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AIMS

Artificial Intelligence to Monitor our Seas

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Deliverable D1.1

Report and datatset from wave models

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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract The Report and dataset from wave models serve as a foundational document for the AIMS (Artificial Intelligence for Marine Surveillance) project. This report describes in details the numerical models used and the setting of the computations. The dataset is shared among the AIMS project partner, and it will represent, together with satellite data and in situ measurements, the meteocean data necessary to develop and validate a new framework for metocean surveying, based on novel Artificial Intelligence (AI) algorithms.

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ABBREVIATIONS

Acronym	Description
AI	Artificial Intelligence
SWAN	Simulating WAves Nearshore
WW III	Wave Watch III

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1. INTRODUCTION

1.1 Deliverable 1.1 inside AIMS project

The Deliverable D1.1 Report and dataset from wave models aims at describing and providing results of numerical wave models. This deliverable concerns the research activities carried out within the WP1 that has the milestone (M1) of building the unique dataset of AIMS. More in particular deliverable D1.1 is related to the task 1.1 "Numerical dataset" of the WP1.
To collocated the present deliverable (D1.1) in the AIMS project framework a short resume of the main objectives is presented in this section.

The major objective of AIMS is to develop and validate a new framework for metocean surveying, based on novel Artificial Intelligence (AI) algorithms for gap-filling of remote monitoring via satellites. The main objective is shown at the bottom-right corner of the methodology Figure 1. Such a framework, achieved for metocean variables by the end of the project, has the potential to be applied to other fields beyond the project: flexibility and interoperability considerations are included to facilitate extrapolation to other domains.

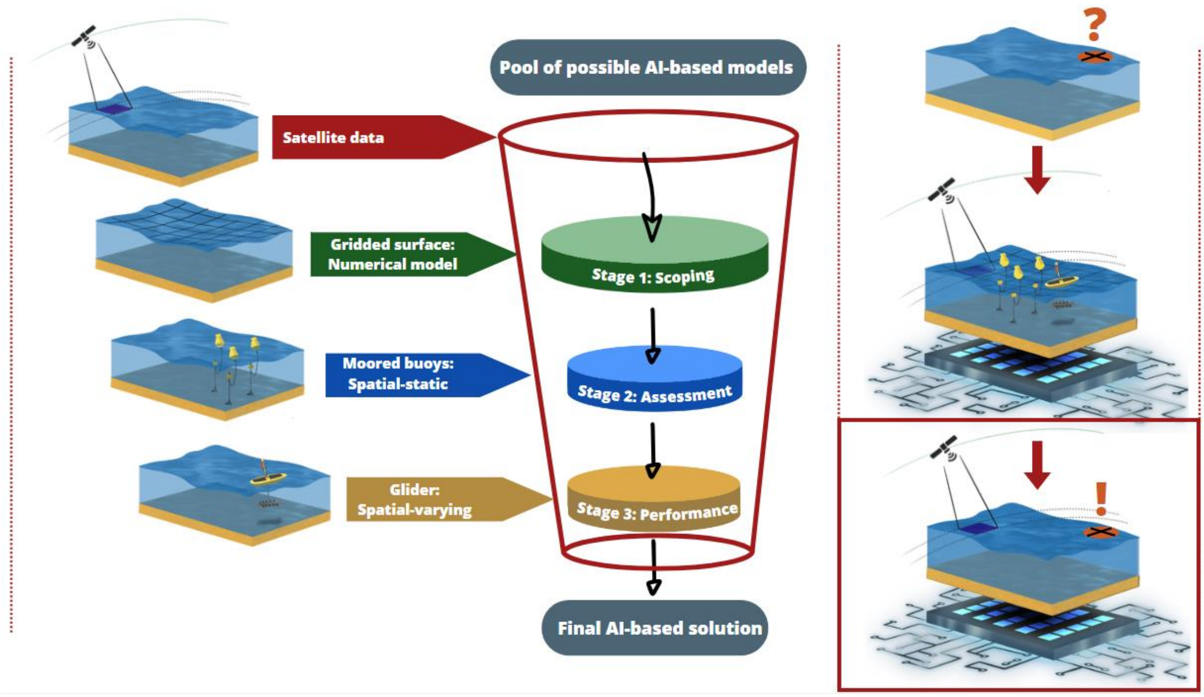

Figure 1. Schematic representation of AIMS methodology

To ensure a smooth and successful progress, and to provide transparent monitoring tools, the main objective is broken into the following SMART results, i.e. Specific, Measurable, Achievable, Realistic, and Time-bound:

- Building the underlying dataset for AI training and validation; it will be a unique composition of heterogeneous sources:

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  - 2 refined numerical downscaling datasets of wave data: SMART, because already consolidated with ROMA3 and CNR, respectively in SWAN (Simulating WAves Nearshore) and WW3 (WAVEWATCH III), and the latter can be re-run to meet AI requirements.
  - Satellite data: SMART because data is available on Copernicus Open Access Hub, selecting altimeters from Sentinel-3A and -3B; other constellations will be considered to further populate this dataset (e.g., SARAL, Jason, Sentinel 6).
  - In-situ measurement, using multiple moored wave buoys installed in proximity in a gridded layout, to provide distributed spatial-static data. This is a unique type of dataset, since buoys are usually deployed singularly or in pairs. The objective is to obtain months of data.
  - In-situ measurement, using a glider, to provide spatial-varying data.
- Performance of the AI algorithms, with a stage-gate approach. The final SMART objectives are:
  - Speedup surveying: > +40%. Estimated by comparing conventional full offshore surveys with the reduced time required for AI training.
  - Cost reduction: > -60%. Based on the reduction of surveying time and on common cost metrics for offshore operations.
  - Gap-filling accuracy: > 90% within a 10km distance from the satellite's direct measurements. Measured by comparing AI outputs with experimental validation subset. Note that AI algorithms provide information in any arbitrary point in space, while the accuracy is expected to decay with the distance from the direct measuring point (satellite orbit swath).
  - Time resolution: < 3h. Related to the typical period of stationarity of sea states, and represents at least a 4-fold increase in resolution with respect to typical revisit times from satellite orbits.
  - Wave period inferring: > 85% accuracy, by comparison with experimental datasets.

On the one hand, AIMS objectives are ambitious, since they lead to a substantial progress with respect to the state-of-the-art, impactful for science and technology; on the other hand, they are also achievable, since

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they are based on previous experience of the partners in offshore experimental campaigns, numerical models and AI solutions.

