

Evaluating the gravity wave energy potential off the Brazilian coast

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ABSTRACT

The wave energy potential on the Brazilian coast is estimated using in-situ buoy data and model data. The results present a greater potential on the southern-southeastern coast than on the northeastern coast, but the variance is also larger. These seem to be associated with the different atmospheric regimes. While in the northeastern portion the trade winds determine the wave regime, in the south the passage of cold front systems plays a major role. For almost all regions and throughout the year, the energy potential oscillates between 10 and 30 kW/m, the most efficient range to implement wave energy converters. The occurrence of sea states is also assessed, showing that the passage of cold front systems also creates different sea states in the S-SW area. Finally, the most common sea states and energy flux are estimated, showing a shift towards longer periods and higher waves for the latter. On the S-SW coast, although the most frequent sea states have waves with periods around 8 s, the energy flux has a more balanced distribution between these and the waves with periods around 11s, the common period for waves generated by cold front systems. This result shows that the most common sea state is not necessarily the one that should be considered when planning wave energy converters for the region.

Descriptors: wave energy, PNBOIA, WaveWatch III, Brazilian coast.

RESUMO

O potencial energético de ondas na costa Brasileira é estimado usando dados de boia in-situ e de modelo numérico. Os resultados mostram um maior potencial na costa sul-sudeste do que na costa nordeste, mas também uma maior variância. Estas diferenças parecem se relacionar com os diferentes regimes de vento nas regiões. Enquanto na porção nordeste os ventos alísios determinam o regime de ventos, a passagem de frentes frias na porção sul desempenha um papel significativo. Para quase todas as regiões e durante todo o ano, o potencial energético de ondas varia entre 10 e 30 kW/m, o intervalo mais adequado para a instalação de conversores de energia. Os estados de mar são, também, analisados, mostrando que a passagem de frentes frias na região sul e sudeste também cria diferentes regimes de ondas. Finalmente, os estados de mar e fluxos de energia mais comuns são estimados, mostrando uma mudança para ondas mais longas e com maiores períodos para o último. Na costa sul-sudeste, embora o estado de mar mais comum seja de ondas com períodos de pico de 8 s, o fluxo de energia é bastante balanceado entre estas ondas e ondas com período de pico de 11 s, que são, normalmente, geradas por frentes frias. Este resultado mostra que o estado de mar mais comum não é, necessariamente, o que deveria ser considerado no planejamento de conversores de energia na região.

Descritores: Energia de onda; PNBOIA; WaveWatchIII; Costa Brasileira.

Submitted on: 6/November/2017

Approved on: 19/May/2018

<http://dx.doi.org/10.1590/S1679-87592018011706602>

INTRODUCTION

The potential of the ocean to provide a renewable and clean source of energy is enormous and includes different alternatives in terms of sources and technologies. There are successful initiatives in harvesting energy from temperature gradients (Tanner, 1995), tides (Rourke et al., 2010), both potential (Frau, 1993) and kinetic (Khan et al., 2009; Roberts et al., 2016), currents (Ponta and Jakovkis, 2008), salinity gradients (Ramon et al., 2011) and waves (Falcão, 2010; Muetze and Vining, 2006). Among these possibilities, the extraction of energy from gravity waves is considered one of the most efficient alternatives due to the total energy available in that form and the fact that it is more predictable than some other renewable sources such as aeolian and solar (Scruggs and Jacob, 2009). Although several kinds of wave can be described as gravity waves [tsunamis, tides and Kelvin waves, for instance], we refer to waves, or gravity waves, as those generated by the wind. However, the use of this energy source depends, initially, on an assessment of the potential energy as well as on the wave characteristics of the area (Iglesias and Carballo, 2010; Gunn and Stock-Williams, 2012). This previous knowledge is necessary for the manufacturing of the wave energy converter, which operates at optimum efficiency at some specific frequency and amplitude (Falnes, 2002; Cargo et al., 2011), and due to the fact that the current plants cannot extract energy at places with a potential below 10 kW/m (Hughes and Heap, 2010).

The assessment of the wave energy resource can be divided into 2 parts. The first evaluates the total wave energy available in a region, considering only the wave climatology and its characteristics using data from buoys, numerical models, altimetry or a combination of them. This first study works as a filter to select places with potential for exploitation. Thus, if the energy available justifies a more complex study, the bulk resource is analyzed considering aspects such as the bottom topography, the coastline, market demand, onshore infrastructure and the interactions of a wave energy plant with other ongoing human activities and valuable biological areas (Hughes and Heap, 2010; Henfridsson et al., 2007). Other aspects that have to be taken into account at this moment are the efficiency and technical constraints of the available Wave Energy Converters (WECs) (Hughes and Heap, 2010). In other words, the first study is used to select target places for a more detailed evaluation.

Several places worldwide have studies estimating their wave energy potential, including Portugal (Rusu and Soares, 2009;2012), Spain (Iglesias and Cabarballo, 2010; Iglesias et al., 2009), the United States (Defne et al., 2009), Canada (Dunnet and Wallace, 2009), South Korea (Kim et al., 2011), Australia (Hughes and Heap, 2010) and Argentina (Lanfredi et al., 1992). There are also studies evaluating the global wave energy resource (Barstow et al., 2009; Cornett, 2008). In fact, despite more powerful waves being concentrated in the western coast of high latitude continents, influenced by west-to-east winds (Rusu and Soares, 2009), not only the potential of a region is important, but the temporal variability has an impact on the efficiency and the viability of a wave energy project. In general, areas with moderate and steady energy fluxes are more advantageous than more energetic ones with larger variance. Within a global frame of reference, the regions between 25°S and 25°N have smaller variability and reasonable average energy flow (Cornett, 2008), presenting greater potential for exploitation. Between this range, the optimal location for power generation are often at depths between 40 and 100 m, once as the waves propagate into the shore, they are modified by bottom effects like refraction, diffraction, bottom friction and wave breaking, resulting in the dissipation of its energy in shallow areas, usually shallower than 40m (Falcão, 2010). Regarding waters deeper than 100 m, considered deep for this study, the limitation is related to impractical and uneconomical conditions to deploy a wave power plant and connect it to a shore-line station, due the long distance from the shore (Scruggs and Jacob, 2009).

