A high resolution wind&wave forecast model chain for the Mediterranean and Adriatic Sea

L. Donatini, G. Lupieri, G. Contento & L. Feudale
HyMOLab, Department of Engineering and Architecture
University of Trieste, Trieste, Italy

A. Pedroncini, L.A. Cusati & A. Crosta
DHI
Genova, Italy

ABSTRACT: DHI (Danish Hydraulic Institute) and HyMO*Lab* (Hydrodynamics and Met-Ocean Laboratory of the Dept. of Engineering and Architecture of the University of Trieste) have undertaken a joint applied research project with the aim to develop a state-of-art wind-wave forecast service at mid resolution for the Mediterranean Sea and at very high resolution for the Adriatic Sea. Weather routing, civil protection, coastal engineering, oil&gas and renewable energy fields, the planning of operations at sea, ... are just few among the multiple potential applications of this service. The meteorological model used in this study is WRF-ARW, one of the most widely used state-of-the-art open-source non-hydrostatic model. Global Forecast System (GFS) dataset provides the boundary and initial conditions. MIKE21-Spectral Waves is used as wave model with resolution ranging from 0.1° to 0.03° approximately. The use of a local area meteorological model guarantees higher levels of resolution and accuracy in an area such as the Mediterranean Sea where the complex orography and coastline induce short-time/small-space weather scales. The model chain runs daily (or twice a day on demand) on the High Performance Computing (HPC) infrastructure of HyMO*Lab*. The validation of the entire model chain and specifically the forecast data obtained for the sea state is continuously updated according to new available data from satellites and buoys. Anyway, a major verification of the performance of the model chain against historic data (hindcast) is almost mandatory. For this aim, we performed a multi-decade test obtaining very good statistical parameters for the entire model chain performance. In this context the hindcast dataset developed by DHI and HyMO*Lab* consists of 35 years of hourly data for the period 1979-2013, with the same model chain. The CFSR d093.0 hourly dataset with a spatial resolution of 0.5° provides the boundary and initial conditions. The atmospheric and wave models performance is checked against six satellite datasets, missions Envisat, ERS-2, Geosat FO, Jason-1, Jason-2, Topex-Poseidon, using a moving window technique procedure. Wave data close to coast are compared with available data from more than 20 buoys. The paper describes the validation procedure adopted for the hindcasted data. Furthermore the forecast service is described too, with specific emphasis to the very high resolution adopted in the Adriatic Sea.

1 INTRODUCTION

The availability of reliable wind-wave forecasts is gaining more and more importance for a wide list of engineering and civil protection applications, both coastal and offshore. With the recent progresses in numerical models, in global forecast datasets and in computational resources, it is now relatively straightforward to obtain sufficiently accurate wind and wave forecasts over open oceans, due to their wide extent and the absence of complications arising from complex coastal shapes or orography. Such consideration, however, cannot be applied to the Mediterranean basin and least of all to the Adriatic Sea, due to their limited extent and the significant importance of the coastal orography on the accuracy of forecasted wind and wave fields.

HyMO*Lab* (*Hydrodynamics and Met-Ocean Laboratory* of the *Dept. of Engineering and Architecture* of the *University of Trieste*) and DHI (*Danish Hydraulic Institute, Genova*) jointly developed a state-of-the-art model chain aimed at the production of a 35 years hindcast database for wind and waves over the Mediterranean basin. The database was produced and extensively validated with satellite and buoy data. Moreover, an operational forecast model chain was developed, which actually runs daily on the HPC cluster of HyMO*Lab*. The results of the wave forecasts are compared with the raw semi-real time buoy data published over the web by the EMODnet (*European Marine Observation and Data Network*). Both the hindcast dataset and the forecast products are part of the package MWM (Mediterranean Wave Model) available at HyMO*Lab* and DHI.

The MWM forecasts are produced at a resolution of 10.5 km for the wind and 10 to 3 km in coastal areas for the wave (unstructured triangular grid). These resolutions, while being adequate for the whole Mediterranean Sea, were not deemed as suitable for high accuracy applications over the Adriatic Sea, especially along the Croatian coast, where the extremely complex island pattern is almost entirely missed with a resolution of 10 to 3 km.

Therefore an experimental forecast model chain was developed, resulting in an Adriatic domain simulated at resolutions of 3.5 km for the atmospheric model and 3 to 0.5 km along the coast for the wave model. In this work, the configuration of this advanced model chain is presented, as well as a brief description of the validations performed on the hindcast dataset and on the forecast data produced at Mediterranean Sea scale. Concerning the high resolution Adriatic simulations, at the time of preparation of this manuscript it was not possible to made extensive comparisons with experimental data due to the lack of buoys data in the areas of interest and due to the lack of reliable satellite data. Nevertheless, two recent significant events of strong *Bora* and *Scirocco* winds are shown to illustrate the resolving capability of the high resolution model.