The originality of AIMS objectives is to inherently combine different sources of data to get the best value out of satellites, both in time and space: while usually gaps are thought only in time, AIMS rethinks gaps in both space and time, adding a new dimension and a realm of new possibilities, both within the ocean monitoring field and beyond. Moreover, AIMS leads to a more informative spatially-distributed information, rather than point-wise. AIMS new perspective opens a new way to cut costs down and accelerate monitoring campaigns, since it reduces the number of required expensive in-situ instruments and the execution time of the survey.

1.2 Numerical wave models

In general, numerical wave models simulate the generation and propagation of wind waves, obtaining realistic estimates of wave parameters in oceanic areas, coastal areas, lakes and estuaries.

Two numerical wave models have been *ad hoc* performed to build a site-specific database, which was the main goal of the first task of WP1. In the next section the two numerical wave models are described in details.

These models solve the spectral energy balance equation without any a priori restrictions on the spectrum for the evolution of wind wave growth. They therefore appear a useful tool in order to get all the wave parameters in a defined geographical area, given the forcing wind conditions.

2. DESCRITPION OF THE WAVE NUMERICAL SIMULATIONS

2.1 Selected area of interest

The numerical dataset, together with in situ measurements and satellite observation data, are essential to train and validate the AI algorithm. The AIMS partners decided to select as specific area for the AI training the North Tyrrhenian sea. In Figure 2 is reported a large-scale overview of the central Mediterranean Sea, with highlighted the selected area of interest.

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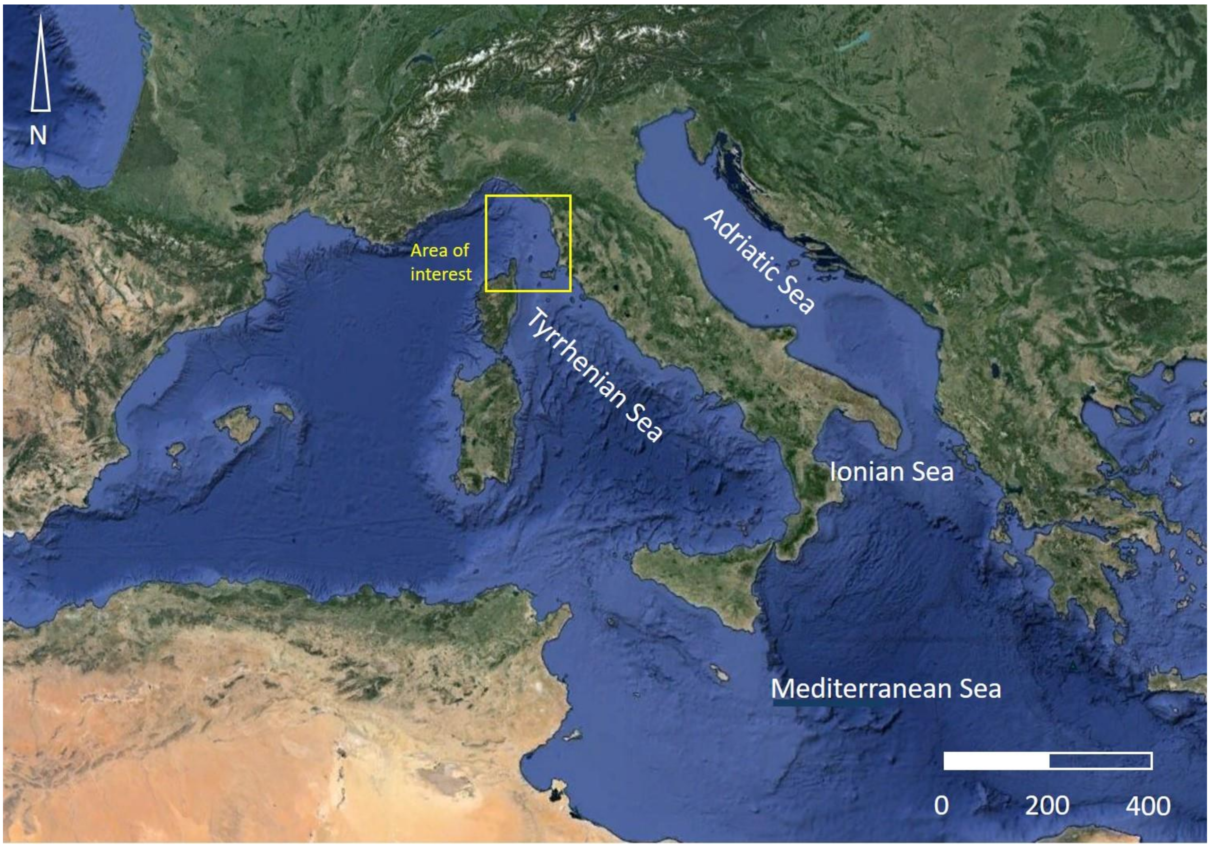

Figure 2: Large-scale framing of the area of interest

The reasons behind the selection of the North Tyrrhenian Sea, are multiple: (i) there already exist in situ measurements (i.e. Gorgona wave buoy); (ii) it is an area where the CNR (within LAMMA measuring device) will easly set the experimental campaign; (iii) it is an area where coastal effects can be relevant, due to the proximity with the coasts and the presence of small islands; (iv) several satellite observation data are available, since there it occur crossing of several satellite trajectories (as can be noted in Figure 3).

