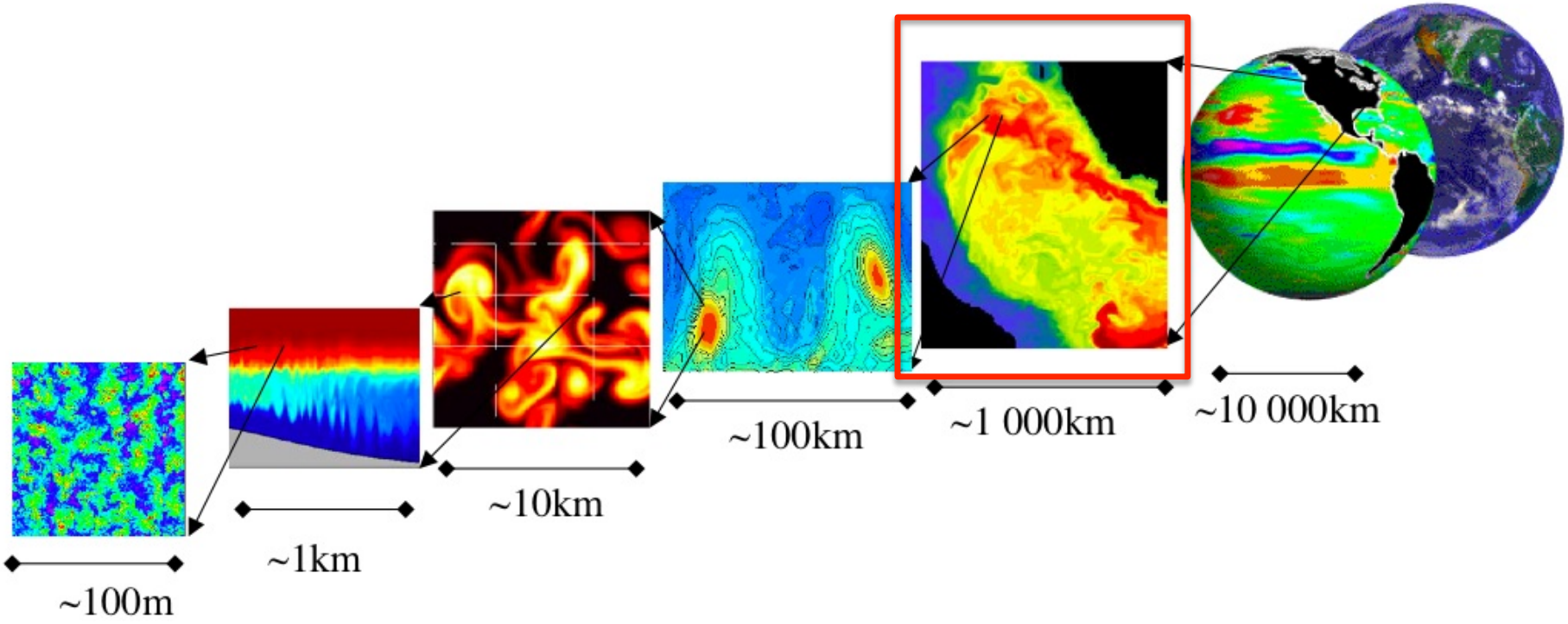
Cubesphere MIT

Which ocean model?



Ocean currents reconstruction (JPL – Nasa)

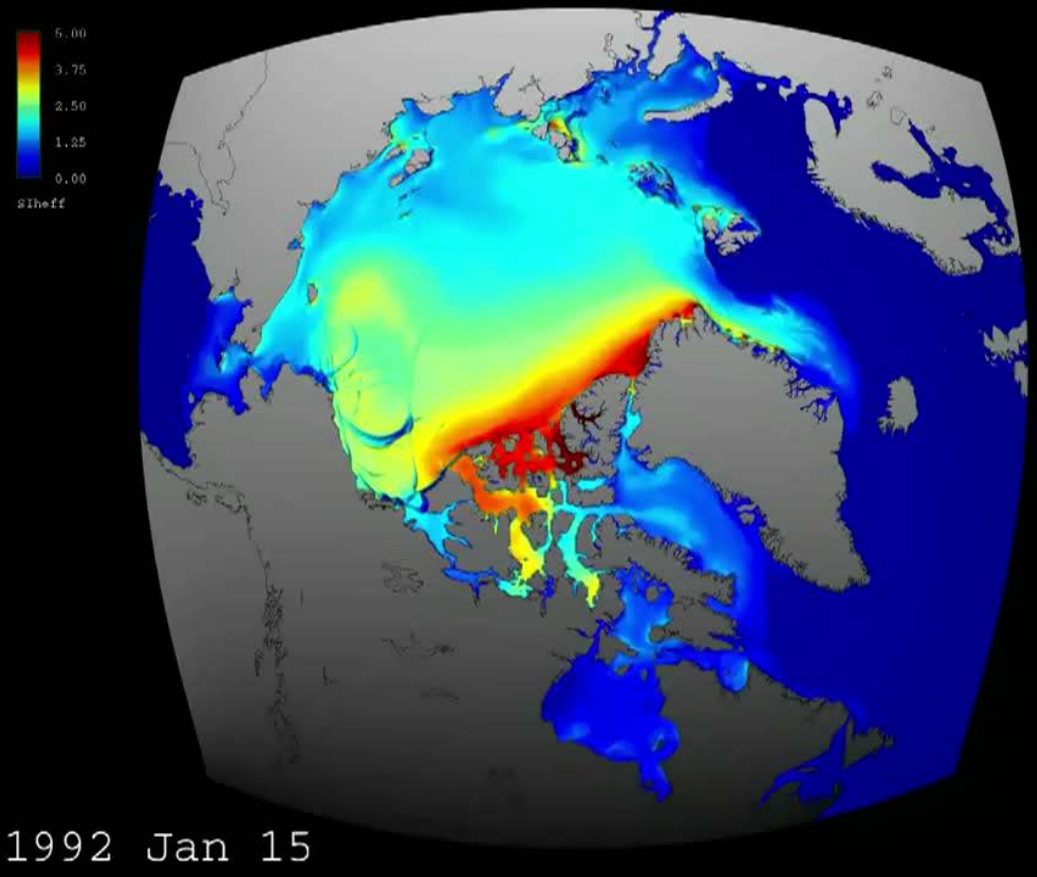
Which ocean model?



A versatile tool for almost every ocean modeling application

http://mitgcm.org

Which ocean model?



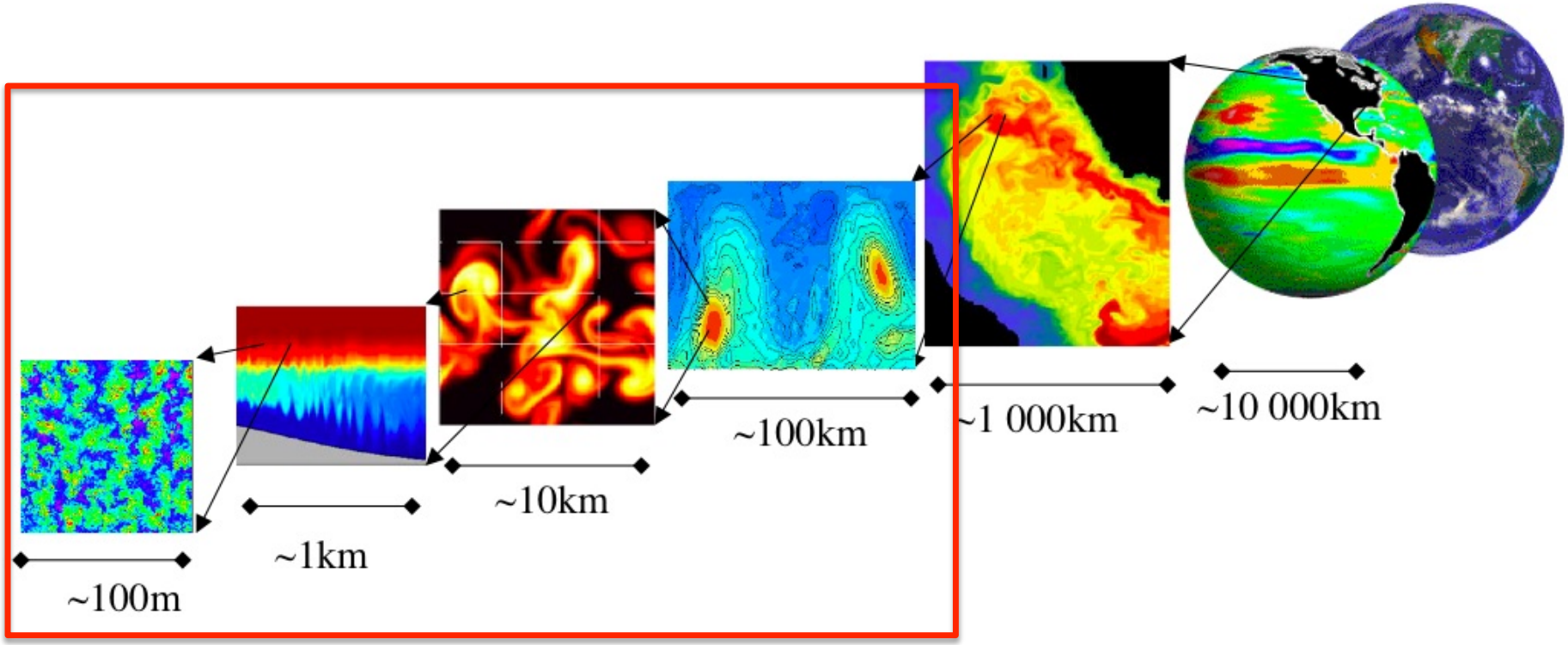
P. Heimbach (MIT – USA)

Ice thickness North Pole reconstruction

Which ocean model?

Mediterranean-North Atlantic EU coasts (JPL – Nasa)

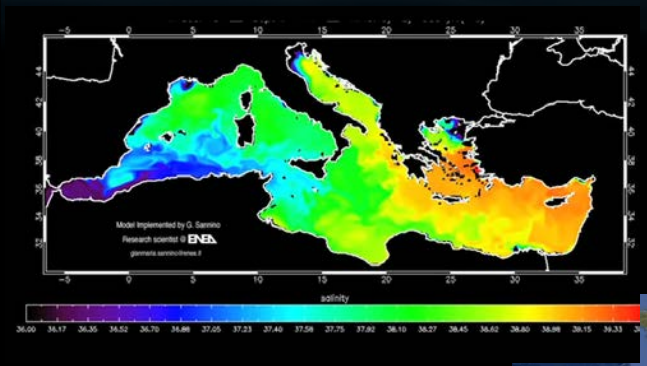
Which ocean model?



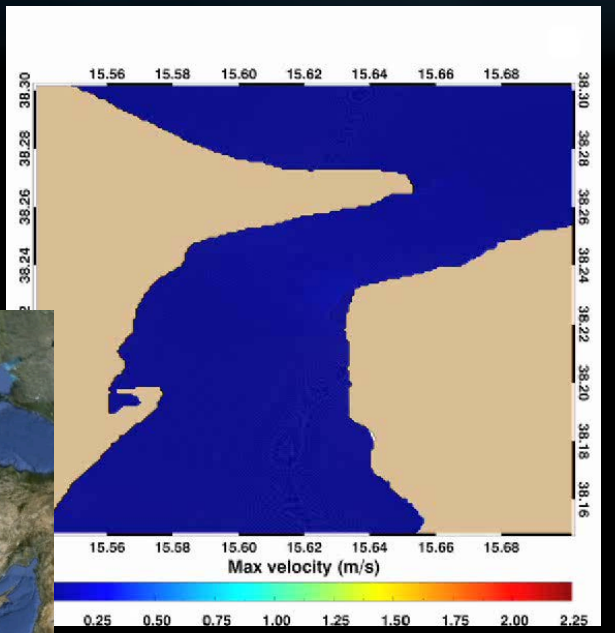
A versatile tool for almost every ocean modeling application

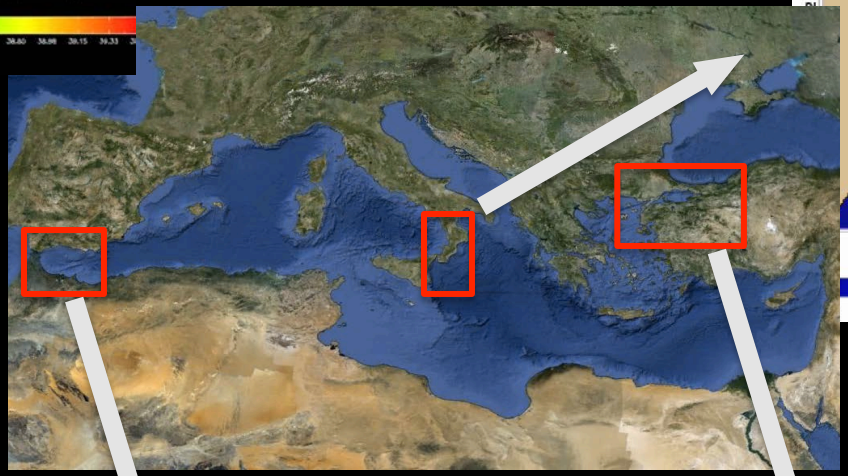
http://mitgcm.org

Background – MIT general circulation model

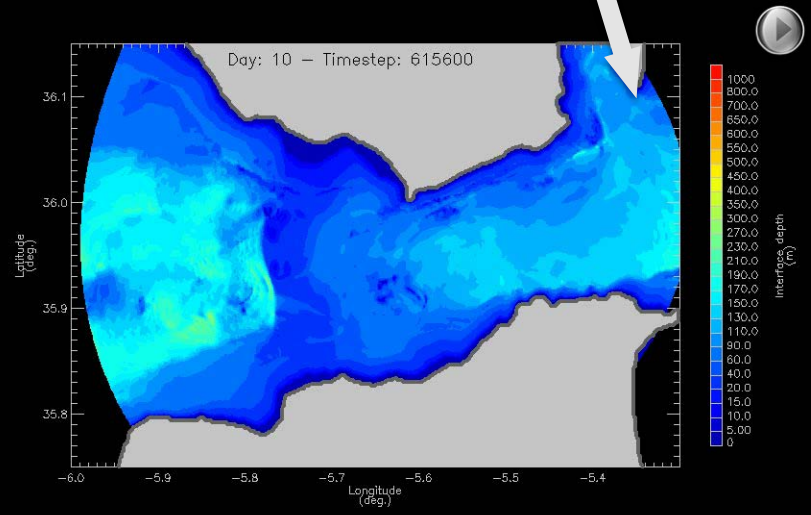


Strait of Messina (ENEA)

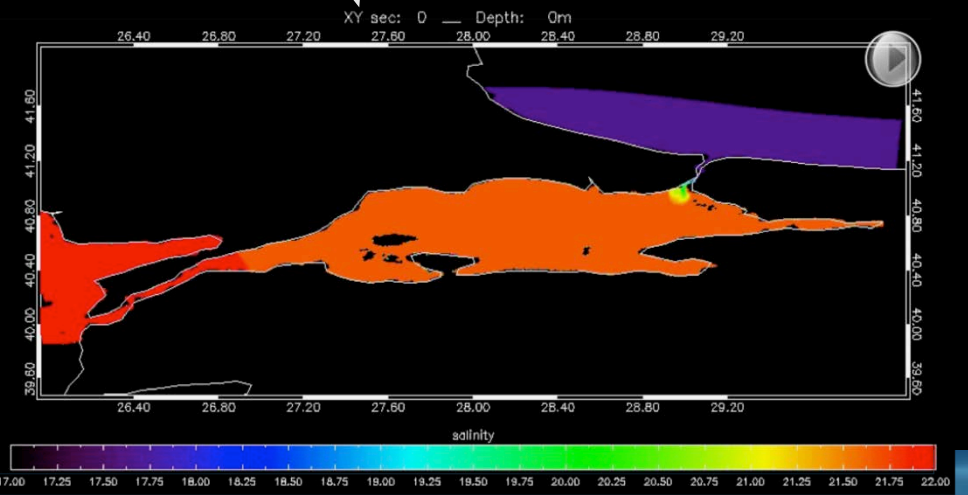




Strait of Gibraltar (ENEA)



Turkish Straits System (ENEA+METU)



http://mitgcm.org/

MITgcm | M.I.T General Circulation Model News and Information

Links

- Source code
- Testing
- Documentation
- Contact Us

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- About News and Features
- Latest News and Features
- Publications
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News Stories

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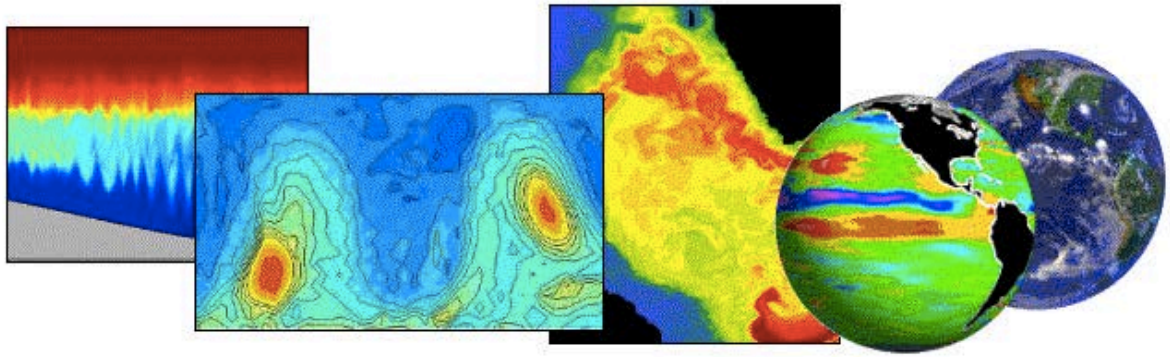
About MITgcm



The **MITgcm** (**MIT** **G**eneral **C**irculation **M**odel) is a numerical model designed for study of the atmosphere, ocean, and climate. Its non-hydrostatic formulation enables it to simulate fluid phenomena over a wide range of scales; its adjoint capability enables it to be applied to parameter and state estimation problems. By employing fluid isomorphisms, one hydrodynamical kernel can be used to simulate flow in both the atmosphere and ocean.

You are welcome to download and use MITgcm.

Papers charting the development of MITgcm can be found here.

Background – MITgcm main features

MITgcm | M.I.T General Circulation Model

- hydrostatic and **non-hydrostatic** capabilities
- vertical z-level (or z^*) or pressure-level coordinates
  - volume (Boussinesq) or mass-conserving
  - **partial cells**
- spatial discretization is finite-volume C-grid
  - cartesian / spherical / general orthogonal **curvilinear coordinate**
  - cubed-sphere topologies
- time-discretization
  - semi-implicit pressure method (elliptic solver)
  - Adams-Bashforth for tracer variables (*T, S*)
  - synchronous or staggered time-stepping of tracer fields
- nonlinear free surface with real freshwater flux
- a large choice of linear & nonlinear advection schemes
- various sub-grid scale parameterizations

http://mitgcm.org

Background – MITgcm main features

$$\frac{D\vec{\mathbf{v}}_h}{Dt} + f\hat{\mathbf{k}} \times \vec{\mathbf{v}}_h + \frac{1}{\rho_c}\nabla_z p = \vec{\mathcal{F}}$$

$$\epsilon_{nh}\frac{Dw}{Dt} + \frac{g\rho}{\rho_c} + \frac{1}{\rho_c}\frac{\partial p}{\partial z} = \epsilon_{nh}\mathcal{F}_w$$

$$\nabla_z \cdot \vec{\mathbf{v}}_h + \frac{\partial w}{\partial z} = 0$$

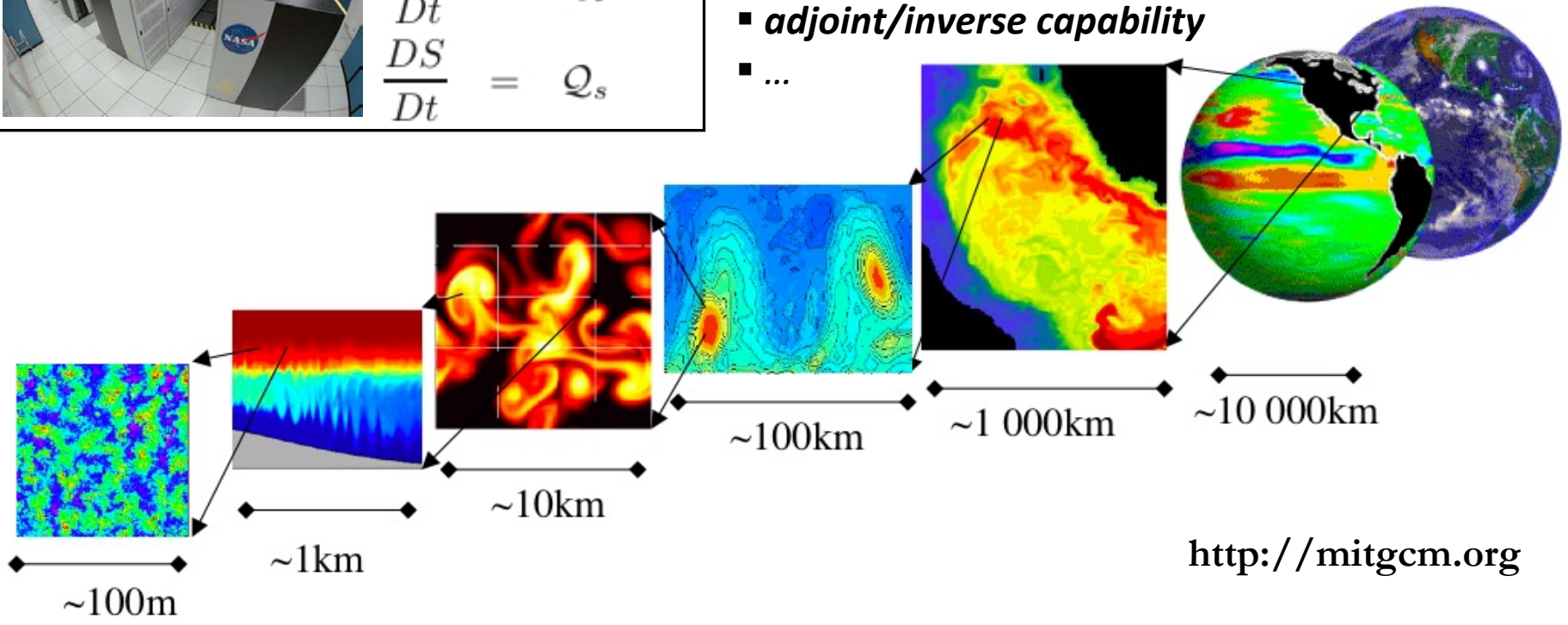
$$\rho = \rho(\theta, S)$$

$$\frac{D\theta}{Dt} = \mathcal{Q}_\theta$$

$$\frac{DS}{Dt} = \mathcal{Q}_s$$

Approximated form of Navier-Stokes equations for an incompressible fluid, consisting of:

- *momentum equation (including Coriolis term)*
- *conservation of mass (continuity equation)*
- *conservation of tracers (heat, salt)*
- *equation of state*
- *subgrid-scale parameterizations*
- *scalable (domain decomposition)*
- *general curvilinear grid (incl. cubed-sphere)*
- ***adjoint/inverse capability***
- *…*



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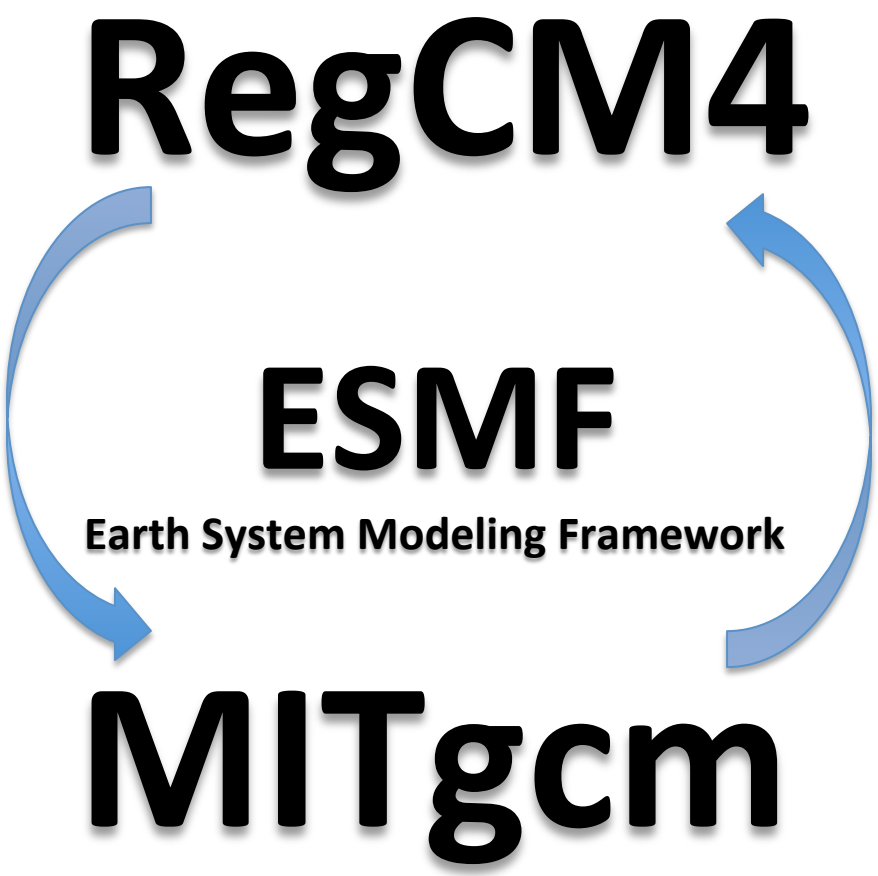
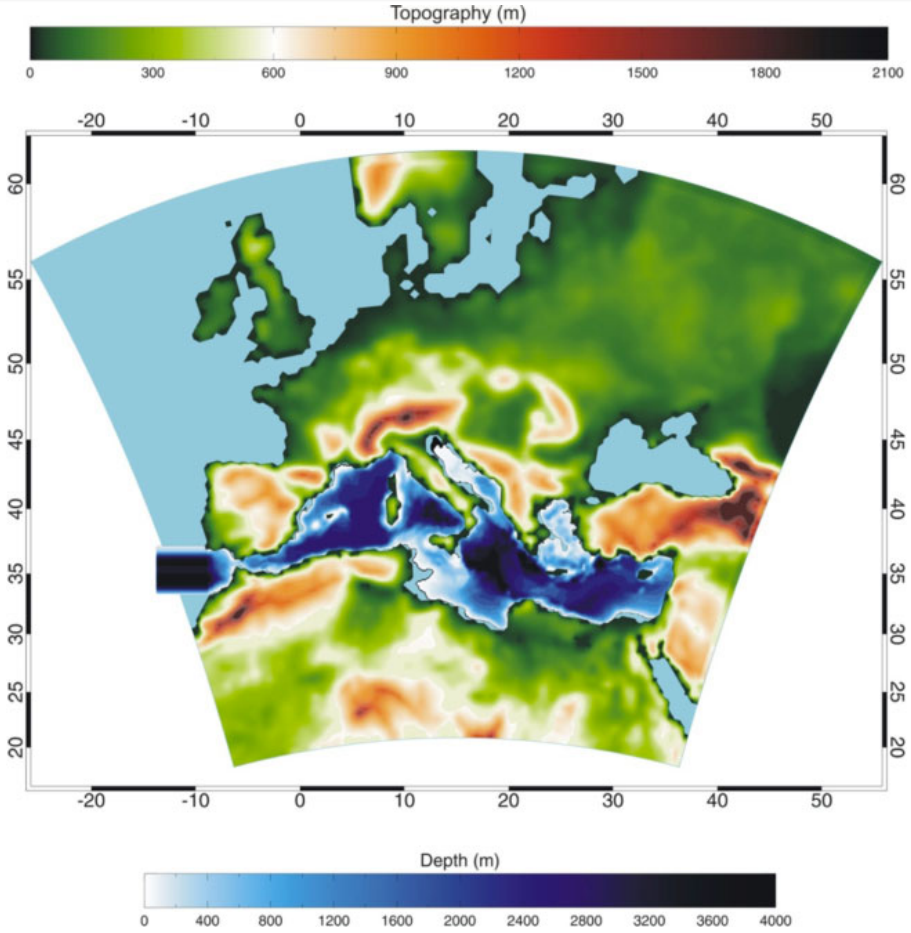


http://www.earthsystemmodeling.org/

Mediterranean AORCM @ ENEA: the past system PROTHEUS 1.0



Model domain

Model components

RegCM3

18 sigma vertical levels

30 Km horizontal resolution

HF-WF-Wind

OASIS 3

Freq. 6h

SST

MedMIT

42 zeta vertical levels (partial cell)