In Brazil, the wave climatology is described in few studies. At Cabo Frio, for instance, the waves come mainly from the SSE-SSW with periods between 11 and 13s (Pereira et al., 2010). On the Southern Shelf of Brazil, waves have amplitudes between 1 and 1.5m, periods between 6 and 14s and come mainly from the southeast (Cuchiara et al., 2009). The analysis of 11 years of model data from the operational system WAVEWATCH III showed that, along the Brazilian coast, the energy of the waves decreases from north to south (Pianca et al., 2010). This result reflects the wind regime on the south-southeastern coast, which is consistently impacted by the passage of cold front systems, with strong winds from the S-SW (Rodrigues et al., 2004; Dominguez, 2006), while on the northeastern coast the trade winds are the main source that generate gravity waves. At the coast of the Santa Catarina state, for instance, most of the wave

energy is from southeastern waves (Contestabile et al., 2015). Basically, the Brazilian coast is under the influence of the South Atlantic Subtropical High, a center of high atmospheric pressure located over the South Atlantic, and the constant passage of cold front systems that are formed further south and are driven by a low atmospheric pressure center that moves northward, usually with winds parallel to the direction of the coastline from southwest. For instance, Dottori and Castro (2009;2018) have shown how these 2 atmospheric systems affect the hydrodynamics over the South Atlantic Bight, and Pianca et al. (2010), how they affect the wave regime.

However, there are no studies about the potential wave energy for the Brazilian coast as a whole, although an experimental plant was developed and is in operation on the northeastern coast, in Ceara (Garcia-Rosa et al., 2014). In fact, although a country with a very long coast, the electric energy production in Brazil in 2015, for instance, came mainly from hydroelectric (61.4%) and thermoelectric power plants (28.6%), according to the National Agency of Electric Energy, in a market that grew from 90.679 MW in 2004 to 138,800 MW in 2015. Also, electric energy production from ocean sources are not even mentioned in this information report. This shows how ocean wave energy is neglected in Brazil, with few studies describing the wave climatology which are, basically, motivated by the influence of the waves on coastal morphodynamics.

This study seeks, therefore, to provide knowledge of this potential, in view of the fact that: (1) a large part of the Brazilian coast is located between 25°S and 25°N, where the variability of the waves is small and, therefore, favorable for the implementation of wave energy converters; (2) a good proportion of the Brazilian population lives close to or on the coast, and (3) there is, already, some onshore infrastructure, due to oil exploitation, which facilitates the implementation of other projects offshore. For this purpose, we used model and *in-situ* data at 6 different locations, covering the Brazilian coast from about 10°S to around 30°S. The NOAA-WAVEWATCH III reanalysis model provided the model data and the project National Buoy Program, the *in-situ* data from buoys. In Section 2 we describe the data sets followed by the methodology in Section 3. Section 4 presents the results and discussion. Finally, Section 5 presents some concluding remarks. This study, however, does not have the intention to analyze technical details

of the energy production itself, such as energy converters efficiency or engineering implementation.

MATERIAL AND METHODS

DATA SET

The National Buoys Program (PNBOIA) is the Brazilian branch of the Global Ocean Observing System (GOOS) and consists of a network, along the Brazilian coast, of both drifting and moored buoys, although this study only used the moored ones. This program is supported by several Brazilian institutions, including the Brazilian Navy, some national universities and PETROBRAS, the Brazilian oil company. Significant wave height and peak periods of the PNBOIA were downloaded (<http://www.goosbrasil.org>) from 6 locations. These buoys lie off the coasts of the states of Pernambuco (PE), Bahia (BA), in the Brazilian northeast coast, Rio de Janeiro (RJ), Sao Paulo (SP), in the southeast coast, and Santa Catarina (SC) and Rio Grande do Sul (RS), in the south coast, as shown in Figure 1, from north to south. The geographical coordinates, local depth and sample periods of the buoys are presented in Table 1. With exception of Rio de Janeiro, these buoys are moored close to the shelf break and the data from them are transmitted by the Argos satellite system. Other data sets are also provided, such as atmospheric parameters and water characteristics, but only the wave variables will be analyzed. The sample period is not the same for all the buoys, but all the data were obtained between the years 2009 and 2015. The second data set was obtained from the numerical model WAVEWATCHIII (WW3), version 2.22 (Tolman, 2002), for the period between February 2005 and June 2015, thus completing more than 10 years of data. This model was developed by the National Centers for Environmental Predictions (NCEP), that works under the coordination of the National Oceanic and Atmospheric Administration (NOAA). The WW3 data include those on wind-wave interactions, non-linear wave-wave interactions and dissipation. In shallow waters, it is also considered a bottom dissipation term. The data used from this model are significant wave height and peak period, similar to the buoy data, and are generated for a global grid with a resolution of 30°X30°. These data are available at <http://polar.ncep.noaa.gov/waves/>. The locations of the grid points used in this study are very close to the locations of the PNBOIA buoys and are shown in Figure 1. Table 2

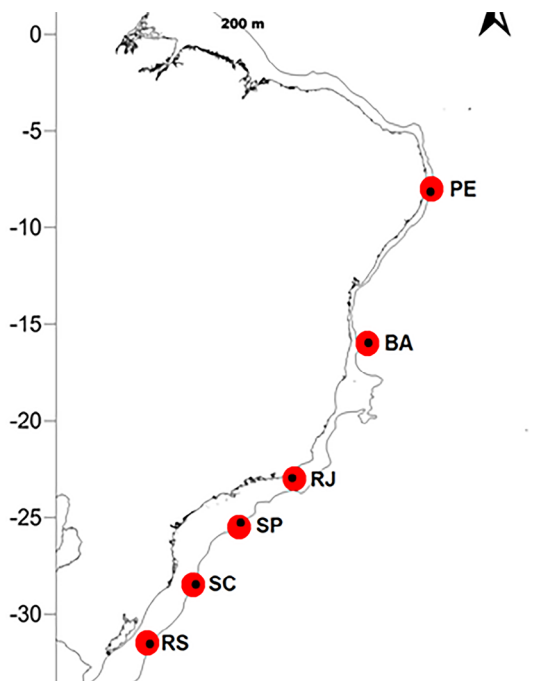


Figure 1. Brazilian coastline and the 200 m isobath. The centers of the red circles indicate the location of the buoys of the PNBOIA program and the black dots, the WaveWatchIII model grid points.

presents the local depths and geographical coordinates of this data set.

It is important to note that the sampling period for the buoy data is considerably shorter than that of the model data. However, the model sampling period includes the whole sampling period of the PNBOIA data set.

METHODS

The evaluation of the energy potential at those 6 locations along the Brazilian coast will be made by estimating the energy density and the energy flux. Basically, the methodology applied for the Australian coast in a previous study (Hughes and Heap, 2010) will be adopted, with few adaptations. Initially, the total energy can be estimated by the classical equation:

$$E = \frac{1}{8} \rho g H^2 \tag{1}$$

where E is the energy density, i.e., the energy per square meter of wave, g the gravity, ρ the water density and H , the wave height. However, the variable available on both data sets is the significant wave height (H_s), which is related to the wave height by:

$$H_s = \frac{H}{\sqrt{2}} \tag{2}$$

Equation (1) can, then, be rewritten as:

$$E = \frac{1}{16} g \rho H_s^2 \tag{3}$$

The energy flux P , i.e., the energy advected by the wave group, can be estimated by:

$$P = E c_g \tag{4}$$

where is the group velocity estimated by:

$$c_g = c \left(\frac{1}{2} + \frac{kh}{\sinh(2kh)} \right) \tag{5}$$

In Equation 5, c is the phase velocity of the wave and is defined by $\frac{g}{\omega \tanh(kh)}$, with $\omega = \frac{2\pi}{T_e}$, T_e being the energetic period. Also, h is the local depth and k is the wavenumber given by $k = \frac{2\pi}{\lambda}$, being λ the wave length.