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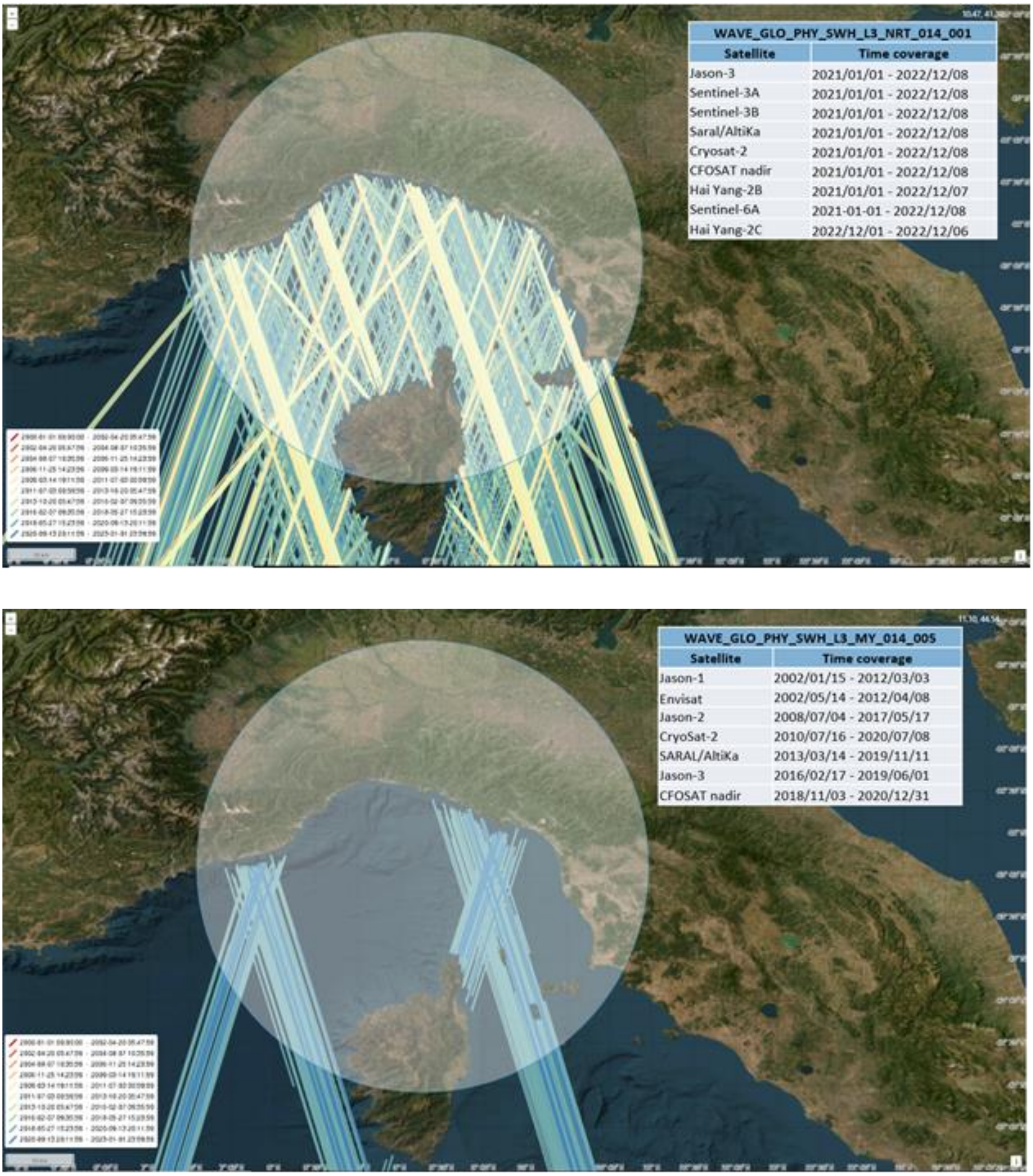

Figure 3: Tracks of satellite orbits in the North Tyrrhenian Sea.

The selected computational domain inside the area of interest of Figure 2, is 1.5° N x 1.5°E, with a nested computational domain of 0.5°x0.5°, as explained in section 3.2.

2.2 Wave models

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In the recent decades, a number of advanced spectral wind-wave models, known as third-generation models, has been developed such as WAM (WAMDI Group, 1988), WAVEWATCH III (Tolman, 1991), TOMAWAC (Benoit et al., 1996) and SWAN (Booij et al., 1999). For the present application SWAN and WAVEWATCH III models have been considered.

2.2.1 SWAN

The description of the wave field in SWAN model is based on the energy density spectrum, which distributes the wave energy over frequencies f and directions θ, and is denoted by $E(f,\theta)$.

Usually, wave models determine the evolution of the action density $N(\vec{x},t;\omega,\theta)$ in space $\vec{x}$ and time t. The action density is defined as $N = E/\omega$ and is conserved during propagation along its wave characteristic in the presence of ambient current, whereas energy density E is not (Whitman, 1974). Wave action is said to be adiabatic invariant. The rate of change of the action density N at a single point in space $(\vec{x};\omega,\theta)$ is governed by the action balance equation, which reads (e.g., Mei, 1983; Komen et al., 1994)

$$\frac{\partial N}{\partial t} + \nabla_{\vec{x}} \cdot \left[\left(\overrightarrow{c_g} + \vec{u}\right)N\right] + \frac{\partial c_\omega N}{\partial \omega} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\omega} \quad (1)$$

The left-hand side is the kinematic part of this equation. The second term denotes the propagation of wave energy in two-dimensional geographical $\vec{x}$-space, including wave shoaling, with the group velocity $\overrightarrow{c_g} = \partial\omega/\partial\vec{k}$ following from the dispersion relation, $\omega^2 = g|\vec{k}|tgh(|\vec{k}|h)$. The third term represents the effect of shifting of the radian frequency due to variations in depth and mean currents. The fourth term represents depth-induced and current-induced refraction. The quantities c_ω and c_θ are the propagation velocities in spectral space (ω,θ). Notice that the second, third and fourth terms are divergence terms representing the amount of flux entering or leaving a point, and hence, they act as source (negative divergence, i.e. flux entering a point) or sink (positive divergence, i.e. flux leaving a point) terms. The right-hand side contains S_{tot}, which is the non-conservative source/sink term that represents all physical processes which generate, dissipate, or redistribute wave energy at a point. They are defined for energy density (i.e. not wave action).

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At deep water without ambient current, Equation (1) is reduced to

$$\frac{\partial E}{\partial t} + \nabla_{\vec{x}} \cdot \left(\vec{c_g} E\right) = S_{tot} \tag{2}$$

which can be considered as a ray equation for a wave packet propagating along its wave ray. In the absence of the generation and dissipation of waves, wave energy is conserved along its propagation path, which implies that the net flux of wave energy along this path is conserved (i.e. the divergence of this flux is zero). This is known as the law of constant energy flux along the wave ray. This law is essentially the bedrock on which the discretization of the action balance equation has been built.
In shallow water, six basic processes contribute to S_{tot}:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \tag{3}$$

These terms denote, respectively, wave growth by the wind (S_{in}), nonlinear transfer of wave energy through three-wave (S_{nl3}) and four-wave (S_{nl4}) interactions and wave decay due to whitecapping ($S_{ds,w}$), bottom friction ($S_{ds,b}$) and depth-induced wave breaking ($S_{ds,br}$).

