The sea state forecast system of ARPA-SIM

A. Valentini[1], L. Delli Passeri[2], T. Paccagnella[1], P. Patruno[1], C. Marsigli[1], D. Cesari[1], M. Deserti[1], J. Chiggiato[1] and S. Tibaldi[1]

[1] *ARPA-SIM, Servizio IdroMeteorologico Emilia Romagna, Bologna, Italy.*

[2] *DPC, Dipartimento della Protezione Civile, Roma, Italy*

(Received: April 21, 2006; accepted: February 12, 2007)

ABSTRACT The “sea state” is the description of the properties of the sea surface waves at a given time and location. This might be given in terms of wave spectrum or more simply in terms of significant wave height, wave direction, mean and peak period; this information can be obtained by means of numerical models. The sea state operational forecast system, daily running at the Hydro-Meteorological Service of ARPA Emilia-Romagna (ARPA-SIM), now covers different geographical domains, from the Mediterranean Sea to the coast of the Emilia Romagna region. The peculiarity of this system is due to the accurate wind field forcing coming from the high resolution (at present 7 kilometres) of the limited area model operating at ARPA-SIM and available with a high temporal frequency (1 hour). Data output are stored in GRIB format in the service database and today, an almost decennial data set is available; daily outputs are published each day in a graphical format on the public web site. This paper aims at describing how the forecast system has been developed during these years and which are the perspectives of ARPA-SIM in this field.

1. Introduction

The sea state forecasting can be used in many fields and in many activities: public assistance and accident prevention, oil-spills, ship routing, tourism, aquatic sports and the planning of such sea activities that are heavily dependent on the wave field state.

The Hydro-Meteorological Service of ARPA Emilia-Romagna, ARPA-SIM (www.arpa.emr.it/sim), began its operational activity in the sea state forecasting of the Adriatic Sea in 1997. The first was the WAM model (WAve Model: WAMDI group, 1988) whose development started under the guidance of Klaus Hasselmann (Max-Plank Institut fuer Meteorologie und Klimatologie of Hamburg).

In the period 1997-2004, WAM was forced by the 10 metre-wind forecast by the limited area model LAMBO (Limited Area Model BOlogna) operational at ARPA-SIM at that time.

Since 2004, the forcing wind is provided by the new operational limited area model LAMI (Limited Area Model Italy), running at ARPA-SIM, which has replaced the former LAMBO. This has led to notable improvements in terms of highly detailed structure, significant stronger and more accurate overall wind speeds (Signell *et al.*, 2005), elements of primary importance for the application of wave models in small and high resolution geographical domains.

In 2004, a new operational suite was also implemented, covering the whole Mediterranean basin and based on the WAM model forced by the wind provided by LAMI and by GME, outside the LAMI integration domain. GME is the Global Meteorological Model (Majewsky, 1998;

Majewsky *et al*., 2002) of the German Weather Service, DWD (Deutscher WetterDienst, Offenbach, D) providing LAMI with the boundary conditions.

Thanks to a cooperation between ARPA-SIM and the National Department for Civil Protection in Rome, and to some EU projects designed to fulfill the increasing interest for the coastal erosion dynamics, ARPA-SIM implemented a new wave model, more suitable for the shallow waters forecast of coastal areas, in 2004.

A new suite was introduced, based on the model SWAN, Simulating WAves Nearshore (Holthuijsen *et al*., 1989; Booij *et al*., 1999; Ris *et al*., 1999; http://fluidmechanics.tudelft.nl/swan/), also forced by the 10 metre- wind by LAMI.

In section 2, this paper introduces the general features of the meteorological and wave models that have been operating at ARPA-SIM during these years; model implementations (past, present and future implementations) are described in section 3, followed by a brief overview of model verification results, later explained in section 4, with the conclusion in section 5.

2. Overview of the models

In this section LAMBO and LAMI, the meteorological models providing the necessary surface forcing, will be outlined before describing the two wave models, WAM and SWAN.

2.1. Meteorological models

2.1.1. The LAMBO model

LAMBO is the ARPA-SIM atmospheric, limited area model that was operational until 2004. It is a finite difference, split-explicit, primitive equation hydrostatic model, based on an early version of the NCEP ETA Model (Mesinger *et al*., 1988; Janijc, 1990).

At ARPA-SIM, the operational suite was based on two consecutive LAMBO runs: the coarser one was at about 40 km of horizontal resolution and 21 vertical levels on terrain following sigma-coordinates. The initial conditions were provided by ECMWF (European Centre for Medium-Range Weather Forecasts) operational analysis, interpolated for the LAMBO resolution; the boundary conditions were provided by the ECMWF operational forecast, available every 6 hours throughout the integration time. The integration domain approximately covered the area 4.W - 29.E, 33.N - 52.N. The higher resolution run had a horizontal resolution of about 20 km and the integration domain covered the Italian peninsula and the Alpine region, with 32 vertical levels again on terrain following sigma-coordinates. Boundary and initial conditions were provided by the coarser run and updated every 3 hours.

LAMBO was operationally run twice a day, nested on ECMWF operational runs of 00 and 12 UTC, the forecast length being 72 and 84 hours, respectively. Outputs were provided every three hours.

2.1.2. The LAMI model

LAMI (COSMO Newsletter, 2004) is the Italian operational implementation of Lokal Modell, LM (Steppeler *et al*., 2003), the limited area model originally developed by the German Meteorological Service, DWD for meso/micro-scale weather prediction and simulation.

LM is developed by several European meteorological services belonging to the COSMO consortium (COnsortium for Small scale MOdelling, www.cosmo-model.org).

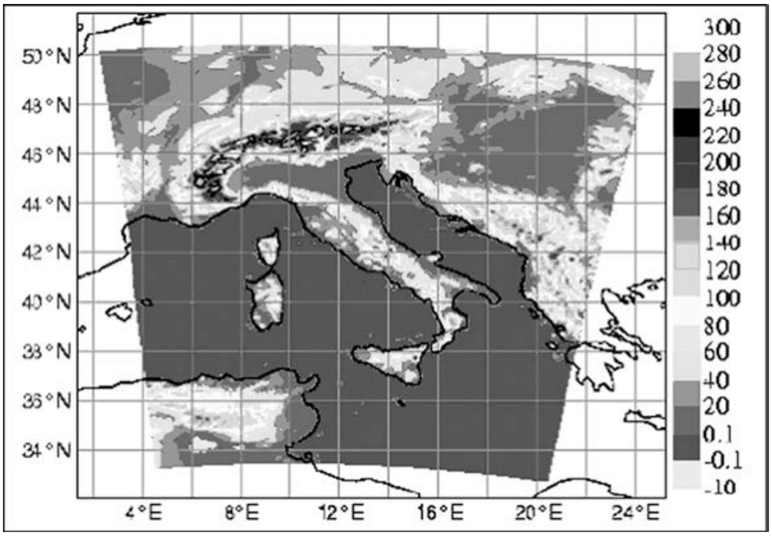


Fig. 1 - The orography field (in decametres) inside the LAMI integration domain

LAMI is managed by ARPA-SIM, UGM (Ufficio Generale per la Meteorologia, Italian Airforce) and ARPA Piemonte. It is based on primitive hydro-thermodynamical equations describing compressible non-hydrostatic flow in a moist atmosphere without any scale approximations. The use of non-hydrostatic compressible (i.e. unfiltered) dynamical equations allows us to avoid restrictions on the spatial scales and on the domain size. The equation of the vertical momentum is not approximate, so that it can describe the phenomena where it is important to take into account the vertical velocity (for example convective storms, sea and mountain breezes) much better. The basic equations are written in advection form and the continuity equation is replaced by a prognostic equation for the perturbation pressure (i.e. the deviation of pressure from the reference state). The model equations are solved numerically using the traditional finite difference method.

