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ORIGINAL PAPER

Hindcast of the Hércules winter storm in the North Atlantic

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Abstract The study describes the Hércules storm hindcast performed with the WAM model during one of the major cyclones that occurred in the North Atlantic in the last several years. A description of the development of a peculiar winter season in which a number of consecutive storms took place severely beating the west of Europe is provided. The performed hindcast was carefully conducted applying WAM model in combination with the reanalysis of NOAA/NCEP (CFSRv2). These results were validated against the network wave buoys of the Port of Authorities (Puertos del Estado) of Spain around the North Atlantic Spanish and Portuguese continental shelf showing a high correlation during the 2 months of the simulation period (1 December 2013 up to 5 February 2014). The study also determined the Benjamin–Feir index and showed that close to the Iberian Peninsula there was a high probability of occurrence of abnormal waves generated in this storm.

Keywords Wind waves · WAM · Hércules storm · North Atlantic · Extreme sea states

1 Introduction

Extreme waves occurring in the ocean and closed seas are dangerous to human activities and personal safety. Despite the scarcity of these events, they can be associated with severe consequences such as considerable damages to ships, offshore structures and potential loss of human life (Faulkner and Buckley 1997; Guedes Soares et al. 2008). The statistical wave data used in climatic databases are normally at selected grid points, but to study the effect of a specific storm, a different approach needs to be adopted (Bernardino et al. 2008).

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New facts were found of the Arctic amplification-enhanced Arctic warning relative to mid-latitudes. This fact may lead in the future to weather patterns more persistent and to an increased probability of extreme weather events (Francis and Vavrus 2012) in the mid-latitudes affecting the frequency and intensity of extreme weather events. In particular, in the last winter (2013–2014), consecutive extreme storms hit the west of European waters producing severe damages and losses.

A high-resolution wave modelling is a mandatory tool to understand the details of the wave systems as they develop, and various studies have analysed storm conditions such as done by Behrens and Günther (2009), Panigrahi and Misra (2010), Panigrahi et al. (2012), Natesan et al. (2013), Sanil Kumar et al. (2013), and Ponce de León and Guedes Soares (2014), Ponce de León and Guedes (2015), among others.

This work is focused on the stormy period of the winter 2013–2014 in which the storms were distinguished by strong gales in the west of Europe inducing severe sea states with peak periods higher than 25 s able to cause significant damages on several coastal sectors of Europe.

The objective of this work was to analyse the effect of the massive waves of the 2013–2014 winter which affected the North Atlantic West European waters by performing numerical simulations. A sea state characterization under the simulated severe sea state conditions is given. A quantification of the performed hindcast errors is presented and discussed. The study period consists of more than 2 months (1 December 2013 up to 5 February 2014).

The paper is structured as follows. Section 2 describes the Hércules storm of the beginning of 2014. Section 3 gives a brief sketch about the wave model set-up and the records used in the study. The wave hindcast results are given and discussed in Sect. 4. Section 5 is devoted to the validation of the hindcast against the wave buoys records around the Iberian Peninsula. Section 6 gives the storm classification based on the recorded data. Conclusions are drawn in the final Sect. 7.

2 The Hércules storm

Dubbed "winter storm Hércules" by the media, an intense low-pressure system, caused several coastal damages along the different coastal region of UK, Ireland, France, Portugal and Spain. The peak of this event occurred on the 5 and 6 January, coinciding with the storminess over the UK. Hércules storm affected not only the west of Europe, but also the USA where over 200 million people were affected with costs in excess of $5bn (Met Office Report 2014).

The stormy weather continued into January with a major cyclone (Hércules) on 5 and 6 January 2014, which caused extensive coastal damage in UK and in the Portuguese and Spanish coasts. With a short interval in January, the stormy weather returned in the first week of February with a sequence of very deep depressions characterized by very strong winds.

The extraordinary duration of the stormy period and the clustering of deep depressions has been a remarkable characteristic of the winter period of 2013–2014.

According to UKMO report (Met Office Report 2014), on 24 December 2013, a particularly deep depression (936 hPa) passed to north of UK. This sequence of storms continued into January 2014, with a deep depression forming over the North Atlantic on 5–6 January (Fig. 1). A remarkable characteristic of this storm was the great size of the

