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An operational forecasting system for the meteorological and marine conditions in Mediterranean regional and coastal areas

M. Casaioli[1], F. Catini[2], R. Inghilesi[1], P. Lanucara[2], P. Malguzzi[3], S. Mariani[1], and A. Orasi[1]

[1]Italian National Institute for Environmental Protection and Research (ISPRA), Rome, Italy
[2]Italian Interuniversity Consortium High Performance Systems (CINECA), Rome, Italy
[3]Institute of Atmospheric Sciences and Climate-Italian National Research Council (ISAC-CNR), Bologna, Italy

Correspondence to: R. Inghilesi (roberto.inghilesi@isprambiente.it)

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Abstract. The coupling of a suite of meteorological limited area models with a wave prediction system based on the nesting of different wave models provides for medium-range sea state forecasts at the Mediterranean, regional and coastal scale. The new system has been operational at ISPRA since September 2012, after the upgrade of both the meteorological BOLAM model and large-scale marine components of the original SIMM forecasting system and the implementation of the new regional and coastal (WAM-SWAN coupling) chain of models. The coastal system is composed of nine regional-scale high-resolution grids, covering all Italian seas and six coastal grids at very high resolution, capable of accounting for the effects of the interaction between the incoming waves and the bathymetry. A preliminary analysis of the performance of the system is discussed here focusing on the ability of the system to simulate the mean features of the wave climate at the regional and sub-regional scale. The results refer to two different verification studies. The first is the comparison of the directional distribution of almost one year of wave forecasts against the known wave climate in northwestern Sardinia and central Adriatic Sea. The second is a sensitivity test on the effect on wave forecasts of the spatial resolution of the wind forcing, being the comparison between wave forecast and buoy data at two locations in the northern Adriatic and Ligurian Sea during several storm episodes in the period autumn 2012–winter 2013.

1 Introduction

In the last two decades there has been an increasing interest in applied meteorology to provide marine forecasts as by-product of the traditional meteorological forecasts. Events like Katrina have compelled the improvement of integrated systems capable of correctly simulate and forecast extreme storm-surge events (see, e.g., Wang and Oey, 2008; Sampson et al., 2010), while economic factors associated with both relatively new meteorological applications like weather-routing (Saetra, 2004) and more traditional coastal dynamics applications, have encouraged the meteorological centers to expand in a field which was previously considered as pertaining mostly to oceanography and to coastal engineering. The process has been clearly favored by the rapid development of reliable numerical models (e.g., The WISE Group, 2007).

At the oceanic scale, the scientific and economic interest in improving forecasting systems is to extend the range of a useful forecast in time, that is, implementing Ensemble Prediction Systems (EPS) to get probabilistic forecasts (Saetra and Bidlot, 2004) and couplings between atmospheric, wave and ocean models (see, e.g., Janssen et al., 2013). At the scale of relatively small, almost enclosed seas like the Mediterranean, it becomes likewise critical to improve the quality of the short-term forecasts in the coastal zones. In fact, since a freighter usually traverses the Mediterranean Sea from east to west in only a few days, it follows that the internal distances put a limit to the practical value of extended medium-range wave forecasts. Moving towards the shore, the interactions with the sea-bottom and with morphological features as islands, gulfs or artificial structures become critical factors in determining the time evolution of the wave fields along their path. The wind-wave dynamics assumes an increasingly "local" nature, until waves reach a point where the solution of the stochastic wave-propagation problem can not satisfy the conditions typical of the surf-zone, and the waves break.

Given the complexity of the processes involved, there is considerable scientific interest in the problem of wave propagation on many different spatial-temporal scales, from the global scale to the regional, local and small scale. Numerical models have been developed specialising in some particular range, that is, deep water – global scale models, near-shore models, surf-zone, small-scale models. While the range of scales on which the models are applied are widening in time, the most common approach to deal with the problem is still to nest different models from the large to the smaller scale. If the models are similar in the formulation, as it happens from large scale models to regional and perhaps local scale, a chain of numerical models can be implemented operationally to produce forecasts. The principal advantage of this approach, when applied to closed or almost-closed basins like the Mediterranean Sea, is that there are no lateral boundary conditions to fix because all boundaries are closed. Then, every nested model inherits boundary conditions from the parent model and the important aspect to be dealt with care is the blending of the different grid geometries, the parametrizations of the models and the external forcings.

The meteorological forcing, operating itself at the synoptic, regional and at local scales, is the cause of the swell and the local wave generation, this making wave forecast to depend almost completely on the accuracy of surface wind field. Unfortunately, the wind is hardly the easiest quantity to forecast, especially at the surface. The two main problems with surface wind forecast are the parametrisation of the boundary layer processes and the spatial resolution of the meteorological model. There are many studies in literature (for Mediterranean Sea see, e.g., Signell et al., 2005; Bertotti et al., 2006, 2009; Cavaleri and Bertotti, 2003; Cavaleri and Sclavo, 2006; Bellafiore et al., 2012) indicating that the use of meteorological hydrostatic limited area models (LAM) can effectively improve wave forecast at regional scale, in particular where the the topography affects significantly the mesoscale flow.

Due to its peculiar weather, some of the mentioned studies were focused on the Adriatic Sea, which is a small, almost-enclosed sea bounded by several mountain ranges along most of its borders. The recurrent flooding of Venice, located inside the Venice Lagoon on the north-western border of the sea, is an example of how the meteorological forcing can affect both the regional and local scales. In fact, the floodings (named aqua alta) are related to south-easterly winds (Sirocco) on the entire Adriatic Sea in connection with high tides generating storm surges and high sea waves directed towards the Lagoon. The bora, which is an almost-katabatic wind forced through the Dinaric Alps at the north-eastern border of the Adriatic Sea, is instead an example of strong wind dominated by highly local structures. The two wind regimes, bora and Sirocco, almost completely define the wave climate in the northern Adriatic Sea.

Clearly, bora is a kind of meteorological feature which can hardly be reproduced by low-resolution general circulation models, and even by LAMs. Non-hydrostatic, very high resolution LAMs (VHRLAM) are traditionally aimed to deal with this kind of local scale (loosely defined as on the lower end of the meteorological meso-β scale) phenomena. With the availability of VHRLAMs the expectation was that they would lead to a definite improvement of local wave forecast, like in the case of bora episodes. On the contrary, even though wind fields produced by VHRLAM are more realistic in reproducing complex-terrain situations, some studies (see, in particular, Signell et al., 2005; Bertotti et al., 2006, 2009) indicated that their use as input of wave models have seldom performed better than the simple LAMs. To be fair, it must also be mentioned that forecast verification at very small spatial and temporal scales presents a real challenge to the traditional methods of analysis (the double penalty issue, see, e.g., Mass et al., 2002). A very well resolved field (in terms of spatial distribution, gradients, etc.) with an active dynamics on the short time scale could be outclassed by a field having a reduced spatial and temporal variability when compared with a small number (or even a single) time series. It has been suggested, at least, that in the long term the use of VHRLAMs would provide a better wave climate statistics due to the enhanced variability of the local fields (Signell et al., 2005).

In pondering the advantages of the downscaling against the complexity of the procedures involved, it is important to consider that the main processes related to wave propagation occur in the coastal zone. For example, the formation of wave-induced currents in the region of wave bottom-induced breaking (the surf zone), and the interaction between breaking waves and currents are crucial for the coastal dynamics and the evolution of the shoreline in the long term. The dispersion of pollutants in coastal areas can also be significantly affected by the presence of waves interacting with currents and riverine plumes or jets. Unfortunately, not all the dynamical processes, like bottom-induced breaking or diffraction induced by obstacles, can be easily taken into account by numerical models.