The hydro-meteorological service of ARPA Emilia-Romagna, ARPA-SIM, has been using LAMI as the operational forecast model since 2001; LAMI is run twice a day (at 00 and 12 UTC) for 72 hours, with a spatial horizontal resolution of 7 km and 35 vertical levels on terrain following coordinates (see in Fig. 1 the geographical domain). Boundary conditions are provided every hour by the GME global model of the DWD. A mesoscale data assimilation is also applied, using a nudging technique (Schraff and Hess, 2003), providing the initial field.

2.2. Wave models

2.2.1. The WAM model

The WAve Model Cycle 4 (WAMC4) is a spectral wave prediction model developed by the WAMDI Group (1988). It is a third-generation wave model that solves the wave transport equation explicitly without any *a priori* assumption on the shape of the wave energy spectrum.

The evolution of the wave spectrum is described by the spectral energy density balance equation which for Cartesian coordinates is:

$$\frac{\partial E}{\partial t}+\frac{\partial (C_x E)}{\partial x}+\frac{\partial (C_y E)}{\partial y}+\sigma\frac{\partial}{\partial \sigma}\left(C_\sigma \frac{E}{\sigma}\right)+\frac{\partial (C_\theta E)}{\partial \theta}=S_{tot} \quad (1)$$

where $E(t, x, y, \sigma, \theta)$ is the wave energy density spectrum, t is the time, σ is the intrinsic angular frequency, θ is the wave direction measured clockwise from the true north, C_x and C_y are the propagation velocities in geographical space, and C_σ and C_θ are the propagation velocities in spectral space frequency and directional space.

The first term on the left-hand side of Eq. (1) represents the local rate of change of wave energy density, the second and third terms represent the propagation in geographical space, the fourth and fifth terms represent shifting of frequency and refraction due to the spatial variation of the depth and current. The right-hand side represents all effects of generation and dissipation of the waves including wind input S_{in}, whitecapping dissipation S_{wcap}, non-linear quadruplet wave–wave interactions S_{nl4} and bottom friction dissipation S_{bot}.

Computationally, Eq. (1) is solved in two parts. The propagation of the energy density is solved by discretisation of the left-hand side, setting the right-hand side equal to zero, into a first-order explicit upwind scheme. The time step for this part is limited by the Courant–Friedrichs–Lewy (CFL) stability condition, and may be calculated on either a spherical or Cartesian grid. The source term contribution is then added using a semi-implicit forward time scheme.

A detailed description of WAM Cycle 4 model can be found in Komen *et al.* (1994).

2.2.2. The SWAN model

SWAN is a third-generation wave action model designed to overcome traditional difficulties of applying wave action models in coastal regions. The SWAN model was developed at Delft University of Technology (TU Delft, NL), with support from the Office of Naval Research (USA) and the Ministry of Transport, Public Works and Water Management (The Netherlands).

The primary difficulty of applying wave models in nearshore regions is that such applications must be computed at high geographic resolution, of the order of 100 metres or less. If a conditionally stable geographic propagation scheme is employed at such a resolution, then a high temporal resolution must be used, which makes computations very expensive. SWAN solves this problem by using an unconditionally stable geographic propagation scheme.

In SWAN, waves are described with the two-dimensional wave action density spectrum. The evolution of the wave spectrum is described in terms of action density spectrum N rather than energy density spectrum E since in the presence of currents, action density is conserved whereas energy density is not (Whitham, 1974).

The spectral action balance equation for Cartesian coordinates is (Hasselmann *et al.*, 1973):

$$\frac{\partial N}{\partial t}+\frac{\partial (c_x N)}{\partial x}+\frac{\partial (c_y N)}{\partial y}+\frac{\partial (c_\sigma N)}{\partial \sigma}+\frac{\partial (c_\theta N)}{\partial \theta}=\frac{S}{\sigma} \quad (2)$$

The first term in the left-hand side of Eq. (2) represents the local rate of change of action density in time, the second and third term *S* represent propagation of action in geographical space with propagation velocities c_x and c_y in spectral space frequency and directional space. The fourth term represents shifting of the relative frequency due to variations in depths and currents (with propagation velocity c_σ in σ-space). The fifth term represents depth-induced and current-induced refraction (with propagation velocity c_θ in θ-space).

The term *S* at the right hand side of the action balance Eq. (2) is the sum of source/sink terms expressed as wave energy density representing the effects of generation, dissipation and nonlinear wave-wave interactions. It is essentially composed of terms proper to general physics, implemented in wave models suitable for large scale and deep water sea state forecasts (input by wind, four-wave nonlinear interactions, and dissipation due to whitecapping), and terms describing generation and dissipation phenomena in shallow waters (three-wave nonlinear interactions, dissipation due to wave breaking and dissipation for bottom friction) that characterize the SWAN model nearshore applicability.

The integration of the action balance Eq. (2) is implemented in SWAN with finite difference schemes in all five dimensions (time, geographic space and spectral space). The numerical scheme in geographic space is a first order implicit upwind scheme that is robust, efficient and economical, its unconditional stability permits relatively large time steps in computations. In spectral space, instead, a mixing of upwind scheme and implicit central scheme has been implemented in order to achieve the accuracy required.

3. ARPA-SIM wave models implementations

3.1. WAM Adriatico at ARPA-SIM

During the period 1997-2004 WAM cycle-4 was forced by the 10 metre-wind computed by the meteorological model LAMBO. Since 2004, the same version of the wave model has been driven by wind predicted by LAMI.

The domain considered is the whole Adriatic Sea area, with about an 8 km horizontal resolution (see in Fig. 2a a run output).

The model is run once a day at 00 UTC (the operational chain is shown in Fig. 2b) after a 24-hour analysis cycle to produce an initial wave field. Each day the 24 hours warm-up cycle starts with a “hotstart” from the wave field produced by the previous one, and is forced by ECMWF global model wind analysis available every 6 hours.

The forecast range was forced by the 10 metre LAMI wind with a range of 72 hours and outputs provided every three hours in GRIB format.

The technical specifications of the WAM Adriatico are as follows:

- geographic domain: 12°-20° (longitude east), 40°-46° (latitude north);
- 10 m wind as forcing: by LAMBO until 2004, by LAMI later;
- computational grid (regular): 1/12 of degree, about 8 km;
- one forecast each day: 00 UTC;
- forecast range: +72 hours with three-hourly outputs;
- output variables: significant wave height, mean direction, mean and peak period.

