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Assessment of the wave spectral characteristics in the Portuguese test zone

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ABSTRACT: A statistical analysis of the wave parameters significant wave height water and peak period) in a location offshore Portugal continental coast is presented. Two points at different depths from the Portuguese pilot zone of São Pedro de Moel were chosen. The spectral and parametric results used in this analysis were obtained from a 12-year hindcast study using two coupled spectral models, WAVEWATCH III and SWAN. The occurrences of the spectral classes are estimated and the variability of the spectral parameters is described. The modelling of the climatic variability of directional spectra provides reliable information of the most relevant parameters of the two locations, i.e., how the spectral parameters and their probability of occurrence vary in the regions studied. The results of this study allow a more consistent knowledge of the sea states characteristics in which a floating platform of renewable energy devices will operate.

1 INTRODUCTION

The economic activities related to the sea waters, as the maritime transport (of people or goods), the fishery, the offshore aquaculture and the renewable energies (from waves, tides or currents), are in constant increase. Therefore, it is important to perform a reliable wave climate prediction in the areas where these activities occur.

Portugal is a European country whose economy is strongly linked to sea activities. This is due to its large coastal area that is surrounded on its west and south coast by the North Atlantic Ocean. Its privileged location, within latitudes where the highest wave energy can be found due to the prevailing western winds and with a long fetch near to its west coast, made this country a target in renewable wave energy studies. In fact, it was placed at its north (nearshore of Aguçadoura) the world's first wave farm with three Pelamis devices that operated in 2008. Besides that, a maritime pilot zone was established at São Pedro de Moel, a coastal area located at Portugal centre, to support the deployment of offshore wave energy prototypes and farms. This pilot zone has an area of 320 km^2 and is sited between 30 m to 90 m of water depth (Huertas Olivares et al., 2007).

The a priori information on wave conditions helps planning the operability and implementation of Wave Energy Converts (WEC).

The spectral parameters that govern the sea states, namely the significant wave height (H_s) and the mean (T_z) or peak period (T_p), are of great importance to have a reliable knowledge of the wave climate. It is usual to describe the ocean waves characteristics by using wave parameters. This approach works well for a single wave-system but fails for more complex situations (Portilla-Yandún et al., 2015). Sea states where wind sea (waves generated locally) and swell are combined are not unusual. In fact, these complex sea states were found in the open North Sea in a rate of 16% (Guedes Soares, 1984), in the North Atlantic in a rate of 22% (Guedes Soares, 1991) and in Portuguese coast in a rate of 23–26% (Guedes Soares & Nolasco, 1992).

There are methods to classify the shape of the directional wave spectrum and eventually to identify the existing wave systems. Various proposals have been made of methods to separate the spectral components based on the frequency spectrum and a comparison between different approaches can be found in Ewans et al. (2006). The parameters of each individual spectral component are enough to allow fitting a double peak spectrum with two JONSWAP components (Guedes Soares, 1984). This was recently validated as an adequate approach for modelling swell (Lucas & Guedes Soares 2015).

With the directional wave spectrum one has the full information of the physical processes that governs the energy balance between wind waves and swell, which allows a better description of the sea conditions than just the use of the wave parameters (H_s and T_p or T_z).The separation of the spectral components is a more complex problem but it has been resolved by Boukhanovsky & Guedes Soares (2009)

To determine the climatic shape of spectra, a reasonable time period is essential and this is only available through wave model hindcasts. This will be followed in this paper in line with Lucas et al., (2016) but with the target area at São Pedro Moel, the pilot zone. The wave power potential of this area was studied, among others, by Silva et al. (2018). They found that the H_s with highest frequency of occurrences were in the range of 1 – 1.5 m at total time and 2–2.5 m at winter time. An analysis of the wave conditions at two grid points with different depths was done. The objective is to see how the wave conditions change when approaching shallow water depth and from this perspective, a statistics on the main spectral parameters and on the different classes of directional spectra for the two points will be presented. Therefore, a hindcast of 12 years (2000 to 2012) modelled with a nested scheme using the spectral wave models WAVEWATCH III (WW III) and SWAN was used.