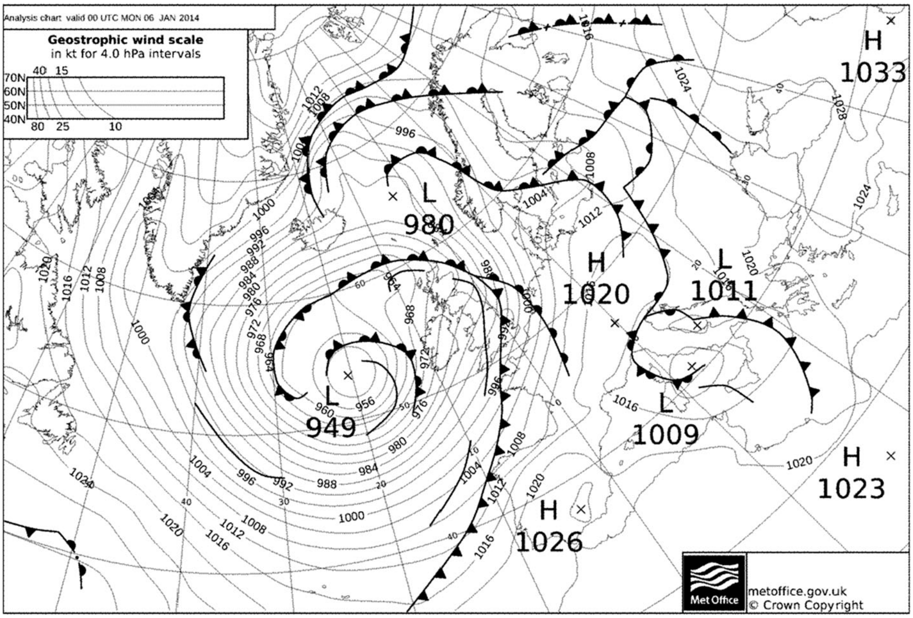

Fig. 1 UKMO surface pressure chart for 6 January 2014 at 00 UTC showing the Hércules extratropical storm

depression (949 hPa), which affected the entire North Atlantic. Storms of such size and intensity are uncommon; the fetch and strength of the winds developed a giant swell with some of highest recorded wave heights (more than 18 m) reaching the Western Europe coastal zones.

According to the Met Office Report (2014), the track of the Hércules storm felt at relatively low latitude for this kind of event, pushing the bulk of the wave energy towards the south-west of Ireland and England, as described also in Bernardino and Guedes Soares (2015).

3 WAM model set-up and data

A standard wave forecasting is based on the energy balance equation which describes the evolution of two-dimensional ocean wave spectra without any assumption on the spectral shape. WAM (Komen et al. 1994) computes the 2D-wave variance spectrum through integration of the balance equation. The version of the wave model used is the latest version of the WAM model (Gunther and Behrens 2012). All spectral components are calculated prognostically from the energy balance equation up to a variable cut-off frequency.

The WAM high-resolution grid model configuration covers almost the whole North Atlantic Ocean with geographical limits: 18°N, 80°N, 90°W, 30°E at spatial resolution of 0.25° (Fig. 1). The bathymetry grid data come from the GEODAS NOAA's National Geophysical Data Centre (NGDC), with a resolution of 1 min of degree in latitude and longitude, which was linearly interpolated spatially to the 0.25° model grid (Table 1).

The solution of the energy balance equation was provided for 36 directional bands and 30 frequencies logarithmically spaced from the minimum frequency of 0.0350 up to

Table 1 WAM model numerical parameters for the North Atlantic

Parameters	Grid
Integration time step (s)	160
Spatial resolution	0.25° (27.8 km)
Number of points (*x*, *y*)	(481,249)
Propagation	Spherical
Frequencies	30
Directional bands	36
Frequency domain (Hz)	0.0350–0.5552 Hz
Latitudes (°N)	18°; 80°
Longitudes (°W)	90°
Longitudes (°E)	30°
Type of model	Deep water
Wind input time step	6 hourly
WAM output time step	6 hourly
Wind field spatial resolution	0.31°

0.5552 Hz (Table 1). The initial condition was a JONSWAP spectrum at every grid point with the following parameters: Phillips' parameters 0.18; peak frequency 0.2 Hz; overshoot factor 3.0; left peak width 0.07; right peak width 0.09; wave direction 0°; and fetch 30,000 m.

3.1 Observations: the wave buoys

In situ measurements were available by moored buoys at four locations (B1, B2, B3 and B4, Fig. 1) around the North Atlantic side of the Iberian Peninsula. The buoys measured hourly significant wave height (Hs), wave periods [zero crossing (Tm02), peak period (Tp)], wave direction and the atmospheric pressure, wind speed, etc. For the study, the wind speed records available were corrected from 3 to 10 m according neutral logarithmic profile described in Bidlot et al. (2002).

B1 (Bilbao Vizcaya) is a deep water buoy (600 m). B2 (Cabo Penha) is moored at 615 m of depth; B3 (Estaca de Bares) also is a deep water buoy placed at 1800 m, and B4 (Cabo Silleiro) is located between the Spanish and Portuguese waters at 600 m of depth. All these buoys are operated and maintained by the Spanish Harbour Authority [Puertos del Estado (PE)]. Their locations are marked with white circles in Fig. 2. The performance of the wave model was assessed with B1, B2, B3, B4 data. In addition, the WAM spectra are analysed in B1, B2, B3 and B4.

3.2 The wind forcing

The simulations for the North Atlantic were performed using the reanalysis from the Climate Forecast System Reanalysis (CFSRv2) from NOAA (Saha Suranjana et al. 2010). CFSR wind fields (subset ds094.1) were linearly interpolated in space to 0.25° to match with the spatial resolution of the WAM model mesh. The wave hindcast temporal resolution was set to 6 hourly wind input/output time step. The Hércules storm wind field is depicted in Fig. 3 according to CFSR reanalysis for 6 January at 00 UTC showing wind speeds higher than 25 m/s for the 6th of January 2014 at 00 UTC; especially for the CFSR winds, the WAM model configuration used a retuning of the source term parameter BETAMAX = 1.33.