1/8° x 1/8° horizontal resolution

Artale et al., Clim. Dynamics. 2009
Mariotti et al., Clim. Dynamics 2011
Dell'Aquila et al., Clim. Dynamics 2011
Dubois et al., Clim. Dynamics 2011
Calafat et al., J. Geophy. Res, 2012
Carillo et al, Clim. Dynamics, 2012
Fenoglio et al, Glob. Plane. Chan. 2012

Gualdi et al., BAMS 2013

Mediterranean AORCM @ ENEA: the new system PROTHEUS 2.0

Model components

RegCM4

18 sigma vertical levels

30 Km horizontal resolution

HF-WF-Wind

ESMF

Freq. << 6h

SST

MedMIT

72 zeta vertical levels (partial cell)

1/12° x 1/12° horizontal resolution

Model components

RegCM3

18 sigma vertical levels

30 Km horizontal resolution

HF-WF-Wind

OASIS 3

Freq. 6h

SST

MedMIT

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1/8° x 1/8° horizontal resolution

F. Giorgi
E. Coppola
R. Farneti

U. Turuncoglu

Mediterranean AORCM @ ENEA: the new system PROTHEUS 2.0

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Mediterranean AORCM @ ENEA: the new system PROTHEUS 2.0

Model components

RegCM4

18 sigma vertical levels

30 Km horizontal resolution

2D MPI domain decomposition
F90 ANSI standard

Model components

RegCM3

18 sigma vertical levels

30 Km horizontal resolution

1D MPI domain decomposition
F77 ANSI standard

- account for the occurrence of fractional clear sky at a given grid box
- aerosolo radiative transfer calculation (Solmon et al., 2008)
- new PBL scheme, the University of Washington PBL (Grenier & Bretherton 2001, Bretherton et al. 2004)
- capability of running separate convection schemes over land and ocean
- 2 new land use types in BATS
- option to use the Community Land Model, version CLM3.5 (Tawfik & Steiner 2011)
- prognostic SST scheme (Zeng & Beljaars, 2005)
- aerosol scheme specifically designed for application to long-term climate simulations
- first-generation aerosol model including SO2, sulfates, organic carbon, and black carbon, desert dust, sea salt
- tropical band configuration

Mediterranean AORCM @ ENEA: the new system PROTHEUS 2.0

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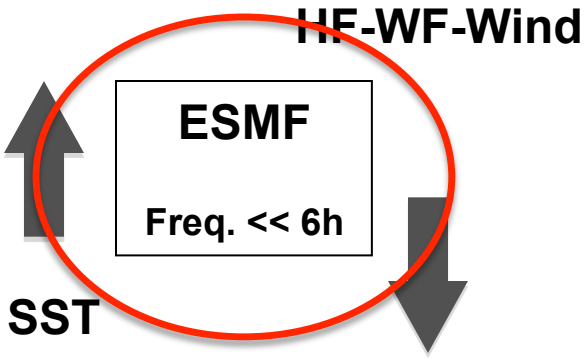

MedMIT

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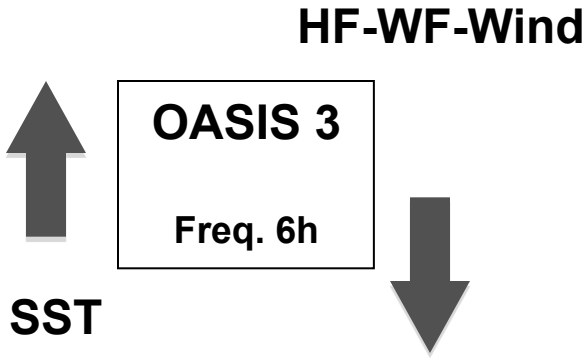

MedMIT

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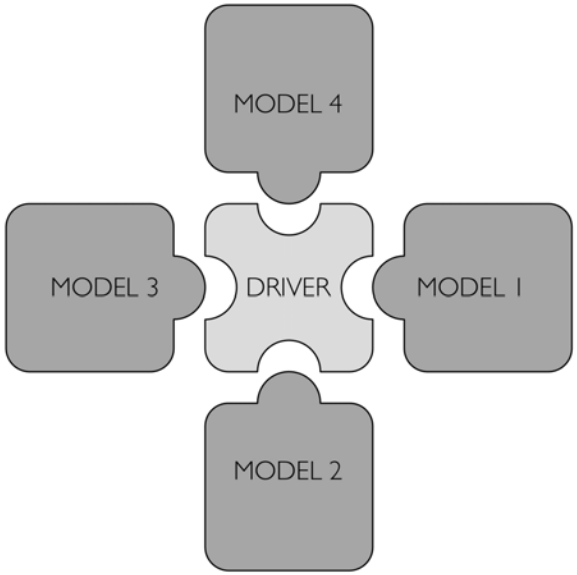
1/8° x 1/8° horizontal resolution

PROTHEUS 2.0: Driver design

- The driver is designed as generic as possible to allow plugging new components easily
- It uses **ESMF** (Earth System Modeling Framework) and **NUOPC** (National Unified Operational Prediction Capability) layer



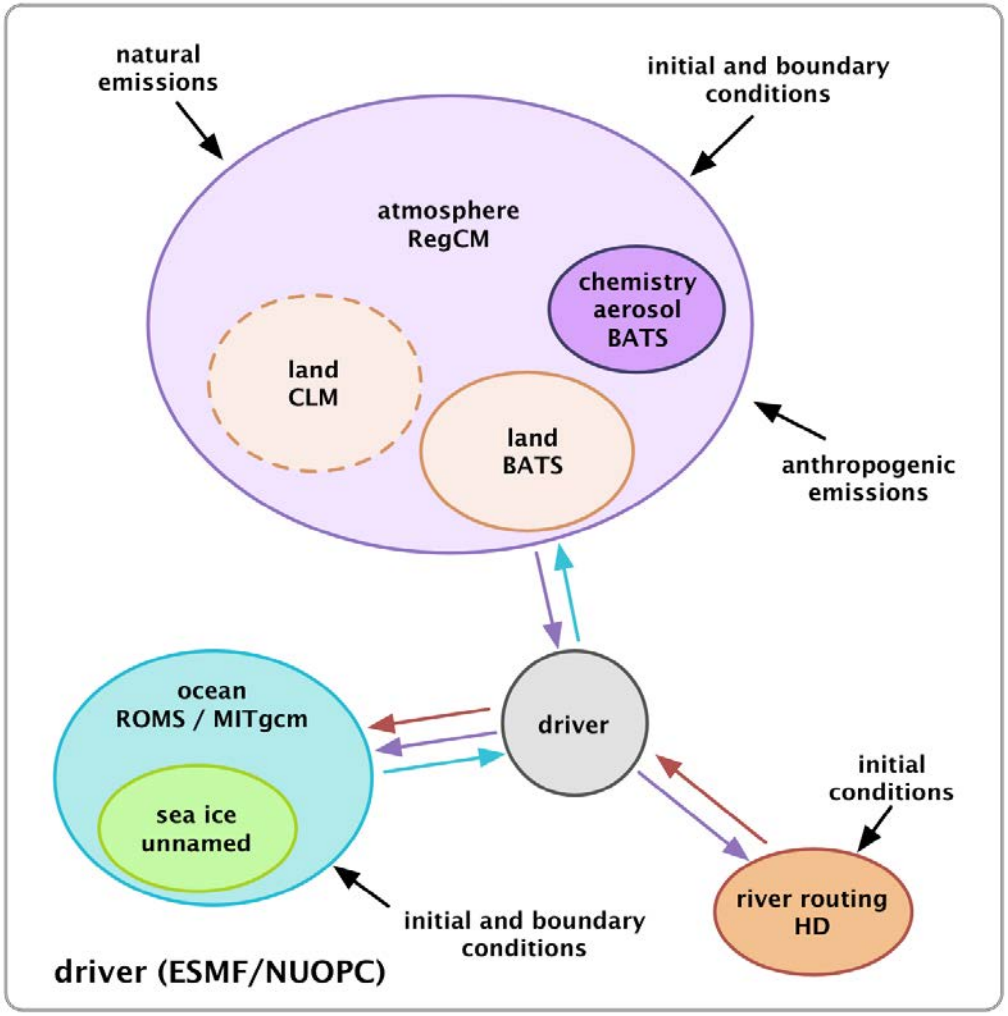
- The driver is responsible for plugging components, orchestration and data exchange
- It is the key part of the "puzzle"
- It has an **generic interface** for the model components

ESMF

NUOPC
NATIONAL UNIFIED OPERATIONAL PREDICTION CAPABILITY

PROTHEUS 2.0: the ESMF coupler

- Currently, it has three different component: ATM/OCN/RTM



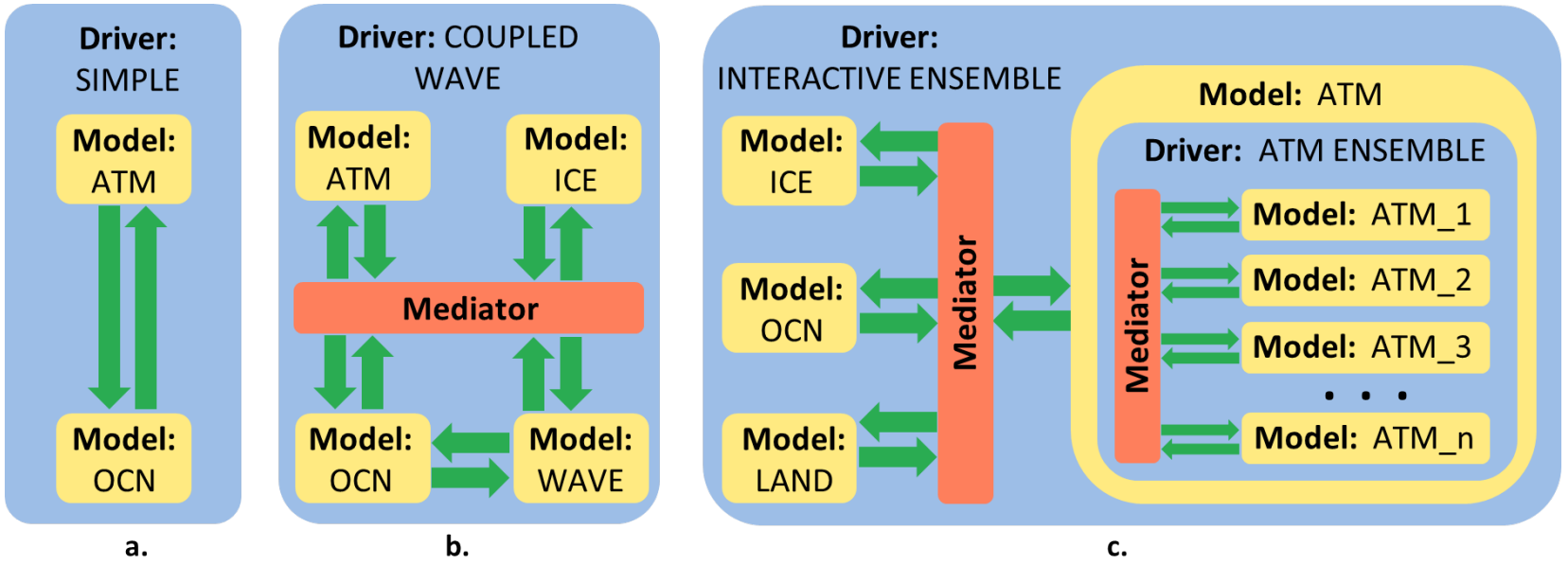
ATM:
RegCM

OCN:
MITgcm/ROMS

RTM:
HD

DRIVER:
ESMF

- Different designs are possible with NUOPC layer



Simple Coupling with Connectors ATM+OCN

Coupling through a Mediator

- The mediator approach is much more efficient when the number of components increase

Mediterranean AORCM @ ENEA: the new system PROTHEUS 2.0

Model components

RegCM4

18 sigma vertical levels

30 Km horizontal resolution

HF-WF-Wind

ESMF

Freq. << 6h

SST

MedMIT

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OASIS 3

Freq. 6h

SST

MedMIT

42 zeta vertical levels (partial cell)

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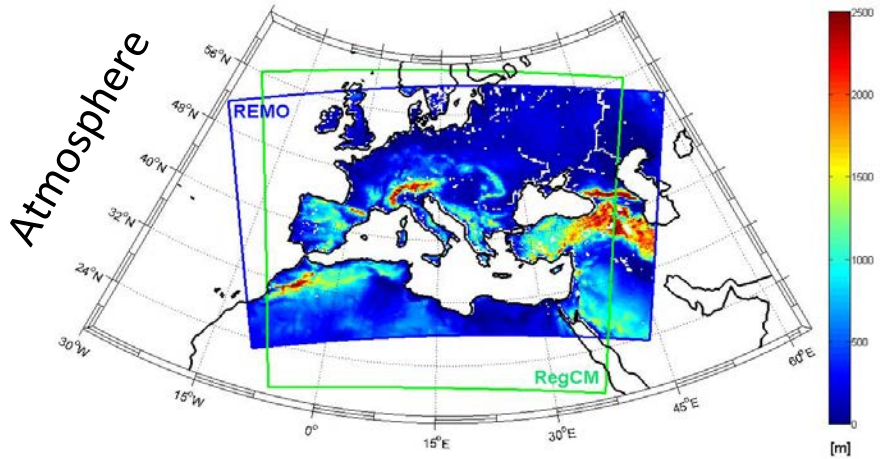
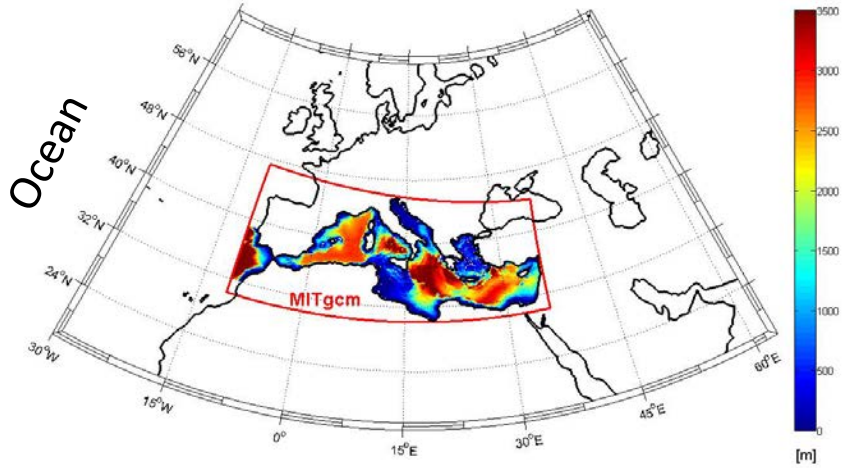
PROTHEUS 2.0: OCE validation - Hindcast simulations (ERA40 1958-2004)

Model configurations



RCM
SURFACE
FLUXES



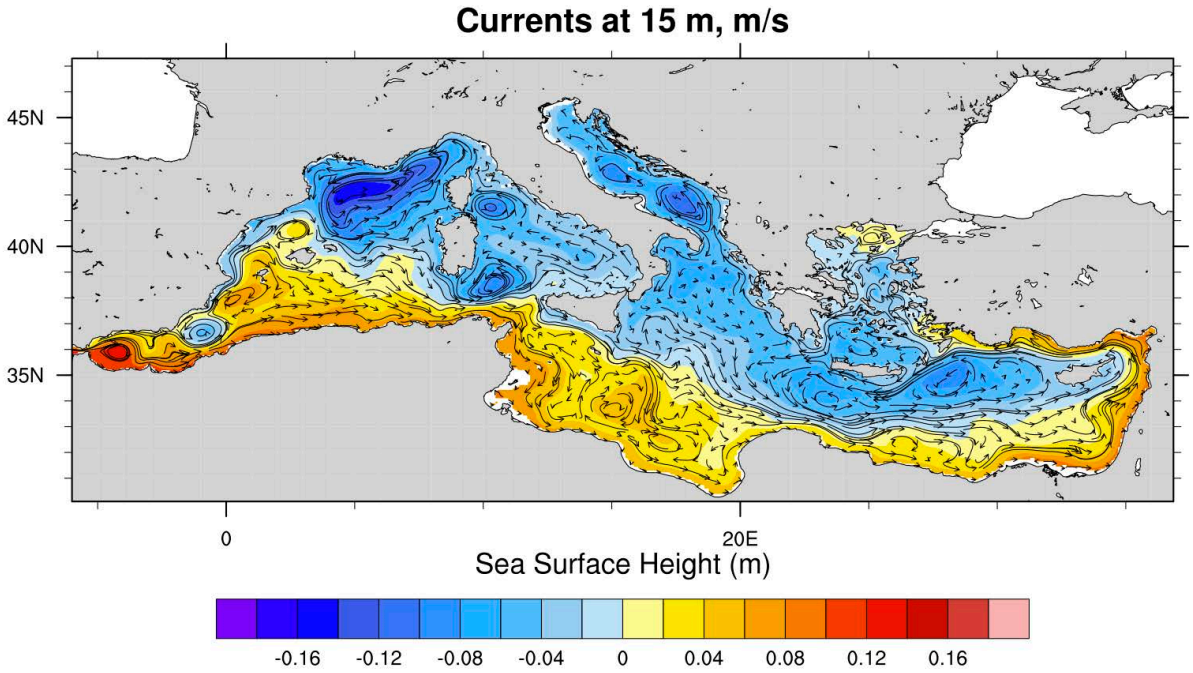
HINDCAST EXPERIMENT
Forcing the MedMIT with ERA40 downscaling produced by REMO.

REMO DOMAIN
- 0.22°x0.22°
- 241x145
- 31 vertical levels

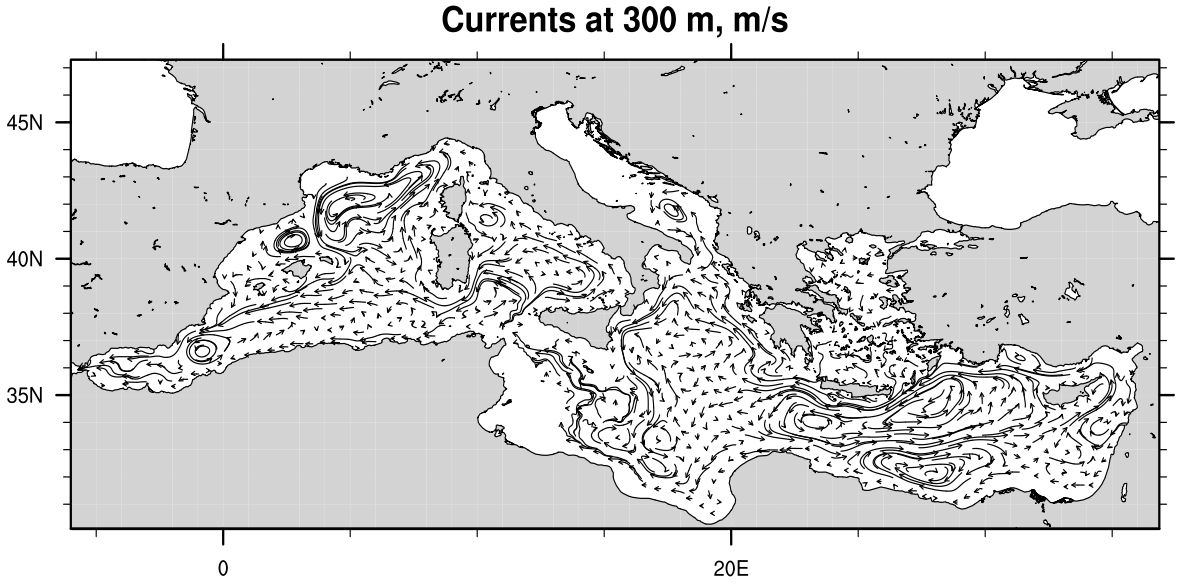
MITgcm DOMAIN (same as NEMO12)
- 1/12°x1/12
- 72 vertical levels

PROTHEUS 2.0: OCE validation - Hindcast simulations (ERA40 1958-2004)

The 1958-2004 time mean Sea Surface Height and circulation at 15 meters depth

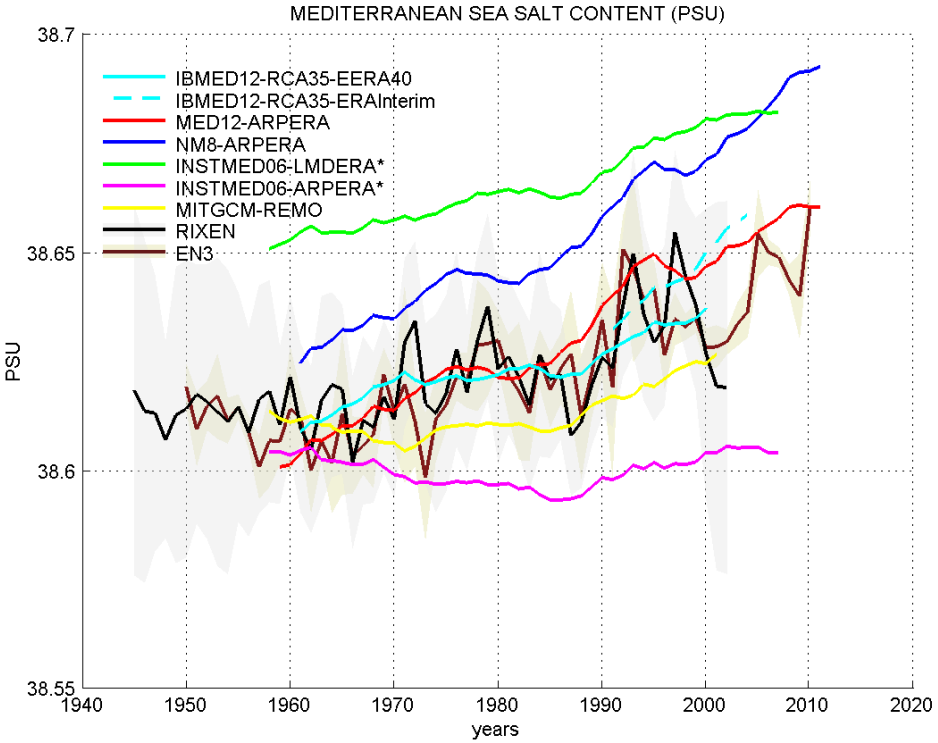


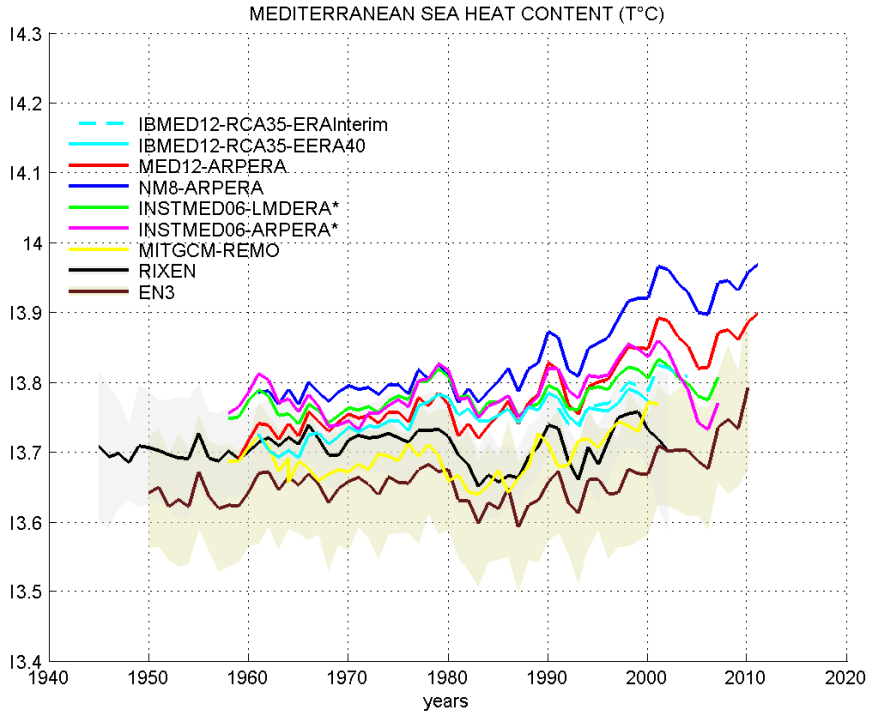
The 1958-2004 time mean circulation at 300 meters depth



Hindcast 1958-2004 results: Med-CORDEX comparison

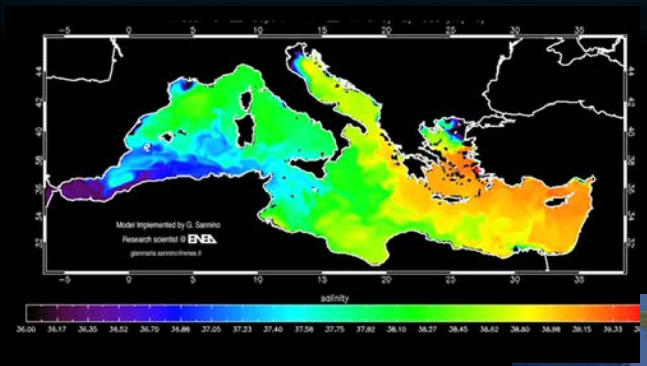
Med-CORDEX initiative has been proposed by the Mediterranean climate research community as a follow-up of previous and existing initiatives. Med-CORDEX takes advantage of new very high-resolution Regional Climate Models (RCM, up to 10 km) and of new fully coupled Regional Climate System Models (RCSMs), coupling the various components of the regional climate.