However, the wave length is not an available datum, like the wave height. Therefore, a bulk formula is used to estimate the product kh and it is given by (Hughes and Heap, 2010):

$$kh = \epsilon^2 + \epsilon \left(1 + 0.666\epsilon + 0.355\epsilon^2 + 0.161\epsilon^3 + 0.0632\epsilon^4 + 0.0218\epsilon^5 + 0.00654\epsilon^6 \right) - 1 \tag{6}$$

where $\epsilon = \omega^2 \frac{h}{g}$

Table 1. Location, water depth, latitude, longitude and sample period of PNBOIA buoys. Figure 1 gives the locations of the buoys.

State Location	Local depth (m)	Lat. (S)	Long. (W)	Period
PE	200	08°09'	34°34'	Aug 6 2012 - Jun 30 2015
BA	200	15°59'	37°57'	Jul 6 2012 - Jun 30 2015
RJ	80	23°03'	41°51'	Jun 24 2012 - Sep 19 2013
SP	200	25°17'	44°56'	Apr 12 2011 - Jun 30 2015
SC	200	28°30'	47°22'	Apr 23 2009 - Jun 30 2015
RS	200	31°34'	49°53'	Apr 29 2009 - Jun 30 2015

Table 2. Location, water depth, latitude and longitude of WaveWatch III model. Figure 1 gives the locations of the grid points.

Location	Aprox. Depth (m)	Lat.(S)	Long. (W)
PE	250	08°00'	34°30'
BA	40	16°00'	38°00'
RJ	80	23°00'	41°30'
SP	140	25°00'	45°00'
SC	160	28°30'	47°30'
RS	150	31°30'	50°00'

Finally, the energetic period needs to be written in terms of the peak period. A conservative relation (Barstow et al., 2009; Tolman, 2002) between these 2 variables is given by:

$$T_e = 0.9T_p \quad (7)$$

The energy density E , given thus by Equation 1, and the energy flux P , by Equation 4, can be estimated using the energetic period (T_e) and the significant height (H_s), the data available on both datasets, the PNBOIA and the WAVEWATCH III, using the approximations given by Equations 2, 3, 5, 6 and 7.

However, before proceeding with any calculation, a quality control process was performed for the peak period and the significant height. Initially, all the negative values of significant wave height were eliminated, as this variable can only be represented by positive values. Also, significant wave height with values above 13 m were disregarded, considering that, on the Brazilian southeastern coast, the highest value observed was just under this outlier limit (Alves et al., 2009). Gravity waves generated by the wind have typical periods between 0.5 and 25 s (Leblond, 2002). Thus periods with values outside this range were disregarded, to focus on this specific type of wave, the most significant means of energy transport in the ocean (Kinsman, 2002). Finally, any value above the average plus 3 standard deviations or below the average minus 3 standard deviations was also removed, for both significant height and peak periods, following the data analysis proposed by Emery and Thonsom (1998). It is important to mention that, for each value of peak period removed, the corresponding significant height was also removed, and vice-versa.

Table 3. Total of data points and fraction of eliminated data of the buoy (PNBOIA) time series (Table 1).

Buoy	PE	BA	RJ	SP	SC	RS
Total Points	15793	3518	16837	34734	28006	22015
Fraction of excluded data (%)	56.3	84.7	46.9	12.6	19.5	12.3

This quality control process eliminated a considerable portion of the buoy data, mainly at the Bahia (84.7%) and Pernambuco (56.3%) locations. Table 3 presents the total amount of data and the fraction eliminated by the process. Even so, all the calculations were made for all the buoy time series, including the 2 locations mentioned above.

The same process applied to the model data, on the other hand, eliminated only 13 pairs of peak period and significant height, out of 183,246 total data points. It is important to mention that the WAVEWATCH III model has already been validated using a series of buoys in the North Atlantic and North Pacific, showing that estimates using this model and *in-situ* data produce similar estimates of wave energy fluxes (Cornett, 2008). On the Brazilian coast, the seasonal characteristics of the waves obtained from a wave-rider in a location on the Southern coast were also well reproduced by this numerical model (Pianca et al., 2010).

The correlation coefficient and the root mean-square deviation (RMSD) were also computed between WW3 and PNBOIA time series. RMSD, specifically, was normalized using the standard deviation of the PNBOIA data as a reference. Taylor (2001) provides a good explanation about the meaning of these coefficients.

RESULTS

Initially, the comparison between WW3 and PNBOIA time series shows a good agreement for the significant wave height, with the correlation coefficient varying between 0.66 and 0.87, all above the 99% confidence level. The only exception would be the Bahia buoy, which has a very limited number of *in-situ* data points. The analysis for this location, however, was maintained so future studies can have some reference for comparison. In any case, it is important to keep in mind that the analysis for this point, basically for PNBOIA time series, is very limited, but not the conclusions obtained using WW3 time series. For this variable, the normalized RMSD varied between 0.49 and 1.22. The peak period, however, did not show an agreement of the same level, with values varying from 0.46 to 0.71, all above the 99% confidence level, and a normalized RMSD between 0.74 and 1.34. Again, the limited number of data points did not allowed a

proper analysis off Bahia. For this variable, the results off Pernambuco are below the 99% confidence level. These results, presented in Table 4, show that WW3 model represents relatively well the observations, as other studies have shown (e.g., Pianca et al., 2010). As a result, as it will be seen later, the energy flux estimates from WW3 and PNBOIA data present similar behavior and conclusions.

Starting with a simple analysis of the averages for significant height and energy flux, we observe that both data sets present similar results within their variances. While the PNBOIA data set gives average values for energy flux between 10 and 20.9 kW/m (Table 5), the WW3 presents values between 13.2 and 21.2 kW/m (Table 6). For significant height, the values are between 1.27 and 2.10 m, for PNBOIA data, and between 1.71 m and 2.13 m, for WW3 data. WW3 presents consistently higher values than the buoy data for significant height and energy flux, except off Bahia, probably due to the reduced length of

the series, thus weakening more robust statistics. Also, in the southernmost part of the domain, the *in-situ* and model data present small differences for both variables. While in the northern part the differences attain values of up to 30%, in the southern portion the maximum relative difference is about 7%. In the northern portion, mainly in Pernambuco and Bahia, the trade winds are responsible for most of the energy that generates waves while, in the southern part, the passage of cold front systems plays a major role in the wave-generating mechanism, suggesting that the model reproduces the ocean's response to the atmosphere better in the latter. Off Rio de Janeiro, both systems seem to play some role, but the local depth (80 m), shallower than that of all the other locations (200 m), might be another cause of some discrepancies between model and buoy data due to a more intense bottom friction.

