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Abstract: A wave hindcast in the Western Mediterranean Sea is carried out in order to assess the performance of six atmospheric models in providing the forcing for a third generation wave model. The wind models have been used as forcing fields for a wave generation model and the resulting significant wave height time history compared with four buoys around the Balearic Islands. Two different wave model grid resolutions are used to get the wave field in the entire Mediterranean and around the Balearic Islands. Results indicate that even if all data sources provide good forcing for operational wave forecast at large scales (wind forecast with grid resolution of 30 and 25 km) for the coastal areas the WRF(1.5 km) model, which has the highest resolution, is the most suitable to obtain the complex wave pattern around the islands since it is able to resolve the spatial variability produced around Archipelagos.

Assessment of wind models around the Balearic Islands for operational wave forecast.

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ABSTRACT

A wave hindcast in the Western Mediterranean Sea is carried out in order to assess the performance of six atmospheric models in providing the forcing for a third generation wave model. The wind models have been used as forcing fields for a wave generation model and the resulting significant wave height time history compared with four buoys around the Balearic Islands. Two different wave model grid resolutions are used to get the wave field in the entire Mediterranean and around the Balearic Islands. Results indicate that even if all data sources provide good forcing for operational wave forecast at large scales (wind forecast with grid resolution of 30 and 25 km) for the coastal areas the WRF(1.5 km) model, which has the highest resolution, is the most suitable to obtain the complex wave pattern around the islands since it is able to resolve the spatial variability produced around Archipelagos.

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1. INTRODUCTION

A proper assessment of wave climate is a previous requirement for scientific and engineering activities in the coastal zone. Beach nourishment, port design and operability, dispersion and diffusion of pollutants are some examples that require a proper estimation of significant wave heights fields (diagnostic) as well as their evolution (prognostic) forward in time. The diagnostic of waves has traditionally been obtained using scalar and directional wave buoys moored at specific locations. Moored instruments are the most reliable systems used to provide wave conditions, but their drawback is that they are expensive and they provide only records at specific locations. In the last decade, satellites and more recently High Frequency Radar systems have overcome at some degree the problem of the spatial lack of data, but the problem of having a large amount of spatial and temporal records were still unresolved.

By contrast, numerical models provide in a regular basis, wave fields at different spatial and temporal resolutions by integrating first physical principles forward in time. To produce reliable numerical simulations, wave models capable of reproducing complex physical processes involved in the generation and transformation of waves have to be implemented [1], [2]. Moreover, accurate wind fields with the adequate resolution are mandatory since realistic forcing terms will provide accurate wave predictions.

Despite the diversity of wave generation models as well as in atmospheric models, numerical predictions of wave fields in a particular region should fail mainly due to an inadequate representation of the physical processes involved in the wave generation or due to errors associated to the spatial and/or temporal wind field resolutions. Wave models are very sensitive to wind field variations which results in one of the main source of errors in wave predictions [3], [4], [5]. Additionally, in small and semi-enclosed seas, wave modelling becomes cumbersome due to the complex orography and the limited fetch. Surface waves are generated by the wind blowing over the sea surface and any error in the input wind field will be reflected in the computation of wave conditions [3].

Deep water wave climate over the Balearic Sea has in general a complex pattern as a result of the complex orography of the surrounding area. In the last years, some studies

have attempted to analyze the accuracy of different wave and wind models in the NW Mediterranean Sea. Signell [6] analyzed the surface wind quality in the Adriatic Sea concluding that for a period of two months the limited area models LAMI and COAMPS provide better amplitude response than the coarser ECMWF. Ardhuin [7] analyzed the accuracy of four atmospheric models and three wind-wave models concluding that quality of the wind fields degrades in the coastal areas. Ponce de León and Guedes Soares [8], compared wave hindcast in the Western Mediterranean sea using the reanalysis wind fields from HIPOCAS and ERA-40 founding systematic negative biases of significant wave height using ERA-40 fields and positive biases for the HIPOCAS data. In spite of these advances, to our knowledge, the effects of local meteorological events around archipelagos in the Mediterranean Sea have not been treated in detail.