2 SPECTRAL WAVE MODELS

The ocean wave's climate can be modelled by third generation spectral wave models, which described the evolution of the wave spectrum in space and time. Depending on the users intends the modelling can be done for forecast or hindcast outputs.

The assessment of the wave conditions in the target area were done using a nested wave prediction system with two spectral wave models, WAVEWATCH III (WW III) version 3.14 (Tolman, 1991) and SWAN version 40.91 (acronym from Simulating Wave Nearshore) (Booij et al., 1999). The nested scheme is a way to connect the wave's propagation from Deep Ocean, simulated by the WW III, to coastal areas, simulated by SWAN. The first model covers almost the entire North Atlantic basin (Figure 1), and the second one has a first area at scale of the Iberian coast (Figure 1) and a second area, with higher resolution, at São Pedro de Moel coast (Figure 2).

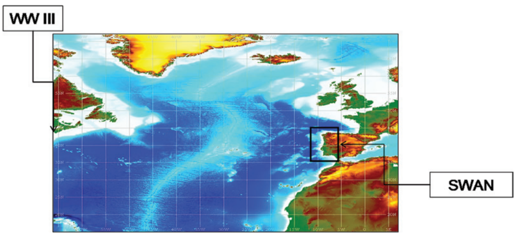

Figure 1. WW III and SWAN first area implementation.

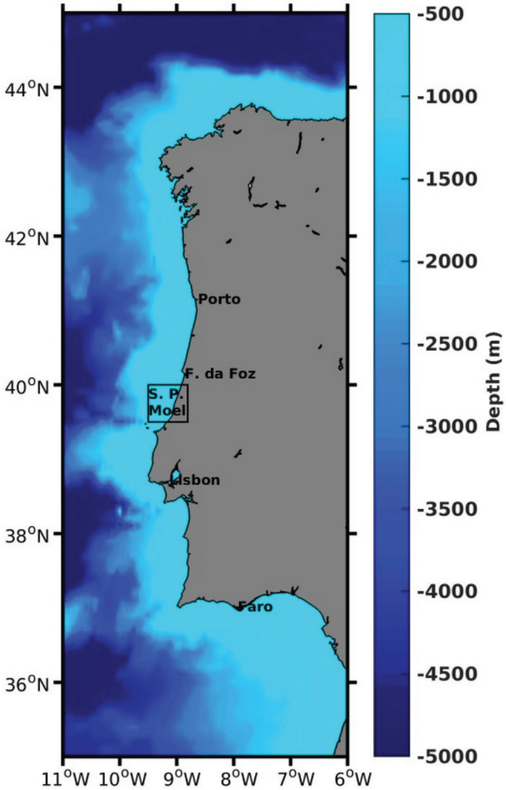

Figure 2. Regional SWAN area: São Pedro de Moel.

Table 1. Computational grids for the geographic areas.

	Coarse grids	
	LAT/LONG	ΔX × ΔY
WW III (North Atlantic)	13°N-72°N/65° W-22°E	1.54° × 1.46°
SWAN (Portugal mainland)	35°N-45°N/11° W-6°W	0.05° × 0.1°
	Nesting áreas	
SP Moel	37.7°N–38.2°N/ 9.2°W-8.7°W	0.5' × 0.5'

The bathymetric data is essential for the models runs. In this study, the WW III used a bathymetry provided by NOOA's GEODAS database and SWAN provided by the GEBCO (General Bathymetric Chart of the Ocean). The characteristics of these grids are presented in Table 1.

To apply the methods described in the sections below, the outputs required for SWAN model were the wave parameters significant wave height (H_s) and peak period (T_p) for a time step of 3 h and the directional wave spectra for a time step of 6 h (synoptic terms).

