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Influence of water depth on the characteristics of spectra at the entrance of major Portuguese ports

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ABSTRACT: A statistical analysis of the wave parameters significant wave height (H_s) and peak period (T_p) is presented in three locations offshore mainland Portugal. The spectral and parametric results used in this analysis were obtained from a 12-year hindcast study using two coupled spectral wave models, WAVEWATCH III and SWAN. The occurrences of the spectral types are estimated and the variability of the spectral parameters is described. The modelling of the climatic variability of directional spectra provides information of the most relevant parameters of the three locations, i.e., how the spectral parameters and their probability of occurrence vary in the studied regions. The results of this study provide long term information on the wave conditions that can be used in the assessment of the operability and safety of shipping as water depth decreases when approaching port entrances.

1 INTRODUCTION

The constant increase of economic activities in coastal waters in particular near the entrance of the ports highlights the importance of a good prediction of the wave climate in these areas.

The recent evolution to implement energy efficiency in ship design and operation has led to lower installed propulsion power, which may limit the manoeuvring ability of ships and create safety problems. The ship manoeuvring abilities will be degraded with adverse weather conditions and thus it is important to determine how the weather conditions affect the manoeuvring capabilities of ships in different conditions: in open sea, in coastal waters and low speed manoeuvring in restricted waters (Papanikolaou et al. 2014; 2015).

The manoeuvring capabilities in open sea generally less restrictive as most often they are not in areas of dense traffic and thus the question that arises is the manoeuvring under storm conditions. Data on storm conditions in the North Atlantic are available from visual observations and from various hindcast databases. The hindcast databases have some problems in predicting the extremes as noted in Bitner-Gregersen & Guedes Soares (2007), although they perform well under moderate sea states and shown recently by Campos & Guedes Soares (2016).

The difficulty in applying this data is that the ships normally follow prescribed routes as established in Vettor & Guedes Soares (2015a) and also they avoid storms by using weather routing systems (e.g. Vettor & Guedes Soares 2015b), which results in being subjected to lower sea states along their routes (Vettor & Guedes Soares 2016).

The operability of ships in coastal areas requires a greater demand on manoeuvrability than in the open sea, because the ships need to perform manoeuvres to maintain the required track and also some speed over ground to enter and leave coastal areas before the environmental conditions become severe (Papanikolaou et al. 2014; 2015).

In coastal areas the environmental conditions are generally less severe than in the open sea, and this has been shown in three locations by Bitner-Gregersen et al. (2016). This paper is a follow up of that one, aiming at characterizing this effect in the coastal area of continental Portugal by comparing the wave climate at offshore and coastal locations adjacent to the entrance of ports.

The incoming waves in Portugal are commonly from northwest, with highest values of sea states at the northwestern coasts and the lowest ones at south. The measurements of significant wave height from buoys near the ports, give an idea of the wave conditions in each region. The average value of this wave parameter for Leixões buoy is around 2.01 m, for Lisbon buoy of 1.31 m and for Sines buoy of 1.60 m, with a maximum values found of about 9.48 m, 6.27 m and 8.12 m, respectively.

However, to obtain the wave conditions in various locations in space so as to compare deep water with shallow water conditions, it is necessary to resort to numerical wave models that can produce wave data in the hindcast mode (Pilar et al., 2008) or in the forecast mode (Guedes Soares et al., 2011). This type of models has been shown to provide good results even at

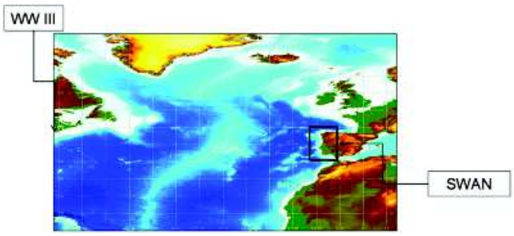

Figure 1. WW III and SWAN first area implementation.

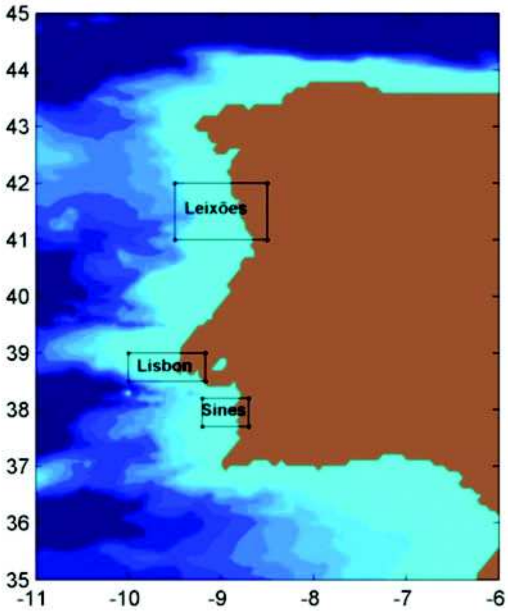

Figure 2. Regional SWAN areas: Leixões, Lisbon and Sines.

the entrance of ports (Rusu & Guedes Soares 2011a, 2013).

