Correction of the predicted wave characteristics using regression methods – a case study for the Iberian coastal environment

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Abstract The west Iberian coast is affected by various storms developed in the North Atlantic Ocean. For this reason, an accurate prediction of the sea state conditions is very important to manage the protection of the harbours and population living in the coastal cities. In recent years computing power has increased significantly, which has allowed the improvement of the numerical models. The wave models have undergone the same evolution, which makes them an important tool for the most accurate prediction of the wave conditions. In this study, the wave predictions on the west Iberian coast are performed with the SWAN model. Simulations are performed in winter 2013-2014 when various storms affected all the European coasts. It is well known that in the simulation of extreme wave events some errors may occur. Altimeter measurements are used to correct the errors that appeared in the simulation results. By using these measurements together with regression methods, it was possible to improve the significant wave height fields simulated with the SWAN model in each point of the computational domain of the target area. This improvement is indicated by the statistical parameters calculated by comparing the simulated significant heights with buoy measurements.

Keywords: SWAN, West Iberian coast, hindcast wave data, correction, regression methods.

1. Introduction

Nowadays numerical models represent an effective tool to predict accurate sea state conditions at various levels, from oceanic to local scale (Cavaleri et al., 2018). However, inaccuracies continue to exist in the results obtained with wave models due to various factors. These can be induced by the inevitable errors existing in the input data used to force the model, such as wind fields (Rusu et al., 2008) or boundary conditions (Butunoiu and Rusu, 2021). The model's physical parameterizations may also have their contribution (see Akpinar et al., 2016), especially when extreme events are present (Rusu, 2016).

Accurate wave predictions are important to have information about the sea state conditions for short- and long-term applications, such as maritime transport (Guedes Soares and Teixeira, 2001), coastal protection (Rusu and Guedes Soares, 2011), and offshore activities (Onea et al., 2017; Ribeiro et al., 2020). Various methods, from sophisticated data assimilation schemes (e.g., Saulter et al., 2020) to simple error correction based on linear regression (Rusu and Guedes Soares, 2014), can be applied to correct the wave parameters delivered by numerical models and provide the users with reliable information

In the operational wave forecasting systems real-time measurements provided by buoys or satellites are necessary for the data assimilation schemes applied to generate an analysis field as accurately as possible, used then as a first guess for the next simulations. On the other hand, error correction approaches can be also implemented independently of the model simulations (Marzban et al., 2006). In such cases, wave fields as resulted from simulations are updated based on the differences between the simulated and observed wave parameters in various points over the computational domain.

The west Iberian coast, the target area of this study, is usually affected in the wintertime by various storms developed in the North Atlantic Ocean. For this reason, to have reliable information about the sea state conditions (especially in the case of extreme events) and their evolution help to choose the best measures to protect the people that live in the vicinity of the coastal area, as well as to choose the best traffic management measures from the areas adjacent to the ports. The economy of Portugal, a country with the largest coast on the western side of the Iberian Peninsula, is closely related to the marine environment by activities such as maritime traffic or fishing. Recently, based on wave parameters forecasts, a methodology was developed for easier identification of the areas in which the fishing activities can be put at risk due to weather conditions (Rusu and Guedes Soares, 2014).

Through the efforts of various research centres and Portuguese institutions, operational systems for wave prediction have been implemented in the target area (Silva et al., 2009; Guedes Soares et al., 2011), at the same time studies on improving wave prediction have been also carried out (Rusu et al., 2005; Gonçalves et al, 2015). In line with the continuous concerns of improving the results obtained by simulations with wave models, in the present study a simple but efficient methodology is presented. Through this, the results obtained by Rusu et al. (2018) on the west Iberian coast at the first level of the SWAN (Simulating Waves Nearshore, Booij et al., 1999) model implementation can be improved.