As far as the surf zone is concerned, the traditional wave propagation models, that is, models based on the the solution of the action balance equation (see Whitham, 1999; Lavrenov, 2003), are not adequate to simulate the coastal dynamics properly, and a completely different approach must be considered, like 3-D Navier-Stokes (NS) equations or possibly Boussinesq or non-hydrostatic shallow water equations (Zijlema and Stelling, 2005). Due to the severe time and computational requirements of the 3-D NS models, the idea of considering a complete operational coverage of the coastal processes up to the shore seems definitely premature at the moment. On the contrary, it is completely possible to determine the sea conditions operationally up to the offshore boundary of the surf zone in a large part of the coastal areas. Along these boundaries, wave spectra generated by the operational models can be stored in order to provide boundary conditions for the application of NS surf-zone models in case studies or in climate analyses. An operational chain of wave models from the Mediterranean to the coastal scale is then aimed at not only providing the numerical forecast at the regional and sub-regional scale but also defining the surf zones and determining the boundary conditions to apply for NS models to resolve the individual waves, the alongshore and the rip currents (see, e.g., Lavrenov, 2003).

These considerations were the rationale for the set-up in the late nineties of the ISPRA Sistema Idro-Meteo-Mare (SIMM) and for its further, recent improvement, including the use of higher-resolution models and the development of the Mediterranean-embedded Costal WAve Forecasting system (Mc-WAF). After one year from the Mc-WAF start-up (September 2012), a first preliminary evaluation of the system performance is presented here.

The paper is organized as follows. The SIMM chain and the advances in the meteorological and marine segments are outlined in Sect. 2. Section 3 illustrates the results from the comparison between Mc-WAF forecast and the wave climate at two different locations in the Tyrrhenian and Adriatic Seas. The use of LAM's and VHRLAM's wind during three case studies at La Spezia, Ancona and Venice is also presented in the section. Finally, conclusions and final remarks are presented in Sect. 4.

2 The SIMM forecasting system

2.1 The original SIMM

SIMM is an integrated forecasting system, based on a cascade of several one-way nested numerical models, which has been providing since 2000 hydro-meteorological and marine forecasts over the Mediterranean basin and storm surge (acqua alta) forecasts in the Northern Adriatic Sea (Speranza et al., 2004, 2007).

The SIMM forecasting system is continually updated to incorporate the latest results of research. In particular, attention has been paid to the improvement of the hydrostatic BOlogna Limited Area Model (BOLAM, developed by ISAC-CNR: Buzzi et al., 1994; Malguzzi and Tartaglione, 1999), since it not only provides weather forecasts over the Mediterranean basin, but also gives the input to the marine models of the SIMM chain. A fully updated, parallelized BOLAM version was implemented in 2009 (Mariani et al., 2014b) even keeping the original 0.1° horizontal grid step and domain extension (Fig. 1).

2.2 The new BOLAM-MOLOCH suite

A new higher-resolution BOLAM configuration was implemented in late 2012 after a sensitivity study based on a massive "reforecast" campaign (Casaioli et al., 2013). In that study, five different BOLAM configurations were intercompared on a densely-instrumented verification area. The comparison was made up by combining different settings, namely horizontal grid spacing, domain extension, initial and boundary condition, nesting design, and code version. The optimal configuration found had 0.25° ECMWF initial and boundary conditions and a 0.07° resolution grid (7.8 km) over an extended domain (Fig. 1).

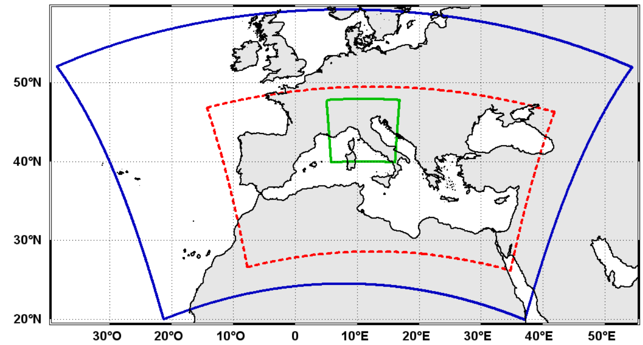

Figure 1. SIMM: model domain for the 0.1° BOLAM (red dashed line), the 0.07° BOLAM (blue solid line) and the 0.0225° MOLOCH (green solid line).

This configuration was hence tested operationally (Ferretti et al., 2013) in the framework of the Special Observation Periods (SOPs) of the international initiative HYdrological cycle in Mediterranean EXperiment (HyMeX, http://www.hymex.org/). In addition, a very-high, 0.0225° version of the convection-permitting ISAC-CNR MOLOCH model (Malguzzi et al., 2006) was implemented in cascade to the hydrostatic BOLAM for SOPs. As shown in Fig. 1, the MOLOCH domain covered Central and Northern Italy. This new configuration will be completely operational within SIMM in 2014.

2.3 Mc-WAF

Mc-WAF is a complex operational tool designed to merge different scales for the generation and propagation of the wave energy in the Mediterranean Sea. The system is effective in connecting the Mediterranean scale with the coastal scale using an intermediate nesting at regional scale. In principle, it allows the use of altimeter data assimilation, regional and coastal surface currents, and also different surface wind fields, that is, LAM's winds at regional scale and VHRLAMS's winds at coastal scale. A high level of modularity in the chain implementation makes also possible to improve the operational system step by step, adding and testing new areas, independently from what was implemented before.

The marine forecast system is the operational implementation of a wind wave hindcasting system which was extensively verified on a series of test-cases in several Italian locations (Inghilesi et al., 2012). The system works on three

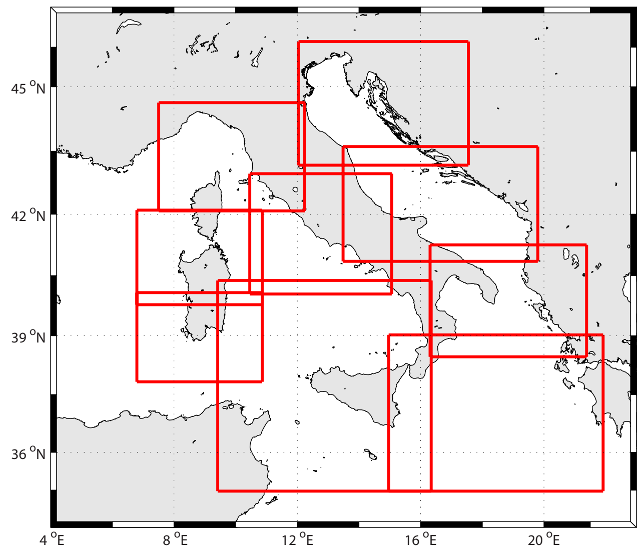

Figure 2. Mc-WAF: implemented regional areas.

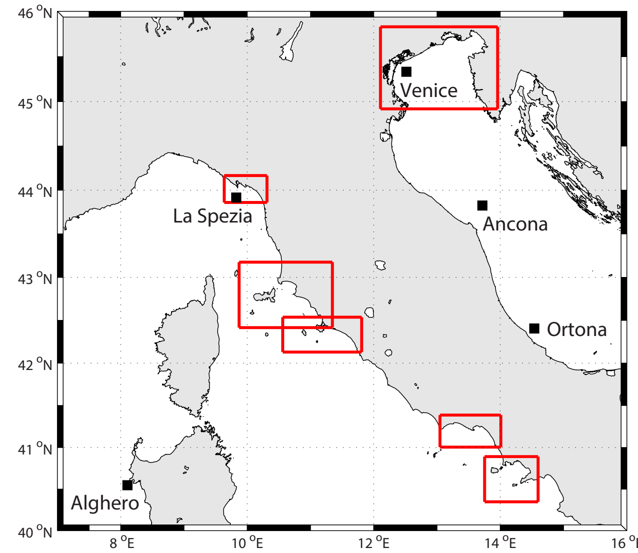

Figure 3. Mc-WAF: implemented coastal areas.

levels of nesting: the Mediterranean model passes the boundary conditions to the regional runs (Fig. 2), each of which, in turn, creates the boundary conditions for all the coastal runs present in the particular regional grid (Fig. 3).

