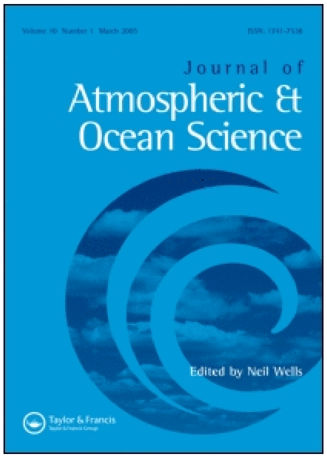

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Wave forecasting at the Spanish coasts

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Wave forecasting at the Spanish coasts

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A wave forecasting system developed by Puertos del Estado (The Spanish holding of harbours) to predict waves at the coast is run in a twice a day cycle with a forecasting horizon of 72 h. This system is driven by wind fields supplied by the Spanish Meteorological Service from the HIRLAM model. Nested within this model a set of local forecasting systems, one for each harbour, covering an area of around 25 × 25 km, has been developed. The narrowness of the Spanish continental shelf requires very high resolution grids to be applied to localised regions near the coast. This fact involves the use of modelling techniques that makes this forecasting system different from other systems implemented in other regions. This article describes the wave forecasting system and the different techniques developed at Puertos del Estado to implement it.

Keywords: Wave forecast; Wave modelling; Grid resolution; Ocean scale; Coastal application; Harbour agitation

AMS Subject Classification: 65C20; 68U20; 76B15; 86A10

1. Introduction

The wave forecasting system developed by Puertos del Estado is designed to provide a wave forecast for the Spanish harbours on the Atlantic and Mediterranean coasts of Spain, which means to predict sea conditions at the entrance of the harbours, well inside the continental shelf (Carretero Albiach *et al.* 2000).

The continental shelf surrounding the Spanish coast is very narrow, ranging from 2 to 50 km wide. This is of great importance when studying the wave dynamics in the region and contrasts with other well-studied regions like the North Sea, both in the physics and in the modelling techniques applied to obtain predictions of the waves at the coastline. Very high resolution grids have to be applied to localized regions near the coast.

During the development and implementation of this system, a number of problems had to be solved, in particular the challenge of numerical modelling of an open and exposed coast with a narrow continental shelf. The usual configuration of nested grids cannot be used in this case. Interpolation and coarse grid errors from

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boundary conditions provided by a global grid very near the coast will not be corrected by a small-scale local application.

The approach adopted to avoid this problem has been to split the system into two steps: an ocean system and a local one. The ocean system solves the basin scale, where waves that propagate to the coast are generated. To obtain high resolution close to the Spanish coast without resorting to high resolution in the deep ocean, the resolution is increased using a two-way-nesting scheme developed at Puertos del Estado (Gómez *et al.* 1997). The local system consists of a set of different local applications, each one nested within the ocean system, covering an area of around 25×25 km, that solves for the coastal scale.

2. The ocean system

The ocean system is based on four implementations of the WAM model (the WAMDI group 1988), three for the Atlantic Ocean and another one for the Mediterranean Sea and one application of the WAVEWATCH model (Tolman 1991) in the strait of Gibraltar. Both models are third generation wave models that solve the wave transport equation explicitly without any presumption on the shape of the wave spectrum. The WAVEWATCH model solves the wave action balance equation in the presence of currents.

An improvement on the original WAMDI numerical spatial integration scheme was introduced at Puertos del Estado (Gómez *et al.* 1997). This consisted of using a two-way nesting scheme that allows the definition of different grid resolutions in various subregions of the model domain. Along the boundary, between these subregions of different resolutions, there are two types of points, those receiving energy by advection and those receiving energy by interpolation. Those points are alternated within the advection algorithm and modified accordingly to minimize the computational cost.

The system is driven with windfields from the HIRLAM model, provided by the Spanish Meteorological Service. The HIRLAM is a hydrostatic numerical model (Undén *et al.* 2002) which is the result of a cooperative project of the national weather services of several European countries for developing a system suitable for short-range numerical weather prediction. The spatial resolution of the application of the HIRLAM model that is run by the Spanish Meteorological Service is 0.16 degrees and the forecast horizon is 72 h.

The ocean system has two main applications for the Atlantic Ocean and the Mediterranean Sea. With the two-way nesting scheme, mentioned earlier, the resolution of the Atlantic application is increased from 1 degree, in the open deep water, to 0.25 degrees close to the continental shelf figure 1. The Mediterranean application has also a variable grid spacing of 10 and 5 min (figure 2).

These two applications of the WAM model provide boundary conditions to four nested applications, third based on the WAM model and the fourth on the WAVEWATCH model.

The three nested applications of the WAM model cover the Cantabrian coast, the Gulf of Cádiz and the Canary Islands. The spatial resolution of the Gulf of Cádiz and the Canary Islands applications is 5 min and the grid spacing of the Cantabrian application is increased, using the two-way nesting scheme, from 5 to 2.5 min (figure 3).