2 ATMOSPHERIC AND WAVE MODELS

The framework of a forecast model chain for wind and wave simulations is rather complex. First of all, the whole atmosphere should be simulated at a global scale, necessarily with a low resolution due to the high computing resources required by such simulations. The atmospheric data produced by a global simulation are then used as the initial and boundary conditions for a local area atmospheric model. The local area simulations can be performed at much higher resolutions, and are responsible for the development of the mesoscale weather phenomena, generally not captured by the global coarse simulations.

The Mediterranean and Adriatic seas are characterized by jagged coast lines and by a complex orography which greatly influences the wind and wave dynamics, especially close to the shore line. The direct use of global scale wind/wave grids is rather questionable for engineering applications in those basins, with potential wrong estimates of the wind speed, significant wave height and directions.

These aspects have been thoroughly discussed in the literature (Cavaleri & Bertotti 2004, Cavaleri 2005, Cavaleri & Sclavo 2006, Ardhuin, Bertotti, Bidlot, Cavaleri, Filipetto, Lefevre, & Wittmann 2007, Athanassoulis, Cavaleri, Ramieri, NoEL, Lefevre, & Gaillard 2004, de León & Soares 2008, Bolaños-Sanchez, Sanchez-Arcilla, & Cateura 2007, among others). A detailed discussion of this problem is also given in Contento, Lupieri, Venturi & Ciuffardi (2001). Therefore, in the application dealt with in this paper, as opposed to ocean applications, the use of a local area atmospheric model is almost mandatory.

The local area models produce a high resolution wind field which is used as the forcing term for the wave model. Among others (Bolaños-Sanchez, Sanchez-Arcilla, & Cateura 2007) concluded that the main sources of error in the wave estimates are related to the quality of the forcing wind fields and its spatial resolution. In order to correctly model the wave patterns in the near shore, especially along the Croatian coast, a very high resolution grid is needed for the wave model. However, adopting very high resolutions over large domains can result in computational efforts too heavy for practical applications. Therefore the need of using a triangular unstructured grid arises, since that type of grid can be highly refined only in the areas of interest, that means close to the shore.

The wind and wave models used in the development of the forecast model chains for the Mediterranean and Adriatic basins were:

- the GFS (*Global Forecast System*) global forecast dataset produced and freely published by NCEP (*National Centers for Environmental Prediction*) (Environmental Modeling Center 2003); the dataset includes three-hourly global atmospheric data with a spatial resolution of 0.5°;
- the atmospheric model WRF-ARW (*Weather Research and Forecast - Advanced Research WRF*) – version 3.4.1, developed by NCAR (National Center for Atmospheric Research) (Michalakes, Chen, Dudhia, Hart, Klemp, Middlecoff, & Skamarock 2001, Michalakes, Dudhia, Gill, Henderson, Klemp, Skamarock, & Wang 2004, Skamarock & Klemp 2008); WRF-ARW is presently considered among the best state-of-the-art non-hydrostatic meteorological models;
- the wave model MIKE21-Spectral Waves developed by DHI; a state-of-the-art third generation wave model with support for unstructured triangular grids (Sorensen, Kofoed-Hansen, Rugbjerg, & Sorensen 2004).

3 DOMAINS AND RESOLUTIONS

3.1 *WRF-ARW model*

As a general rule, the horizontal dimensions of the atmospheric model domain should be closely related to the characteristic length scale of the weather fronts

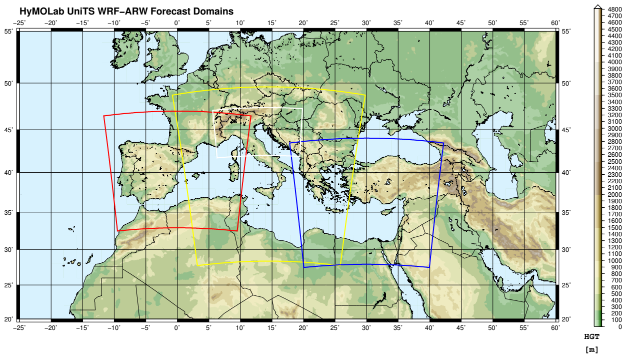

Figure 1: Forecast domains for the WRF-ARW model

typical of the zone under investigation. Comparing different domains with the same grid resolution in fact, a very large domain, whose size is set much larger than the typical weather front size, is likely to show a pronounced departure of its results from the forcing data. On the other hand, a very small domain is supposed to be too much influenced by the boundary conditions and it can be not sufficiently free to develop mesoscale weather structures. The best configuration for the domain dimension can be obtained from a compromise between these upper and lower limits.