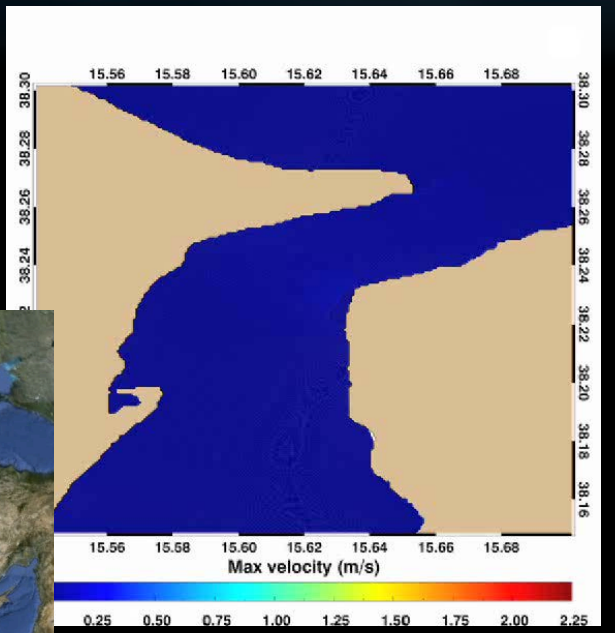


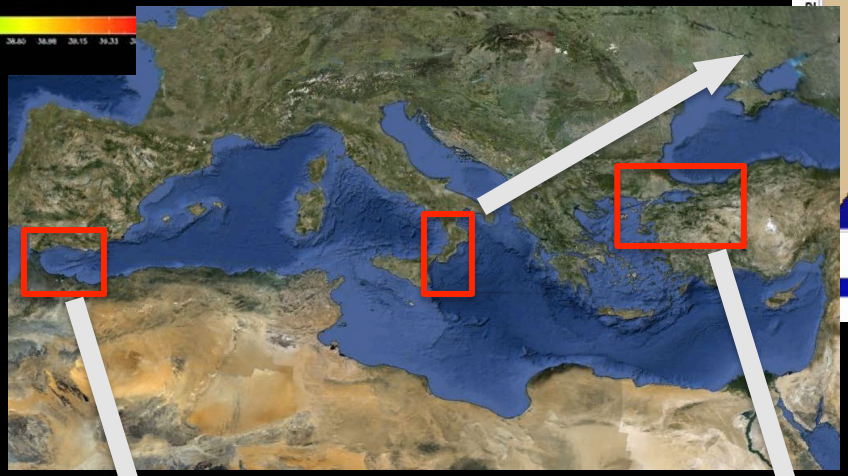
*Med-CORDEX is a coordinated contribution to **CORDEX** that is supported by **HyMeX** and **MedCLIVAR** international programs.*

Background – MIT general circulation model



Strait of Messina (ENEA)





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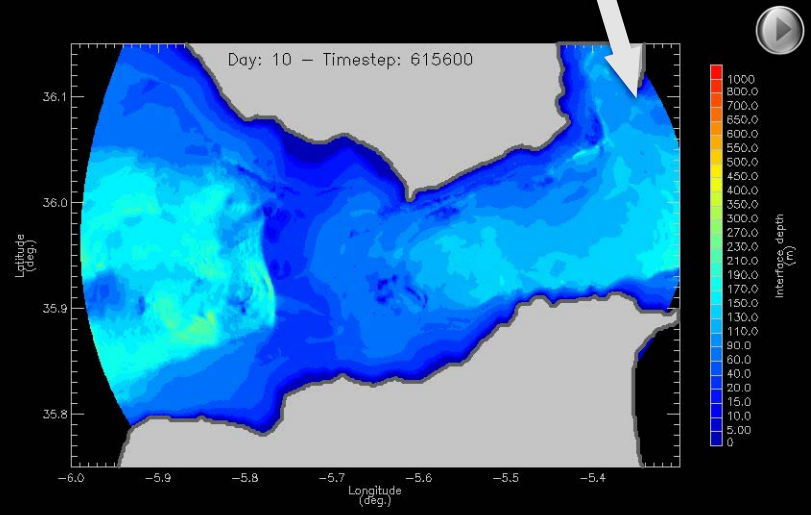
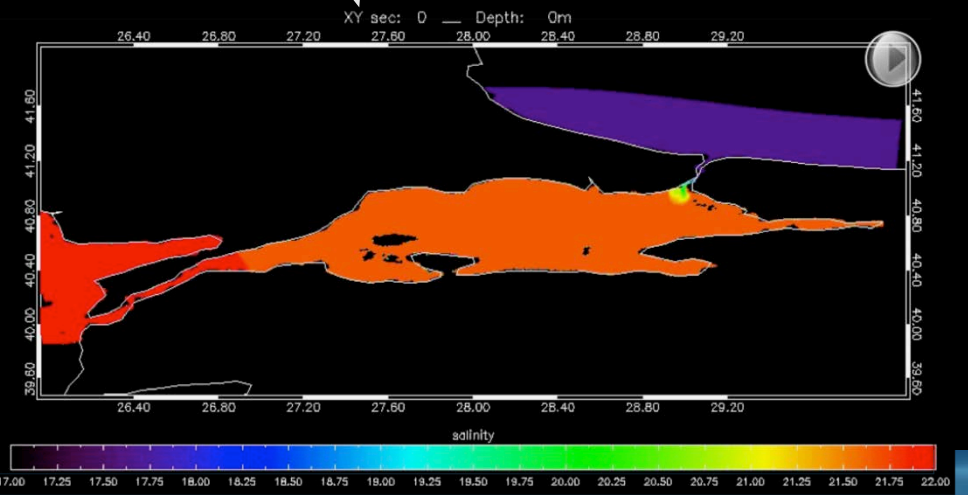
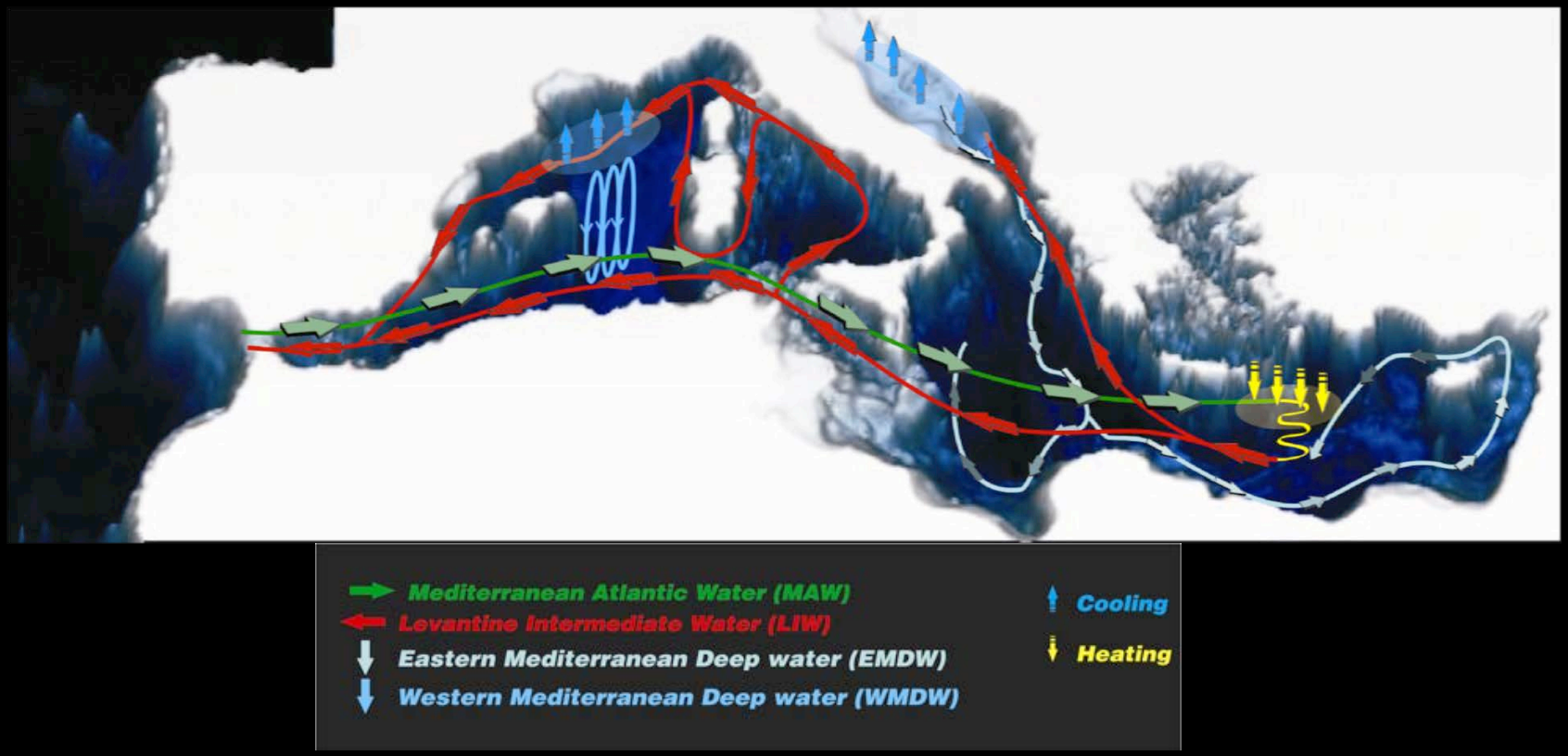


Turkish Straits System (ENEA+METU)



MITgcm applied to the Mediterranean Sea

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

Recent advancements on modelling the exchange flow dynamics through the Turkish Strait System

Middle East Technical University
Institute of Marine Science

Adil Sözer

Emin Özsoy

Italian Agency for New Technologies, Energy and Sustainable Economic Development

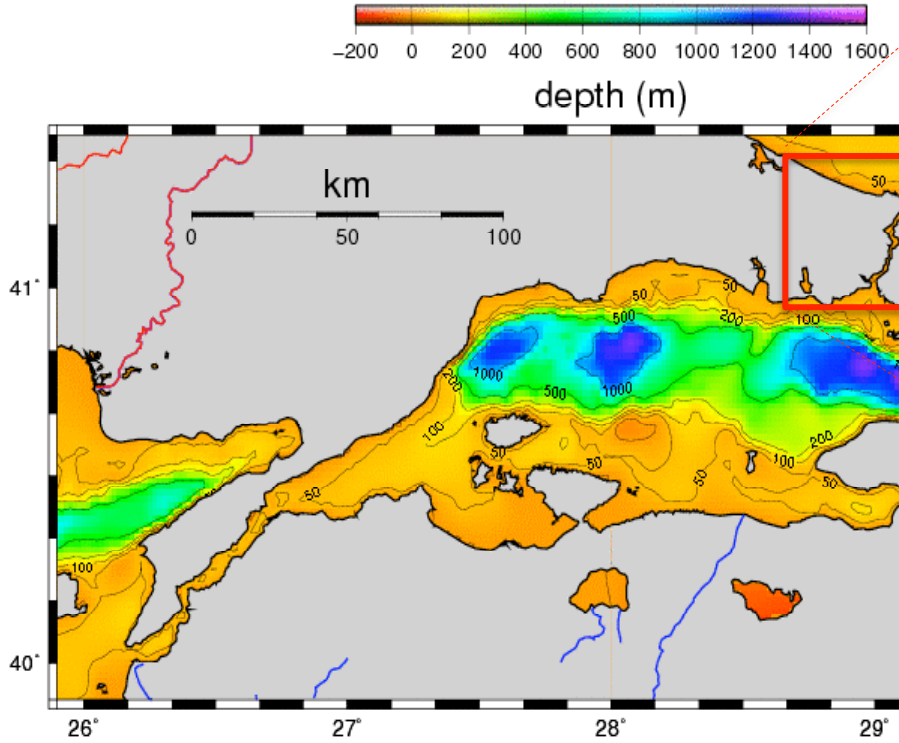
ENEA

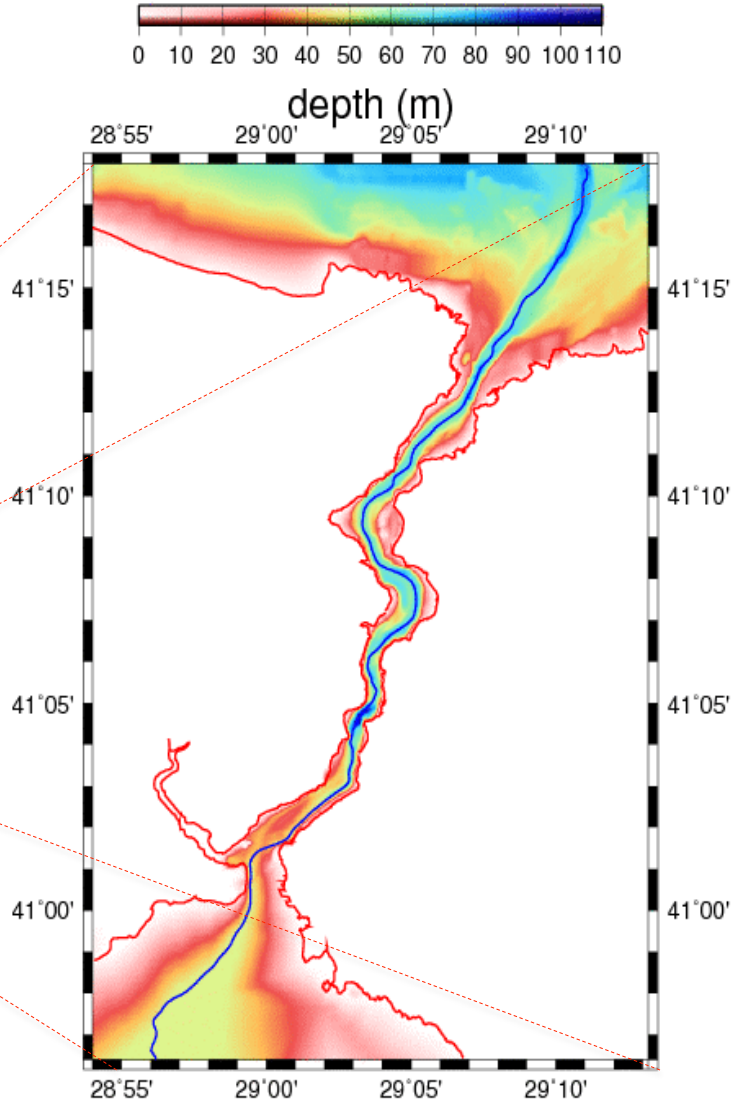
Gianmaria Sannino

Turkish Strait System Background: Where?

Turkish Strait System Background: Where?

Turkish Strait System Background: Bathymetry



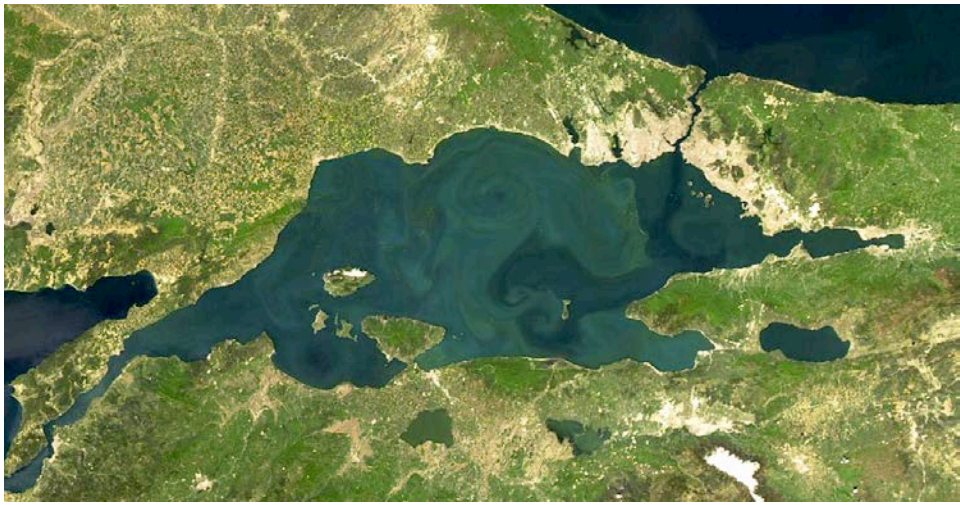


Length 35 km
Min. width 0.7 km

Turkish Strait System Background: Surface Circulation

26 April 2013

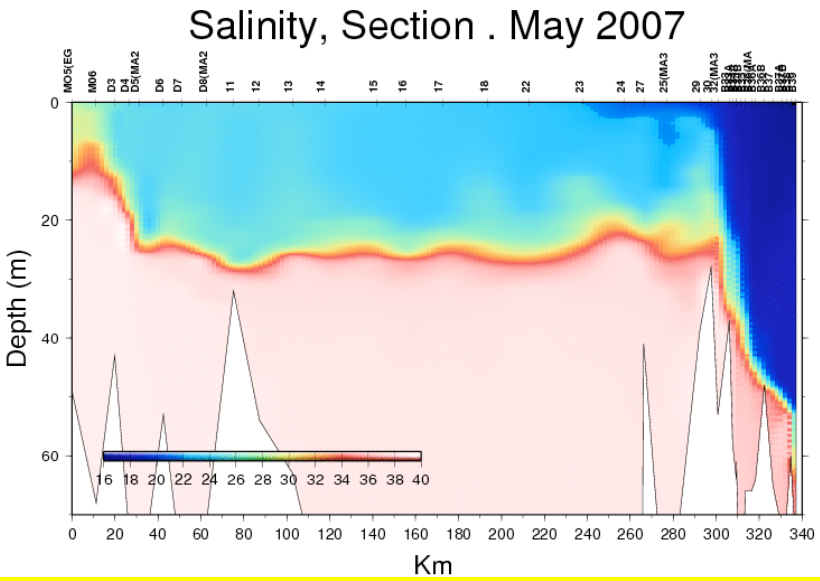
27 April 2013



Turkish Strait System Background: Surface Circulation

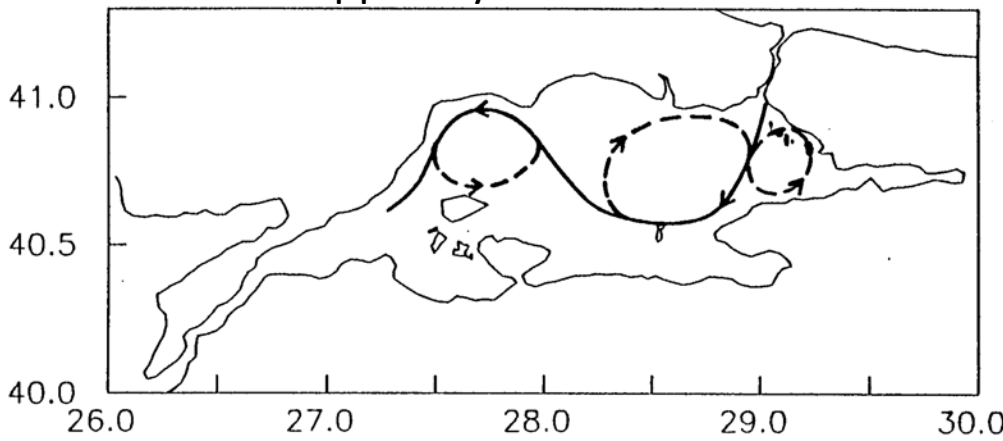
29 April 2013

Turkish Strait System Background: 2-layer circulation

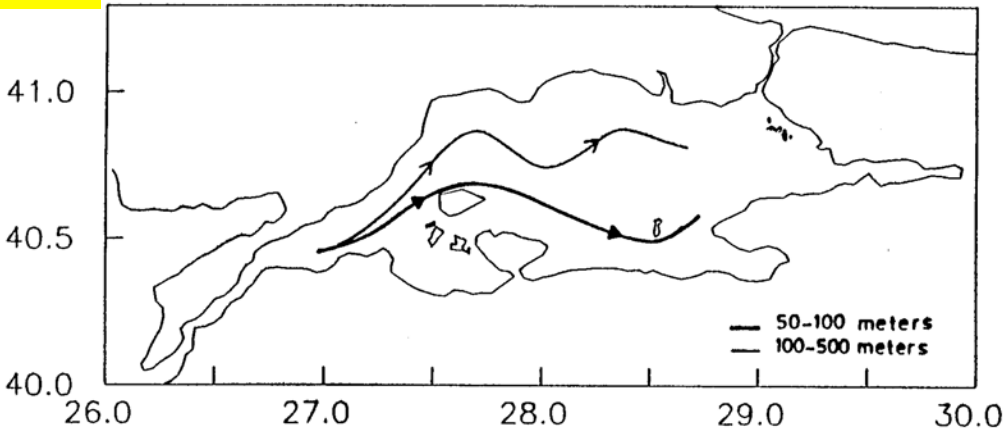


Dardanelles Strait | **Marmara Sea** | **Bosphorus Strait** | **Black Sea**

upper layer circulation



lower layer circulation

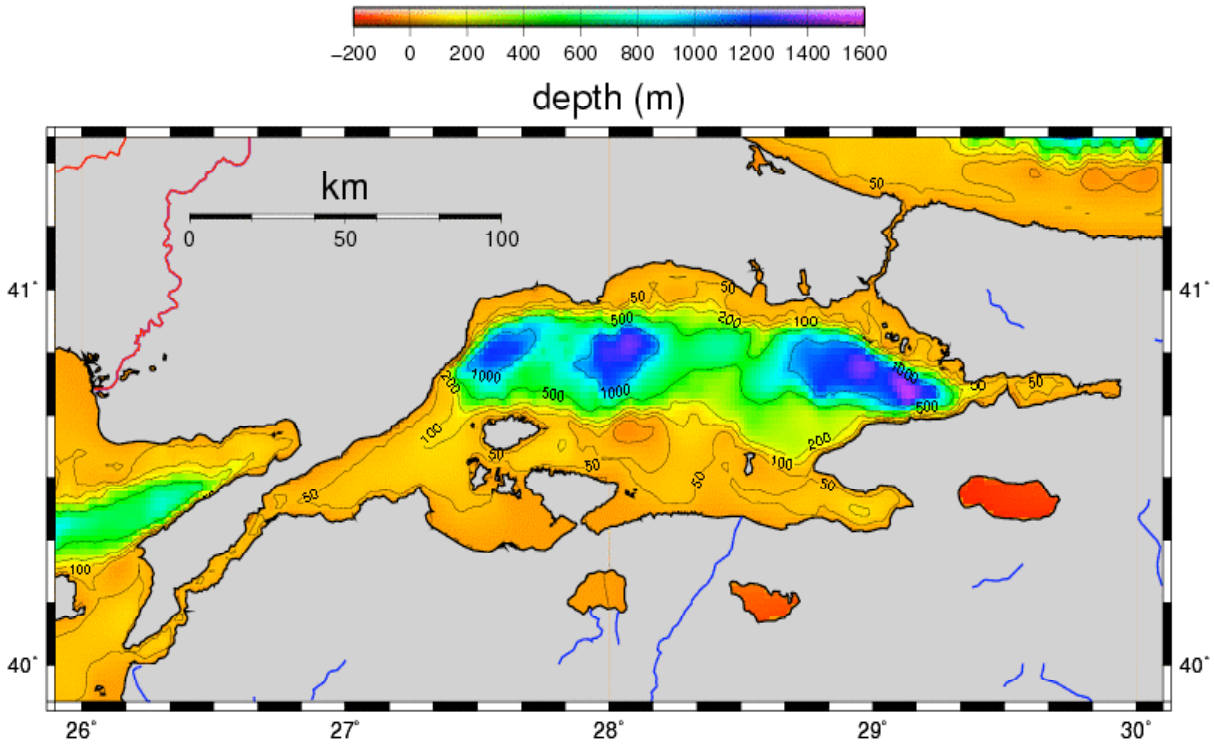


Beşiktepe et al. 1994

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.



Question:

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

Turkish Strait System: our finite difference modeling approach

Model choice

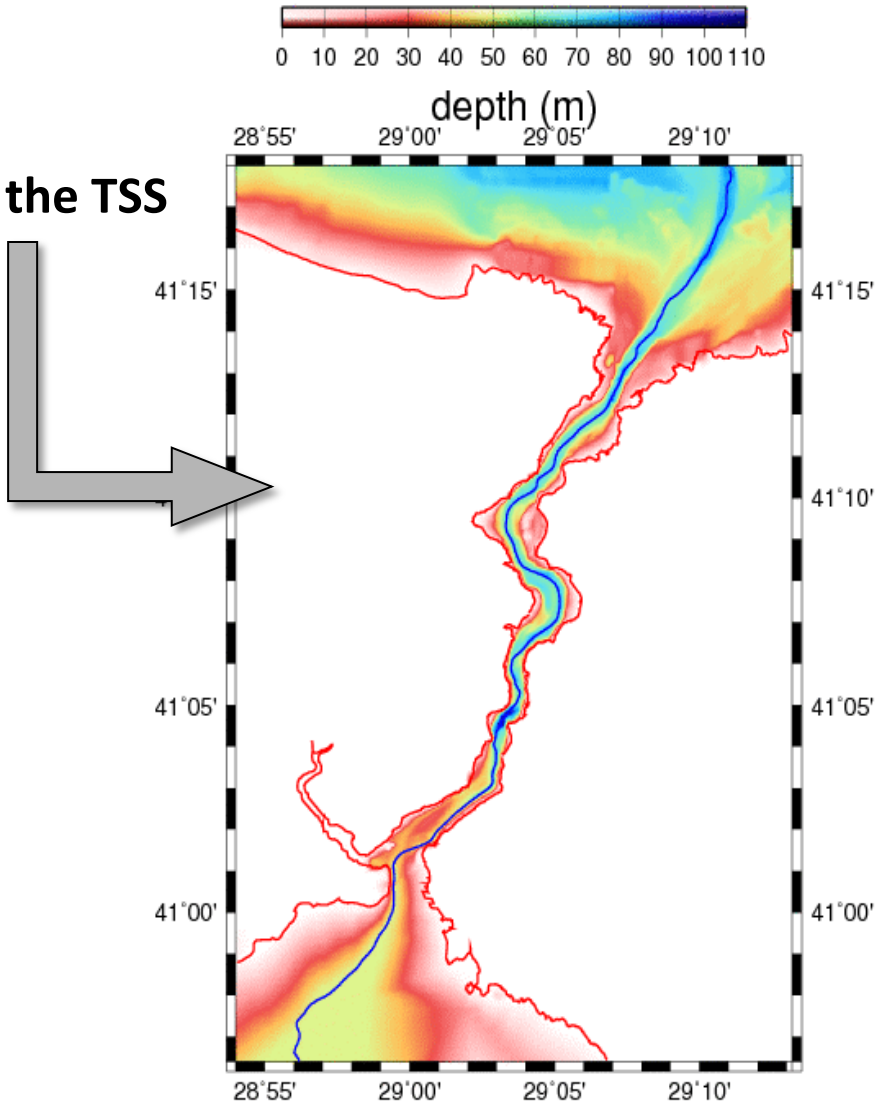
Application to the most challenging place of the TSS

z-level **σ-level**

ROMS

MITgcm

Performances
Comparison



Bosphorus Strait

Bosphorus Modeling: Two Models – One Model configuration

Model Grid

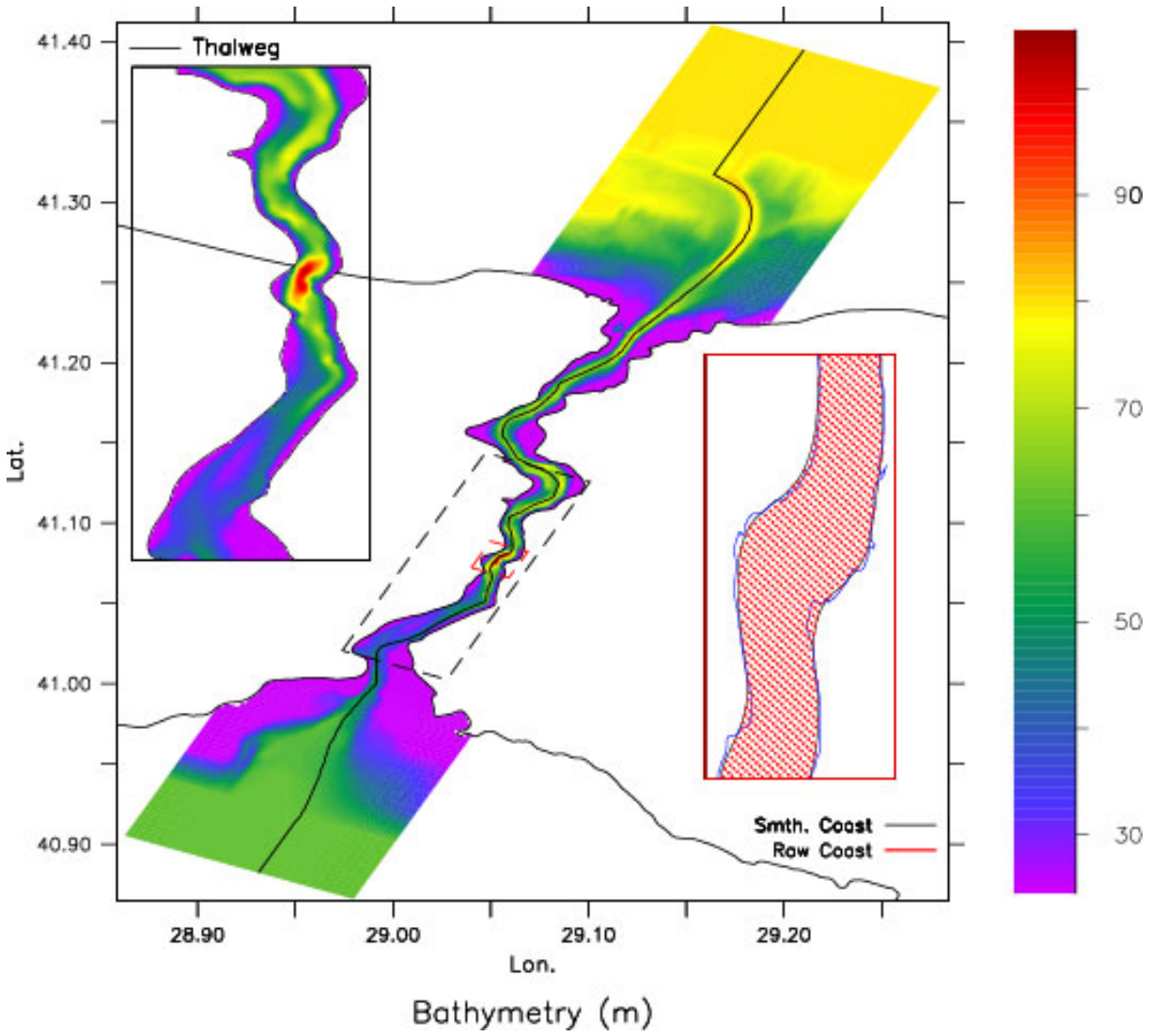
Dx = 50-200m
Dy = 50-325m
L = 11,500m
M = 61,475m
Min Depth=25m

