Extreme wave height events in Algarve (Portugal): comparison between HF radar systems and wave buoys

M. Fernandes (1), C. Fernandes (2), T. Barroqueiro (2), P. Agostinho (1) N. Martins (1) and A. Alonso-Martirena (1)

(1) Qualitas Instruments, Madan Parque, Rua dos Inventores, 2825-182 Caparica - Portugal, maria.fernandes@qualitasinstruments.com

(2) Hydrographic Institute, Rua das Trinas, 49 – 1249-093 Lisboa – Portugal

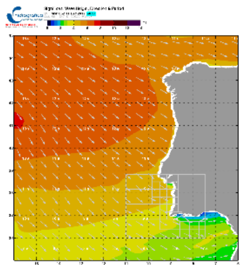
The Southwestern Portuguese coast (SW Portugal) is a region that has lately been affected with several strong events influenced by the presence of low pressure systems in the mid-Atlantic Ocean and the periodic passage of storms that give rise to severe sea states. The objective of this study is to characterize the most extreme wave height events in the coast of Algarve over the wintertime of 2017-2018 by using reliable high-frequency radar wave parameters in concert with Hydrographic Institute insitu buoys. Special attention was focused on monitoring Ana and Emma storms —two of the major storms on record in the southwestern Portuguese coast during this winter. Overall, the results reveal the significant accuracy of high-frequency radars and prove that a combined observational can provide a comprehensive characterization of severe wave conditions in coastal areas.

Key words: HF radar, wave measurement, storm events.

1. INTRODUCTION

The Southwestern Portuguese coast (SW Portugal) facing the Atlantic on the southwestern corner of the Iberian Peninsula (Figure 1a) is a region that has been strongly influenced by the presence of low pressure systems in the mid-Atlantic Ocean in the winter of 2017-2018. Since it is a region with intense maritime traffic between the Atlantic and the Mediterranean, a comprehensive characterization of the significant wave height (Hs) events is required in order to minimize the associated risks, and increase marine safety in coastal waters. In this context, a multidisciplinary methodology based on the integration of insitu and remote sensed observations could constitute a useful approach to properly interpretation of the ocean state and its variability. As previous works have unequivocally revealed the importance of rigorous validation of operational wave forecasting systems (Sembiring et al., 2015; Carraccedo et al., 2005) and the analysis of extreme wave height events using models (Bell et al., 2017; Gimaraes et al., 2014) and shore-based high-frequency radar (HFR) (Atan et al., 2015; 2016), the objectives of this paper were to analyze the main features of extreme wave height events in Algarve over the wintertime of 2017–2018 by using HFR remote-sensed hourly wave parameters together with an insitu offshore buoy maintained by Hydrographic Institute and Copernicus wave model (Figure 1b). Attention was focused on monitoring Ana and Emma storms. Although weakened to a post-extratropical cyclone, they brought impactful weather in terms of heavy rain, damaging gusts (up to 120 km/h^{-1}), large waves, small tornados and storm surges with subsequent coastal flooding.

a)



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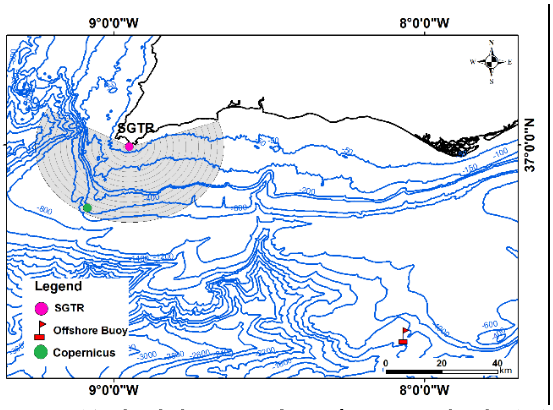


Figure 1. (a) The daily averaged significant wave height (Hs) predicted in the Atlantic regional domain (10 December 2017); (b) General area of study and High-Frequency (HF) radar coverage area (SGTR), where arcs are shown emerging concentrically from one radar site. Locations of the offshore and coastal buoys and local point of Copernicus model data.