The aim of this work is to further study the accuracy of a third generation wave model forced by six different atmospheric wind fields with different spatial resolution (30, 25, 16, 6, 5 and 1.5 km) around the Balearic Islands (NW Mediterranean Sea) prior to the development of a real time operational system for wave prediction in the area.

The paper is structured as follows: Section 2 presents the singularities of the study area. Section 3 provides a description of the atmospheric models, in situ measurements as well as wave model set-up. Section 4 presets the results and provides the discussion and finally Section 5 concludes the work.

2. STUDY AREA

The Western Mediterranean (WM) has a complex structure with numerous peninsulas and islands that complicates wave prediction models [9]. Moreover, the WM is an important cyclogenetic area where the main hydrodynamics is conditioned by the severe atmospheric-climatic forcing during winters [10]. Most of the strong winds observed in the Mediterranean belong to the category of local winds and are originated as down slope flows by air-flow/mountain interaction or due to channelling effects [11]. The WM area is forced by northerly and north-westerly winds during most of the year, while less intense cyclogenetic activity is observed during the rest of the year [12], [13]. The

mountains range in the vicinity is a key factor in its climatic characteristics [14]. The role of the Pyrenees in the western area and the Alps in the north-eastern area are decisive boundaries for the pressure and wind distribution over the basin. Wind speeds for a 100-year return period shows a maximum located in the Gulf of Lions with winds up to 30 m/s. The low-pressure systems entering to the Mediterranean Sea from the Atlantic Ocean tend to dissipate moving east, with the major storms taking place in the WM [8].

The Balearic Archipelago, near the eastern Mediterranean coast of Spain is formed by four major islands that may lead to a reduction of the wave energy in the basin during winter period due to the shadowing effect of the islands (Ponce de León and Guedes Soares [15]).

The present work has been centred in the southern coast of Mallorca Island for operational purposes where a high resolution wave model (1500 m) has been implemented and nested to general wave model covering the entire Mediterranean. Resulting wave fields are compared with in situ data from deep and shallow waters wave buoys.

3. DATA AND METHODS

3.1 Atmospheric models

Three different sources of atmospheric models are used to test the accuracy of wave fields within this work (HIRLAM, ECMWF and WRF). To assess the sensitivity of wave fields to the wind, data sets have been divided into two groups according to their spatial resolution. The first group consists of atmospheric models with a relatively coarse resolution HIRLAM(16), WRF(30) and ECMWF(25) with 16, 30 and 25 km resolution respectively. The second group includes the atmospheric models with higher resolution HIRLAM(5) with 5 km and two WRF(6/1.5) configurations with 6 km and 1.5 km.

The HIRLAM (High Resolution Limited Area Model) is a primitive-equation model that uses a regular grid spatially staggered [16]. In the WM, HIRLAM forecasts are provided by the Spanish Meteorological Agency (AEMET) providing wind fields every 3 hours at 16 km (low resolution) and 5 km (high resolution).

The ECMWF (European Center for Medium Weather Forecast) model provides wind fields every 6 hours with a horizontal resolution is about 25 km [17]. Finally, the WRF (Weather Research and Forecasting) is a next-generation mesoscale non-hydrostatic numerical weather prediction system from NCEP (National Centers for Environmental Prediction) with a horizontal resolution of 1.5 km [18]. The WRF model coarse grid uses time dependent boundary conditions from the NCEP-NCAR (National Center for Atmospheric Research) reanalysis.

3.2 Wave model

The WAMPRO, a third generation wave model based on the original code of WAMC4 [19] has been chosen for the experiment in the study area. It is suitable to simulate shallow water waves including processes such as depth-induced wave breaking and wave-current interactions [20].