3.1.1 *Mediterranean domain*

In this specific work the parent atmospheric model domain should be wide enough to cover the Mediterranean Sea area. It has been assumed that the boundary and initial conditions data (GFS data) sum up the main features of the large scale weather fronts, leaving to the local area model the role to take into account the local characteristics of the territory and thus to capture smaller scale events. Since a domain covering entirely the area of interest proved to be excessively large, three smaller, overlapping domains were designed, covering respectively the Western, Central and Eastern Mediterranean Sea. These domains, which will be referred as MEW, MEC and MEE hereafter, are represented in red, yellow and blue in Figure 1.

Concerning the resolution, a decision was made to adopt a grid size of 10.53 km in both directions for each of the three sub-domains. Basically, this choice is the result of the grid ratio with the forcing data (GFS 0.5° x 0.5°). The selected grid size gave the possibility to run WRF-ARW directly without the need to pre-arrange an outer coarser grid, as the grid ratio between the forcing data and the atmospheric model resolution is under the recommended limit of 1:5. Additionally, the resolution of 10.53 km is good for the introduction of multiple nested domains with a standard grid ratio (1:3), up to 3.51 and 1.17 km (or lower) respectively. Since the wave model needs a single forcing wind field over its domain, a blending procedure for the medium resolution data of the three overlapping domains was necessary to produce a unified wind field over the entire Mediterranean Sea.

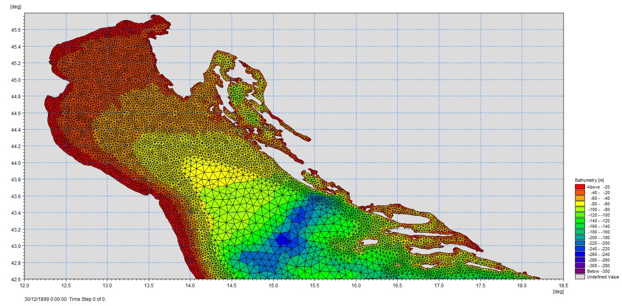
Figure 2: Mediterranean grid over the Northern Adriatic.

The final approach adopted was to interpolate each of the three domains on a common, Mediterranean wide Cartesian grid. Then, data blending is performed point-by-point in the overlapping areas; at every superimposition grid point the blending process weights the values corresponding to each domain with the distance of the point from the domain border, privileging the inner points.

3.1.2 *Northern Italy domain*

In order to feed the high resolution wave simulations with a congruent wind field, a high resolution atmospheric model domain was set up. The decision was taken to arrange a single domain including the entire Northern Italy as well as the Northern part of the Adriatic Sea with a horizontal resolution of 3.51 km. This high resolution domain is represented in white in Figure 1.

The ITN domain is simulated as a nest of the MEC domain, following the standard WRF-ARW two-way nesting approach. This means that the large scale domain benefits from the higher resolution of its child domain, since the two simulations are performed in a strictly coupled way.

3.2 *MIKE21-SW model*

3.2.1 *Mediterranean domain*

The Mediterranean domain was discretized with a triangular unstructured grid. The resolution adopted for this domain, intended as the mean triangle side, ranges from around 10 km in the open sea to around 3 km in the shallow water areas. In Figure 2, a detail of the Mediterranean grid over the Northern Adriatic Sea is shown.

The Mediterranean domain was considered as an enclosed basin, i.e. it was not forced by boundary conditions at the Gibraltar Strait.

3.2.2 *Adriatic domain*

The Adriatic domain covers the whole Adriatic sea, from 39.00° N of latitude up to its Northern Italy coast. The resolution of this domain ranges from 3 km in the open sea to 500 m in the near shore area. In Figure 3, the same area shown in Figure 2 is presented for the Adriatic grid. The increased resolution is immediately perceivable from the density of the computa-

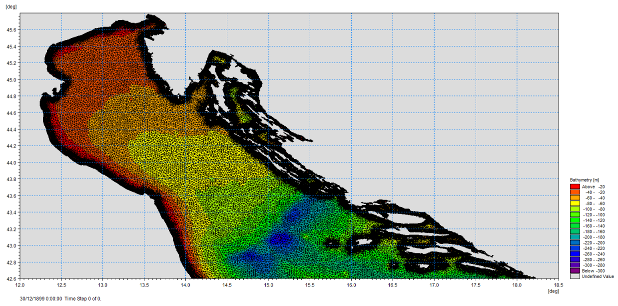

Figure 3: Adriatic grid over the Northern Adriatic.

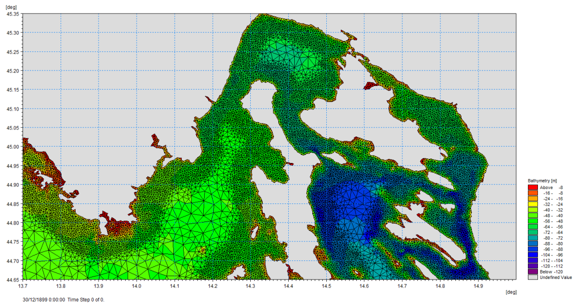

Figure 4: Detail of the Adriatic grid over the Quarnaro area.

tional elements as well as from the way more defined coast line.

