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One year validation of wave forecasting at Galician coast

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A wave forecasting system based on the third generation model WAVEWATCH III was developed by MeteoGalicia (Regional Meteorological Office of Galicia). During 2005 two implementations of the wave forecasting system were operational, running daily to perform a wave forecast at different scales for the next 96 h. In the initial implementation, wave generation was calculated using the global NCEP/NOAA (National Center for Environmental Prediction) GFS (Global Forecast System) and MeteoGalicia ARPS (Advanced Regional Prediction System) 10-m wind forcing as input. New improvements to this system were introduced in spring 2005 using only GFS wind forcing. The influence on wave forecasting of these two different wind inputs is analysed in detail and results are compared with one year field data from the Puertos del Estado-Clima Marítimo (PE-CM) deep water buoys network.

Keywords: Galician coast wave modelling; Wind forcing; WAVEWATCH III; Wave forecasting validation

1. Introduction

Galicia is located in the north-west of Spain, to the north of Portugal, and it is characterized by steep hills and sea inlets bathed by the Atlantic Ocean. The coastal bays, called rias, that characterize the southwest coastline, have a strong influence on the local weather. Most of the dynamics of the sea and weather is due to the presence of low and high pressure systems in the mid-Atlantic Ocean. In particular, most of the waves, near the coast, come from the generation of wind waves over large areas at the North Atlantic Ocean and arrive on the coast as swell. In order to properly understand and forecast waves at the Galician coast, modelling of large ocean areas is needed.

Several approaches to regional wave forecasting have been used in recent years by the European agencies (UK Met. Office, Puertos del Estado-Clima Marítimo). The first approach is to run a high resolution regional model which receives

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boundary conditions from a global model and in the second approach a self-contained model is run covering all the generation areas with a variable grid spacing scheme that allows for an increase in the spatial resolution near the coast. As an example of the last procedure, Puertos del Estado-Clima Marítimo (PE-CM) has developed a very sophisticated two-way nesting self-contained procedure based on WAM CY4 model (Komen *et al.* 1994, WAMDI Group 1998), running the basin and local scales at once without using outer boundary conditions, (Gómez Lahoz and Carretero Albiach 1997). The WAM model was the first model to solve the energy balance equation (Janssen 2004).

The present version of the MeteoGalicia wave forecasting system is based on the third generation model WAVEWATCH III (Tolman 1991, 1999). It provides both, regional and deep ocean wave forecasts using both approaches described above. The forecasts for the next 96 h are available daily for the weather forecasters and general public on the Galician regional forecast Web site (http://www.meteogalicia.es). This forecasting system covers all North Atlantic generation areas, but instead of using a variable grid spacing scheme, a one-way nested subset is used to obtain the desired spatial resolution. The quality of wave forecasts is to a large extent determined by errors in the forcing wind field. The increase in atmospheric model spatial resolution results in a more realistic representation of the sub-synoptic scales, which are the ones that are relevant for the interaction of wind and waves (Janssen *et al.* 2002).

During the past 10 years, a number of agencies and research institutions around the world, and particularly in Europe, have been developing strategies and methodologies for monitoring the ocean and its coastal areas. Forecasting sea conditions for operational activities related to safety, pollution control or harmful algal blooms and effects of man-induced forcing on climate change are some of the issues addressed by most of these actions. As a result, high-resolution models have been implemented at the local-scale by different agencies. The difficulty in predicting at local scales stems from the limited predictability of highly non-linear systems such as the atmosphere-ocean system. Besides, the physics behind most of parameterizations within the ocean and atmosphere models is sometimes extended beyond the conditions for which the model is valid.

At MeteoGalicia, the atmospheric ARPS (Advanced Regional Prediction System) (Xue *et al.* 2000, Balseiro *et al.* 2003, Souto *et al.* 2003) has been operational since 1999. The ARPS was chosen because of its non-hydrostatic dynamics, generalized terrain-following coordinate and nesting capabilities are well suited for the complexities of the Galician region. It uses the global NCEP/NOAA (National Center for Environmental Prediction) GFS (Global Forecast System) model as boundary conditions and the nesting is set up to achieve a 10-km finer grid at NW-Spain. For wave generation, two different approaches have been studied in MeteoGalicia depending on the wind forcing. Initially, during 2005, wave generation was calculated using GFS model winds as input for the lowest resolution grid, while ARPS 10 m wind forcing at 50 and 10 km resolution were used near the coast, in higher resolution grids. Then, a new implementation of the wave forecasting system was tested during spring 2005 using only GFS wind forcing. This article discusses the results obtained from the statistical analysis of the initial implementation that was operational at MeteoGalicia during 2005, and a test period performed during April 2005 when both systems were available.