SWAN model is suitable for both nearshore and oceanic applications; it therefore properly accounts for deep and shallow water wave processes (e.g. wind input, white capping, quadruplets, surf breaking and triads), and employs
flexible meshes (curvilinear and triangular grids) to accommodate both small and large-scale simulations.
The discretization of the action balance equation must be simple, robust, accurate and economical for applications in coastal waters. Therefore, a finite difference approach is employed based on the so-called method of lines. This means that the choice for time integration is independent of the choice for spatial discretization. In addition, time integration is fully implicit, which implies that the employed finite difference schemes are stable for an arbitrarily large
time step irrespective of grid size. These schemes need only to be accurate enough for a time step and a grid size solely determined by physical accuracy for the scale of the phenomena to be simulated.

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The finite difference schemes for propagation of wave action in both geographic and spectral spaces must comply the causality principle, which is an essential property of the hyperbolic equation. Preservation of causality ensures that wave energy propagates in the right direction and at the right speed. Moreover, the finite difference schemes must also obey the law of constant energy flux along the wave ray, which is necessary for correct wave shoaling, especially in case of rapidly varying bathymetry (e.g. seamounts, shelf breaks, main channels estuaries, and floodplain areas in rivers).

2.2.2 Wave Watch III

Wavewatch III (WW3) is a third-generation wave model developed by the National Oceanic and Atmospheric Administration (NOAA). It is designed to simulate and predict wave conditions across the globe, solving - like the SWAN model previously described - the spectral action density balance equation for wave distribution, and accounting for the effects of wind input, nonlinear wave-wave interactions, and wave dissipation due to breaking and bottom friction. WW3 is capable of operating on unstructured grids, allowing for high-resolution simulations in coastal areas and complex marine environments, making it suitable for both large-scale global wave predictions and high-resolution regional studies. The model includes advanced source term parameterizations for wind-wave interaction and dissipation and is widely used in operational wave forecasting by various meteorological and oceanographic agencies (Tolman, H. L. 2009). WW3 is extensively used for operational wave forecasting by national and international agencies.

The key differences between WW3 and SWAN include their application scope, with WW3 designed for global and regional wave simulations and capable of high-resolution coastal modeling, while SWAN is tailored for coastal and shallow water applications, including harbors and inland waters. WW3 includes advanced parameterizations for global-scale processes, such as wind-wave interactions and dissipation, while SWAN is more focused on coastal processes, including depth-induced breaking, bottom friction, and wave diffraction.

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3. NUMERICAL SWAN DATASET

3.1 Bathymetry data

In order to run numerical wave models, it is essential to digitize the bathymetric data, which need as input data for the wave propagation models.

The nautical chart of the area of interest has been considered, obtained from the public website Navionics, which reports the bathymetric lines at different levels of detail through its "Chart Viewer" function. Then AutoCad software was used to georeference the bathymetric information.

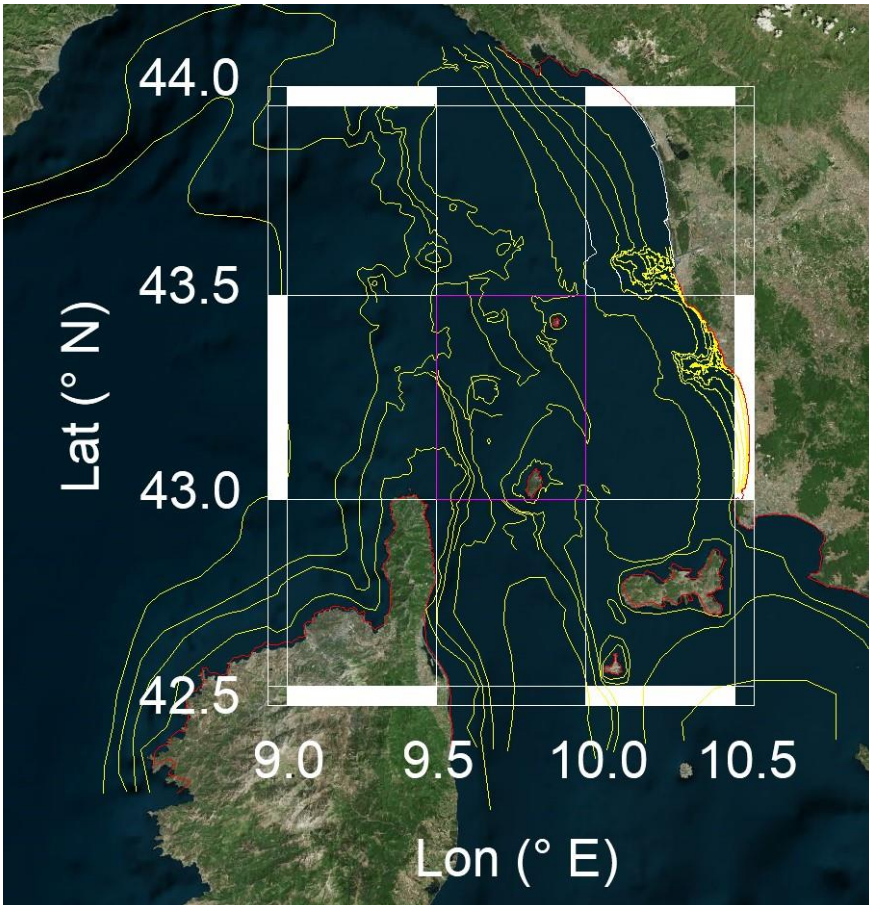

Figure 4: Area of interest, North Tyrrhenian Sea

In Figure 4, are reported the bathymetric lines in yellow, while the red lines represent the coastline. After georeferencing and the bathymetry harmonization operations it was possible to import the point cloud (consisting of the x, y, z coordinates of the bathymetric lines) into special Matlab computational software. The point cloud has then been interpolated

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on a regular grid, which corresponds with the computational grid, and it has been figured and defined in the next section.

3.2 Computational grid

A Cartesian coordinate system has been used. First the model runs over a bigger and coarser domain, then the model runs over a smaller domain, nested inside the bigger one.

The bigger domain is limited from 42.5° N to 44.0°N in latitude and from 9.0°E to 10.5°E in longitude, with a discretization of 5 km both in north and east directions. While the nested computational grid has been built, from 43.0° N to 43.5°N in latitude and from 9.5°E to 10.0°E in longitude, with a discretization of 1 km in both directions.

In Figure 5 and in Figure 6, the interpolated bathymetric data are reported for the coarser computational domain (Figure 5), and the nested finer computational domain (Figure 6). Red lines in Figure 5 indicate the computational discretization of the domain, while the white rectangle indicates the nested domain.