Currently, the wind input is provided by the 0.1° BOLAM model: the same hourly wind fields are used by all wave models in the operational version of the system. The forecast range is 84 h, with 1 h frequency output. The system will be upgraded to use the higher resolution meteorological input tested in the present work in the late 2014, after the complete implementation of the refined meteorological segment of the system.

2.3.1 Mediterranean scale

The marine forecast system at the Mediterranean scale is the first step of the wave operational forecast. The model used is the WAve Model (WAM) cycle 4.5.3 implemented on a grid extending from 5.5° W to 35.73° W in longitude and from 30.0° N to 46.0° N in latitude at 1/30 degree resolution. WAM is a third-generation wave model, that is, it integrates the wave energy-balance equation:

$$\frac{\partial E}{\partial t} + \overrightarrow{c_{\mathrm{g}}} \cdot \nabla_{\mathrm{xE}} = S_{\mathrm{wind}} + S_{\mathrm{nl}} + S_{\mathrm{ds}}, \tag{1}$$

where $E(f,\theta)$ is the variance density spectrum of surface elevation, $f = \omega/2\pi$, is the spectral frequency, θ is the direction, $c_{\mathrm{g}} = \partial\omega/\partial\kappa$ is the group velocity, and ω and κ are related by means of the dispersion relationship. The S functions on the right hand side of the equation represent the sources for wind-wave interaction, resonant nonlinear wave-wave interaction and dissipation, respectively. In the WAM cycle 4.5.3 the wind-generation function and dissipation terms implement the Janssen's formulation, and the nonlinear interaction source function is evaluated using the discrete interaction approximation (see, e.g., Janssen, 2008).

It is perhaps worth mentioning that the use of the Hamiltonian formulation for the time evolution of wave packets implied in the equation relies on the hypothesis formulated by Whitham about the averaged Lagrangian (described in Whitham, 1999). The consequence is that any information about the phase of the waves which constitute the actual sea state is lost. The class of wave models based on the approach described are sometimes named stochastic wave models as opposed to deterministic wave models, which can reproduce the evolution of individual waves (used mostly in the surf zone).

In WAM, the number of directions considered is 24, whereas the number of frequencies is 25 ranging from 0.04177 Hz to 0.4114 Hz. The bathymetry used is the general Bathymetric Chart of the Ocean (GEBCO) at 30 arc-second grid resolution.

2.3.2 Regional scale

In all regional areas, WAM is implemented as in the Mediterranean grid, except for the position and dimension of the grids and for the resolution, which is 1/60° in latitude and longitude. As shown in Fig. 2, the nine regional areas covering all the Italian Seas are: Ligurian-North Tyrrhenian Sea, North Sardinia, South Sardinia, Central Tyrrhenian Sea-Sicily Channel, Ionian Sea, Gulf of Taranto-Otranto Channel, Central Adriatic Sea, Northern Adriatic Sea. The GEBCO bathymetry was locally corrected in each area using the Istituto Idrografico della Marina (IIM) digital maps.

2.3.3 Coastal scale

At the moment, there are six coastal areas implemented: three are imbedded in the northern Tyrrhenian regional area (Carrara, Elba Island and Giglio Island), two are in the central Tyrrhenian (Terracina and the Gulf of Naples), and the last one is in the northern Adriatic Sea. The position of the coastal areas is shown in Fig. 3. The areas are very different in extension. The smallest one, Carrara, covers a surface of about $120 \times 60\,\mathrm{km}^2$, whereas the bigger one, in the northern Adriatic Sea, is almost six times larger. All coastal grids have $1/240°$ resolution in both directions, corresponding to an horizontal cell size of approximately $400 \times 400\,\mathrm{m}^2$. The bathymetries are based on the regional GEBCO-IIM sets, refined nearshore by the inclusion of all local information available (multi-beam cruises and other sources of data).

The model in use in all coastal areas is the Simulating WAves Nearshore (SWAN) model 40.91, cycle III (The SWAN Team, 1993). SWAN is also a third-generation wave model, differing from WAM mostly in the numerical methods used and in the presence of additional source functions in Eq. (1) for shallow water applications.

The forecasts in coastal areas are very sensitive to the correct parametrization of the physical processes, that is, wind generation-whitecapping, shoaling and bottom refraction. Consequently, it is very important to determine in each case which combination of numerical schemes gives the better results and how smooth is the transition from the regional to the coastal scale. Tests in all areas indicated that, for wind generation and white-capping dissipation, the nonlinear saturation-based scheme described in Van der Westhuysen et al. (2007) gives the best results and a good coupling between WAM and SWAN at different scales (see Inghilesi et al., 2012).

3 Test and upgrade of the system

Forecast verification is an important component of the system. SIMM meteorological forecasts have been monitored and verified for over a decade and there is a well-established methodology (see, e.g., Casaioli et al., 2013; Mariani et al., 2014b), which drives the evolution of the meteorological chain of models. Marine verification, implemented originally for deep water forecasts (Speranza et al., 2007), is now being extended to check also the new coastal system. Due to the nesting procedure, accurate forecasts in deep sea are a necessary condition for good forecasts in coastal areas, thus marine forecast verification is still a key factor in the assessment of the reliability of the whole Mc-WAF system. Several aspects have to be considered: the climatological, long-term reliability of the forecasts, the accuracy in the forecast of single storms as compared to buoy or satellite data, and the reliability of the forecast for a given event in terms of probability of occurrence. In this paper, only the first issue is considered, being a more thorough analysis of the problem at the regional and coastal scale the aim of a more focused future study. Unfortunately, a large fraction of the Italian national wind wave buoy network (Rete Ondametrica Nazionale, or RON) was unavailable in the winter 2012–2013 due to serious maintenance problems. In particular, the two buoys moored off the north-western coasts of Sardinia and central Adriatic were un-operational from September 2012 to June 2013.

Nevertheless, a general evaluation of the behavior of the forecasting system can be assessed, at least on the long term, by comparing the joint frequency distributions (JFD) of observed and simulated time series of significant wave height (H_{m0}) and wave direction (or observed and simulated wave climate). Hence, the distribution obtained from the hourly series of H_{m0} forecast in the 10-month period September 2012–June 2013 was compared with the wave climate evaluated over 12 years of hourly data at the corresponding buoy location in the period 1989–2002. For all the analyses presented in this study, forecast time series were assembled using the first 24 h of every daily forecast, starting at 00:00 UTC. A preliminary analysis was aimed at extracting a set of independent values of H_{m0} from both the time series. As a first step, individual storms (continuous periods for which H_{m0} is over a given threshold) were identified on the assumption that different storms are separated by at least 48 h of "calm" sea (H_{m0} < a given threshold). Then, for each storm the maximum value was taken as representative of the event. The procedure was exactly the same used to statistically analyse the extreme wave events in the Mediterranean Sea; a full description of the methodology can be found in Inghilesi et al. (2001).