This prediction system was already validated against buoys measurements and the results reported by Silva et al. (2015b). The coastal model revealed a good performance as the results showed a good agreement with the buoys.

In order to provide a better knowledge of the area, a detailed analysis of the wave regime was executed in two different water depths near the test pilot area of São Pedro de Moel located in the center of Portugal. The two points are located in shallow and deep water (at P1 – 41 m and P2 – 529 m, Figure 3) and the statistical analysis was computed for significant wave height and peak period for the 12 years period. The detailed analysis consisted in the number of observations, the mean, the median, the standard deviation, the minimum value, the maximum and the symmetry of the sample as it is presented in Table 2 for the significant wave height and in Table 3 for the peak period.

From the analysis of Tables 2 and 3, it is observed that the values of the mean, minimum and maximum, are higher for the H_s parameter of the offshore point (P2 – 529 m). In the case of the peak period parameter, there is no significant difference between the two points (the shallower and the deeper point).

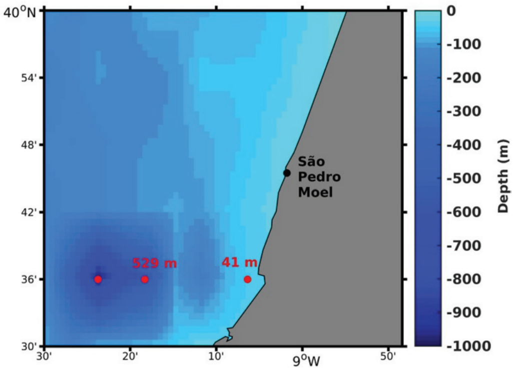

Figure 3. Geographical location of the deepest and shallowest points near São Pedro de Moel.

Table 2. Descriptive statistics of the six points for the parameter H_s of the period 2000 to 2012.

Statistics	P1 – 41 m	P2 – 529 m
N° obs	36742	36742
Mean	1.63	1.94
Median	1.43	1.67
St. dev	0.85	1.06
Minimum	0.20	0.25
Maximum	6.22	8.15
Symmetry	1.30	1.34

Table 3. Descriptive statistics of the six points for the parameter T_p for the period of 2000 to 2012.

Statistics	P1 – 41 m	P2 – 529 m
N° obs	36742	36742
Mean	10.16	10.26
Median	10.08	10.08
St. dev	2.04	2.03
Minimum	3.93	3.93
Maximum	16.85	16.85
Symmetry	0.11	0.13

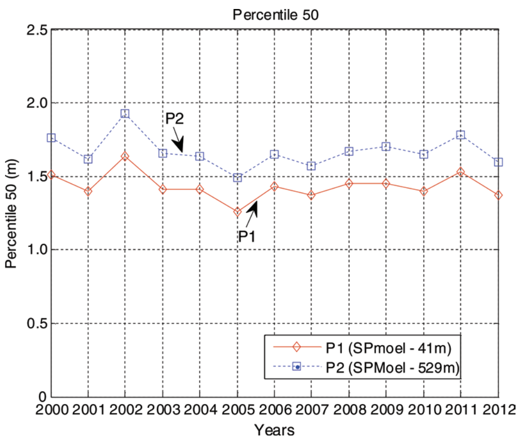

Figure 4. The 50th Percentile profile for the two points (the shallower and the deeper) which are located in the pilot test zone of São Pedro de Moel.

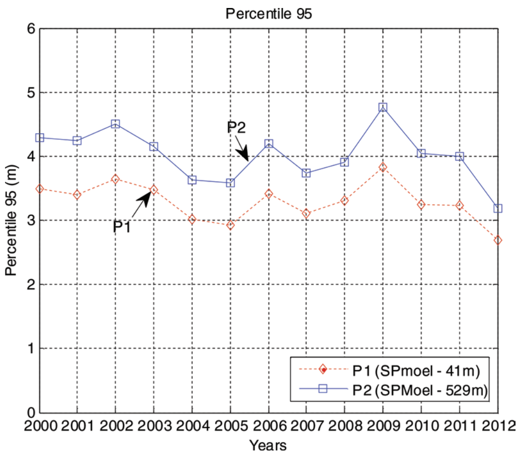

Figure 5. The 95th Percentile profile for the two points (the shallower and the deeper) which are located in the pilot test area of São Pedro de Moel.