The southern part of the domain has waves that are higher and more energetic than the ones in the northern

Table 4. Correlation coefficient and root mean-square deviation (RMSD) for significant wave height and peak period at all buoys (Figure 1) between WaveWatch III model and PNBOIA data. The RMSD is normalized by the standard deviation of the PNBOIA data. Note that Bahia data is not shown due to the limited number of data. Also, the correlation coefficient for the peak period at Pernambuco is below the 99% confidence level and, therefore, is not shown.

	Correlation coefficient (significant wave height)	Normalized RMSD (significant wave height)	Correlation coefficient (peak period)	Normalized RMSD (peak period)
PE	0.68	0.99	-	1.34
RJ	0.66	1.22	0.53	1.01
SP	0.87	0.51	0.70	0.74
SC	0.77	0.69	0.71	0.74
RS	0.77	0.49	0.55	1.31

Table 5. Average and maximum of significant height and energy flux for the buoy data (PNBOIA).

	mean H_s (m)	Max. H_s (m)	Mean P (kW/m)	Max. P (kW/m)
PE	1.54±0.38	4.34	10.0	146.0
BA	1.84±0.84	7.49	17.1	108.0
RJ	1.27±0.65	3.49	10.5	124.6
SP	1.92±0.68	4.25	18.5	178.5
SC	1.95±0.67	4.40	18.9	235.0
RS	2.10±0.76	5.15	20.9	187.6

Table 6. Average and maximum of significant height and energy flux for the model data (WAVEWATCHIII).

	Mean H_s (m)	Max. H_s (m)	Mean P Year (kW/m)	Max. P Year (kW/m)
PE	1.93 ±0.44	4.14	16.8	104.2
BA	1.71 ±0.48	4.17	13.2	87.8
RJ	1.87 ±0.57	5.33	17.2	173.9
SP	2.03 ±0.72	5.89	20.2	207.7
SC	2.10 ±0.78	6.36	21.2	210.8
RS	2.13 ±0.79	6.16	21.0	201.6

part. The highest values for energy flux are observed in Rio Grande do Sul, Santa Catarina and São Paulo, all of them very close to each other on both data sets. At the other end, the smallest value is observed off Bahia, for the PNBOIA data, and off Pernambuco, for WW3 data. These differences are clearly associated with the wind regimes mentioned above and the region off Rio de Janeiro seems to be the transition area between these 2 portions, as it is possible to observe in Pianca's (2010) study. The monthly energy flux averages show a clearly more energetic period during the austral fall and winter seasons (Figures 2 and 3), between the months of April and September. During the

austral summer, the northern portion presents results that are very close to, or even below, the 10 kW/m limit. In the southern portion, the averages are always between 10 and 30 kW/m, the optimum range for operating a wave converter, on both data sets. Although the fall and winter seasons have higher energy fluxes, during these periods the variance is higher too, which might hinder the implementation of an energy converter. This large variance is associated with the passage of cold front systems, which will be clarified below. By way of comparison, the southern Australian margin holds average energy flux of 29-45 kW/m in deep water (Hughes and Heap, 2010), the

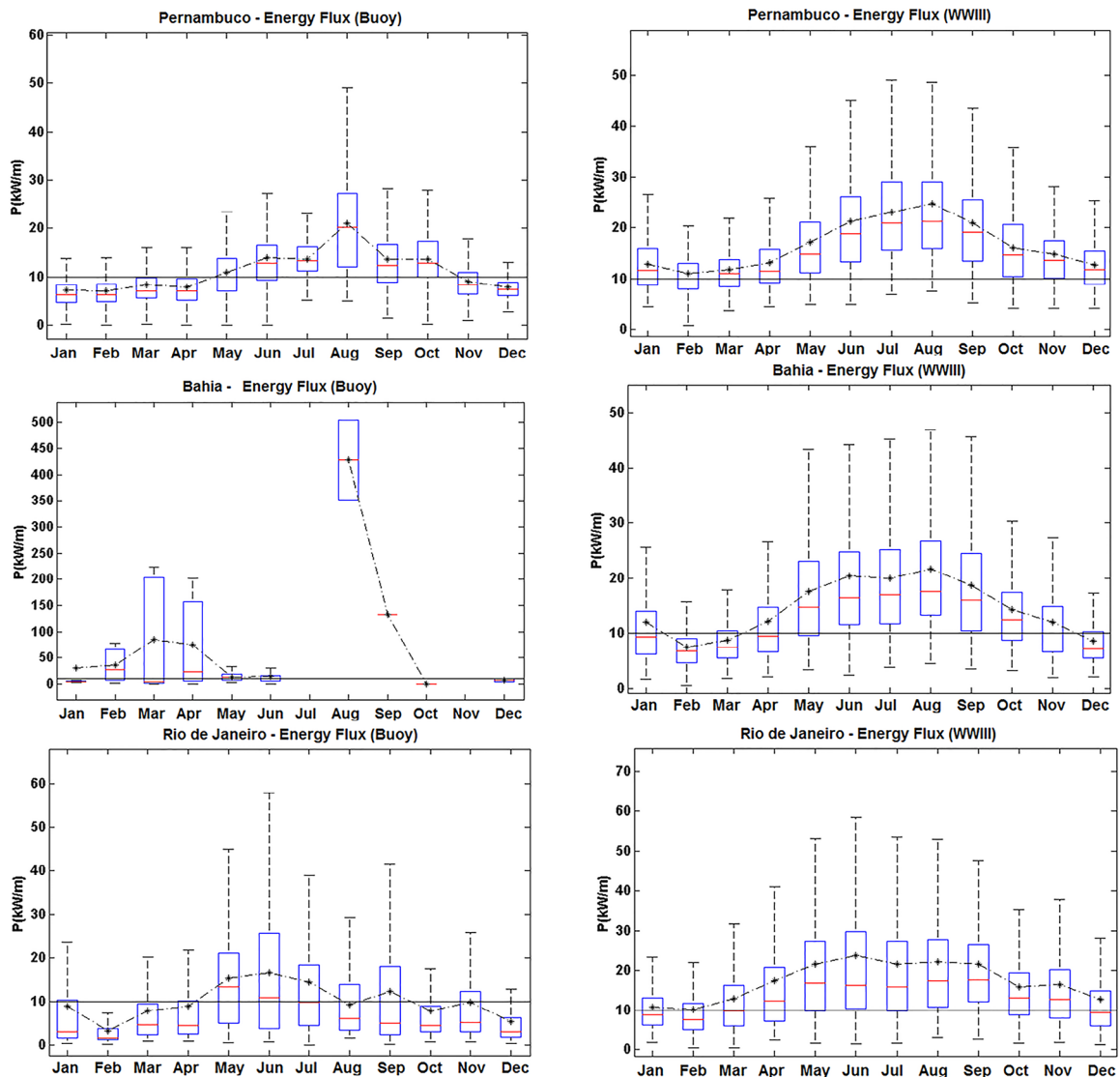


Figure 2. Boxplots of the monthly energy flux averages in the northern portion of the domain.

