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

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OUTLINE

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- Numerical Model
- Physical validation
- Effects of the tides on the circulation
- Conclusions

Introduction

The tidal dynamics in the Mediterranean Sea have been studied since the 80s, but a detailed description of their effects on the circulation is still *lacking*.

This is mainly due to the great complexity of the basin morphology and bathymetry.

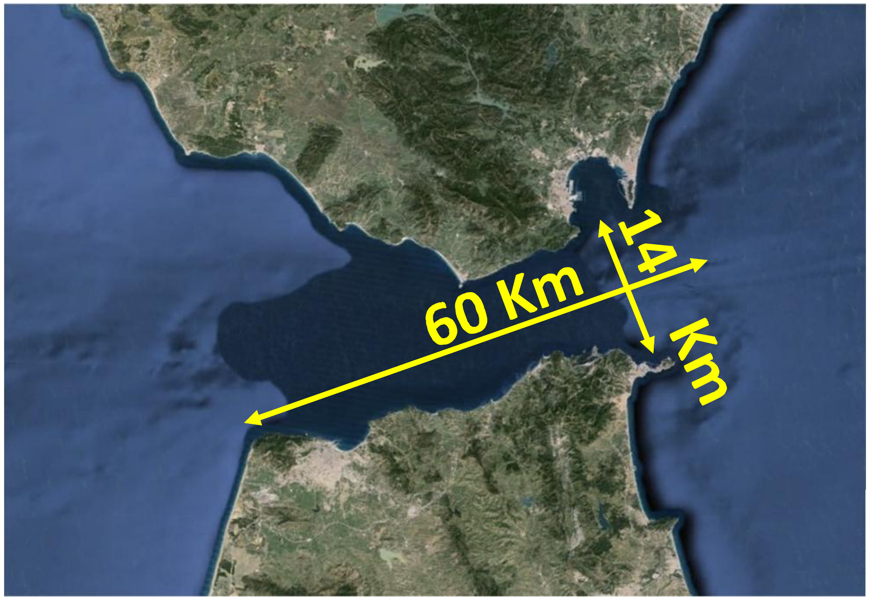
Background geography

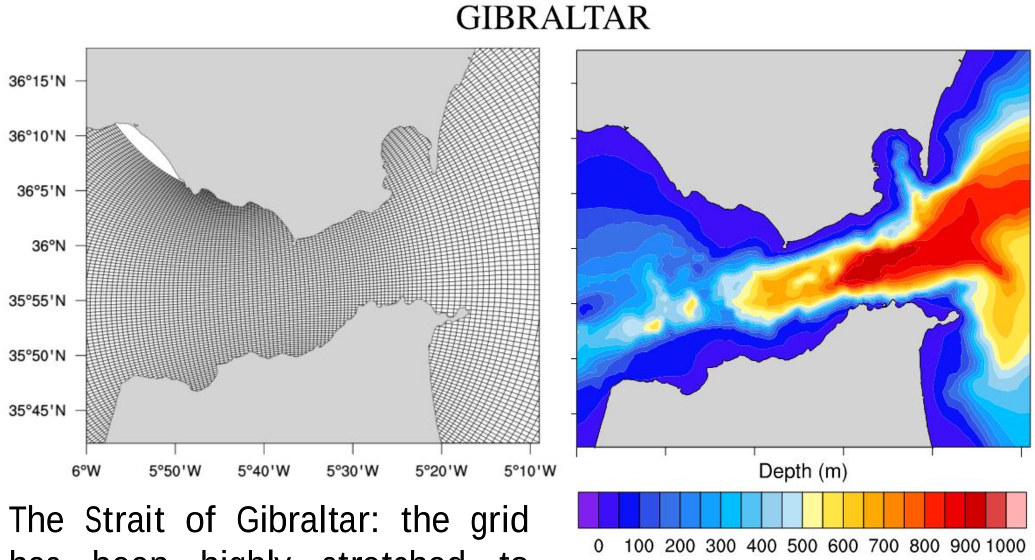
New modeling strategy for the Mediterranean

MITgcm
(MIT General Circulation Model,
Marshall et al.,1997)

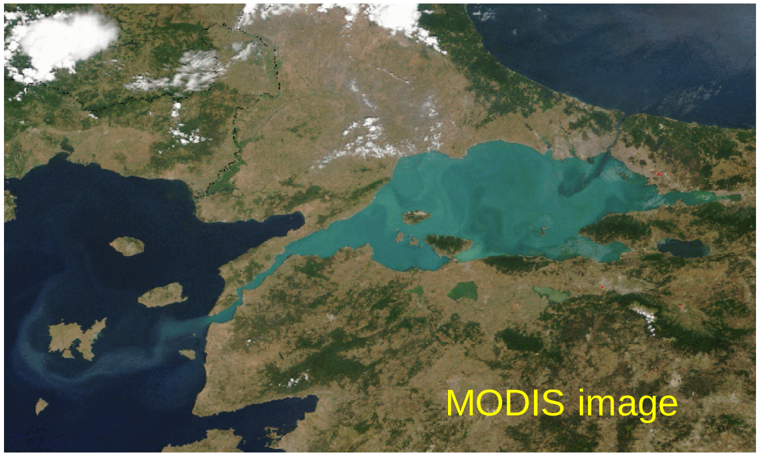
- Average resolution 1/48° (2.3 Km)
- 100 Vertical Levels
- MITgcm – Explicit Tides (M2,S2, K1, O1) – Lateral Tide + Tidal Potential
- Forced at the surface by hourly wind stress and heat and fresh water fluxes derived from the high-resolution (5 km), non-hydrostatic, SKIRON model
- Driven at the lateral open boundary by the tracer and velocity fields provided by the NEMO operational model

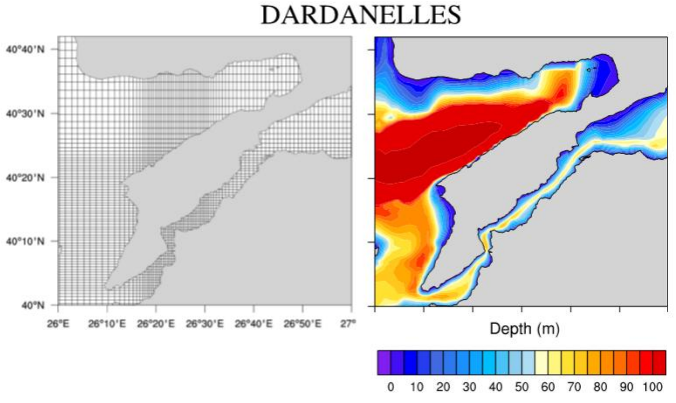
New modeling strategy for the Mediterranean

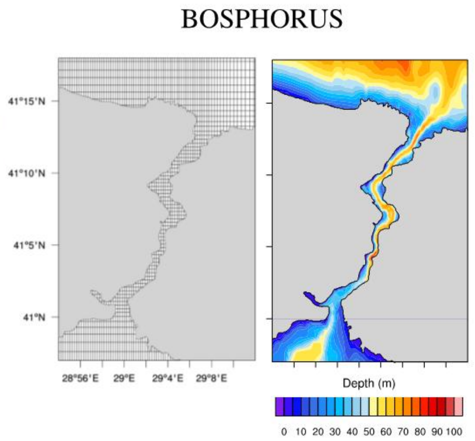




The Strait of Gibraltar: the grid has been highly stretched to reach a maximum resolution of 1/800° (about 120 m)







The Straits of Dardanelles and of Bosphorus: a smooth thinning of the grid in the latitudinal and longitudinal directions allows for a maximum resolution of 1/250° (about 380 m)

The vertical mixing can be defined using *GGL90 scheme (Gaspar et al.1990)*;

The turbulent vertical fluxes are parameterized using the classical concept of eddy viscosity:

$$\overline{-U'w'} = K_m \, \partial\bar{U}/\partial z$$

The eddy viscosity are related to the TKE according to

$$K_m = c_k l_k \bar{e}^{1/2}$$

where C_k is a constant to be determined, l_k is a mixing length, *e* is the TKE

Classical concept of eddy diffusivity:

$$\overline{-T'w'} = K_h \, \partial\bar{T}/\partial z$$

$$\overline{-S'w'} = K_s \, \partial\bar{S}/\partial z$$

$$K_s = K_h = K_m/P_{rt}$$

Calibration:
Y= mixing efficiency coefficient
Rf= Richardson flux number

Rf/1-Rf = Y

Lilly at al. (1974) assume that Rf=0.25; accordingly deduce that Y=0.33

$$Y=2\,Ck\,Ce^{-1}Prt^{-1}$$

Turbulent Kinetic Energy (TKE)

$$\bar{e} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

a single prognostic equation is developed:

$$\frac{\partial \bar{e}}{\partial t} = -\frac{\partial}{\partial z}\left(\overline{ew'} + \frac{\overline{p'w'}}{\rho_o}\right) - \overline{u_h'w'} \cdot \frac{\partial U_h}{\partial z} + \overline{b'w'} - \epsilon$$

TKE is diagnosed at the surface and at the bottom. The bottom value for TKE (e_0) is fixed to a numerical minimal threshold, while the surface value includes a dependence on the wind stress:

$$\bar{e}_{surface} = \max(3.75u^{*2}, \bar{e_0})$$

$$\bar{e_0} = 10^{-11}\, m^2 s^{-2}$$

The Leith viscosity

Leith [1996] finds an alternative to the Smagorinsky viscosity by focusing on resolving the direct enstrophy cascade in 2D turbulence rather than the direct energy cascade in 3D turbulence.