2. Wave model simulations

2.1. Wave modelling system

The sea state conditions in the area covering the entire western coasts of the Iberian Peninsula were simulated with the SWAN model implemented in a computational domain with geographical limits 2° S, 80° N, 90° W, 33° E and a spatial resolution of 0.5° (Rusu et al., 2018), as illustrated in Figure 1. The boundary conditions used to force the SWAN model were provided by the WAM model (Günther and Behrens, 2012) driven by wind fields from the National Centers for Environmental Predictions (NCEP), Climate Forecast System Reanalysis version 2 (CFSR, Saha et al., 2014).

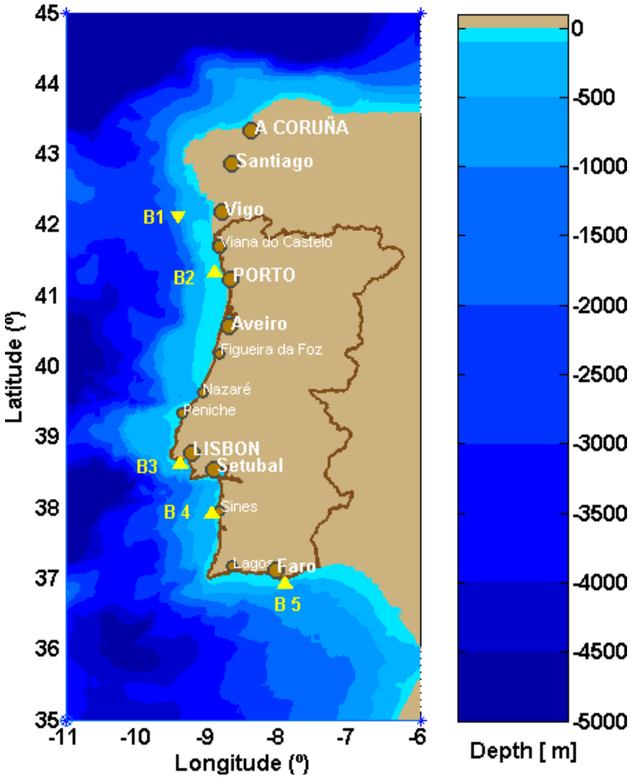


Figure 1. The west Iberian computational domain considered for SWAN model simulations and the buoy positions.

The same wind fields with 6 hours and 0.5° temporal and spatial resolutions, respectively, were used for regional simulations. The simulations considered in this study are performed from the 1st of December 2013 to the 31st of January 2014, a period when the western Iberian coast was affected several times by unusually high waves generated by various extreme storms developed in the North Atlantic Ocean.

2.2. Validation of the results

To evaluate the accuracy of the wave parameters obtained as output (with a temporal resolution of 3 hours) from SWAN, comparisons with in-situ measurements are further made. The positions of five buoys deployed on the western Iberian coast, in deep and shallow water, are illustrated in Figure 1 and they are denoted from B1 until B5 starting from the northernmost position. Thus, the position of B1 (Cabo Silleiro) is in deep water at 9.43º W/ 42.12° N, while the next three buoys are in the proximity of the most important Portuguese harbours as Leixões (B2-8.983ºW/41.316ºN, 83m water depth), Lisbon (B3-9.386°W/38.624°N, at about 33m depth) and Sines (B4-8.93ºW/37.92ºN at approximately 97m depth), respectively. In the southern Portuguese coast is the fifth buoy B5 (Faro, 7.898°W/36.905°N) at about 93m depth.

Only the significant wave heights (*Hs*) recorded by all these buoys are used for comparisons with the same wave parameter resulted from SWAN simulations. The measurements from B3 cover only the first three weeks in December (with some gaps for the storm conditions) while for the other four buoys they are available for the entire period considered. All the measurements used in this study have a time step of 3 hours. Some statistical parameters usually used for comparisons between simulated and measured wave parameters are computed and presented in Table 1 (the same notation as in the previous studies is used, e.g., Rusu et al., 2018). A positive *Bias* indicates an overestimation of the measurements by simulations. The same is suggested by the value of the symmetric slope $S > 1$.