A very high resolution such as the one used for the experimental Adriatic domain was deemed as necessary to adequately resolve the complex coastline and islands pattern of the North-eastern Adriatic Sea. A detailed insight of the refined grid can be seen in Figure 4, a zoom of the Adriatic grid over the Quarnaro area.

The Adriatic domain is forced by the high resolution wind computed over ITN, completed by the wind field computed over MEC in the southern areas not covered by ITN. The use of a wind field coming from two different atmospheric model domains is not affected by discontinuities due to the aforementioned two-way nesting approach.

Concerning the wave spectra boundary conditions, the Adriatic domain is set up to receive them from the Mediterranean domain. The boundary conditions are provided over the 39th parallel. For the wave model, the nesting follows a one-way approach, meaning that the simulations at Mediterranean scale are run before those at Adriatic scale; therefore, as opposite to the atmospheric model configuration, the coarse resolution domain cannot benefit from the high resolution data.

4 DATA VALIDATION

4.1 *Hindcast dataset validation*

The 35 years medium resolution Mediterranean dataset MWM was extensively validated with satellite and buoy data. The hindcast simulations were forced with a different global database from the one used for forecast simulations, the CFSR (*Climate Forecast System Reanalysis*) dataset produced by NCEP (Saha et al 2010). Nevertheless, the validation performed on

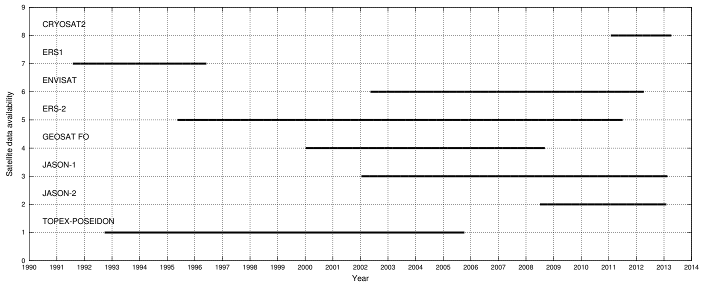

Figure 5: Radar altimetry data availability for the satellite missions.

the hindcast data can be used as a tool to assess the general reliability of the Mediterranean chain of models.

For both the satellites and the buoys data, the comparison with the model data was summarized in the form of probability scatter plots, PSP, i.e. a bi-variate occurrence probability distribution $p(x, y)$. The more the probability distribution of these plots lays around the bisector, the more accurate the model results are with respect to the measured data.

4.1.1 *Satellite*

The significant wave height H_S resulting from the simulations was compared with the data of the Ifremer dataset, which includes the validated radar altimetry data of eight satellite missions (Queffeulou 2004, Queffeulou & Croizé-Fillon 2010).

The satellite data availability intervals are depicted in Figure 5. A ten years interval, from 2002 to 2011 was selected as the most appropriate to perform a uniform comparison between the model results and the data coming from six of the available satellites.

In this paper we show briefly the results of one of the most reliable satellite missions, Jason1, over the whole Mediterranean basin, Figure 6, as well as over a Northern Adriatic sub-basin, Figure 7.

4.1.2 *Buoys*

The wave results from the simulations were compared with the results of more than 20 buoys over the entire Mediterranean Sea. Both the H_S and the peak period T_P were compared with the measured data. The only available buoy in the Northern Adriatic was the Ancona buoy of the RON (*Rete Ondametrica Nazionale*) network (043.830° N; 013.715° E). In this paper, the PSP relative to the Ancona buoy are shown, both for H_S, Figure 8, and T_P, Figure 9.

4.2 *Mediterranean forecast performance assessment*

As a raw working tool, the wave data produced by the operational Mediterranean scale forecast are daily compared with the quasi real-time data published over the internet for several buoys. The comparison is made by an overlap of the buoy timeseries with the timeseries of different forecast runs.

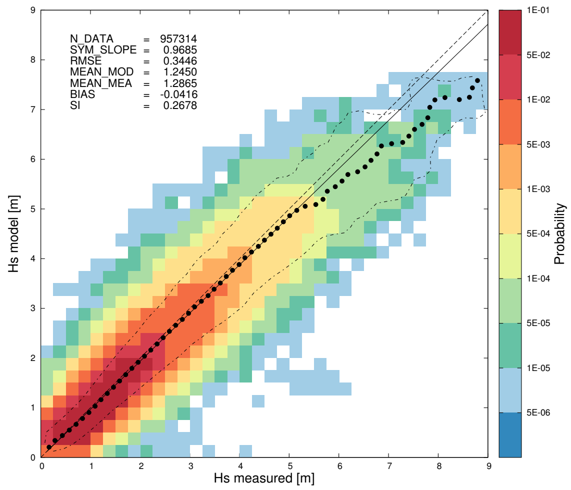

Figure 6: PSP of the comparison between modeled and Jason1 measured H_S. Valid over the entire Mediterranean basin for the period 2002-2011.