2D turbulence?

Strictly speaking, there are no two-dimensional flows in nature.

Approximately 2D: soap films, stratified fluids, geophysical flows.

In 2D flows, there is a second conserved quantity in addition to energy, the enstrophy:

$$< G > = \frac{1}{V} \iiint \frac{1}{2} (\nabla_h \times u)^2 \, dV$$

Enstrophy per unit mass (angle brackets are volume mean), V is the domain volume, ∇_h is the horizontal differential operator, u is the velocity.

The Leith viscosity

In two-dimensional turbulence, energy cascades to larger scales, so there is no concern about resolving the scales of energy dissipation. Instead, enstrophy is conserved in 2-d turbulence, and it cascades to smaller scales where it is dissipated.

Kraichnan [1967] notes that there might be an inertial enstrophy cascade analogous to the energy cascade.

The tools developed for engineering-scale simulations, where the Smagorinsky viscosity is appropriate, may be adapted to the direct enstrophy cascade of mesoscale flows where the Leith viscosity is appropriate.

The Leith viscosity

The Leith viscosity was implemented in the Massachusetts Institute of Technology general circulation model (MITgcm) (B.Fox-Kemper, D. Menemenlis, 2008)

$$A_{hLeith} = \left(\frac{viscC2Leith}{\pi}\right)^3 L^3 \, |\nabla\overline{\omega_3}|$$

$$|\nabla\omega_3| \equiv \sqrt{\left[\frac{\partial}{\partial x}\left(\frac{\partial\bar{v}}{\partial x} - \frac{\partial\bar{u}}{\partial y}\right)\right]^2 + \left[\frac{\partial}{\partial y}\left(\frac{\partial\bar{v}}{\partial x} - \frac{\partial\bar{u}}{\partial y}\right)\right]^2}$$

The Leith viscosity

2d flow -> vorticity is conserved

$$\frac{d\omega}{dt} = 0$$

Important quantities:

Mean energy

$$E = \langle \frac{1}{2} u^2 \rangle \qquad \frac{dE}{dt} = -2\nu Z$$

Enstrophy (mean square vorticity)

$$Z = \langle \frac{1}{2} \omega^2 \rangle \qquad \frac{dZ}{dt} = -2\nu \langle (\nabla\omega)^2 \rangle$$

For ν -> 0 we get $\frac{dE}{dt}$ -> 0

Physical validation

To evaluate the performances of the new model we have performed a tide-including simulation spanning the period 19 March-30 April 2018.

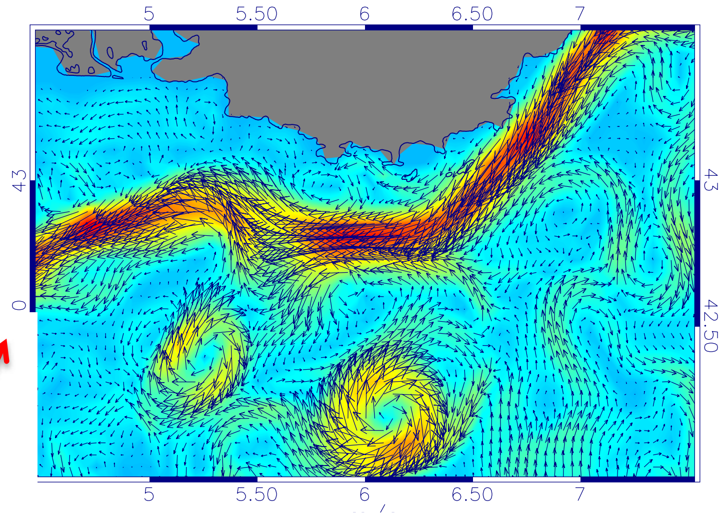
This relatively long simulation allows us to assess the performances of the model in absence of assimilation.

We have made a general assessment of:

- ***Surface circulation***
- ***Sea surface temperature***
- ***Tidal dynamics***

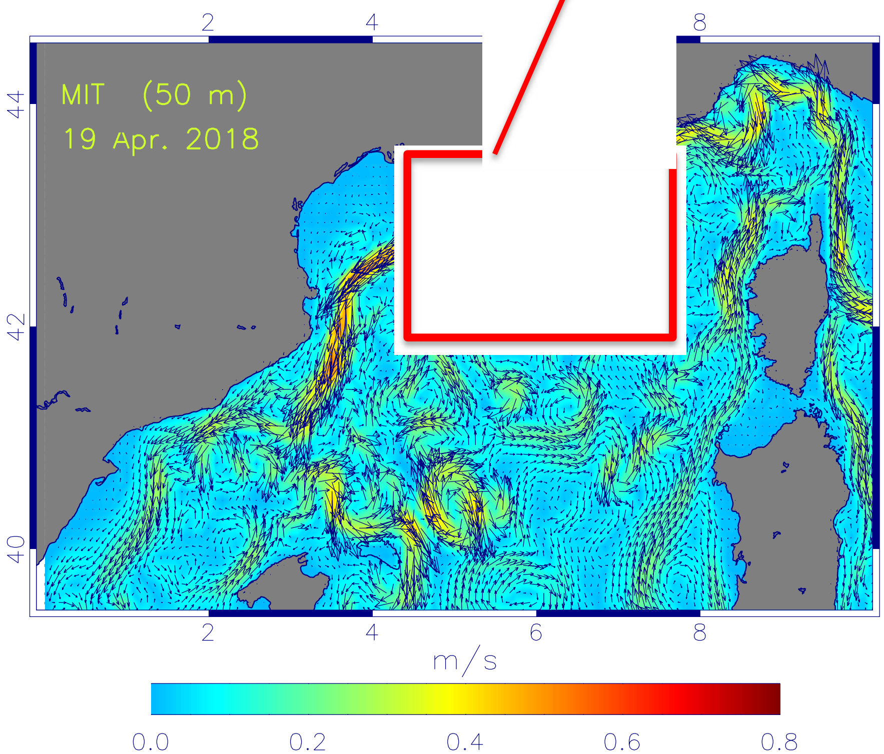
Results: surface circulation

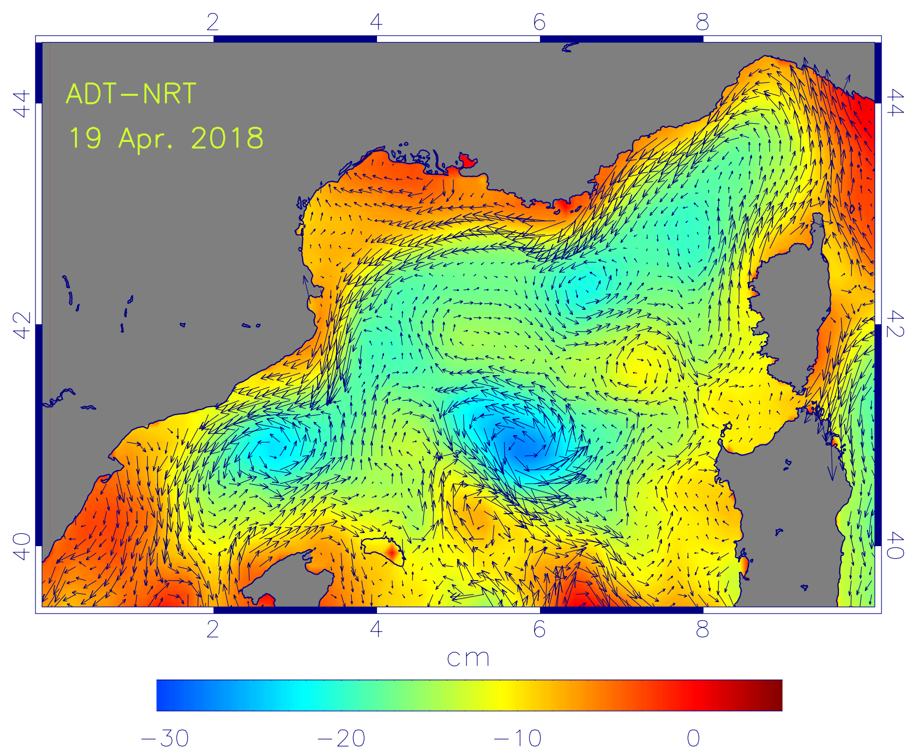
Comparison between the surface circulation (50 m of depth) of the Liguro-Provencal basin (April 19; one month after the beginning of the simulation). In the top panel: a zoom of the circulation in the region in the red box, indicating instability of the Northern current.