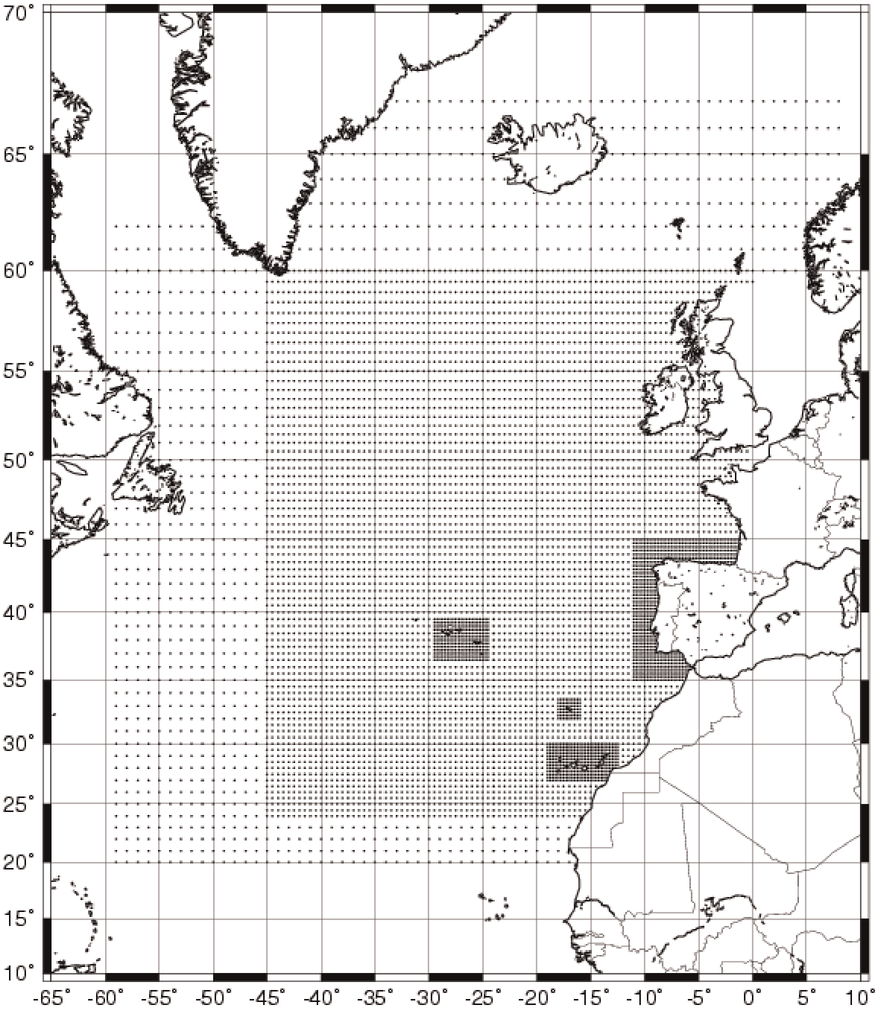

Figure 1. The Atlantic grid of the ocean wave forecast system. The resolution varies from 1 to 0.25 degrees.

The nested WAVEWATCH application covers the Strait of Gibraltar with a resolution of 1 min and receives boundary conditions from both, the Mediterranean and the Atlantic applications.

With this scheme, combining the two-way nesting procedure with local nested grids, the Spanish coast is covered with at least a resolution of 5 min with the ocean system. This resolution is further increased by the local system in which the different local applications have a resolution between 200 and 500 m.

The ocean wave forecast system is operated on a twice a day cycle, and the results, maps, time series and tables can be looked up at the Spanish Meteorological Service web page, www.inm.es, which is open and free for all users.

The forecast results are verified on real time using the data from Puertos del Estado buoy network. The results from this real time verification process are shown at the same web page, so the users are able to get a hold of both, the forecast itself as well as the accuracy of the previous days forecast cycles.

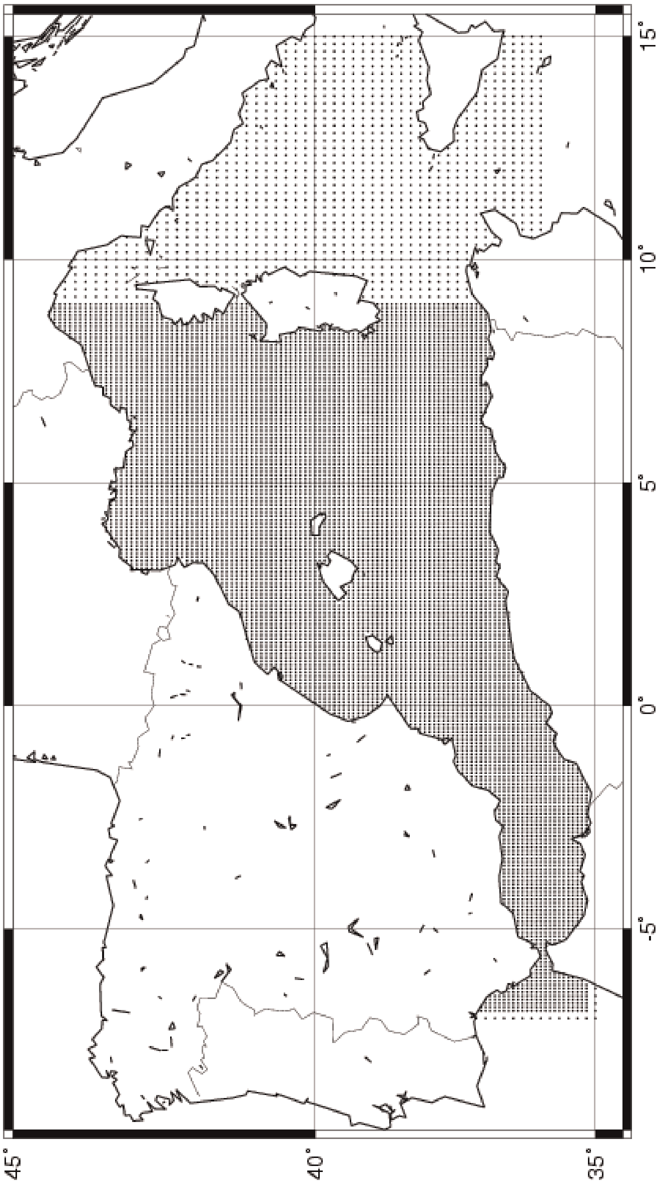

Figure 2. The Mediterranean Sea grid of the ocean wave forecast system. The resolution varies from 10 to 5 min.