2. Modelling system

The mixture of scales involved in wave forecasting at Atlantic Iberian margin ranges from basin scale to coastal scale. In other words, it is not possible to build a self-contained wave forecasting system for Galician coast without covering at least wide areas of the North Atlantic Ocean. For this purpose, a three level one-way nesting was developed (figure 1). The first model grid covers the North Atlantic Ocean from 90°W to 5°E and 15–75°N at 0.5° resolution, which is a sufficiently large area to cover all synoptic events which generate swell in the region that cannot be solved within regional model grids. The intermediate model grid covers the Iberian margin from 24–0°W and from 33–48°N at an intermediate resolution of 15′. Spectral boundary conditions are supplied by the coarser (0.5° resolution) North Atlantic grid. Finally, a regional grid covering the Galician coast from 10.75–6°W and 41–44.75°N downscaling to 2.5′ resolution was used. Table 1 shows the main characteristics of each model grid.

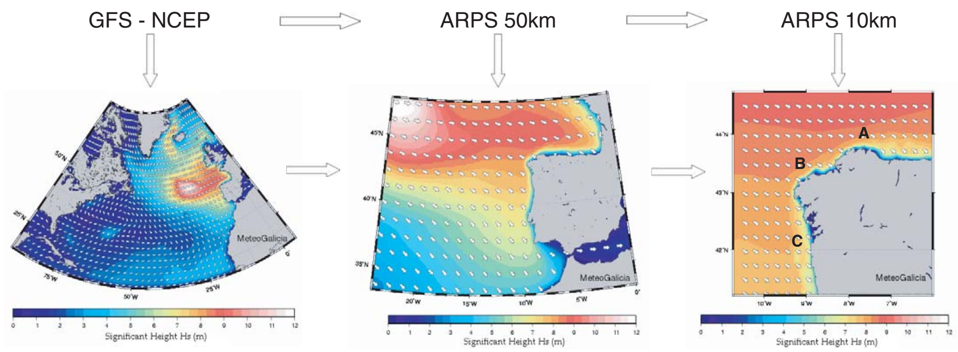

Figure 1. Snapshot of significant wave height H_s (background colour) and mean wave direction Dir_m (arrows) for three nested models. Galician grid shows buoys location: A – Estaca de Bares, B – Vilano-Sisargas and C – Silleiro. See table 2 for a detailed description of the buoy network.

Table 1. Main configurations of WAVEWATCH III model for each grid.

Specification	North Atlantic Ocean	Iberian margin	Galician coast
Wind forcing	NOAA GFS 1°	ARPS 50 km	ARPS 10 km
Grid spacing	0.5°	15′	2.5′
Northern limit	75°N	48°N	44.75°N
Southern limit	15°N	33°N	41°N
Western limit	90°W	24°W	10.75°W
Eastern limit	5°E	0°W	6°W
Lowest frequency	0.0418 Hz	0.0418 Hz	0.0418 Hz
Frequency factor	1.1	1.1	1.1
$n°$ directions	24	24	24
$n°$ frequencies	25	25	25
Δt spatial propagation	900 s	700 s	180 s
Δt intraspectral	3600 s	3600 s	1800 s
Δt source terms	300 s	300 s	180 s

2.1. *The wave model*

The wave forecasting system is based on WAVEWATCH III model (Tolman 1991, 1999) which is a third generation wave model originally developed at Marine Modelling and Analysis Branch (MMAB) of the NOAA/NCEP, which is in the spirit of the WAM model (WAMDIG 1988, Komen *et al.* 1994). WAVEWATCH III is a phase-averaging model that solves the spectral action density balance equation for wavenumber-direction spectra. The governing equations include refraction of the wave field, due to temporal and spatial variations of the mean water depth, and the mean current. Source-sink terms include wind wave growth and decay, non-linear interactions, dissipation ('whitecapping') and bottom friction (Tolman and Chalikov 1996). The physics included in WAVEWATCH III model do not cover conditions where the waves are severely depth-limited, and it is not able to simulate physical processes within the surf zone. In some aspects, WAVEWATCH III model is more efficient than WAM; for example, the use of a third-order numerical propagation scheme (Tolman 1992) prevents the numerical diffusion of swell as happens in many WAM cases.

Although WAVEWATCH III use is limited to deep waters, the continental shelf at Galician coast is narrow enough to achieve a wave forecast at locations close to the Galician coast and with high resolution.

2.2. *Meteorological forcing*

Meteorological forcing for the wave forecasting system comes from the GFS and ARPS models. The GFS model, known before as AVN (AViation Model), was originally developed by NCEP/NOAA. NCEP runs four GFS assimilation cycles per day (00, 06, 12 e 18 UTC) at a resolution of 1°, with a horizon of 16 days, and all forecasts are freely available for public use.

The ARPS is applied to operational numerical weather prediction in MeteoGalicia (Souto *et al.* 2003). ARPS was developed at the University of Oklahoma and the CAPS (Center for Analysis and Prediction of Storms) (Xue *et al.* 2000). It is a non-hydrostatic atmospheric model and uses a generalized terrain-following coordinate system defined for a compressible atmosphere (Pielke and Martin 1981). The governing equations of the ARPS include conservation equations for momentum, heat, mass, the six categories of water substance (water vapour, cloud water, rainwater, cloud ice, snow and hail), subgrid-scale (SGS) turbulent kinetic energy (TKE) and the equation of state of moist air. The continuous equations are solved numerically using finite-difference methods on an Arakawa-C grid.