The objective of the present work is to analyse the average wave conditions in locations with different water depths in areas near the three major Portuguese ports. The study was performed in three areas of key importance near the principal ports of Portugal (Leixões, Lisbon and Sines). Lisbon port is located in a basin with 32 mil hectares where the Tagus River flows with the Atlantic Ocean, allows receiving ships of all sizes. Leixões port is the second largest port in Portugal. With good shipping, road and railway accessibilities, it represents 25% of Portugal international market. Sines port is the first largest port, where different types of goods can be handled, in specialized terminals.

The study uses wave data from a period of 12 years (2000 to July 2012). The spectral wave models WAVEWATCH III (WW III) and SWAN were used to produce a hindcast dataset of directional wave spectra.

The knowledge of the spectral parameters that govern the sea states, namely the significant wave height (Hs) and the mean (Tz) or peak period (Tp), are the accepted parameters to establish the wave climate in specific ocean areas.

It is common to use these parameters to describe the wave characteristics at sea, but this only gives good results for a single wave-system, as for more complex situations this approach fails (Portilla-Yandún et al. 2015). The complex sea states of wind-sea (waves generated locally) and swell are not an atypical situation. In fact, the global percentage of complex seas states is about 16% for the open North Sea (Guedes Soares, 1984), 22% for the North Atlantic (Guedes Soares, 1991) and 23–26% for Portuguese coast (Guedes Soares and Nolasco, 1992). For many years the importance of considering the combined sea states in the design approach was neglected by the marine structures industry. It has been an increasing interest in using this information in applications of marine structures (e.g. Teixeira and Guedes Soares, 2009).

The directional wave spectrum provides the full information about the physical processes that govern the energy balance between wind waves and swells that come from other regions, generated at earlier times and by other wind fields. Methods to classify the shape of the directional spectra and eventually to identify the existing wave systems in a given directional wave spectrum allow a better description of the sea conditions than just the use of the Hz-Tp (or Tz) parameters.

This work will provide statistics of the main spectral parameters and also statistics on the different classes of directional spectra that occur offshore and in the corresponding coastal location so as to give a detailed picture about how the wave conditions change when approaching shallow water.

2 SPECTRAL WAVE MODELS

Third generation spectral wave models have emerged as useful tools to study ocean waves providing forecast or hindcast products. For assessing the wave conditions close to the Portuguese coast at different water depths, two state-of-art models were nested, to make the connection from deep ocean to coastal areas. The two models considered are the WAVEWATCH III (WW III) version 3.14 (Tolman, 1991), which covers almost the entire North Atlantic basin, and the SWAN version 40.91 (acronym from Simulating Wave Nearshore) (Booij et al., 1999) to account for the nearshore physical processes, with at first a large domain at scale of the Iberian coast (Fig. 1) and three medium resolution areas (Leixões, Lisbon and Sines) nested inside it (Fig. 2).

The WW III and the SWAN models used different databases for the bathymetric data. The database from NOAA's GEODAS was used in the WW III model and the GEBCO (General Bathymetric Chart of the Ocean)

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	
Leixões	41°N-42°N / 9.5°W-8.5°W	0.5′ × 0.5′
Lisbon	38.5°N-39°N / 10°W-9.2°W	0.5′ × 0.5′
Sines	37.7°N-38.2°N / 9.2°W-8.7°W	0.5′ × 0.5′

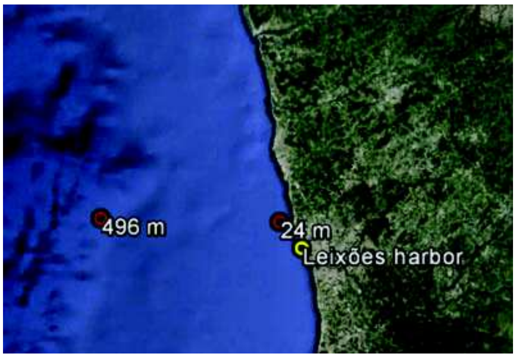

Figure 3. Geographical location of the deepest and shallowest points near Leixões harbour (Google Earth image).

was used in the SWAN model. The characteristics of these grids are presented in Table 1.