A coarse mesh covering the whole Mediterranean Sea (30° N to 46° N and 6° W to 37° E) was implemented in order to provide the boundary conditions -hereinafter WAMPRO1- (Fig. 1, bottom). Bathymetry was obtained from the ETOPO1 database and interpolated to the final resolution of 0.25° in a 173×65 mesh. A high resolution mesh covering the area of 38.75° N, to 39.75° N and 1.75° E- 4.0° E was nested to the former -hereinafter WAMPRO2 (Fig. 1 top). This domain includes the southern part of Mallorca Island as well as the Cabrera Archipelago. Bathymetric data was interpolated to the final grid of 181×81 nodes with a resolution of $1/80^{\circ}$. The WAMPRO1 mesh was arranged to match with the resolution provided by ECMWF(25) model in the whole Mediterranean while the WAMPRO2 mesh arranged to coincide with the high resolution WRF(1.5) model in the Balearic Sea. Data from HIRLAM(16/5) were internally interpolated to both WAMPRO1 and WAMPRO2 meshes. Integration time steps were set as 600 and 40 seconds for WAMPRO1 and WAMPRO2 respectively.

The energy balance equation was integrated for 24 directions and 25 frequencies. A JONSWAP spectrum was imposed as the initial condition at every grid point with a spectral peak enhancement factor of 3, a spectral peak frequency of 0.2 Hz. The

Phillip's parameter was set as 0.018, the right peak width as 0.09, the left peak width as 0.07 and the fetch as 30 km.

3.3 Buoy data

Numerical simulations are validated at four locations with measurements from moored buoys. The first location is western Dragonera Island in the western side of the domain, 20 km offshore Mallorca Island (B1 in Fig. 1). This mooring consists on a directional wave buoy from the Spanish Harbour Authority (Puertos del Estado, PE) at 135 meters depth. The second location, Cap de Pera is a scalar shallow water buoy in the north-eastern side of the numerical domain, 4 km offshore at 45 m depth (B2 in Fig. 1). The third location, Cabrera is a scalar buoy operated from IMEDEA moored at 70 m depth in the channel between Mallorca and Cabrera islands (B3 in Fig. 1). Additionally, a deep water Buoy located in Maó (Menorca Island) from PE (B4 in Fig. 1, bottom panel) has been used to validate numerical simulations for the coarse model implementation. The geographical coordinates of the wave buoys are provided in Table 1.

4. RESULTS

Different experiments were carried out in order to compare the assessment of wind input models according to Table 2. The low resolution wind fields - HIRLAM(16) and ECMWF(25)- were used as the forcing for WAMPRO1 which in turns provided the boundary conditions for WAMPRO2. Moreover, WAMPRO2 was forced with all wind data sets.

During November 2008, four isolated storms crossed the area with wind gustiness over 15 m/s which in some periods passes the 48 hours in duration. These storms produced significant wave heights (H_s) at B1 larger than 5.5 m (recorded at November 29th at 15 UTC). These storms are used to study the accuracy of the wave model against the different wind fields.

4.1 Performance of WAMPRO1 in providing BC

To test the performance of WAMPRO1 in providing the boundary conditions for the high resolution wave model, a hindcast for November 2008 was done. The wave model was forced with the low resolution winds HIRLAM(16) and ECMWF(25) and resulting wave time history compared with *in situ* data at Maó Buoy (B4).

The wind input at the mooring location B4 for both HIRLAM(16) and ECMWF(25) are compared with the wind measurements in Fig. 2 top panel. Despite some discrepancies in wind speed are evident for both wind data sets, they are not specially relevant for the prediction of the significant wave height (Fig. 2 bottom panel). Even if HIRLAM(16) wind fields exhibit some lag for the intense events, both winds provide good results for the predicted Hs. The bias (defined as the difference between the mean observation and the mean prediction) between B4 and model results is presented in Table 3. As seen, both wind models give similar results in the large scale. The scatter index (defined as the standard deviation of the data with respect to the best-fit line, divided by the mean observations) is also of the same order. The low values of the biases are associated with the fact that at the coarse resolution grid, Menorca Island (B4 buoy is placed) is represented by only a dry point. It is necessary to point out that at the nested domain this location is out (see Fig. 1).