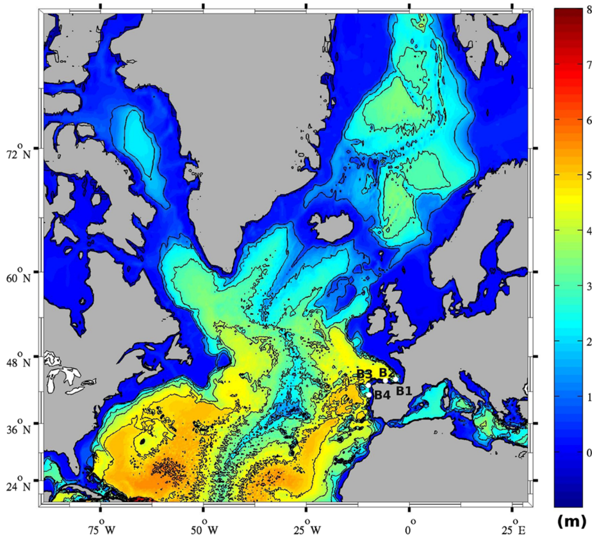

Fig. 2 Bathymetry grid for the WAM grid. Location of the buoys and the output WAM are marked with *circles*; B1–Bilbao Vizcaya; B2—Cabo Penha; B3—Estaca de Bares; B4—Cabo Silleiro

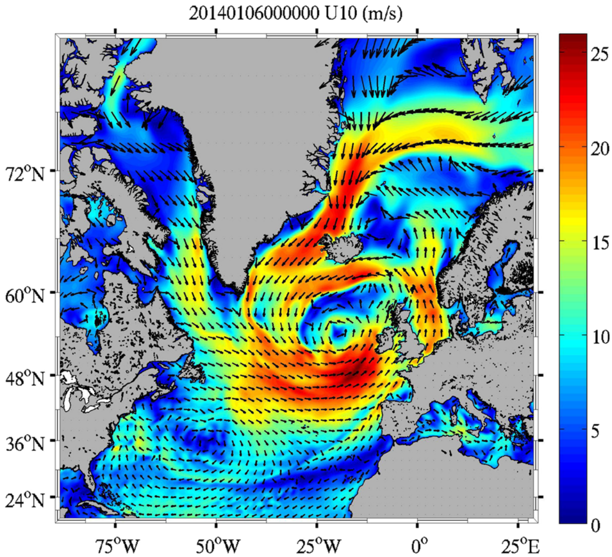

Fig. 3 The Hércules storm from the CFSR reanalysis of NOAA wind field for 6 January at 00 UTC

4 The WAM hindcast

The significant wave height (Hs) map from the WAM hindcast for the 6th of January at 00 UTC shows values higher than 18 m (Fig. 4) to the south-west of UK arriving to the western European waters. In addition, the WAM peak period map for the same date shows values higher than 25 s (Fig. 5), a very strong swell as the result of the Hércules storm which reached many countries of the west of Europe.

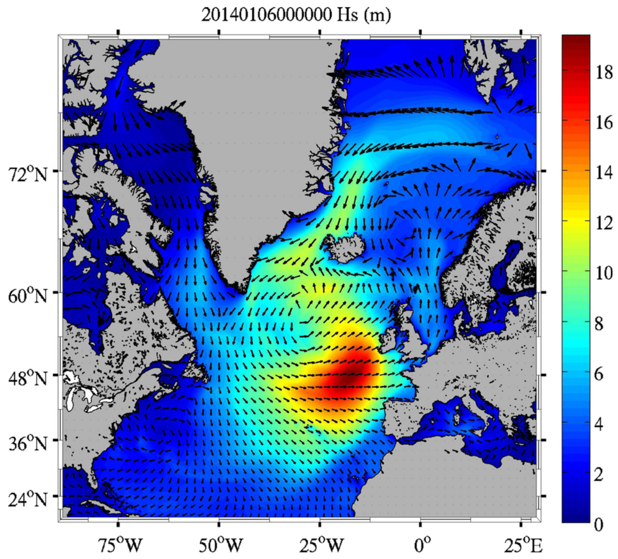

Fig. 4 WAM Hs map during the Hércules storm. Date: 6 January at 00 UTC

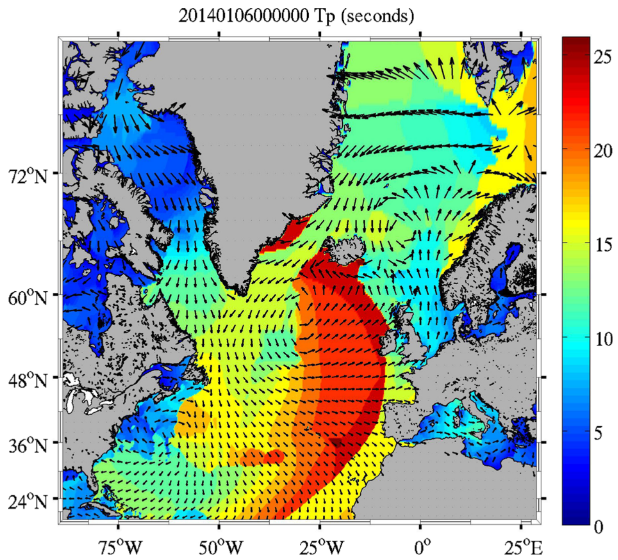

Fig. 5 WAM peak period (Tp) map during the Hércules storm. Date: 6 January at 00 UTC

