A high-resolution operational system for the forecasting of sea state in the Mediterranean and the Black Sea for energy harvesting

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Abstract— **A high-resolution, primitive equations ocean circulation model of the Mediterranean Sea-Black Sea system (MITO) has been developed and tested, and is currently being run in operational mode. The model explicitly includes the effects of the main components of the astronomical tides and is therefore capable of providing valuable information on the best suitable sites for tidal energy exploitation in the basin. MITO, which is based on the Massachusetts Institute of Technology (MIT) general circulation model, achieves a uniform resolution of 1/48° (about 2 km) over most of the domain, increased to a few hundred meters in correspondence of the Straits of Gibraltar, Dardanelles and Bosphorus, in order to correctly resolve the local dynamics. Higher resolution forecasts can be obtained by performing local nested simulations with a model configuration specifically tailored to the end users' needs. Operative wave forecasts complement the ocean circulation forecast, providing basin-wide information on wave parameters at 1/32° resolution (WAM model), which is further increased to 1/124° (SWAN model) over interesting areas along the Italian coast. The integrated system MITO + wave models represents an invaluable instrument for the design, testing and operative management of marine energy converters in the Mediterranean.**

Keywords—**Mediterranean-Black Sea system, resource assessment, resource forecast, tides.**

I. Introduction

IN the last decades, there has been growing interest in the development of techniques for extracting energy from the sea; see, e.g., the site https://www.ocean-energy-systems.org, where annual report on the progress of ocean energy technologies are regularly made available. In Europe, these activities have become an important element in the context of blue growth initiatives (see https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en). After a phase of research and testing of a variety of prototypes, there are now full-scale devices that have been installed, and the most promising technological solutions are in a pre-commercial stage [1], [2]. A recent review on the perspectives for marine energy exploitation in the Mediterranean Sea is given in [3].

Detailed knowledge of the average sea state and surface circulation is required for the individuation of the most promising energy harvesting sites and for the choice of the best technological solutions. On the other hand, in the development phase, and in the management of production devices, operational forecasting of the sea state and of the currents, including those due to the tides, becomes fundamental.

Tidal amplitudes in the Mediterranean Sea are generally small, but they are locally amplified by bathymetric features in several regions (Figure 1), such as the Strait of Gibraltar (hereinafter SoG), which is the entrance door for the Atlantic water (AW) and for the tides propagating from the Atlantic, and the Sicily Channel, which separates the western Mediterranean from the eastern sub-basin (Levantine).

Tidal effects are also relevant in the northern part of the Adriatic Sea, and in the Strait of Messina, where rich dynamics have been observed, including propagating solitary waves (see, e.g., the recent work by Droghei *et al*. [4] and references therein) and very intense tidal currents. A recent assessment [5] indicates that these currents are strong enough to be harvested by actual tidal turbines.

When modelling ocean circulation in these areas, the effect of tides cannot be neglected, particularly in high-resolution models of coastal dynamics, which therefore need to be nested with coarser resolution models that fully account for tidal effects.

To resolve the short-time, local effects that are relevant to the applications, we have developed and implemented a high-resolution, operational model of the Mediterranean Sea-Black Sea system. In the first part of this paper, we describe the new model, perform some

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comparisons between the model results and the observations in a dedicated test case, and point out some interesting effects of the tides on the dynamics.

The new operational model complements a system for the forecasting of waves over the Mediterranean Sea that has been running operationally since 2013, whose main features are described in the second part of the paper. The wave forecast system has been developed to assist the operational phase of some wave energy converters recently installed along the Italian coasts [6]

II. THE CIRCULATION FORECASTING MODEL

The new ocean circulation forecasting model is based on the Massachusetts Institute of Technology ocean circulation model (MITgcm [7], and [8]), which solves the Navier-Stokes equations for an incompressible fluid under the Boussinesq approximation; in the present operational implementation, the hydrostatic version of MITgcm has been used. The model makes use of a finite-volume spatial discretization, implicit non-linear free surface formulation [9], rescaled vertical height (z*) coordinate [10], and partial step topography (see, e.g., [11] for details).