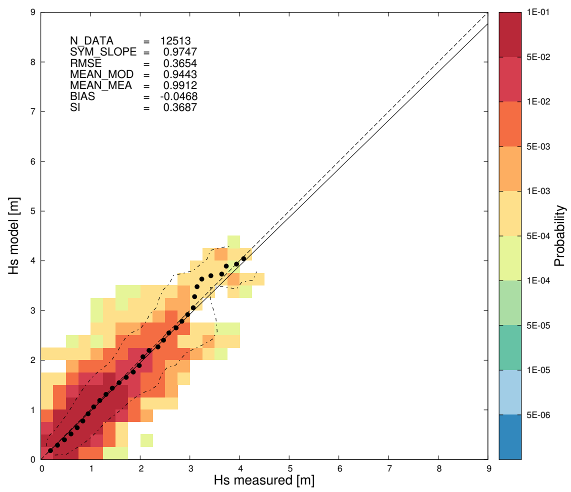

Figure 7: PSP of the comparison between modeled and Jason1 measured H_S. Valid over the North Adriatic sub-basin for the period 2002-2011.

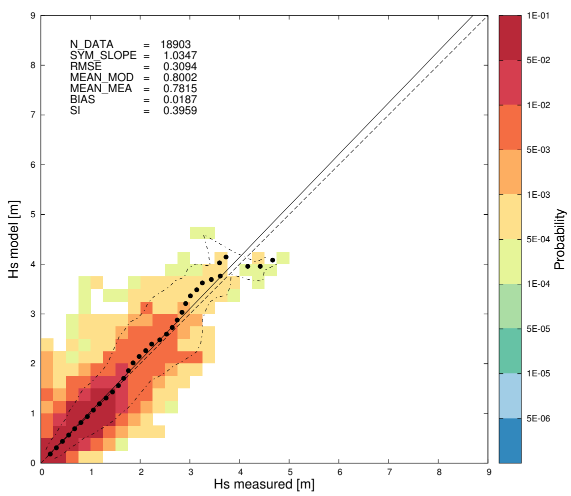

Figure 8: PSP of the comparison between modeled and buoy measured H_S. Valid for the Ancona buoy and for the period 2002-2011.

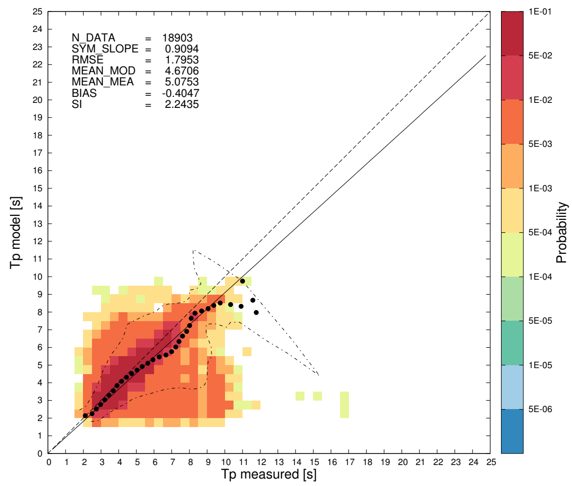

Figure 9: PSP of the comparison between modeled and buoy measured T_P. Valid for the Ancona buoy and for the period 2002-2011.

The results of the Ancona buoy cannot be shown due to the service shutdown of the RON network dating back to 2015/01/01. Therefore, two significant cases of very heavy storms registered by the Mahon buoy of the PdE (*Puertos del Estado*) network (039.718° N; 004.442° E) are shown in Figures 10 and 11.

5 HIGH RESOLUTION FORECAST OVER THE ADRIATIC SEA: TWO STRONG EVENTS

The high resolution model chain, developed as described in section 3, was preliminary tested for two significant harsh events. These cases are recent occurrences of strong wind fields over the Adriatic Sea. The two cases were chosen as they represent the most common causes of harsh sea conditions in the Adriatic Sea. Specifically, they are a strong *Scirocco* (SE wind) event occurred in the morning of the 4th of February 2015 and a quite exceptional *Bora* (NE wind) event occurred between the 4th and the 5th of March 2015.

In order to show here the consistent improvements brought by the use of the higher resolution model chain, for the first case of interest one single hourly frame was taken into consideration. The wave field maps (H_S and mean wave direction) for both the medium resolution and the high resolution models are shown, Figures 12 and 13. The maps are limited to a specific area of the Adriatic Seas with an appropriate level of zoom, selected to show in a better way the effects of the higher resolution. The most evident of these effects is the ability to correctly see and resolve the numerous islands and the complex coastline, in a way impossible for the medium resolution model.

Moreover, in Figures 14 and 15 the maps for the wind and wave fields concerning the exceptionally violent Bora case of the 5th of March 2015 over the Quarnaro area are shown.