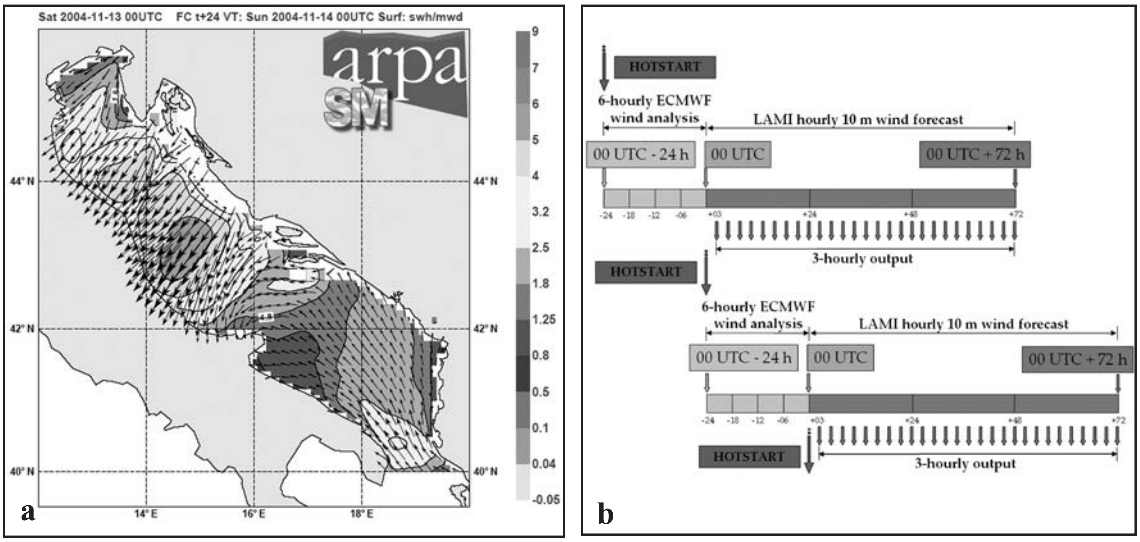


Fig. 2 - WAM model over the Adriatic Sea: a) significant wave height (in metres) and wave direction by a run; b) the operational chain; each forecast run is initialized with a wave field produced by a continuous warming-up (analysis) cycle restarted every 24 hours. Each of these daily cycles produces an hotstart field for the following one. The analysis cycle if followed by 72 hours of forecast forced by the high resolution limited area wind.

3.2. WAM Mediterraneo at ARPA-SIM

Since the end of 2004, the service has been running the WAM model (cycle-4) over the Mediterranean Sea with a resolution of 10 kilometres (see a run output in Fig. 3).

Outside the LAMI integration domain, WAM is driven by the GME wind. Consistency at the edge is respected because boundary conditions of LAMI are provided exactly by the same GME model.

The model is run once a day at the Super Computing Centre CINECA (Consorzio Interuniversitario per il Calcolo Automatico dell'Italia Nord Orientale) according to the operational chain shown in Fig. 4. Outputs are provided in GRIB format every three hours for a maximum forecast range of 72 hours; a more technical and detailed description of this suite is given in the following description of the technical specifications of the WAM Mediterraneo:

- geographic domain: 6° (longitude west) - 37° (longitude east), 30° - 46° (latitude north);
- 10 m wind as forcing: by LAMI and by GME outside the LAMI integration domain;
- computational grid (regular): 1/10 of degree;
- one forecast every day: 00 UTC after a 6-hour analysis cycle to produce an initial wave field. Each day the 6-hour warm-up cycle starts with a "hotstart" from the wave field forecast at 18 UTC by the previous run, and is forced by the 00 UTC GME global model wind analysis.
- forecast range: +72 hours with three-hourly outputs;
- output variables: significant wave height, mean direction, mean and peak period.

3.3. SWAN model operational at ARPA-SIM

The coast of the Emilia Romagna region, but in general the whole northern Adriatic, is characterized by very low bathymetry with a mildly sloped, sandy bottom. Thus, in 2004 ARPA-

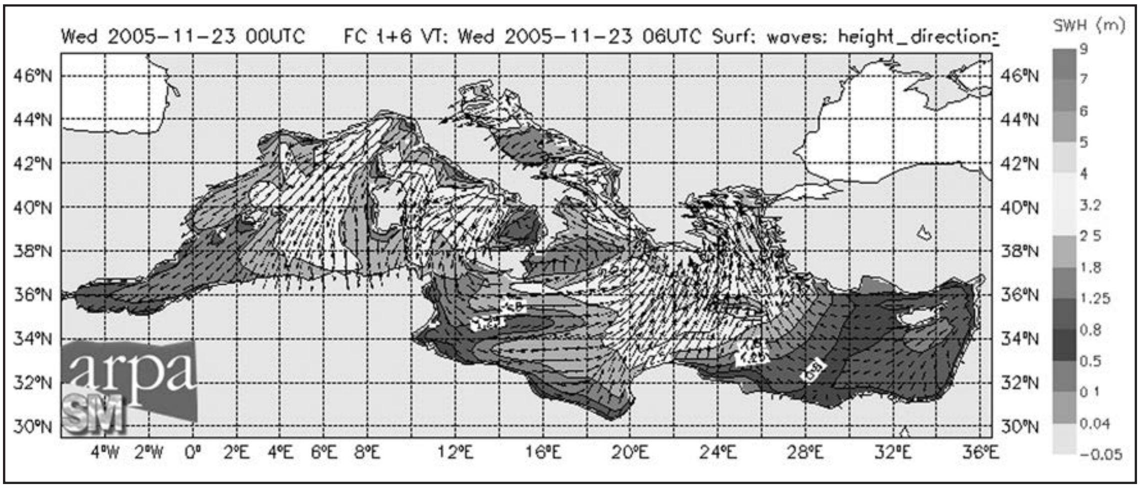


Fig. 3 - Significant wave height (in metres) and wave direction by a WAM model run over the Mediterranean Sea.

SIM implemented a new operational suite based on the SWAN model. This model well describes shallow water physics (as mentioned in paragraph 2.2.2) and allows a more reliable sea-wave forecasting near the coast which is of primary importance for the study of coastal erosion dynamics and for sea-based activities.

The SWAN version running at ARPA-SIM is the 40.41AB with default physical parametrization and is driven by the 10-metre wind computed by the meteorological model LAMI.

The operational system is designed in two steps, the first one is a run over the Adriatic Sea area, with a 8 km horizontal resolution that is approximately the same one of the meteorological model (7 km horizontal resolution). The overall forecast of the Adriatic Sea also provides the boundary conditions necessary for the nested run over the Emilia Romagna coastal area (see Fig. 5a), which has a computational resolution of about 1.7 km. This nesting technique allows us to achieve good results in limited areas where a really high forecast accuracy

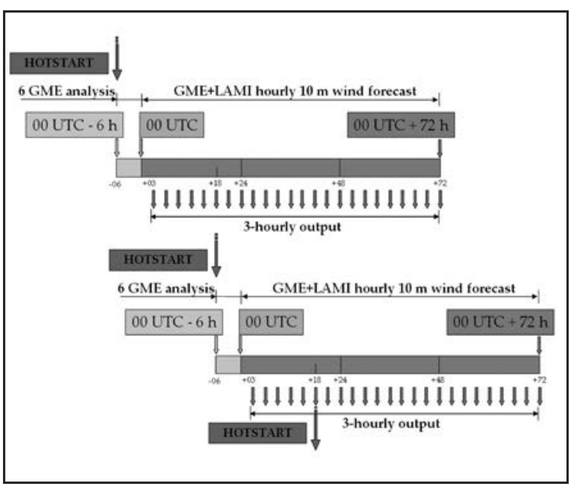


Fig. 4 - WAM Mediterraneo operational chain; each run starts with a warm-up step of 6 analyses (wind analyses by GME, the DWD global model) initialised using a wave field produced at the end of the warm-up stage of the previous run (“hotstart”). This stage is followed by 72 hours of forecast driven by the winds resulting from the interpolation of LAMI and GME.