2. MATERIALS AND METHODS

2.2. In Situ Observations

The coverage area of the Algarve HFR system includes a multiparametric buoy deployed two years ago in the southern waters of the Iberian Peninsula, operated by Hydrographic Institute. It is moored on the edge of the continental shelf: offshore buoy (36.39º N, 8.06º W; 75 km from shore; 1200 m depth). Hourly-averaged quality-controlled measurements of spectrally significant wave height (Hs), the wave period at spectral peak (or peak period, Tp), and the mean wave direction (Wd) were provided by a directional Waverider sensor.

2.3. HF Radar (HFR)

HFR technology is based on measurements of the radio wave backscattered signal from ocean surface gravity waves in the 13 MHz range of the electromagnetic spectrum (Crombie, 1995). Consistent estimations of the surface current field can be derived from the strong signal produced by the resonant first-order Bragg waves, whereas wave parameters can be extracted from the weaker second-order sea-echo Doppler echo spectrum using methods of integral inversion (Lipa et al., 2005). There is a minimum sensitivity threshold for sea states below which the lower-energy second-order spectrum is closer to the floor noise and more likely to be contaminated (Lipa et al., 2005). There is also a limiting factor for the HFR during extreme weather events as the wave height increases and exceeds the saturation limit defined (on an inverse proportion) by the radar transmit frequency. If the radar spectrum saturates, the first-order spectra merge with the second-order and interpretation of the spectra becomes impossible with existing methods.

The CODAR SeaSonde long-range 13 MHz HFR system used in this work was deployed in Algarve in 2015 in Sagres (SGTR) operated by Hydrographic Institute. This system provides 30-min wave data that are subsequently subsampled at 60 min intervals to provide consistency in the temporal resolution of the data for validation and analysis. HFR data were retrieved from 15 individual range cells (RCs) from SGTR (Figure 1b), from cell 1 to cell 15 (1.8 and 27.8 km from site origin, respectively). The outermost HFR radar RC (cell 10-15) were selected to perform the comparison against the offshore buoy and Copernicus model.

2.4. Copernicus wave model

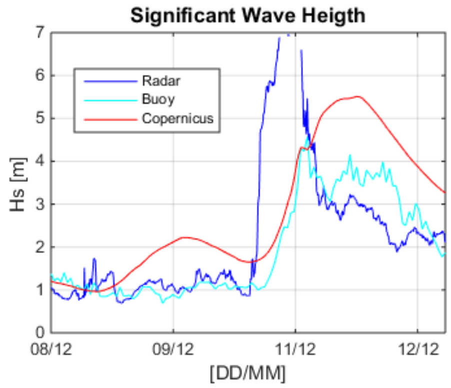
On July 18th, 2017, the Copernicus Marine Environment Monitoring Service (CMEMS) released the first real-time global wave product based on satellite data. It came after the launch last April (2017) of the wave product based on models, and is part of a series of releases listed in the WAVE product roadmap. This new product from satellite altimeter data contains the **Significant Wave Height (SWH)** from Jason-3 and Sentinel-3A satellite altimeter data, provided within 3 hours after data acquisition with 7 km resolution. Monitoring Service (CMEMS), provides a 5-day regional wave forecast, which is updated twice a day.

3. RESULTS

3.1. Preliminary Skill Assessment of HF Radar Wave Height Estimations

Previous comparisons against moored buoys have unequivocally proven the positive contribution of HF system radar to retrieve reliable directional wave information (Atan et al., 2015; López et al., 2016 and Long et al., 2011). In this context, a preliminary accuracy assessment of southwestern Algarve HFR-derived wave data has been conducted for winter 2017/2018, when a number of extreme wave height events (Hs above 3 m) took place. HF radar appears to properly capture the main peaks of Hs and the minimal spatial variation between both sites, although, HF radar estimations seem to slightly overestimate Hs field in the Algarve region. Since these results are in line with previous literature on HFR-buoy wave height comparisons (Lipa et al., 2014), we can state that HFR performance is consistent and it can act as a useful ancillary tool, especially when no in situ wave observations are available. In this context, were analized extreme events like Ana (Figure 2a, 2b and 2c) and Emma (2d, 2e and 2f) storms.

a)



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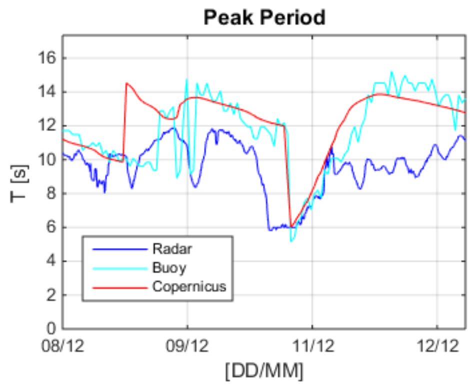