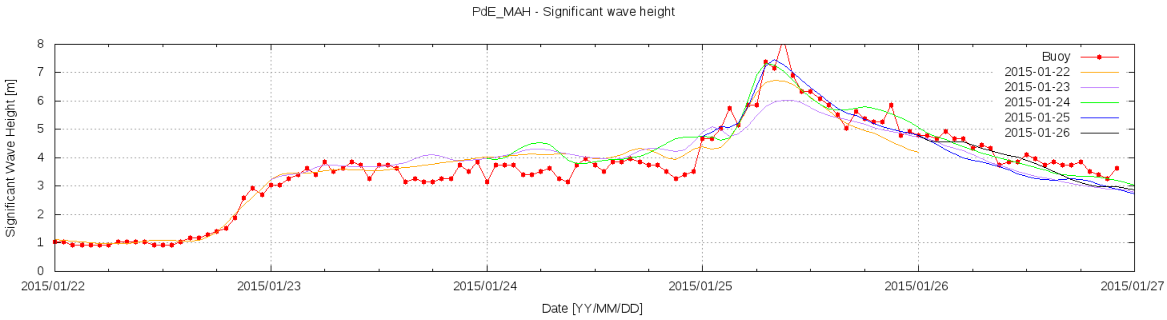

Figure 10: Forecast model chain performance for the Mahon buoy, 2015/01/22 to 2015/01/27.

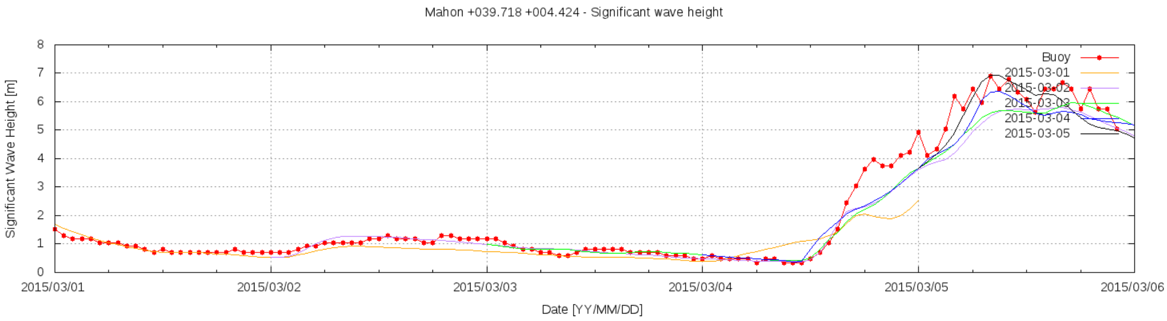

Figure 11: Forecast model chain performance for the Mahon buoy, 2015/03/01 to 2015/03/06.

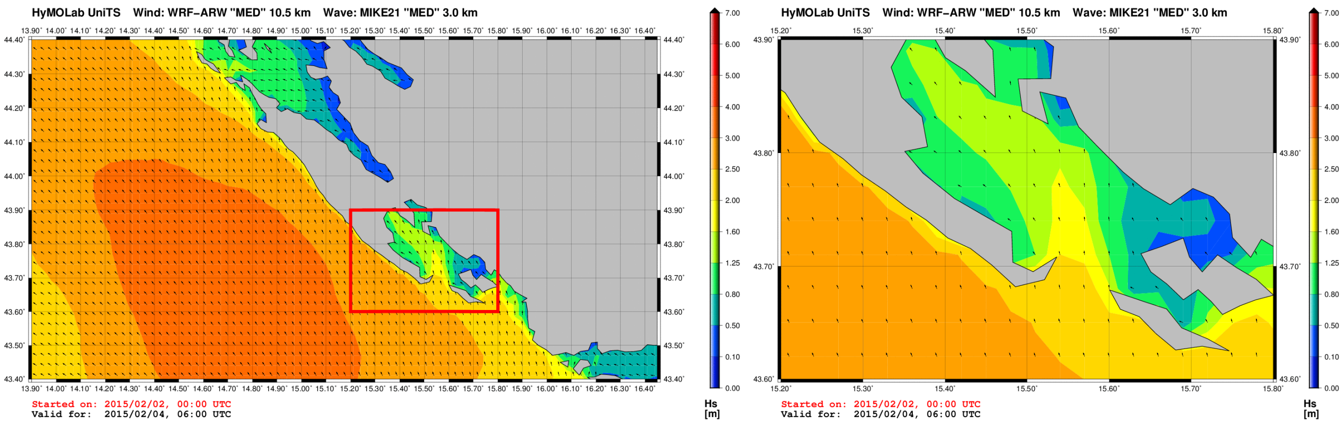

Figure 12: *Scirocco* occurred on 4th February 2015. Medium resolution.