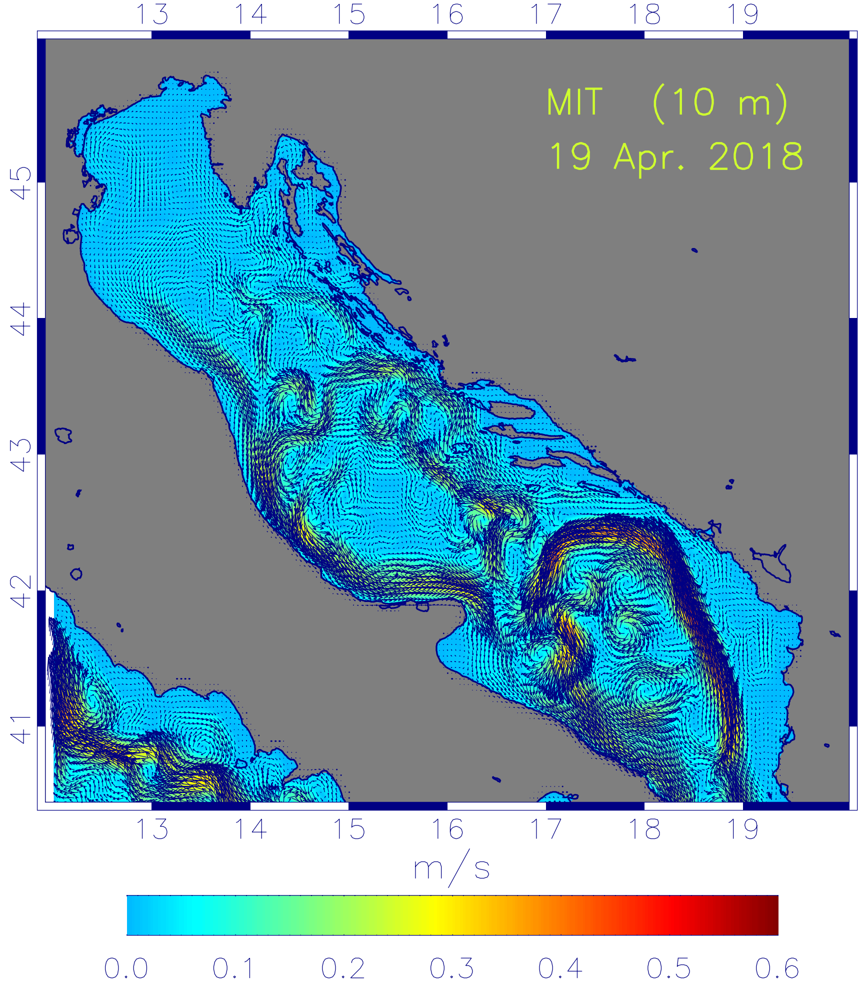
Near Real Time map of Absolute Dynamic Topography (ADT)

Nominal horizontal resolution of 1/8° (about 14 km)