In SWAN the user can choose, from a wide range of options, the wave parameters and the time step intended for the output results. This work used as outputs for the points of study, the parameters significant wave height (H_s) and peak period (T_p), as well the directional wave spectra, for a time step of 6 h (synoptic terms).

The evaluation of the performance of this model set up was already done and reported in Silva et al. (2015). The coastal model results were validated against measurements from buoys and the results showed good agreement.

A detailed analysis of the wave regime was performed in two different water depths near the three important ports of Portugal. The first two points are located in the area of Leixões in shallow and deep water (at P1–24 m and P2–496 m, Figure 3), the third and the fourth in the area of Lisbon (P3–46 m and P4–1105 m, Figure 4) and the fifth and the sixth point near Sines (P5–35 m and P6–412 m, Figure 5). Statistics

Figure 4. Geographical location of the deepest and shallowest points near Lisbon harbour (Google Earth image).

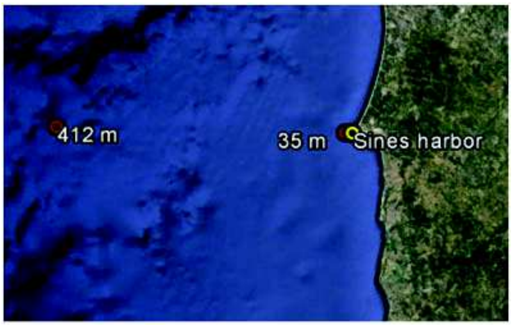

Figure 5. Geographical location of the deepest and shallowest points near Sines harbour (Google Earth image).

were computed for significant wave height and peak period for the 12 years period.

Those statistics are the number of observations, the mean, the median, the standard deviation, the minimum value, the maximum and the symmetry of the sample (Table 2 and 3). The statistics values of the mean, minimum and maximum show that H_s is higher offshore. In the case of T_p there is no significant difference between the offshore and the nearshore points.

The 50 percentile and the 95 percentile were also determined for each point and presented in Figures 6 and 7. It is possible to see the evolution of the significant wave height through the years in the several points, and it can be seen once again that it is in the offshore points where the highest values can be found.

Among these years, 2002 reveals be the year with the highest waves in mainland Portugal coast, with a 50th percentile from 1.5 m (P5) to 2 m (P4). In the case of the 95th percentile, the H_s values go from 3.71 m (P1) to 4.91 m (P4). The opposite occurs for the year of 2005, where the significant wave height is the smaller one at each point, with values from 1 m (P5) to 1.63 m (P4) at the 50th percentile and from 2.82 (P1) to 3.73 m (P4) at the 95th percentile. It has to be highlight that the highest values for the H_s parameter are in P4, which is the deepest point.

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

	Leixões		Lisbon		Sines	
	P1	P2	P3	P4	P5	P6
N°obs	18372	18372	18372	18372	18372	18372
Mean	1.52	1.93	1.76	2.05	1.50	1.80
Median	1.32	1.66	1.53	1.76	1.27	1.53
St.dev	0.84	1.07	0.93	1.09	0.89	1.03
Minimum	0.11	0.23	0.29	0.38	0.11	0.19
Maximum	6.24	7.76	7.11	8.57	6.22	7.26
Symmetry	1.29	1.33	1.34	1.40	1.34	1.34

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

	Leixões		Lisbon		Sines	
	P1	P2	P3	P4	P5	P6
N°obs	18372	18372	18372	18372	18372	18372
Mean	10.12	10.23	9.94	10.07	10.02	10.14
Median	10.08	10.08	10.08	10.08	10.08	10.08
St.dev	2.07	2.03	2.07	2.12	2.13	2.06
Minimum	3.60	3.60	3.60	3.60	3.31	3.31
Maximum	16.85	16.85	18.36	18.36	16.85	16.85
Symmetry	0.11	0.13	0.33	0.14	0.19	0.15

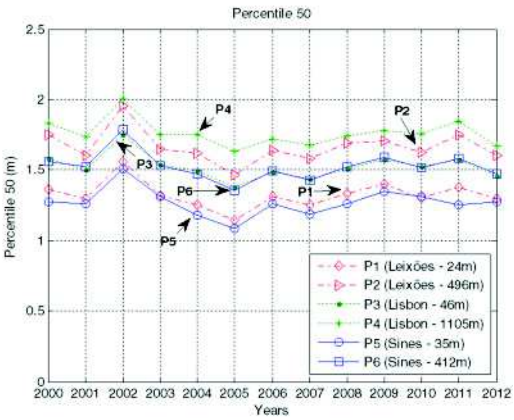

Figure 6. The 50th Percentile profile for the six points (the shallower and the deeper) which are located in front of the three major ports of Portugal.

