Wave energy potential: A forecasting system for the Mediterranean basin

ENEA is performing ocean wave modeling activities with the aim of both characterizing the Italian sea energy resource and providing the information necessary for the experimental at sea and operational phases of energy converters. Therefore a forecast system of sea waves and of the associated energy available has been developed and has been operatively running since June 2013. The forecasts are performed over the entire Mediterranean basin and, at a higher resolution, over ten sub-basins around the Italian coasts. The forecast system is here described along with the validation of the wave heights, performed by comparing them with the measurements from satellite sensors.

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Introduction

Wave energy is a promising renewable resource that is receiving particular attention in countries facing large oceans, where the greatest wave energy potential is found. In Europe, most of the pilot plants either planned or in operation are located along the Atlantic coasts, in countries such as Ireland, Portugal, Spain, Norway, and the UK. The intensity of waves is in fact determined by the winds blowing over the sea and reaches the highest values in the presence of strong winds and long fetches.
The Mediterranean is a semi-enclosed sea and is characterized by lower values of wave energy with respect to the major oceans. Nevertheless, the conversion of wave energy can represent, even under these conditions, an economically profitable resource if ad-hoc designed energy converters are developed. In these lower energy areas, in fact, devices of reduced size can be more suitable to extract energy. This, together with the need of facing lower extreme weather conditions, can significantly reduce installation and maintenance costs.
The first step to perform for the development of wave energy production is the characterization of the resource. Climatology of the energy available in the Mediterranean basin has been performed using a wave model at the horizontal resolution of 1/16°; results are presented in [1]. The most productive areas along the Italian coasts have been identified in western Sardinia and north-western and southern coasts of Sicily.
Actually some wave energy converters developed for the Mediterranean conditions are at the field experimental stage. A wave forecast system has been implemented with the aim of providing a support to field activities. It has to be stressed that high resolution forecast in specific sites will be also necessary in the operational stage, for the management of the energy network in which the

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wave resource will be inserted. It will also provide an important support for the planning of marine operations and the device maintenance.
The operational forecast system has been achieved at the spatial resolution of 1/32° for the entire Mediterranean basin. Boundary conditions provided by this model are then used to force laterally ten higher resolution models developed in the most interesting areas around the Italian coasts. The forecast system has been running for more than one year and now a validation against data derived from satellite measurements has been performed.

Numerical models

Wave simulations are performed using a parallel version of the WAM wave model Cycle 4.5.3. [2, 3]. WAM is a spectral model that solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. The model is widely applied at basin scale and has been developed to simulate wave propagation in deep water. 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 [4] by averaging the depths of data points falling in each computational cell. Figure 1 shows the computational domain and the model bathymetry.
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 next one.

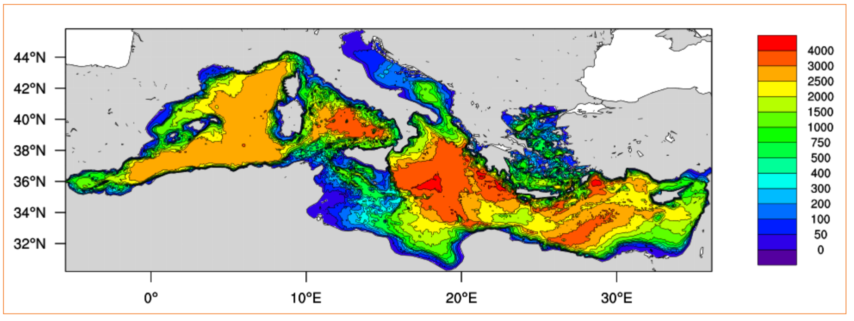


FIGURE 1 Model bathymetry for the Mediterranean basin (in meters)