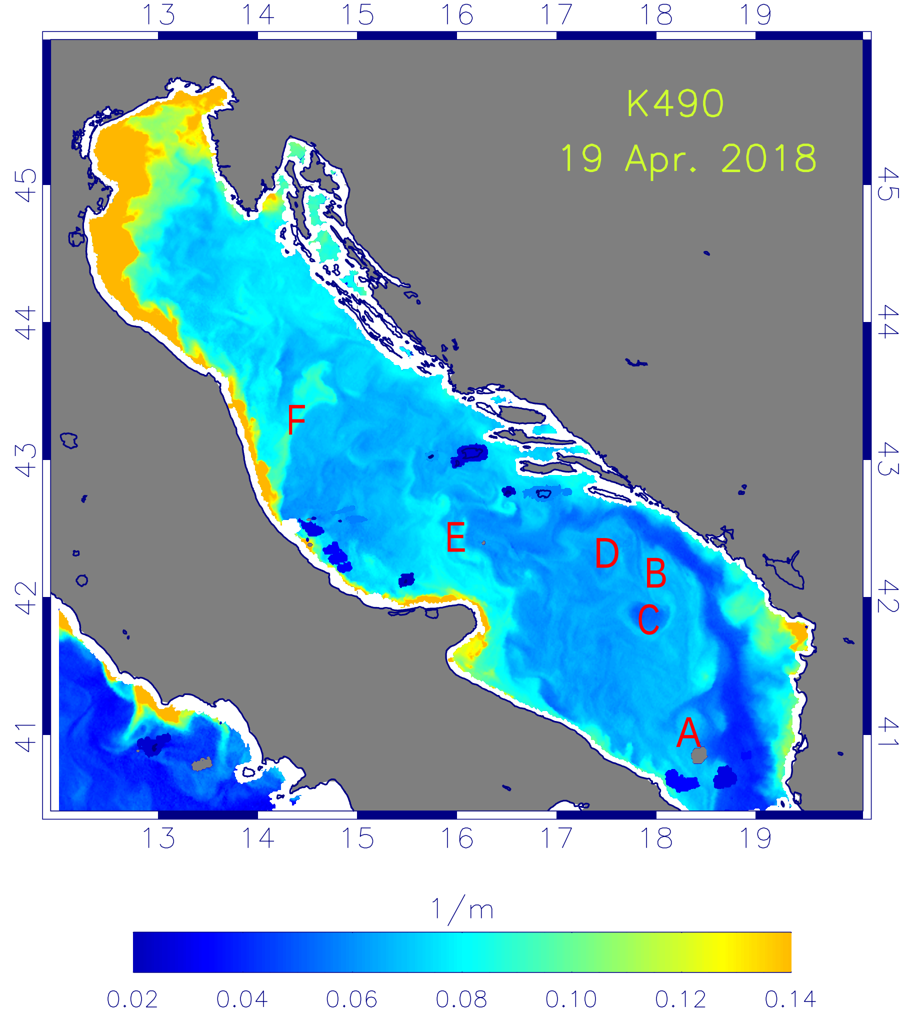




Results: surface circulation

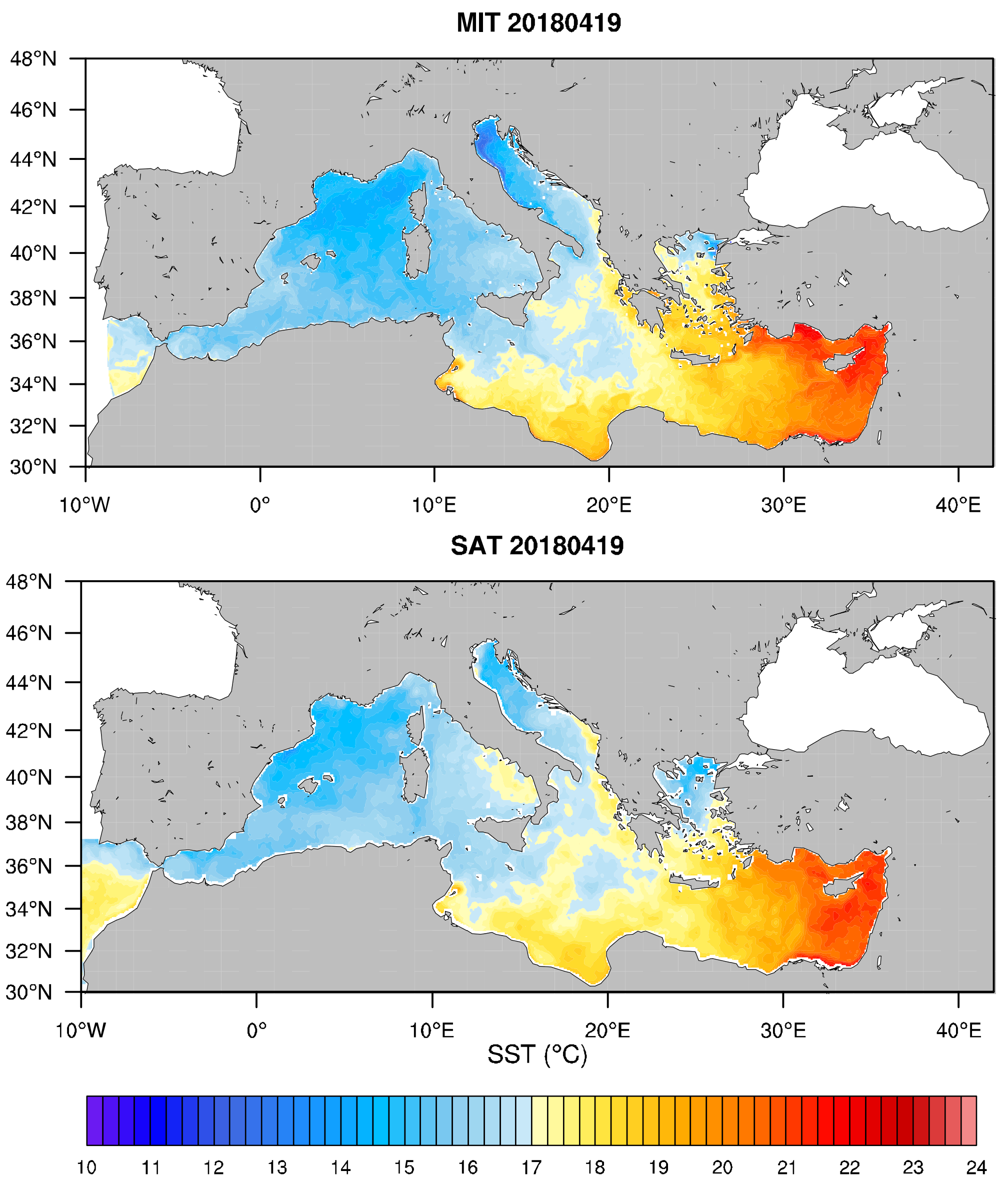


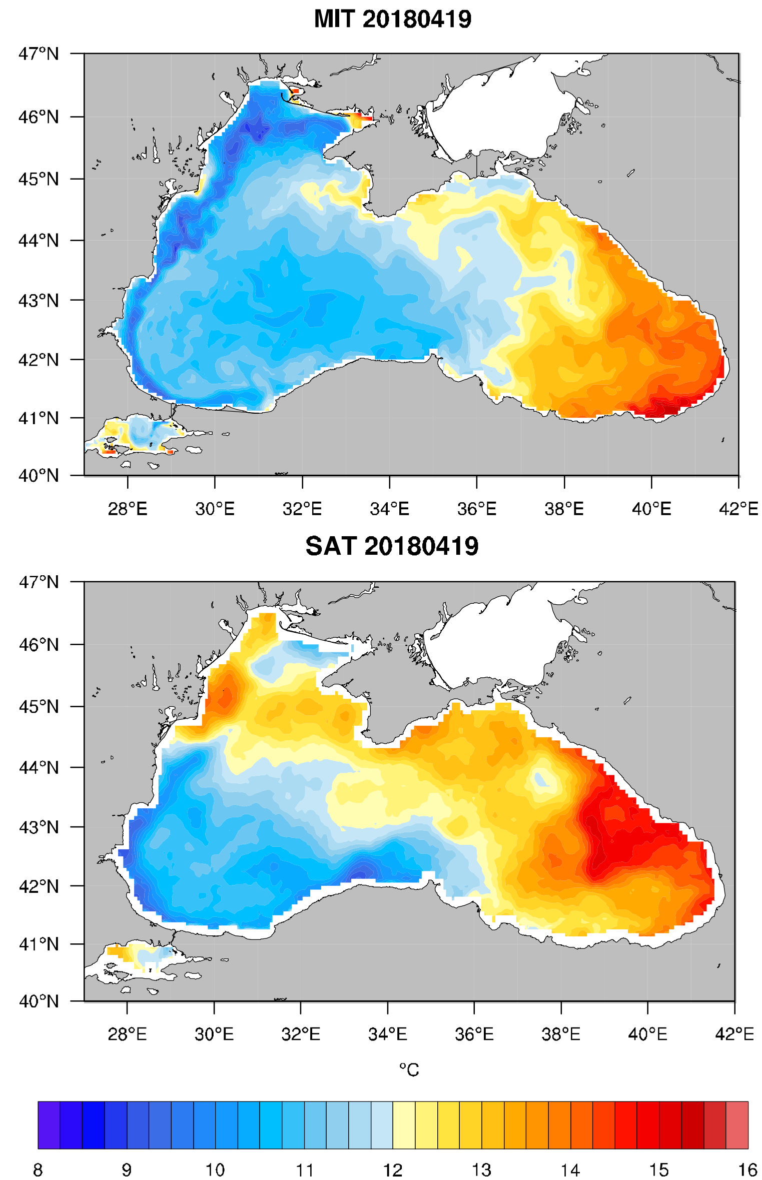
Comparison between the model surface circulation (10 m of depth) of the Adriatic Sea (April 19; one month after the beginning of the simulation) with a high-resolution (1 km) satellite map of K490 (turbidity). The letters highlight small scale circulation features that are present in both maps.



High-resolution (1 km) map of K490
(the light attenuation coefficient at 490 nm)