The model runs twice a day for 96 h forecasts using two nested grids. One, with a lower resolution of 50 km covers Western Europe; the other, with a nested higher-resolution grid of 10 km, centred in the Galicia region. The ARPS model starts from a 6 h analysis cycle in both domains and uses the boundary conditions also from the GFS model at a 3 h interval on a coarser grid. Radiosonde and surface data are assimilated on a 6 h cycle basis by optimal interpolation.

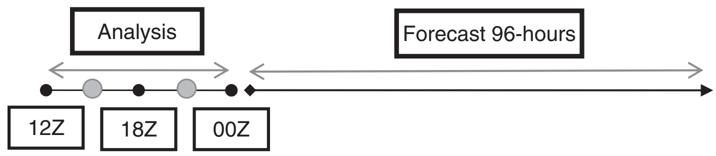

Figure 2. Scheme of a 00 Z model run. First 12-hour GFS winds are used to obtain 00 Z wave model initial condition. Black circles show GFS model analyses and big grey circles show 3-hour forecast of previous GFS model cycle run.

2.3. *Initial implementation of the wave forecasting system (WW3)*

The initial implementation (thereafter WW3) of the wave forecasting system at MeteoGalicia has been operative since 2003. This basin scale, low resolution grid (0.5°) uses no spectral boundary conditions, i.e. no wave energy comes across boundaries, but energy can propagate outside the domain. Figure 2 shows the ensemble of grids and wind forcing used in this implementation. NCEP/NOAA GFS 10 m, 1° resolution wind is used as wind forcing for the North Atlantic model grid, as well as it is used as boundary condition by ARPS 50 km model.

In the second model grid, ARPS 50 km wind forcing is used for the Iberian margin grid. Spectral boundary conditions are supplied by a coarser 0.5° resolution North Atlantic grid. This procedure is updated using ARPS 10 km nested wind forcing and a 2.5′ resolution model grid, covering the Galician coast. Two nested grids were used, for the wave forecast system, to benefit from the high resolution surface wind provided by the regional model ARPS at 50 and 10 km resolution, respectively. Thus, the finer grid near the coast achieves a final spatial resolution of 2.5′. This strategy improves wind forcing resolution as well as wind wave forecasts at points near the coastline.

Model data from the WW3 wave forecasting system are available until November 2005, when a new implementation became operational. During this period, only one cycle (00 Z cycle) was executed daily.

2.4. *New implementation of the wave forecasting system (WW3n)*

The new implementation (thereafter WW3n) of the wave forecasting system has been operational since November 2005, with a test period of 1 month during April 2005 when both systems were available. In this new configuration, grids and nesting structure were not modified, and this article focuses on the main wave model improvements: the establishment of two forecasting cycles per day, and the use of the GFS wind data for forcing for the wave model.

To achieve the best possible initial condition using GFS 10 m wind data, the initial condition of the previous cycle run is propagated for 12 h. In other words, at the 00 Z cycle run, a nowcast is generated using the previous 12 Z cycle run as an initial condition. The 12 h wind data from 12, 18 and 00 Z GFS cycles are shown in figure 2.

Table 2. PE-CM buoys locations used for statistical analysis.

	Type	Longitude	Latitude	Depth (m)
Estaca de Bares	Directional	7°37.2′ W	44°3.6′ N	386
Vilano-Sisargas	Directional	9°12.6′ W	43°29.4′ N	386
Silleiro	Directional	9°24.0′ W	42°7.2′ N	323

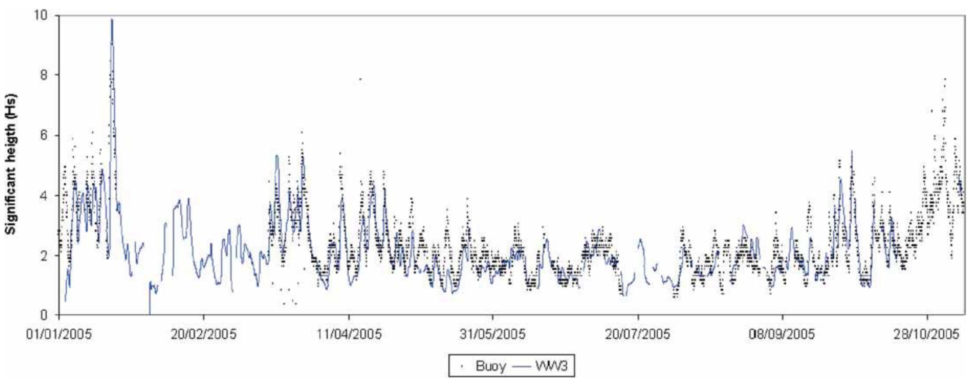

Figure 3. Forecasted (solid line) and buoys data (black spots) significant wave height (H_s) at Vilano-Sisargas buoy location.