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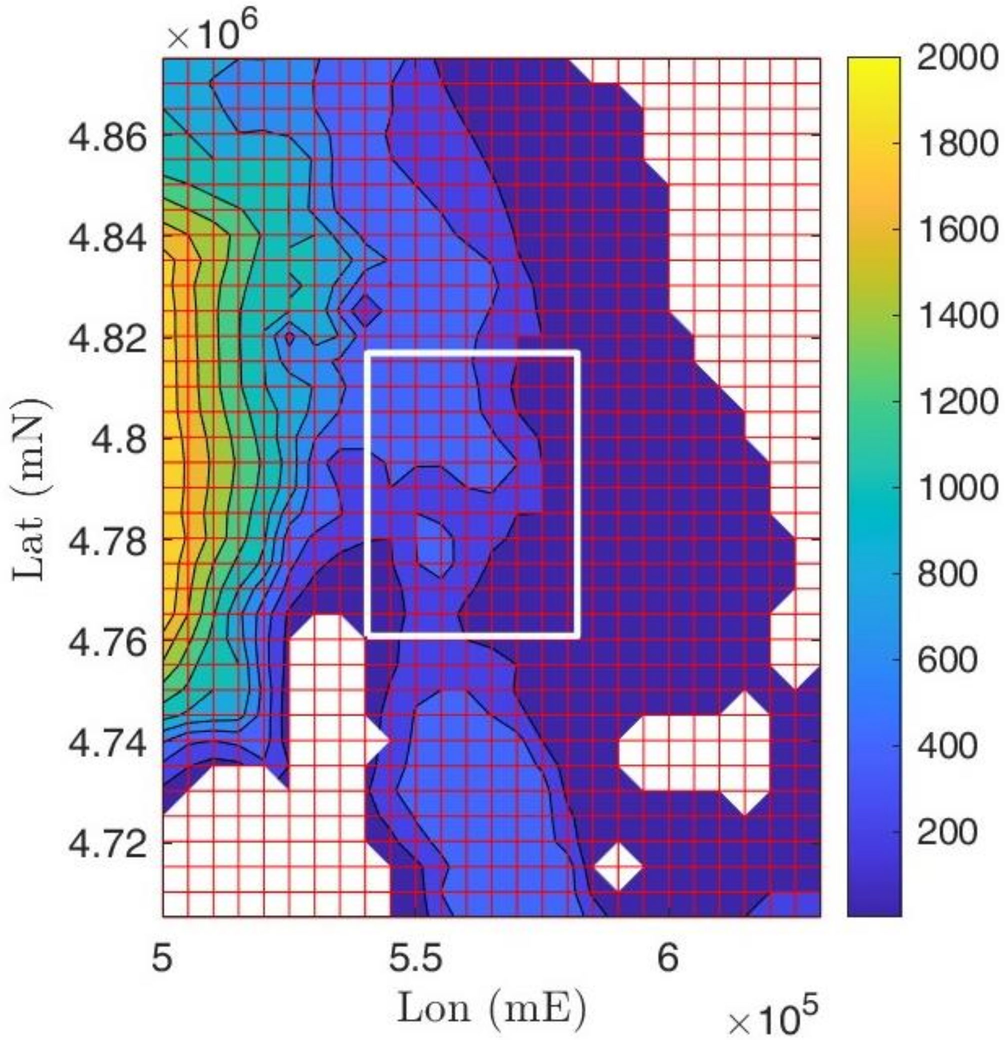

Figure 5: Bathymetry data in the coarser computational domain. Red lines define the computational grid with a discretiazition of 5 km both in East and North directions. The white rectangle defines the finer nested computational domain.

In Figure 6 the gray lines indicate the compuational space discretization of the nested finer domain, and the white spots are the Capraia island (south) and Gorgona island (north).

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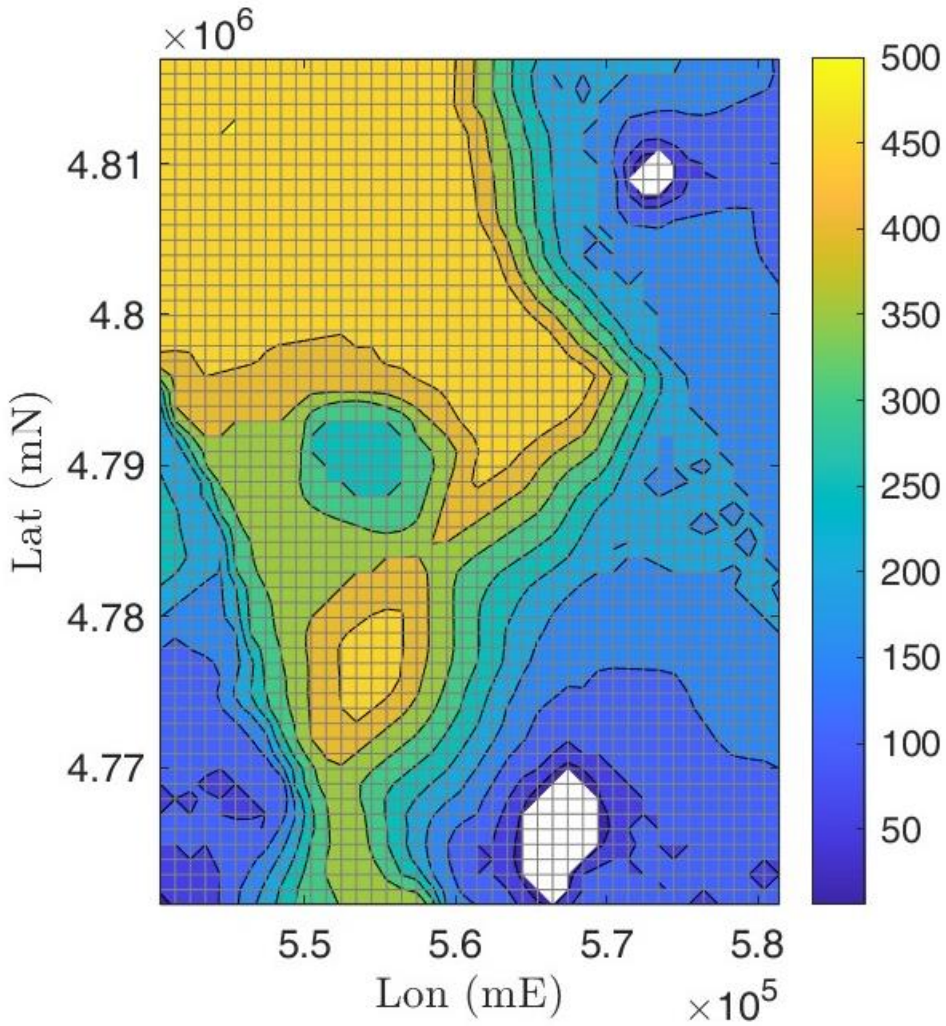

Figure 6: Bathymetry data in the finer computational domain. Gray lines define the computational grid with a discretiazition of 1 km both in East and North directions.