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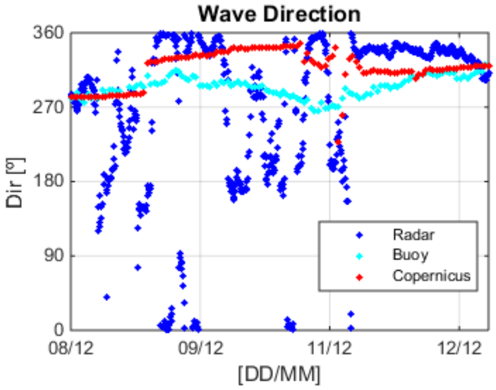

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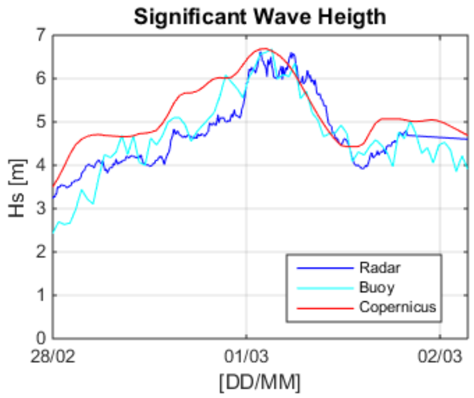

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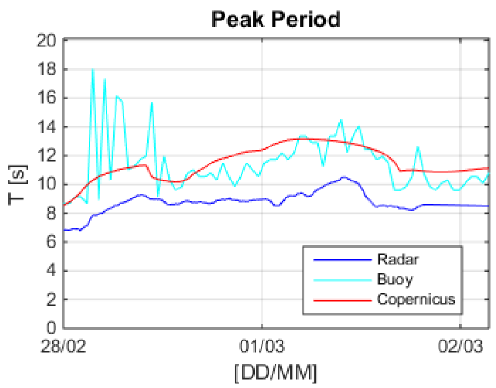

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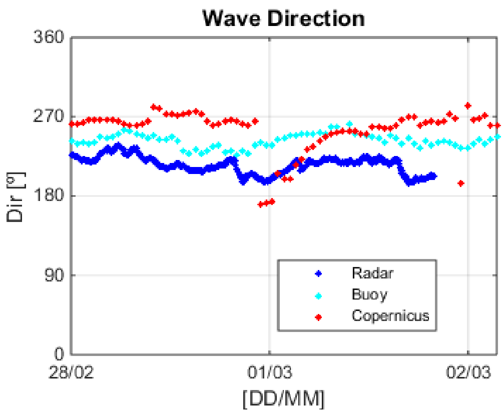

Figure 2. Comparison of high-frequency radar (HFR)-derived significant wave height (a), peak period (b) and wave direction (c) against insitu observation (wave buoy) and Copernicus model for two selected wintertime periods (a, b, c – 09-13/12/2017) and (d, e, f - 28/02/2018 – 02/03/2018).

Table 1. Summary of statistical parameters derived from the intercomparison of high-frequency radar (HFR) wave height, period and wave direction against in situ buoy for two selected wintertime periods (09/12/2017 – 13/12/2017 and 28/02/2018 – 02/03/2018).

08 December - 13 December	Hs (m)	Tp (s)	Dir (deg)
RMS	1.26	2.99	25.65
CI	0.54	0.35	-0.18
Availability SGTR (%)	95.70	95.70	95.70
Availability Buoy (%)	100.00	100.00	100.00

08 December - 13 December	Hs (m)	Tp (s)	Dir (deg)
RMS	1.02	4.95	12.06
CI	0.93	0.53	0.17
Availability SGTR (%)	100.00	100.00	100.00
Availability Copernicus (%)	100.00	100.00	100.00

28 February - 02 March	Hs (m)	Tp (s)	Dir (deg)
RMS	0.58	3.56	27.74
CI	0.84	0.30	0.57
Availability SGTR (%)	91.118	91.118	91.118
Availability Buoy (%)	100.00	100.00	100.00