4.2 Performance of WAMPRO2 vs. WAMPRO1

To solve adequately the effects of the orography on the wave field, a fine mesh resolving geographical indents has to be implemented. However, to forecast operationally large coastal areas, this approach is unaffordable and therefore, a nesting strategy is mandatory. In this study, we have nested WAMPRO2 which has 1.5 km grid resolution in the southern part of Mallorca Island to WAMPRO1. Fig. 3 displays the predicted Hs from WAMPRO1 and WAMPRO2 using inputs from HIRLAM(16) and ECMWF(25). As observed, the hindcast is noticeable better using the small grid although the coarse winds are used.

To get a better insight on the performance of the model in front grid resolution, the bias and scatter index of WAMPRO1 (coarse) and WAMPRO2 (nested grid) using

ECMWF(25) and HIRLAM(16) are given in Table 4. It can be seen that increasing the spatial grid resolution produces a better adjustment of the forecasted value of Hs only at B3. The improvement at this location is explained with the fact that Cabrera Island is fully resolved by the spatial resolution of WAMPRO2.

At B1, which is located at deep waters and therefore not affected by sheltering effects, no remarkable improvement is obtained (Table 4). At B2, the WAMPRO1 underestimated the Hs values whereas WAMPRO2 overestimates them as seen from Table 4.

4.3 Influence of wind spatial resolution on the nested grid (WAMPRO2)

To assess the performance of the wind models a hindcast for November 2008 was done with all wind data fields. HIRLAM(16) and HIRLAM(5) were nested with HIRLAM(16) in WAMPRO1 while ECMWF(25) and WRF(1.5, 6, 30) were nested with ECMWF(25) (see Table 2 for details).

Normalized (by observations) differences between the modelled Hs forced with WRF(30), HIRLAM(16) and ECMWF(25) and B1, B2 and B3 buoys are shown in Fig. 4 (top, middle and bottom panels, respectively). It can be seen that the three wind fields provide reasonable good results at all locations for the period analyzed. The differences between modelled and measured Hs are due to the fact that the model does not properly resolve the small scale wind direction specially for those directions not associated with the dominant fetch (NE).

Normalized differences between modelled Hs at B1, B2 and B3 are shown for WRF(1.5), HIRLAM(5) and WRF(6) in Fig. 5. Some anomalies can be observed during the first 15 days with HIRLAM(5) at B1 (top) and B2 (middle), where as at B3 the highest negative inconsistency was obtained at the end of the period with WRF(6) and WRF(1.5).

The scatter plots between WAMPRO2 predictions and measurements for the WRF(30), HIRLAM(16) and ECMWF(25) are displayed in Fig. 6 (left panels). It can be observed

that the best predictions are obtained at B2 site which turns to be oriented to the dominant fetch (slopes of 1.03 for WRF(30), 0.95 for HIRLAM(16) and 0.91 for ECMWF(25)) . At B1, the model underestimates the observed data for the three wind fields analyzed and at B3, the model overestimates the real data for the three atmospheric models.

For the high resolution wind inputs the scatter plots are displayed in Fig. 6 (right panels). The hindcasted wave heights at the three locations present similar trends than the large resolution wind models. The best fit is obtained at B2 with slope of 1.03 for WRF(1.5), 0.93 for WRF(6) and 0.94(HIRLAM5).

In general, the scatter index for the low and high resolution winds gives similar values which indicating that the location where data are compared is crucial. The slope and the scatter index are similar at B1 and B2, but higher values are obtained for B3. The scatter indexes range from 0.18 up to 0.5 at B1 and B2, where as at B3 this parameter reaches 0.63. The larger scatter indexes obtained at B3 indicate that the wave model does not properly resolve the refraction-diffraction effects at the small scale between islands (less than 10 km).