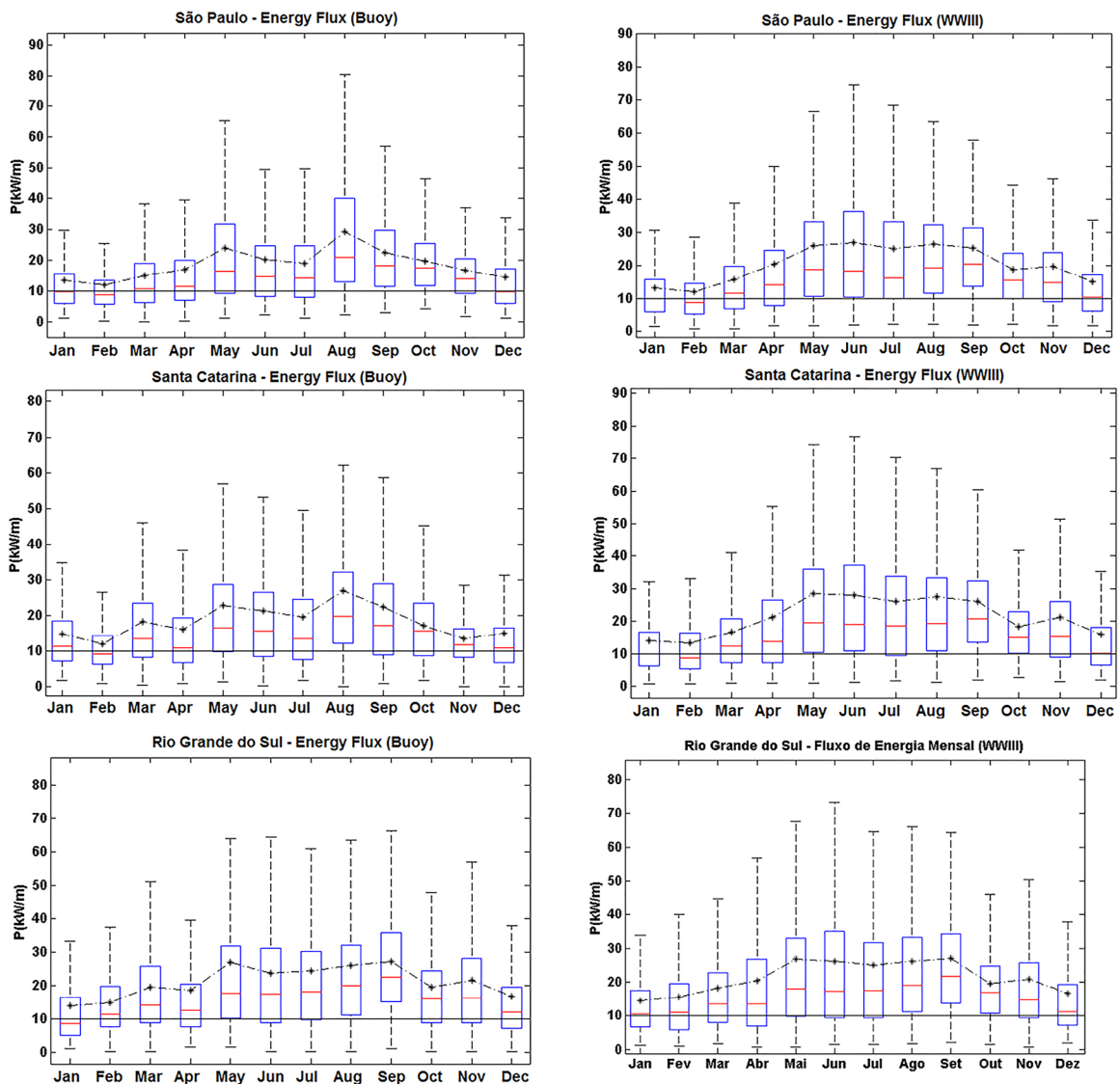


Figure 3. Boxplots of the monthly energy flux averages in the southern portion of the domain.

Iberian Peninsula holds 30-40 kW/m in Portugal (Rusu and Soares, 2009) and 15-50kW/m in Spain (Iglesias et al., 2009). While these higher latitude locations have a more powerful potential resource than the Brazilian coast, the latter has the mean energy flux within the optimum range already mentioned.

Besides the general statistics for the energy flux, it is also important to estimate what the sea states are, which would propel energy converters, since these devices operate at an optimum frequency and amplitude. The characterization of the sea states was obtained by estimating the fraction at which a specific pair of significant height and peak period occurs and the fraction of energy flux for the same data. In

both data sets, significant wave height has a resolution of 0.5 m and peak period, 1s.

Starting with the buoy data, Figures 4 and 5 present the occurrence of sea states and energy flux. In Pernambuco, the most common sea state is around a peak period between 7 and 8s and significant height between 1 and 1.5m (Figure 4). The energy flux fraction, however, does not follow exactly the same pattern, with an energy flux concentrated at 8s, for peak period, and 1.5 m, for significant height. Off Bahia, the most common sea state is similar to the one observed off Pernambuco, but the energy flux shifts to significant heights around 2 m. From Rio de Janeiro to Rio Grande do Sul, the average