3. Results and validation

3.1. *Initial implementation validation*

The outputs of the WW3 wave forecasting system are verified monthly using the PE-CM deep water buoy network. Results correspond to the period January–October 2005 as the new implementation (WW3n) became operational in November 2005. Field data were obtained from the real time PE-CM deep water buoy network located near the Galician coast at points at least 25 miles away from coastline (table 2).

During the validation period a total of 14 869 hourly data after quality control were collected: 4725 at Estaca de Bares buoy, 5113 at Vilano-Sisargas and 5031 at Silleiro. Three variables H_s (significant wave height), T_p (wave peak period) and Dir_p (wave peak direction) were used for statistical analysis to analyse the forecasting system performance. These variables are derived from the analysis and first day forecast WAVEWATCH III modelled bi-dimensional spectrum at the buoy location, and from frequency spectrum derived from buoy collected data. Bias, mean absolute error (MAE) and the root mean square error (RMSE) are used as skill scores to study the performance of the model.

Figures 3–5 show the time evolution of the significant wave height, wave peak period and peak direction respectively, compared with the Vilano-Sisargas buoy data. Although not shown here, similar results were obtained at Estaca de Bares and Silleiro buoys locations. During all the analysed period, results show a slight tendency of the wave forecasting system to underestimate significant wave height and

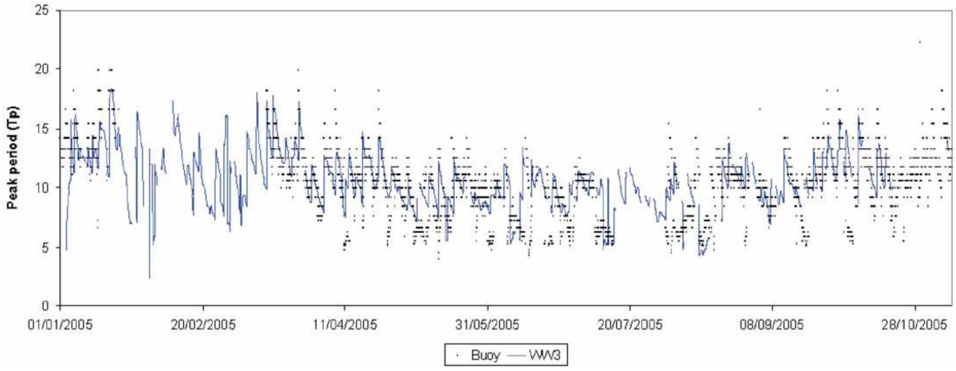

Figure 4. Forecasted (solid line) and buoys data (black spots) wave peak period (T_p) at the Vilano-Sisargas buoy.

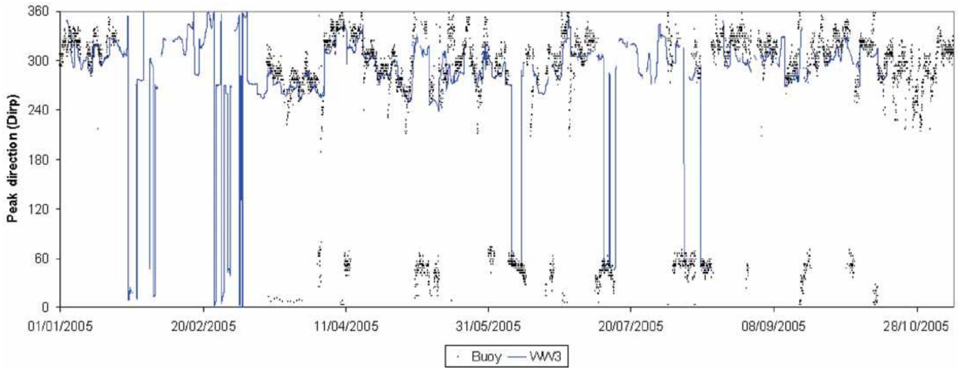

Figure 5. Forecasted (solid line) and buoys data (black spots) wave peak direction (Dir_p) at the Vilano-Sisargas buoy.

overestimate peak period. Table 3 shows the performance of the model in terms of the skill scores.

Plots of peak direction show an interval which is suppressed due to the orientation of the Galician coastline, i.e. it is not possible to observe peak directions from the NE at the Silleiro buoy, but they are observed at Estaca de Bares and Vilano-Sisargas buoys. In this case, it is important to realize that situations characterized by a sudden change in peak direction are less accurately represented by the model simulations. Figures 5 and 6 show this behaviour for the Vilano-Sisargas buoy, which shows the normal 'gap' at 70–250°, but peak directions of $<70°$ (E–NE direction) are not well reproduced by the model data. These sudden changes in peak directions are associated with a sudden fall of peak period (figure 4), showing that, in these situations, fetch is located over the Cantabrian Sea. In this case, north-east peak directions (0°–70° but depending on buoy position) and low values of peak period are addressed.