3 MODELLING THE CLIMATIC VARIABILITY OF DIRECTIONAL WAVE SPECTRA

The use of spectral models open a way of having more extensive descriptions of the climatic variability of sea states than just the significant wave height or the joint distribution of significant wave height and a characteristic period. The description of the sea wave climate in ocean regions is addressed by modelling the climatic variability of directional wave spectra allowing determining the expected spectra in stormy seas.

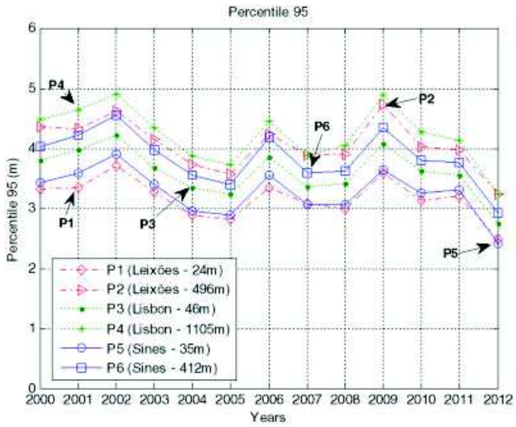

Figure 7. The 95th Percentile profile for the six points (the shallower and the deeper) which are located in front of the three major ports of Portugal.

To describe the variability of the total group of directional wave spectra, the approach that is based on parametric presentation of directional wave spectrum $S(f, \theta) = (f, \theta|\Xi)$, were Ξ is the set of parameters, is required as described in Lopatoukhin et al. (2005) and Boukhanovsky & Guedes Soares (2009). The problem of parameter estimation is complicated due to the many occasions in which the sea state cannot be described simply by those spectral models that represent a single wave system and that in many cases it was necessary to describe sea states resulting from a combination of swell and wind sea and even with more than one swell component.

The data used in the work in form of directional wave spectra allows modelling the climatic variability of directional wave spectra, which is a proposal to describe the sea wave climate in these regions. The methodology presented in this study was developed and presented by Boukhanovsky et al. (2007) and Boukhanovsky & Guedes Soares (2009). The method of identifying and classifying multipeaked spectra which proposes an approach for the probabilistic modelling of the spectral parameters was applied in four locations in the Portuguese coast and one in the Northeast Atlantic (Lucas et al., 2011). Providing information of the most relevant parameters of the referred locations, and giving as contribute how the spectral parameters and their probability of occurrence were varying in the regions studied.

3.1 *Parametric modelling of directional wave spectrum*

The approach for statistical analysis and modelling of directional wave spectra is based on a parametric description of the directional wave spectrum and adopts a numerical optimization procedure to identify the spectral type and parameters.

The 12 year hindcast dataset (2000 to 2012) generated by the SWAN model, was used and more than 18.384 directional spectra were processed for each location. Furthermore the statistical analysis allows for estimating the occurrences of 5 classes of climatic wave spectra, which is the spectrum averaged over an ensemble of spectra (Boukhanovsky et al., 2007), in each of the three locations: Leixões, Lisbon and Sines and the synoptic variability of climatic spectra as transition probabilities from one class to another.

The spectral parameters of the model are described by the definition of total directional spectrum:

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

where 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:

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

Here $S^*(\cdot)$ is the target spectrum, and $S(f, \theta, \Xi)$ is the parametric model of spectrum by equation (1).

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 these 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 $i = 0 \ldots n(t)$, 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 classification is based on the two types of characteristics, the number of the wave systems and their separation in frequency and direction. In this way, a set of general wave types is clearly separated, e.g., the minimum number of types is $M = 5$ (wind waves, swell, wind waves and one swell, two swells, complex multipeaked spectrum). In more detail, the selected classes are as follows.

One-peaked spectra: one wave system prevails – either the wind waves (*class* I) or the swell (*class* II). In equation (3), $N = 0$ and only one peak (f_p, θ_p) is considered. Separation between wind waves and swell is based on the non-dimensional steepness defined as,

$$\Delta = \frac{H_s}{\lambda_p} = \frac{2\pi H_s}{g T_p^2} = \frac{8\pi}{g}\sqrt{m_0} f_p^2 \tag{3}$$

here λ_p is the wave length associated with the spectral peak, m_0 the zero spectral moment, f_p the peak frequency and g the gravitational acceleration. For obtaining the limiting steepness value, a set of wind wave and swell patterns were analysed. As result, the rule $\Delta > 0.011$ is derived for selection of a wind wave system and otherwise a swell is expected.