4.1 Computation of extreme wave parameters

Abnormal, rogue or freak waves are transient very high waves in relation to the sea state in which they occur and they are normally identified by the Abnormality Index which is the ration of the maximum wave height by the significant wave height of the sea state (Dean 1990). The mechanisms that generate these waves are various as discussed among others by Kharif and Pelinovsky (2003). Important changes in the shape of the local spectra were also identified in the analysis of time series of two abnormal waves (Cherneva and Guedes Soares 2008, 2014). Furthermore, Lopatoukhin et al. (2005) analysed hindcast data that occurred just before and after various measured abnormal waves in the North Sea (Guedes Soares et al. 2003) and concluded that in all cases, the occurrence of the abnormal wave was associated with very quick changes in the shape of the wave spectrum, suggesting that hindcast data could be used to identify those situations with largest potential of occurrence of abnormal waves, although in a not very practical way as the sequences of sea states would need to be studied and their transitions in time be examined (Boukhanovsky and Guedes Soares 2009).

The deviations from normality are measured in terms of the kurtosis C4 of the surface elevation probability density function, which was found to relate to the freak or abnormal waves that occur in the ocean (e.g. Onorato et al. 2001; Guedes Soares et al. 2003, 2004). The Benjamin–Feir index (BFI) is related to the kurtosis and depends on water depth and wave directional spreading. The BFI is the ratio between nonlinearity and dispersion; its relation to the kurtosis has been found in the limit of large times and narrowband spectra neglecting directional spreading (Janssen 2003). For long-crested waves exists a relation between the BFI and the occurrence of extreme wave and crest heights (Janssen 2003; Mori and Janssen 2006), and thus, the BFI provides a more practical way to determine when there is an increased probability of occurrence of abnormal waves.

When the wave group approaches shallow water, the nonlinear focussing effect disappears for $k{*}d = 1.363$, and when $k{*}d$ becomes less than this critical values, even defocusing occurs as a consequence for $k{*}d > 1.363$ C4 > 0, while the opposite case C4 < 0. In the WAM 4.5.4, a parameterization was developed for this case following the work of Janssen and Onorato (2007).

The present version of the WAM model (Gunther and Behrens 2012) includes the assessment of the BFI index, which allows that this study also indicates the areas with high probability of occurrence of a rogue waves during the extreme weather conditions produced by the Hércules storm. According to the spatial distribution of the BFI obtained from the WAM hindcast, the BFI reaches values of about 1.5 indicating that this region is more prone to abnormal waves. On 6th of January at 18 UTC, the BFI and kurtosis maxima values region (shaped strip) reached the north-west side of the Iberian Peninsula (Fig. 6) affecting the coasts. The maritime and coastal authorities of Portugal believed that this was probably the one of the largest swells ever recorded in their coasts.

The BFI and kurtosis maxima are mainly found in the fourth quadrant of the cyclones which was reported in previous studies (Mori 2012; Ponce de León and Guedes Soares 2014). The BFI and kurtosis maxima are due to the steepness of the waves (Mori 2012) because in this area occurs the maximum Hs, where U10 is high with values of 27 m/s and the Hs is also high (Hs higher than 18 m) (Figs. 3, 4).

5 The wave hindcast validation

The authors have used the WAM model at several occasions to represent the wave conditions in the Atlantic Ocean, and good results were obtained (e.g. Ponce de León and Guedes Soares 2005; Pilar et al. 2008). However, to model such localized storms, a high-resolution model needs to be adopted as discussed in Ponce de León and Guedes Soares (2014), implying that, also in this case, it is important to validate the model adopted.