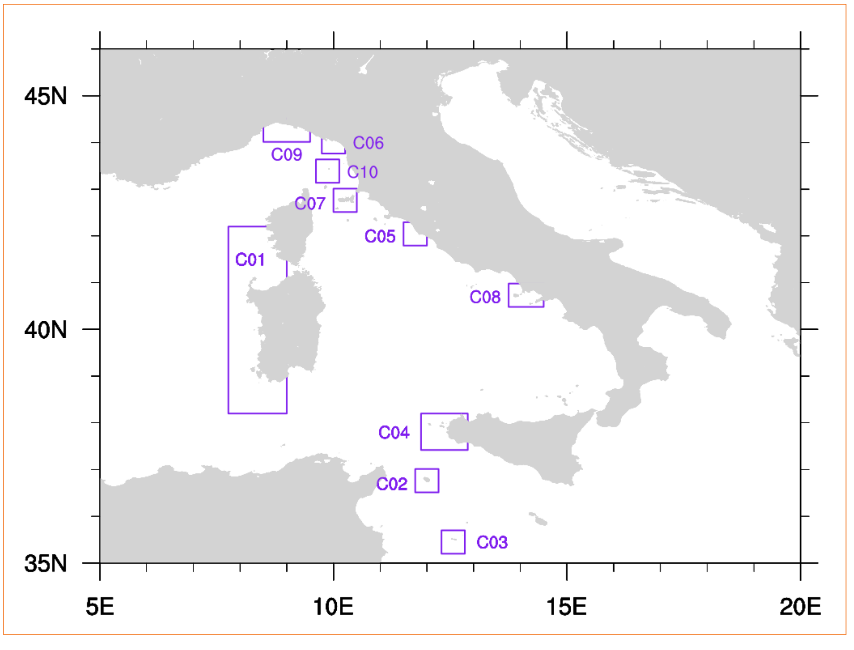


FIGURE 2 Model domains of the ten higher resolution models around the Italian coast

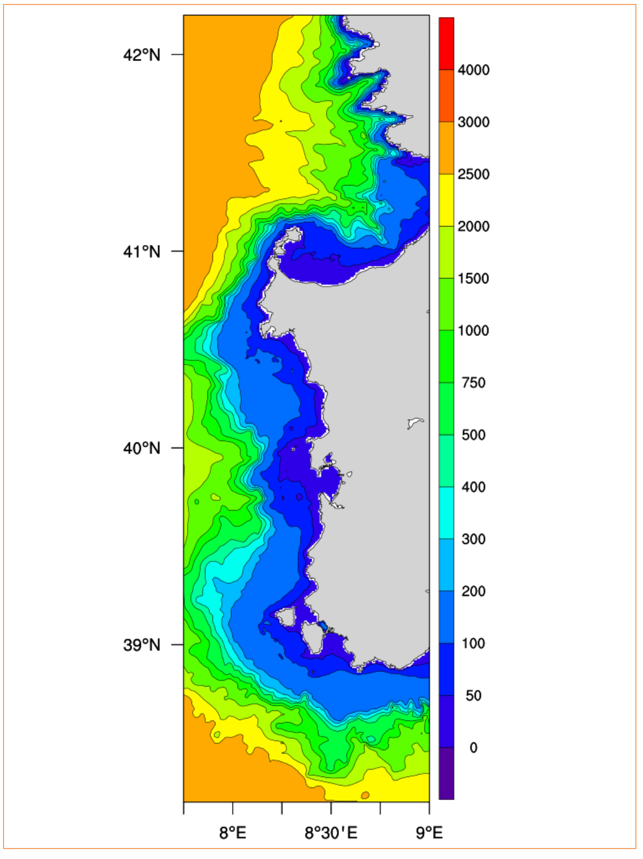


FIGURE 3 Model bathymetry for the western Sardinia sub-basin (in meters)

Higher resolution forecast simulations are computed over ten sub-basins around the Italian coasts. In order to take into account both waves generated locally by winds and waves propagating from distant areas, a nesting procedure has been applied. Spectral wave data derived from the WAM model are used as boundary conditions for the higher resolution models. The domains, shown in Figure 2, have been selected looking at the wave energy production. The most extended areas include the entire western coast of Sardinia (Fig. 3) and the westernmost part of Sicily, that are the most energetic in the Central Mediterranean, being reached by the strong north-westerly winds from the Gulf of Lions. Other areas have been defined around some minor Italian islands, where wave energy production can contribute significantly to the energy independence. All these models have a spatial resolution of 1/128°, the boundary conditions are applied hourly.