Scatter plots of the three analysed points (figures 6 and 7) show the same behaviour, suggesting that the generation over the Cantabrian Sea is underestimated under some circumstances. Peak direction statistics (table 3)

Table 3. Significant wave height, wave peak period and peak direction skill scores for WAVEWATCH III model (WW3) at the three buoys locations.

		Bares	Sisargas	Silleiro
H_s (m)	BIAS	−0.095	−0.133	−0.175
	MAE	0.346	0.406	0.415
	RMSE	0.471	0.573	0.583
T_p (s)	BIAS	0.760	0.226	0.263
	MAE	1.730	1.534	1.563
	RMSE	2.426	2.138	2.327
Dir_p (°)	MAE	33.495	29.782	22.125
	RMSE	57.257	48.577	32.432

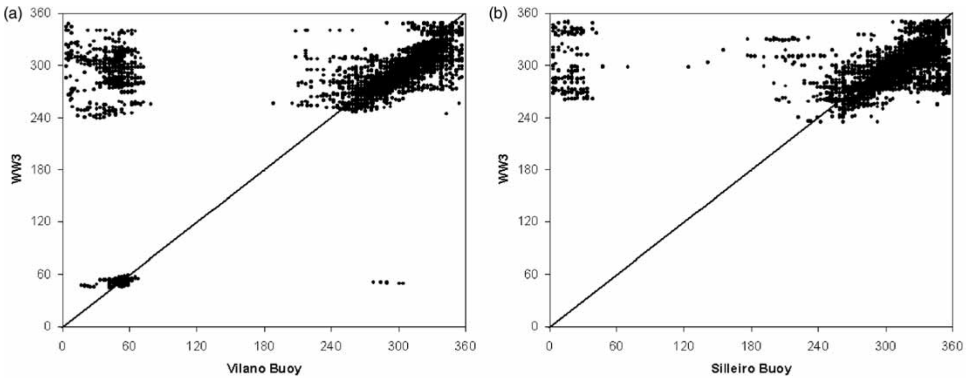

Figure 6. Scatters plot of peak direction for Vilano-Sisargas (a) and Silleiro (b) buoys against model data. A gap between 70° and 240° is observed for Vilano-Sisargas data, while the gap is between 30° and 250° for the Silleiro buoy. In both cases, the gap is consistent with buoy positions.

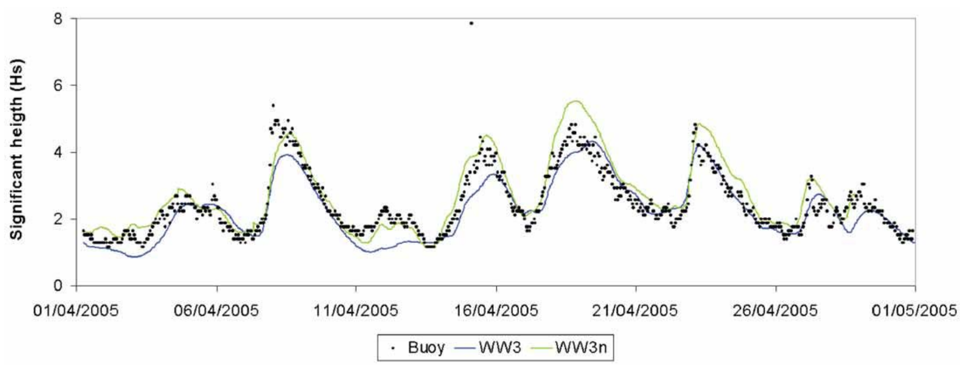

Figure 7. Significant height calculated for both wave forecasting systems for April 2005. Dots correspond to measured data at Vilano-Sisargas buoy.

show that MAE and RMSE is larger at buoys in the Cantabrian Sea (Estaca de Bares buoy) or with a strong Cantabrian Sea influence (Vilano-Sisargas buoy), than at the Silleiro buoy where the peak direction from the NE is suppressed by the coastline.

Table 4. Peak direction (Dir_p) skill scores for WAVEWATCH III model (WW3) at the three buoys locations. Table shows the number of data/MAE/RMSE for the three buoys locations.

	0–90°	90–180°	180–270°	270–360°
Estaca de Bares	541/92.61/109.14	151/154.01/156.5	268/19.56/27.33	2483/14.79/19.5
Vilano–Sisargas	800/83.43/98.62	0/–/–	320/25.05/34.63	2832/15.16/20.25
Silleiro	175/80.83/87.13	5/157.02/157.58	306/31.32/46.87	3699/18.4/24.81

In order to confirm the above mentioned results and to show the directional performance of the forecasting system, similar peak direction statistics are given, but ordered by buoy measured direction and grouped in four quadrants (0–90° N–NE, 90–180° SE–S, 180–270° SW–W and 270–360° NW–N). Table 4 shows that the larger errors are obtained for the first and second quadrant. Most data are grouped into NW-N (270–360°) buoy for the measured peak direction and the main source of error, shown at table 3, comes from the first and second quadrant, as is shown at Estaca de Bares.