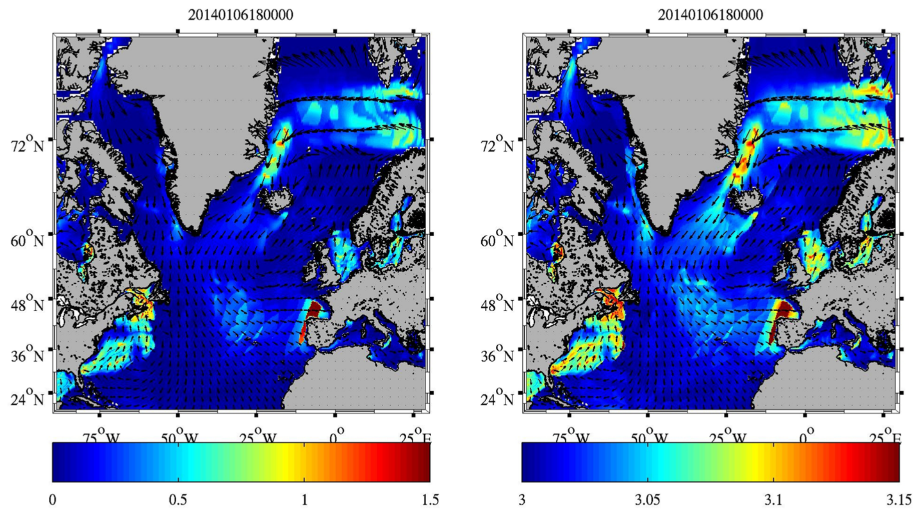

Fig. 6 WAM Benjamin–Feir index (*left*) and kurtosis (*right*) crossing and affecting the coastal region of the west Iberian Peninsula during the Hércules storm. Date: 6 January at 18 UTC

The WAM hindcast was compared against the wave records collected by the PE measuring network described in Sect. 3. Buoy records were compared to model output extracted from the nearest computational node for the period of 1 December 2013 up to 5 February 2014. The validation was performed by qualitatively comparing the model and buoy time series. After assessing the good quality of the results, more accurate comparisons were carried out by constructing scatter plots between the model and wave buoy values and by computing the main statistical parameters considered: scatter index, the slope.

The bias was defined as the difference between the mean observation and the mean prediction. The scatter index (s.i.) was defined as the standard deviation of the predicted data with respect to the best fit line, divided by the mean observations.

As seen from the records, the highest Hs observed was 12.8 m at Estaca de Bares (1 February 2014 at 21 UTC). Very high Hs values were recorded during this exceptional winter, and all of these were higher than 6 m in a very short period. In general, a good correlation can be seen from the comparison performed (Fig. 7).

The slopes obtained are in the range of 0.97 up to 1.11, and the bias varies from −0.46 up to 0.08; the scatter indexes are from 0.16 up to 0.39, and the correlation coefficients are between 0.92 and 0.94. It is necessary to point out that negative biases were obtained in all locations denoting some overestimation of the wave model and the only positive bias value (0.08) corresponded to Cabo Penha (Fig. 7).

The wind speed and direction were evaluated at Cabo Silleiro and Bilbao Vizcaya locations (B1 and B4 in Fig. 1) where the records were available. From the comparison of the time series and from the statistical coefficient computed, it can be seen that the CFSR wind parameters and the recorded data are very similar. However, some inaccuracies were obtained at the beginning of the simulation period at these locations (first 2 days). Recorded data showed some variability of the wind (Figs. 8, 9); however, for the same times, the atmospheric model wind (CFSR) did not show any variation. From the statistical point of view, the scatter indices resulted similar for the wind direction at Silleiro (0.31)

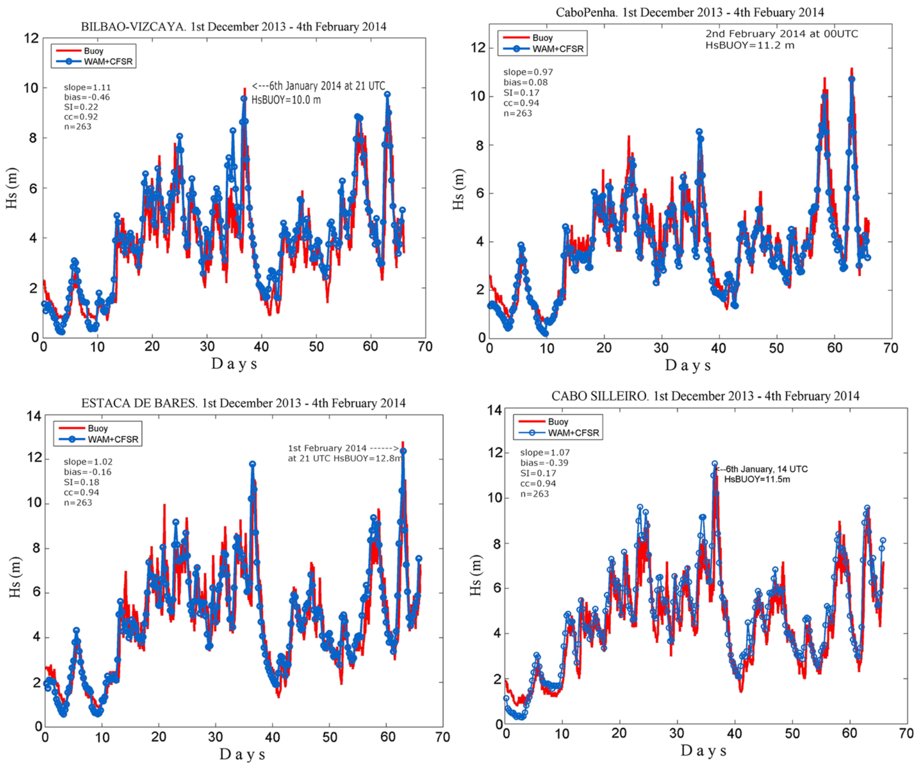

Fig. 7 Time series for the Hs from the WAM hindcast against the Spanish wave buoys (B1—*left top*); B2 (*top right*); B3 (*bottom left*); B4 (*bottom right*) (Fig. 1). Period: 1 December 2013–5 February 2014