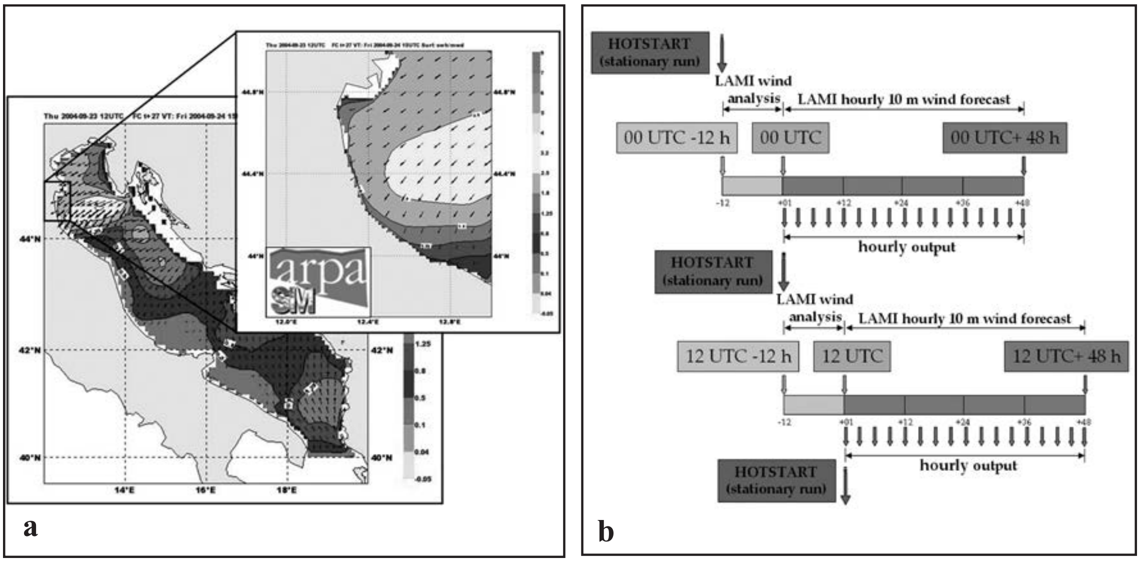


Fig. 5 - The SWAN model over the Adriatic Sea: a) significant wave height (in metres) and wave direction: coarse run over the Adriatic Sea and nested run over the Emilia Romagna coast; b) model operational chain; each run is warmed-up by 12 hours of analyses, initialised using a wave field produced at the end of the warm-up stage of the previous run ("hotstart"), producing then 48 hours of forecast

is needed and which has been improved by activating the triad wave-wave interactions option provided by the model.

The model is run twice a day (00 and 12 UTC). Each run starts with a warm-up step of 12 analyses (hourly wind analyses by LAMI) initialised using a wave field produced at the end of the warm-up stage of the previous one ("hotstart") if available; otherwise initialized by a stationary run over the whole domain. Twenty-four hours of forecast follows this warm-up stage. The operational chain is shown in Fig. 5b.

The technical specifications of the Adriatic Sea scheme (SWAN Adriatico) are as follows:

- geographic domain: 12°-20° (longitude east), 40°-46° (latitude north);
- 10 m wind forcing from LAMI;
- computational grid (regular): 1/12 of degree, about 8 km;
- two forecasts each day: 00 and 12 UTC;
- forecast range: +48 hours with hourly outputs;
- output variables: significant wave height, mean direction, mean and peak period;

The technical specifications of the scheme of nesting over the regional coast of Emilia Romagna (SWAN Emilia Romagna) are as follows:

- geographic domain: 12°-13° (longitude east), 43.8°-45° (latitude north);
- computational grid (regular): 1/60 of degree, about 1.7 km;
- The other specifications are the same as those of SWAN Adriatico.

3.4. SWAN MEDITARE (MEDiterraneo - ITAlia - REgione)

As mentioned before, the SWAN model can be applied both to deep waters and to shallow

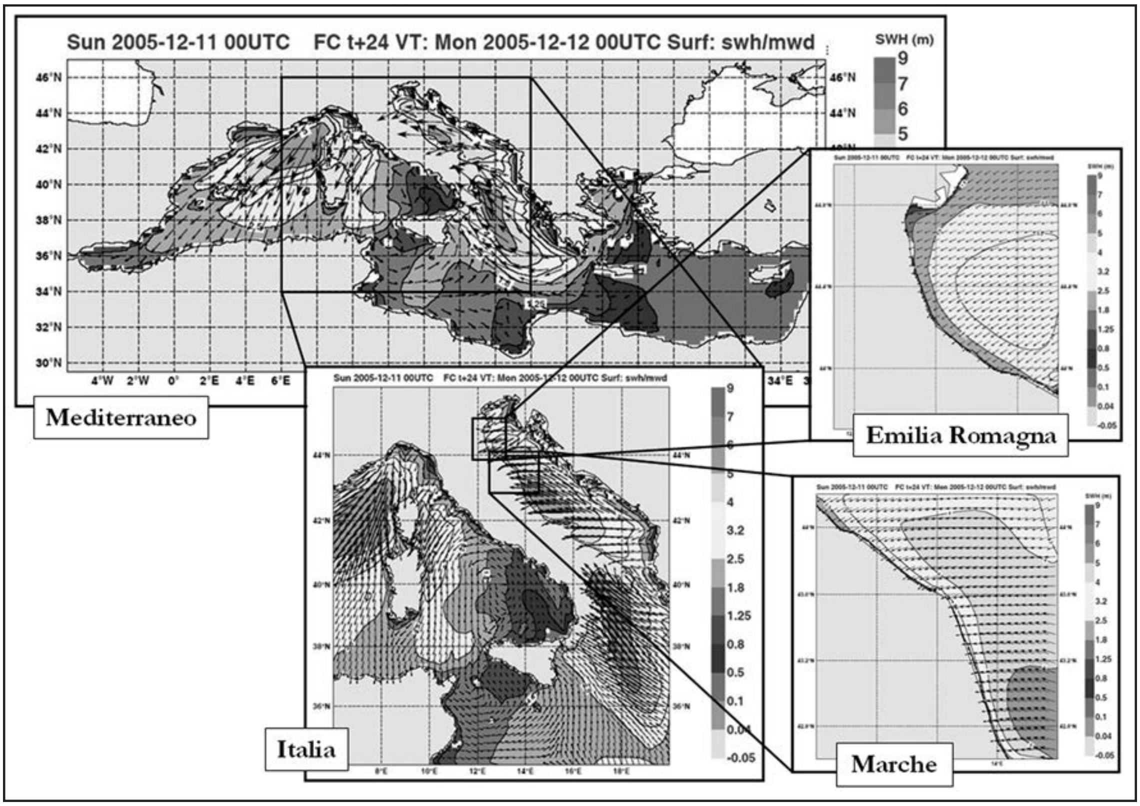


Fig. 6 - Significant wave height (in metres) and wave direction by SWAN model. The cascade of nested runs starts with a coarse run over the Mediterranean Sea (25 kilometres). The resolution of the Italian domain is about 8 kilometres whereas the resolution of the coastal areas is 800 meters

waters because the general physics of both conditions is implemented inside its model code. For this reason an operational suite based on SWAN has been designed and is going to be implemented in the very near future.