These simulations are carried out using SWAN model (Simulating WAves Nearshore) [5]. SWAN is specifically built to be used in shallow water and includes depth-induced wave breaking and triad wave-wave interactions, which are important for near-shore wave prediction. SWAN is a third-generation wave model integrating the action density spectrum, without any assumption on the spectral shape. The equation is solved using an implicit propagation scheme based on finite differences. Here the same discretization in frequency and direction has been used as that defined for the WAM model.

The entire forecast system composed by WAM and SWAN models is forced with hourly wind fields obtained from the meteorological operational system SKIRON, developed by the Atmospheric Modeling and Weather Forecasting Group of the University of Athens [6]. The atmospheric model is based on the limited area model Eta/NCEP and is run daily over the Mediterranean basin at the horizontal resolution of 0.05° × 0.05°. The forecast spans over a period of five days.

Wave forecast for the entire Mediterranean basin and the ten sub-basins are performed daily for the following five days. The main wave variables are stored at each grid point every hour, in particular: the wave significant height, mean wave period and mean direction of propagation, and the same parameters for the swell and sea components separately. Moreover, the wave power flux per unit crest, defined by the expression:

$$J = \frac{\rho g^2}{64\pi} T_e H_s^2$$

where J is in Watt per meter of wave crest, g is the gravity acceleration, r the sea water density assumed to be r =1025 kg m^{-3}, H_s the significant wave height, and T_e the significant wave period. A web page is daily updated with images of the hourly forecast of the main integrated wave parameters.

Model validation

The forecast system has been operatively running since June 2013. A validation of the wave forecasts has been performed by comparison with satellite data from radar altimeters that provide significant wave heights (Hs) measurements. In this work data from two satellites, Jason-2 and Saral/Altika, in service over the last year and downloaded from the AVISO web site [7], have been used. In Figure 4 satellite tracks are shown, over which measures are periodically performed. Jason-2 repeats its cycle every 10 days and the tracks are spaced 315 kilometers at the equator; the Saral satellite, instead, repeats its cycle every 35 days but the separation between tracks is only 75 kilometers at the equator.

The comparison with these data can be used to evaluate the overall behavior of the model over the entire Mediterranean Sea.

Data have been processed following the procedure described by Queffeulou and Bentany [8] to remove outliers. This procedure is based on the statistical analysis of the difference between consecutive points along the track. Tracks represented by less than three points are not considered, and points where the depths derived by the satellite and the model depth differ of more than 50% are also removed. Satellite data have been directly compared with the nearest model point, without any interpolation in space nor in time.

Significant wave heights derived by the WAM model for the entire Mediterranean basin have been validated using data obtained for the first, second and third day of the simulation.

Table 1 reports, for each satellite, the values of the statistical indices used to evaluate the model performance. In our analysis we included the bias between model and measures (*bias*), the root mean square error (*rmse*), the scatter index (*si*) and the slope of the best fit line passing through the origin (*slope*). Considering the series of n measures x_i and the corresponding model values y_i, these indices are calculated as follows:

$$bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$$

$$rmse = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - x_i)^2}$$

$$si = \frac{rmse}{\frac{1}{n}\sum_{i=1}^{n} y_i}$$

$$slope = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i x_i}$$

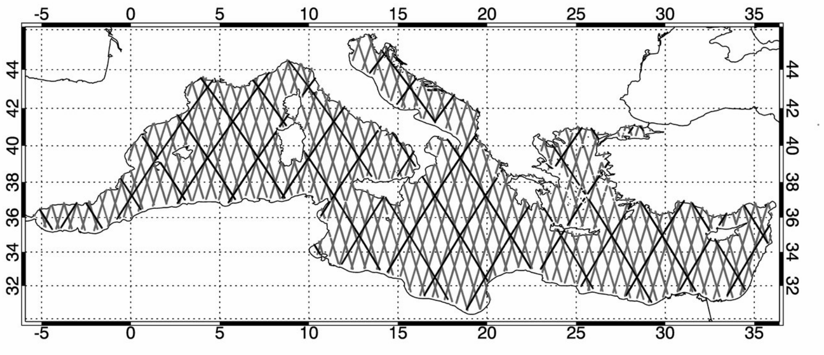
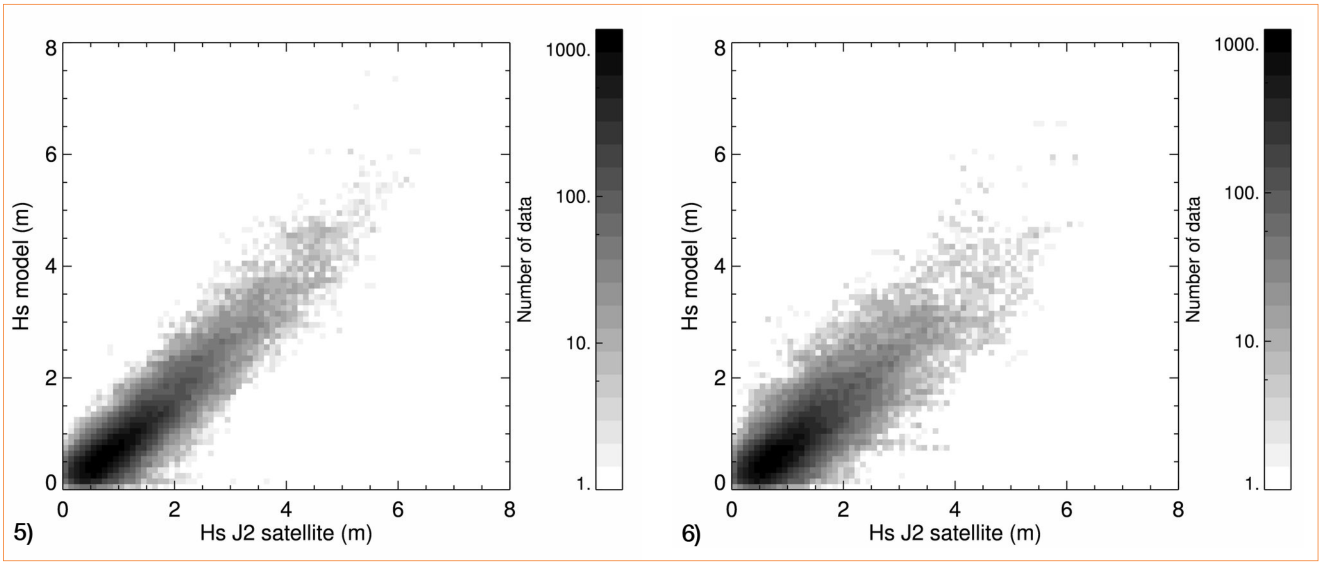


FIGURE 4 Satellite ground tracks used for model validation. Black lines identify Jason-2 and gray lines Saral/Altika

Satellite	forecast	samples	Bias (m)	Rmse (m)	si	slope	d
Jason-2	Day 1	100,399	0.20	0.40	0.34	0.83	0.93
	Day 2	101,036	0.22	0.44	0.37	0.81	0.92
	Day 3	99,386	0.24	0.50	0.42	0.78	0.89
Saral/ Altika	Day 1	74,709	0.19	0.38	0.36	0.82	0.93
	Day 2	74,896	0.20	0.42	0.39	0.80	0.91
	Day 3	74,691	0.21	0.46	0.44	0.78	0.89

TABLE 1 Satellite statistics and model significant wave-height comparison for the entire Mediterranean basin



FIGURES 5-6 Scatter plot of model vs. Jason-2 satellite Hs for the entire Mediterranean basin. Values are grouped in 0.2 m wide bins. Model data are taken from the first day of forecast

The last index shown in the table is represented by the Willmott index (d), defined as:

$$d = 1 - \left[\sum_{i=1}^{n} (y_i - x_i)^2 \Big/ \sum_{i=1}^{n} (|y'_i| - |x_i'|)^2 \right]$$

where y_i' and x_i' are the deviations with respect to the average. This index assumes a value of 1 when the match between the two series of data is perfect. For each satellite the comparison has been performed using model outputs derived separately from the first three days of the forecast. All the statistical parameters do not change significantly from the first to the third day of the simulation; statistical parameters regularly get lightly worse with the number of the forecasted day. However the Willmott index always remains close to 0.9 and the bias near 0.2 m. A systematic underestimation is always present with values of the slope around 0.8. Scatter plots computed using all the available Jason-2 satellite data and WAM significant wave heights, respectively from the first and the third day of the forecast, are shown in Figures 5 and 6. A logarithmic scale has been used to represent the number of data in each bin. Values are grouped in bins of 0.2 m. The increase in the spreading of data in the third day of forecast with respect to the first can be observed.