ROMS

Dz=0.7-2.9m
Grid Size=163x716x35

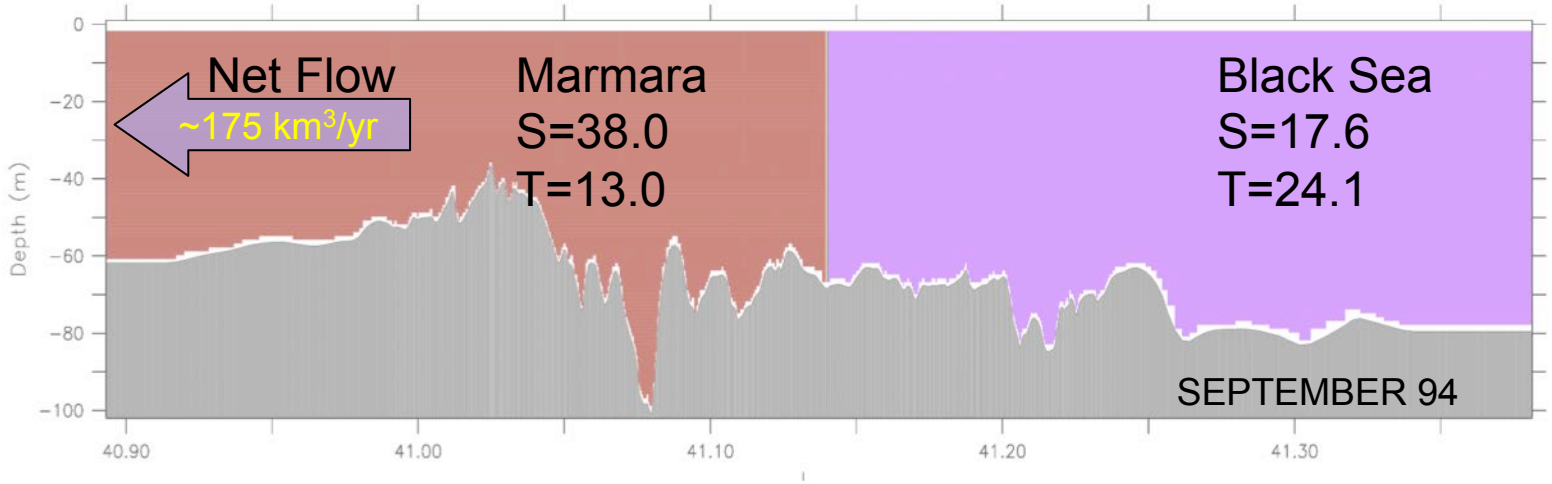
MITgcm

Dz=1.4m
Grid Size=163x716x70

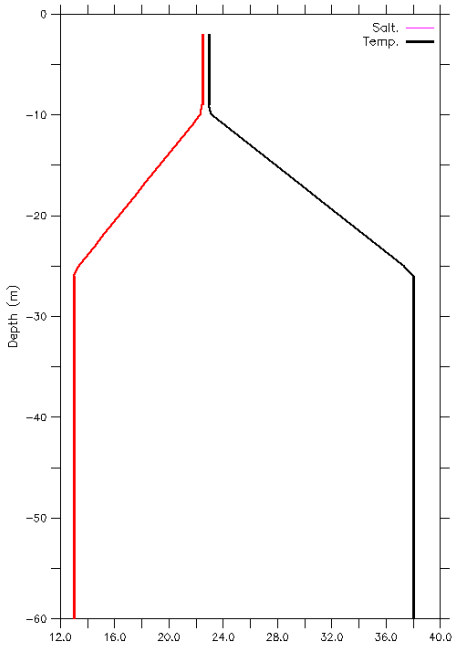


Bosphorus Modeling: Two Models – One setup

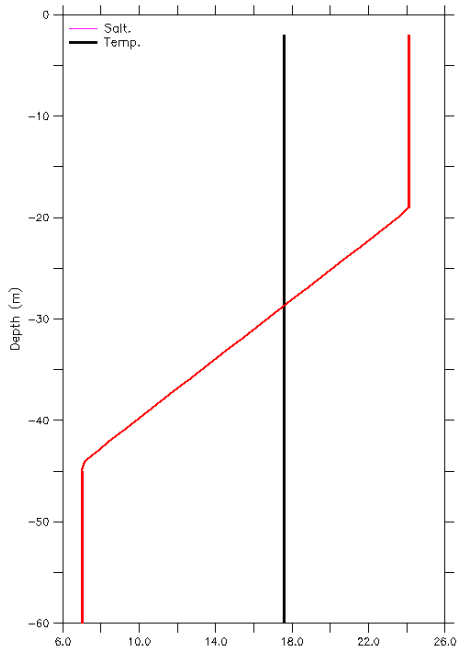
Orlanski Radiation



Orlanski Radiation

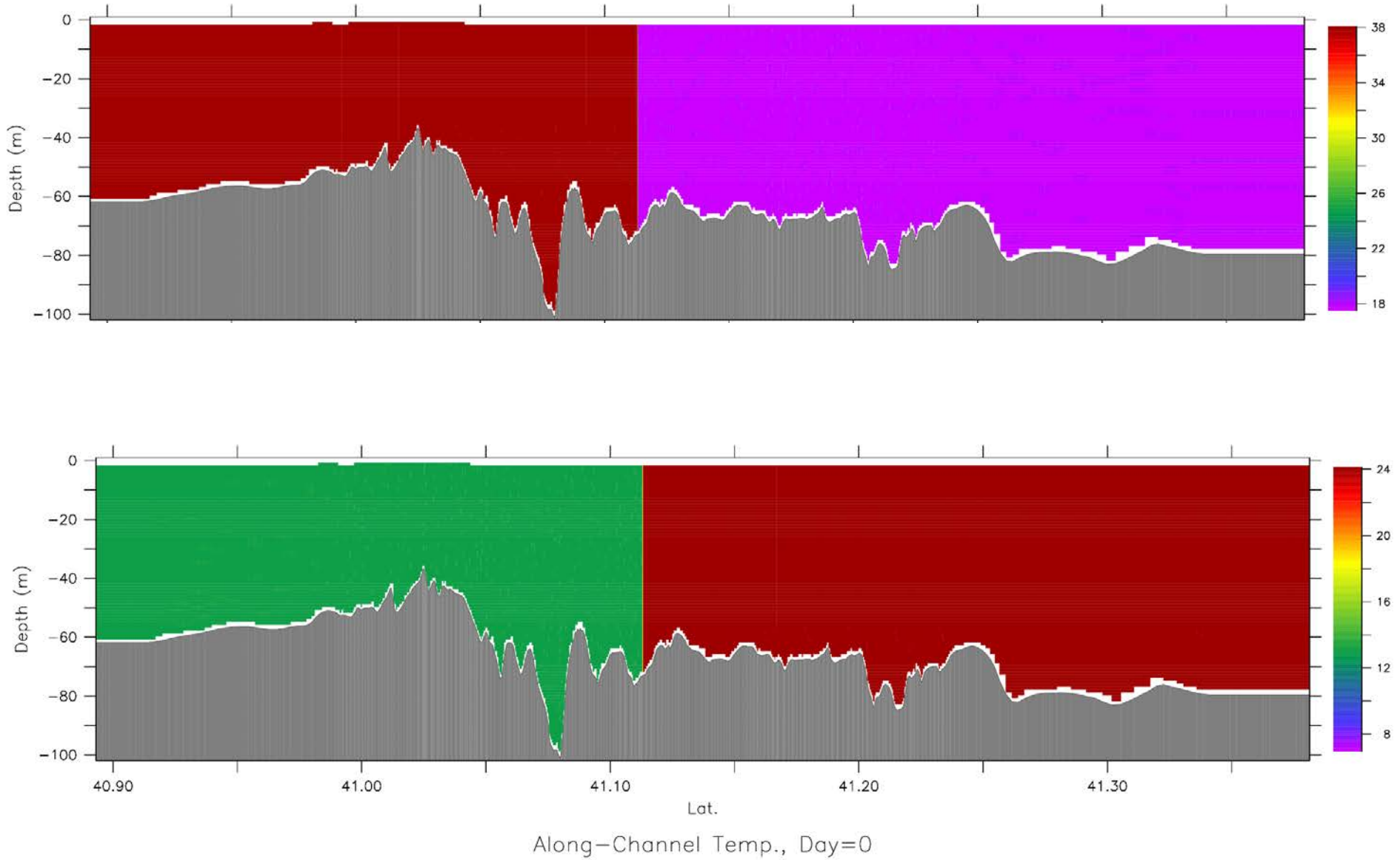


MARMARA



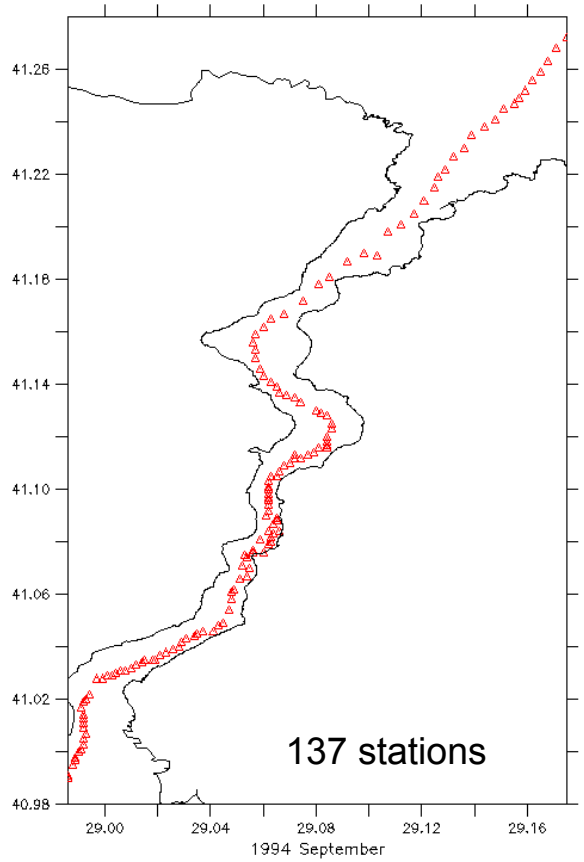
BLACK SEA

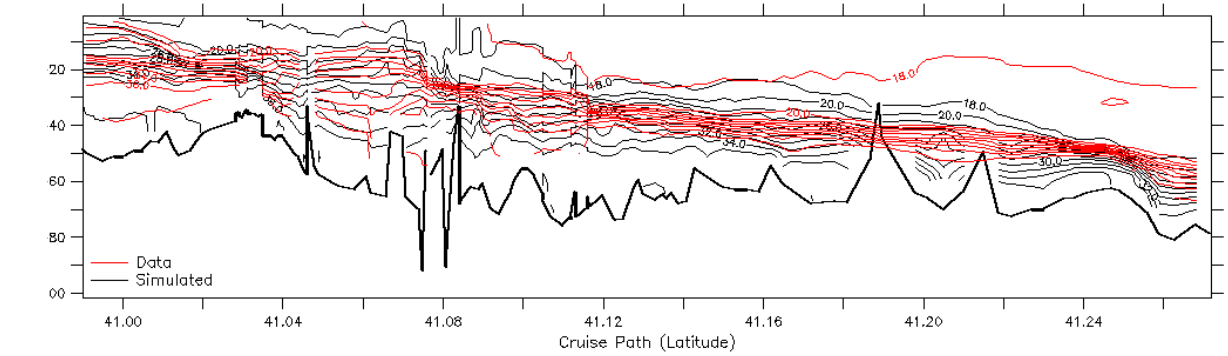
Bosphorus Modeling: Two Models – One setup



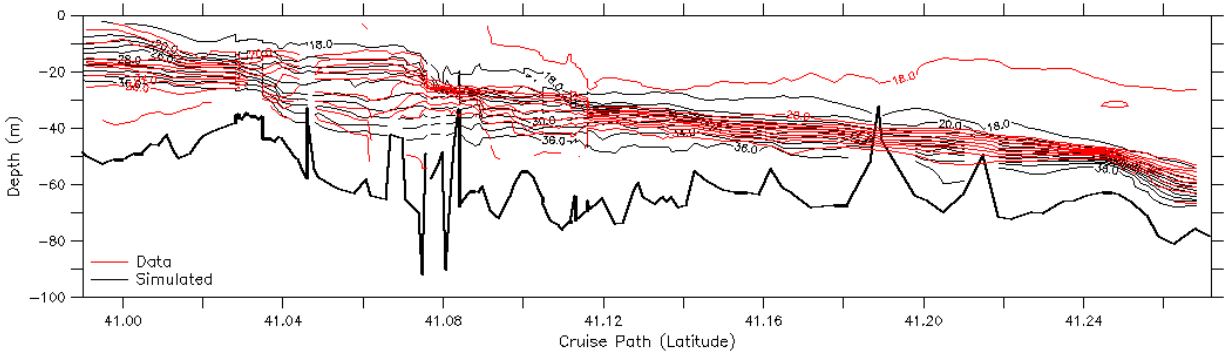
Bosphorus Modeling: ROMS and MITgcm validation

Models VS OBS. DATA





ROMS, Salinity

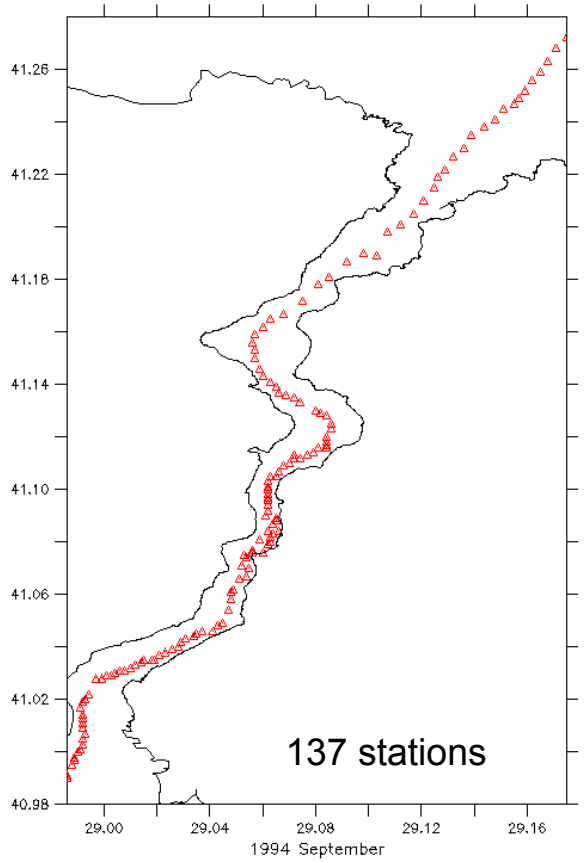


MITgcm, Salinity

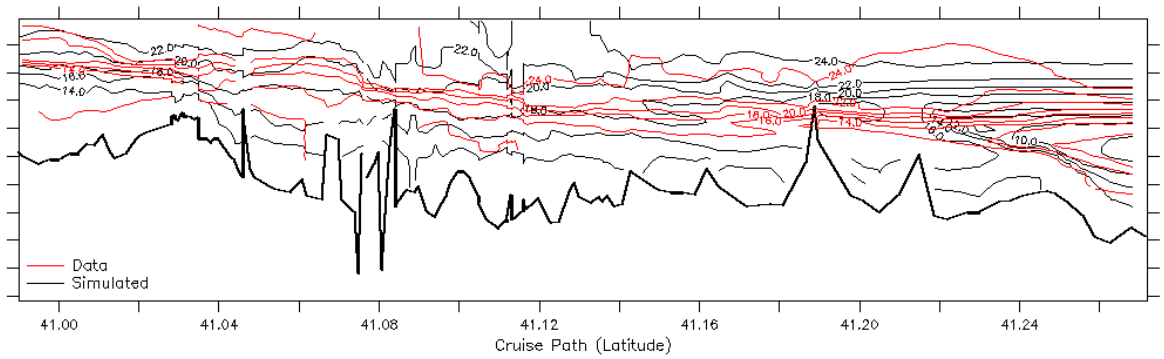
7-9 September 1994

Bosphorus Modeling: ROMS and MITgcm validation

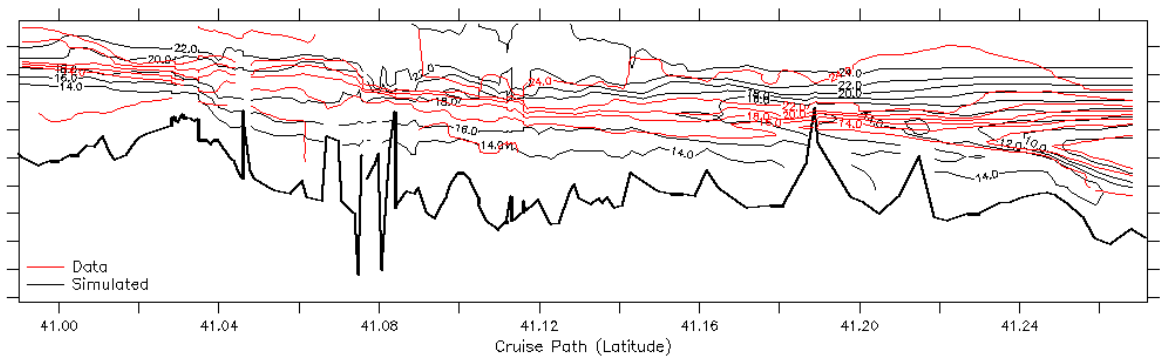
Models VS OBS. DATA



7-9 September 1994



ROMS, Temperature



MITgcm, Temperature

Turkish Strait System: our modeling approach

Model choice

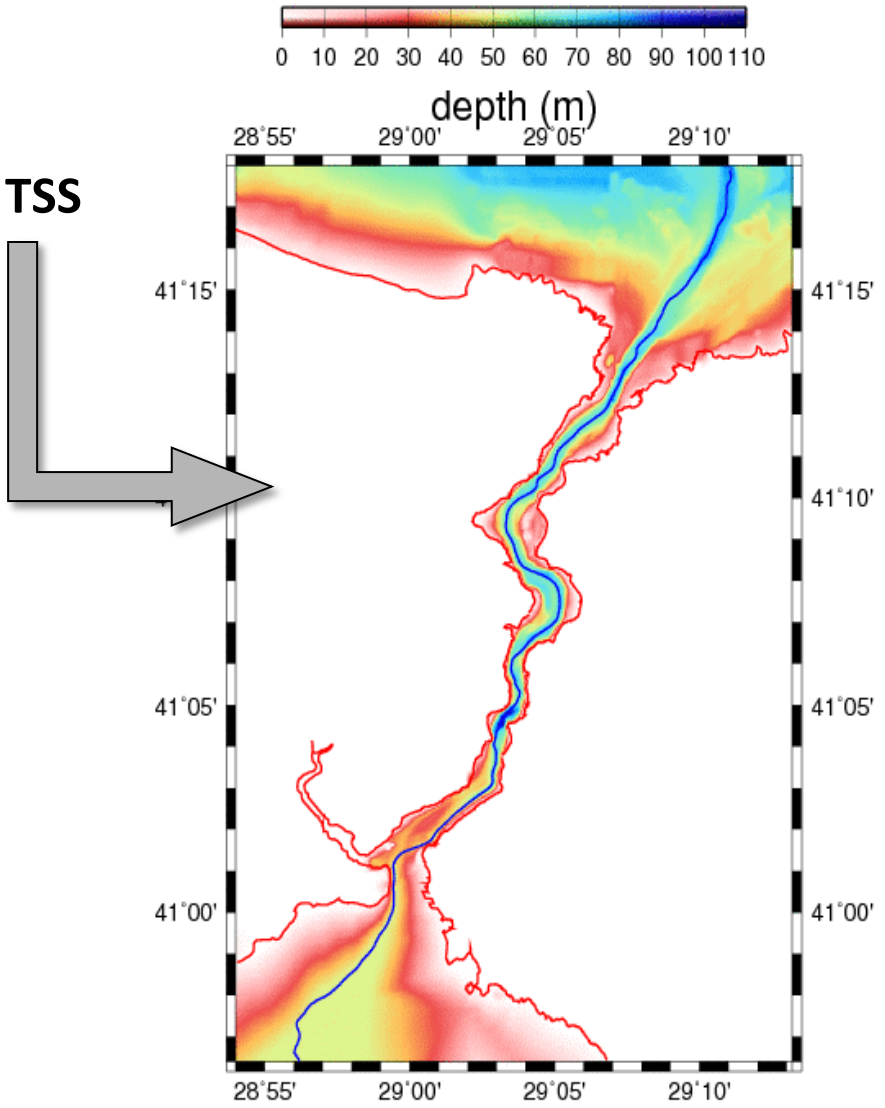
Application to the most challenging place of TSS