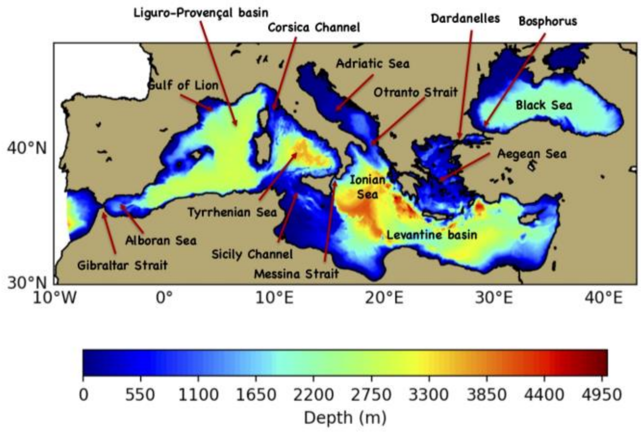

Fig. 1. The computational domain, which covers the Mediterranean Sea-Black Sea system, and the corresponding bathymetry. The location of the main sub-basins and of passages between them is also indicated.

The computational domain (see Figure 1) covers the whole Mediterranean Sea-Black Sea system, so that the only open boundary is to the west of the SoG, in the Atlantic Ocean. The horizontal grid (2500 x 750 points) has a uniform resolution of 1/48° (about 2km) over most of the domain, except in three regions where higher resolutions are needed to correctly resolve the local dynamics. These are the SoG, where the grid has been highly stretched, to reach a maximum resolution of 1/800° (about 120 m), and the Straits of Dardanelles and of Bosphorus, where 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 domain is discretized using 100 z-levels, with a grid spacing increasing from 2 m near the surface to 62 m at the depth of 1500 m; beyond 1500 m, a uniform grid spacing of 62 m is used till reaching the bottom.

The model bathymetry has been constructed using the 2016 European Marine Observation and Data Network (EMODnet) dataset for the Mediterranean basin and the Black Sea, a high-resolution digitalized chart [12] for the SoG, and a high-resolution bathymetry for the Bosphorus and Dardanelles Straits [13], and [14]. The vertical eddy viscosity and diffusivity coefficients here used are obtained from a turbulence closure model developed for the atmosphere [15] and adapted to the oceanic case in [16], whereas the spatial-dependent horizontal viscosity is obtained from the turbulence closure scheme by Leith [17], which focuses on resolving the enstrophy cascade towards the smaller scales characteristic of 2D turbulence [18]. The constant horizontal diffusivity coefficient is chosen as $Kh = 2\cdot10^{-2}$ m^2 s^{-1}. Bottom drag is expressed as a quadratic function of the mean flow in the bottom layer (the dimensionless quadratic drag coefficient is set to $2.5\cdot10^{-3}$); no-slip conditions for momentum are imposed at the bottom and at the lateral solid boundaries. The tracer advection scheme is a third-order direct space-time flux limited scheme.

The model is forced at the surface by hourly wind stress, heat, and fresh water fluxes derived from the high-resolution (5 km), non-hydrostatic SKIRON/Eta regional atmospheric modelling system of the National and Kapodistrian University of Athens, and is driven at the western lateral open boundary by the tracer, surface elevation, and velocity fields (hourly data) provided by the NEMO operational model [19].

At the open boundary, an Orlanski radiation condition [20] is used for the depth-dependent velocity, while a forced Orlanski radiation condition [21] and a zero gradient condition are used for the surface elevation and for the depth-integrated velocity, respectively [22]. Boundary conditions for both temperature and salinity are specified by using an upwind advection scheme that allows advection of temperature and salinity into the model domain under inflow conditions.