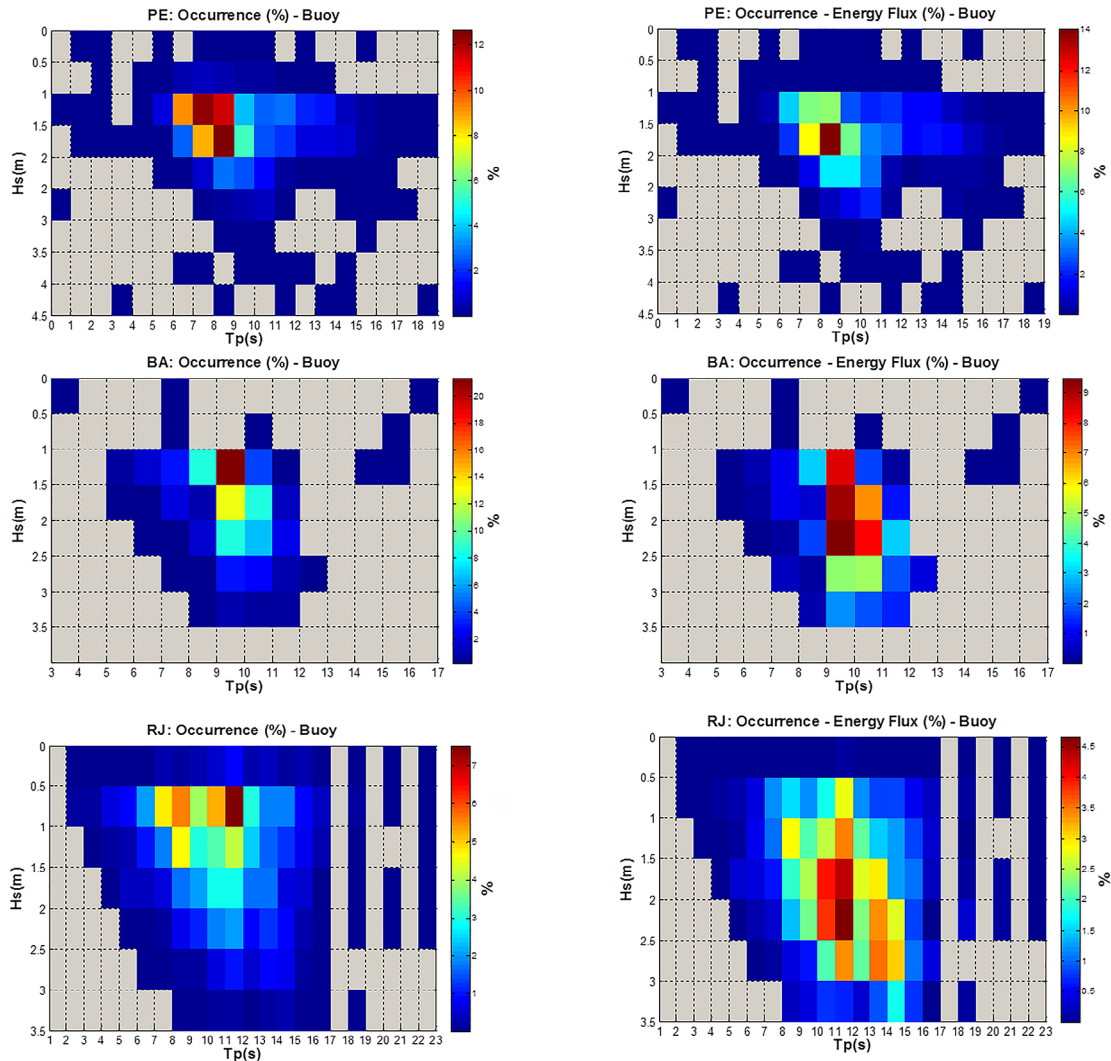


Figure 4. Left panels show the occurrence of sea states and right panels, the occurrence of energy fluxes for buoy (PNBOIA) data. From top to bottom, the locations of Pernambuco (PE), Bahia (BA) and Rio de Janeiro (RJ).

sea states present different behavior, with a maximum occurrence at 8s but another local maximum at 11s of peak period. Off Rio de Janeiro, the most common sea state has a significant height of 0.5m, while between São Paulo and Rio Grande do Sul significant height jumps to 1.5m, presenting a clearly higher energy potential, as mentioned above. The energy flux also presents these 2 local maxima with a more balanced distribution than the occurrence of sea states. In São Paulo, for instance, there is more energy flowing with a peak period of 11s than at 8s, although the latter is the period most frequently observed. Off Sao Paulo and Santa Catarina, the maximum energy flux for the waves with a peak period of 8s occurs at 1.5m of significant wave height and, for the waves with a peak

period of 11s, 2m of significant height. Off Rio Grande do Sul, for both periods, the maximum energy flux occurs for waves with significant height of 2 m. Again, these results show that the northern and southern portions are subject to different wave regimes, with the passage of cold fronts playing a major role south of Rio de Janeiro. Although off Rio de Janeiro waves with periods of 8 and 11 s can be observed, significant height for both is considerably lower than in the other places further south. This difference in significant height can be attributed to a shallower local depth (80 m), that can increase the energy dissipation at the bottom, and also to the fact that Rio de Janeiro is farther from the region where the waves are generated, resulting, again, in greater energy dissipation.