To complete the analysis the 50% percentile and the 95% percentile were also determined for each point (Figures 4 and 5). The evolution of the significant wave height (H_s) through the years for the deeper and shallow point is shown and it is possible to conclude that it is in the offshore point where the highest value can be found.

The analysis made to the period of twelve years revealed the year of 2002 presents the highest waves with a 50th percentile from 1.64 m (P1) to 1.93 m (P2). The 95th percentile of H_s presents values of 3.6 m (P1) to 4.51 m (P2). The lower values were detected for the year of 2005, 1.25 m (P1) to 1.49 m (P2) at the 50th percentile and from 2.92 (P1) to 3.59 m (P2).

3 CLIMATIC VARIABILITY OF DIRECTIONAL WAVE SPECTRA

In the presence of combined sea states, the directionality of the wind sea and swell components need to considered. An accurate description of the combined sea states requires information about the angular distribution of energy and the relative directions between the two wave systems, wind sea and swell. For both components the directional wave spectrum is assumed to be given as the product of a frequency spectrum by the spreading function, although the swell component is restricted to a narrow range of directions. Therefore, the importance of representing the combined sea states by wind sea and swell components (sometimes with more than one swell component) separately when assessing the wave induced loads effects in the marine structures is demonstrated by heir different directionality.

This work adopts the method of identifying and classifying multipeaked spectra presented by Boukhanovsky & Guedes Soares (2009) proposing an approach for the probabilistic modelling of the spectral parameters. This approach is based on a parametric description of the directional wave spectrum and adopts a numerical optimization procedure to identify the spectral type and parameters (Lucas et al., 2011; Lucas et al., 2016), providing information of the most relevant parameters of the target locations, and giving as contribute how the spectral parameters and their probability of occurrence were varying in the regions studied.

This work was performed with in form of directional wave spectra allowing modelling the climatic variability of directional wave spectra, which is a suggestion to describe the sea wave climate in these regions.

3.1 *Theoretical background*

In this study, the 12 year hindcast dataset (2000 to 2012) generated by the SWAN model, was used and more than 18.372 directional spectra were processed for each location. The statistical analysis applied allowing estimating the occurrences of 5 classes of climatic wave spectra, which is the spectrum averaged over an ensemble of spectra (Boukhanovsky & Guedes Soares 2009), in the location of São Pedro de Moel and the synoptic variability of climatic spectra as transition probabilities from one class to another.

A general sea state consists of a locally generated wind sea and one or more swell systems. Thus, if the non-linear interaction between the wind waves and the swell are negligible, then the total directional spectrum is defined by:

$$S(f,\theta) = \sum_{i=0}^{N} S_i(f,\theta) \tag{1}$$

In which, the index $i = 0$ is associated with wind waves, and N is the number of swell systems present. The functions $S_i(f, \theta)$ and $S_j(f, \theta)$ at $i \neq j$ allow for overlapping spectral contributions from each model over some values of frequency and direction (f, θ). Each spectral component S_i is characterized by the set of their moments m_{kl}, which correspond to characteristics of the sea state. The problem of parameter identification is formulated as the optimization of the quality functional by equation:

$$J^{(N)}(\Xi) = \sqrt{\int_0^{\infty}\int_0^{2\pi} \left[S^*(f,\theta) - S(f,\theta,\Xi)\right]^2 df d\theta} \xrightarrow[N,\Xi]{} \min. \tag{2}$$

The $S^*(\cdot)$ is the target spectrum, and $S(f, \theta, \Xi)$ is the parametric model of spectrum by equation (1), where Ξ is the set of parameters ($\Xi = (m_0^{(i)}, f_p^{(i)}, \theta_p^{(i)}, \gamma_i, s_i, A_{pi}, \beta_i)$) for the JONSWAP based model).