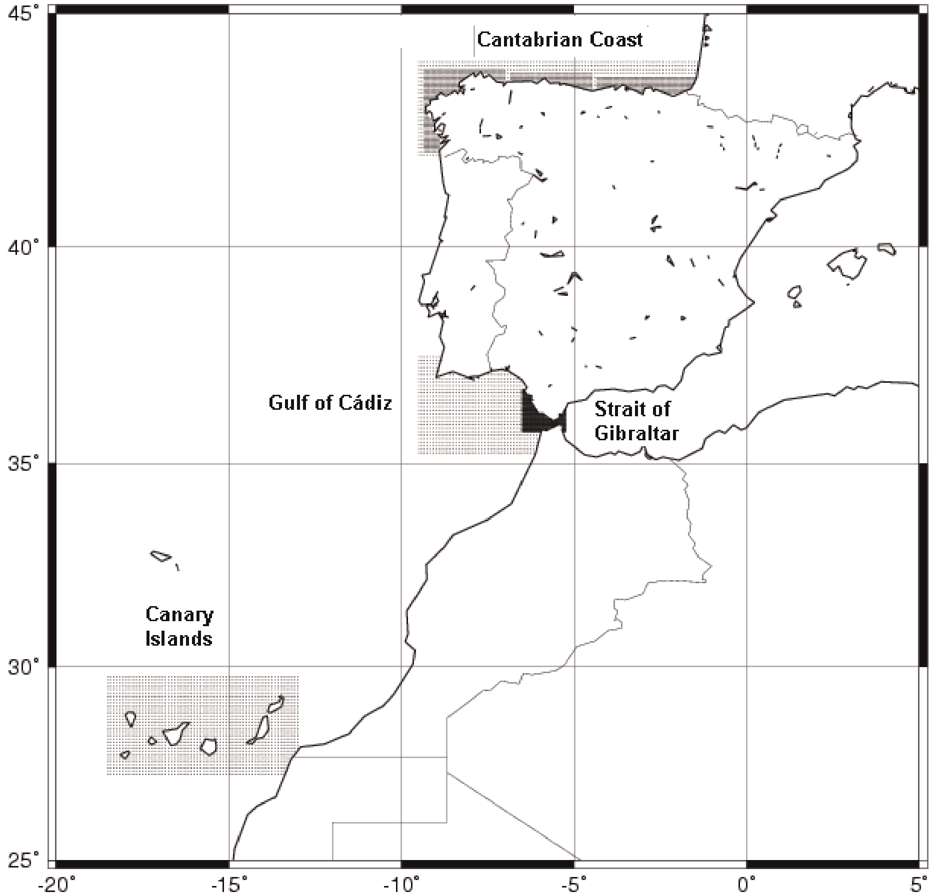

Figure 3. The nested grids of the ocean wave forecast system covering the Strait of Gibraltar, with a resolution of 1 min, the Cantabrian Coast, with a resolution of 2.5 min and the Gulf of Cádiz and the Canary Islands with a resolution of 5 min.

3. The local system

The local system is based on the SWAN model (Boij *et al.* 1999). This model is a third generation wave model that solves the wave energy balance equation, explicitly without any presumption on the shape of the wave spectrum:

$$\frac{\partial}{\partial t}E+\frac{\partial}{\partial x}C_xE+\frac{\partial}{\partial y}C_yE+\frac{\partial}{\partial \sigma}C_\sigma E+\frac{\partial}{\partial \theta}C_\theta E=S(\sigma,\theta) \tag{1}$$

In the presence of currents the spectrum that is considered in SWAN is the action density spectrum $N(\sigma, \theta)$ rather than the energy density spectrum $E(\sigma, \theta)$ since the action density is conserved whereas energy density is not. The action density is equal to the energy density divided by the relative frequency: $N(\sigma, \theta)=E(\sigma, \theta)/\sigma$.

This model is especially developed to predict realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions.

The term in the left-hand side of equation (1) represents the evolution of the energy density spectrum in time, the propagation in geographical space and the depth and current induced refraction. C_x, C_y, C_σ and C_θ are the propagation velocities in x-space, y-space, σ-space and θ-space, respectively.

The term $S(\sigma, \theta)$ at the right hand side of equation (1) is the source term, in terms of energy density, representing the effects of generation, dissipation and non-linear wave-wave interactions:

$$S = S_{in} + S_{dis} + S_{nl4} + S_{bot} + S_{nl3} + S_{brk} \tag{2}$$

It can be distinguished by the source terms that are active primarily in deep water, namely energy transfer from wind to waves, S_{in}, dissipation due to white capping, S_{dis}, and non-linear quadruplet interactions, S_{nl4}, from those that are active exclusively in shallow water, namely bottom friction, S_{bot}, nonlinear triad interactions, S_{nl3}, and depth-induced breaking, S_{brk}.

The SWAN model has several options for the formulation of the different source terms. For the local forecast applications described in this article, the formulations that are being used for the deep water source terms are: the source terms of wind input, S_{in}, and white capping, S_{dis} (Komen *et al.* 1984) and the Discrete Interaction Approximation (DIA) for computing the quadruplet interaction, S_{nl4}, (Hasselmann *et al.* 1985). With regard to the shallow water source terms, the formulations that are being used are: the empirical model of JONSWAP (Hasselman *et al.* 1973) for the bottom friction term, S_{bot}, the Lumped Triad Approximation (LTA) of Eldeberky (1996), for the triad wave-wave interactions, S_{nl3}, and the bore-based model of Battjes and Janssen (1978) for the formulation of the energy dissipation due to depth-induced breaking, S_{brk}.

This system is made up of one application of the SWAN model for each harbour. These applications typically cover an area of 25 × 25 km around the harbour, with a grid resolution of 200 m and receive wave boundary conditions from the ocean system. An additional module of these local applications is the implementation of an agitation model inside the harbour coupled to the SWAN model.