z-level **σ-level ROMS**

MITgcm

Performances Comparison

Similar results but slightly better MITgcm

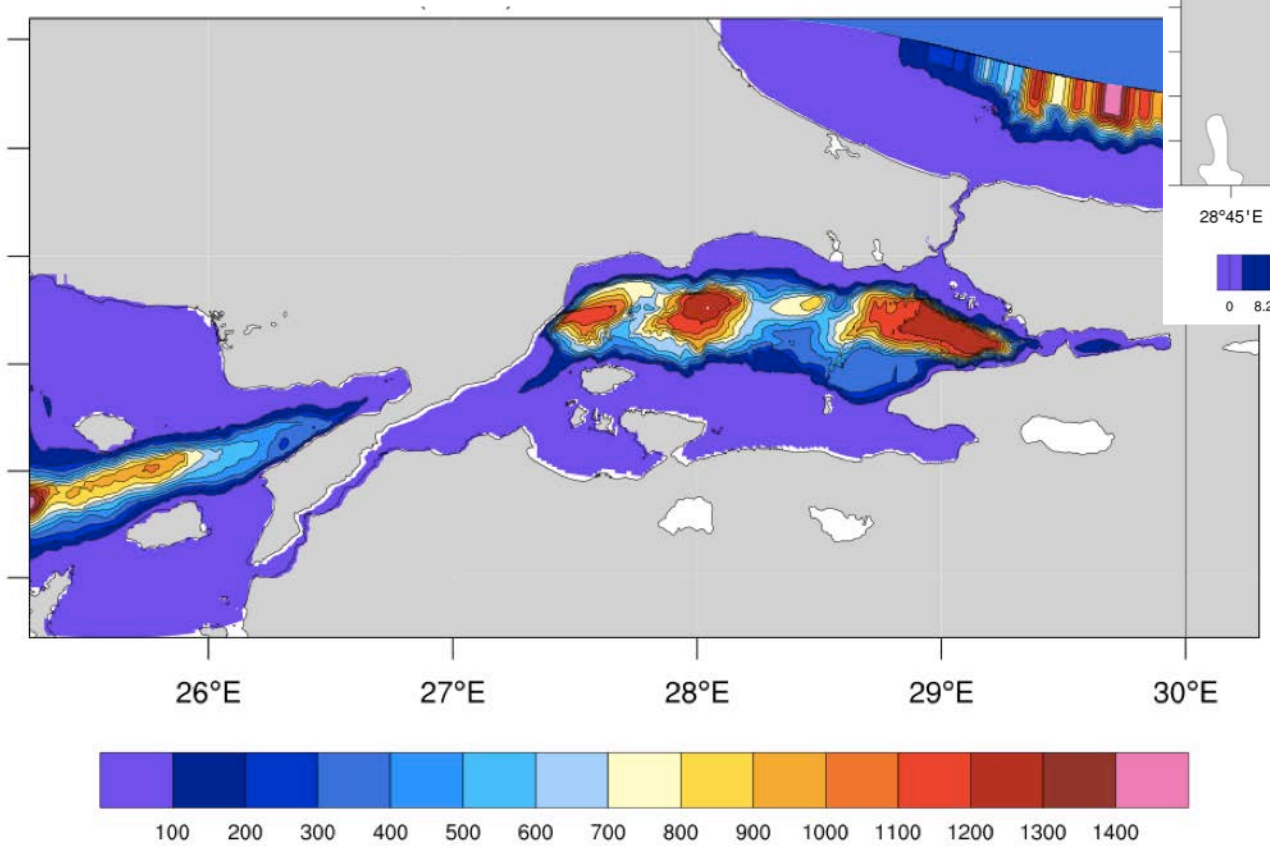


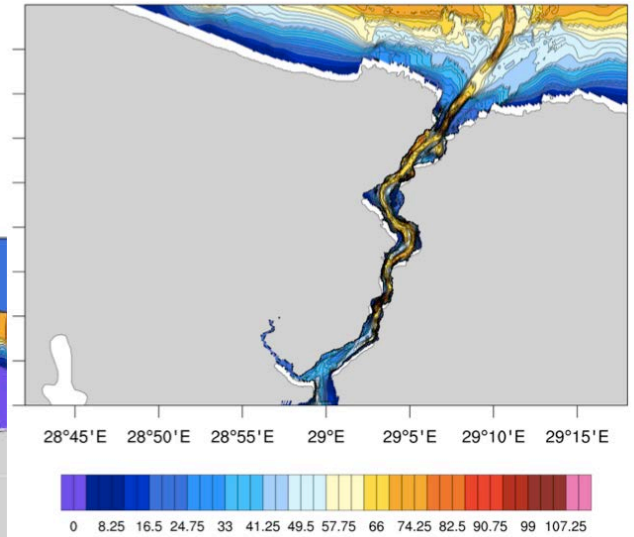
Bosphorus Strait

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

MITgcm

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



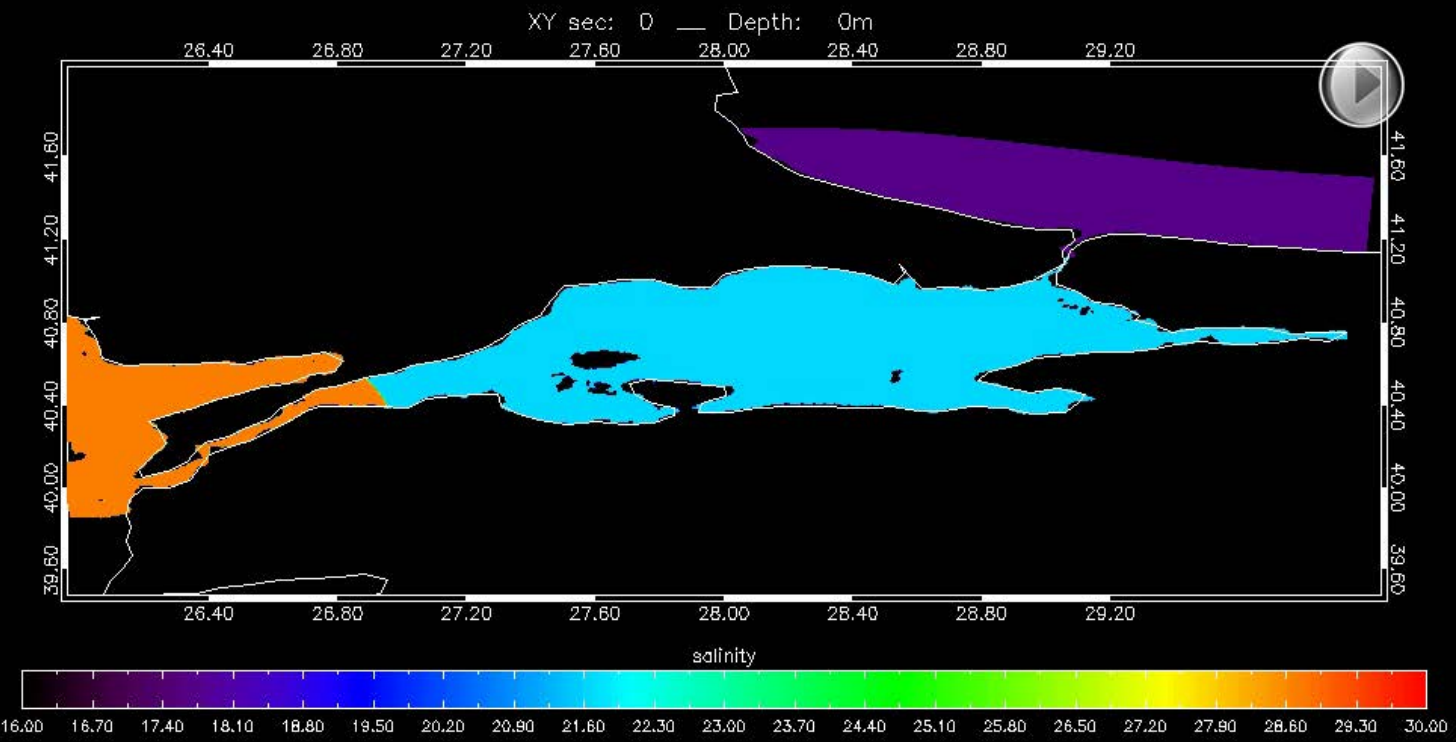


MOTUS

High-Resolution Modelling Study of the Turkish Straits System Utilizing HPC

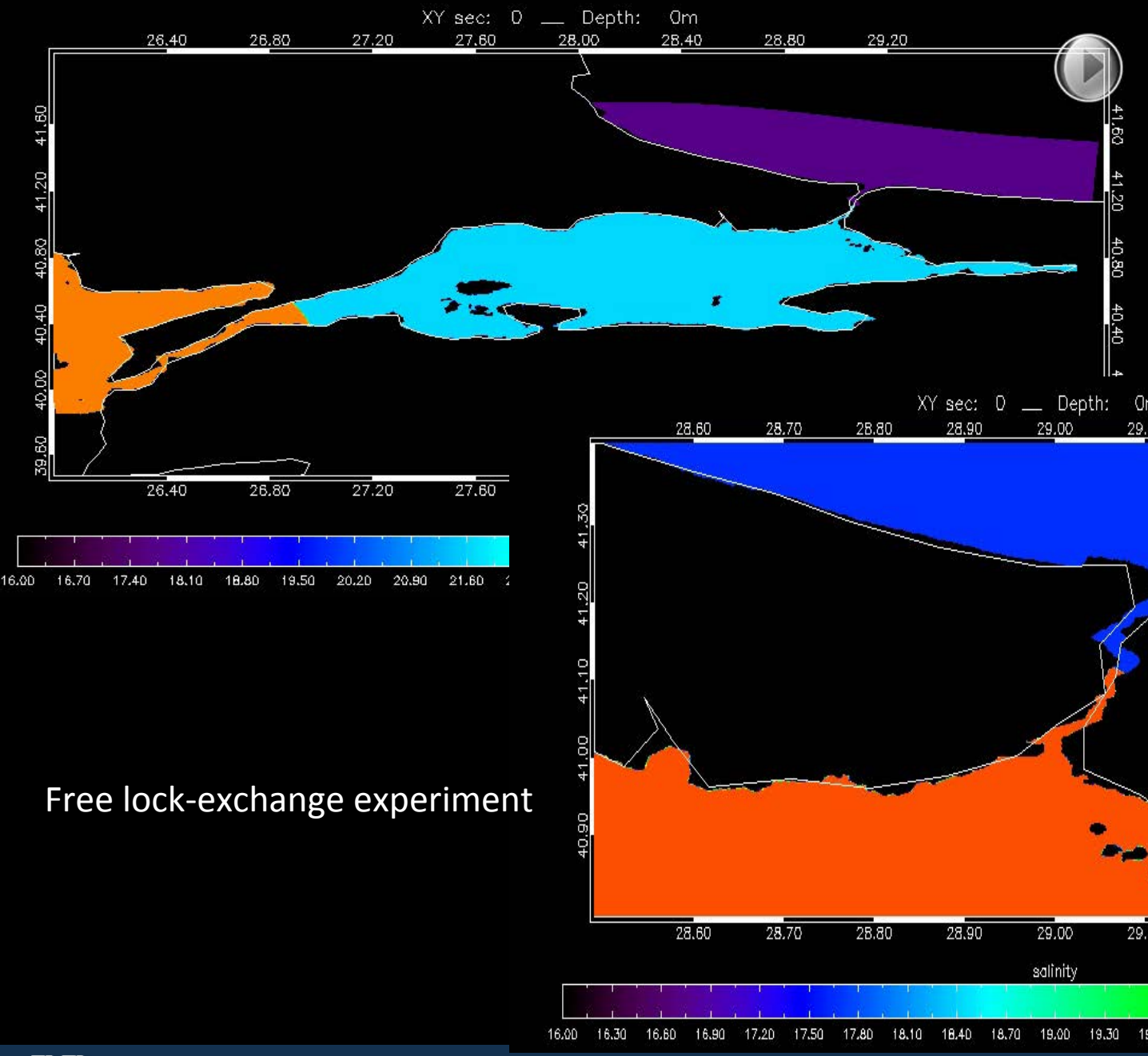
The extreme environment has been represented as a whole and with the full details of its highly contrasting properties. The huge computing resources needed to run such an ambitious model have been provided by the EU initiative PRACE (Partnership for Advanced Computing in Europe).

MITgcm TSS model: Initial Conditions

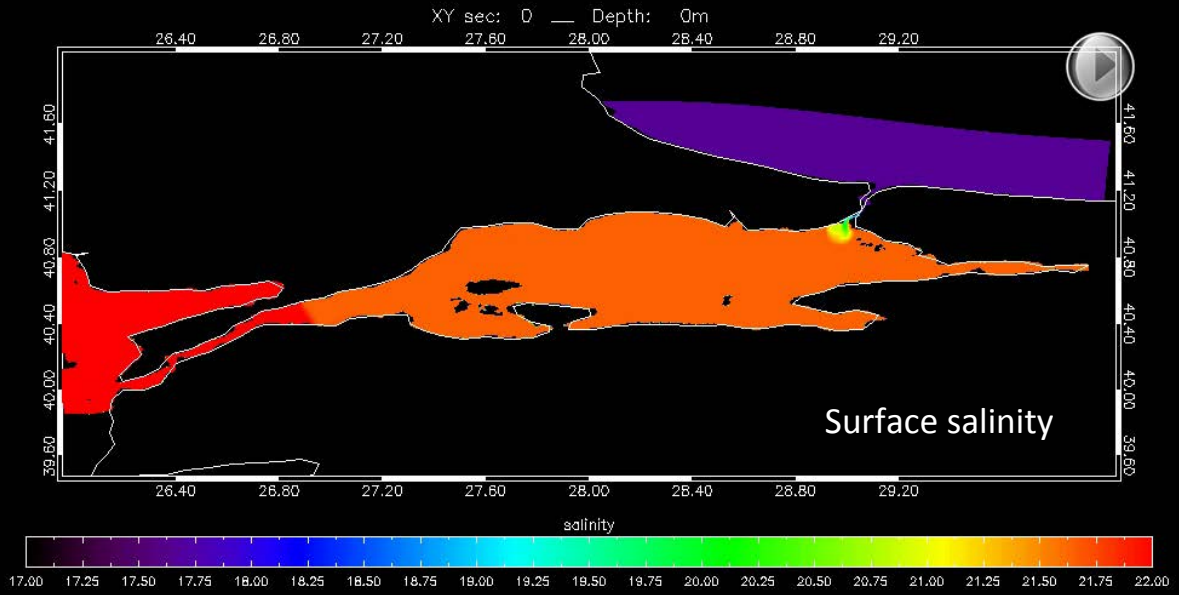


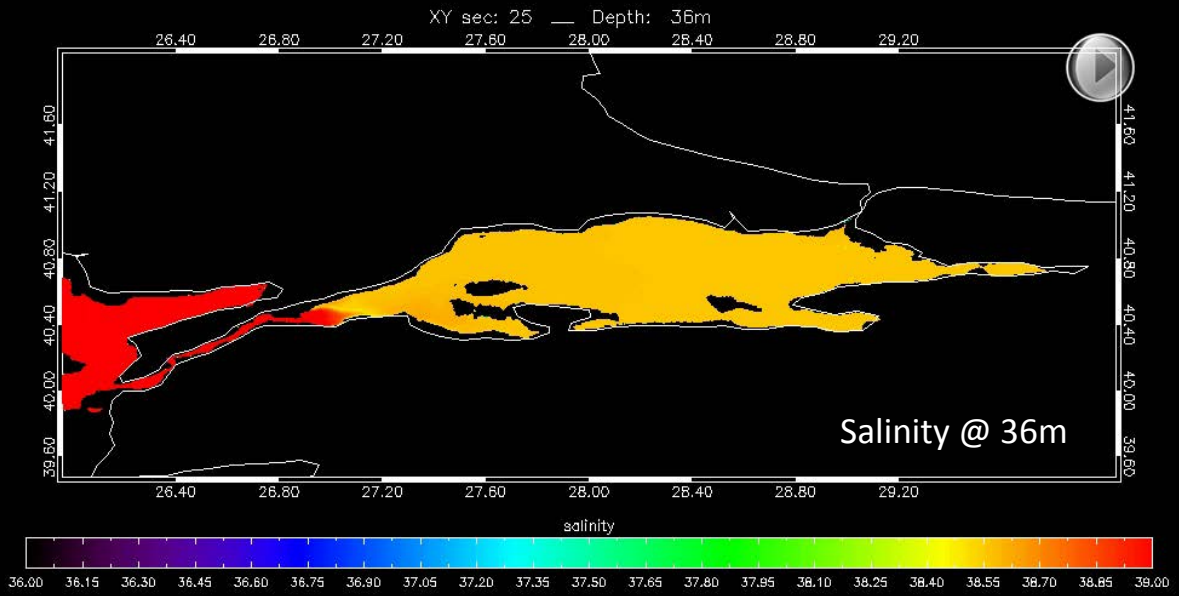
The model is initialized with three different water masses filling the western part of the domain, the Marmara Sea and the eastern side of the domain respectively, with vertical profiles selected from CTD casts obtained during the cruise of the R/V B˙IL˙IM of the Institute of Marine Sciences in **June-July 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.

MITgcm TSS model: free adjustment – salinity field



Free lock-exchange experiment

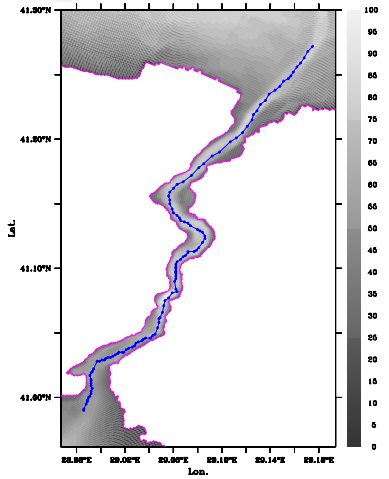




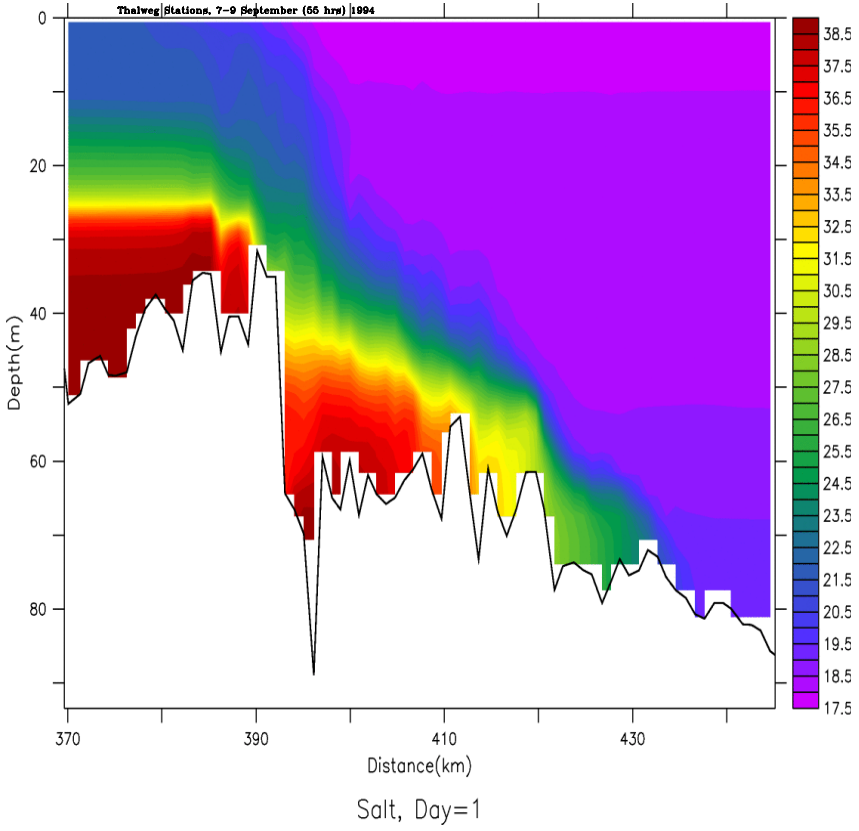
Forced net barotropic flow 18000 m^3/sec experiment

Three additional experiments were conducted to study the sensitivity of the circulation to different net barotropic flows: **5600**, **9600**, **18000, and 50000** m^3/sec

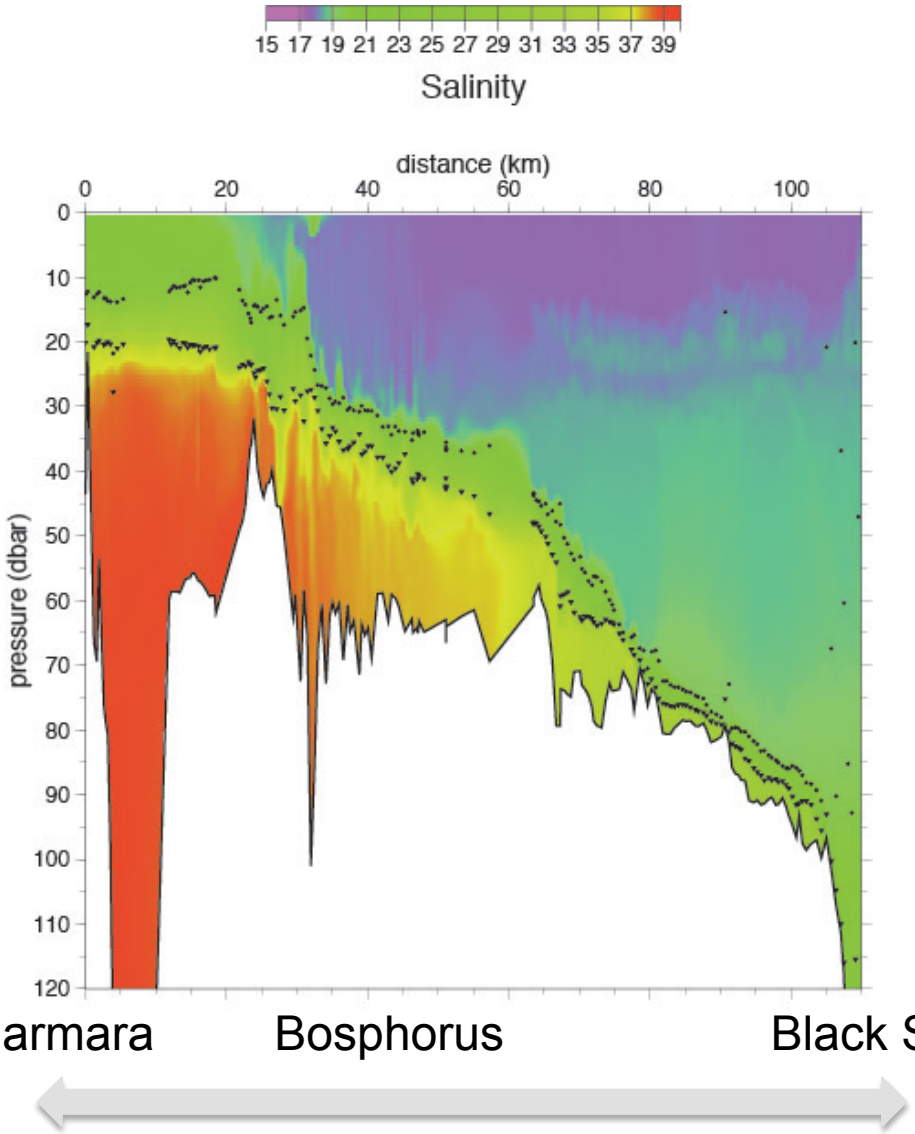
MITgcm TSS model: Bosphorus along-strait salinity field



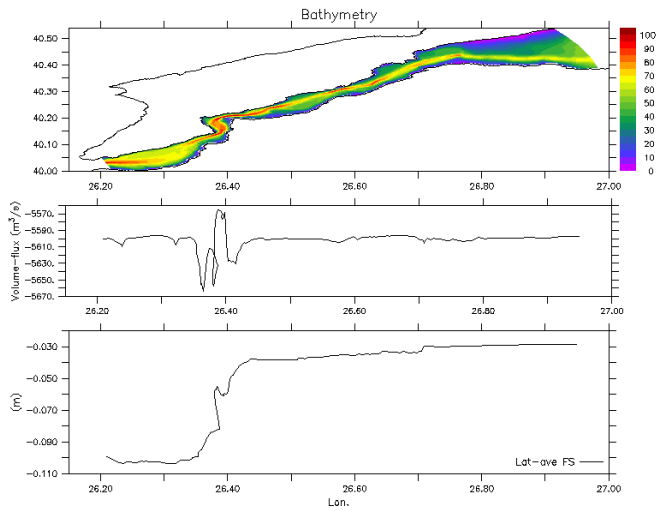
Flux=-5600m^3/s



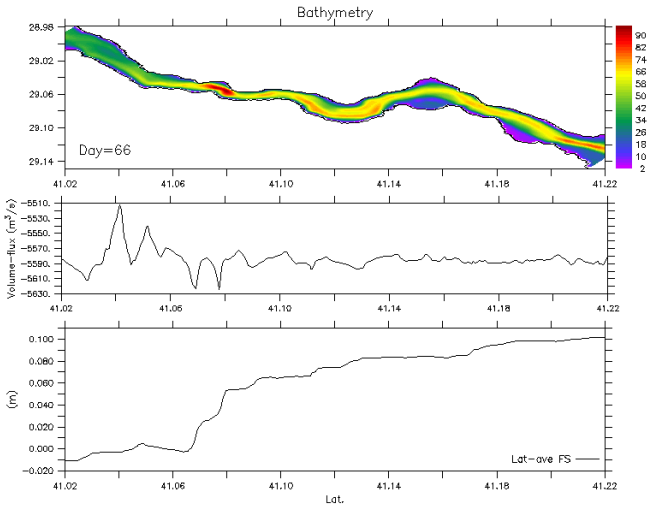
OBSERVATIONS

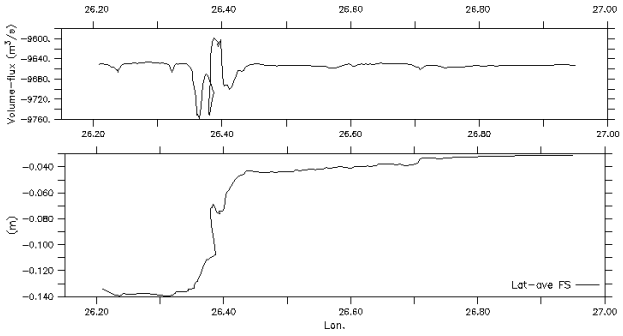


TSS model: along straits net flow and sea level anomaly

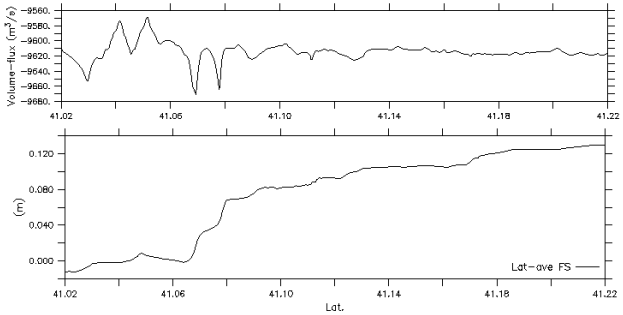


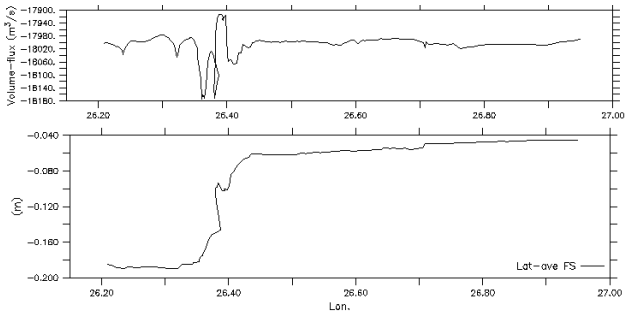
5600 m3/sec



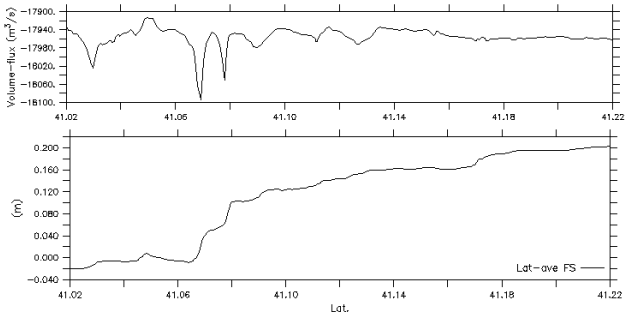


9600 m3/sec



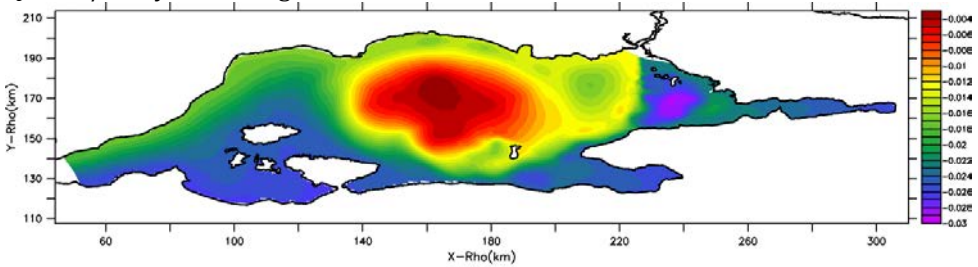


18000 m3/sec



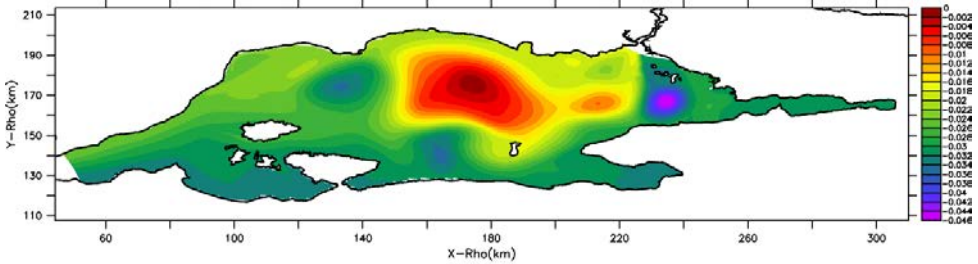
MITgcm TSS model: sea level anomaly field

Q=0 m³/s, day=100, range=3.5cm



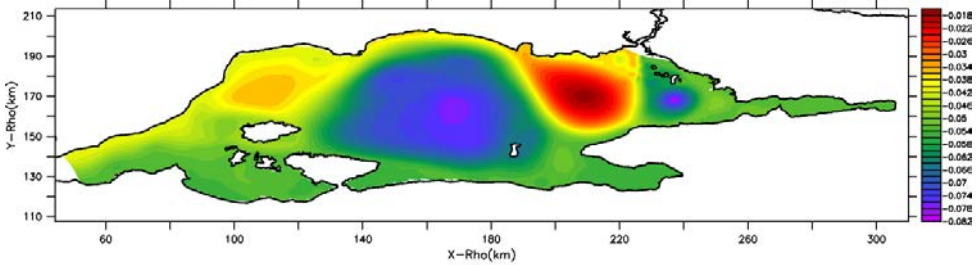
FS, Day=100.00

Q=5600 m³/s, day=65, range=4.5 cm (-)



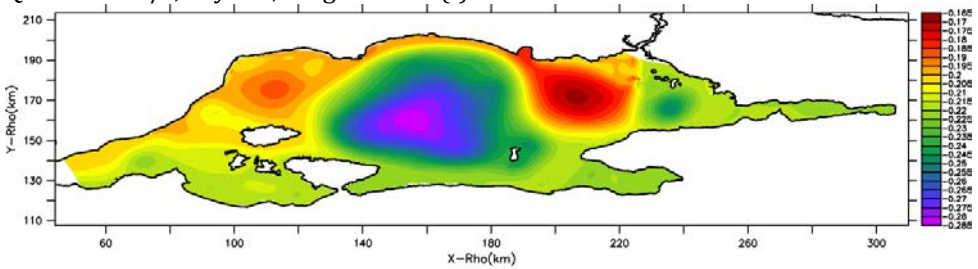
FS, Day=066.00

Q=18000 m³/s, day=65, range=6.5cm (-)