Table 1. Statistical results for the significant wave height at the five buoys.

Buoy	Bias	RMSE	SI	r	S	N
B1	-0.32	0.65	0.16	0.96	1.07	496
B2	-0.07	0.59	0.17	0.94	1.01	410
B3	0.73	0.93	0.49	9.11	1.39	150
B4	0.20	0.51	0.17	0.95	1.04	496
B5	-0.11	0.26	0.20	0.92	0.93	496

Direct comparisons between the measured and simulated *Hs* show a good correlation of them, with more pronounced differences especially in storm conditions (see Figure 2 for B1 and B4). Taking into consideration the importance of a reliable prediction of the sea state conditions in general, but mainly of the extreme conditions which are also the most dangerous, we tried to find simple and efficient methods to correct them independently of the simulation with the SWAN model.

3. Correction of the simulation results

3.1. Description of the correction method

In order to make a consistent correction of the *Hs* fields, measurements that cover the entire domain are necessary to be compared with simulations. Altimeter measurements from three missions (JASON 2, Cryosat 2 and SARAL) are available for the period considered and they are distributed by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data).

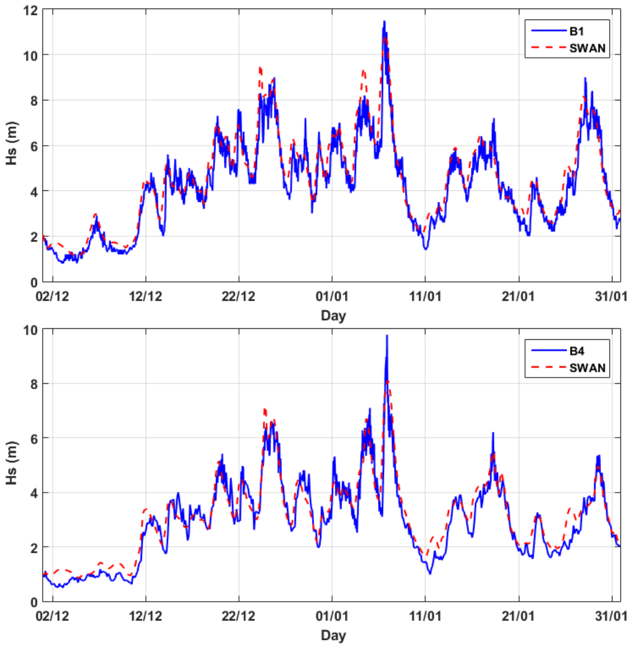


Figure 2. Graphical comparison between *Hs* registered at B1 (top panel) and B4 (bottom panel) buoys and the results of the SWAN simulations for the time interval 2013/12/01h00 - 2014/01/31h21.

To correct the *Hs* field simulated by SWAN, a recursive SCM (successive correction method) algorithm is implemented at each point of the computational grid. Thus, to apply the correction to the waves predicted in day *d*, a linear regression is applied (the detailed theoretical background of this method is presented in Soukissian and Kechris, 2007; Rusu and Guedes Soares, 2014) using the ensemble of the altimeter measurements and the corresponding predictions in the previous $t = 20$ days. The regression parameters (a_d and b_d) are estimated by using the Ordinary Least-Square (OLS) method for each day:

$$b_d = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \quad \text{and} \quad a_d = \bar{y} - b_d\bar{x}, \qquad (1)$$

where y is the predicted *Hs*, x is the measured *Hs*, $\bar{x}$ and $\bar{y}$ denote the mean values of the variables x and y, n is the valid number of measurements on the t-days period considered. The regression parameters are then used to correct the predicted *Hs* values at day d.

It should be also mentioned that for a day d, in each grid point we have *Hs* values every 3 hours (8 values/day). For all these *Hs* values of the day, the same regression parameters are used in the correction process.