Numerically, $S^*(f_k, \theta_l) \equiv S^*_{kl}$ are the values of the target spectrum at regular grid points. This parametrization allows for a reduction in the data dimensionality to a generic classification of homogeneous sea state conditions on the base of the time series of spectral parameters. The methodology of analysis is based on this approach which allows to obtain, for a certain location, the time series of spectral parameters $\Xi_i = \Xi_i(t)$ for each wave system (i) in a spectrum $S(f, \theta, t)$, where t is the time, for the certain location. Here $i = 0 \dots n(t)$, where $n(t)$ is number of the wave systems, which is varying over t. To determine the spectral parameters of the model described by equation (1), the problem of parameter identification is formulated as the optimization of the quality functional by equation (2). The set $\Xi_i(t)$ contains the estimates of significant wave height, peak period, peak direction, etc.

The number of wave systems and their separation in frequency and direction are the two types of characteristics in which the spectra classification is based. Therefore, a group of general wave types is clearly separated, the minimum number of types is $M=5$ (wind waves, swell, wind waves and one swell, two swells, complex multipeaked spectrum). The five classes are described as:

The *One-peaked spectra:* one wave system prevails—either the wind waves (*class* I) or the swell (*class* II). The division between wind waves and swell is based on the non-dimensional steepness:

$$\Delta = \frac{H_s}{\lambda_p} = \frac{2\pi H_s}{gT_p^2} = \frac{8\pi}{g}\sqrt{m_0}f_p^2 \quad (3)$$

where, $N=0$ and only one peak (f_p, θ_p) is considered. The λ_p is the wave length associated with the spectral peak, the m_0 the zero spectral moment, the f_p the peak frequency and g the gravitational acceleration. The limiting steepness value was obtained through the analysis of a set of wind wave and swell patterns, which result the rule $\Delta > 0.011$ is derived for selection of a wind wave system and otherwise a swell is expected.

The *Double-peaked spectra (classes III, IV):* in this class two wave systems exist simultaneously, in equation (1), $N = 1$. Two sub-classes are separated with respect to the wave-making conditions, associated with wave fetch and time of wave propagation: the "*matured*" sea and the *complex* sea.

The "*matured*" sea class: described by double-peaked spectra with two swell systems (*class* III). Normally, it includes all other two-peaked spectra with arbitrary relation between the frequencies $f_p^{(0)}$ and $f_p^{(1)}$. There are two pronounced maxima $\left(f_p^{(0)}, \theta_p^{(0)}\right)$ and $\left(f_p^{(1)}, \theta_p^{(1)}\right)$ separated both by frequency and direction. Generally, one of the swell systems belongs to local wave conditions, and the second one to the swell propagating from distant storm.

The *complex* sea class (*class IV*): mainly consists of two wave systems—wind waves and swell. Equation (3) is used for the selection of classes *III* and *IV*.

The Multipeaked spectra: defined by complicated wave fields with two or more swells (*class* V). In this class, the spectrum has more than two pronounced peaks, and $N \geq 2$ in the equation (3).

This classification allows for the association of each directional spectrum $S(f, \theta, t)$ with certain class c. For classes denoted by the numbers $c = 1 \ldots M$ (here $M = 5$) the sequence $c(t)$ can be considered as a Markov chain. The Markov chain with given parameters is considered as the simplest model of synoptic variability of the sea wave spectra and allows to compute the probabilities of all the transitions and jumps between the classes. Transition is the event when the wave spectrum changes the class during one synoptic term (e.g., 3 hours); the probability of transition from class c to class d is π_{cd}. Jump is the event when the wave spectrum changes the class and comes back during two synoptic terms (e.g., 3+3 hours); the probability of transition from class c to class d and back is π_{cdc}. The class of jumps probabilities considered is the marginal π_{cdc} (for all spectra in their class).