The coarser computational grid results of 27 points along longitude and 35 points along latitude, for a total of regularly spaced 945 nodes. The finer computational grid results of 42 points along longitude and 54 points along latitude, for a total of regularly spaced 2394 nodes.

3.3 Input wind and wave data

The SWAN model has been run imposing at the sea boundary conditions the wave spectrum built from the synthetical wave parameters given by ERA5,

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the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis for the global climate and weather.
The reason for the selection of the ERA5 is that it represents a state-of-the-art database, freely available for the Copernicus program users and with global coverage. Hindcasts are available since 1950. ERA5 is also updated in almost real-time (the delay is of the order of one week), and data can be downloaded easily from the web.

ERA5 wave data are provided with a spatial discretization of 0.5° both in longitude and in latitude directions. In Figure 7 are reported the positions of ERA5 wave data used as wave boundary conditions, with black circles. In particular, the synthetical wave parameters of significant wave height, H_s, peak wave period, T_p, mean wave direction, θ, and directional spectral width have been extracted from the ERA5 database, each hour from 01/01/2018 to 31/12/2022. These data have been read in Matlab and written in a file readable from SWAN model as wave boundary conditions. SWAN computes the wave energy spectrum from the synthetic wave parameters; for the present simulations the JOSNWAP spectrum with 3.3 as peak enhanced factor was used.

ERA5 database provides also wind data, each 0.25° in latitude and longitude directions. In particular, wind velocity at 10 m of elevation above mean sea level has been extracted. The wind data of all the simulating time have been given as input data to the SWAN model. Always in Figure 7 the red diamond markers indicate the positions where ERA5 wind data are provided to SWAN model.

The computation results of the coarser domain have been saved at the boundaries of the finer domain (with rectangle in Figure 7), as input for the nested simulations

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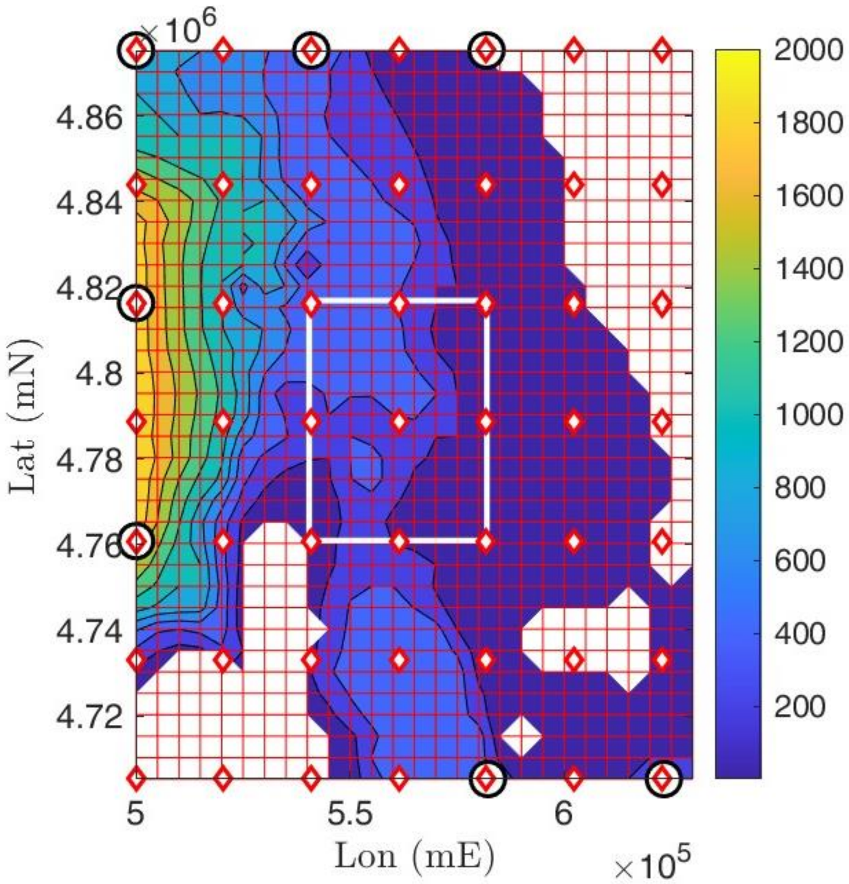

Figure 7: Coarser computational grid with bathymetric information and locations (black circle markers) of ERA5 wave data used in SWAN simulations at boundary conditions, and locations (red diamond markers) of ERA5 wind data used as input conditions.

3.4 Wave output data

Wave results have been extracted at each node of both computational domains. The synthetical wave parameter (H_s, T_p, θ) have been saved, and for the finer computational grid also the wave energy spectrum at each node have been saved. The temporal resolution of these results is of one hour.

Moreover, results have been saved at the location of Gorgona buoy, allowing the comparison of the model with field measurements.

In Figure 8, the time series of the significant wave heights, H_s, are shown, red markers are the measurements of the Gorgona buoy, while blue markers are the SWAN simulation results saved at the position of Gorgona buoy (573629.19 mE, 4811190.64 mN).