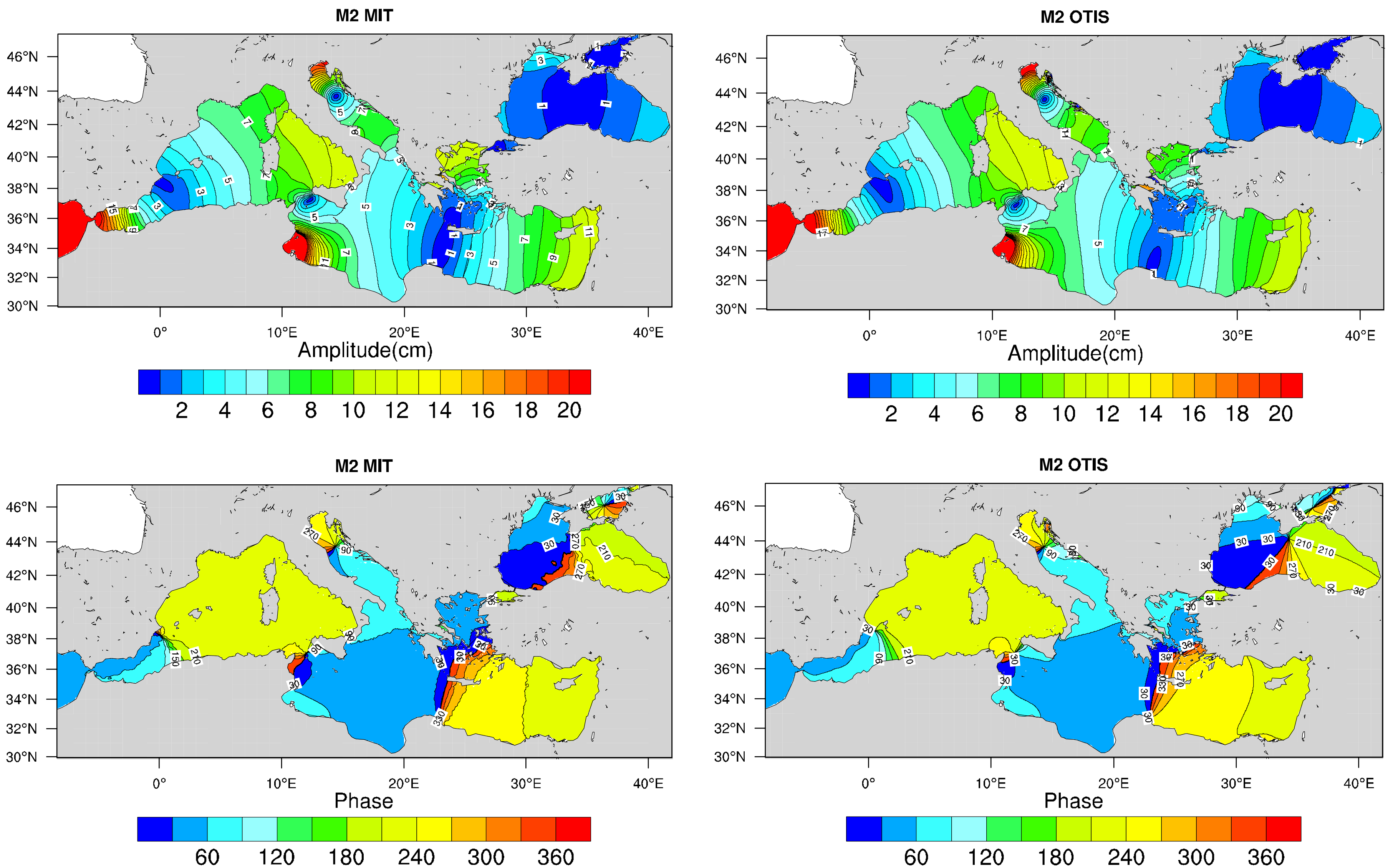
Results: sea surface temperature





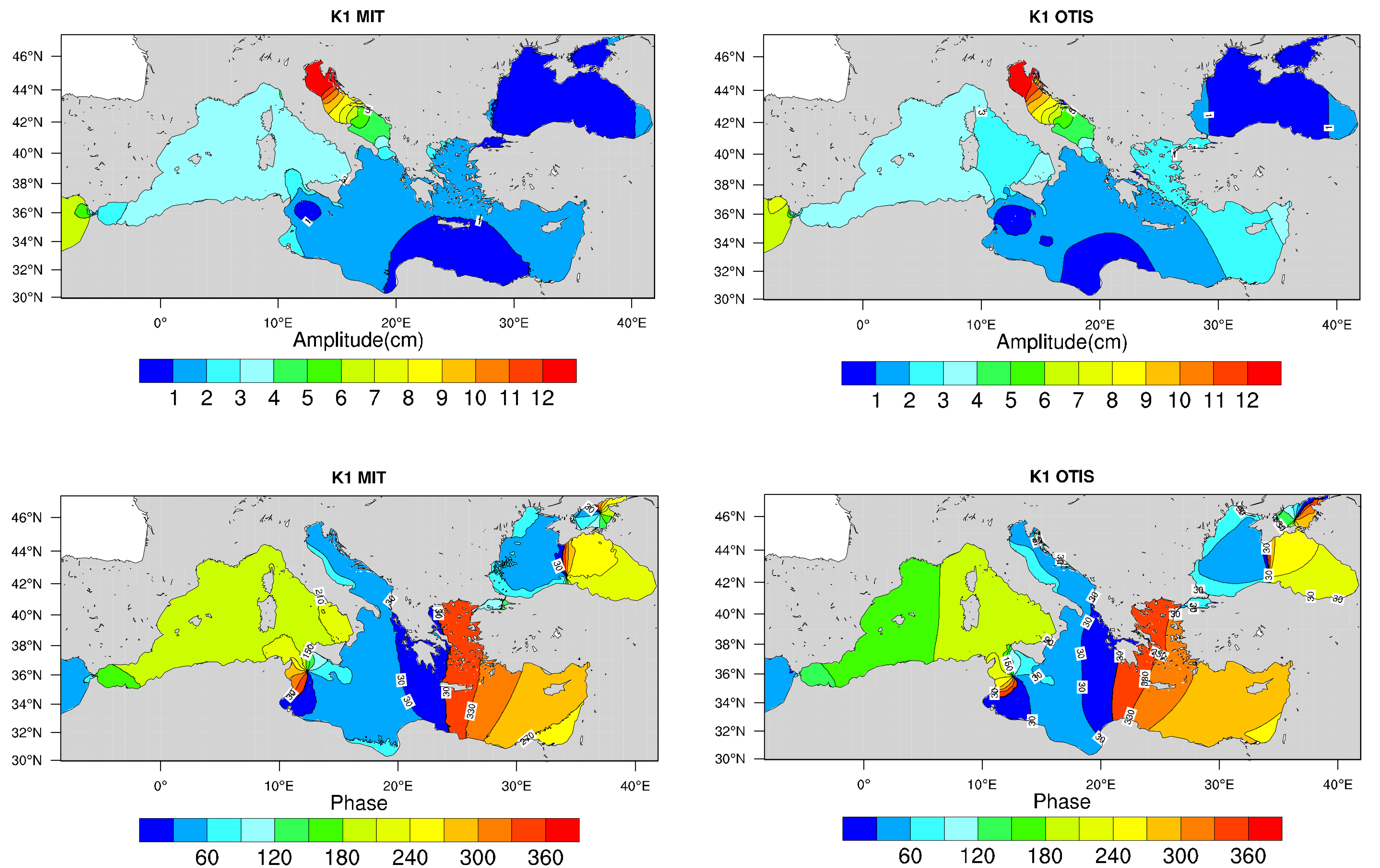
Results: validation of the tidal dynamics

M2 co-tidal map. Upper panels, amplitude in cm, lower panels, phase in degrees



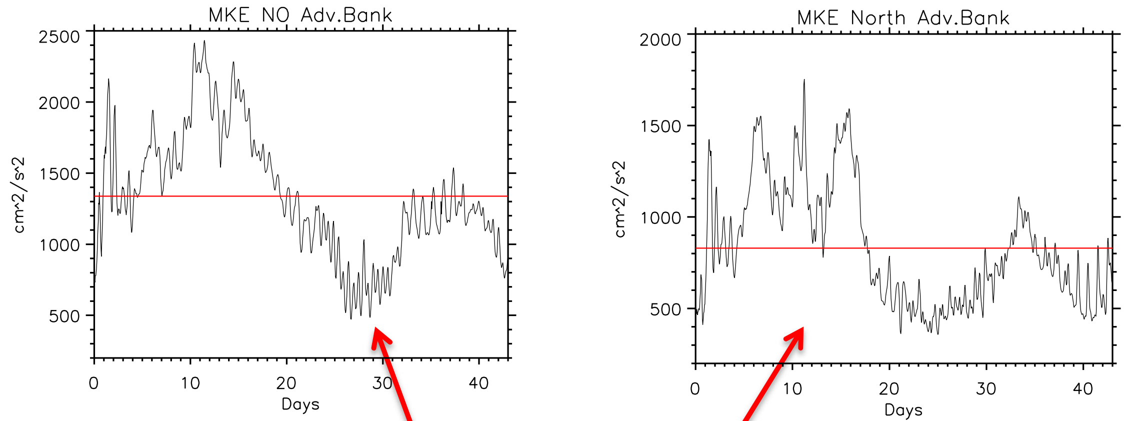
Results: validation of the tidal dynamics

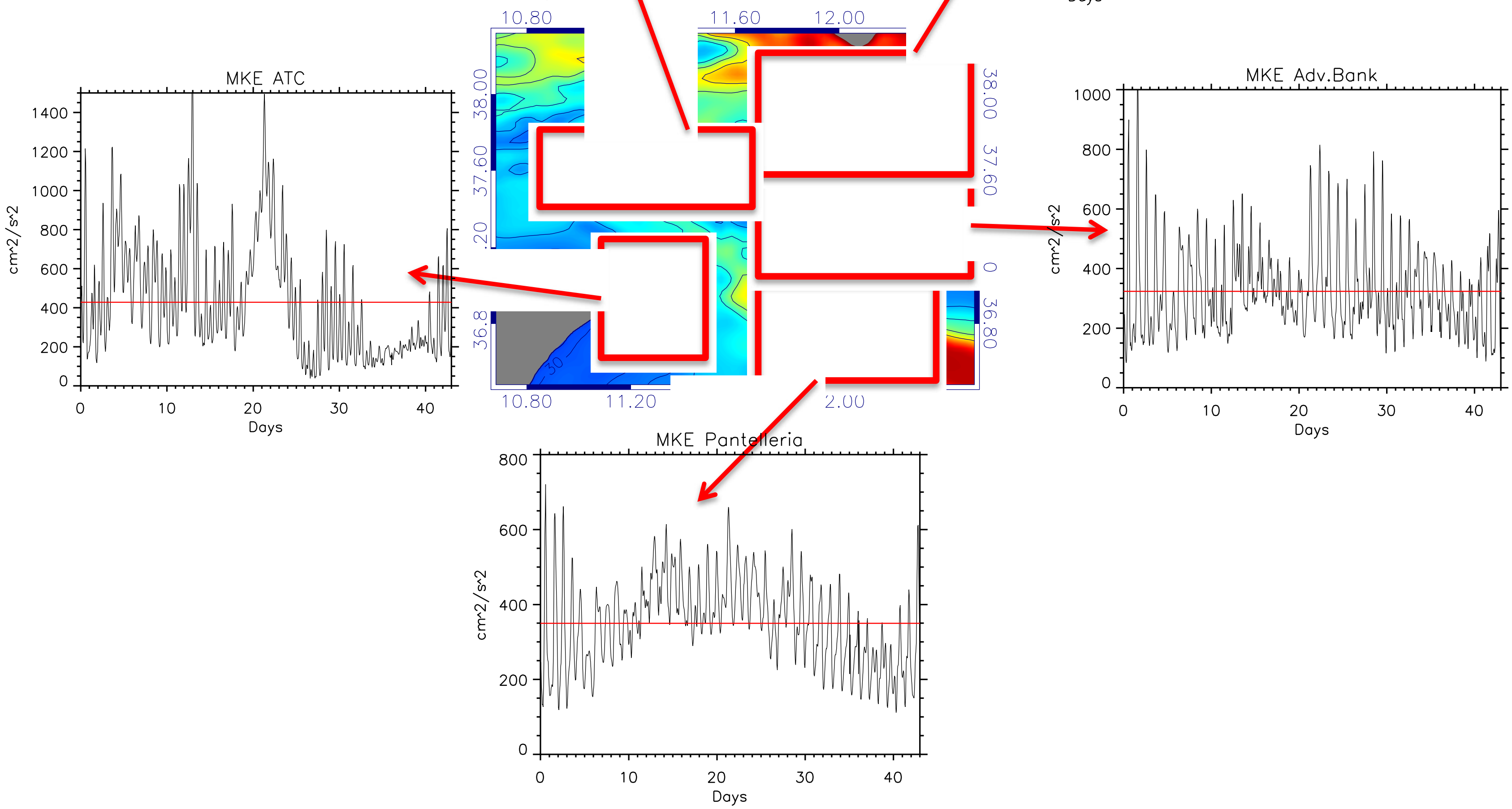
K1 co-tidal map. Upper panels, amplitude in cm, lower panels, phase in degrees