Tidal forcing includes both the tide generating potential as a body force in the momentum equations (internal tide) and the tide propagating from the Atlantic Ocean through the open Atlantic boundary (see [23] and [7] for details). The four main lunar, solar and luni-solar tidal components (M2, O1, S2, K1) have been prescribed inside the computational domain.

Climatological daily river discharge for 27 major Mediterranean rivers was computed via the water balance model WBM_{plus} [24], [25], [26], and prescribed as a boundary condition. WBM_{plus} is a spatially distributed, grid-based model that relies on a simple yet robust soil moisture budget and simulates the vertical water exchange between the land surface and the atmosphere, as well as the horizontal water transport along a prescribed river network, at daily time resolution. WBM_{plus} was used at 0.1°x0.1° resolution, in a parsimonious configuration that only requires near surface air temperature and precipitation as atmospheric input, which were derived from the WFDEI dataset [27], and uses an equally basic soil parameterization.

III. MODEL VALIDATION

The new model, named MITO (MIT Operational), has been implemented operationally on the ENEA CRESCO supercomputers. Since spring 2018, five days forecasts (hourly fields) are produced daily, using initial conditions, boundary conditions, and surface atmospheric forcing derived from operational forecasting models (NEMO and SKIRON).

A longer, dedicated simulation, spanning the period 19 March-30 April 2018, has also been made. This simulation, which does not include any kind of data assimilation or relaxation, has been performed to assess the capability of the model to correctly describe the variability of the circulation and hydrology in the period in consideration.

Local time series of the model surface elevation, covering the period of the run, have been compared with corresponding surface height time series extracted from the tide gauges available through the Copernicus portal, whose positions (54 stations) are shown in panel a of Figure 2.

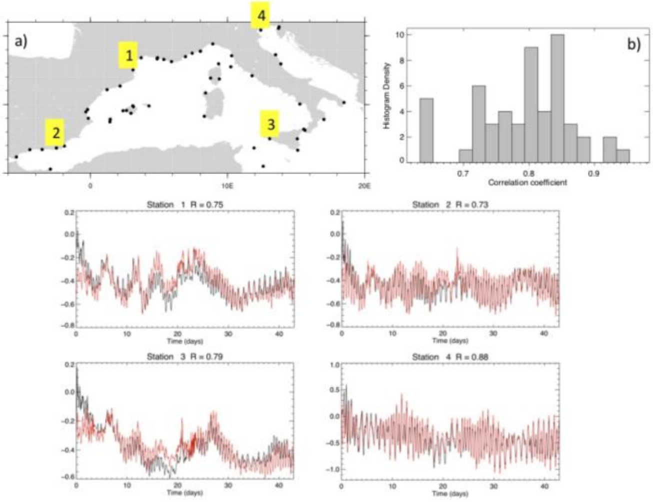

Fig. 2. Validation of the tidal dynamics through comparison with tide gauge data, taken at the stations indicated in the left upper panel. The lower panels show time series (hourly data) of the model (black) and tide gauge (red) elevation at stations 1-4, with the corresponding correlation coefficients (R) indicated in the titles. The right upper panel is a histogram of R over the whole dataset.

Panel b of the figure provides a histogram plot of the correlation coefficient (R) between the two time series, computed at each site. Values of the coefficient are high in almost all stations (R > 0.8 for 31 of the 54 tide gauges). In the lower panels, we plot the experimental (red) and model (black) time series in four stations, representative of different regions of the computational domain. The experimental and numerical time series agree quite well; maximum discrepancies are usually concentrated in the first days of the simulation, in which adjustment to the initial conditions takes place.

Comparisons of the model results with altimeter data and observed vertical profiles of temperature and salinity have also been performed, with very good results. The main structures of the circulation are maintained after one month of simulation, during which the model also develops small mesoscale features that cannot be resolved in the altimeter maps. More details about the model performances can be found in [28].