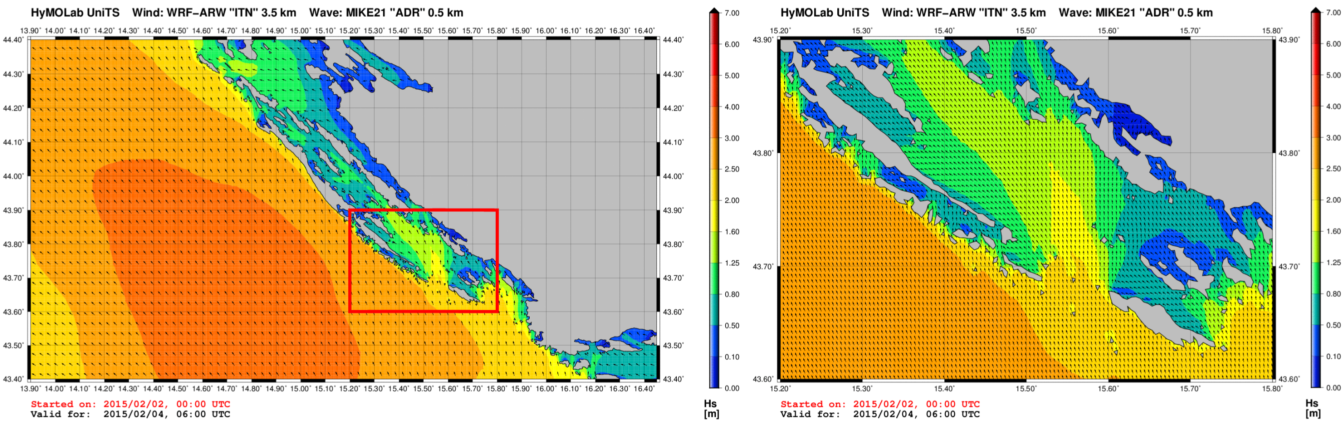

Figure 13: *Scirocco* occurred on 4th February 2015. High resolution.

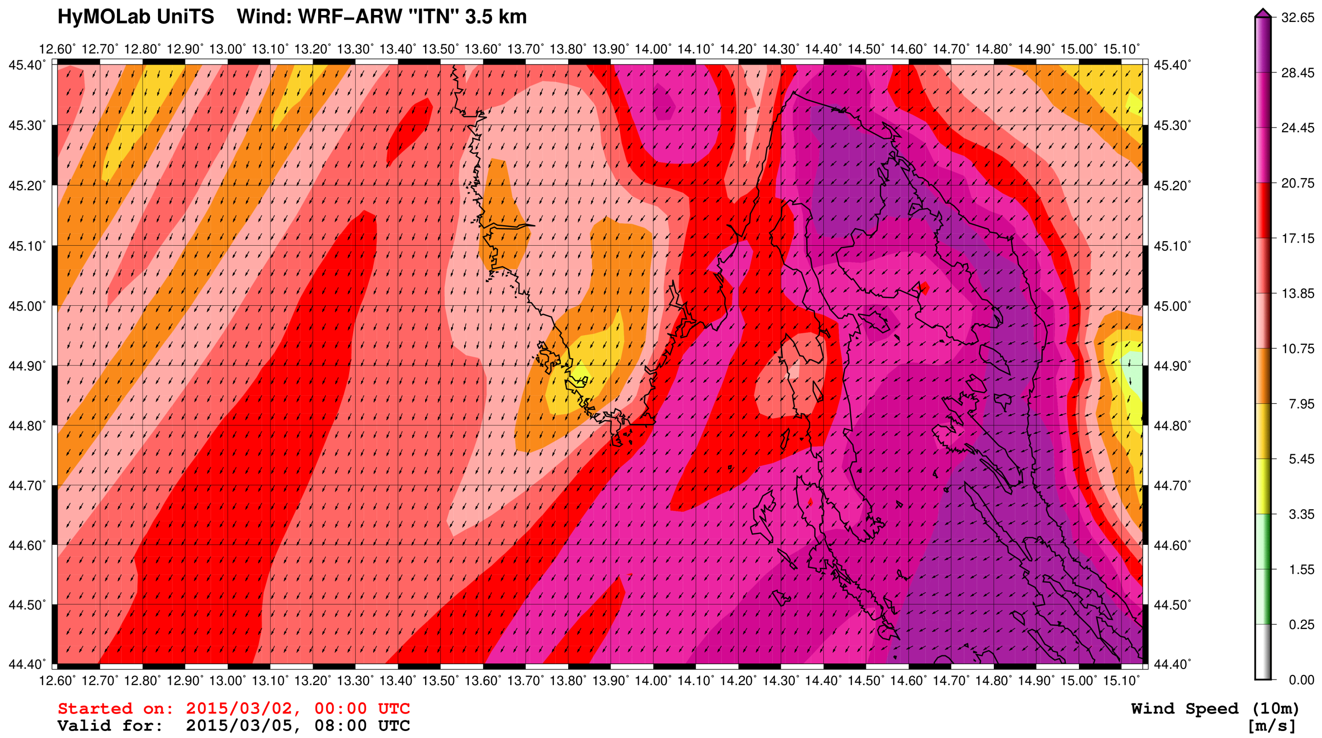

Figure 14: *Bora* occurred on 5th March 2015. High resolution. Wind field.