The datasets of directional wave spectra discriminated in 30 frequencies (H_z) and 36 directions (º) for each point were fitted to the model presented in equation (1) by the approach represented in equation (2).

A classification of the directional wave spectra in the two points (P1, P2) at the test pilot zone of São Pedro de Moel in classes of general wave types was performed (Table 4), with the aim of contributing to a better knowledge of the wave conditions in that area. This knowledge is important due to the several activities of which these regions are targeted as the implementation of marine structures, WECs, traffic of ships (Silveira et al., 2013).

The classification of the directional spectra in classes of spectra in the two points with different water depths indicated that, the percentage of one-peaked spectra is always greater for the point located in the deepest area (P2). In relation to the class of double-peaked spectra, its presence is higher in the area of the shallow water point (P1) which is very close to the coast. In the case of multipeaked spectra (class with more than 2 peaks) the deeper point presents a higher percentage in comparison to the shallow water point (P1 – 41 m).

The polar graphs presented in Figure 6 shown the spectral characteristics of the waves as the direction, frequency and the wave energy variance. The time frame of 17 February of 2011 at 00h was chosen due to the occurrences of high significant

Table 4. Classification of the directional spectra in classes of general wave types of the São Pedro de Moel points (P1 and P2).

Class of spectra	One-peaked spectra (%)		Double-peaked spectra (%)		Multipeaked spectra (%)	
	Depth (m)					
Years	41 m	529 m	41 m	529 m	41 m	529 m
2000	24.9	45.7	64.4	32.9	10.7	21.4
2001	23.6	37.5	62.7	40.1	13.8	22.4
2002	22.4	38.5	71.0	42.9	6.6	18.6
2003	23.6	37.1	68.7	45.4	7.7	17.5
2004	29.4	47.2	58.8	33.4	11.8	19.4
2005	33.6	45.6	54.9	34.3	11.5	20.2
2006	24.0	42.9	63.7	37.2	12.3	19.9
2007	26.4	45.6	62.6	37.6	11.0	16.8
2008	28.2	54.4	64.9	31.0	6.9	14.6
2009	24.7	42.6	66.5	39.5	8.8	17.9
2010	26.3	34.6	60.9	42.4	12.8	23.0
2011	28.7	50.5	64.5	35.4	6.8	14.1
2012	18.4	30.5	67.4	44.5	14.1	25.0
Years average	23.8	42.5	63.9	38.2	10.4	19.3

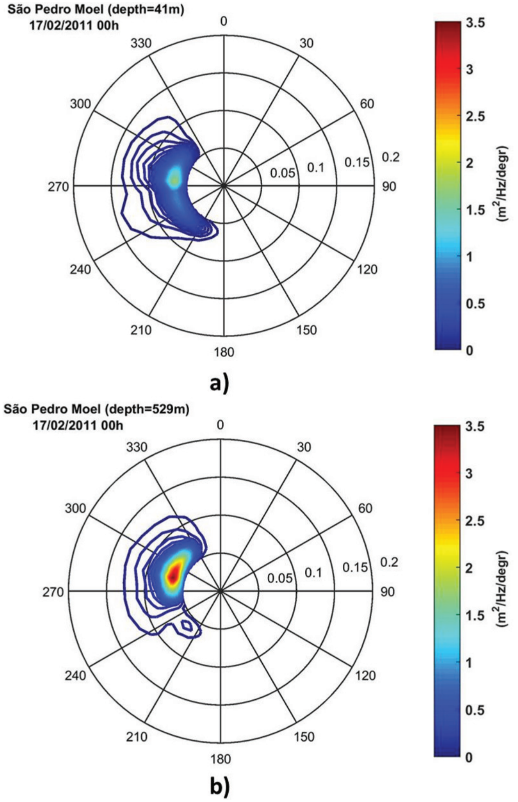

Figure 6. Wave spectra variance in a polar representation at the two points of study: a) P1 – 41 m and b) P2 – 529 m. The time frame: 2011.02.17 00:00.