Figure 3 shows the time evolution of the average sea surface temperature (SST) for the whole Mediterranean Sea (Med), the western Mediterranean (Wmed), the eastern Mediterranean (Emed), and the Black Sea (Black). The black curves correspond to the values from the simulation, whereas the red curves are obtained from satellite data. The model and data SST values are quite close all along the simulation, with differences smaller than 0.5 °C everywhere, except in the Black Sea, in the last ten days of the simulation. This is a good result, also considering that the simulation period is characterized by a relevant warming of the Mediterranean basin.

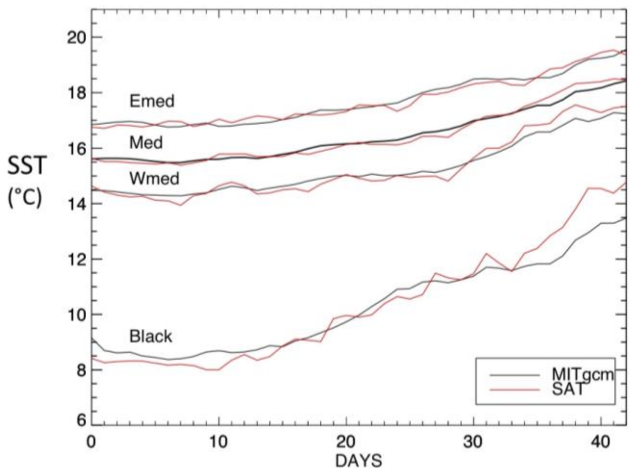

Fig. 3. Evolution of the average SST for four basins: the whole Mediterranean Sea (Med), the western Mediterranean (Wmed), the eastern Mediterranean (Emed), and the Black Sea (Black). The black curves correspond to the values from the simulation, whereas the red curves are obtained from satellite data.

Good agreement with data is also found when looking at the spatial distribution of the SST. After one month of simulation, the bias between the model and the satellite SST fields is smaller than 1 °C in most of the Mediterranean Sea, and is comparable to the bias in the initial condition (not shown).

To evaluate the global quality of the representation of the tidal dynamics we have performed a one-year integration with a barotropic version of the model. The maps of the tide constituents, obtained from the harmonic analysis of the surface elevation of this run using the software package T_TIDE developed by Pawlowicz et al. [29], were found to be in good agreement with reference maps obtained using the Oregon State University (OSU) Tidal inversion software (OTIS) [30]. Moreover, we have compared the model values of the amplitudes and phases for the main tidal components with reference observed values [31] from 63 tide gauges distributed over the Mediterranean Sea. For each harmonic constituent, the vector difference has been computed, as a distance in the complex plane (see, e.g., [32]). The comparison is generally good; the root mean square deviations of the vector differences are 1.6, 1.5, 0.7 and 0.5 cm for the M2, S2, K1 and O1 component, respectively, which are comparable to the values obtained for a similar comparison in [33].

We have also explored the effects of tides on the circulation, in specific regions of our model domain. Among these, the Sicily Channel, which plays a crucial role in the Mediterranean Sea dynamics, and is one of the places where tides are known to have a strong effect on the dynamics [34]. Figure 4 focuses on the portion of the Channel that hosts a wide, shallow area named Adventure Bank (red box in the upper panel, where the bathymetry of the area is displayed).

In the lower panel of the figure is shown the power spectrum computed from the the time series of mean kinetic energy (MKE), averaged over the red box, and over the first 100 m of the water column (the red line indicates the standard significance level, corresponding to a 95% confidence level). We have highlighted the peaks corresponding to the four tidal components that are included in the model; the main diurnal component (K1) is found to be the dominant one, in agreement with the observations [34]. It should be noted, however, that two other significant spectral peaks are also present, corresponding to shorter periods (8 and 6 hours). Since no other physical forcing acts on these time scales, they must represent harmonics of the diurnal and semidiurnal components. The nonlinear interactions that produce these components have been studied in the English Channel and in the North Sea (see the review [35]), but these effects have not been observed before inside the Mediterranean Sea. This is an important result, because it shows that in the Sicily Channel 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.