Further analysis is needed to understand the origin of this disagreement between the field and forecasted data, but the peak direction and wave period skill scores suggest, an underestimation of the wind fields over the Cantabrian Sea, as a possible explanation.

3.2. *The new implementation and validation for two forecasting cycles (00, 12 Z)*

In order to estimate WW3n performance based on two forecasting cycles (00, 12 Z), a statistical analysis for one month's data was performed using both forecasting systems. For this purpose, April 2005 was selected for the analysis when both systems were available.

The data used in this statistics came from the first 24 h forecast of the old implementation, and the 12 h analysis of both cycles (00 and 12 Z) corresponding to the new implementation. Similar results are obtained from first day forecast data of each cycle. As in the previous section, the same buoys and statistical variables were used to validate the wave model. During April 2005, the Estaca de Bares buoy malfunctioned and its data were rejected, while the Silleiro buoy collected hourly data only from April 1, 2005 00:00 to April 16, 2005 05:00.

Table 5 shows the skill scores for both model implementations at the Silleiro and Vilano-Sisargas buoys. WW3n implementation improves the sea state parameters at the Silleiro buoy, obtaining similar values of MAE and RMSE, to those at Vilano-Sisargas, although as stated before, slight overestimation is present. Figures 7–9 show the time evolution during April 2005 of the measured parameters for both model implementations. Figure 7 shows a good agreement between the modelled significant wave height and buoy data at Vilano-Sisargas. Although skill scores for both implementations are quite similar, measured peaks of significant wave height at buoys show a higher correlation with the new implementation of the modelled data.

Peak period (T_p) and peak direction (Dir_p) forecasting using the new implementation are improved, specially in situations where the sea state is characterized by a small 'fetch' and consequently low peak period, for example with events which are generated over the Cantabrian sea. Figure 9 shows a period between April 9 and April 4 when a sudden change of peak direction

Table 5. Significant wave height, wave peak period and peak direction skill scores calculated for both wave model implementations during April 2005.

		WW3n		WW3	
		Sisargas	Silleiro	Sisargas	Silleiro
H_s (m)	BIAS	0.242	−0.013	−0.186	−0.386
	MAE	0.360	0.352	0.344	0.498
	RMSE	0.485	0.430	0.483	0.592
T_p (s)	BIAS	0.021	0.009	0.182	0.028
	MAE	1.247	1.355	1.315	1.490
	RMSE	1.826	1.984	1.940	2.075
Dir_p (°)	MAE	19.335	15.073	20.305	15.797
	RMSE	37.917	19.670	38.826	20.543

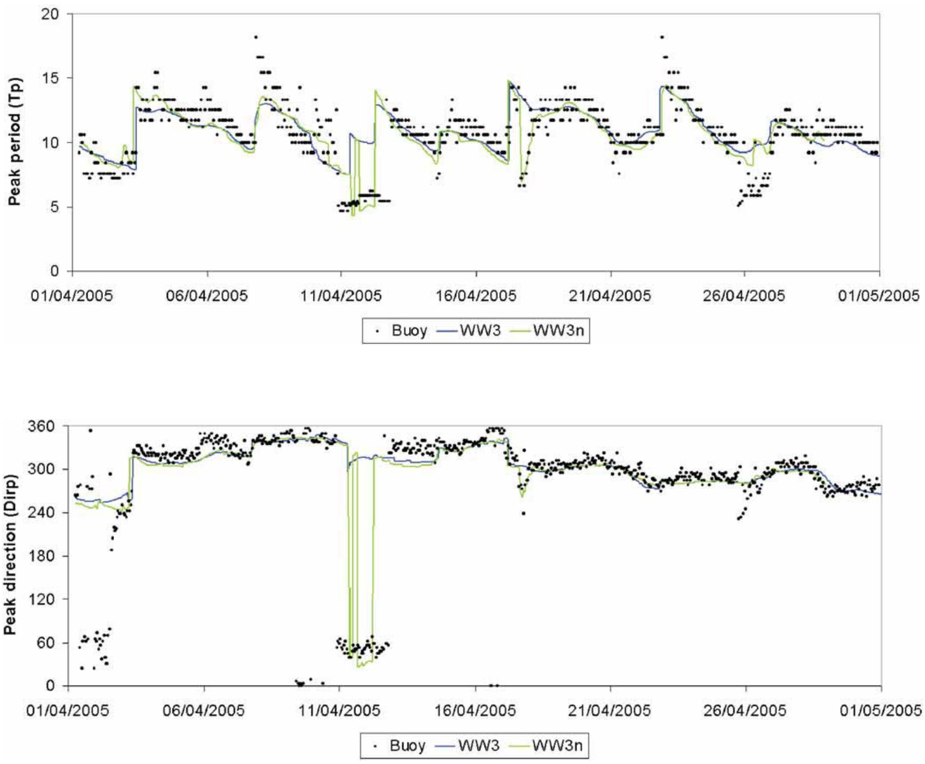

Figure 9. Peak direction calculated for both wave forecasting systems for April 2005. Dots correspond to measured data at Vilano-Sisargas buoy.