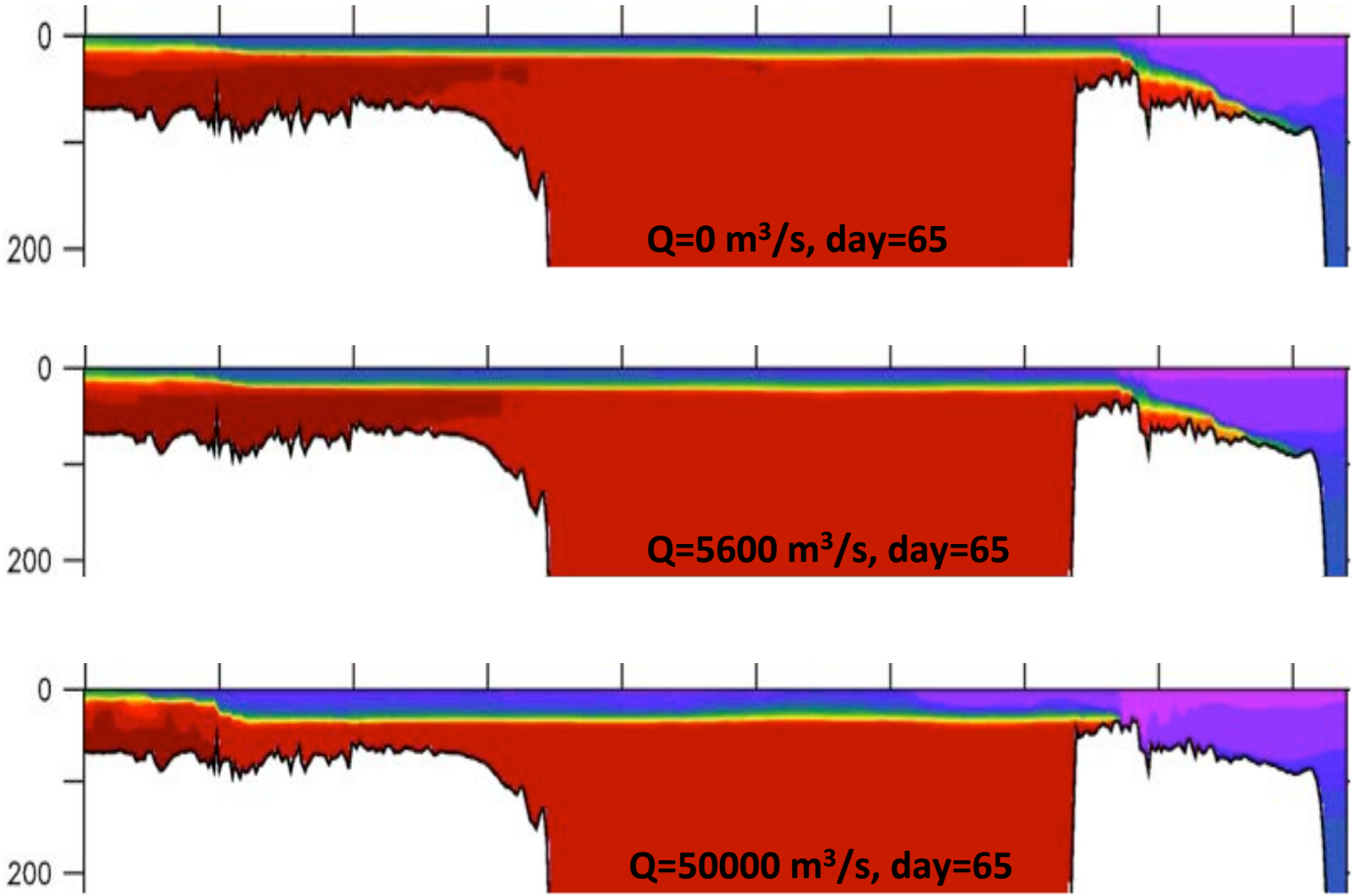
FS, Day=065.00

Q=50000 m³/s, day=65, range=12 cm (-)



FS, Day=125.00

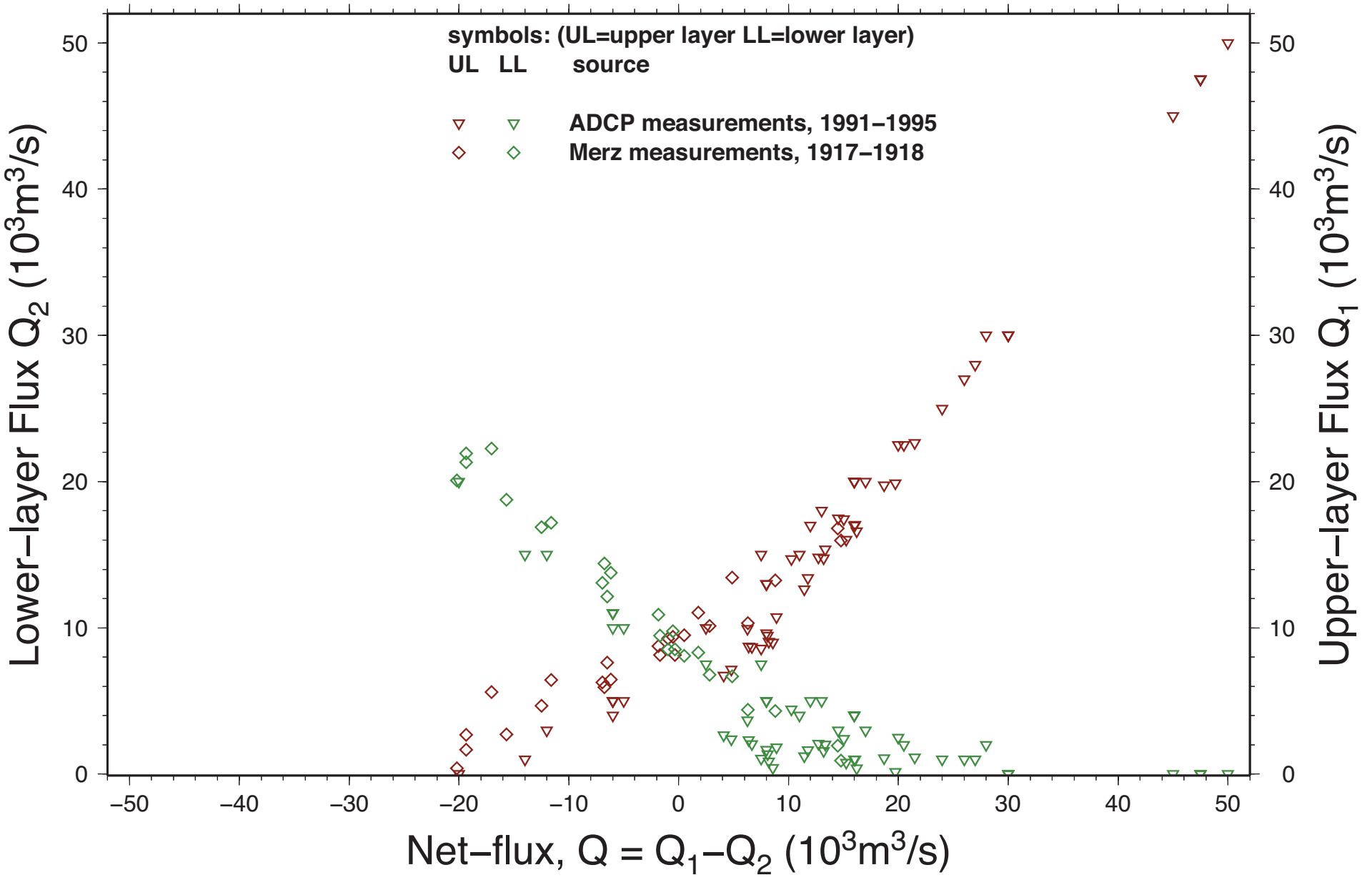
MITgcm TSS model: TSS cross-section salinity field



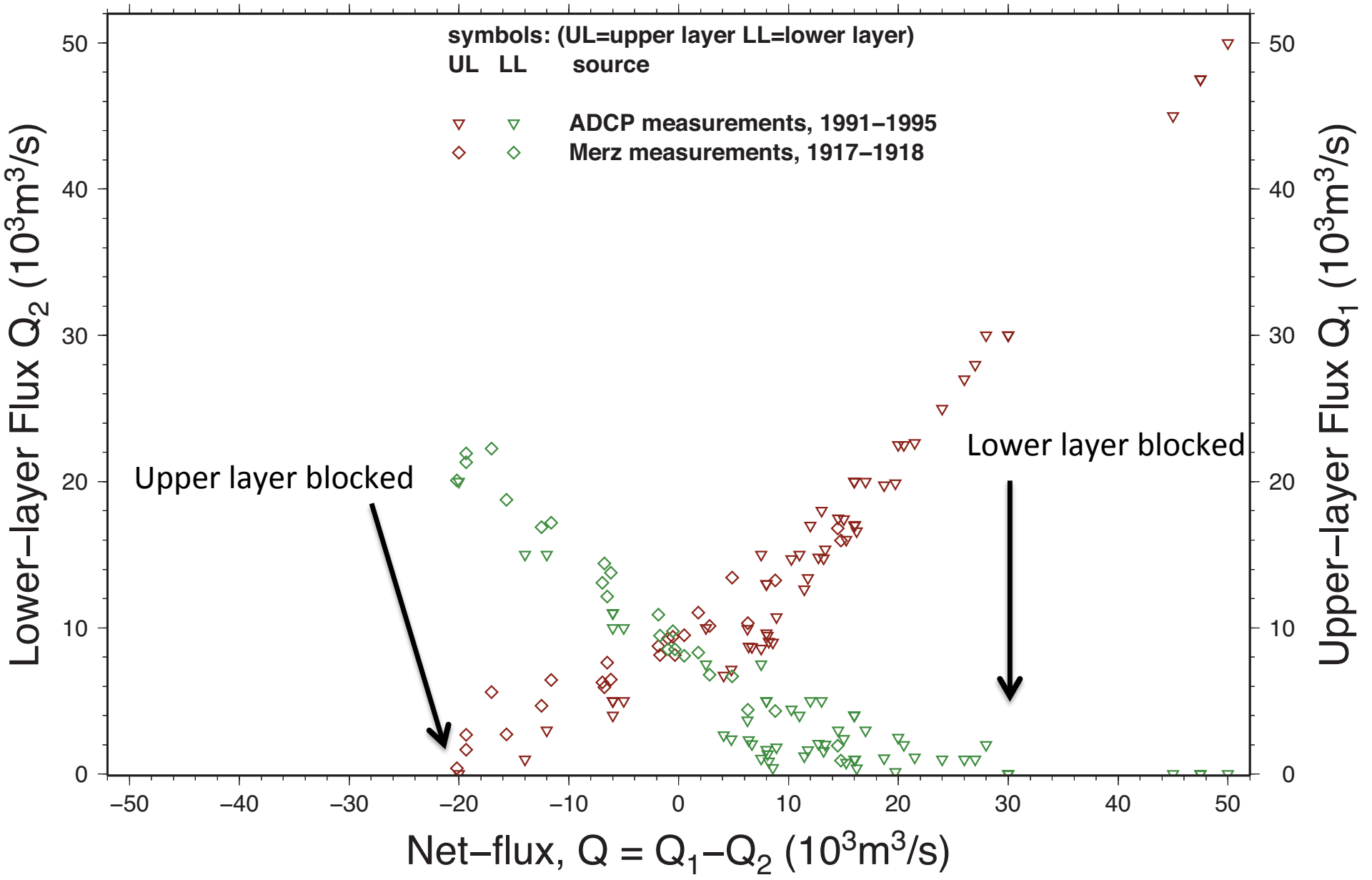
AegeanSea

Black Sea

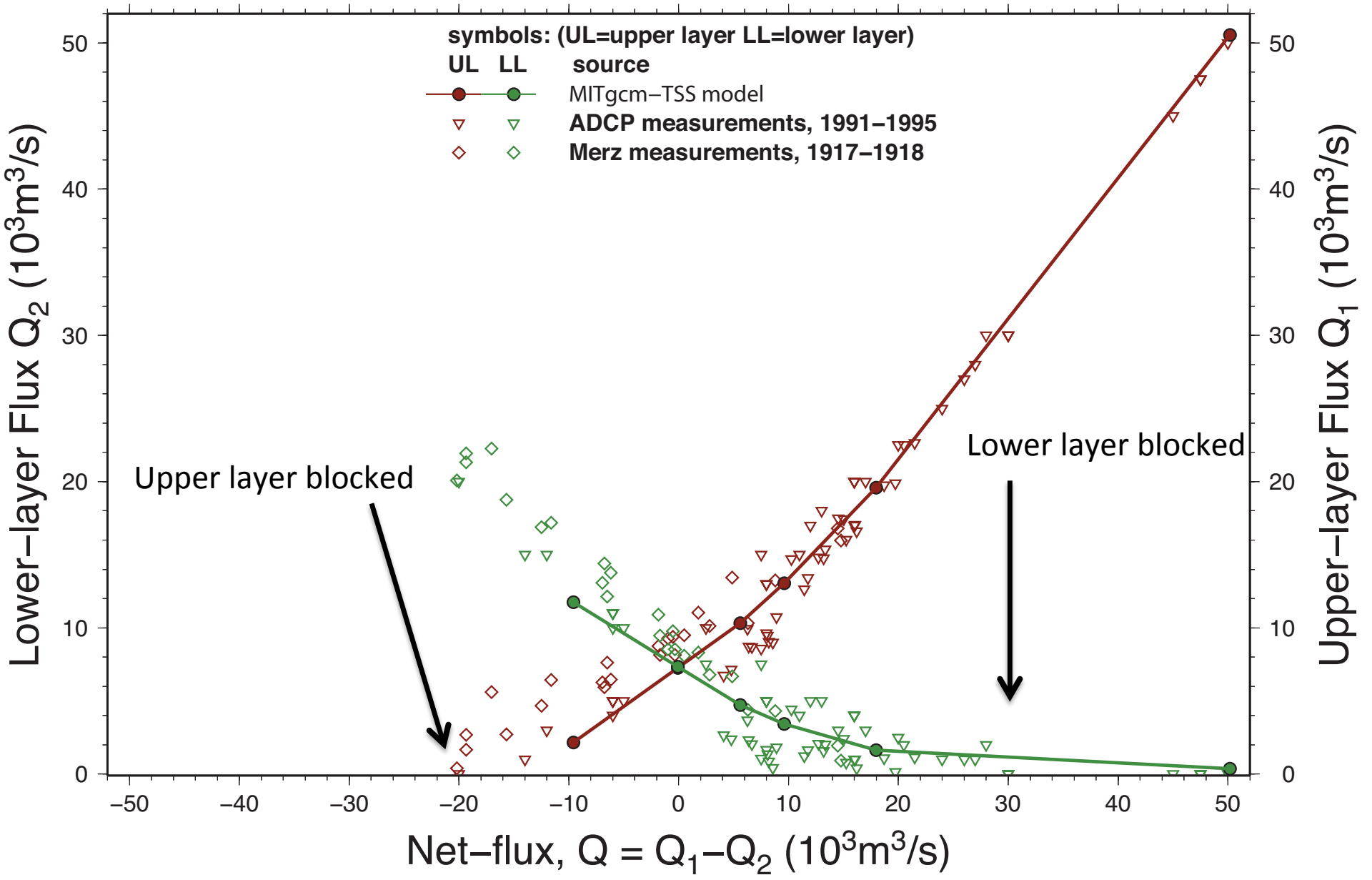
TSS model: Bosphorus transport – Model vs Observations



TSS model: Bosphorus transport – Model vs Observations



TSS model: Bosphorus transport – Model vs Observations



TSS Modeling: Conclusions and future work

We have demonstrated that it is feasible to reproduce **correctly** the two-layer exchange through the Turkish Strait System with a 'standard' finite difference model:

- the model has been able to reproduce the two layer structure of the TSS circulation;

- the model has been able to capture the hydraulics of both Straits

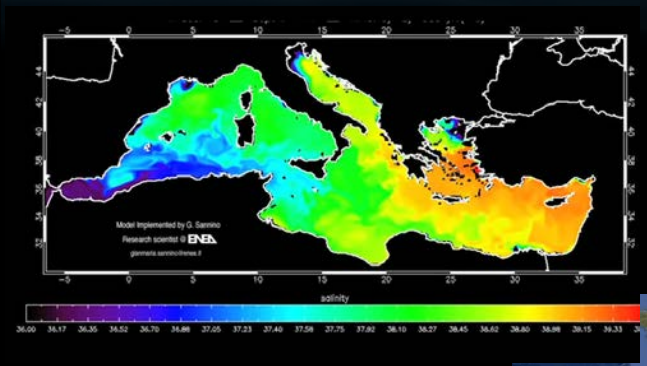
- the model has been able to capture the Bosporus upper and lower transports

As first result the model as shown that the circulation of the Sea of Marmara is strongly modified by the net barotropic flow applied at the Bosporus strait.

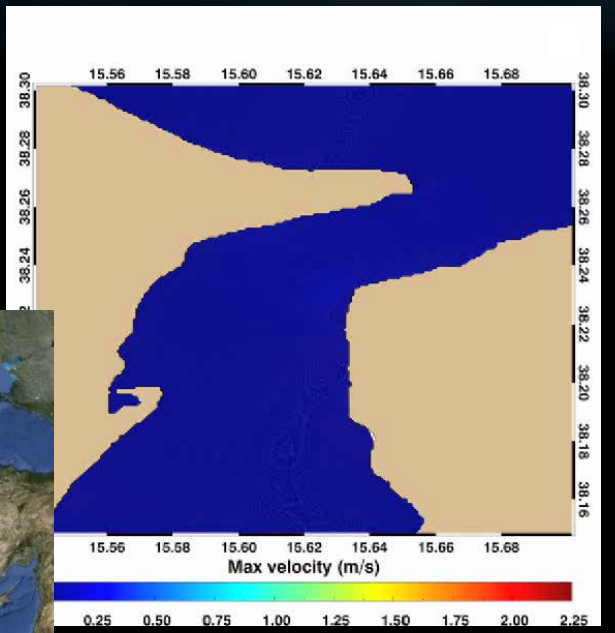
Next Step:

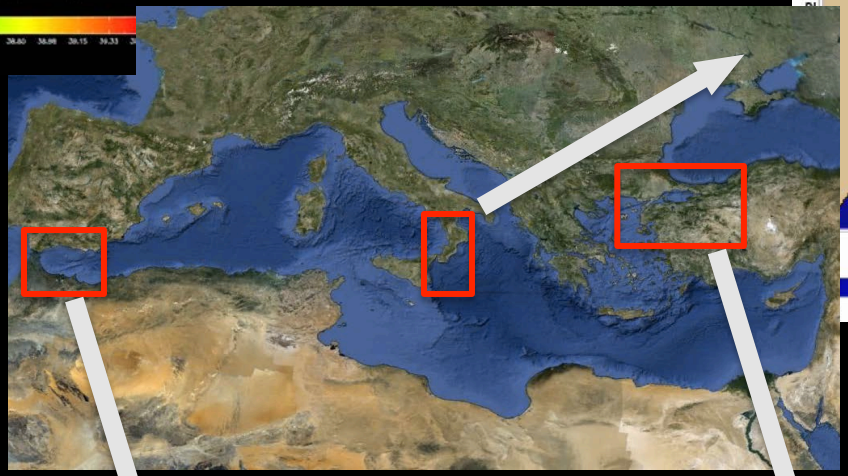
Include atmospheric forcing: wind, surface pressure and surface fluxes

Background – MIT general circulation model

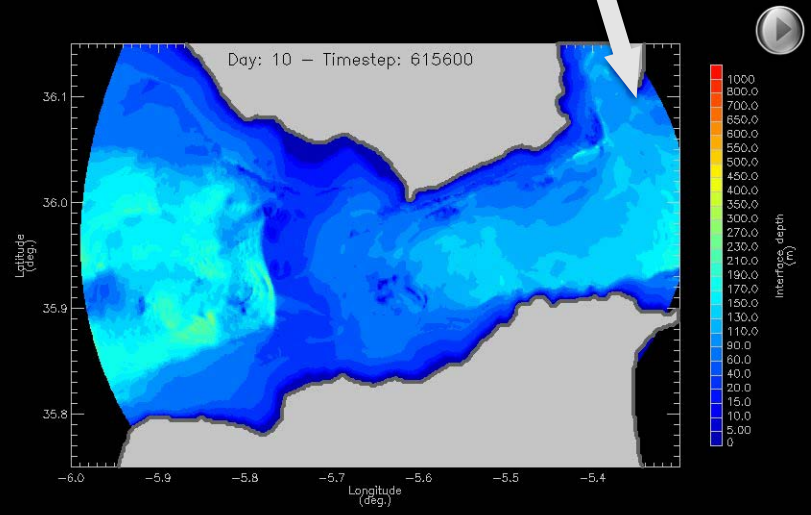


Strait of Messina (ENEA)

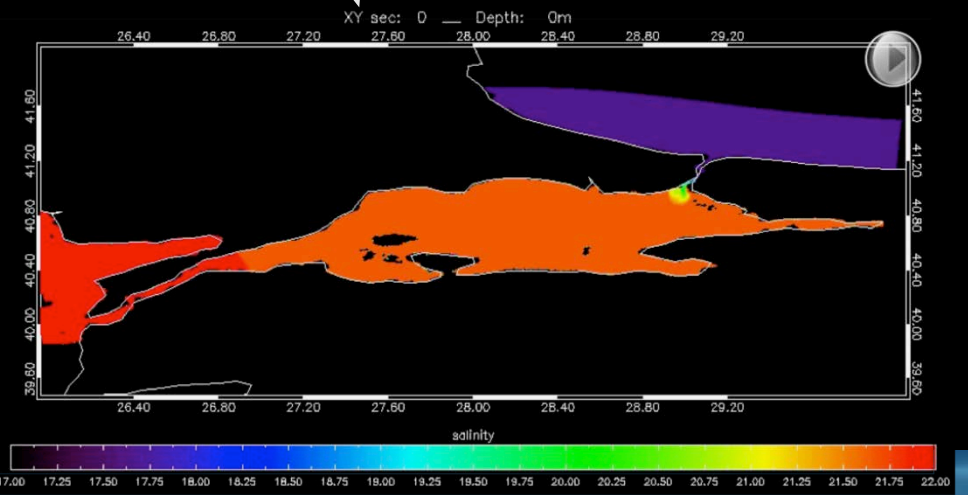




Strait of Gibraltar (ENEA)

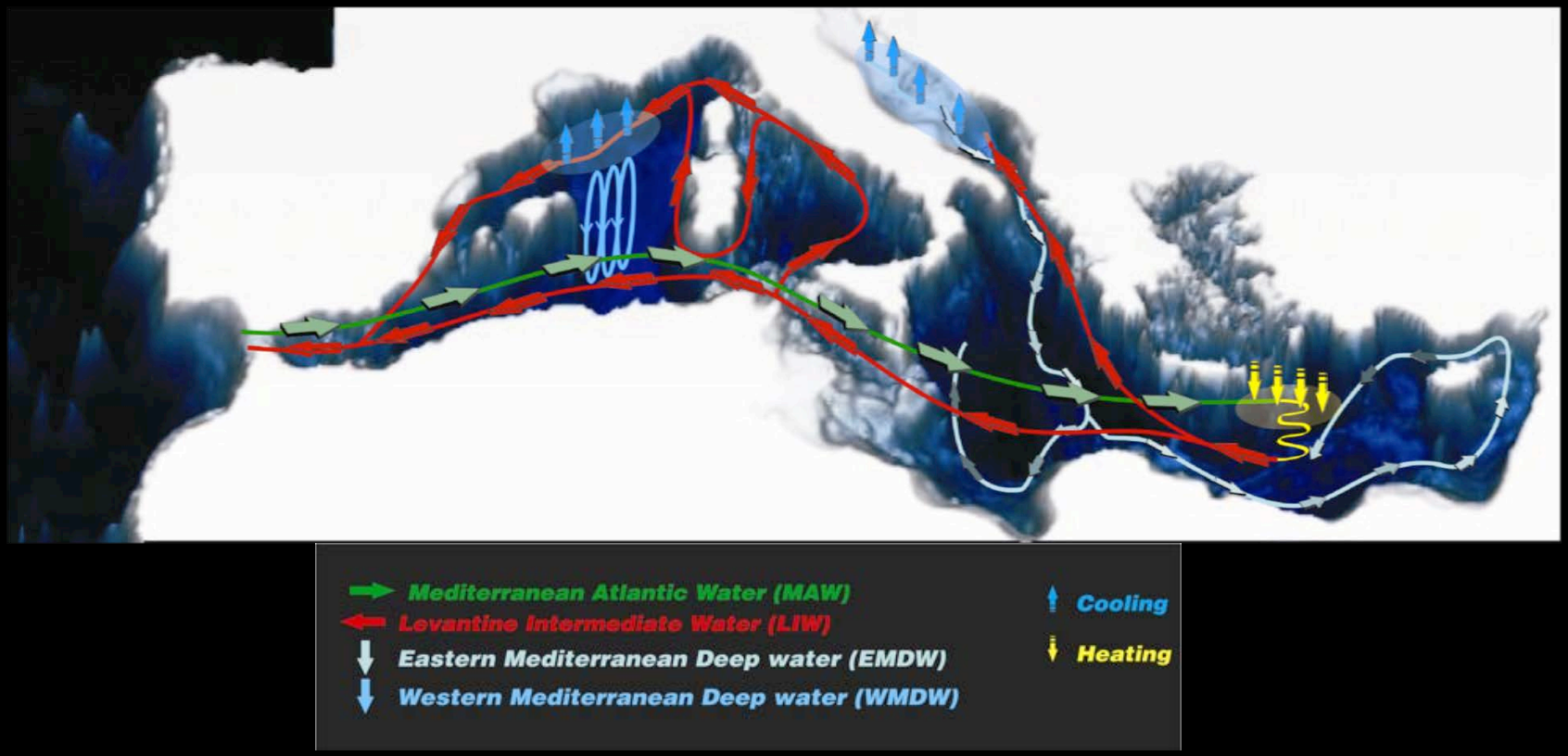


Turkish Straits System (ENEA+METU)