The harbours where this local system has been implemented are: Barcelona, Cartagena and Almería in the Mediterranean Sea and Gijón and Ferrol on the Cantabrian coast. Two more applications at Valencia in the Mediterranean Sea and La Coruña on the Cantabrian coast are being developed (figure 4).

These local applications are driven by the same wind fields used to drive the ocean system. These wind fields are supplied by the Spanish Meteorological Service using the HIRLAM model and they have a spatial resolution of 0.16 degrees and a forecast horizon of 72 h. The time resolution of the wind fields is 6 h. One of the next objectives is to obtain higher resolution wind fields for these local wave forecast applications, by applying the mesoscale atmospheric model MM5 at the same scale as the SWAN model.

The wave boundary conditions of these applications come from the Ocean System and consist of the 2-D spectra at the border of the local application in the spatial resolution of the grid in which the harbour is located, i.e. 5 min for the harbours at the Mediterranean Sea, the Gulf of Cádiz and the Canary Islands, 2.5 min for the harbours at the Cantabrian coast and 1 min for the harbours located at the strait of Gibraltar (figure 5). The time resolution of the boundary conditions is 1 h.

Figure 4. Locations of the harbours where the local forecast system is operative.

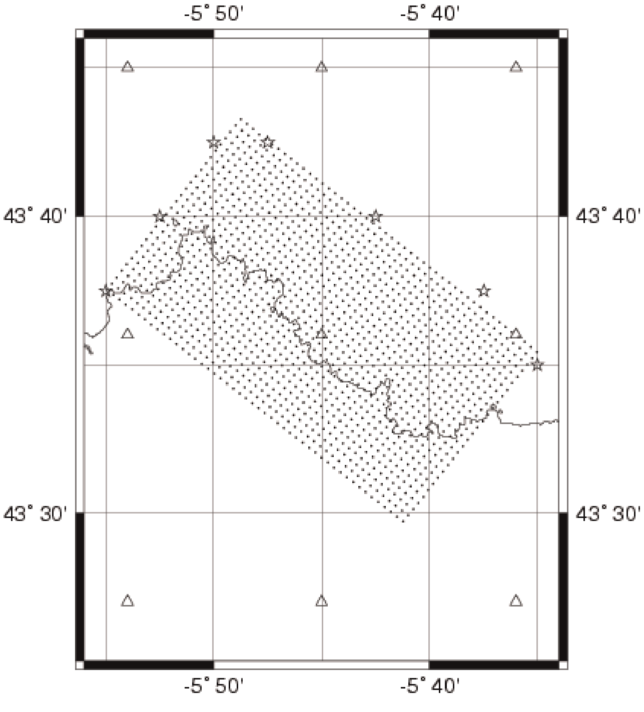

Figure 5. Local application at Gijón. The black points show the grid points, the stars show the wave boundary conditions input and the triangles show the wind grid.

The spectrum discretization in the frequency–directional space is the same used with the WAM model, therefore no interpolation is needed: 24 directions and 25 frequencies for the Atlantic Ocean applications and 30 for the Mediterranean Sea, where $f_1 = 0.0418\,\mathrm{Hz}$ and $f_n = 1.1 f_{n-1}$.

The wind fields and the wave boundary conditions are interpolated in space and time to match the spatial and time resolution of the SWAN application. This interpolation is bi-linear, and is made by the SWAN model

The bathymetries of the local wave forecast applications are modified, each hour, using the output of the sea level forecast system developed at Puertos del Estado (Alvarez *et al.* 2001). This system is based on the ocean circulation HAMSOM model (Backhaus 1985) and on the harmonical prediction of tides computed from data measured by the tide gauge network of Puertos del Estado. The system is executed twice a day and is forced by meteorological fields, supplied by the Spanish Meteorological Service from the HIRLAM model.

The local applications are implemented on a PC, run under Linux, located at the port office. The wave boundary conditions, the wind fields and the sea level forecast are received twice a day by e-mail sent by the Puertos del Estado computer, located at Madrid. Once the e-mail arrives the forecast process starts automatically and the information generated by the forecast system is post-processed. At the computer at the harbour a web server has been installed to enable all the results to be visualized on any of the harbour's computers with a navigator through the intranet. One of the most important objectives, when the system was developed was that it could work automatically without the need of any intervention or maintenance.

The standard output of the local wave forecast system consists of significant wave height maps, time series and tables. In addition to the standard output, each harbour can make a special request based on any special feature. A good example of these particular requests is a prediction of overtopping implemented at Barcelona for a dike for which there is pedestrian and vehicle traffic. With this forecast the harbour authorities can estimate the danger and even close the highway to traffic (figure 6).

The overtopping is computed using the significant wave height, the peak period and the mean period of the three SWAN model grid points, nearest to the dike. This dike has four sections with different physical characteristics and the overtopping is computed for each section. Finally three different formulations have been used: Owen (1980), van der Meer *et al.* (1995) and Pedersen *et al.* (1992). Therefore, the overtopping discharge per unit length of structure is computed $3 \times 4 \times 3 = 36$ times, one for each input grid point, one for each dike section and one for each overtopping formulation. The processed output is the mean and the maximum of the 36 values for overtopping discharge per unit length, related to the level of safety. This maximum and mean overtopping values are computed for each hour of the 72 h forecast horizon.

A real time verification process similar to the one mentioned in the last section is carried out for the local applications. The buoy data is sent to the harbour in the same e-mail message containing the wind fields, the boundary conditions and the sea level forecast.