The hypothesis that the distribution of independent events extracted from the forecast series was identical to the distribution of the independent events extracted from the buoy time series was consequently tested. In order to test the hypothesis, the U Mann-Whitney-Wilcoxon test (hereafter U test) was applied on both the distributions of independent events measured and forecast at Alghero (NW Sardinia) and Ortona (central Adriatic). This statistical non-parametric test is commonly used to decide whether two population distributions are identical without assuming them to follow any known distribution (for more information and applications see, e.g., Mood et al., 1974; Wilks, 2011). In particular, given two samples of independent data and without assuming the data to have normal distribution, it allows to decide at the a-priori significance level $p = 0.05$ whether the data have identical distribution or not. If the result of the test, p value, does not exceed 0.05 the null hypothesis – that the difference is due to random sampling – is rejected, and it is concluded that the two populations are distinct. If the p value > 0.05, the test do not support the rejection of the null hypothesis.

3.1 Alghero

Time series of data and forecasts refer to the position 40.545° N, 8.011° E, corresponding to a water depth of 90 m.

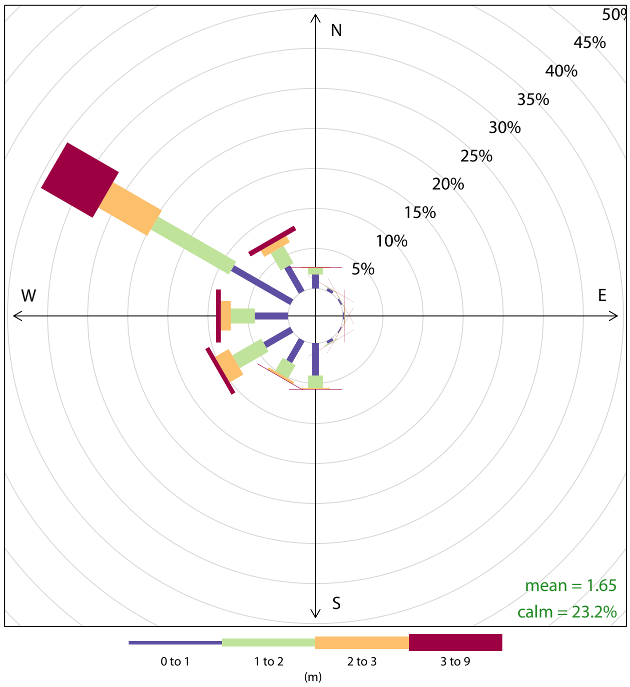

Figure 4. Observed wave climate over 12 years of hourly time series at Alghero (1989–2002).

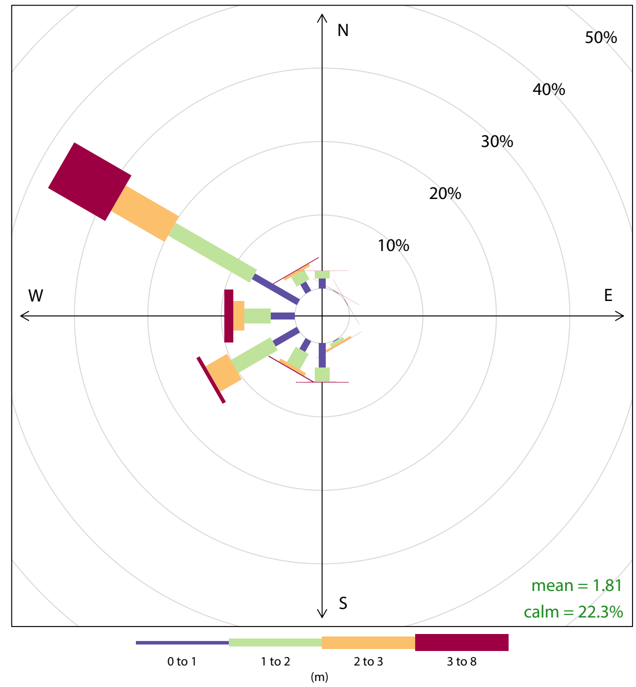

Figure 5. Simulated wave climate over 10 months of hourly time series at Alghero.

The buoy is off the north-western coast of Sardinia (see Fig. 2). Being directly exposed to mistral wind generated in the Gulf of Lyon, the area has experienced the highest storms recorded in the Italian seas since 1989, with maximum observed H_{m0} close to 10 m. The buoy wave climate (Fig. 4), is mostly unimodal, with the higher waves and the higher frequency occurrence of waves over the $H_{m0} = 2$ m threshold directed toward south-east (see Inghilesi et al., 2001; Franco et al., 2004). The JFD relative to 10 months of forecasts are illustrated in Fig. 5. The two distributions look very similar, both indicating that the higher waves come mainly from north-west, with smaller contributions from west and south-west. The set of independent values extracted from 12 years of buoy data have 403 records, the dimension of the set of independent events extracted from the 10 months of forecasts is 28.

The U test was applied to test the null hypothesis that the measured and forecast independent H_{m0} are identical populations. The p value turns out to be 0.8439, exceeding the 0.05 significance level. As a consequence the null hypothesis cannot be rejected and the distribution of the forecast wave climate is identical to the buoy wave climate.

3.2 Ortona

Time series of data and forecasts refer to the position 42.406° N, 14.537° E, corresponding to a water depth of 72 m. The location is representative of the climate of the central and southern Adriatic Sea. The buoy wave climate (see Fig. 6) is mostly bimodal, corresponding to the two main regimes of northerly and easterly winds. The higher waves have been recorded in the northern sector, with maximum waves around $H_{m0} = 7$ m. This is also the sector with the highest frequency of occurrence of episodes with $H_{m0} > 1.5$ m. Maximum waves exceeding $H_{m0} = 4$ m in the eastern sector have been occasionally recorded since 1989 (see Franco et al., 2004). The polar diagrams of the JFD of H_{m0} and mean wave direction relative to 10 months of forecasts are shown in Fig.7.

In the forecast wave climate, it is clear the presence of the same directional sectors found in the observed one, one from north and the other from east. However, the angular distribution of the northern sector is much more narrow and the directional separation between the sectors is much more definite. The set of independent values extracted from 12 years of buoy data has 336 records, whereas the dimension of the set extracted from 10 months of forecast is 22 records. The U test applied to Ortona gives a p value < 0.03, which is less than the 0.05 significance level. Consequently, the null hypothesis of identical distributions is then rejected. The result of the test is that the distribution of the forecast is not identical to the buoy distribution, the two populations are distinct and the differences cannot be explained purely in terms of random sampling.

The consequence of the application of the U test is that, while it is expected that the forecast system will reproduce correctly the wave climate of the western Mediterranean Sea

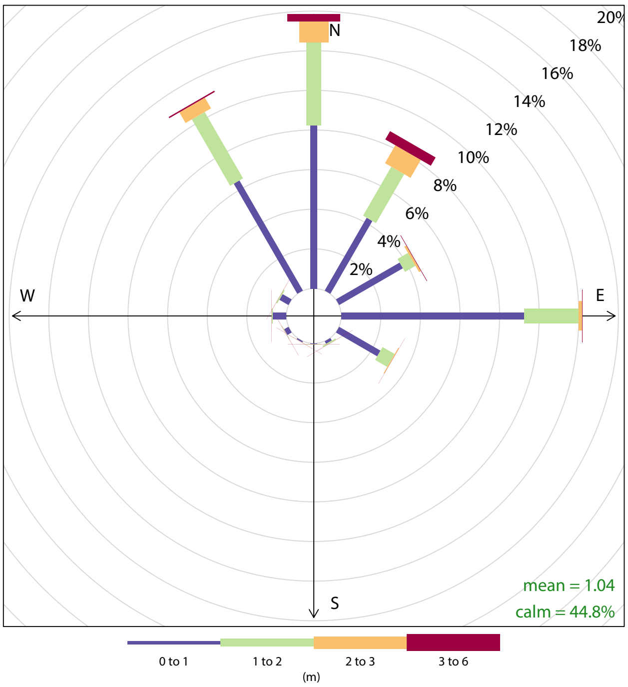

Figure 6. Observed wave climate over 12 years of hourly time series at Ortona (1989–2002).