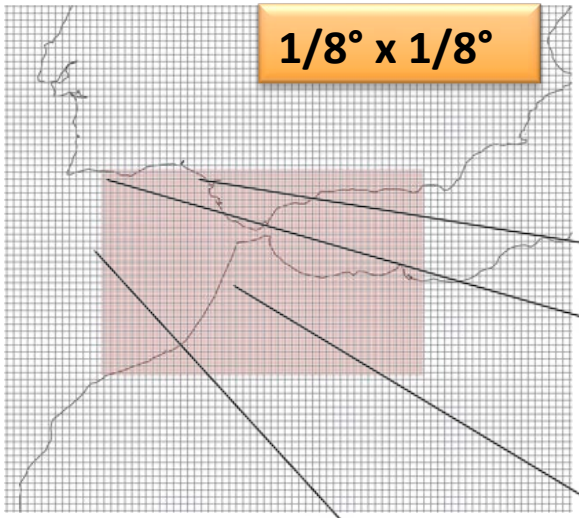
MITgcm applied to the Mediterranean Sea

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

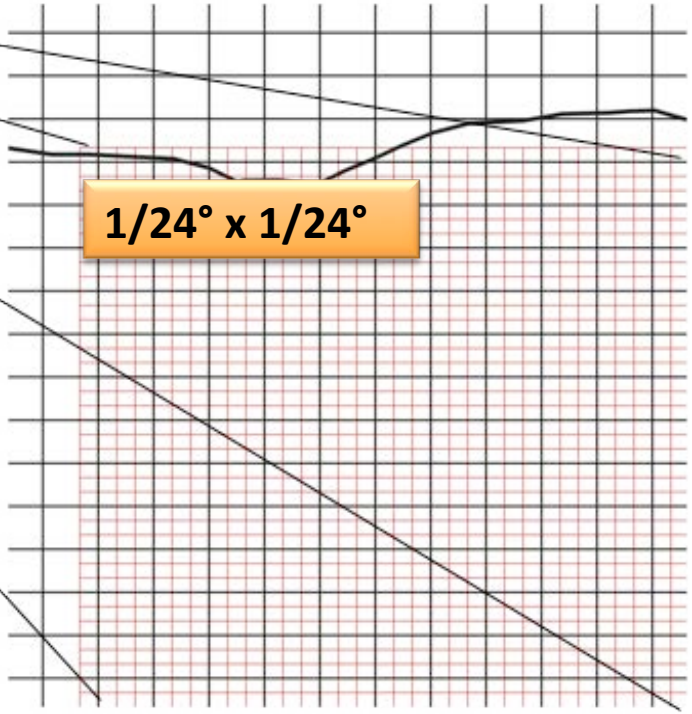


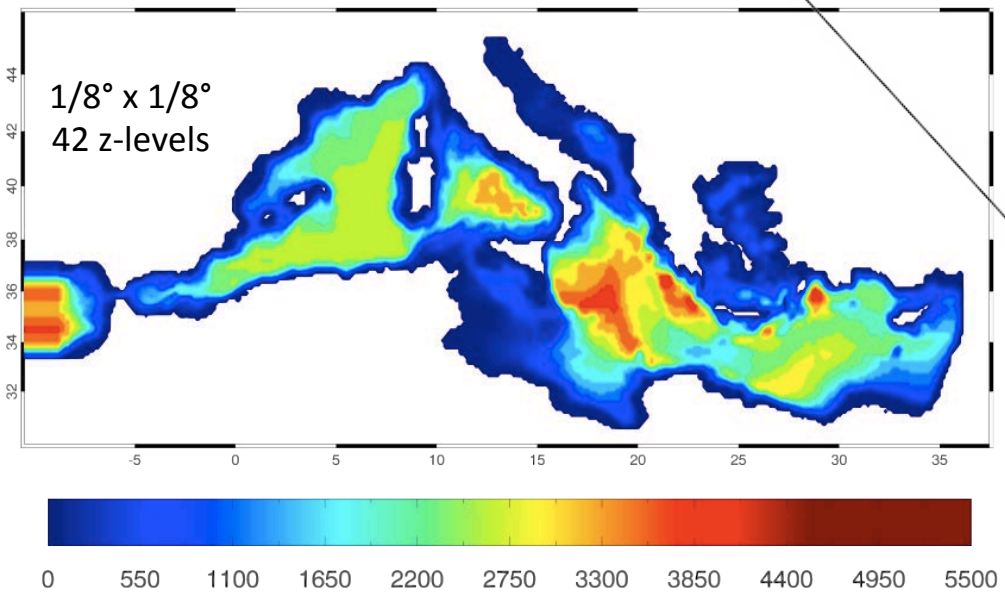
The atmospheric forcing drives the Mediterranean basin toward a negative budget of water and heat, and toward a positive budget of salt. Over the basin, evaporation exceeds the sum of precipitation and rivers discharge, while through the surface a net heat flux is transferred to the overlying atmosphere.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

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



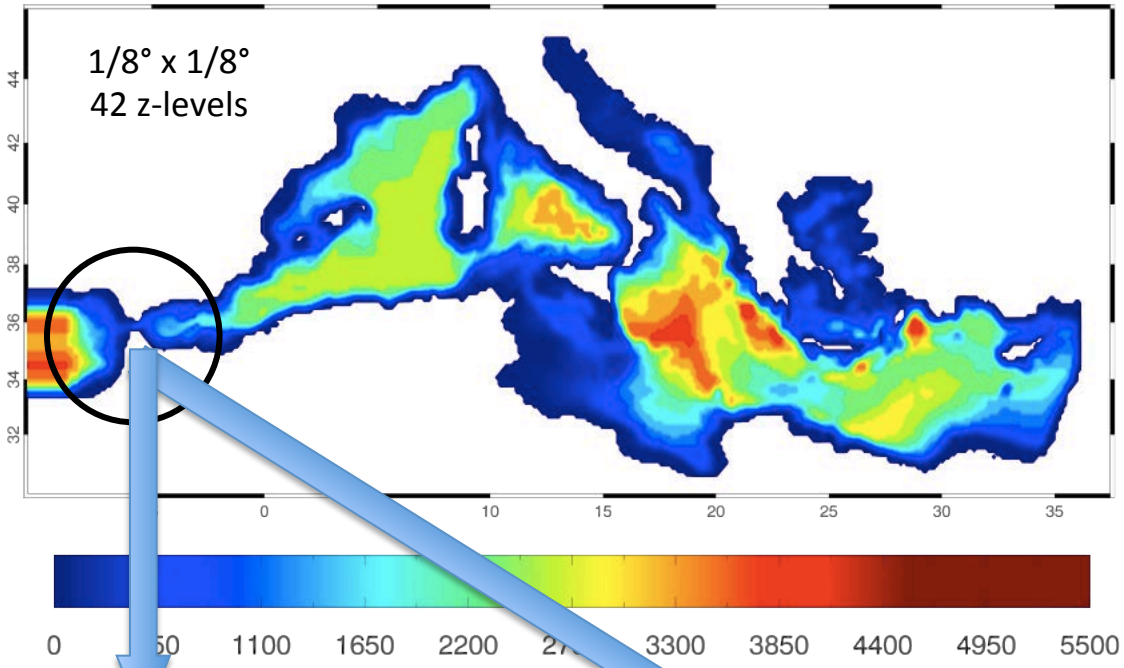
Ratio = 3:1

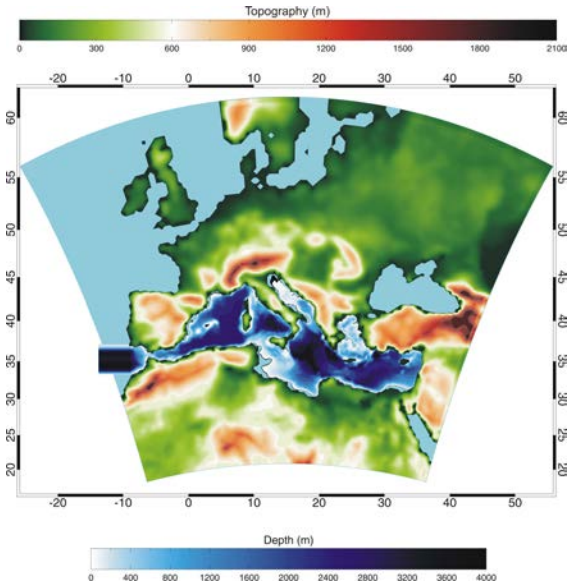




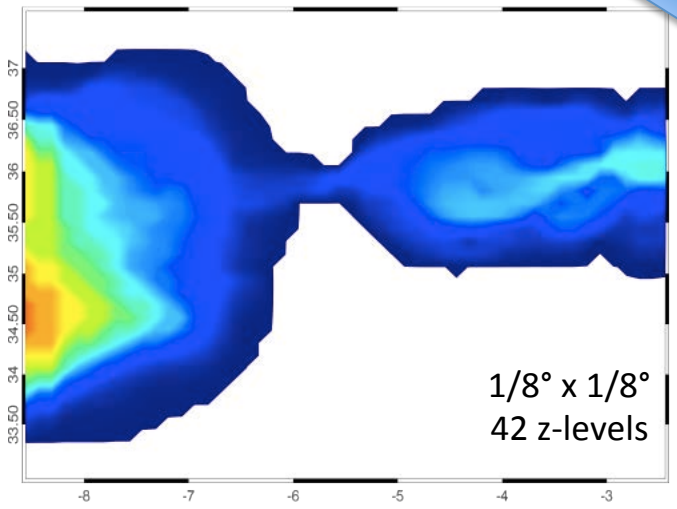
Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean. Modeling

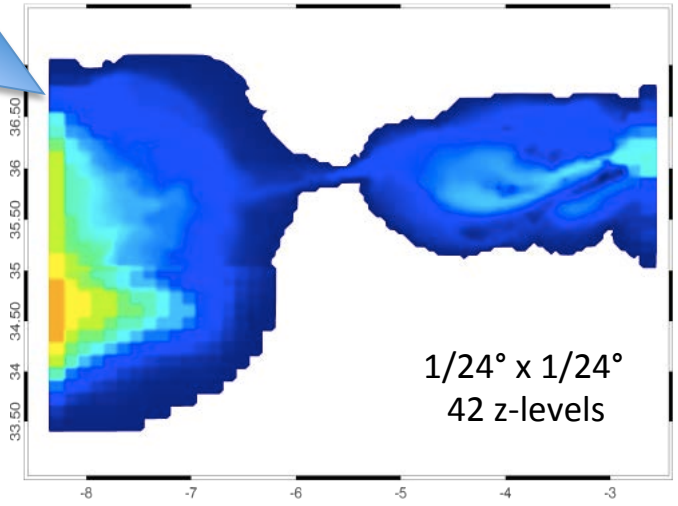
Effects of high resolution at Gibraltar in a 1/8° Mediter. model



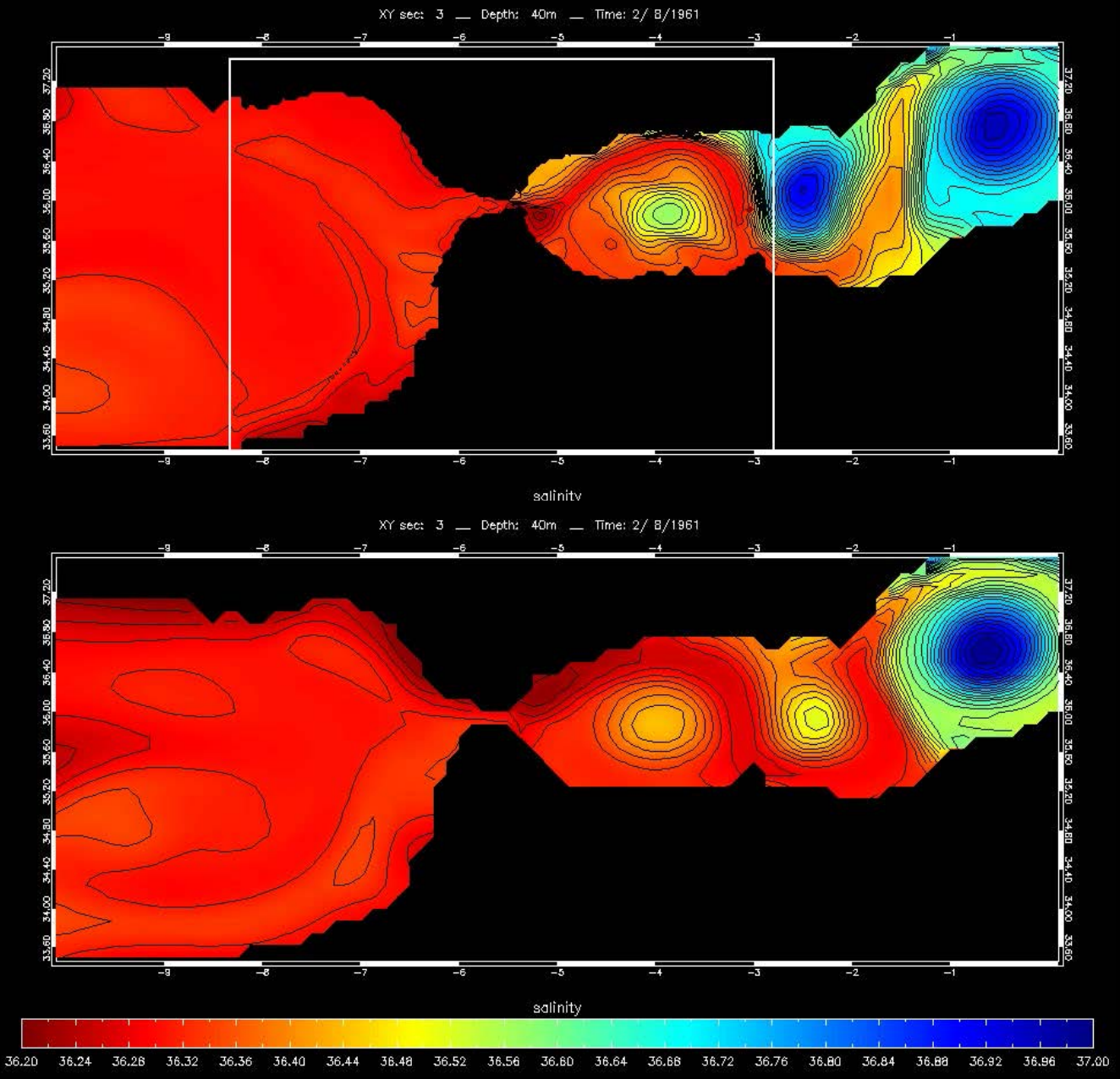


Oceanic component in the
PROTHEUS *regional climate system*

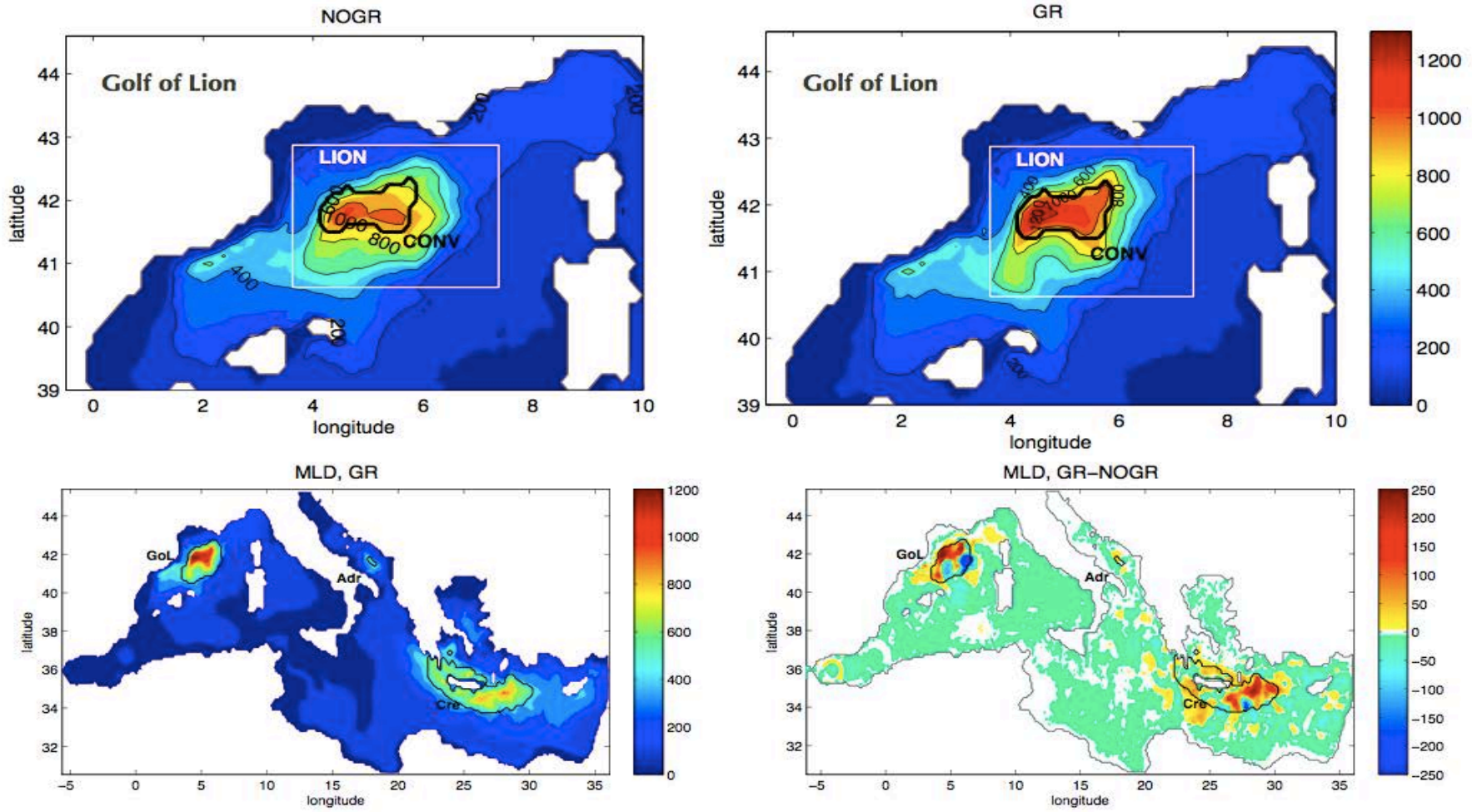




Effects of high resolution at Gibraltar in a 1/8° Mediter. model



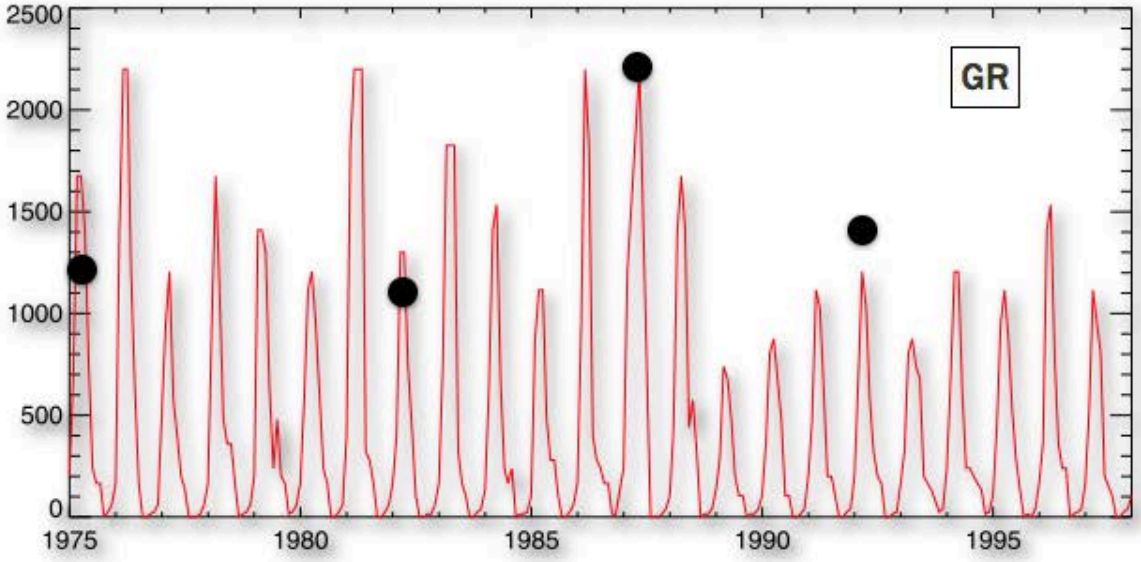
Effects of high resolution at Gibraltar in a 1/8° Mediter. model

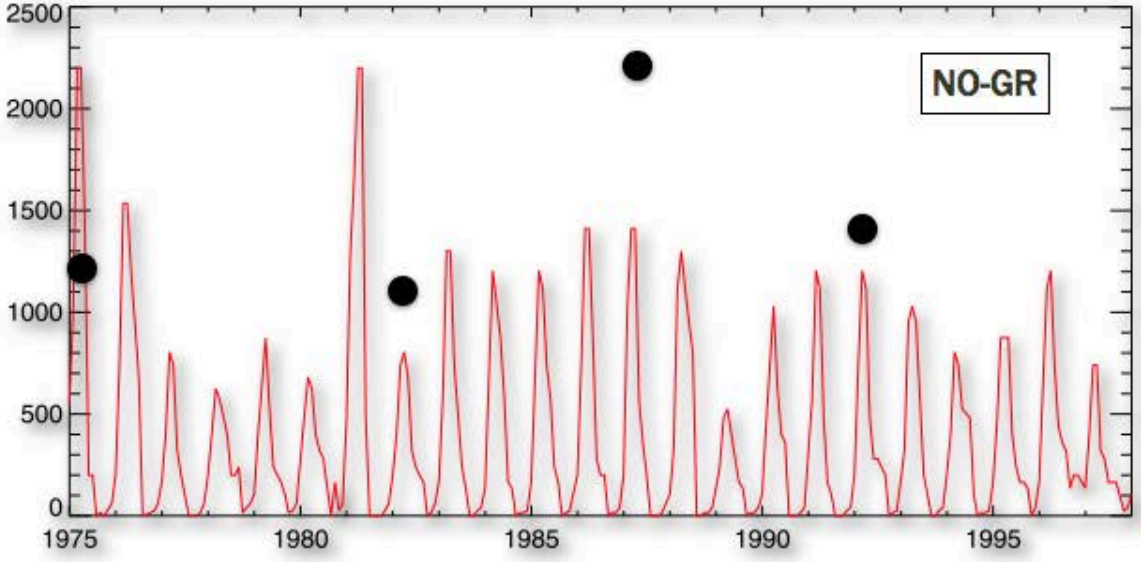


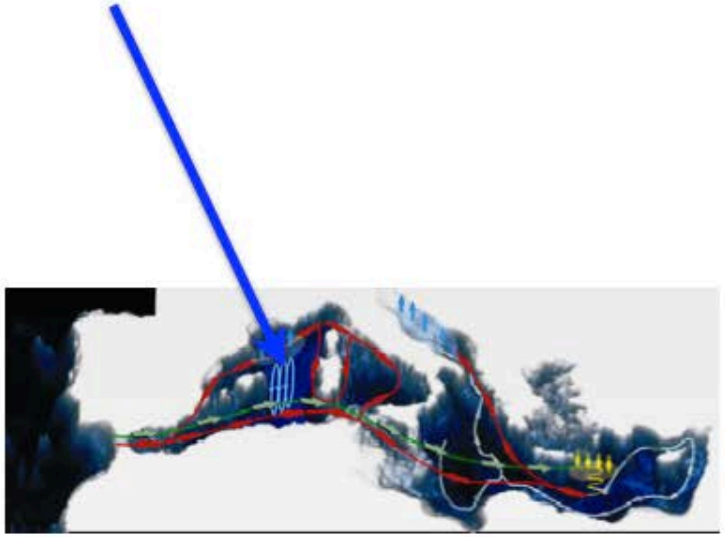
Sannino et al. 2009, “An eddy-permitting model of the Mediterranean Sea with a two-way grid refinement at the Strait of Gibraltar”. Ocean Modeling

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

Convection depth in the Gulf of

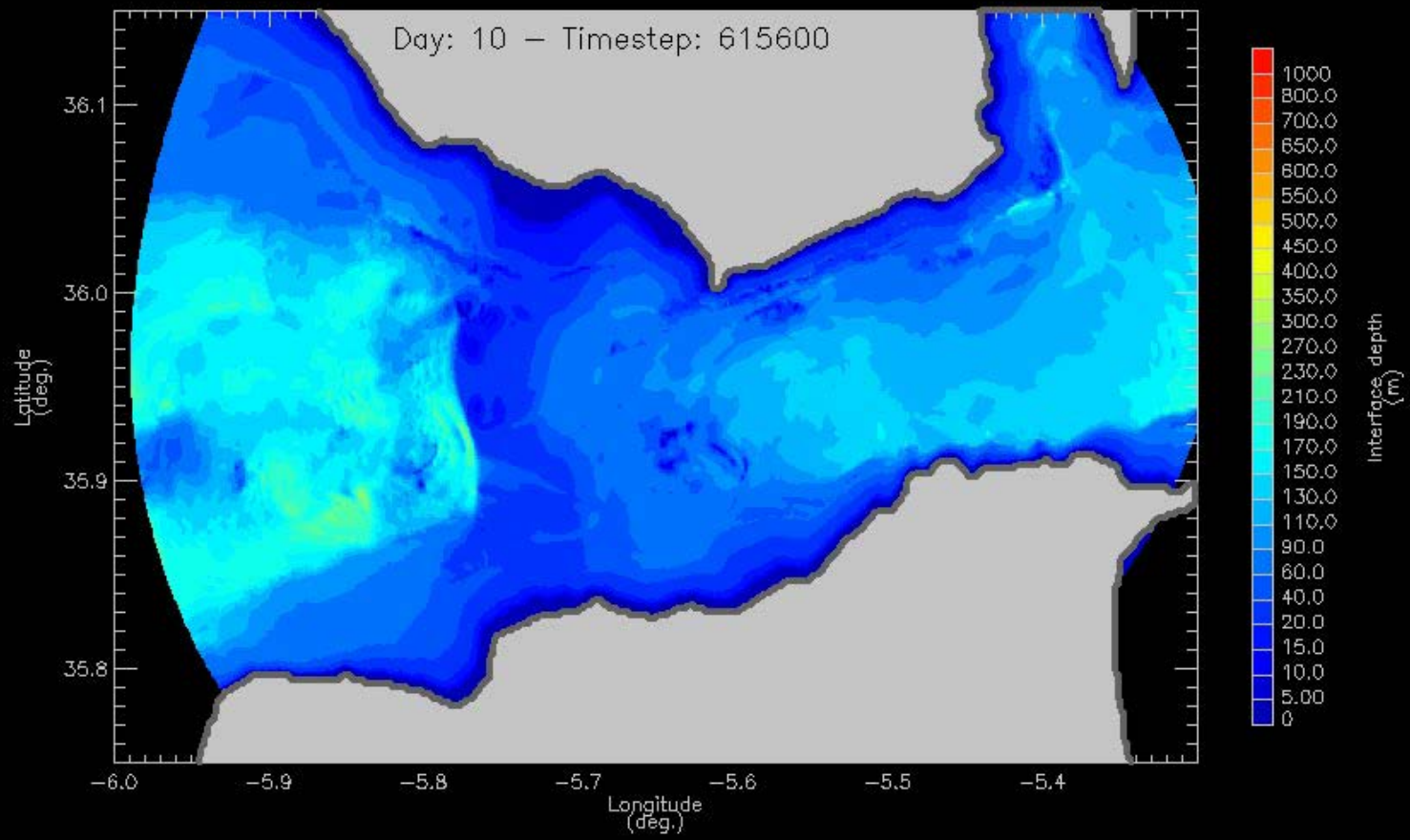






Black circles mark the experimentally observed convection depth (Mertens and Schott, 1998).