A warning system has been implemented in these local wave forecast applications. A threshold, for the significant wave height and the wind speed, has been fixed. When the forecasted parameters reach this threshold a warning message is automatically sent by e-mail to a list of addresses. The thresholds are fixed taking into account the experience of the port authorities. Some harbours have requested

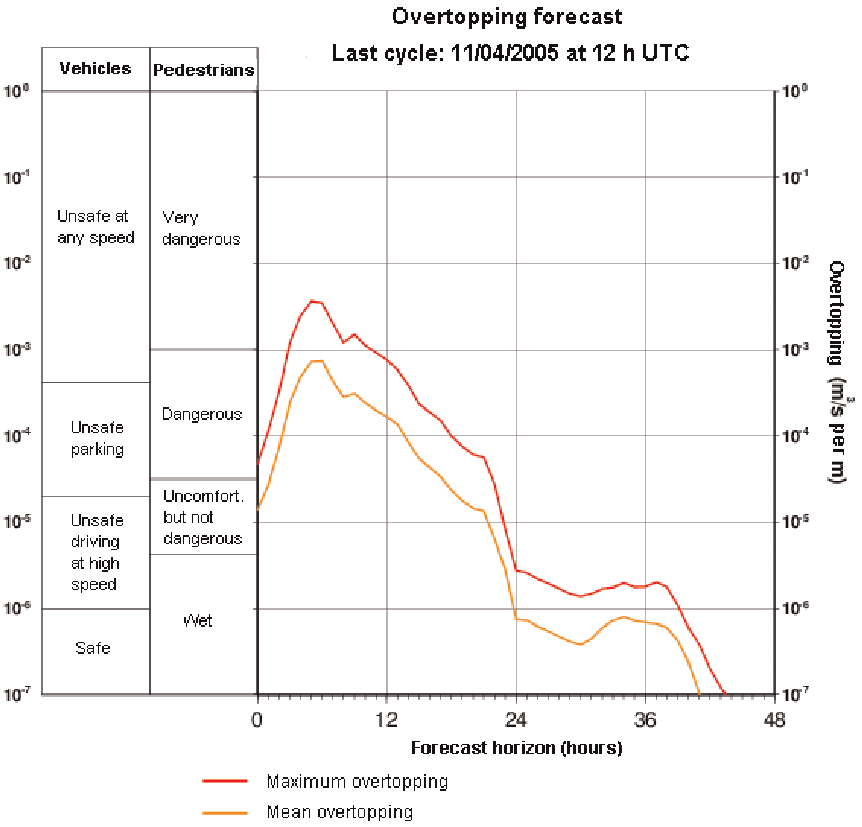

Figure 6. Overtopping forecast in $m^3 s^{-1}$ per m. These two lines represent the maximum and the mean overtopping each hour of the forecast horizon. On the left hand, different levels of safety for vehicles and pedestrians are indicated.

that an alert based on the wave direction should be added to the wave height and wind speed. This option is fully operative at Barcelona.

3.1. *The agitation module*

The local wave forecast system is completed with a module developed to predict the agitation inside the harbour using an elliptic model based on the Mild Slope equation (GIOC 2004) (figure 7). The model used has two versions, a monochromatic and a spectral one.

The aim of the work is to use a time series of wave spectra from the SWAN model output, at the nearest grid point of the harbour entrance, as input for the agitation model. This wave spectra time series is made of 72 spectra, one for each hour of the forecast horizon. The first approach was to use the spectral version of the model and run it 72 times, one with each spectrum as input, but this method consumes far too much computer time for a forecast system.

To avoid this expense in CPU time, the method finally adopted was to first run the monochromatic version of the model for a range of wave periods and wave directions for monochromatic waves of 1 m height. Once this work is finished the SWAN spectrum output can be modified by handling each component as a

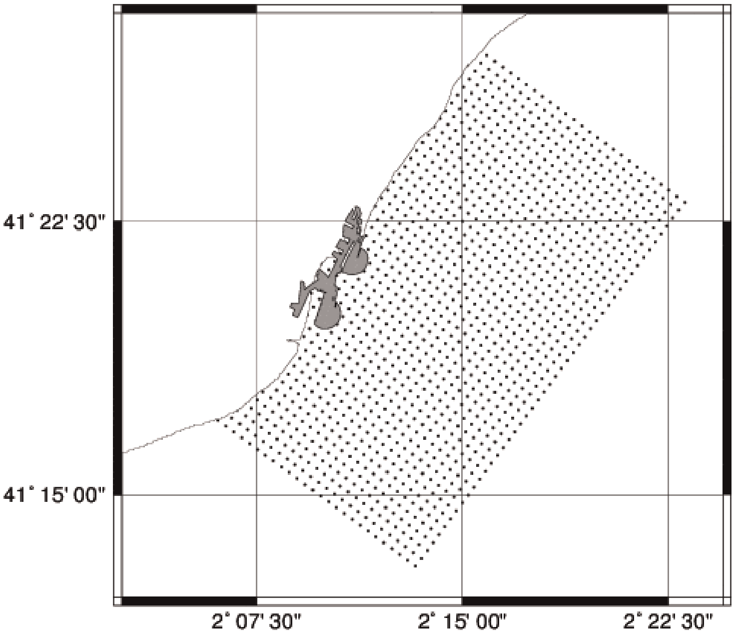

Figure 7. Local application at Barcelona. The black dots are the grid points of the SWAN model and the grey area is the grid of the agitation model.

monochromatic wave, i.e. for each frequency and each direction of the spectrum the wave height is computed from the variance density as follows:

$$H(i,j) = 2\sqrt{2S(i,j)\Delta f_i \Delta\theta_j} \qquad (3)$$

where $H(i,j)$ = the wave height, $S(i,j)$ = the i,j component of the spectrum, Δf_i = the frequency interval and $\Delta\theta_j$ = the direction interval.