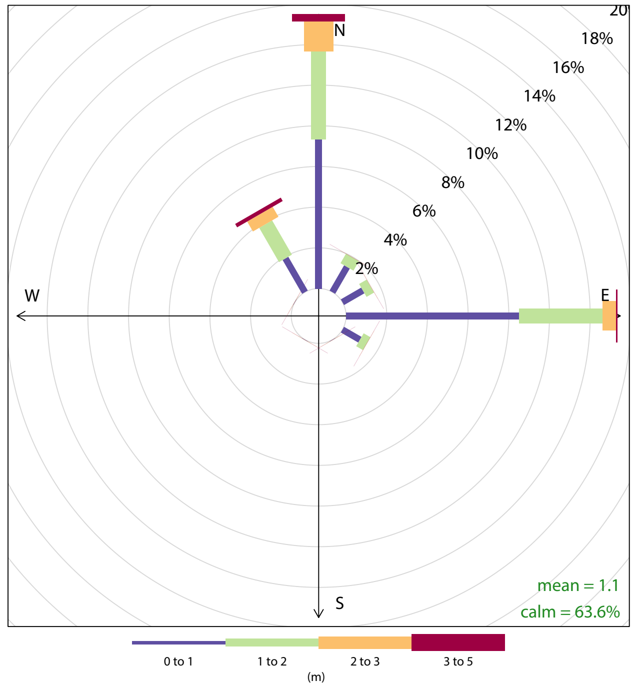

Figure 7. Simulated wave climate over 10 months of hourly time series at Ortona.

related to the mistral wind, there is the possibility that the wave climate in the Adriatic Sea will not properly reproduced by the system. The differences between the directional distributions are mostly in the east sector, like if some of the north-eastern episodes that should have been forecasted were erroneously placed here. This is an indication that the problem is in the correct prediction of the bora-easterly winds. This problem has been recently discussed from the meteorological point of view in Bellafiore et al. (2012) for the northern Adriatic Sea. In view of the complex orography of the area, given that the operational BOLAM runs at 0.1° resolution, an improvement in the wind accuracy can be expected by simply increasing the BOLAM resolution or, alternatively, using a more complex model as MOLOCH. The effects of the two methods of downscaling are discussed in the next section.

3.3 Use of high-resolution wind

During the HyMeX SOPs, a common platform was implemented to compare products from different numerical weather prediction models and efficiently support the planning of the observing strategy of high-impact hydro-meteorological and marine events. Given the positive performance of the new BOLAM-MOLOCH suite during this forecasting activity (Ferretti et al., 2013; Mariani et al., 2014a), it was decided to test and quantify the forecast skill of the Mc-WAF marine component when fed by the high-resolution wind fields generated with both the 0.07° BOLAM and the 0.0225° MOLOCH.

The test was made in two regional areas, that is, the Ligurian Gulf and the northern Adriatic Sea, and in one coastal area, in the upper Adriatic.

Given the availability of forecast and observations during the period September 2012–March 2013 (which includes the two HyMeX SOP campaigns), three different test-cases were selected: the first was in early Autumn, from 25 October to10 November 2012; the second was in late autumn, from 4 to 18 December 2012, and the last was in late winter, from 12 to 26 March 2013. The test was organized as a comparison between forecast and observed data at the buoy locations of La Spezia, Ancona and Venezia.

For Ancona and La Spezia, which are in reasonably deep waters, the forecast time series considered were those obtained from the outputs of WAM at regional scale. The model was driven by three different wind fields generated with: (i) the operational 0.1° BOLAM (wave forecasts indicated as $\mathrm{WAM_{OP}}$); (ii) the new 0.07° BOLAM configuration (wave forecasts indicated as $\mathrm{WAM_{B78}}$); and, (iii) the 0.0225° MOLOCH (wave forecasts indicated as $\mathrm{WAM_{MO}}$). Since the Venice buoy is moored at only 20 m depth, the four H_{m0} forecast series considered in the comparison were obtained using (i) the operational $\mathrm{WAM_{OP}}$ as a reference, (ii) the WAM model fed by the new 0.07° BOLAM (i.e., $\mathrm{WAM_{B78}}$), (iii) the WAM model fed by the 0.0225° MOLOCH (i.e., $\mathrm{WAM_{MO}}$), and, finally, *iv*) the SWAN model fed by the new 0.07° BOLAM (i.e., $\mathrm{SWAN_{B78}}$).

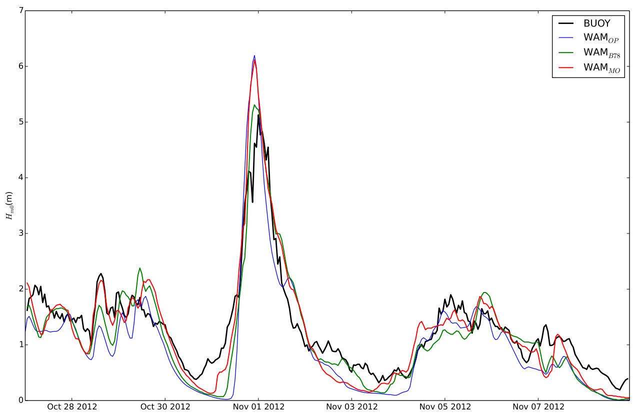

Figure 8. Test-case 1: comparison between forecast and buoy data at Ancona location.

Table 1. Statistics for the Ancona forecast verification.

model	ρ	bias	MSE	MAE	mean	case
Buoy	–	–	–	–	1.19	1
WAM_{OP}	0.92	0.79	0.25	0.40	0.92	1
WAM_{B78}	0.93	0.89	0.16	0.32	1.12	1
WAM_{MO}	0.94	0.95	0.15	0.29	1.08	1
Buoy	–	–	–	–	1.21	2
WAM_{OP}	0.82	0.73	0.37	0.47	0.87	2
WAM_{B78}	0.83	0.75	0.37	0.45	0.97	2
WAM_{MO}	0.82	0.97	0.43	0.46	1.08	2
Buoy	–	–	–	–	1.29	3
WAM_{OP}	0.95	1.01	0.13	0.28	1.31	3
WAM_{B78}	0.95	0.95	0.11	0.26	1.19	3
WAM_{MO}	0.95	1.14	0.18	0.32	1.27	3

Several statistics were taken into account for the test: the correlation coefficient (ρ), the mean square error (MSE), the mean absolute error (MAE), the fractional bias expressed as the ratio between the the mean of the forecast H_{m0} and the mean of the observed H_{m0}, and finally the mean value of H_{m0} in the considered time period.

3.3.1 Deep water – Ancona

The Ancona buoy is located in the north-central Adriatic Sea at the position 43.821° N, 13.717° E (see Fig. 2), and its depth is 70 m.

In the first test-case (see Fig. 8), a single 5 m storm was recorded between 31 October and 2 November 2012. The episode is related to the passage of a small but intense depression over the northern part of Italy. The pressure low was blocked for some days resulting in southerly winds carrying moist, warm water interacting with the dry and cold air to the north of the Adriatic Sea (see Fig. 9). There were intense rainfall episodes, aqua alta at Venice and wind-waves exceeding 4 m in both the Tyrrhenian and the Adriatic Seas.