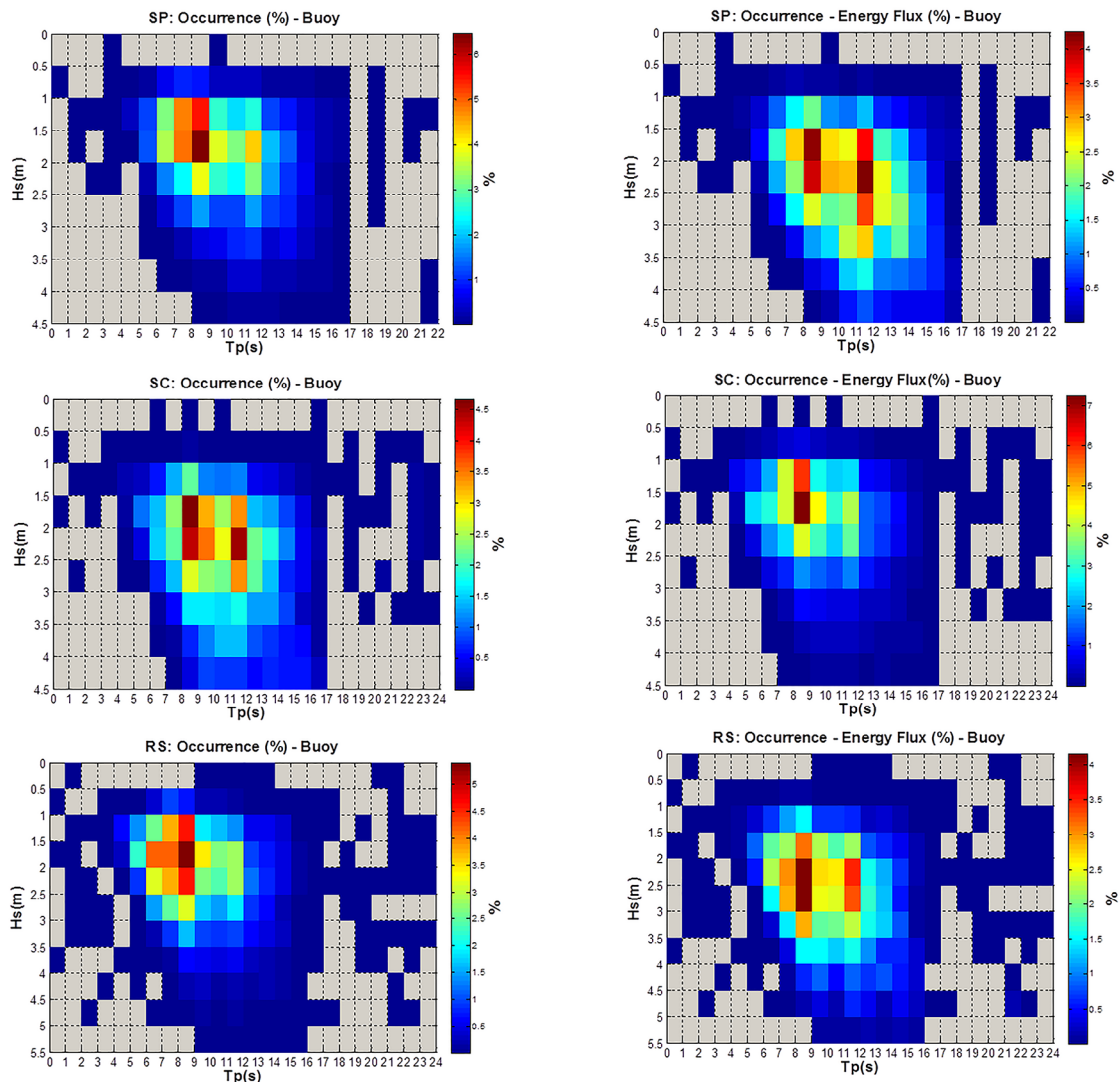


Figure 5. Left panels show the occurrence of sea states and right panels, the occurrence of energy fluxes for buoy(PNBOIA) data. From top to bottom, the locations of Sao Paulo (SP), Santa Catarina (SC) and Rio Grande do Sul(RS).

The WW3 data present similar results (Figures 6 and 7). Off Pernambuco, the model shows that the most common sea state occurs at 7s of peak period and 1.5m of significant height. Off Bahia, the peak period has a broader range - between 7 and 8s - maintaining the same significant height of 1.5 m. From Rio de Janeiro to Rio Grande do Sul, the most common sea state has a peak period of 8s, and significant height of 1.5m. When the energy flux is analyzed, all places show a shift to greater significant height and longer peak periods. In the northern portion, off Pernambuco, the highest energy flux is observed at 8s and 2m, while off Bahia, at 8s and between 1.5 and 2m. From Rio de Janeiro to Rio Grande do Sul, the highest energy

fluxes are observed at peak periods between 8 and 11 s, and significant height between 1.5 and 3m. It is important to note that, for the WW3 model, the 2 local maxima are not clear for sea state occurrences in the southern portion, as observed for the buoy data. Instead, there is a continuous change from waves with peak periods around 8s to waves with peak periods around 11s. When the energy flux is computed, the local maximum at 11s of peak period appears again, with a clear shift towards greater significant height. In any case, both buoy and model data present a scenario where the waves generated by the frontal systems (peak periods of 11s) in the southern portion play a major role in terms of the energy flux being, in some cases, more

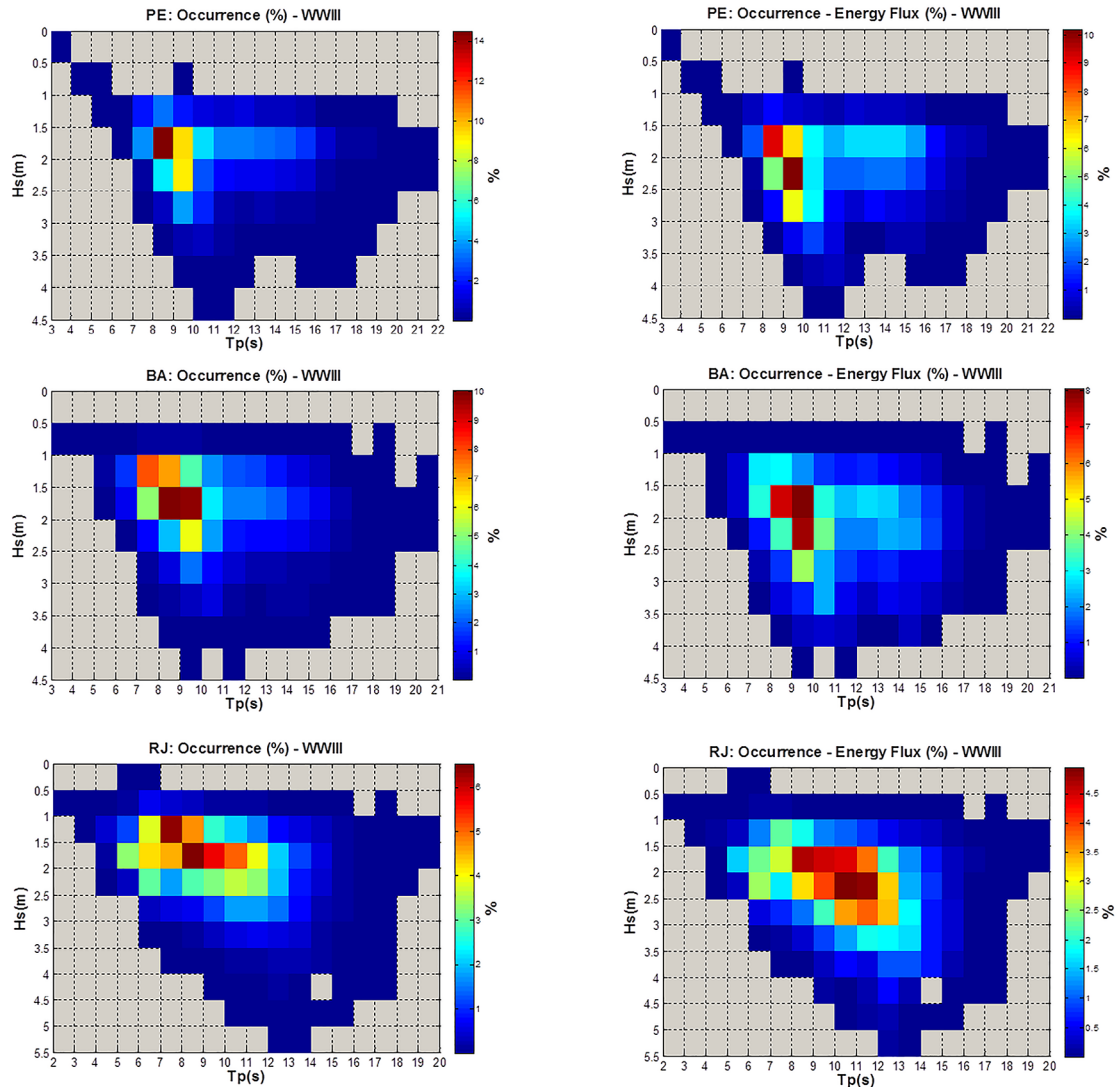


Figure 6. Left panels show the occurrence of sea states and right panels, the occurrence of energy fluxes for model (WaveWatchIII) data. From top to bottom, the locations of Pernambuco (PE), Bahia (BA) and Rio de Janeiro (RJ)

important than the most common but less energetic waves (peak periods of 8s).