IV. TIDAL DYNAMICS IN THE STRAITS OF GIBRALTAR AND MESSINA

Other places in which the tides are known to be important are the SoG and the Messina Strait. Maps of the amplitude and phase of the main semi-diurnal (M2) tidal constituent in the SoG and in the Messina Strait area are shown in Figures 5 and 6, respectively.

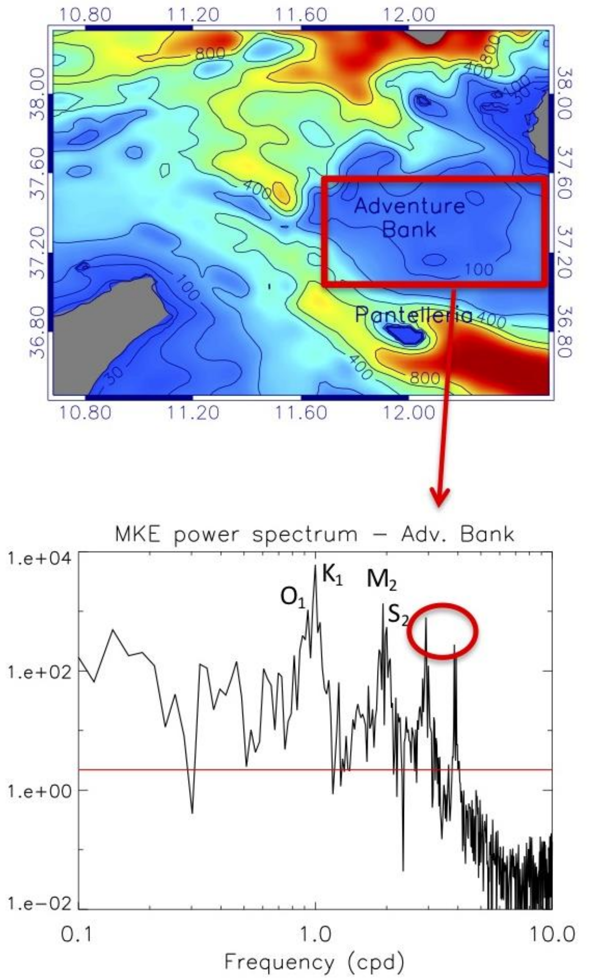

Fig. 4. Upper panel: bathymetry of the Sicily Channel. Lower panel: power spectrum of the time series of MKE (averaged over the red box over the Adventure Bank, and over the first 100 m), with the red line indicating a 95% confidence level. Besides the peaks corresponding to the four main tidal components, there are two significant peaks (red oval), at 8 and 6 hours, produced by nonlinear interactions.

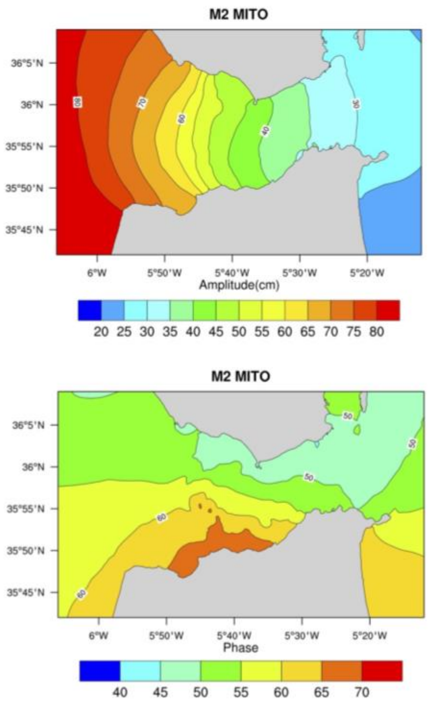

Fig. 5. Spatial distributions of amplitude and phase of the main semi-diurnal (M2) tidal constituent in the SoG area. The maps are obtained from the harmonic analysis of the sea surface height simulated in a dedicated one-year run of the MITO model.