Results: effects of the tides on the circulation – Sicily Channel

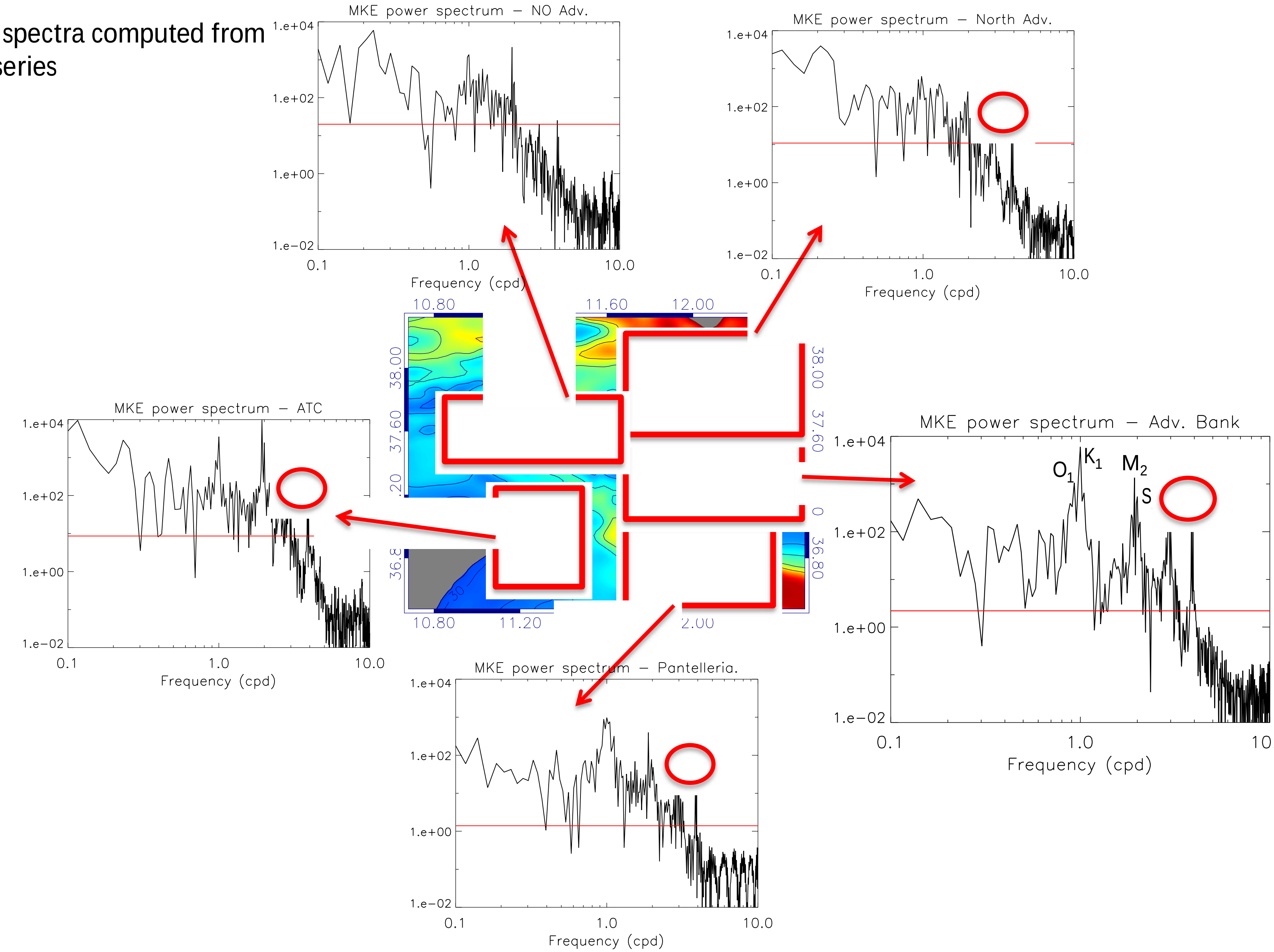
The time series of the Mean kinetic energy (MKE), averaged over the red boxes drawn in the central panel, and over the first 100 m of the water column.





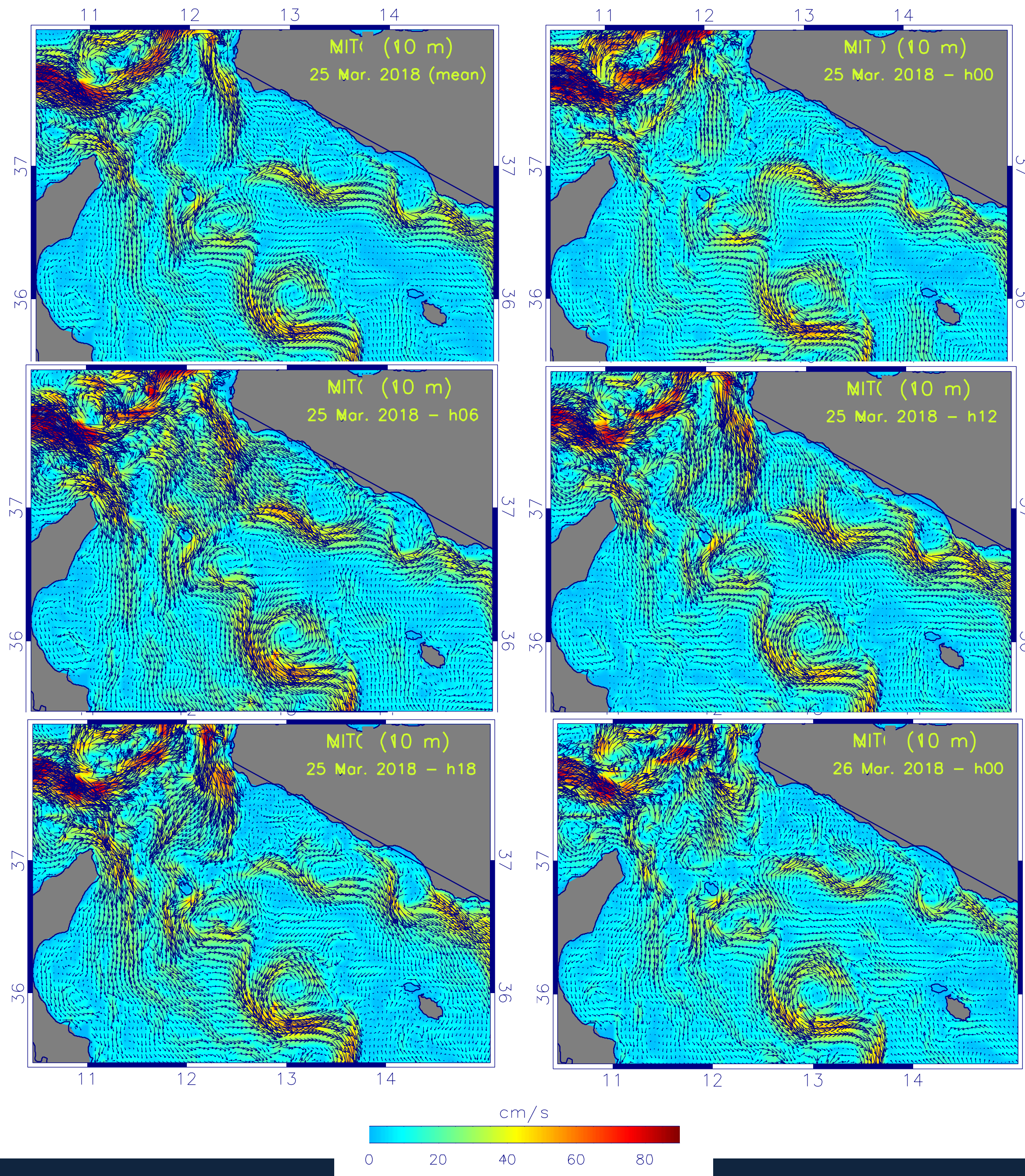
Results: effects of the tides on the circulation – Sicily Channel