5. Spatial variability

The spatial variability of wind fields is a key factor specially for the small scale features that can only be resolved by the high resolution models. As an example, Fig. 7 shows the wind speed and direction for WRF(1.5) (top panel) and for ECMWF(25) (bottom panel) for November 14th 2008 at 12 UTC. As seen, for the same Tramuntana event, both wind fields largely differ not only in the small scale features, but in the large scale pattern which leads to significant difference in the wave field. The wind fields (left) and the forecasted wave fields (right) for WRF(1.5)(top) and for ECMWF(25)(bottom) are displayed in Fig. 8 for November 4th at 12 UTC. As seen, small scale wind pattern are captured in the WRF(1.5) such as wind gust of about 24 m/s in November 29th 2008 at 18 UTC (Fig. 9 top panel) with a duration of 2 days.

The wind gustiness is an important information, missed in the low resolution HIRLAM(16) wind field (and the other models) represented in Fig. 9 (bottom panel). These wind gustiness are crucial for obtaining a better description of the sea conditions in coastal forecasts, because they are probably characteristic for the region of Balearic Islands.

In order to analyze the quality of the variability of the WRF(1.5) high resolution winds a comparison is done Fig. 10 using ASCAT (Advanced SCATterometer) measured data (Portabella and Stoffelen [21], Verhoef and Stoffelen [22]). Despite the orbit of the EUMETSAT's MetOp satellite Scatterometer is at 8:24 a.m. and not exactly at 9:00 UTC as on the case of the map of WRF(1.5), it can be seen a similar pattern between the ASCAT wind speeds and directions and WRF(1.5) wind. This allows inferring that the variability shown in the present work is valid for operational wave forecast around the Balearic Islands.

6. CONCLUDING REMARKS

The impact of different spatial resolution atmospheric models has been evaluated using a third generation wave model. The hindcast has been carried out nesting a coarse grid ($\Delta x = \Delta y = 0.25^\circ$) for the whole Mediterranean Sea with a finer mesh for the Balearic Islands ($\Delta x = \Delta y = 1.5$ km). Wave fields obtained using the different input forcings are validated against four different wave moorings (deep and shallow waters) around the coast. Results indicate that that the analyzed wind fields provide sufficiently good results for operational wave forecast with at time interval of 6 hours.

Even if the large wind models WRF(30), ECMWF(25) and HIRLAM(16) provide similar wave forecast which are in good accordance with measurements, they are too coarse to reproduce the complex wave field produced around the islands which in some cases accounts for a large part of the wave variability in the Balearic Islands. However, the resolution of these atmospheric models is sufficiently good to provide accurate forecast in open seas and are suitable for large scale operational wave models.

In insular systems characterized by a complex topography as the case studied, the grid size has to be reduced to forecast properly the whole wave spectra and to solve accurately the shallow water processes. Therefore, small scale wind fields have to be used. From our results we conclude that all high resolution models analyzed HIRLAM(5), WRF(6) and WRF(1.5) provide similar results in terms of slope and scatter index when compared with the coastal buoys but the data from the WRF(1.5) wind model provide more realistic spatial distributions of waves since it is able to capture the high frequency variability time intervals less than 6 hours of local winds that accounts for a large portion of wave variability in the Balearic Islands. These results are in accordance with a recent work by [23] who verified the ability of the atmospheric model WRF to reproduce properly the sea breezes.

For small areas, in the sheltered zone of the islands, such as the one located at B3, the WAMPRO model should be further improved including those physical processes such as diffraction of the waves .

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Fig. 1 Area of study and locations of the buoys.

Fig. 2 Wind speed (u10) at B4 buoy (solid line) and from HIRLAM(16) (crosses) and ECMWF(25) (dashed line), top panel. Significant wave height (Hs) at B4 buoy (solid line) and from HIRLAM(16) (crosses) and ECMWF(25) (dashed line) bottom panel.