28 February - 02 March	Hs (m)	Tp (s)	Dir (deg)
RMS	0.68	0.89	18.42
CI	0.80	0.78	0.40
Availability SGTR (%)	94.118	94.118	94.118
Availability Copernicus (%)	100.00	100.00	100.00

3.2. Analysis of Extreme Wave Height Events in Algarve (2017–2018)

Intercomparisons of Hs, Tp and Wd have been conducted for the two selected periods, by using in situ measurements (offshore buoy), remote-sensed estimations (SGTR HFR site), and modeled data (Copernicus) in the closest grid point (Figure 1a). As it can be seen, for Ana storm event, there is a significant difference among the three data sources. This statement is supported by the skill metrics gathered in Table 1, with RMS and CI values for Hs in the ranges of 1.26 (between radar and buoy) and 1.02 m (between radar and Copernicus model) and CI 0.54–0.93, respectively. The main peaks are fairly well captured reaching the ~4.5m in the buoy and 7 m in the radar, although some of the most extreme wave height events are fairly captured by the Copernicus model as shown in Figure 2a. For Tp, during Ana strom event, the values decrease from ~12s to ~6s. This parameter is seen by the three sources although with some time delay (figure 2b) also marked by the RMS values in Table 1. The wave direction parameter reveals itself quite consistent between the buoy and model while between radar and the buoy this parameter is instable during the storm recovering its stability afterwards.

Considering Emma storm, there is a significant resemblance among the three data sources. This statement is supported by the figure 2d, 2e, 2f and the statistics in Table 1, with RMS and CI values for Hs in the ranges of 0.58 (between radar and buoy) and 0.68 m (between radar and Copernicus model) and CI 0.84–0.80, respectively. The Tp is very consistent in its behavior although it presents low CI values between radar and buoy (0.30) and higher CI values between model and buoy (0.78). For wave direction the behavior is better performed between radar and buoy (0.57) than between Copernicus and buoy (0.40).

4. DISCUSSION

On average and according to the proposed observations model approach, wave height events in Algarve are defined as high (extreme) when Hs exceeds 3 m. The associated peak period lies typically in the range of 10-12 s, whereas the prevailing incoming wave direction is the WSW sector (Figure 2c and 2f. HFR has been proven to be a valid shore-based remote-sensing instrument to efficiently monitor the wave field in the Algarve region, with skill metrics (CI above 0.90) in accordance with those reported elsewhere (Long et al., 2011). However, HF radar seems to slightly overestimate waves of higher amplitude as seen in Figure 2a but not in Figure 2d. This is especially true for low sea states when the strength of the second-order spectra is very weak and therefore such spurious contributions to the spectrum would have a more relevant impact. Also, the presence of bi-modal seas are expected to induce overestimation on HF radar significant height.

Previous studies have acknowledged that the discrepancies detected here in the mean wave direction and peak period might be partially attributable to several factors: (i) such parameters are much more sensitive to non-sea signals (interference or ships) in the radar backscatter; (ii) in low sea states directional spectra can be contaminated by noise due to spurious features that are probably associated with antenna sidelobes (Lopez et al., 2016); (iii) the distance (80 km) between the buoy and the selected radar range cell (RC10-15) is non-negligible and therefore the wind field over this region could be non-uniform.

Since in situ devices present some instrumental limitations and HFR is constrained to uniquely overlook coastal areas, the coordinated use of Copernicus model and wave buoy can provide detailed wave information for specific severe weather episodes.

Finally, there are currently some ongoing actions focused on the analyses of bi-modal seas and how this can interfere in the performance of HF radar measurements.

5. CONCLUSIONS

The characterization of the most extreme wintertime wave height events in Algarve have been conducted by robust HFR-derived wave parameters, insitu buoy and Copernicus model were used in concert on an hourly basis. The results reveal that waves can be considered as extreme when Hs exceeds 3 m and the prevailing incoming wave direction is in the SW sector. Equally, Copernicus model performance was rather consistent despite underestimating the most extreme wave height events. The HFR system has been demonstrated to be a sound remote sensing tool to retrieve wave information in coastal areas, although a slight overestimation was detected in Hs measurements. Overall, these results prove that a synergistic observational and modeling approach can provide a comprehensive characterization of severe wave conditions in coastal areas and show benefit from the complementary nature of both systems.

Acknowledgements

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