The power spectra computed from MKE time series

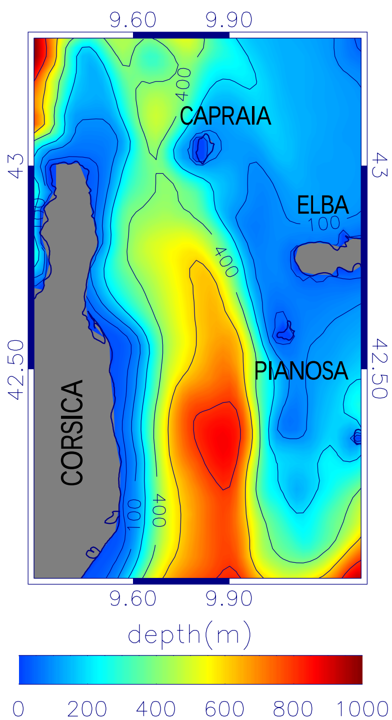


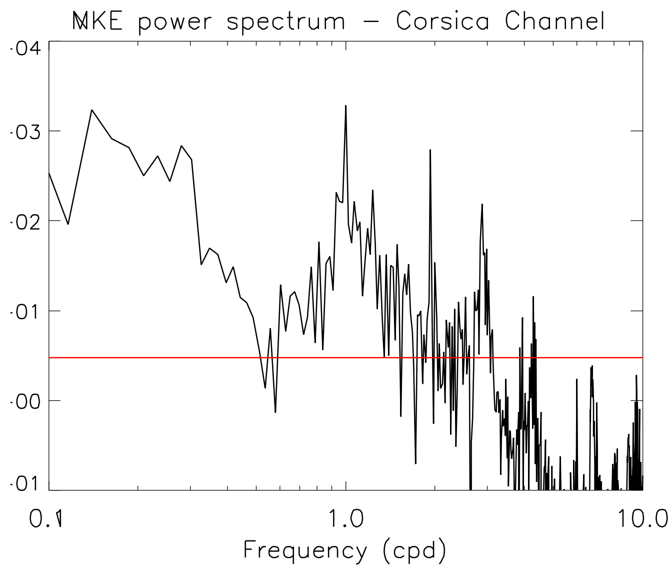
Results: effects of the tides on the circulation – Sicily Channel

25 March circulation at 10 m of depth, with colors indicating the flow strength

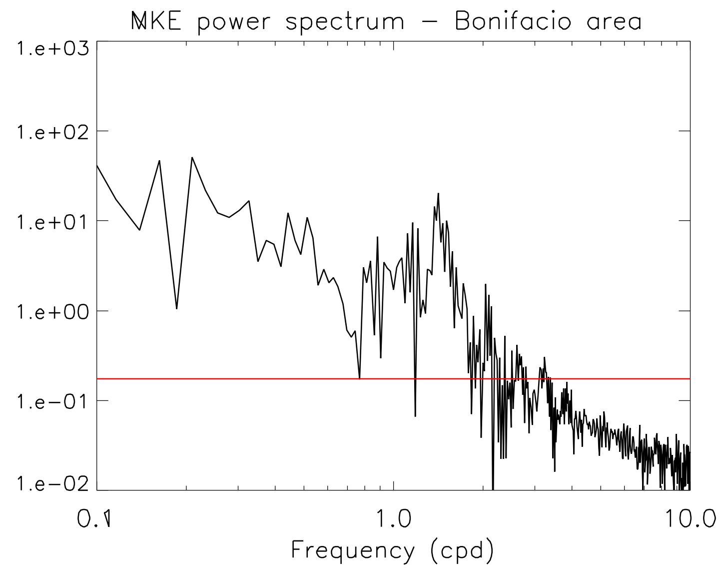


Results: effects of the tides on the circulation–Corsica Channel





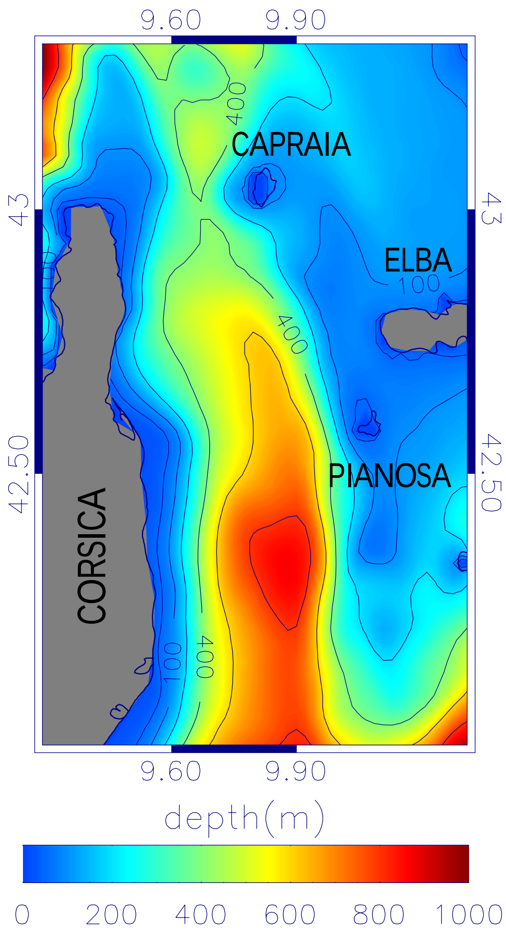
The MKE spectrum

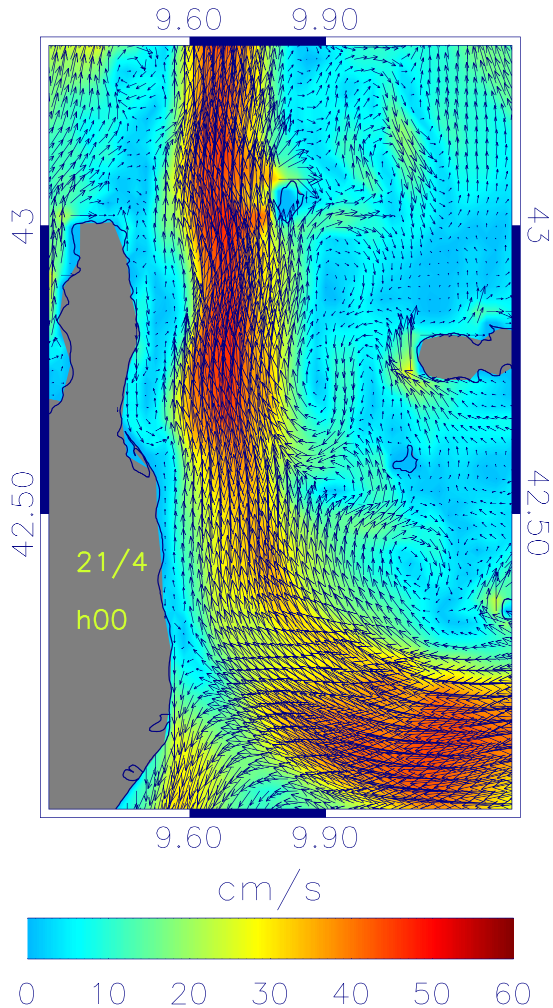


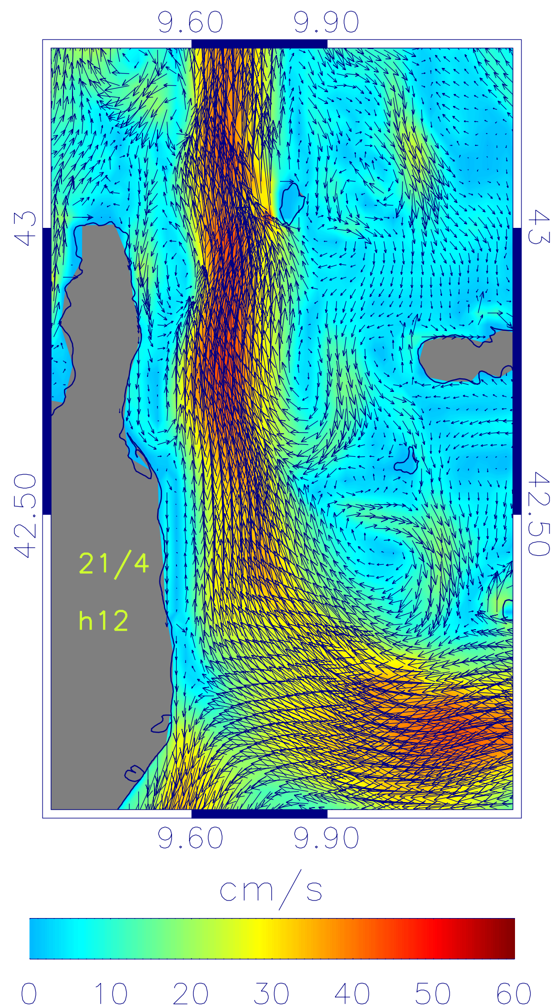
The MKE spectrum for an area just to the south of the channel