The maps are obtained from the harmonic analysis of the sea surface height simulated in a dedicated one-year, barotropic run of MITO. The SoG maps are close to those obtained using the OTIS software (not shown), and the amplitude map is also close to that recently computed in [33].

The same tidal maps, for the Messina Strait, are shown in Figure 6. Despite the limited resolution of MITO in this narrow passage, and the consequent non-optimal representation of the bathymetry, the main features expected, e.g., the sharp south-north increase of the amplitude and of the phase (by about 180°) across the Strait (see, e.g., the recent review [36]) are correctly reproduced.

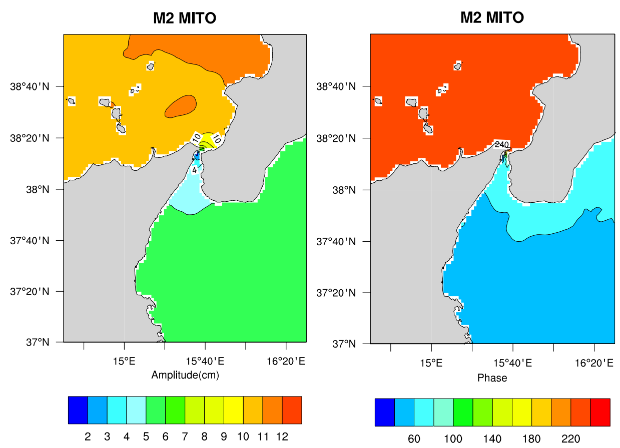

Fig. 6. Spatial distributions of amplitude and phase of the main semi-diurnal (M2) tidal constituent in the area of the Messina Strait.

Figure 7 shows that, with a 2 km horizontal resolution, the model is capable of capturing rich dynamics in the region surrounding the Messina Strait. In the surface circulation map in the upper panel (average over April 7, 10 m of depth), which is not at full resolution, a strong southward current is present in the Strait, with maximum strengths just below 1m/s. The current is strongly modulated by the tide; this is shown in the bottom panel of the figure, which displays the time series of the velocity in a small area close to the sill, which is marked by the yellow star in the map. This is an area in which high current velocities have been observed, just to the south of the eastern tip of Sicily (see, e.g. [37]). The peak velocity values in the figure, which often exceed 2 m/s, are not far from those observed. It should be noted, however, that a higher resolution model of the strait region, as the one developed in [4], would still be needed to resolve the local dynamics with the very high spatial detail required for supporting the implementation and management of devices for energy extraction. Such a model could be nested in MITO, which would provide sufficiently well-resolved initial and boundary conditions that take into account the effects of the tides in a consistent way.