As shown in Fig. 8, all forecast time series closely follow the development of the storm, the main difference being in the magnitude of the storm peak. Both WAM_{OP} and WAM_{MO} forecast a maximum H_{m0} exceeding 6 m, while WAM_{B78} forecast a value around 5 m that is close to the observed maximum. The lag between the forecast and observed peaks is only one hour. The statistics, shown on top of Table 1, indicate indeed a high correlation for all the series. WAM coupled with the new meteorological suite has a better performance in terms of correlation and bias than those operational. In addition, WAM_{MO} gives a slightly better results in terms of MSE and MAE.

The second test-case occurred with several small events. It was observed a maximum of H_{m0} around 2 m in the period 2–19 December, and a peak reaching 4 m of H_{m0} between 8 and 10 December 2012 (not shown). The statistics, reported in the middle part of Table 1, indicate results similar to the

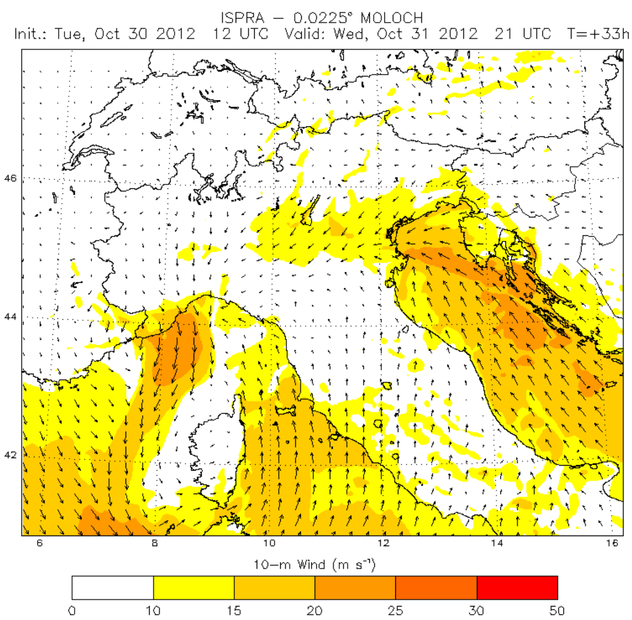

Figure 9. Test-case 1: MOLOCH wind forecast at 21:00 UTC 31 October 2012, initialized at 12:00 UTC 30 October 2012 using 0.07° BOLAM forecasts

first for all the series, but with lower correlations. The best correlation is given by WAM_{B78} with $\rho = 0.83$. The peak of the bigger storm was slightly overpredicted by WAM_{OP} and largely overpredicted (more than 2 m) by WAM_{MO}. The peak given by WAM_{B78} was close to the observed one. The high value of the fractional bias obtained for WAM_{MO} indicates that the large overprediction of the main event acts to compensate the underprediction in the remaining part of the time period considered.

In the third test-case (not shown), there were three small episodes associated with south-easterly winds around 2.5–3.0 m. The correlation, shown at the bottom of Table 1, is high for all series ($\rho = 95\,\%$). In all episodes, WAM_{MO}

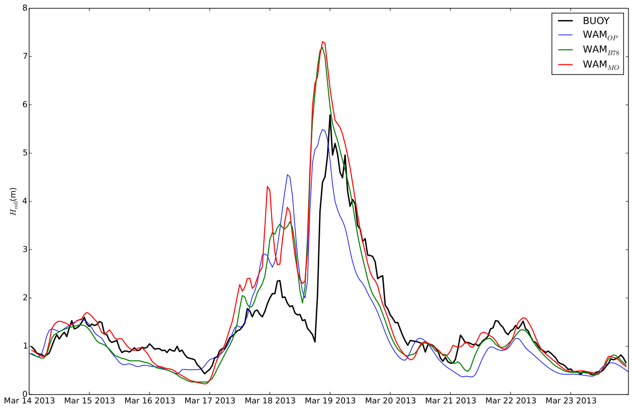

Figure 10. Test-case 3: comparison between forecast and buoy data at La Spezia buoy location.

Table 2. Statistics for the La Spezia forecast verification.

model	ρ	bias	MSE	MAE	mean	case
Buoy	–	–	–	–	1.64	1
WAM$_{OP}$	0.86	0.91	0.35	0.46	1.46	1
WAM$_{B78}$	0.92	1.23	0.64	0.6	1.91	1
WAM$_{MO}$	0.92	1.32	0.95	0.75	2.03	1
Buoy	–	–	–	–	1.49	2
WAM$_{OP}$	0.85	0.91	0.21	0.33	1.35	2
WAM$_{B78}$	0.89	1.1	0.37	0.42	1.30	2
WAM$_{MO}$	0.88	1.2	0.41	0.45	1.33	2
Buoy	–	–	–	–	1.31	3
WAM$_{OP}$	0.78	0.93	0.45	0.42	1.24	3
WAM$_{B78}$	0.84	1.01	0.53	0.38	1.29	3
WAM$_{MO}$	0.86	1.12	0.56	0.37	1.30	3

overpredicted the peak of the storm by more than 0.5 m, and the WAM$_{OP}$ overpredicted two out of three peaks. WAM$_{B78}$ was reasonably close to the observed series during all the period. For this event, the statistics clearly indicate that WAM$_{B78}$ performs better than its competitors.

3.3.2 Deep water – La Spezia

The location of La Spezia buoy is in the Ligurian Gulf, position 43.914° N, 9.827° E (see Fig. 2); it is moored at 90 m depth. The wave climate of the area is mostly unimodal, with waves coming from south-west.

In the first test-case considered (25 October–8 November 2012; Fig. 9), a 5 m H_{m0} event was observed between 27 and 29 October 2012, followed by two smaller events between 3 and 4 m H_{m0} (not shown). The peak of the first event was underpredicted by WAM$_{OP}$ by more than 1 m, while both WAM$_{B78}$ and WAM$_{MO}$ overpredicted the peak by respectively 1 m and more than 1.5 m. The two smaller events were both also largely overpredicted by the new suite of meteorological models. The statistics at the top of Table 2 indicate that the new chain (0.07° BOLAM and 0.0225° MOLOCH + Mc-WAF) performed better in terms of correlation than the operational run (0.1° BOLAM + Mc-WAF). On the contrary, they showed a larger fractional bias and MSE.

In the second test-case, an event exceeding 4.5 m was recorded between 4 and 5 December, followed by two smaller events reaching 2–3 m at the peak of the storm. All models overestimated the most important storm, the operational run by more than 1 m, the others by more than 2 m. The smaller events were more or less closely reproduced by all the models. The statistics in the middle of Table 2 indicate a relatively low correlation for all models, similar bias (WAM$_{OP}$ underestimating, the others overestimating), and shown that the errors are significantly larger for WAM$_{B78}$ and WAM$_{MO}$ than for the operational model.

In the third test-case, a single event exceeding 5 m was observed between 19 and 20 March 2013 (see Fig. 10). The event had an abrupt growth after a small peak occurred the day before, and a short duration. The peak of the storm was anticipated by a few hours by the forecasts, WAM$_{OP}$ being very close to the recorded value. WAM$_{B87}$ and WAM$_{MO}$ both largely overpredicted the peak by approximately 2 m, and all models overpredicted the small storm precursor by more than 2 m. As a consequence, the statistics at the bottom of Table 2 indicate that the correlation is relatively low, with WAM$_{MO}$ and WAM$_{B78}$ being better than the operational run. The fractional bias indicates the overprediction tendency of the new model chain (0.07° BOLAM and 0.0225° MOLOCH + Mc-WAF) opposite to the underprediction tendency of the operational model chain (0.1° BOLAM + Mc-WAF). The MSE of WAM$_{MO}$ and WAM$_{B78}$ are significantly larger than the operational run.