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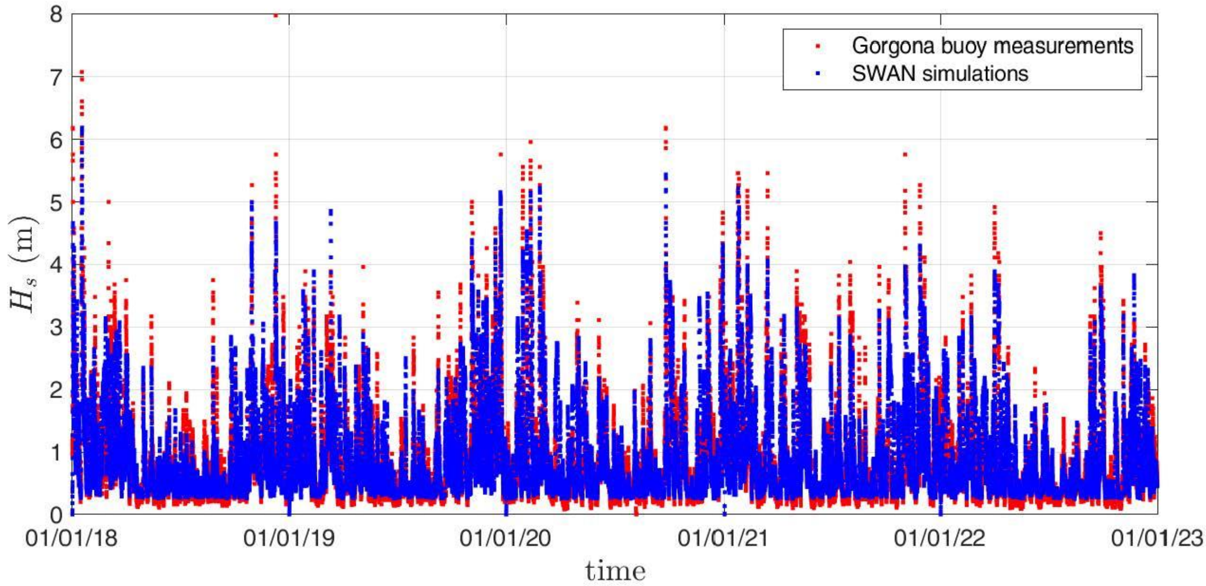

Figure 8: Time series of significant wave heigths from the Gorgona buoy measurements (red dots) and SWAN results saved at the location of Gorgona buoy (blue dots).

In Figure 9 the H_s values measured and computed by SWAN are compared in a scatter plot.

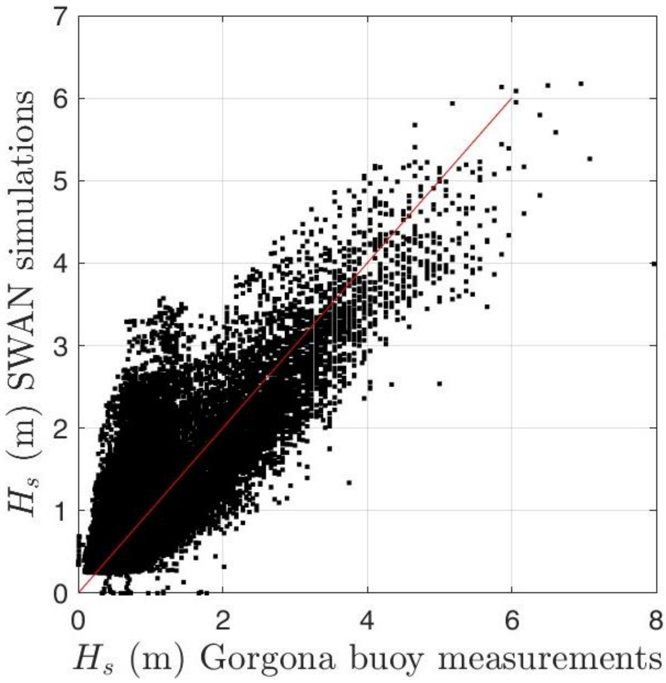

Figure 9: Scatter plot of the significant wave heigths measured by the buoy and simualted by SWAN. The red lines is the bisector and indicates the complete agreement.

In Figure 10 the comparison between measured wave data by the Gorgona buoy and the SWAN simulated data are presented in a polar plot, where it is

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possible to notice the occurrence frequency of wave data, both in terms of significant wave heights and wave mean direction.

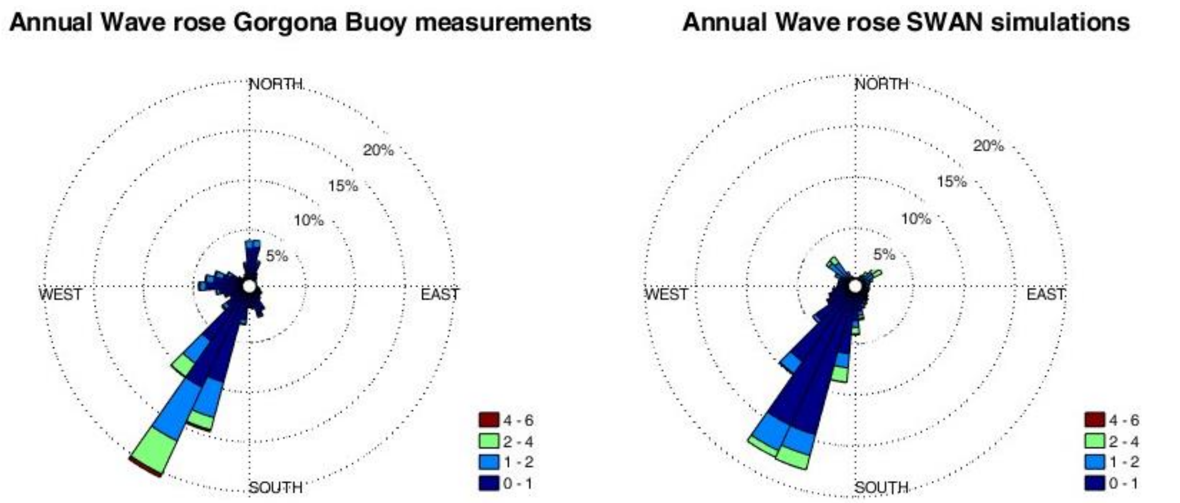

Figure 10: „Wave rose", polar frequency plot of significant wave heigths and directions of measured data (left) and SWAN simulated data (right).

4. NUMERICAL WW3 DATASET

4.1 Bathymetry data

The bathymetry data used for the WW3 wave model encompasses the entire Mediterranean Basin and an area extending 150 km west of the Strait of Gibraltar. The EMODnet bathymetry version 2018 served as the primary data source for the whole domain. For regions within Tuscany and Liguria, bathymetric data from local surveys and nautical charts were utilized to replace EMODnet data for depths less than 100 meters. This adjustment ensures greater accuracy in shallow coastal areas. To prevent numerical instabilities, a minimum offshore water depth of 4 meters was set, while a constant depth of 2 meters was maintained along the wet grid points on the coastline.