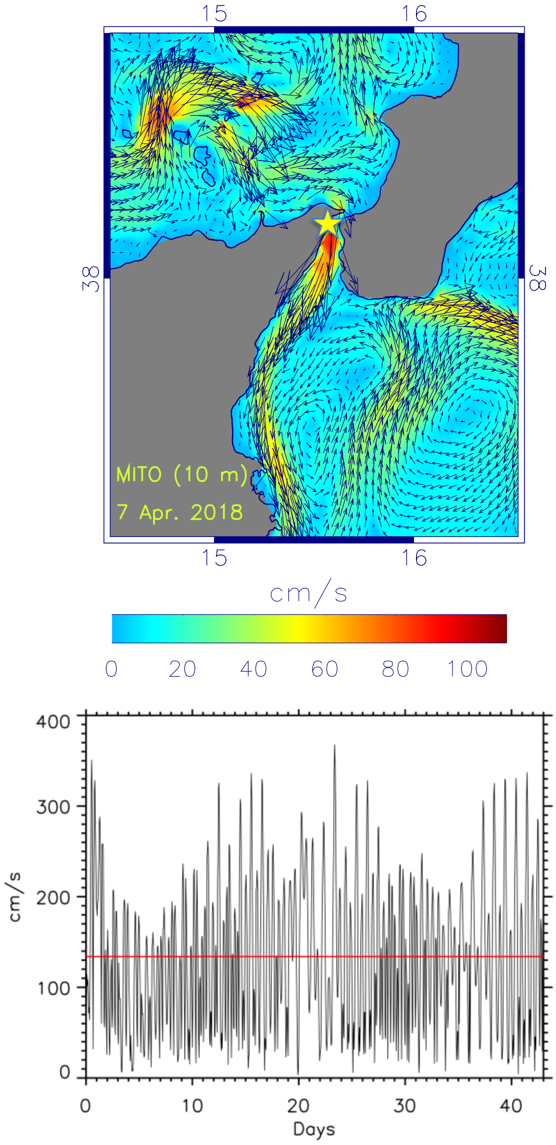

Fig. 7. Top: daily map of the MITO surface circulation (April 7, 10 m of depth); only one point out of two is shown. Down: time series of the velocity in a small area to the south of the eastern tip of Sicily (yellow star in the map), covering the whole simulation period. The red line indicates the average over the period.

IV. WAVE FORECASTING SYSTEM

The Mediterranean Sea is characterized by values of wave energy that are lower than those found in the major oceans. Nevertheless, the exploitation of wave energy can represent an economically profitable resource if ad-hoc designed wave energy converters are developed, adapted to the peculiar characteristics in frequency and amplitude of waves. Moreover, due to less severe weather conditions, the installation and maintenance costs of the devices are reduced.

We have developed a wave forecasting system over the Mediterranean Sea, capable of providing the information necessary for experimental activities. This information may also be crucial for the operational phases of energy converters, because in some of them parameters depending on the wave conditions can be tuned to augment the productivity [38]. A forecast covering the whole Mediterranean basin is performed daily; moreover, ten sub-basins have been identified around the Italian peninsula in which higher resolution simulations are performed (see Figure 8, showing the model bathymetry around the Italian coast, in which the boxes indicate the areas of the zooms).

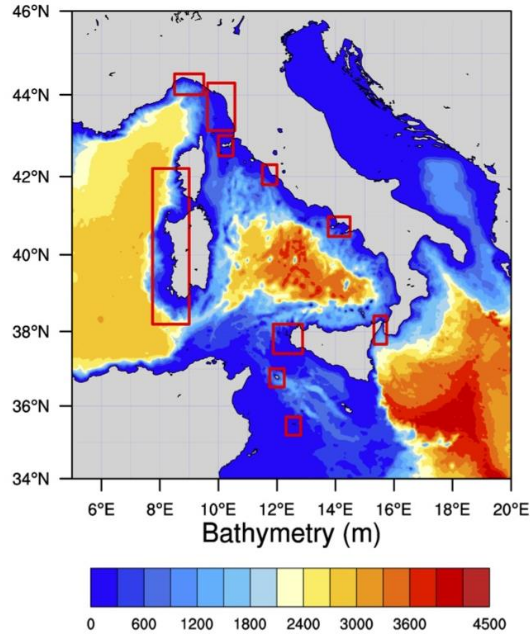

Fig. 8. Model bathymetry for the area around the Italian coast, with rectangles indicating the ten areas in which higher resolution zooms are performed.

The ten sub-domains have been selected to include the most energetic areas, such as the western coast of Sardinia and the westernmost part of Sicily, identified in [39] through the analysis of a dedicated, ten years climatic simulation. Areas around some minor Italian islands have also been selected, since wave energy production in these sites could contribute significantly to their energy independence. The forecast system has been running operatively since June 2013.