and Vizcaya (0.32), whereas the correlation coefficient differs [Silleiro (0.76) and Vizcaya (0.67)]. The wind speed was validated at Vizcaya where a good agreement can be seen (Fig. 9), and high correlation coefficient (0.82) and low negative bias (−0.73) were obtained. In general, the bias for the wind speed and direction at both locations resulted negative which is related to some errors of the CFSR reanalysis (overestimates). However, the correlation coefficient was in the range of 0.67 up to 0.82.

The rest of the wave parameters (peak period and the mean wave propagation direction) were evaluated showing that in general, a good correlation (model and records) was obtained (Figs. 8, 9). In particular, for the wave propagation direction, a good correlation was obtained (Fig. 8 top right panel; Fig. 9 bottom left panel) in terms of the slope (0.91 and 0.95, Silleiro and Vizcaya, respectively) and low scatter index (0.23 (Silleiro) and 0.19 (Vizcaya)). The correlation coefficient resulted the highest at Vizcaya (0.73). The reason of the differences obtained at the beginning of the time series (model and buoys) could be associated with the fact that the hindcast was initialized the 1st of December without any data assimilation on to the wave model.

The peak period was assessed for the whole hindcast period for which the data were available. The highest peak period of 24.8 s was recorded at Silleiro (Fig. 8, bottom) on 6 January at 12 UTC during the Hércules storm. A good agreement between the peak periods obtained from the hindcast and records can be seen (Fig. 8 bottom and Fig. 9 bottom right).

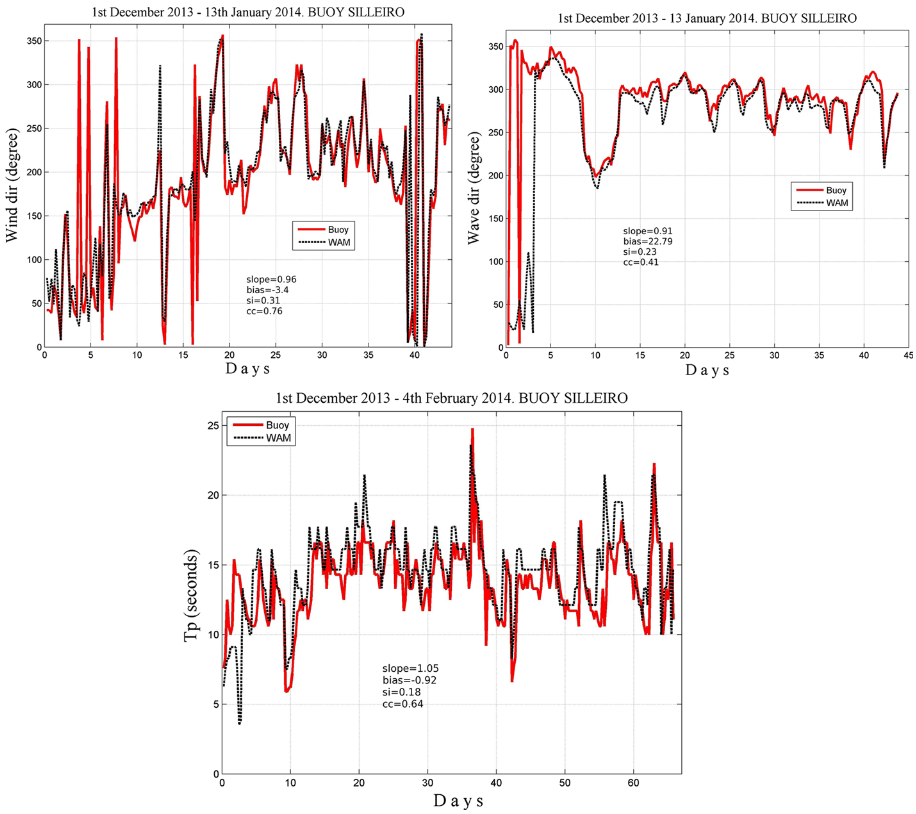

Fig. 8 Wind direction (*top left*), mean wave propagation direction (*right panel*) and the peak period (*middle bottom*) time series from the WAM hindcast against records at B4 (Fig. 1)

A good correlation was obtained in terms of the slope (1.05 for both locations), the scatter index resulted lower at Silleiro (0.18), and the correlation coefficients, however, were lower and similar in the both locations (around 0.65).

6 The winter storms of 2013–2014

The study of the storms of 2013–2014 is of a high relevance because they took place in a very short time period producing destructive consequences for the coastal regions.