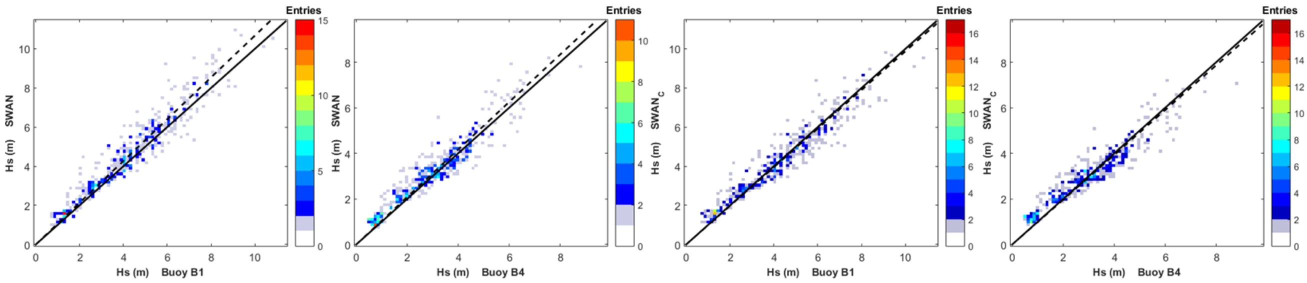
3.2. Results

After the implementation of the algorithm presented in the previous section, the corrected *Hs* fields are obtained. In order to compare these new values of *Hs* with the buoy measurements, the corrected fields are spatially interpolated (bilinear interpolations) to the locations of the five in-situ measurements. The *Hs* time series (corrected values vs measurements) are then compared, and the corresponding statistical parameters computed are given in Table 2 for each buoy.

The good effect of the correction method is also observed from the scatter diagrams presented in Figure 3, where with $SWAN_C$ are denoted the corrected SWAN values.

Table 2. Statistical results for the corrected significant wave height at the five buoys.

Buoy	Bias	RMSE	SI	r	S	N
B1	0.02	0.56	0.13	0.96	0.99	496
B2	-0.12	0.60	0.17	0.94	0.95	410
B3	0.67	0.83	0.44	9.11	1.20	150
B4	0.06	0.50	0.17	0.95	0.98	496
B5	-0.05	0.23	0.18	0.92	0.96	496



a) b) c) d)

Figure 3. H_s scatter diagrams, SWAN results and $SWAN_C$ against measurements at B1 (a and c) and B4 (b and d) buoys. The solid lines denote the perfect fit to the modelled and observed values and the dashed lines represent the best-fit slope

The comparison between the statistical parameters from Tables 1 and 2 indicates a small improvement in terms of Bias, RMSE and SI after correction, while the correlation coefficients maintain the same values. A more consistent improvement is observed in the case of the symmetric slope (S). Initially, this parameter had values higher than 1 for all buoys, while after applying the correction only for B3 such a value is maintained.

4. Conclusions

In the present study a linear regression method to improve the simulated sea state conditions was proposed and evaluated. The correction method applied to the SWAN simulations on the west Iberian coast for storm conditions show good results.

The improvement is indicated by the statistical parameters calculated by comparing the simulated and corrected significant heights with five buoy measurements. In this way more reliable wave predictions are provided by the wave modelling system and this accuracy enhancement is particularly important for the extreme storm events.

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References

Cavaleri, L., Abdalla, S., Benetazzo, A., Bertotti, L., Bidlot, J. R., Breivik, Ø., ... and van der Westhuysen, A. J. (2018). Wave modelling in coastal and inner seas, *Progress in oceanography*, **167**, 164-233.

Rusu, L., Bernardino, M. and Guedes Soares, C. (2008), Influence of the wind fields on the accuracy of numerical wave modelling in offshore locations, Proceedings of the 27th International Conference on Offshore Mecanics and Arctic Engineering (OMAE2008), ASME, Paper OMAE2008-57861, June 15-20, Estoril, Portugal, AMER Soc MECHANICAL ENG., New York, Vol. 4, 637-644.