Double-peaked spectra (classes III, IV): two wave systems exist simultaneously and in equation (1), $N = 1$. For double-peaked spectra 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 is described by double-peaked spectra with two swell systems (*class* III). Generally, its include all other two-peaked spectra with arbitrary relation between the frequencies $f_p^{(0)}$ and $f_p^{(1)}$. There are two pronounced maxima $(f_p^{(0)}, \theta_p^{(0)})$ and $(f_p^{(1)}, \theta_p^{(1)})$ 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. For selection of classes III and IV the equation (3) is used.

Multipeaked spectra: complicated wave fields with two or more swells (*class* V). In this case, the spectrum has more than two pronounced peaks, and $N \leq 2$ in the equation (3). Therefore, using the above mentioned 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., 3hours); the probability of transition from class c to class d is π_{cdc}. Jump is the event when the wave spectrum changes the class and comes back during two synoptic terms (e.g., 3 + 3hours); 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).

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

The coastal regions are usually characterized by high traffic of ships (Silveira et al. 2013) and therefore a good knowledge of the wave conditions is vital to

Table 4. Classification of the directional spectra in classes of general wave types of the Leixões points (P1 and P2).

Class of Spectra	One-peaked spectra (%)		Double-peaked spectra (%)		Multipeaked spectra (%)	
Depth (m)	24 m	496 m	24 m	496 m	24 m	496 m
2000	33.9	43.0	52.5	34.1	13.6	22.9
2001	25.2	31.6	60.8	42.7	14.0	25.8
2002	26.2	33.7	62.7	44.5	11.1	21.8
2003	25.8	32.6	61.8	45.8	12.3	21.6
2004	33.1	42.2	54.7	36.3	12.2	21.5
2005	34.9	42.1	52.2	36.4	12.9	21.4
2006	26.0	34.7	63.0	44.2	11.0	21.1
2007	28.3	37.3	60.4	40.7	11.3	22.0
2008	33.2	46.9	57.6	36.0	9.2	17.1
2009	27.9	36.8	64.7	43.2	7.5	20.1
2010	25.7	28.9	60.2	43.1	14.1	28.0
2011	35.3	42.9	56.0	40.8	8.7	16.2
2012	17.1	27.8	71.4	46.8	11.5	25.4
Years average	28.7	37.0	59.8	41.1	11.5	21.9

Table 5. Classification of the directional spectra in classes of general wave types of the Lisbon points (P3 and P4).

Class of Spectra	One-peaked spectra (%)		Double-peaked spectra (%)		Multipeaked spectra (%)	
Depth (m)	46 m	1105 m	46 m	1105 m	46 m	1105 m
2000	50.0	45.3	31.9	29.6	18.1	25.1
2001	44.7	36.0	36.4	34.2	18.8	29.7
2002	49.7	39.0	35.9	36.0	14.4	25.0
2003	50.1	37.9	35.6	36.3	14.2	25.8
2004	51.8	46.7	31.8	30.5	16.4	22.9
2005	46.4	41.1	36.9	31.4	16.6	27.5
2006	48.3	40.4	32.9	32.5	18.8	27.1
2007	50.2	41.7	34.1	34.6	15.7	23.7
2008	57.1	51.5	30.8	30.1	12.1	18.4
2009	51.4	40.2	35.0	35.4	13.6	24.4
2010	41.7	35.5	43.8	37.7	14.5	26.8
2011	52.4	47.6	35.8	31.6	11.8	20.8
2012	42.7	31.8	39.1	37.0	18.2	31.2
Years average	49.0	41.1	35.4	33.6	15.6	25.3

prevent accidents or even ecological disasters. Therefore, a classification of the directional spectra in the six points (P1, P2, P3, P4, P5 and P6) at the entrance of the ports of Leixões, Lisbon and Sines in classes of general wave types was executed and is presented in Tables 4, 5 and 6 for the period of 12 years.

The percentage of one-peaked spectra is greater for the points of the deep waters of Leixões (P2–496 m) and Sines (P6–412 m) than for the points located in the shallow waters and very close to the coast. The presence of double-peaked spectra is lower in the deep water points of these two areas. In the case of multipeaked spectra (with more than 2 peaks) the deeper point in Leixões presents a higher percentage in comparison to the shallow water point (P1–24 m), already in case of Sines (Table 6) this was not observed, in some years the number of spectra were lower than the number observed in the shallow water point (P5–35 m).