4.2 Computational grid

The computational domain of the wave model was discretized using an unstructured mesh with variable resolution, specifically designed to achieve high resolution along coastal areas. This setup ensures detailed modeling

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of wave dynamics in regions with dense coastal features and numerous islands, particularly in the North-Western Mediterranean Sea (NWMED):

- **High Resolution:** Up to 500 meters along the North-Western Mediterranean coasts, including Tuscany, the Tuscan Archipelago, Eastern Liguria, and the Straits of Bonifacio and Messina. The dense presence of coastlines and islands in the NWMED allows for a very high model resolution, capturing complex wave interactions and coastal processes effectively.
- **Medium Resolution:** About 1 km along the coasts of Sardinia and Corsica, and 3 km along other Tyrrhenian coasts and the Straits of Gibraltar.
- **Low Resolution:** Approximately 6 km along the remaining Mediterranean coasts, with a minimum offshore resolution reaching 30 km. This mesh configuration is optimized to balance computational efficiency while providing detailed insights into coastal wave dynamics, especially in areas with intricate coastal geography.

4.3 Input wind and wave data

The input data for the wave model were derived from a dynamical downscaling of the ERA5 reanalysis dataset (Vannucchi et al., 2021; Capecchi et al., 2023). This process was implemented through a nested domain configuration using the BOLAM and MOLOCH atmospheric models developed by the Italian National Research Council (CNR ISAC): BOLAM, a hydrostatic model with parameterized convection, provided hourly lateral boundary conditions to MOLOCH, a nonhydrostatic model with a grid spacing of 2.5 km. The atmospheric models produced high-resolution wind fields essential for accurate wave modeling. The wind fields were integrated into a 2.5 km grid over the entire Mediterranean domain, combining high-resolution MOLOCH data in the inner domain with interpolated BOLAM data in the outer domain, ensuring a smooth transition between different resolutions.

4.4 Wave output data

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The wave model's output data include several key parameters recorded hourly at all grid points. Like for the SWAN code implementation by the University of Roma 3, the synthetical wave parameter $(H_s, T_p, T_m, \theta_p, \theta_m)$ have been saved.

Additional output (spectra) was recorded hourly at 2048 strategic points, including locations matching buoy positions and distributed across the Mediterranean with varying resolutions (111 km generally, 55 km in the North-Western area, and finer resolutions along specific coasts). These detailed outputs were crucial for calibrating and validating the wave model, ensuring its reliability in simulating the Mediterranean wave climate. Wave spectra may also serve to provide boundary conditions to further models

Figure 11: Point output of the WW3 wave hindcast.

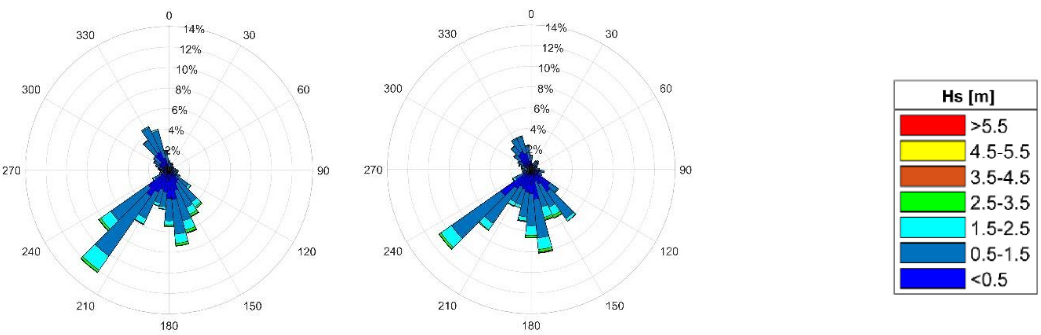

Figure 12: „Wave rose", polar frequency plot of significant wave heigths and directions of measured data (left) and WW3 simulated data (right), for the buoy of Glannutri.

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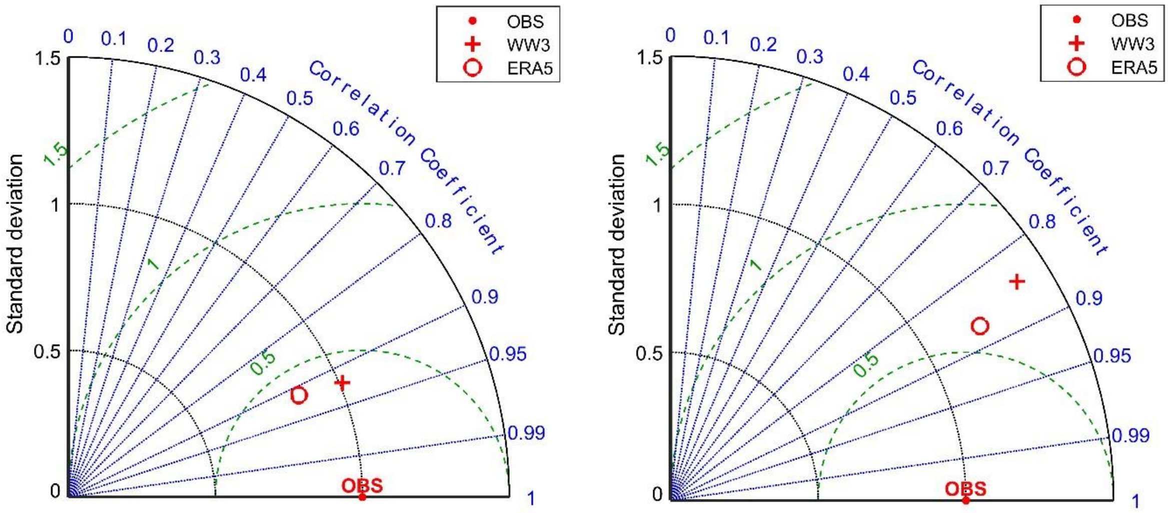

Figure 13: Normalized Taylor diagrams for the Giannutri wave point.

5. CONCLUSIONS

Numerical modeling chains, based on a European reanalysis free dataset (ERA5) and on open-source wave models (SWAN, WW3), allowed to perform simulations at regional level, for spatial domains ranging from the Mediterranean Sea to sub-basin scales (NWMED) with outstanding time coverage. Numerical datasets were validated with available in-situ measurements (wave buoy data). The flexibility of these model in the production of new numerical datasets (hindcast) highlights the importance of such numerical simulations, validated with physical measurements, to provide reliable data aimed at calibrating and training AI algorithm.

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