Satellite	model	samples	Bias (m)	Rmse (m)	si	slope	d
Jason-2	WAM	1,421	0.33	0.60	0.40	0.82	0.93
	SWAN	1,421	0.32	0.51	0.34	0.83	0.95
Saral/ Altika	WAM	860	0.26	0.50	0.38	0.78	0.91
	SWAN	860	0.24	0.40	0.30	0.81	0.94

TABLE 2 Satellite statistics and model significant wave height comparison for the first day of the simulation in the sub-basin C01, corresponding to western Sardinia

In order to compare the results obtained by the WAM model with those of the higher resolution SWAN model, the procedure of validation has been performed using the first forecast day, also using only data from the domain of Sardinia's sub-basin. In

Table 2 are reported the statistical parameters computed using significant wave heights in this domain from the two simulations. Even if only few tracks are included in the area, the number of samples is sufficient for the comparison. Statistical results obtained in this region for the WAM model present higher values of bias and rmse with respect to those computed for the entire Mediterranean basin. This can be explained with the better representation of waves in the open ocean than those near-shore. All the statistical values obtained using the SWAN model show a clear improvement for both satellites.

Conclusions

A wave forecast system for the Mediterranean basin is currently running at ENEA. It provides output data for the following five days at the temporal resolution of an hour. The system consists in a simulation performed with the WAM model at the spatial resolution of 1/32° and ten nested simulations performed using the SWAN model at a resolution of 1/128°. A validation of the significant wave heights against the data measured by two satellites (Jason-2 and Saral/Altika) has been achieved using the data produced over the period between June 2013 and November 2014, both for the entire Mediterranean basin and the largest sub-domain considered, corresponding to the western coasts of Sardinia. The comparison executed separately over the first three days of the forecast has shown a reasonable agreement; in particular, the Willmott index and the slope do not vary significantly in the different days. The statistics of the significant wave height computed using only data in the sub-domain corresponding to western Sardinia show a slight improvement of the higher resolution simulation performed using SWAN model against the results obtained using the global simulation.

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references & notes

[1] L. Liberti, A. Carillo, G. Sannino, WAM energy assessment in the Mediterranean, the Italian perspective, in *Renewable Energy 50*, 938-949, 2013.

[2] WAMDI-group: S. Hasselmann, K. Hasselmann, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky, J.A. Ewing, The WAM model - a third generation ocean wave prediction model, in *J. Phys. Ocean*, 18, 1775-1810, 1988.

[3] H. Günther, A. Behrens, The WAM model validation document version 4.5.3, Tech. Rep. Institute of Coastal Research Helmholtz-Zentrum Geesthacht (HZG), 2011.

[4] GEBCO.http://www.gebco.net/data and products/gridded bathymetry data/.

[5] N. Booij, R.C. Ris, L.H. Holthuijsen, A third-generation wave model for coastal regions: 1. Model description and validation, in *J. Geophys. Res*, vol. 104, C4, 7649-7666, 1999.

[6] G. Kallos, The regional weather forecasting system SKIRON, in *Proceedings, symposium on regional weather prediction on parallel computer environments, 15-17 October 1997*, Athens p. 9, 1997.

[7] The altimeter products were produced and distributed by *Aviso* (http://www.aviso.altimetry.fr/), as part of the Ssalto ground processing segment.

[8] P. Queffeulou, A. Bentamy, Analysis of wave height variability using altimeter measurements: application to the Mediterranean sea, in *Journal of Atmospheric and Oceanic Technology*, 24(12), 2078-2092, 2007.