A different behaviour was verified in the area of Lisbon (Table 5), the deepest point (P4–1105 m) has less sea states with just on peak and a more complicated sea states than the nearshore point (P3–46 m).

This area is of great importance in the Portuguese continental nearshore, is the coastal environment in the neighbourhood of Lisbon. This area is subjected to high navigation traffic and high current conditions can occur making the interactions between waves and currents relevant in this area (Rusu et al. 2011b). This region was the subject of several studies performed by Costa et al. (2001) concerning the wave climate in the Portuguese coastal environment. Sines region was study by Pires Silva et al. (2002) with simulations produced by SWAN model.

In the navigation channel of the Tagus estuary the swell that comes from the ocean never propagates in to the upstream part of the Tagus estuary and only the downstream part (main navigation channel with 46 m of depths) which is the southern part of the channel (south of Lisbon) is exposed to waves and often in the highest waves, swell is the dominant component in that part of the channel.

Table 6. Classification of the directional spectra in classes of general wave types of the Sines points (P5 and P6).

Class of Spectra	One-peaked spectra (%)		Double-peaked spectra (%)		Multipeaked spectra (%)	
Depth (m)	35 m	412 m	35 m	412 m	35 m	412 m
2000	19.9	47.5	57.9	34.4	22.2	18.1
2001	18.8	42.1	60.2	36.5	21.0	21.4
2002	19.1	42.0	59.9	40.3	21.0	17.7
2003	19.7	42.2	61.4	39.5	18.9	18.2
2004	26.0	47.5	55.7	33.6	18.4	18.9
2005	22.9	43.9	55.6	35.8	21.5	20.3
2006	19.9	44.8	60.4	38.6	19.7	16.6
2007	19.0	46.1	61.1	36.0	19.9	17.9
2008	20.8	50.6	60.7	35.0	18.4	14.3
2009	21.9	44.9	61.8	40.3	16.3	14.8
2010	22.6	36.8	63.4	46.6	14.0	16.6
2011	25.3	52.0	56.1	32.5	18.6	15.6
2012	12.0	33.7	70.9	44.2	17.1	22.1
Years average	20.6	44.2	60.4	37.9	19.0	17.9

The spectral characteristics of the waves (direction, frequency and the waves energy variance), can be visually seen in a polar graph presented in Figure 8. These polar graphs were produced using the 2D spectral outputs from SWAN model, for the time frame of 17

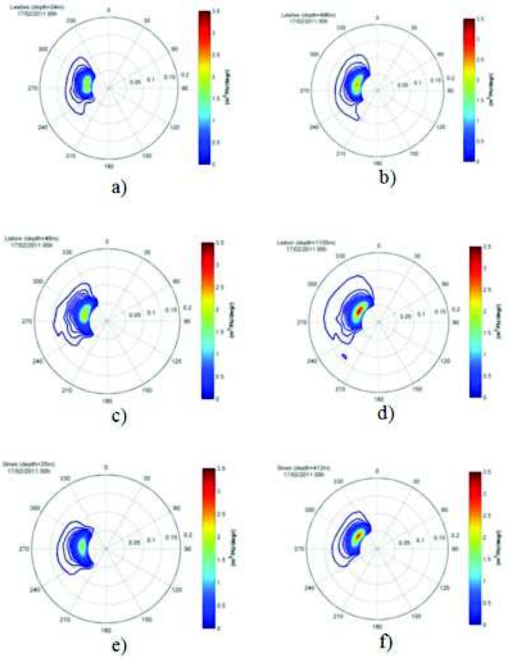

Figure 8. Wave spectra variance in the six points of study (from up to down: Leixões, Lisboa and Sines) in a polar representation. The time frame: 2011.02.17 00:00.

February of 2011 at 00h, which was chosen due to the occurrences of high significant wave height (around 7 m in deeper points and 6 in shallow points).

The prevailing directions of the waves are from W and NW, with a decaying of the energy variance towards the coast. This reduction of energy is explained by the physical processes that waves are exposed when approaching the shallow waters, making the energy dissipated. The Figure 8 a,b presents combined conditions of wind waves and "old" swell in both depths (P1–24 m and P2–496 m), while in the points near Lisbon port (Fig. 8 c,d) present combined conditions of wind waves and "fresh" swell (P3–46 m) and wind waves and "old" swell (P4–1105 m). In the case of Sines, Figure 8e presents swell conditions (P5–35 m) while Figure 8f presents combined conditions of wind waves and an "old" swell (P6–412 m).