This wave height is multiplied by the computed wave height at each node of the agitation model. Once the wave spectrum components are modified this way, a new spectrum can be recomputed at each node and similarly for all the other spectral parameters such as the significant wave height. This method assumes a linear behaviour of the sea surface.

4. Verification

In addition to the real time verification process, mentioned on section 2, a more complete verification is carried out using buoy and satellite data. The buoy data used for this verification process are produced by the Puertos del Estado buoy networks, shown in figures 8 and 9. For the moment, only the Ocean system results have been validated, pending the validation of the local system.

Using the model output of the grid point nearest to the buoy location, the errors of the forecast system are quantified by the standard statistical parameters: correlation index, bias, scatter index, standard deviation, regression fit, etc. This comparison is made for the significant wave height, the mean period and the peak period.

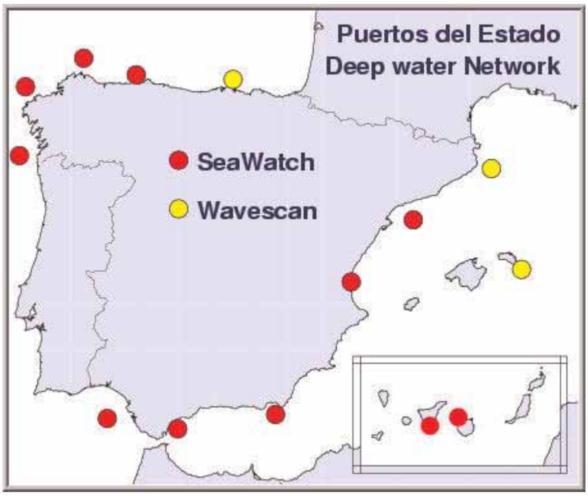

Figure 8. Locations of the Puertos del Estado deep water buoy network.

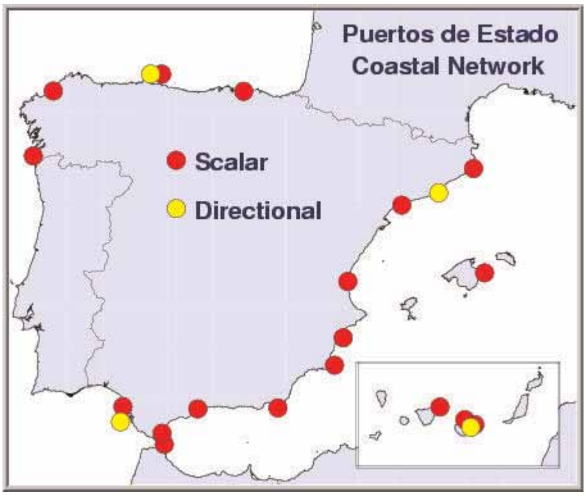

Figure 9. Locations of the Puertos del Estado coastal buoy network.

The details of this validation process is out of the scope of this article; however some examples are shown in this section just to give an overview of the behaviour of the ocean system. Figures 10 and 11 show the locations of the buoys that are used to illustrate these examples.

By comparing the model output for different forecast horizons with the buoy data the quality of the forecast can also be checked (figure 12).

The verification of the Puertos del Estado forecast system shows a good agreement in the Atlantic Ocean with correlations of ~0.9 and scatters ~25%. These values do not decay with the forecast horizon. The correlation drops to values of ~0.8 at the Mediterranean Sea with scatter ~30%. These values become worse after 36 h of forecast.

For the detection of possible errors in the wave forecast system, which are not easily detected by the statistical comparison, for example, a systematic

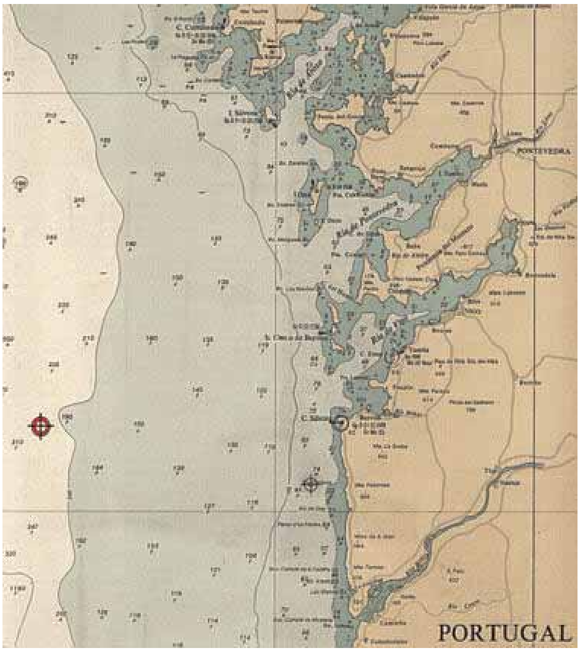

Figure 10. Silleiro buoy location. The buoy is moored at 323 m depth.

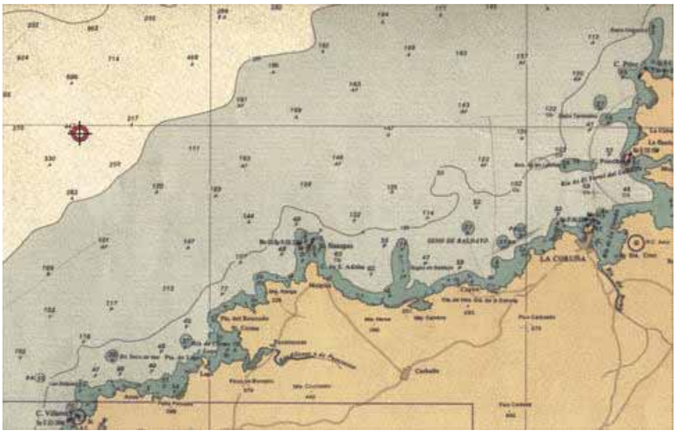

Figure 11. Villano buoy location. The buoy is moored at 386 m depth.

underestimation or overestimation of the significant wave height peaks, the time series for the wave parameters are represented. These time series show the model output together with the buoy data, and therefore any anomaly is detected by visual check (figure 13).