This suite consists in a sequence of nested runs that starts from a coarse run over the Mediterranean Sea at a resolution of about 25 kilometres. Such a run produces the necessary boundary conditions for the following run over the whole Italian domain (that is entirely inside the LAMI domain) at a resolution of 8 kilometres.

The following step is designed to achieve quite high resolutions (about 800 meters) in small coastal domains, by means of the same nesting technique (see in Fig. 6). The quality of the results of this last computational phase are highly affected by the resolution of bathymetry. It is of primary importance, thus, to have a fine resolved bathymetry for a good forecast of wave parameters in the surf zone, where shallow water phenomena are dominant. The coastal nestings are, now, in the Emilia Romagna and the Marche regions but, in line with the plans of cooperation between ARPA-SIM and the National Department for Civil Protection in Rome, the perspective of the next years is to patch, all the Italian coast at the same resolution.

Operationally, the chain provides one run each day at 00 UTC and a forecast range of 72 hours with hourly outputs. A detailed description of the operational technical specifications of every stage is given in the following paragraphs.

The technical specifications of the SWAN Mediterraneo are as follows:

- geographic domain: 6° (longitude west) - 37° (longitude east), 30°-46° (latitude north);
- 10 m wind as forcing: by LAMI and by GME outside the LAMI integration domain;
- computational grid (regular): 1/4 of degree;
- one forecast each day: 00 UTC after a 24-hour analysis cycle to produce an initial wave field. Each day the 24-hour warm-up cycle starts with an "hotstart" from the wave field produced by the previous one, if available, otherwise it starts with a stationary run over the whole domain. This Cycle is forced by GME global model wind analysis available every 3 hours;
- forecast range: +72 hours with hourly output;
- output variables: significant wave height, mean direction, mean and peak period.

The technical specifications of the SWAN Italia (nesting) are as follows:

- geographic domain: 6°-20° (longitude east), 34°-46° (latitude north);
- 10 m wind as forcing by LAMI;
- computational grid (regular): 1/12 of degree, about 8 kilometres;
- one forecast each day: 00 UTC. Each run starts with a warm-up step of 24 analyses (hourly wind analyses by LAMI) initialised using a wave field produced at the end of the warm-up stage of the previous one ("hotstart"), if available, otherwise initialized by a stationary run over the whole domain.

The other specifications are the same as those of the SWAN Mediterraneo.

The technical specifications of the SWAN Regionale (Emilia Romagna nesting) are as follows:

- geographic domain: 12°-13° (longitude east), 43.8°-45° (latitude north);
- 10 m wind forcing by LAMI;
- computational grid (regular): 1/120 of degree, about 800 m;
- one forecast each day: 00 UTC. Each run starts with a warm-up step of 24 analyses (hourly wind analyses by LAMI) initialised using a wave field produced at the end of the warm-up stage of the previous one ("hotstart"), if available, otherwise initialized by a stationary run over the whole domain;

The other specifications are the same as those of the SWAN Mediterraneo and SWAN Italia.

The technical specifications of the SWAN Regionale (Marche nesting) are the same as those of the SWAN Regionale except for the geographic domain that is: 12.5°-14.5° (longitude east), 42.6°-44.2° (latitude north).

4. Wave model verification (April-October 2005)

The verification is the assessment and quantification of the relationship between a matched set of forecasts and observations. An objective verification is an important tool that guarantees continuous monitoring of the system's performance, moreover it is an essential step that provides information about such models (general behaviour, bias, root mean square error, etc.) and link it to its forecast quality. Verification activities are useful only if they lead to some decision regarding the product being verified.

That decision will either generate changes in the product or in the way forecasts are made, or it might be a “do nothing” decision which confirms that the product or service is satisfactory.

At ARPA-SIM, wave verification is carried out comparing observed values directly at the station points against the forecast value on the nearest grid point, it is thus possible to determine indices like the mean value, the bias, the mean absolute error and the root mean square error. Moreover, by evaluating the contingency tables for different thresholds, it is possible to deduce other indices like Threat Score, False Alarm Rate, Probability Of Detection, Heidke Skill Score and Bias Score. For a detailed description of indices and scores see Wilks, (1995).

In the aim of the Archimede Project, the purpose of the following subsections is to give a sample of the more detailed verification procedures that are carried out by ARPA-SIM in order to investigate model behaviour.

In this work, the three wave models that cover the Adriatic Sea domain have been compared by verifying forecasts against observation data provided by buoys. The three models are: SWAN Adriatico (SWAN_AD), WAM Mediterraneo (WAM_MED) and WAM Adriatico (WAM_AD).

The verification was carried out between April-October 2005 and the results are related to the significant wave height and the wave direction. The three-hourly observations available were provided by three buoys located down the Adriatic Sea that are part of the RON (Rete Ondametrica Nazionale) network of APAT (Agenzia per la Protezione dell’Ambiente e per i Servizi Tecnici): Ancona, Ortona and Monopoli.

4.1. Significant wave height data observed by the Adriatic buoys of the RON network

The significant wave height recorded by the three buoys during the verification period are shown in Figs. 7, 8 and 9. Looking at the data records it is clear that even if the verification period does not include the most windy months, the signal due to wave storms is anyhow present many times, and in one case the value of the significant wave height is even higher than 3.5 m (cf. Ortona 08 June 2005).

4.1.1. Ancona

The geographical location of the Ancona buoy is 43.82967°N and 13.71283°E, at this point the water depth is about 75 m. Considering the buoy efficiency as the ratio between the number of observations recorded in the period and the expected total number of observations in the considered time period, the efficiency of Ancona in the period April - October 2005 is 83.2%.

The highest value of the significant wave height in the period is 2.67 m and it was recorded during the storm of the September 18, 2005.

4.1.2. Ortona

The geographical location of the Ortona buoy is 42.40667°N and 14.53667°E, in this point the water depth is about 70 m. During the verification period the buoy efficiency is 78.4% and the maximum value of the significant wave height is 3.56 m that was recorded the June 8, 2005.