(from N–NW to N–NE direction) is followed by a sharp peak period diminution from 10 s to 5 s (figure 8).

Another example on April 17 shows a rapid change in peak direction and a rapid diminution of wave period. These cases occur when wave generation in the Cantabrian Sea is dominating that from the North Atlantic Ocean. The new WW3n implementation reproduces these kinds of events much better than its predecessor.

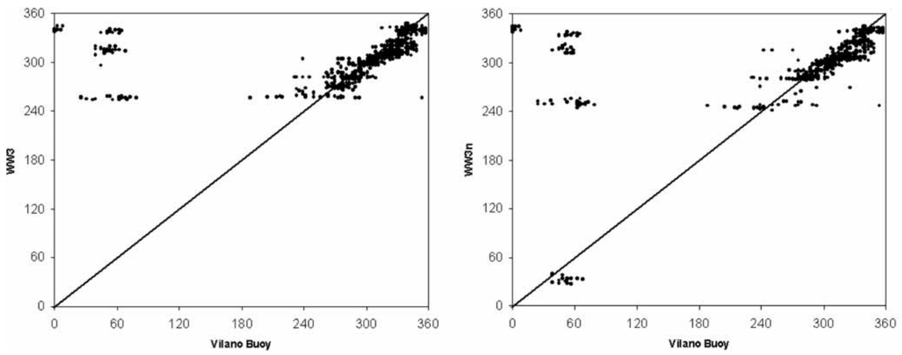

Figure 10. Scatters plots of peak direction for Vilano-Sisargas buoy for both implementations of the wave forecasting system. A gap between 70° and 250° is observed which is consistent with buoy position.

Scatter plots shown in figure 10 also confirm a better forecast of events with a peak direction between 0° (N) and 70° (E–NE), although as stated before, the Vilano-Sisargas buoy with an influence from the Cantabrian Sea, have skill scores for peak direction (table 5) with a larger MAE and RMSE. This behaviour was found in the old implementation using GFS and ARPS wind data, and it is reproduced again with the new implementation which only use GFS 10 m wind field. Again, further analysis is needed to understand the origin of this disagreement, but since the ARPS model uses initial and boundary conditions from GFS, preliminary conclusions suggest an underestimation of wind field in Cantabrian Sea by the GFS model.

3.3. *Wind forcing validation*

In order to better understand the origin of observed differences between the experimental data collected by buoys and modelled data, a statistical analysis of three different wind forcings is considered here. These are from the following models: NCEP GFS, MeteoGalicia ARPS 50 km and ARPS 10 km.

The same data set from the PE-CM deep water buoy network has been used here. Modeled data came from the initial implementation wind output from three model grids (i.e. North Atlantic, Iberian margin and Galician coast) at buoy locations (figure 1).

Figure 11 shows overestimation of GFS winds in all directions, which is consistent with the general overestimation of significant wave height shown for new implementation skill scores. For the ARPS 50 km resolution modelled wind, in general, is underestimated, with a larger underestimation in the N–NE direction. In this situation, local and Cantabrian sea wave generation is underestimated, thus giving incorrect values of peak period (T_p) and peak direction (Dir_p), as has been shown before. Therefore a better performance of the new implementation is found only with GFS wind forcing.

ARPS 10 km wind statistics show the best performance of all modeled winds, with an overall BIAS of $< 0.15\,\mathrm{m\,s^{-1}}$, but still showing an underestimation of winds from the N–NE directions. Additional examples of good performance from the ARPS 10 km, related to wind prediction and weather forecasting, have been provided by Souto *et al*. (2003) and Balseiro *et al*. (2003).

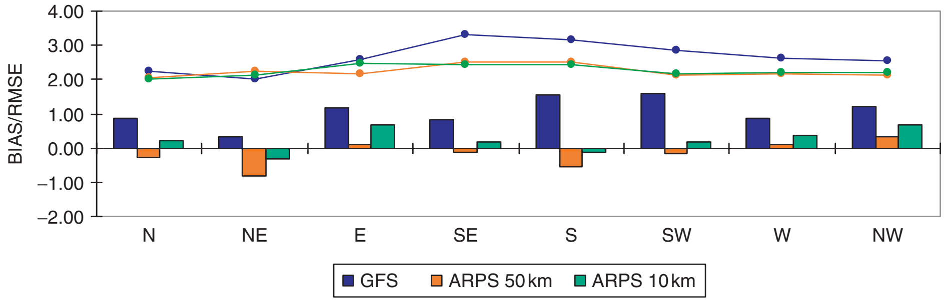

Figure 11. Overall wind speed BIAS (colour bars) and RMSE (colour lines) by octants for GFS, ARPS 50 km and ARPS 10 km wind forcing.