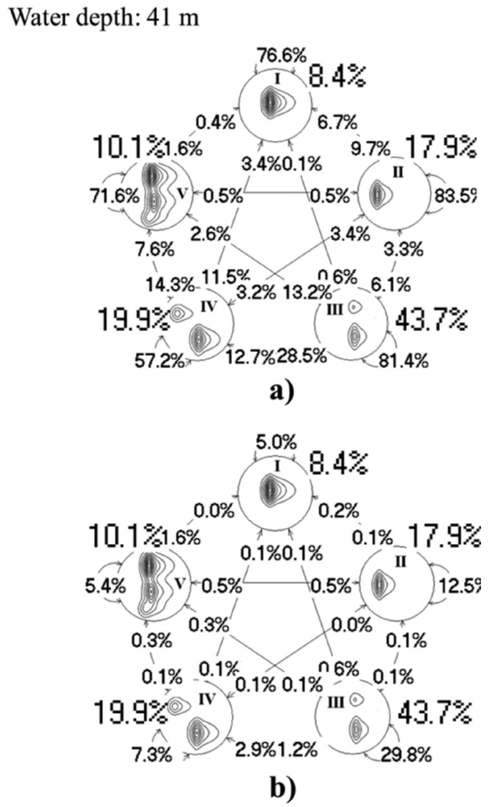

Figure 7. a) Star transition diagram; b) star jump diagram, of directional spectra transitions from São Pedro de Moel (2000 to 2012).

wave height, H_s, around 8 m in the deeper point and 6 m in the shallow water point. The predominant direction of the waves is from W an NW, with a decaying of the energy variance towards the coast. The physical processes that waves experience when approaching the shallow waters, making the energy to dissipate, explains the reduction of energy. Figure 6 a,b shown combined conditions of wind waves and "old" swell in both depths (P1 – 41 m and P2 – 529 m). It is possible to verify a change in the direction of the waves from the deeper to the shallow point, 290º to 270º. In these quadrants (*W*, *WN*), the arrival of a strong swell can result from the refraction of the wave, due to the difference in depth. This effect leads to a change of direction.

3.2 *Variability of directional spectral classes*

In this study an application is presented of statistical analysis of the variability of directional spectra of complex seas with spectral variability formulations, based on a 12-year hindcast. Figures 7 and 8 presents the star diagrams of directional spectra transitions for the locations of São Pedro de Moel point P1 (water depth – 41 m) and P2 (water depth – 529 m). For the shallower (Figure 7 a)) point the five main types of spectra are: wind waves (I, 8.4%), decaying waves or swell (II, 17.9%), the two swell systems of different ages (III, 43.7%), wind waves and swell (IV, 19.9%) and the complex multipeaked spectra (V, 10.1%). In the figures the arrows indicate the transitions between the types during synoptic terms (every 3 hours). This means that, if in present time the type I (wind waves) is observed, the conditional probability for the spectrum of type IV (wind waves and swell) is 11.5%, and to return back in the following time step is 3.4%. Furthermore, the probability for the wave spectrum to remain in the type I in the next step is 76.6%. In Figure 7 b), it is presented the star jump diagram, the significant jumps, i.e., the non-zero probabilities are indicated by arrows. For the shallower point of São Pedro de Moel, the absolute probability of occurrence of the spectral jump I-IV-I is 0.1%, and IV-I-IV is also 0.1%.