4.1.3. Monopoli

The geographical location of Monopoli buoy is 40.975°N and 17.37667°E, in this point the water depth is about 90 m. The efficiency is 95.4% and the maximum value of the significant

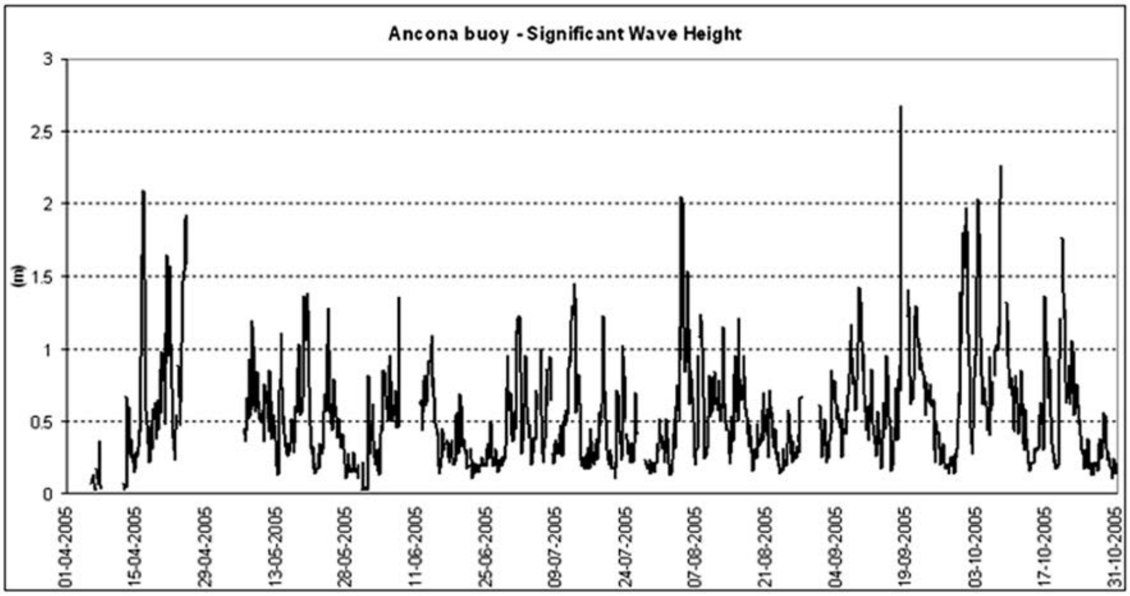


Fig. 7 - Significant wave height recorded by the Ancona buoy in the period April-October 2005.

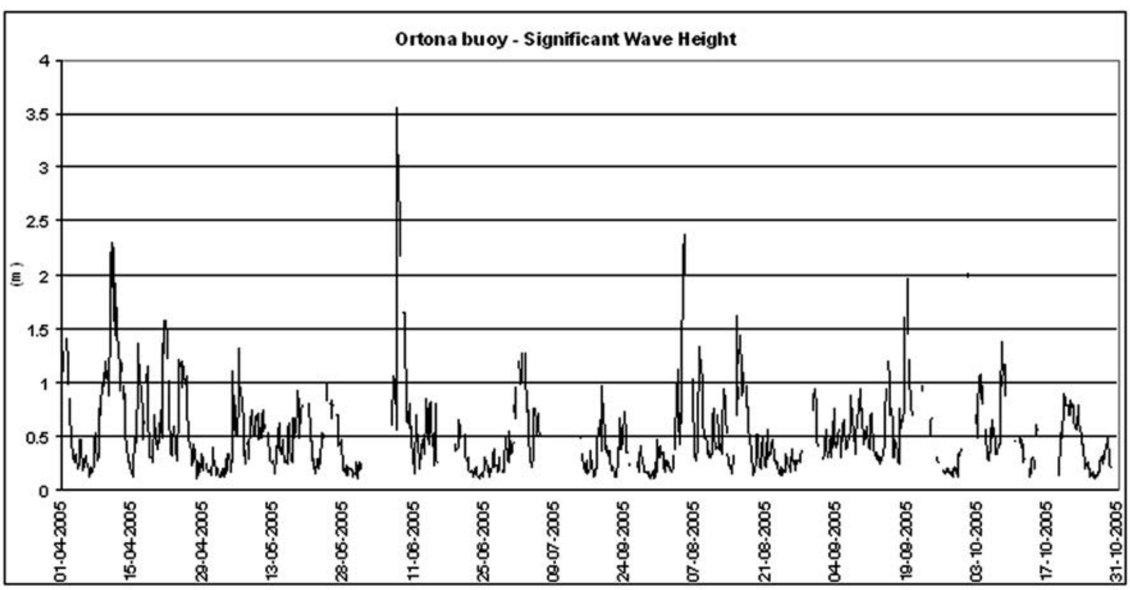


Fig. 8 - Significant wave height recorded by the Ortona buoy in the period April-October 2005.

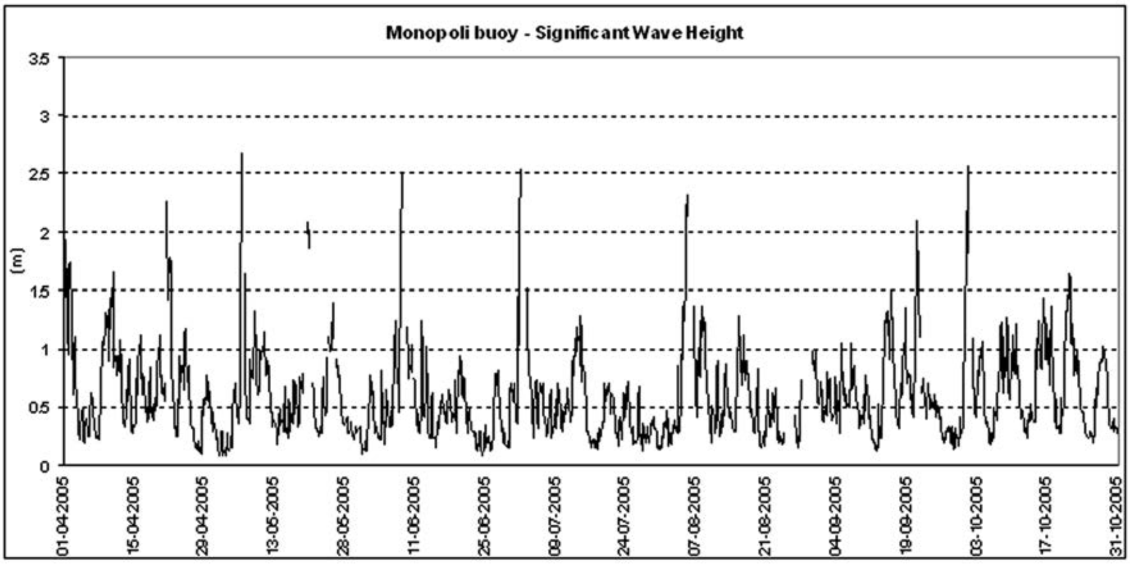


Fig. 9 - Significant wave height recorded by the Monopoli buoy in the period April-October 2005.

wave height is 2.67 m that was recorded the May 7, 2005.

4.2. Verification results

The values of the significant wave height, its associated bias and root mean square error with increasing forecast range over the whole period and stations are shown in Fig. 10.

In Fig. 10a one can note a good behaviour both for SWAN_AD and WAM_MED compared with observations, whereas WAM_AD shows an evident model spin-up during the first 12 hours, likely due to an underestimation of the strength of ECMWF wind analyses used during the warm-up cycle.