The mean wave direction is also validated by means of the representation of wave directional distribution of the model output and the buoy data (figure 14).

Additionally the error introduced in the system by the wind input can be quantified by comparing the wind fields with the wind measurements. The wind data must be measured in open waters, and not be influenced by the local orography, nor assimilated by the atmospheric model, and, if it is necessary, the wind has to be

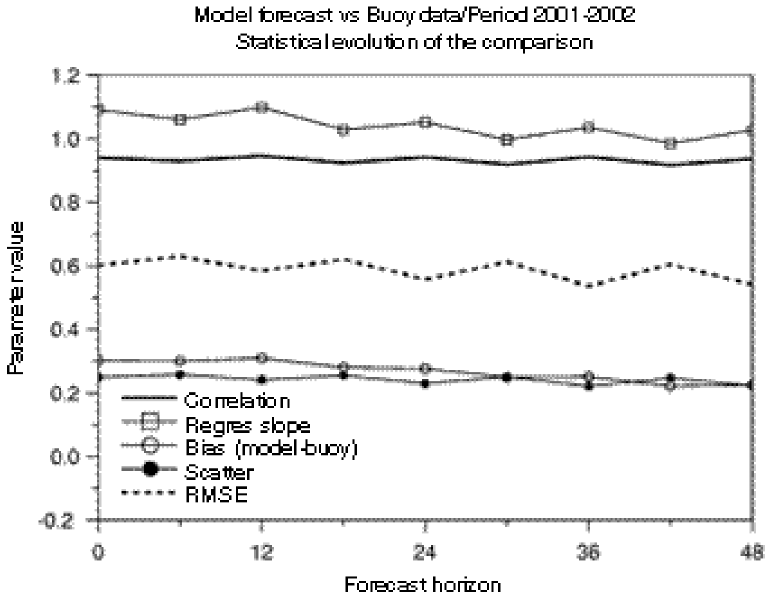

Figure 12. Evolution of different statistical parameters along the forecast horizon at the Sillerio buoy, in the Atlantic Ocean. The location of the buoy is shown in figure 10.

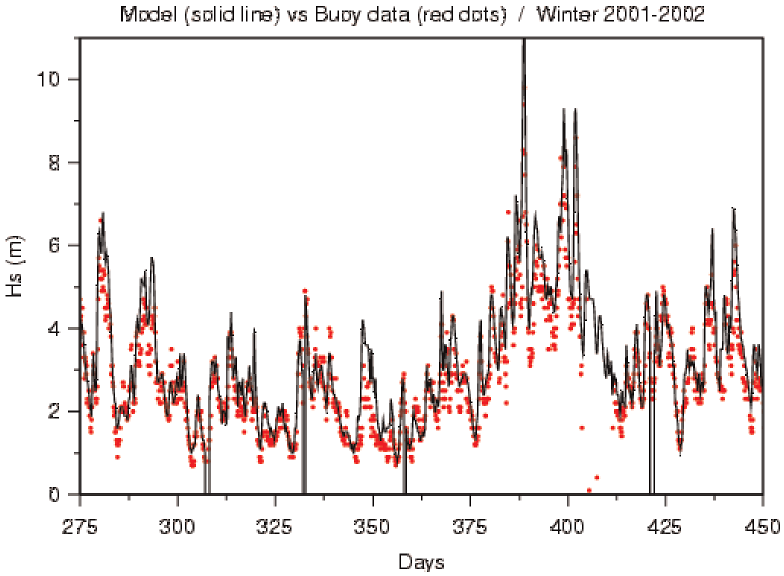

Figure 13. Time series of the significant wave height comparing the model output with the Silleiro buoy, in the Atlantic Ocean. The dots represent the buoy data and the solid line the model output. The location of the buoy is shown in figure 10.

modified to a standard height of 10 m. Finally, the time variability of the wind data needs to be filtered before the comparison.

The buoys are usually close to the coast and there are not a large number of them, and therefore, it is also interesting to make more global comparisons in the deep

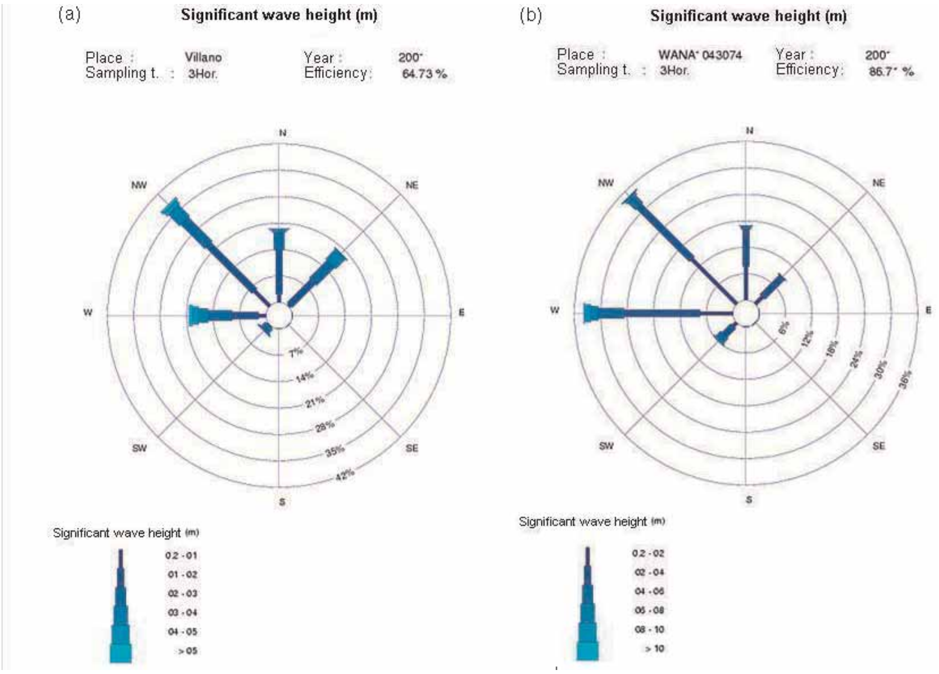

Figure 14. Wave directional distribution of the significant wave height. The model output is represented at the left hand and the Villano buoy, in the Atlantic Ocean, at the left hand. The location of the buoy is shown in figure 11.