Fig. 3 Significant wave height (Hs) for November 2008 at B3 (solid line) and modelled with HIRLAM(16) from WAMPRO1 (dotted line) and WAMPRO2 (star line) and from ECMWF(25) from WAMPRO1 (crosses) and WAMPRO2 (dash dotted line).

Fig. 4 Normalized deviations between Hs at B1 and from WAMPRO2 with WRF(30) (dash dotted line with triangles), HIRLAM(16) (dotted line with circles) and ECMWF (25) (dash dotted line) for the fifteen first days of November 2008 (top panel). The same at B2 (middle panel) and at B3 (bottom panel).

Fig. 5 Normalized deviations between Hs at B1 and from WAMPRO2 with WRF(1.5) (dash dotted line with triangles), HIRLAM(5) (dotted line with circles) and WRF(6) (dash dotted line) for the fifteen first days of November 2008 (top panel). The same at B2 (middle panel) and at B3 (bottom panel).

Fig. 6 Scatter plots of the results obtained using the low resolution winds: WRF30 (triangle), HIRLAM15 (cross) and ECMWF(square)-(left) at B1 (top), B2 (middle) and B3 (bottom). Scatter plots using the high resolution winds: WRF(1.5)(triangle), WRF(6)(box) and HIRLAM(5)(plus)-(right) at B1 (top), B2 (middle) and B3 (bottom).

Fig. 7 Wind fields for 14th of November at 12 UTC according high and low wind resolutions: WRF(1.5) and ECMWF(15), respectively.

Fig. 8 WRF(1.5) wind field (left) and the corresponding Hs (m) (right) from WAMPRO2 for November 4th 2008 at 12 UTC (top panels). The same for ECMWF(25) (bottom panel).

Fig. 9 WRF(1.5) high resolution wind field (top) and HIRLAM(16) (bottom) for November 29th 2008 at 18 UTC.

Fig. 10 WRF(1.5) wind field for 29th of November 2008 at 09 UTC and ASCAT(12.5) measured data from the orbit at 08:24 UTC (white flags).

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	Dragonera (B1)	Cap de Pera (B2)	Cabrera (B3)	Maó (B4)
Latitude (° N)	39.55	39.75	39.23	39.72
Longitude (° E)	2.10	3.50	2.96	4.42
Depth (m)	135	45	70	300

Table 1 Geographical location of buoys and depths.

Experiment	WAMPRO1 (dx=dy=25 km)	WAMPRO2 (dx=dy=1.5 km)	Wind input time step (hours)
1	HIRLAM (16 km)	HIRLAM (16 km)	3
2	HIRLAM (16 km)	HIRLAM (5 km)	3
3	ECMWF (25 km)	ECMWF (25 km)	6
4	ECMWF (25 km)	WRF (1.5 km)	6
5	ECMWF (25 km)	WRF (6 km)	6
6	ECMWF (25 km)	WRF (30 km)	6

Table 2 Experiments performed for November 2008.

Parameters	HIRLAM(16)	ECMWF(25)
bias	0.05	0.08
SI	0.25	0.20

Table 3 Bias and the best-fit scatter index between measured and modelled Hs at B4 with WAMPRO1 for November 2008.

Location	B1		B2		B3	
Parameters	bias	S.I.	bias	S.I.	bias	S.I.
HIRLAM(16) (WAMPRO1)	0.19	0.24	-0.16	0.40	-0.29	0.60
HIRLAM(16) (WAMPRO2)	0.18	0.23	0.05	0.29	-0.02	0.39
ECMWF(25) (WAMPRO1)	0.26	0.18	-0.08	0.30	-0.39	0.63
ECMWF(25) (WAMPRO2)	0.26	0.18	0.13	0.28	-0.12	0.48

Table 4 Bias and the best-fit line scatter index between measured Hs at B1, B2, B3 and modelled with WAMPRO1 and WAMPRO2 for November 2008. The mean buoys Hs values are 1.53 m for B1, 1.45 m for B2 and 0.71 m for B3.