Butunoiu, D. and Rusu, E. (2012), Sensitivity tests with two coastal wave models, *Journal of Environmental Protection and Ecology*, **13**(3), 1332-1349.

Akpınar, A., Bingölbali, B. and Van Vledder, G.P. (2016), Wind and wave characteristics in the Black Sea based on the SWAN wave model forced with the CFSR winds, *Ocean Engineering*, **126**, 276-298.

Rusu, E. (2016), Reliability and applications of the numerical wave predictions in the Black Sea, *Frontiers in Marine Science*, **3**, 95.

Rusu, E. and Guedes Soares, C. (2011), Wave modelling at the entrance of ports, *Ocean Engineering*, **38**(17-18), 2089-2109.

Guedes Soares, C. and Teixeira, A. P. (2001), Risk assessment in maritime transportation, *Reliability Engineering & System Safety*, **74**(3), 299-309.

Onea, F., Ciortan, S. and Rusu, E. (2017), Assessment of the potential for developing combined wind-wave projects in the European nearshore, *Energy & Environment*, **28**(5-6), 580-597.

Ribeiro, A., Costoya, X., de Castro, M., Carvalho, D., Dias, J. M., Rocha, A. and Gomez-Gesteira, M. (2020), Assessment of Hybrid Wind-Wave Energy Resource for the NW Coast of Iberian Peninsula in a Climate Change Context, *Applied Sciences*, **10**(21), 7395.

Saulter, A. N., Bunney, C., King, R. R. and Waters, J. (2020), An application of NEMOVAR for regional wave model data assimilation, *Frontiers in Marine Science*, **7**, 897.

Rusu, L. and Guedes Soares, C. (2014), Local data assimilation scheme for wave predictions close to the Portuguese ports, *Journal of Operational Oceanography*, **7**(2), 45-57.

Marzban, C., Sandgathe, S. and Kalnay, E. (2006), MOS, perfect prog, and reanalysis, *Monthly weather review*, **134**(2), 657-663.

Rusu, L.and Guedes Soares, C. (2014), Forecasting fishing vessel responses in coastal areas, *Journal of Marine Science and Technology*, **19**(2), 215-227.

Silva, F. S., Pinto, J. P. and Almeida, S. (2009), Operational wave forecasting system for the Portuguese coast, *Journal of Coastal Research*, **SI56**, 1055-1059.

Guedes Soares, C., Rusu, L., Bernardino, M. and Pilar, P. (2011). An operational wave forecasting system for the Portuguese continental coastal area, *Journal of Operational Oceanography*, **4**(2), 17-27.

Rusu, L., Pilar, P. and Guedes Soares, C. (2005), Reanalysis of the wave conditions in the approaches to the Portuguese port of Sines, Maritime transportation and exploitation of ocean and coastal resources, Vol. 2, 1137-1142.

Gonçalves, M., Rusu, E. and Guedes Soares, C. (2015), Evaluation of two spectral wave models in coastal areas, *Journal of Coastal Research*, **31**(2), 326-339.

Rusu, L., Gonçalves, M. and Guedes Soares, C. (2018), Prediction of storm conditions using wind data from the ECMWF and NCEP reanalysis, *Developments in Maritime Transportation and Harvesting of Sea Resources – Guedes Soares & Teixeira (Eds)*), Taylor & Francis Group, London, UK, Vol. 2, 1111-1117.

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 Research*, **104**, 7649–7666.

Günther H. and Behrens A. (2012), The WAM model. Validation document Version 4.5.4, Institute of Coastal Research Helmholtz-Zentrum Geesthach (HZG), January 2012, 92 pp.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Pan, H.L., Behringer, D., Hou, Y.T., Chuang, H., Iredell, M., Ek, M., Meng, J. and Yang, R. (2014), The NCEP Climate Forecast System version 2, *Journal of Climate* **27**(6), 2185–2208.

Soukissian T and Kechris C. (2007), About applying linear structural method on ocean data: Adjustment of satellite wave data, *Ocean Engineering*, **34**(3-4), 371-389.