open ocean with satellite data. In this case, the grid points closer than a certain distance to the satellite track, are used to make the comparison (figure 15). The validation is done, as for the buoy data, using the statistical parameters and the representation of wave parameter series. In this case, instead of time the satellite track is represented by the x-axis (figure 16).

5. Conclusions

The wave forecasting system developed by Puertos del Estado provides a wave forecast for the Spanish harbours on the Atlantic and Mediterranean coasts of Spain, predicting the sea conditions at the entrance of the harbours, well inside the continental shelf.

The continental shelf surrounding the Spanish coast is very narrow, ranging from 2 to 50 km wide. Very high resolution grids have to be applied to localized regions near the coast. The system solves the challenge of numerical modelling of an open and exposed coast with a narrow continental shelf without using the usual configuration of nested grids

The approach adopted has been to split the system into two steps: An ocean system and a local one. The ocean system solves the basin scale, where waves that propagate to the coast are generated. The local system consists of a set of different

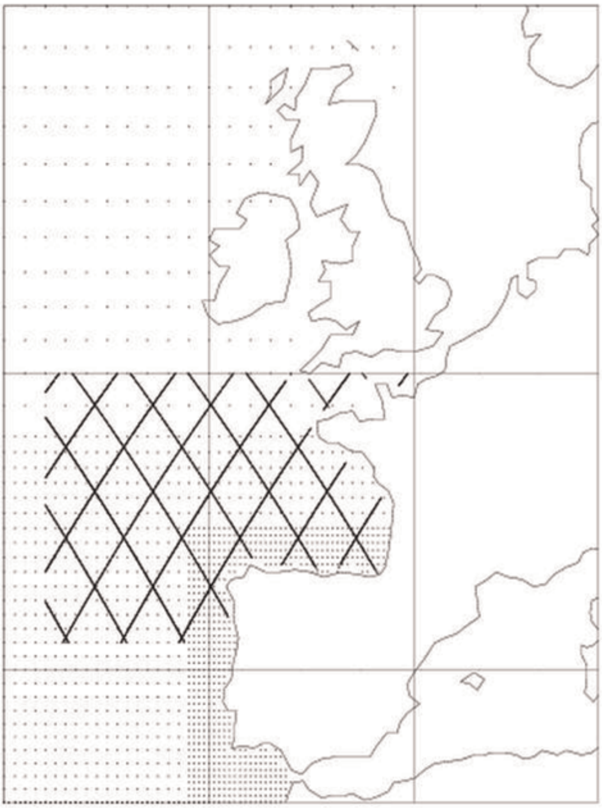

Figure 15. Tracks of the satellite TOPEX/POSEIDON, from November 1995 to March 1996 in a rectangle covering the Cantabrian coast of Spain. The background black dots are the model grid points.

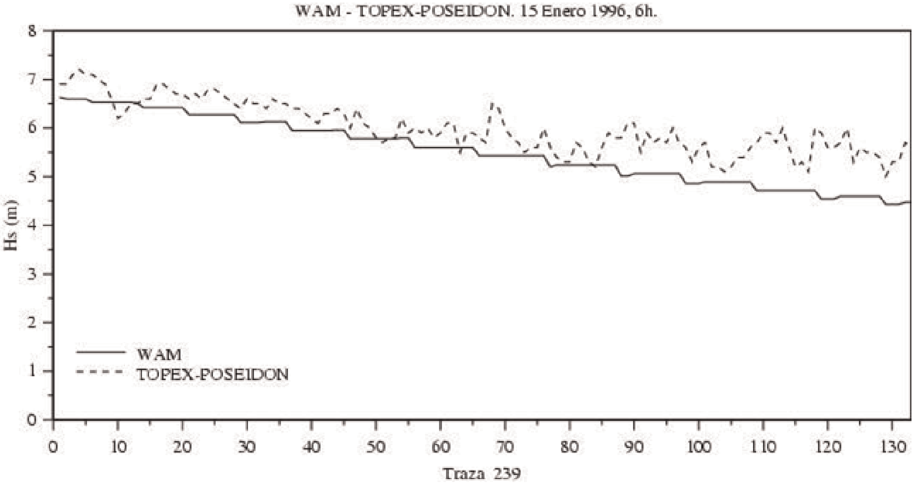

Figure 16. Significant wave height series comparing the model output with the satellite data. The satellite track is represented by the *x*-axis. The dashed line is the satellite data and the solid line the model output.

local applications, each one nested within the ocean system, covering an area of around 25 × 25 km, that solves for the coastal scale.

The local wave forecast system is completed with a module developed to predict the agitation inside the harbour using an elliptic model based on the Mild Slope equation

The verification of the Puertos del Estado forecast system compares the model output with buoy data and shows a good agreement for the Atlantic Ocean with correlations of ~0.9 and scatter of ~25%. These values do not decay with the forecast horizon. The correlation drops to values of ~0.8 for the Mediterranean Sea with scatter around 30%. These values become worse after 36 h of forecast.

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