Results: effects of the tides on the circulation–Corsica Channel

The circulation at 10 m of depth for April 21, at h00 and h12

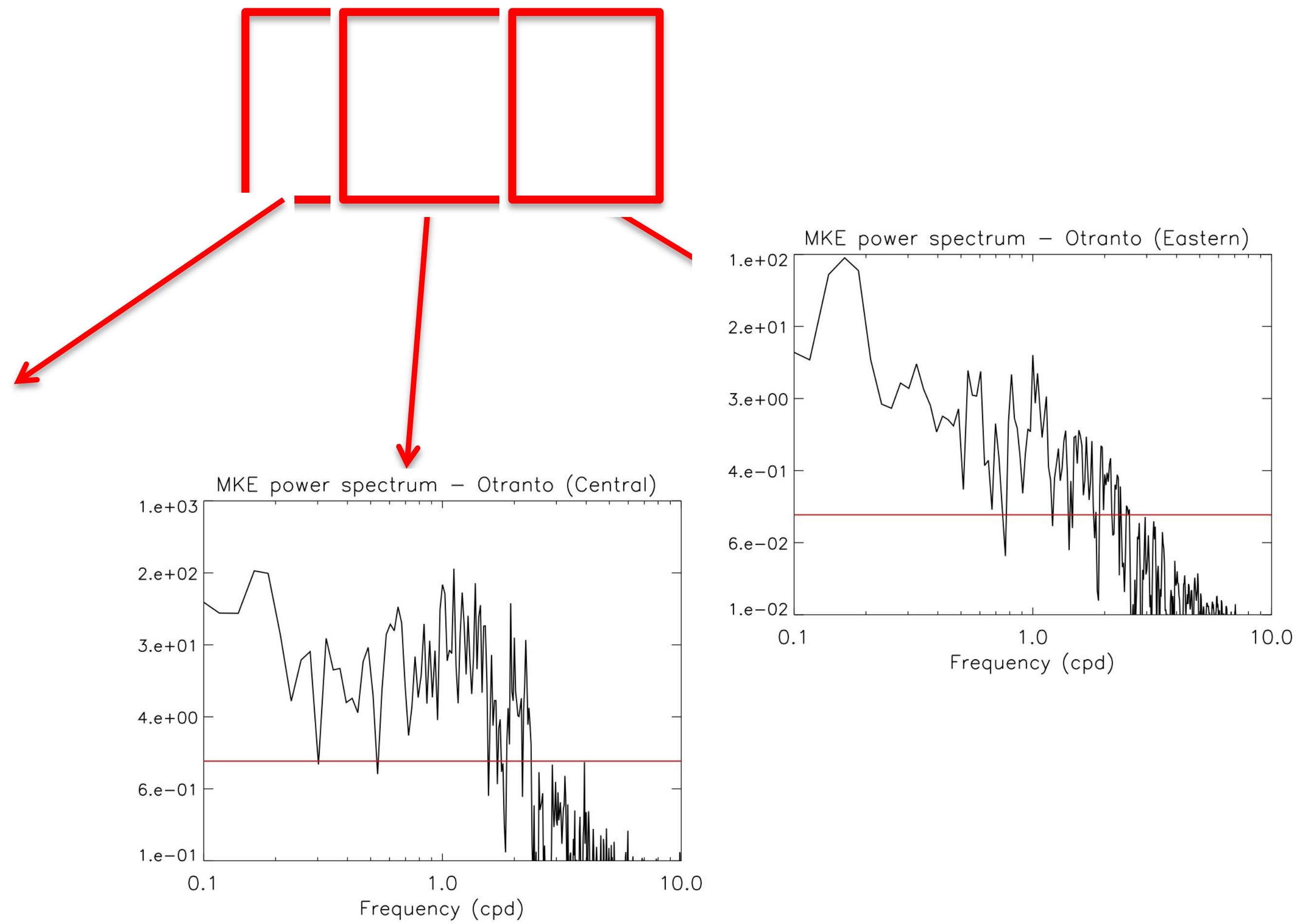






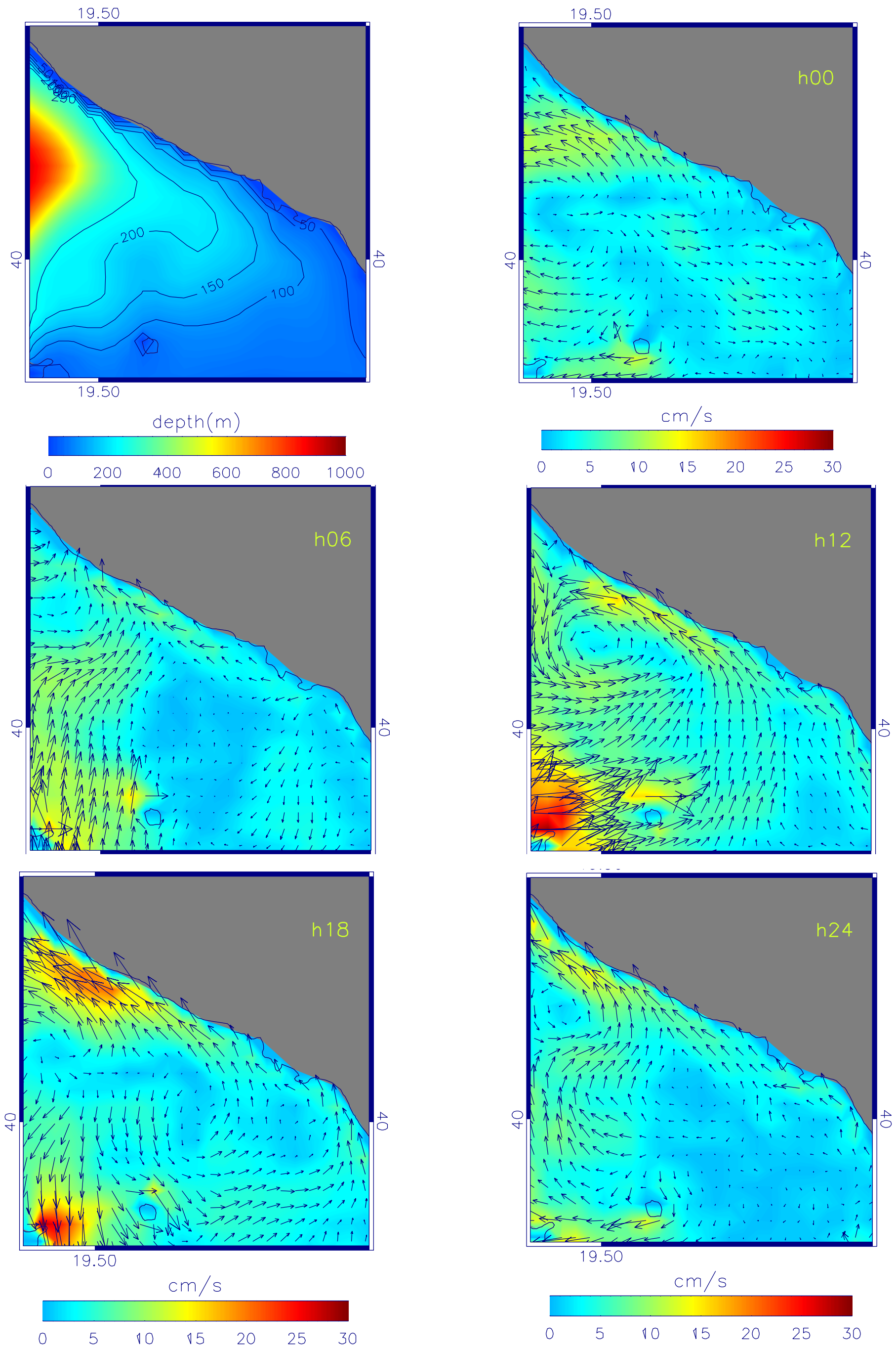
Results: effects of the tides on the circulation – Otranto Strait

The MKE power spectra in the three regions indicated by the red boxes



Results: effects of the tides on the circulation – Otranto Strait

The circulation at 10 m of depth, with colors indicating the flow strength



Conclusions

- A new high-resolution model of the circulation of the Mediterranean Sea-Black Sea system has been developed, which includes the effects of the four main astronomical tides.

- A physical validation of the model has been performed, comparing the results of a 40 days run with available satellite observations. After one month of simulation, during which no assimilation was applied, the model circulation and the sea surface temperature distribution were still found to be in good agreement with the observations, proving the capability of the model to follow the evolution of the system in a period - beginning of spring - characterized by complex dynamics and significant changes in the surface heat fluxes.

Conclusions

- Effects of the tides on the local circulation have been highlighted, such as a significant modulation of the strength of some current. In three passages, more complex effects of the tides have also been found, which manifest as clockwise rotations of the flow over shallow bathymetric features.

- Spectral analysis of the mean kinetic energy in the Sicily and Corsica Channels has revealed the presence of spectral peaks corresponding to periods of about 8 and 6 hours, which can be interpreted as harmonics of the diurnal and semidiurnal tidal components, generated true nonlinear interactions. This is an important result, because it shows that in these areas *the effect of the tides cannot be correctly recovered by just adding the appropriate tidal signal to the results of a not tide-including simulation.*


Thank you for the attention!