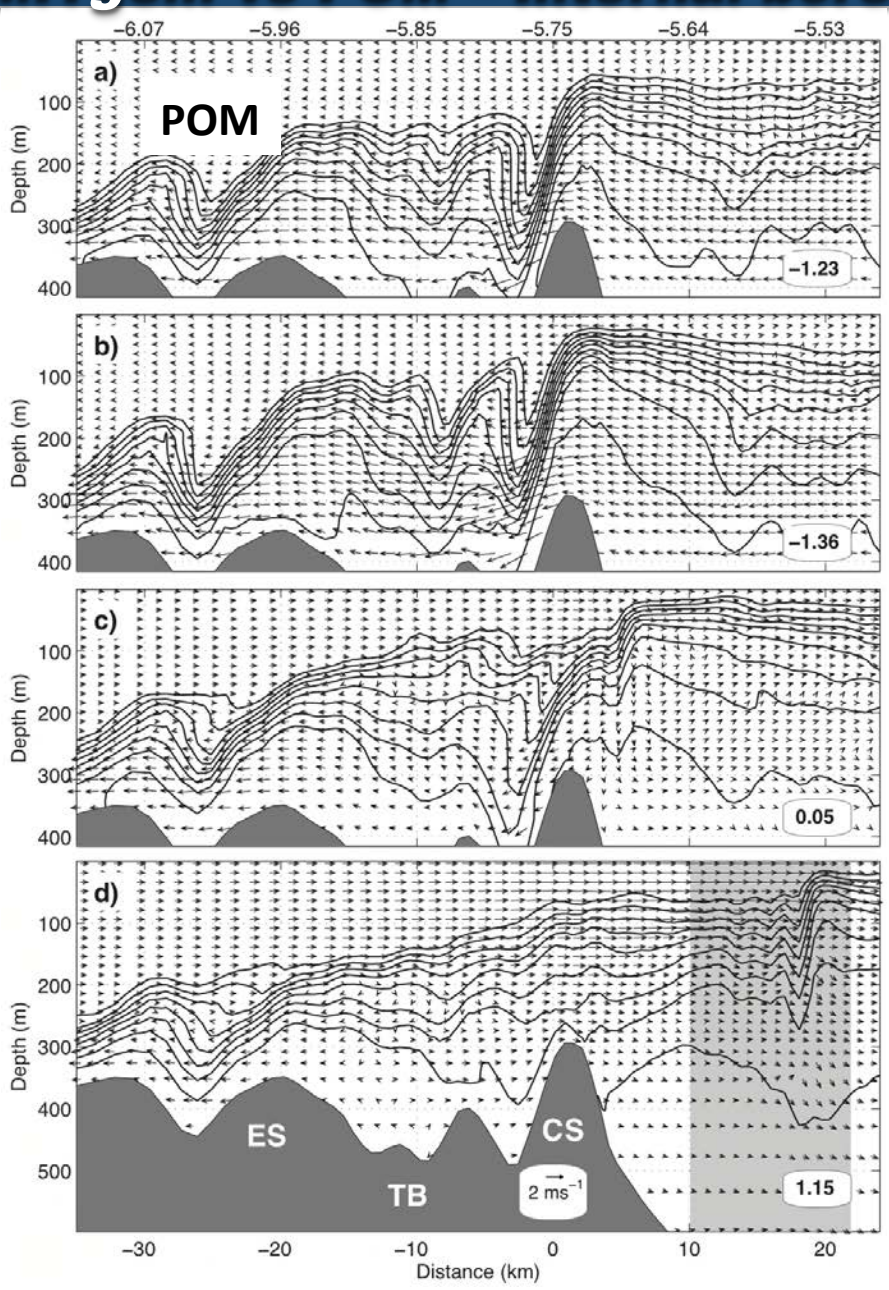
MITgcm model simulation

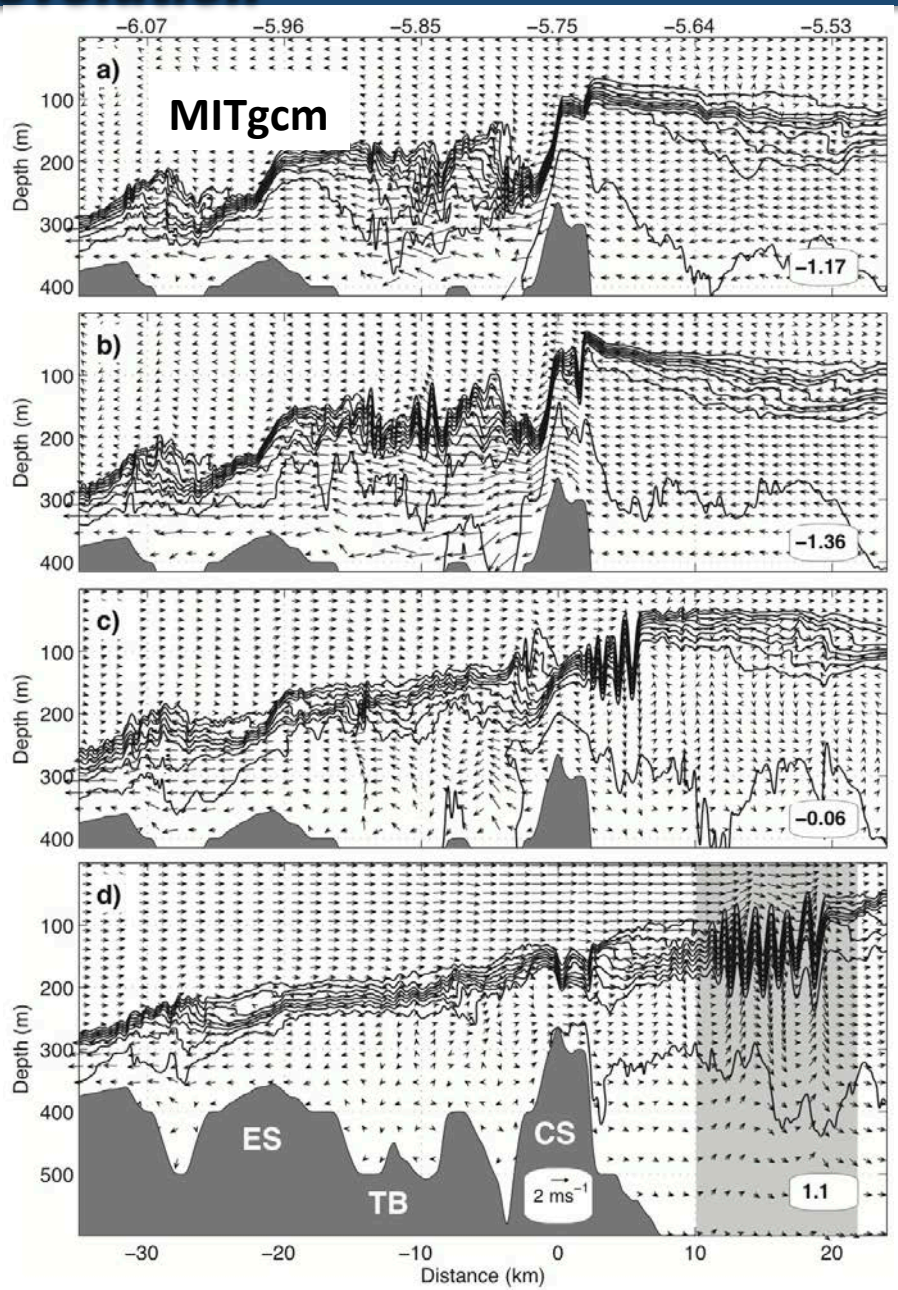


Garrido et al. jgr 2011

Interface depth evolution

MITgcm vs POM – Internal bore evolution





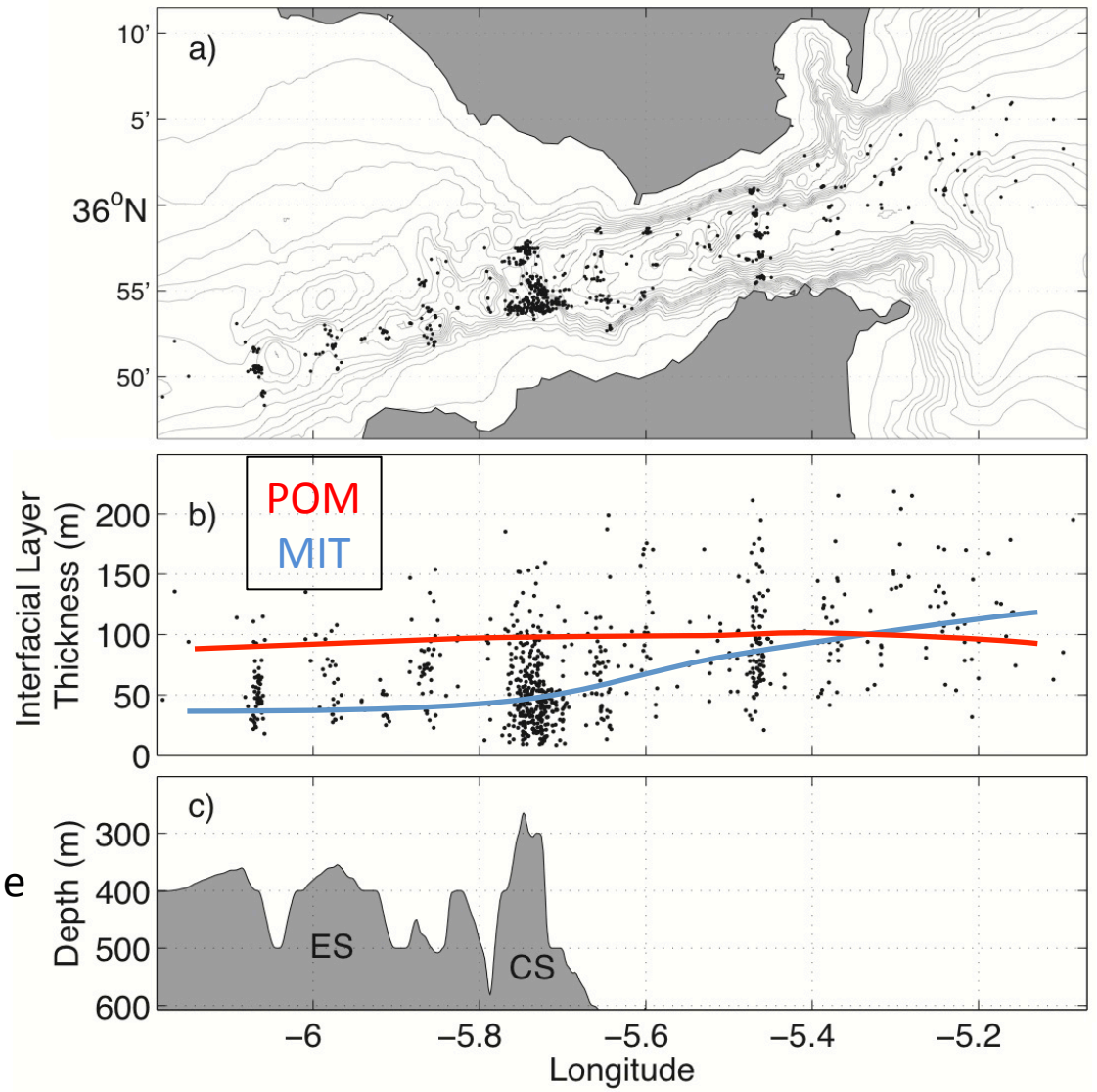
Garrido et al. jgr 2011

Observed and models interface layer thickness

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

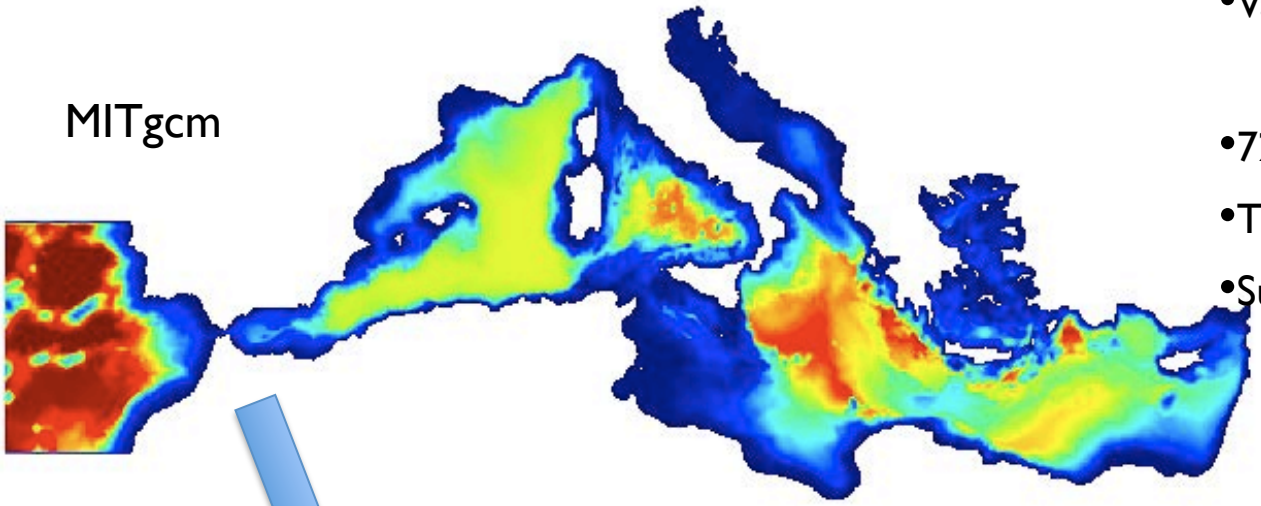
b) Interface layer thickness computed from CTD data.

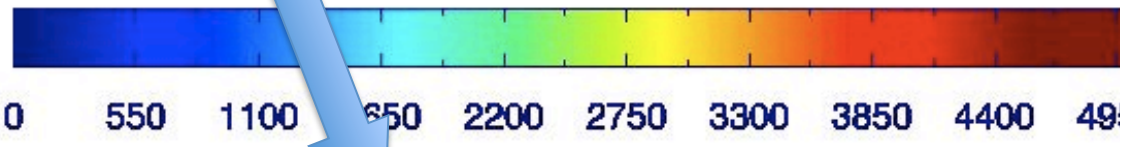
c) Bottom topography along the central axis of the Strait.

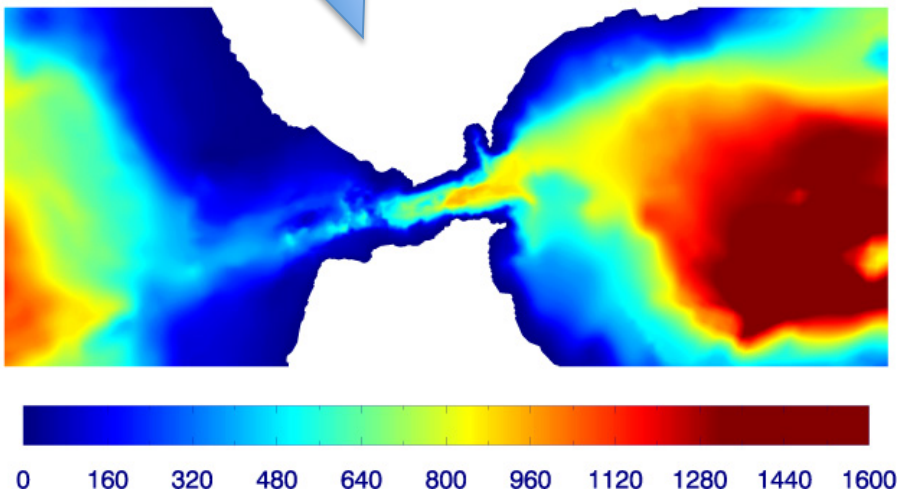


New modeling strategy for the Mediterranean

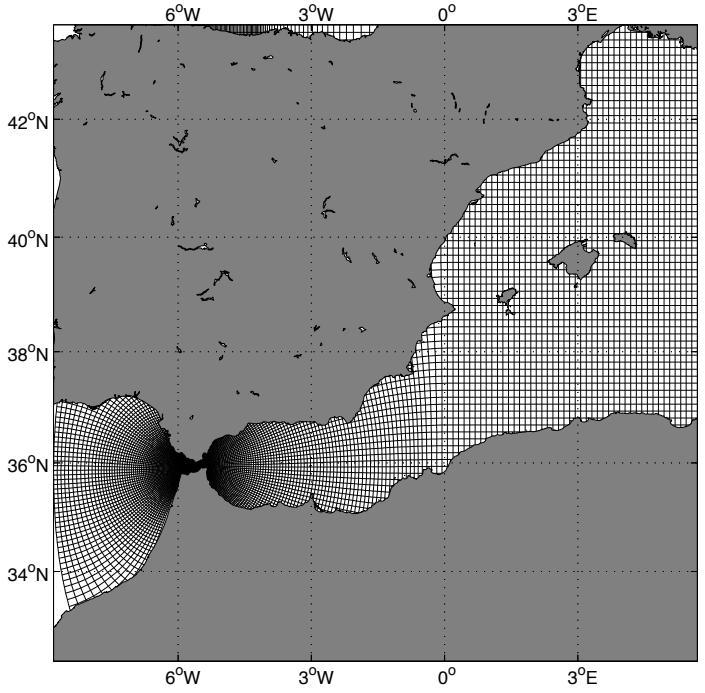
MITgcm



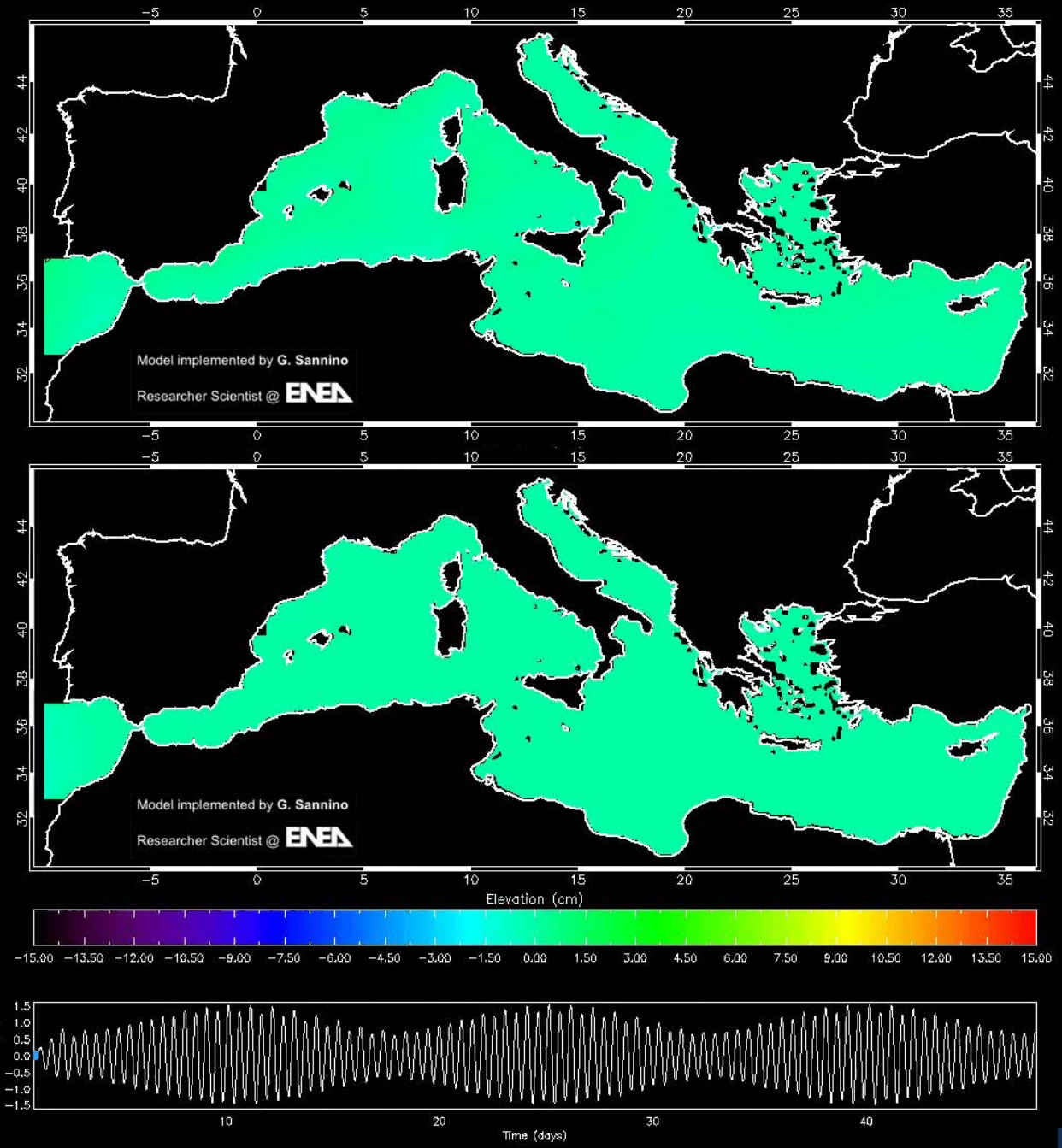




- Variable horizontal resolution (1/16° up to 1/200°)
- 72 vertical levels
- Tidal forcing (main 4 components)
- Surface atmospheric pressure



New modeling strategy for the Mediterranean

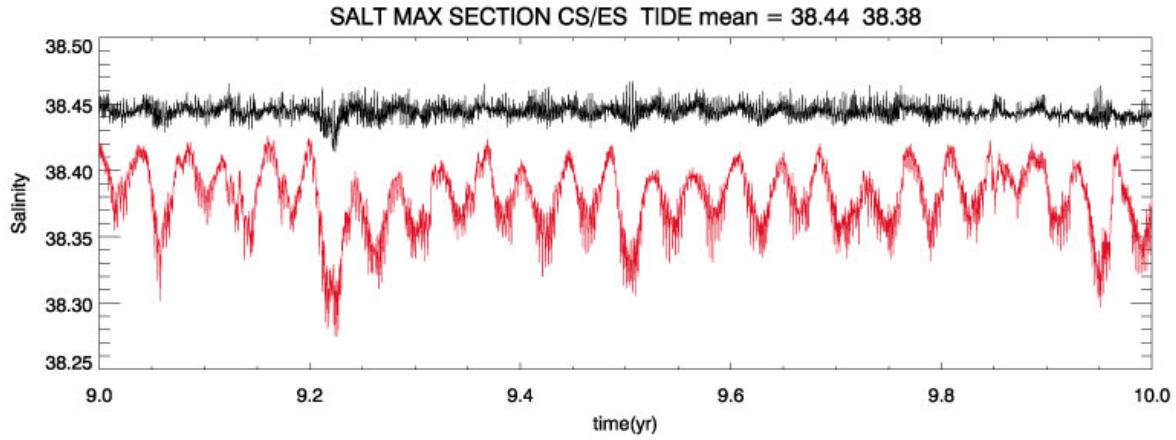


CINECA
ISCRA GRANT

PROTHEUS 2.1: model improvements

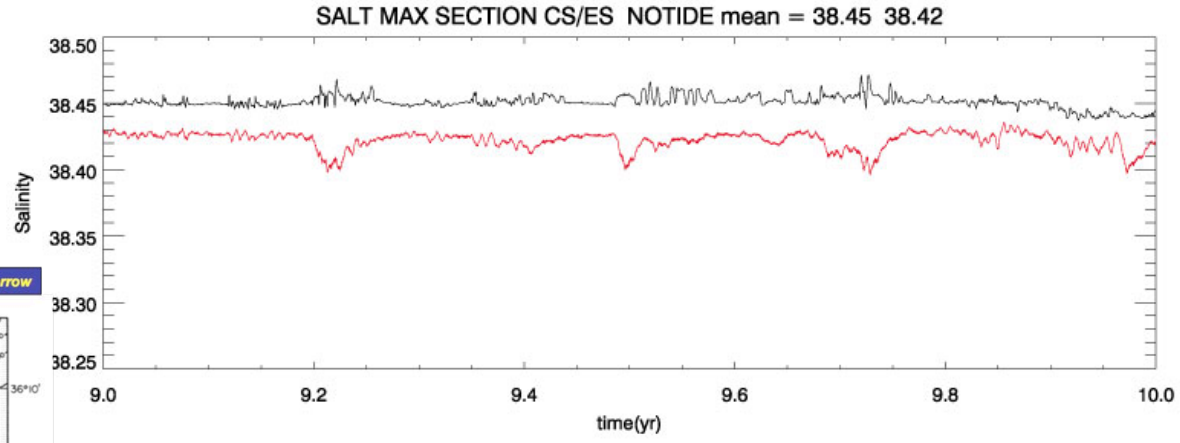
Camarinal Sill - TIDE

Espartel Sill - TIDE



Camarinal Sill - NOTIDE

Espartel Sill - NOTIDE



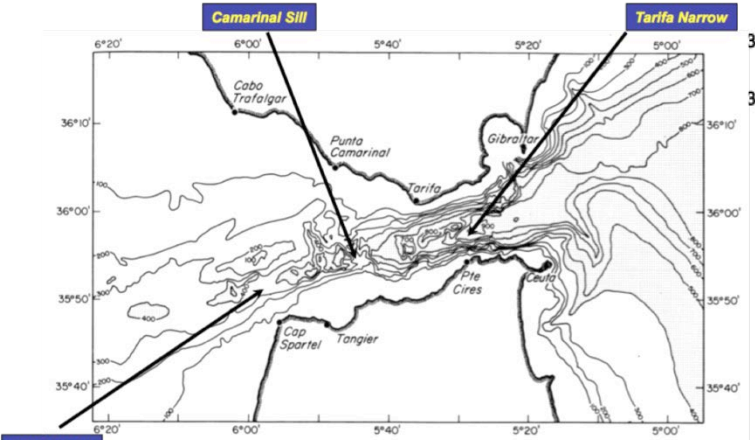
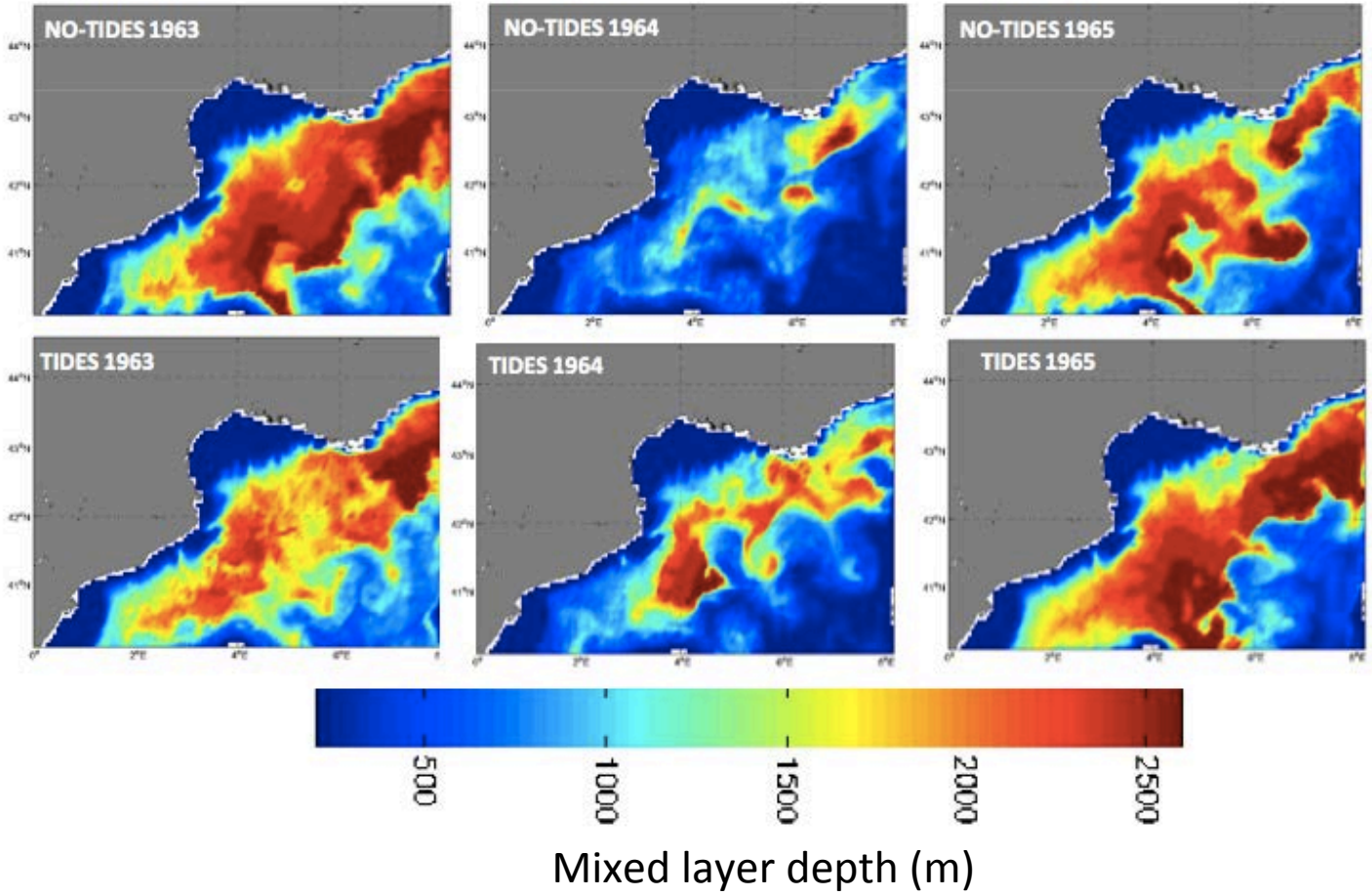


Chart of the Strait of Gibraltar showing the principal geographic features. Areas deeper than 400 m are shaded

PROTHEUS 2.1: model improvements

NO-TIDE

TIDE



Conclusions

- MITgcm is on of the best state-of-art ocean model
- Our experience is more than positive
- So we encourage you to use it both in stand-alone and coupled version