3.2 *Variability of directional spectral classes*

The work presented in this study extends the previous formulations of spectral variability and presents an application of such kind of modelling for the statistical analysis of the variability of directional spectra of complex seas in the Portuguese coastal waters on the basis of hindcast data (12 years). In Figure 9 to 11a) presents the star diagrams of directional spectra transitions for the locations of Leixões, Lisbon and Sines for the period of 12 years. For Leixões (water depth – 24 m) Figure 9a) presents the five main types

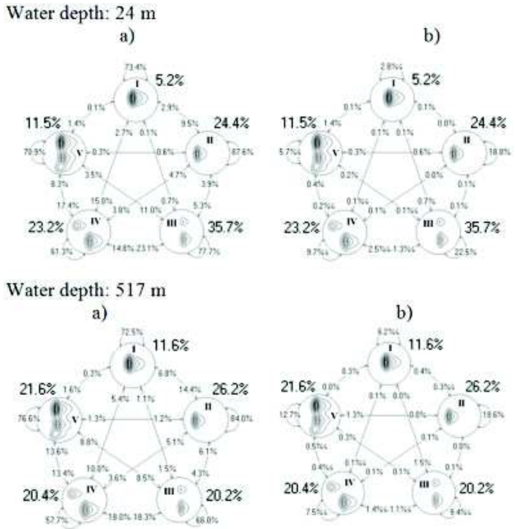

Figure 9. a) Star transition diagram; b) star jump diagram, of directional spectra transitions from Leixões (2000 to 2012).

of spectra: wind waves (I, 5.2%), decaying waves, or swell (II, 24.4%), two swell systems of different ages (III, 35.7%), wind waves and the swell (IV, 23.3%) and complex multipeaked spectra (V, 11.5%). The arrows in the figures denote the transitions between the types during synoptic terms (every 3 hours), e.g., if in the present time type I is observed, the conditional probability for the spectrum of type IV to occur in the next time step is 15.0%, and to return back in the following time step is 2.7%. The probability for the wave spectrum to remain in the type I in the next step is 73.4%. The star diagrams of the jumps are presented in the Figures 9 to 11b), were the significant jumps or the non-zero probabilities are denoted by arrows. In the case of Leixões the absolute probability of occurrence of the spectral jump I-IV-I is 0.1%, and that of IV-I-IV is 0.1%.

For Lisbon location (water depth – 46 m) the five types of spectra present are: the wind waves (I, 9.0%), decaying waves, or swell (II, 26.2%), two swell systems of different ages (III, 13.0%), wind waves and swell (IV, 22.1%) and complex multipeaked spectra (V, 15.4%). 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 6.6%, and to return back in the following time step is 12.3%. The probability for the wave spectrum to remain in type II in the next step is 85.7%. In Figure 10b) the star diagram of the spectral jumps are presented, it is seen that, for Lisbon (46 m), the absolute probability of occurrence of the spectral jump I-IV-I is 0.1%, and that of IV-I-IV is 0.2%.

For Sines (water depth – 35 m) the five types of spectra present are: wind waves (I, 8.0%), swell (II, 13.3%), two swell systems of different ages (III,

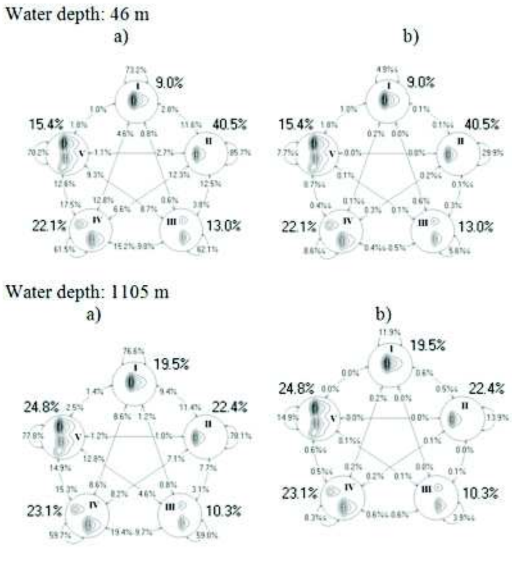

Figure 10. a) Star transition diagram; b) star jump diagram, of directional spectra transitions from Lisbon (2000 to 2012).