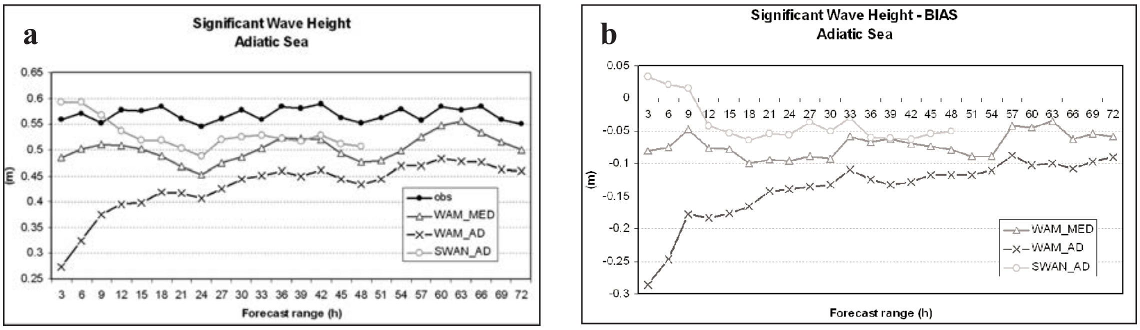
In general, compared to other observations, SWAN_AD seems to be the best from the point of view of both wave height and its temporal evolution.

These behaviours are confirmed by the bias graph of Fig. 10b: SWAN_AD starts with a positive bias that lasts for the first 9 hours, levelling off at a very low negative bias of about 5 cm for the remaining forecast range. WAM_MED shows a more constant behaviour than SWAN but it tends to underestimate the significant wave height more than SWAN, showing a mean negative bias of about 7 cm.

Finally, WAM_AD shows high negative bias values during the first 12 hours, compared with the mean significant wave height of the verification period, with the same spin-up behaviour already seen in Fig. 10a.

Both WAM_MED and WAM_AD have a small positive trend whereas SWAN seems to have no trend (excluding the first 12 hours).

The root mean square error (see Fig. 10c) confirms an initial high value of WAM_AD whereas the other two models have lower values, in general after the 12 h forecast step the three models



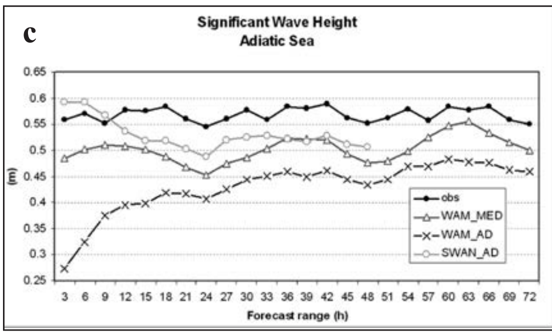


Fig. 10 - Scores computed for the significant wave height measured or forecast during the whole period and over all the buoys for the different forecast ranges (h): a) significant wave height values (in metres); b) bias values (in metres) of the significant wave height; c) root mean square error values (in metres).

have comparable behaviours and magnitude.

The values of the mean wave direction and its associated bias with increasing forecast range over the whole period and stations are shown in Fig. 11.

If one splits the geographic domain into eight octants, the average of the observed wave direction values over the three buoys (Fig. 11a) is about 163°N (SE), in agreement with the climatology of the coming-from wave direction of the Adriatic Sea. Model forecasts reveal

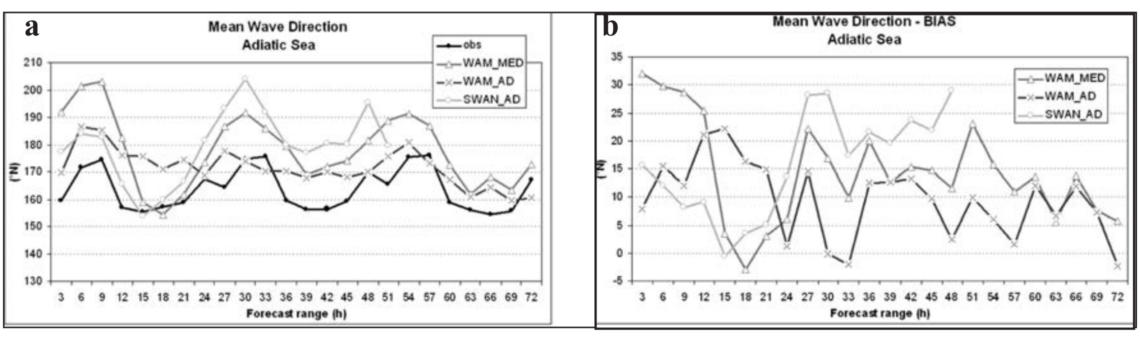


Fig. 11- Scores computed for the mean wave direction measured or forecast during the whole period and over all the buoys for the different forecast ranges (h); a) mean wave direction values (in degrees with respect to the north); b) bias values (in degrees with respect to the north) of the mean wave direction.