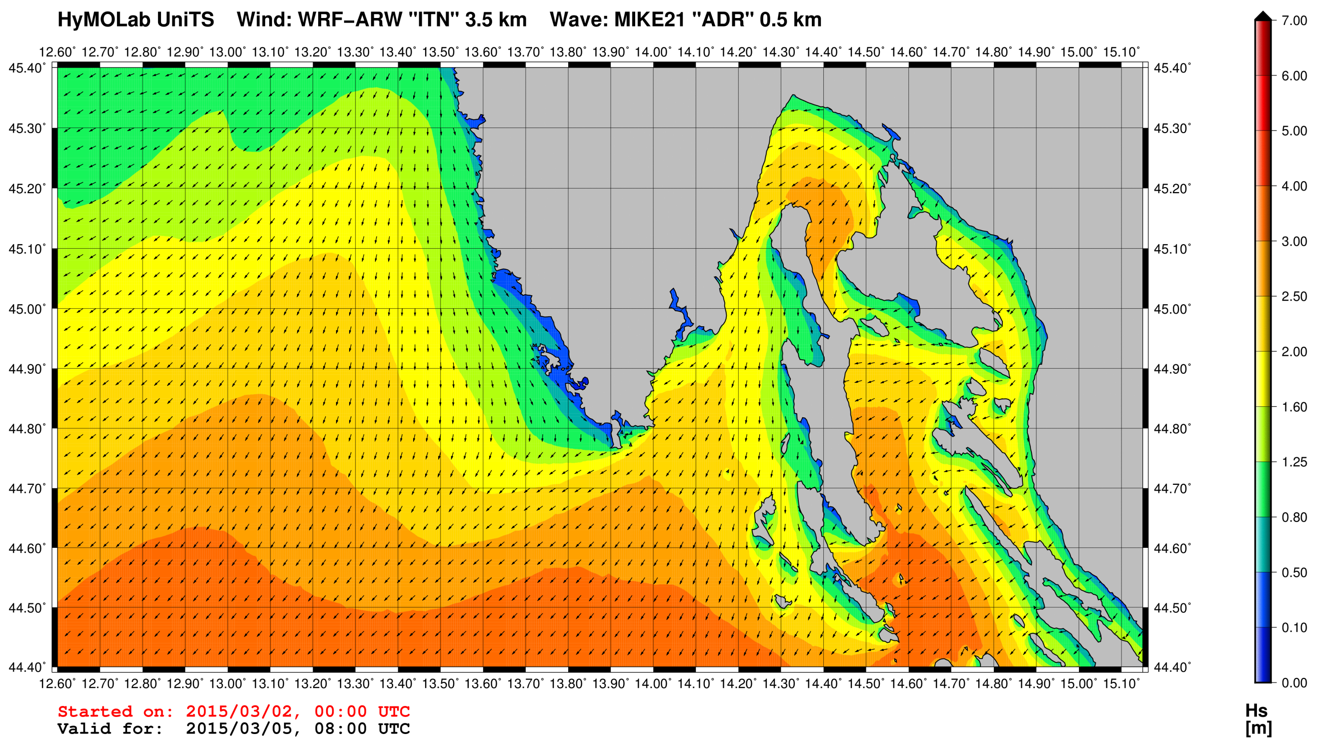

Figure 15: *Bora* occurred on 5th March 2015. High resolution. Wave field.

6 CONCLUSIONS

A complete met-ocean model chain was developed by the authors for medium resolution (around 10 km) wind and wave simulations over the Mediterranean Sea. The model chain was used to develop a 35 years hindcast database as well as an operational forecast service. The results obtained proved to be reliable for both hindcast and forecast applications.

However, it was clear that higher resolutions were needed in order to correctly resolve the jagged coast line and the complex orography of the Adriatic basin.

A very high resolution wind&wave model chain for the Adriatic Sea was set-up by the authors as a nested simulation taking the boundary conditions from the Mediterranean scale domains. Some test cases were run to assess the behavior of the new high resolution model chain. The results obtained show that the 0.5 km resolution set-up for the wave model in the near shore is more than adequate to correctly model the basin of interest. Moreover, the triangular mesh approach allows to obtain burdensome but affordable computational times.

At the time of preparation of this manuscript, no wave data from wave buoys were available along the Croatian coast and not even at the buoy of Ancona (RON). Hopefully, the work will be further developed as soon as these data will be available again, for a complete and objective assessment of the accuracy achieved by the use of very high resolution models.

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