3.3.3 Intermediate-shallow water – Venice

The location of the Venice buoy is in the north-eastern part of the Adriatic Sea (marked in Figs. 3 and 11), at latitude 45.330° N, longitude 12.516° E, and it is moored at 20 m depth.

Two events with H_{m0} around 3–4 m were observed during the first episode, in the period 28 October–8 November 2012 (Fig. 12). In the second test-case, only one small event reaching 2.5 m at the top of the storm was recorded between 7 and 9 December (not shown). In the third test-case, two similar events with H_{m0} not exceeding 2.5 m were observed between 17 and 27 March 2013 (not shown). Since the focus of the study is mainly on wave peaks exceeding 2.5 m, only the results of the first Venice test-case are illustrated in the present study.

The case considered is the evolution at regional and local scale of a complex meteorological condition of blocking. It began with a bora wind, with strong north-easterly winds

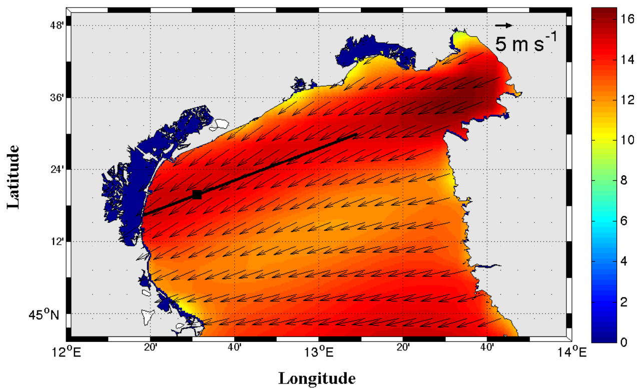

Figure 11. Test-case 1: the 0.07° BOLAM wind field (black arrow), the WAM$_{B78}$ wave height field (color filled contour plot) and a transect at the peak of the storm on 29 October. The Venice buoy is also indicated as a black square.

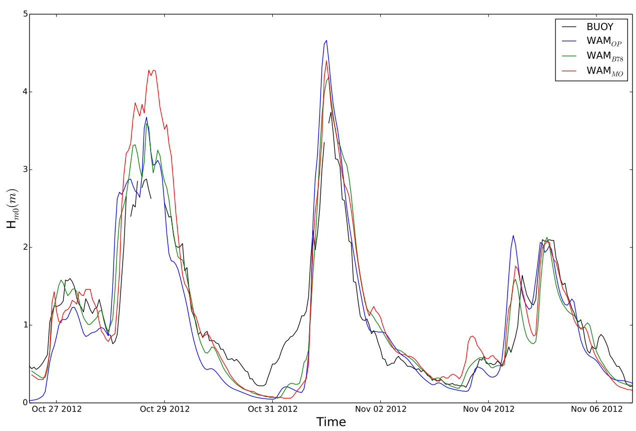

Figure 12. Test-case 1: comparison between forecast and buoy data at Venice buoy location.

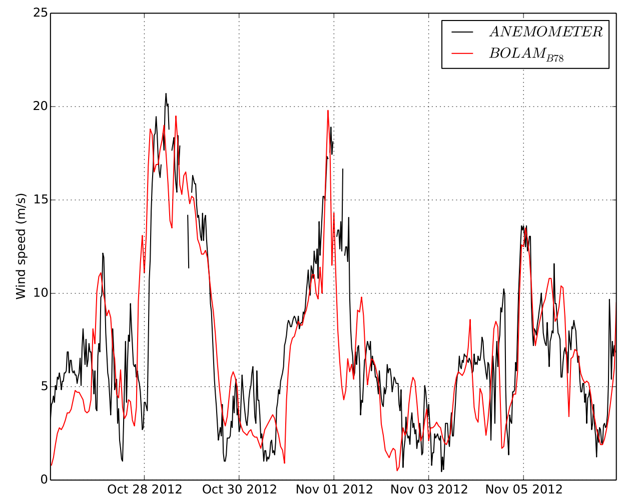

Figure 13. Test-case 1: Comparison between wind forecast and anemometer data at Venice during the first test case.

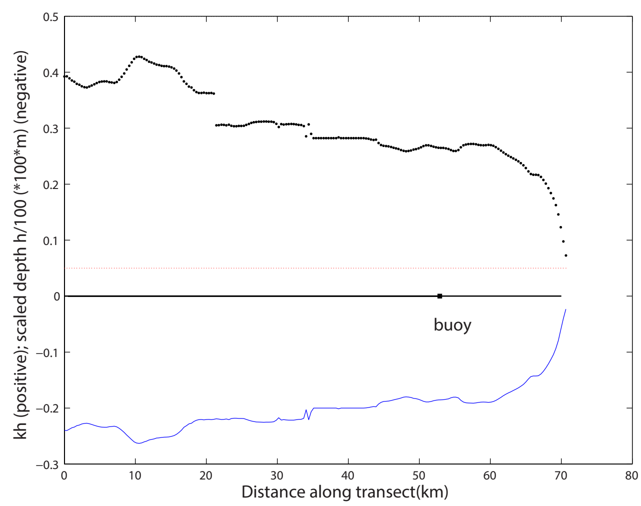

Figure 14. Test-case 1: *kh* and depth *h* along the transect in Fig. 11.

in the north Adriatic Sea and wind speed up to 20 m s^{-1} occurring on 29 October. The wind field forecast by the 0.07° BOLAM at 00:00 GMT, 29 October is illustrated in Fig. 11. In the same figure is marked in black the position of a 70 km long transect traced along the direction of the waves crossing the buoy position. Few days after the first case, the wind was strong and south-easterly in all the Adriatic Sea except in the very upper part of the basin, where it rotated locally counter-clockwise in the north-easterly direction (see Fig. 9). It was the result of a typical blocking situation. The wind in this circumstances is referred to as "dark bora", because the southerly flux of warm and moist air which impinges against the blocking cold air to the north of the Adriatic Sea carries dark clouds and rain. This complex situation produced severe weather conditions on 1 November.

The comparison between buoy data and the regional scale models, shown in Fig. 12, indicates that all the models reproduced the evolution of the two storms both in the growth and in the decay of the events. In the first bora episode, the regional WAM$_{B78}$ and the WAM$_{OP}$ overestimated the peak of the storm by approximately 1 m, while the WAM$_{MO}$ overestimated the peak by more than 2 m. In the second "dark bora" episode, all models overestimated the peak by approximately 1 m. The regional WAM$_{B78}$ implementation is better correlated, but WAM$_{OP}$ has smaller bias and MSE. The WAM$_{MO}$ statistics reflect the fact that the 29 October peak was largely overestimated. Wind data collected on the buoy is available for the time period considered, even though the data quality is not ideal. The comparison between 0.07° BOLAM and the anemometer data corrected for the reference 10 m height indicates that the agreement between the forecast and the anemometer data is acceptable (see Fig. 13). The comparison with MOLOCH and the operational BOLAM produces very similar results, with MOLOCH wind speed just 1 m s^{-1} stronger than the other forecasts during the first episode.

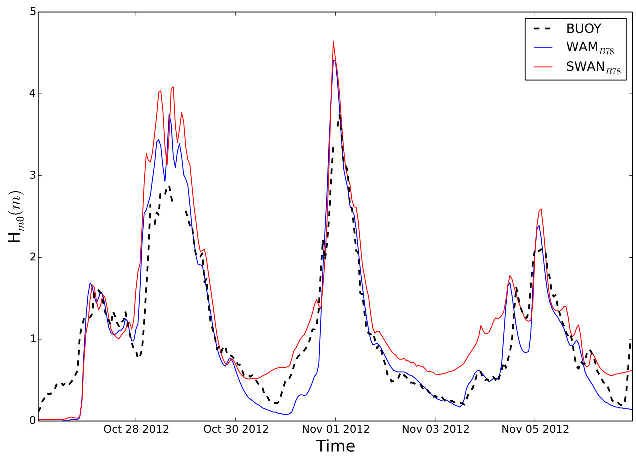

Figure 15. Test-case 1: comparison between SWAN$_{B78}$ and WAM$_{B78}$ at Venice buoy location.