The duration of the storms was computed based on the atmospheric pressure records at B4. This location is situated between Spain and Portugal continental waters facing the ocean, and for this reason, the location B4 was selected. It was considered here that values higher than 1013 hPa would represent a storm. In this way, seven storms were observed as can be seen from the Table 2.

The records of the atmospheric pressure (top panel), the wind speed (middle) and the Hs (bottom) are depicted in Fig. 10: two clear low atmospheric pressure values (Fig. 10), first one with a pressure of 996 hPa occurred around the Christmas dates (storm 1 in Table 2) and the second one took place around 19 January 2014 (992 hPa).

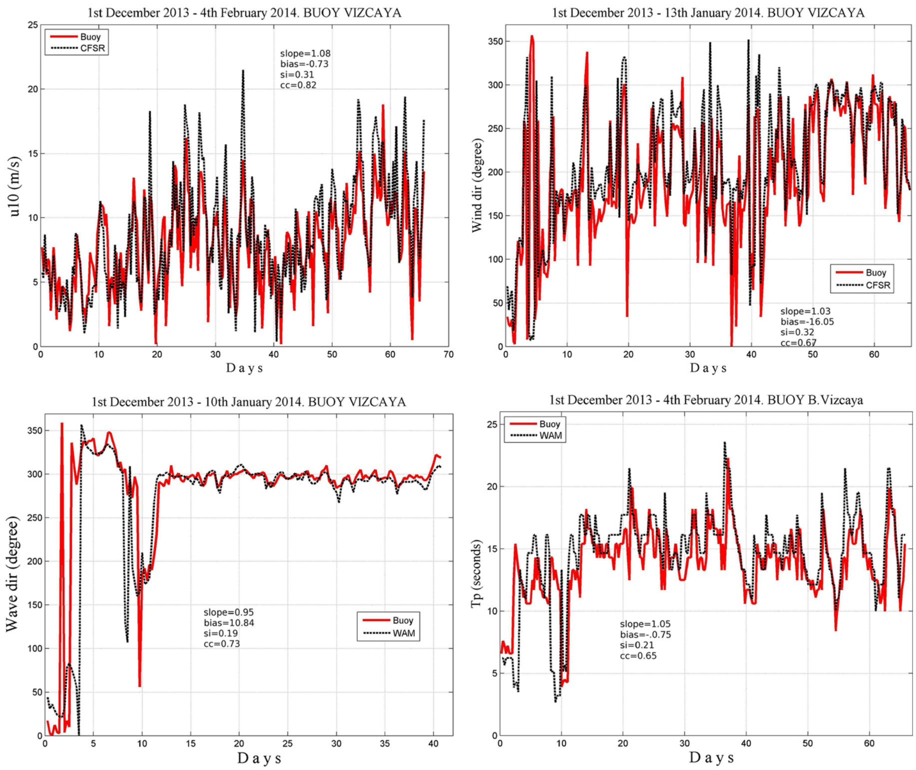

Fig. 9 Wind speed and direction (*top left* and *right panels*), mean wave propagation direction (*left bottom panel*) and the peak period (*right bottom panel*) time series from the WAM hindcast against recorded data at B1 (Fig. 1)

The highest Hs value recorded at B4 (Cabo Silleiro (11.5 m) was measured on 6 January at 14 UTC (bottom) during the Hércules storm. However, this maximum took place after a period of strong winds with U10 higher than 20 m/s (middle panel). However, from the records at B4, it can be seen that the highest wind speed (around 21 m/s) was recorded before the Christmas days around the 22 December 2013. However, from the Hs records, it can be seen that the maximum value of 9.0 m was reached on 25 December 2013 at 19 UTC.

From Table 2, it can be seen that during the Hércules storm (5–6 January 2014), the Hs and the Tp were the highest, i.e. 11.5 m and 24.8 s, respectively, from the records. The explosive Hércules storm was the shortest one (18 h), but the most destructive one. However, at this location (Cabo Silleiro), the wind speeds were not the highest recorded (8–15 m/s) during this storm. From the WAM directional spreading (Table 2), it can be seen that the lowest directional spreading (21°) was observed during the Hércules storm.

The second explosive storm was the storm 1 during the Christmas dates (23–26 December 2013) with duration of 56 h. Under these storm conditions, the Hs recorded reached the value of 9.0 m at the same time for low atmospheric pressure (996 hPa) and wind speeds of about 20 m/s. These records have shown that the duration of the storms varied from a short period of 14 h (storm 3) up to 56 h (storm 1).