Wave simulations are performed using a parallel version of the WAM wave model Cycle 4.5.3. [40], [41]. WAM is a third-generation spectral model that solves the wave transport equation explicitly without any assumptions about the shape of the wave spectrum. In the forecast system, the model domain covers the entire Mediterranean Sea, from 5.50°W to 36.125°E of longitude and from 30.2°N to 45.825°N of latitude. The domain is discretized in spherical coordinates, with a uniform resolution of 1/32° in each direction, corresponding to a linear mesh size of about 3.5 km. Model bathymetry has been calculated from the General Bathymetric Chart of the Oceans (GEBCO) 30 arc-second gridded data set [42] by averaging the depths of data points falling in each computational cell.

The directional wave energy density spectrum is discretized using 36 directional bins, corresponding to an angular resolution of 10°, and 32 frequency bins starting from 0.06 Hz, with relative size increments of 0.1 between one frequency bin and the following one.

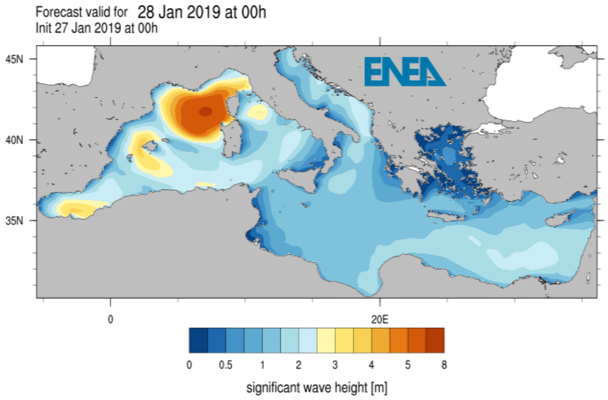

Fig. 9. Example of significant wave height forecast for the Mediterranean basin.

After the global integration is performed, the higher resolution simulations (1/128°) are carried out using the Simulating WAves Nearshore model (SWAN [43]), which takes spectral boundary conditions from the WAM simulation hourly. SWAN is a third-generation wave model integrating the action density spectrum, specifically built to be used in shallow water. It includes depth-induced wave breaking and triad wave-wave interactions that are important for near-shore wave forecast. The equation is solved using an implicit propagation scheme based on finite differences. The same discretization in frequency and direction defined for the WAM model has been used.

The forecast system composed by the WAM and SWAN models is forced with hourly wind fields obtained from the same meteorological operational system used for MITO, that is the high-resolution (5 km), non-hydrostatic SKIRON/Eta regional atmospheric modelling system of the National and Kapodistrian University of Athens. The daily wave forecast spans a period of five days. An example of forecast is given in Figure 9.

V. Conclusion

In this work, we have briefly described two high-resolution operational systems for the Mediterranean Sea, for the forecasting of the sea state and of the ocean circulation, developed and currently used at ENEA. The main focus has been on MITO, the system for the forecasting of the circulation, which is, at present, the only operational model of the Mediterranean Sea dynamics that includes the main tidal forcing. The model has other distinguishing features, such as the non-uniform horizontal resolution, which is smoothly increased in some crucial areas (e.g., the SoG), and the inclusion of the Black Sea, which allows to explicitly resolve the dynamics in the Turkish Straits, which should otherwise be prescribed as a boundary condition.

We have presented some examples of validation of the MITO circulation and tidal dynamics, and pointed out some novel (for the Mediterranean Sea) effects of the tides on the circulation. In particular, the presence of nonlinear interactions between tidal components in the Sicily Channel, which produce local dynamics that could not be obtained by just adding the tidal forcing to the results of a not tide-including model. This indicates that a tide-including model like MITO could be profitably used for the nesting of higher resolution local models, in areas of interest for energy harvesting. These can be coastal areas in which the wave energy is sufficiently high, or places like the Messina Strait, where tidal currents are robust, and strong enough for the installation of turbines. The newly developed MITO operational model, together with the operational wave system, including higher resolution zooms in many interesting regions, provide an integrated environment that may prove very useful for the testing and management of marine energy converters in the Mediterranean Sea.

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