In order to verify whether the waves produced during a major bora storm propagate in deep, intermediate or shallow waters up to the buoy location, the wavelength k along the 70 km long transect x indicated in Fig. 11 has been evaluated using SWAN$_{B78}$ data for the predicted 4 m H_{m0} peak related to the 29 October event. Figure 14 shows, on the negative y axis, the bathymetry $h(x)$ along the transect x scaled as 1/100 m. The product $k(x)h(x)$ is shown on the positive y axis. The bathymetry along the transect up to the position of the buoy rises very gently up to $h = 20$ m. From this point up to the shoreline the depth climbs much more rapidly. The value of $kh < 0.5$ along all the transect indicates that, up to the buoy, the propagation of the wave is not in "deep water", meaning that the phase velocity of the waves is not independent of h, but neither is equal to the group velocity, as it would be if it was $kh < 0.05$ somewhere. It means that, even when the waves are relatively high, the propagation is affected mainly by the effect of the shoaling. The dissipative effects directly related to the bottom (friction, breaking, triads nonlinear interaction), which are typical of shallow waters, are not very significant in intermediate water. In this situation both WAM and SWAN are applicable, WAM becoming more and more overpredicting as the waves move to the region $kh < 0.1$ close to the shoreline.

The comparison between H_{m0} buoy data, SWAN$_{B78}$ and WAM$_{B78}$ is shown in Fig. 15. For $H_{m0} > 1$ m there are small differences between the two models, while for small values of H_{m0} it seems that SWAN$_{B78}$ overestimates systematically. It is probably a symptom that the Mc-WAF implementation of the nesting WAM/SWAN in the northern Adriatic area is not adequate in very low wind conditions. The statistics in Table 3 indicate that all series are well-correlated with the buoy data.

The SWAN results in the coastal areas directly affected by the north-easterly winds, corresponding to the bora peak on 29 October, are shown in Fig. 16. The position and the extension of the regions where the friction and breaking induced by the bathymetry are clearly visible in the figure, in particular to the north of the Venice Lagoon and to the south, in the region of the Po river delta.

Table 3. Statistics for the Venezia forecast verification.

model	ρ	bias	MSE	MAE	mean	case
Buoy	–	–	–	–	0.89	1
WAM$_{OP}$	0.91	0.95	0.16	0.28	0.82	1
WAM$_{B78}$	0.92	1.03	0.12	0.23	0.96	1
WAM$_{MO}$	0.91	1.09	0.15	0.26	1.01	1
SWAN$_{B78}$	0.91	1.31	0.20	0.30	0.95	1

4 Conclusions

An operational forecasting system for the Mediterranean Sea working at regional and coastal scale has been implemented coupling several meteorological and wave models. The system is aimed to forecast meteorological events at regional scale in complex orography, and is able to predict the generation and propagation of wind waves in marine and coastal areas. The coastal-scale simulations provide not only operational forecast but also the mapping of the shallow water areas and the extension of the surf zones in relation to the local wave climate. The information gathered at coastal scale is the basis for the investigation of coastal scale processes like wave breaking induced currents and interactions with jets and riverine plumes.

A preliminary test on the capability of the system to reproduce the wave climate features in the west Mediterranean and in the Adriatic Sea has been performed. The U test was aimed to assess if the JFD of the events predicted in the first year of Mc-WAF operativity has identical distribution as the distribution extracted from 12 years time series of buoy data. The results indicate substantial differences in the reliability of the forecasts in the two areas. In the north-west Mediterranean Sea the simulated wave distribution is in close agreement with the observed wave climate, indicating that the mistral regime is well-reproduced by the system. In the central Adriatic Sea the test concluded that the distribution of the forecast is not identical to the known wave climate, indicating a possible systematic error in the reproduction of the weather at regional scale. In particular, the analysis of the differences of the JFD of H_{m0} an direction suggests that a significant fraction of the bora events were not correctly reproduced. In order to investigate the methods to improve the forecasts at sub-regional scale, several tests were made to assess the benefit of using a downscaling in areas bordered by complex topography. In this work two different methods for meteorological downscaling were applied: the refinement of the BOLAM grid in order to better resolve the orography and the use of a more complex, non-hydrostatic model, MOLOCH.

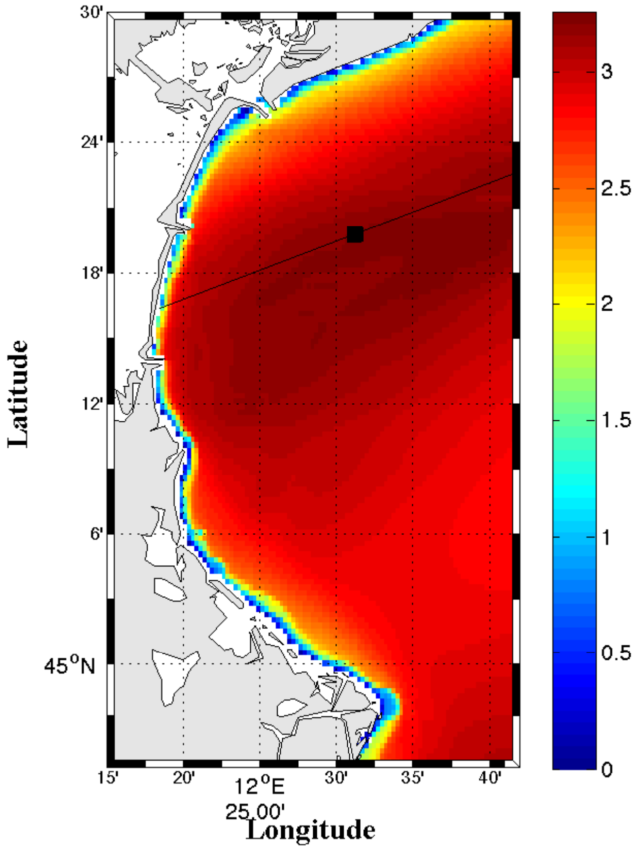

Figure 16. Test-case 1: field of H_{m0} produced by $\mathrm{SWAN_{B78}}$ at the peak of the storm on 29 October.

The downscaling has been applied to three test-cases in order to test the limitations and the benefits of the use of more intensive and time-consuming operational procedures. The first test-case was particularly severe for the system, in that the particular meteorological blocking considered proved to be dynamically complex with strong spatial gradients and rapidly varying local conditions. Nevertheless, the marine conditions were reasonably well forecasted both in the Tyrrhenian and the Adriatic Sea.

The results of the comparisons between forecast and buoy data during several high-impact meteo-marine events in the Ligurian and Adriatic Seas are encouraging and support the operational implementation of the new high-resolution BOLAM in all the regional areas. The improvement is due to the increase in spatial resolution of the model but also to an optimization in the nesting with the ECMWF IFS model. The use of VHRLAM MOLOCH did not provide better performances than the BOLAM in the test-cases considered. It was seen that often the wave forecasts overpredicted the buoy data more than the other implementations, and the MSE and MAE were generally higher. On the contrary, the test-cases considered were relatively few, especially in the northern Adriatic Sea where, due to the complex orography, the potential benefits of the use of VHRLAM are larger.

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