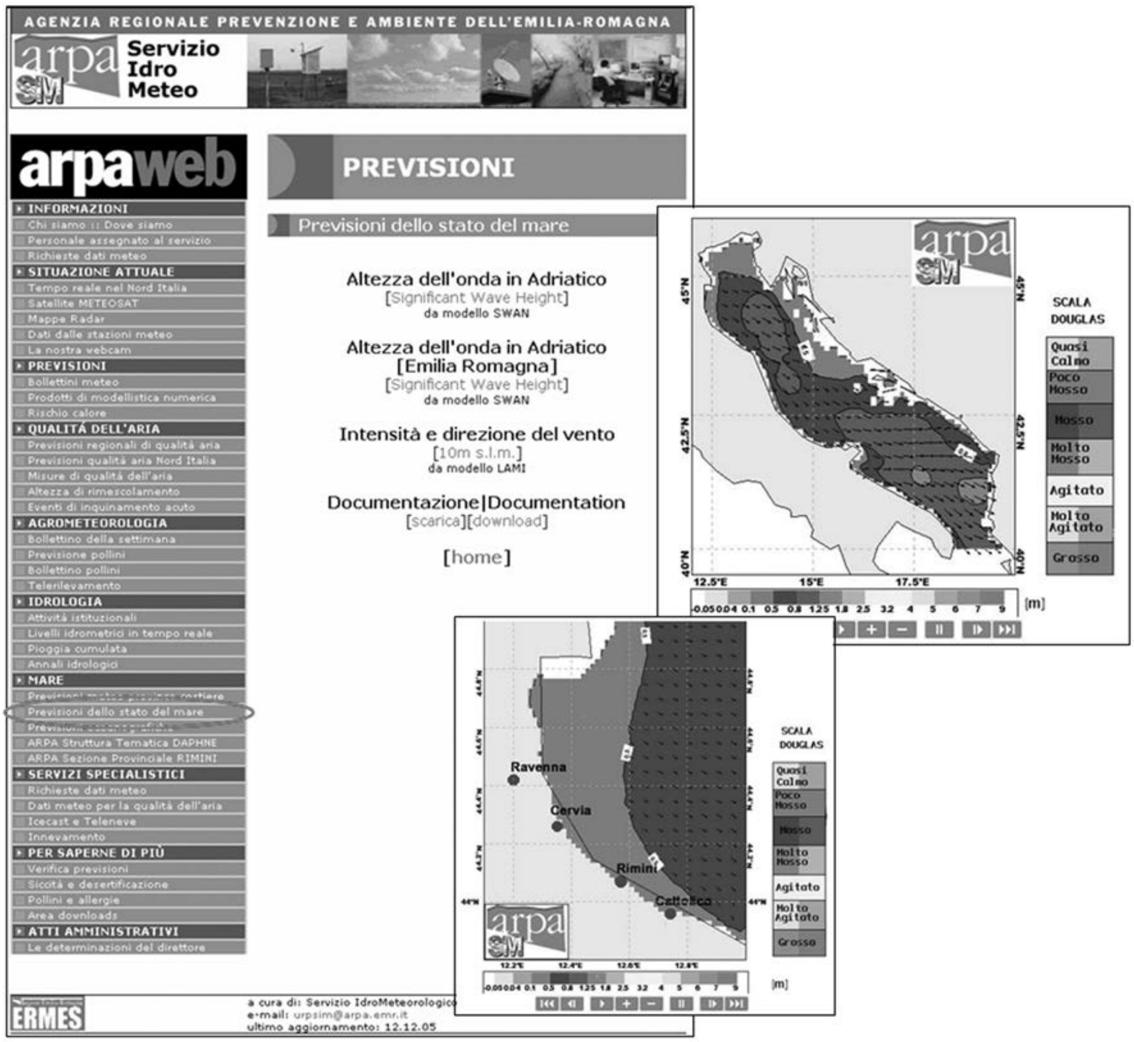


Fig. 12 - ARPA-SIM sea state forecast section on the public web site.

different values instead, respectively 178°N for WAM_MED, 172°N for WAM_AD and 179°N for SWAN_AD, that means a south coming-from direction. Observing the bias (Fig. 11b) it is possible to assert that there is an error that varies with the linear law and that affects forecast data, but while for the WAM model the bias has a linearly decreasing trend, for SWAN it is increasing, with a steeper slope than the other model.

As a conclusion for this verification section, it is possible to assert that the transition to the SWAN model has led, in general, to a bias reduction in the wave height forecasts keeping the same mean square error performances of the other operational models. It has led, instead, to a little increment of the bias error in wave direction estimation, SWAN tends to shift the coming-from direction of waves (i.e. SE) a little more south than WAM. It is necessary to note that the forecast indication of the wave direction given by all the models is, however, the same.

5. Conclusion

The whole forecast system described in the above paragraphs has been producing data since 1997. These data, stored in GRIB format in the ARPA-SIM database, have been generated thus by different operational suites that have been changing over the years. For this reason, and for the problems of model characterization explained in paragraph 4, the model associated verification results are very important for a proper use of the data set. A useful application of the ARPA-SIM database could be the integration of the gaps among available observations or the reconstruction of a sea wave climate, that is difficult to do using only single point data (e.g. there are just three buoys publicly available on the Italian side of the Adriatic Sea). This database could represent, thus, a precious tool to join all the other existing wave observation databases.

Furthermore, the sea state forecast outputs by SWAN Adriatico and Emilia Romagna are available every day in a graphical format on the public web site of ARPA-SIM under the "Mare" section (http://www.arpa.emr.it/sim/pagine/previsioni/swan/) as shown in Fig. 12 and can be very useful for all the uses and activities that are deeply dependent on the wave field state, as already mentioned in introduction.

Acknowledgements. Most of the activity described in this paper has been funded by the National Department for Civil Protection and by the CADSEALAND EU VI framework project. The authors would like to thank APAT (Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici) for the opportunity given at ARPA-SIM to present its wave forecast system during the Archimede Meeting that was held in Rome in the period November 29-30, 2005, and for data observations of the buoys by RON (Rete Ondametrica Nazionale) network.

REFERENCES

Booij N., Ris R.C. and Holthuijsen L.H.; 1999: *A third-generation wave model for coastal regions. Part.I - Model description and validation*. J. Geophys. Res., **104**, 7649– 7666.

COSMO Newsletter; 2004: *Operational Applications – ARPA-SIM (BOLOGNA)*. Deutscher WetterDienst (DWD), Offenbach, **6**, 25-26.

Hasselmann, K., Barnett T.P., Bouws E., Carlson H., Cartwright D.E., Enke K., Ewing J.A., Gienapp H., Hasselmann D.E., Kruseman P., Meerburg A., Müller P., Olbers D.J., Richter K., Sell W. and Walden H.; 1973: *Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)*. Dtsch. Hydrogr. Z., **12**, 1-95.

Holthuijsen L.H., Booij N. and Herbers T.H.C.; 1989: *A prediction model for stationary, short-crested waves in shallow water with ambient currents*. Coast. Eng., **13**, 23–54.

Janijc J.; 1990: *The step-mountain coordinate: physical package*. Mon. Weather Rev., **118**, 1429–1443.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S. and Janssen P.A.E.M.; 1994: *Dynamics and modelling of ocean waves*. Cambridge Univ. Press, Cambridge, 532 pp.

Majewsky D.; 1998: *The new global icosahedral–hexagonal grid point model GME of the Deutscher Wetterdienst*. In: Seminar on Recent Developments in Numerical Methods for Atmospheric Modelling, 7-11 September 1998, ECMWF, Reading (United Kingdom), pp. 173–201.

Majewsky D., Liermann D., Prohl P. Ritter B., Buchhold M., Hanisch T., Paul G., Wergen W. and Baumgardner J.; 2002: *The operational global icosahedral – hexagonal gridpoint model GME: description and high resolution tests*. Mon. Weather Rev., **130**, 319– 338.

Mesinger F., Janjic Z. I., Nickovic S., Gavrilov D. and Deaven D. G.; 1988: *The step-mountain co-ordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of Appalachian redevelopment*. Mon. Wea. Rev., **116**, 1493-1518.

Ris R.C., Booij N. and Holthuijsen, L.H.; 1999: *A third-generation wave model for coastal regions. Part II - Verification*. J. Geophys. Res., **104**, 7667–7681.

Schraff C. and Hess R.; 2003: *A description of Nonhydrostatic Regional Model LM – Part III: data assimilation*. Available on the COSMO web site (www.cosmo-model.org).

Signell R.P., Carniel S., Cavaleri L., Chiggiato J., Doyle J.D., Pullen J. and Sclavo M.; 2005: *Assessment of wind quality for oceanographic modeling in semi-enclosed basins*. Journal of Marine Systems, **53**, 217-233.

Steppeler, J., Doms G., Schättler U., Bitzer H. W., Gassmann A., Damrath U. and Gregoric G.; 2003: *Meso-gamma scale forecasts using the nonhydrostatic model LM*. Meteorol. Atmos., **115**, 488-504.

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

Whitham G.B.; 1974: *Linear and nonlinear waves*. Wiley J. (ed) New York, 636 pp.

Wilks D. S.; 1995: *Statistical methods in the atmospheric sciences. An introduction.* Academic Press, New York, 467 pp.

Corresponding author: Andrea Valentini
ARPA-SIM
Servizio Idrometeorologico Emilia Romagna
V.le Silvani 6, 40122 Bologna, Italy
phone: +39 051 525922; fax: +39 051 525936; e-mail: avalentini@arpa.emr.it.