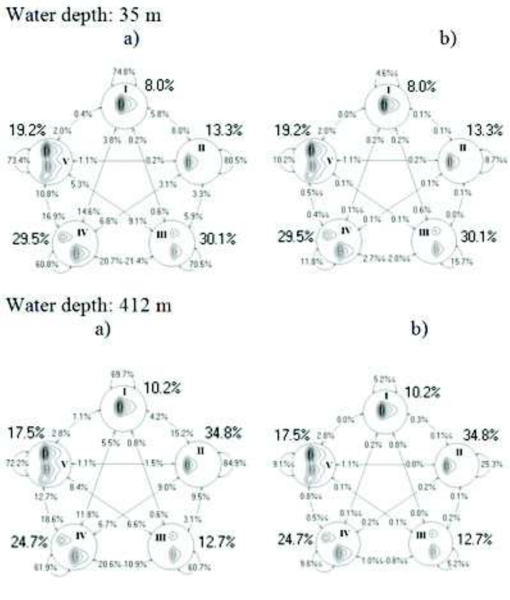

Figure 11. a) Star transition diagram; b) star jump diagram, of directional spectra transitions from Sines (2000 to 2012).

30.1%), wind waves and swell (IV, 29.5%) and complex multipeaked spectra (19.2%). If in the present time type I is observed, the conditional probability for the spectrum of type IV to occur in the next time step is 14.6%, and to return back in the following time step is 3.8%. The probability for the wave spectrum to remain in the type I in the next step is 74.8%.

In Figure 11b) the star diagram of the spectral jump is shown, only the significant jumps, correspondent to non-zero probabilities are denoted by arrows. It is seen that, for Sines, the absolute probability of occurrence of the spectra jump I-III-I is 0.6% and for III-I-III is 0.2%. The same type of analysis was made for the deeper points.

4 CONCLUSIONS

The work presented in this paper had the objective of characterizing the different sea states occurrences in six locations in different water depths, located at the entrance of the major Portuguese ports (Figures 3 to 5). Using a 12 years hindcast database provided by the SWAN model, a statistical and a spectral analysis was performed in those locations, as well as a parametric approach, which allows to obtain the type of wave systems present and its spectral parameters. From the statistical analysis, it can be seen that it is in the deep water points where the H_s is higher. Taking into account the 50th and the 95th percentile for this wave parameter, a variation from 1 m to 2 m and 2.5 m to 5 m, respectively, was found from shallow to deep water points, with the year of 2002 having the highest waves and 2005 the lowest ones. In relation to T_p no differences between the deeper and the shallowest points were found.

The polar representation (Fig. 8) for the wave spectra variance densities shows the main direction of the waves, which are from W and NW, covering approximately the range of sectors from 240° to 330°.

A good knowledge of the wave conditions in coastal areas, it is an important contribution for operation and safety of shipping and for the design of civil engineering structures. So, the classification of the directional spectra in classes of general wave types was executed near the ports. According to this classification, it can be noticed that the percentage of one peaked spectra is greater for the deep water points of Leixões (P2–496 m) and Sines (P6–412 m), while in Lisbon this occur in the shallow water point (P3–46 m). In the case of multipeaked spectra (with more than two peaks), Leixões presents a greater percentage at the deepest point in opposition to the shallowest point, as in Lisbon. In Sines the number of mutipeaked spectra in the deepest point (P6–412 m) is slightly lower than the shallowest point (P5–35 m).

The directional spectra processed for each location for the period of 12 years, were classified in five classes of climatic wave spectra (wind waves – I, swell – II, two swells – III , wind waves and one swell – IV, complex multipeaked spectrum – V). At Leixões (P1), 5.2% are wind waves (I), 24.4% are decaying waves, or swell (II), 35.7 % are two swell systems of different ages (III), 23.3% are wind waves and swell (IV) and 11.5% are complex multipeaked spectra (V). For Lisbon location (P3), 9.0% are wind waves (I), 26.2% are decaying waves, or swell (II), 13.0 % are two swell systems of different ages (III), 22.1% are wind waves and swell (IV) and 15.4% are complex multipeaked spectra (V). At the Sines case (P5), 8.0% are wind waves (I), 13.3% are swell (II), 30.1% are two swell systems of different ages (III), 29.5% are wind waves and swell (IV) and 19.2% are complex multi-peaked spectra (V). In short, for Leixões and Sines shallow water points, the sea states with more probability to occur are the two swell systems at different ages (class III), and for the case of Lisbon the probability is higher for one swell system (class II). For the deeper water points of Leixões and Sines the sea states more likely to occur are the class II and in the case of Lisbon is class V.

The work provides information of the most relevant parameters of the six locations referred, giving a contribute on how the spectral parameters and their probability of occurrence were varying in the shallowest and deeper points of the regions studied. The characterizations of the environmental conditions are extremely important for the seakeeping and manoeuvring of ships in adverse conditions.

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