Water depth: 529 m

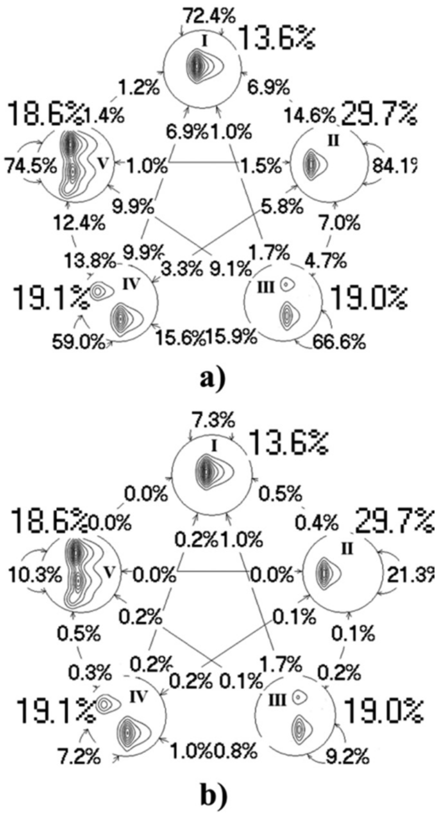

Figure 8. a) Star transition diagram; b) star jump diagram, of directional spectra transitions from São Pedro de Moel (2000 to 2012).

In the case of the deeper point (P2 – 529 m) the five types of classes are: the wind waves (I, 13.6%), decaying waves or swell (II, 29.7%), two swell systems of different ages (III, 19.0%), wind waves and swell (IV, 19.1%) and the complex multipeaked spectra (V, 18.6%). If in the present time Type II is observed, the conditional probability for the spectrum of type IV to occur in the next time step is 3.3%, and to return back in the following time step is 5.8%. Thus, the probability for the wave spectrum to remain in type II is 84.1% (in the next step). In Figure 8 b) the star jump is presented, it is seen that the absolute probability of occurrence of the spectral jump I-IV-I is 0.2%.

4 CONCLUSIONS

The objective of the present work is to characterize the long term climatic spectra in two grid points located at different water depths (Figure 3) at São Pedro de Moel pilot zone.

To study the type of wave systems that is present in the two locations, a statistical and spectral analysis were done using a 12 years hindcast from the SWAN model. The statistical analysis showed that the Hs are higher at the deeper point, which is the type of result expected. Looking at the H_s 50th and 95th percentile, it can be seen that the values varies from 1.2 m to 2 m and 2.80 m to 5 m respectively. The years that had the highest values were 2002 and 2009 and the lowest one 2005. In respect to T_p no differences were found between the two points.

The wave spectra variance, illustrated in a polar representation, showed that the main direction of the waves are *W* and *NW*, within a range of the sectors 210º to 330º.

In the last decades the characterization of the nearshore wave conditions along the Portuguese coast has been a subject of increasing interest in coastal management and environmental assessment studies, due to the fact that the Portuguese economy is very influence by the proximity of the ocean (Silva et al., 2015a). Therefore, the classification of the directional spectra in classes of general types was performed in the two grid points (São Pedro de Moel). This classification led to the conclusion that the deeper point has a greater percentage of one peak spectra than the shallow water point. In the case of multipeaked spectra (complicated wind fields with two or more swells) the deeper point presents the higher percentage of this type of spectra.

For each location (P1 and P2, in this study) the directional spectra was processed, for the dataset of 12 years, in five classes of climatic wave spectra. These classes are: wind waves – I, swell – II, two swells – III, wind waves and one swell – IV, complex multipeaked spectrum – V. In P1 (41 m) it was detected 8.4% of wind waves (I), 17.9% of decaying waves or swell (II), 43.7% of two swell systems with different ages (III), 19.9% of wind waves and swell and 10.1% of complex multipeaked spectra (V). At P2 (529 m), 13.6% are wind waves (I), 29.7% are decaying waves, or swell (II), 19.0% are two swell systems of different ages (III), 19.1% are wind waves and swell (IV) and 18.6% are complex multipeaked spectra (V).

This work intends to contribute to the spectral characterization of the pilot test zone of São Pedro de Moel, providing information of the principal spectral parameters H_s and T_p and showing how the spectral parameters and their probability of occurrence are changing in the shallow and deeper points.

ACKNOWLEDGEMENTS

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