However, similar RMSE are found for ARPS 50 and 10 km winds and larger errors are found in NCEP GFS winds, especially for directions from the SE and S.

4. Conclusions and future work

A wave forecasting system for North Atlantic and regional scale has been presented in this article. The main goal of this system is to provide a wide area wave forecast, from basin to regional scale in a self-contained way where only wind forcing is needed to perform the forecast. This system is able to achieve a high resolution down to 2.5′, which is needed for other wave model applications.

Statistical analysis performed here show a good agreement between the modelled data and the buoy network from PE-CM. A disagreement between the initial implementation and the buoy data is found in cases where the buoy measured peak direction is mainly from the N–NE, corresponding to cases with important wave generation in the Cantabrian Sea. These cases represent the main source of error at all buoys locations. Statistical analysis for different wind forcings, show an important underestimation of the ARPS 50 km resolution modelled winds mainly in those cases. The new implementation using only GFS wind forcing, introduced late spring 2005, has shown a better performance and also an improvement in the forecast. Further analysis is needed to understand the origin of observed differences between the buoys and modelled data. Determination of the overall performance of the new implementation introduced here is planned in the near future.

Recently, MeteoGalicia has developed a high resolution wave forecast nested to the WAVEWATCH III model which is applied to especially sensitive regions of the Galician coast, for example areas of important economic significance, such as Artabrian Gulf and Rias Baixas. For this purpose the SWAN model (Simulating Waves Nearshore) developed by Delft University of Technology is used. Although both models solve wave action spectra propagation, SWAN is specifically designed for coastal applications (Booij *et al.* 1999). This high resolution wave forecasting system is being tested and the results will be presented elsewhere.

Finally, as a further application of the wave forecasting system in the coastal zone, the two-way interaction of wind and waves and the effects of ocean currents on wave propagation (and vice versa) are being studied.

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References

Balseiro, C.F., Carracedo, P., Gómez, B., Leitão, P.C., Montero, P., Naranjo, L., Penabad, E. and Pérez-Muñuzuri, V., 2003, Tracking the Prestige oil spill: an operational experience in simulation at MeteoGalicia. *Weather*, **58**, pp. 452–458.

Booij, N., Ris, R.C. and Holthuijsen, L.H., 1999, A third-generation wave model for coastal regions. 1. Model description and validation. *Journal of Geophysical Researchm*, **104-C4**, pp. 7649–7666.

Gómez Lahoz, M. and Carretero Albiach, J.C., 1997, A two-way nesting procedure for the WAM model: application to the Spanish coast. *Journal of Offshore Mechanics and Artic Engineering*, **119**, pp. 20–24.

Janssen, P.A.E.M., Doyle, J.D., Bidlot, J., Hansen, B., Isaksen, L. and Viterbo, P., 2002, Impact and feedback of ocean waves on the atmosphere. In *Advances in Fluid Mechanics*, W. Perrie (Ed.), **1**, pp. 155–197 (Southampton, UK: Wit Press).

Janssen, P.A.E.M., 2004, *The Interaction of Ocean Waves and Wind*, p. 300 (Cambridge, UK: Cambridge University Press).

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. and Janssen, P.A.E.M., 1994, *Dynamics and Modelling of Ocean Waves*, p. 532 (Cambridge, UK: Cambridge University Press).

Pielke, R.A. and Martin, C.L., 1981, The derivation of a terrain-following coordinate system for use in a hydrostatic model. *Journal of Atmospheric Sciences*, **38**, pp. 1707–1713.

Souto, M.J., Balseiro, C.F., Pérez-Muñuzuri, V., Xue, M. and Brewster, K., 2003, Impact of cloud analysis on numerical weather prediction in the Galician region of Spain. *Journal of Applied Meterology*, **42**, pp. 129–140.

Tolman, H.L., 1991, A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depth and currents. *Journal of Physical Oceanography*, **21**, pp. 782–797.

Tolman, H.L., 1992, Effects of numerics on the physics in a third-generation wind-wave model. *Journal of physical Oceanography*, **22**, pp. 1095–1111.

Tolman, H.L. and Chalikov, D., 1996, Source terms in a third-generation wind-wave model. *Journal of Physical Oceanography*, **26**, pp. 2497–2518.

Tolman, H.L., 1999, User manual and system documentation of WAVEWATCH-III version 1.18. NOAA/NWS/NCEP/OMB Technical Note 166, p. 110.

WAMDI Group: Hasselman, S. and K., 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. *Journal of physical Oceanography*, **18**, pp. 1775–1810.

Xue, M., Droegemeier, K.K. and Wong, V., 2000, The Advanced Regional Prediction System (ARPS) – A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: model dynamics and verification. *Meteorology and Atmospheric Physics*, **75**, pp. 161–193.