Table 2 Duration and description of the storms following the criterion of the atmospheric pressure (low-pressure centre are values lower than 1013 hPa) from the Cabo Silleiro records

Storms	Duration (h)	Min. atm. pressure (hPa)	Max U10	Hs max (m)	Peak period (s)	WAM dir. spreading
Storm 1 Explosive (23 December 19 UTC–26 December 2013 03 UTC)	56	996	20.7	9.0	18.2	25
Storm 2 (1 January 07 UTC–3 January 2014 02 UTC)	43	1006	19.6	7.0	18.2	23
Storm 3 (3 January 22 UTC–4 January 2014 11 UTC)	14	1004	16.7	8.2	18.2	22
Storm 4 Hércules Explosive (5 January 2014 22 UTC–6 January 2014 16 UTC)	18	1008	16.2	11.5	24.8	21
Storm 5 Explosive (15 January 12 UTC–19 January 2014 19 UTC)	31	992	14.8	7.2	16.6	22
Storm 6 (28 January 2014 06 UTC–30 January 01 UTC)	43	998	14.8	8.4	18.2	24
Storm 7 (2 February 19 UTC–5 February 2014 00 UTC)	54	993	19.8	7.4	16.6	27

The directional spreading was obtained from the WAM model

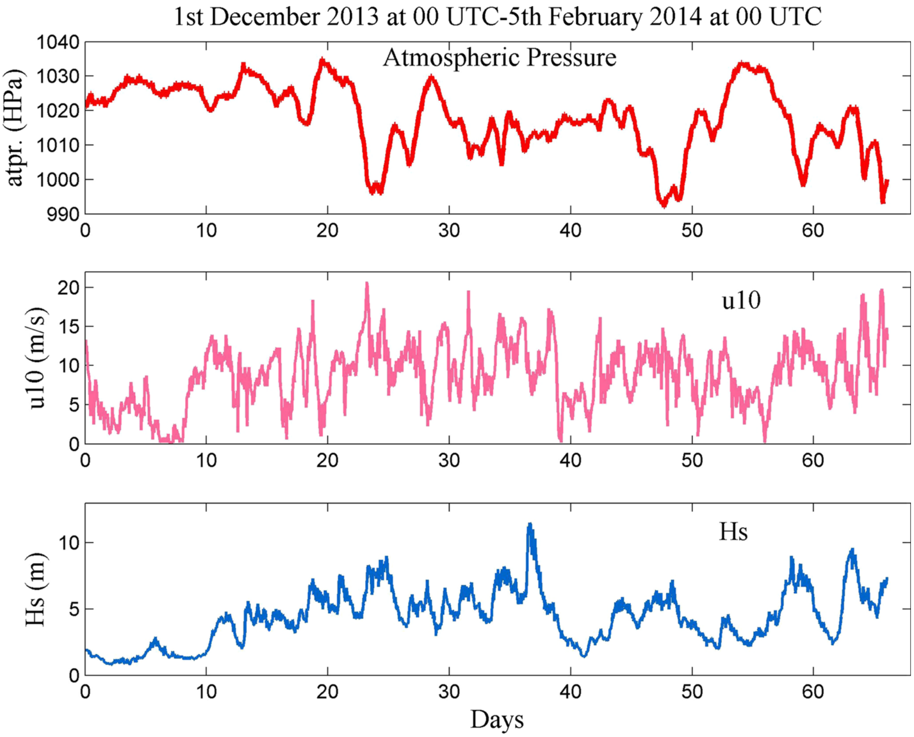

Fig. 10 The atmospheric surface pressure (*top*), corrected to 10 m of height wind speed (*middle*), significant wave height (Hs) (*bottom*) records from the Cabo Silleiro wave buoy. Period: 1 December 2013–5 February 2014

Additionally, the deepening rate was calculated at the centre of the Hércules storm at every 6 h using the atmospheric pressure obtained from DWD (Germany's National Meteorological Service). On 4th of January, the deepening rate was positive reaching the value of 2.5 at 00 UTC. On 5th of January, the deepening rate decreased to 1.666 at 18 UTC which means that Hércules storm experienced a small variation (decrease) of the atmospheric pressure from 950 up to 940 hPa. On 6th of January, negative deepening rates were obtained (−0.833) which means that the storm is at the most powerful stage. On 7th of January, the lowest deepening rate value was reached (−1.666) at 12 UTC which can be related to the dissipation of the Hércules storm.

7 Conclusions

One of the most destructive North Atlantic storms (Hércules) was analysed, described and characterized in this work based on the performed hindcast, validated with buoy records around the Iberian Peninsula. A remarkable characteristic of this storm was the large dimension which affected the whole North Atlantic. Storms of such size and intensity are rare; the fetch and power of the winds developed vast swell with some of highest recorded wave heights, higher than 18 m in some locations of the west of Europe. The waves generated under this storm produced a damaging swell, and we show in this work how these extreme waves reached the Iberian Peninsula.

The Hércules storm was reproduced with the WAM model. Peak periods of about 25 s and Hs higher than 18 m can be observed from the hindcast. In addition, peak period of 24.8 s (peak period) was recorded by one of the wave buoys of Puertos del Estado (Silleiro) on 6 January at 12 UTC during the Hércules storm.

The performed simulation for the unusual winter period was compared against wave buoy records showing a high correlation in terms of the scatter index, slopes, bias and correlation coefficient. The validation of the hindcast (wind and wave parameters) was done using the records from the Puertos del Estado of Spain around the Iberian Peninsula (Atlantic side) at deep waters.

The results of the simulation showed high values of the BFI in areas close to the Iberia Peninsula, indicating that in addition to the storm conditions, the probability of occurrence of abnormal waves in those sea states is high.

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