Considering that the frontal systems are more frequent during the fall and winter seasons, this fact should be taken into consideration for the southern portion of the domain. During these seasons, there is a greater energy flux, but the variance also increases, which can lead to concerns when projecting a converter for the region.

DISCUSSION

As one could expect from previous studies, the southern-southeastern coast of Brazil has a larger energy potential than the northeastern coast, with regard to gravity

waves. From São Paulo to Rio Grande do Sul, the energy potential is very similar, both in terms of the energy fluxes and the associated sea states. The influence of the cold front systems in the S-SE region brings waves with longer periods and larger ranges than the ones observed on the NE coast, influenced by the winds driven by the South Atlantic Subtropical High. Also, the variance in the S-SE region is larger than that observed in the NE region. So, considering both parameters, although the NE region has a smaller energy potential, this might be compensated for by a more stable and constant sea state, which is also important for the energy converters. Moreover, the NE region has a narrower continental shelf than S-SE, thus the energy loss in consequence of the bottom interaction will be lower.

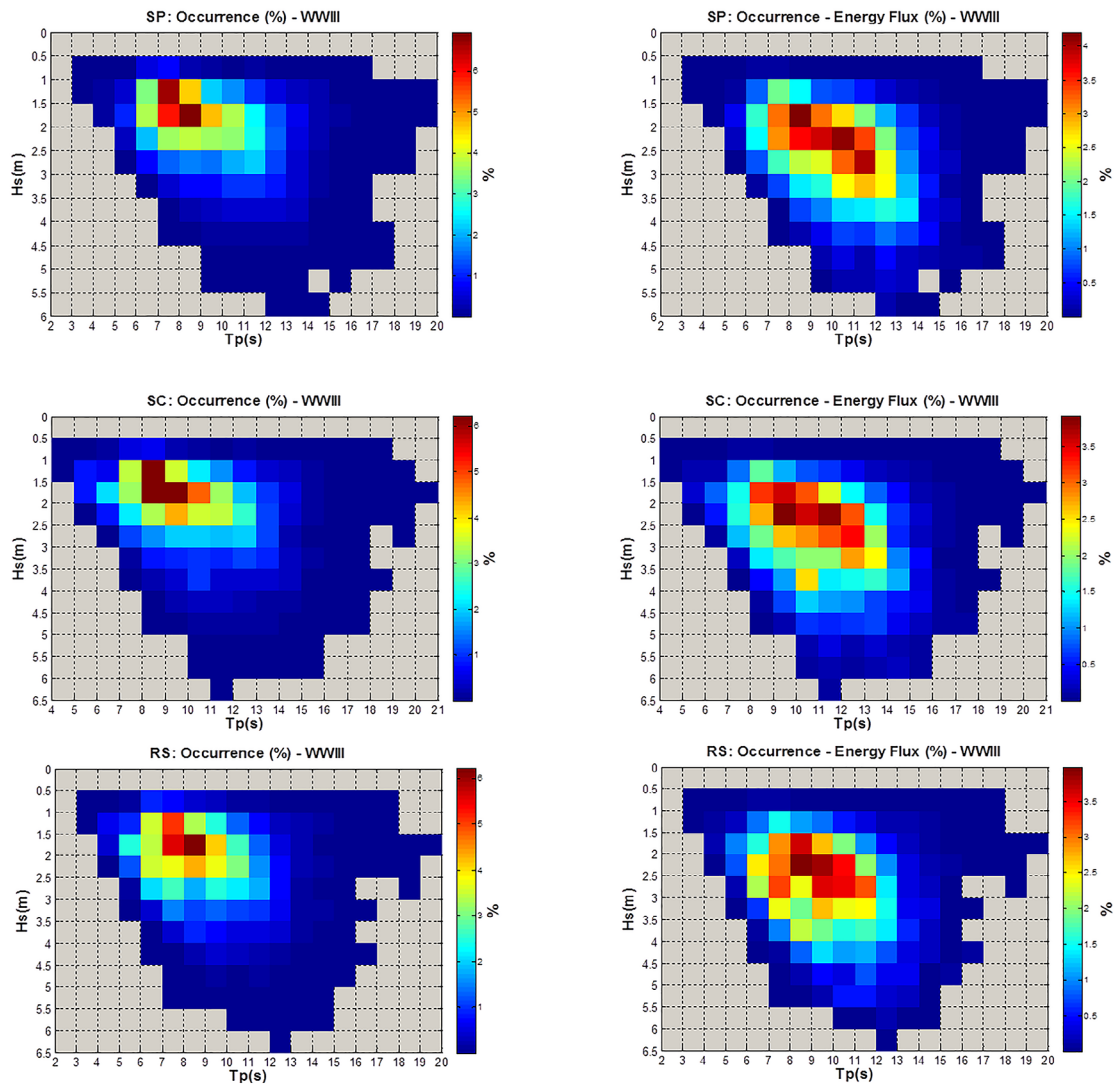


Figure 7. Left panels show the occurrence of sea states and right panels, the occurrence of energy fluxes for model (WaveWatchIII) data. From top to bottom, the locations of Sao Paulo (SP), Santa Catarina (SC) and Rio Grande do Sul (RS).

Also, the narrower shelf allows the energy converter to be located closer to the consumption area, decreasing the costs of the converter implementation. The region off Rio de Janeiro seems to work as a transitional area between these 2 portions. However, this is not conclusive since the buoy data and the model data off Rio de Janeiro is located in a shallower area than that of the other more southerly locations, which can increase the energy dissipation due to friction with the bottom.

The buoy data present 2 distinct sea states for the S-SE region, one similar to those observed in the NE region, and associated with the winds driven by the South Atlantic Subtropical High, and another with waves with greater

significant height and longer periods, caused by the passage of cold front systems. Although the former is commoner than the latter, when the energy flux is analyzed they present similar distributions. These 2 different sea states also present different occurrences during the year. While the spring/summer seasons are dominated by a wind regime that generates waves with peak periods around 8s and significant wave height around 1.5m, the fall/winter seasons are subject to a greater number of frontal systems reaching the S-SE coast, generating waves with peak periods around 11s and significant wave height around 2-2.5m. It is clear, then, that any energy converter project should consider not only the most common sea state but, especially, those sea

states that result in the maximum energy fluxes and how they occur throughout the year. In fact, for both data sets in all regions, the highest energy fluxes are observed during longer peak periods and with greater significant wave heights than the most common sea states observed and they are unequally distributed over the seasons.

CONCLUDING REMARKS

The most important conclusion of this preliminary study is that the Brazilian coast presents a reasonable wave energy potential to implement wave energy converters. Almost all the points analyzed in this study show results that open up the possibility of harnessing energy from ocean gravity waves between 10° and 30° S. For instance, the estimated averaged energy fluxes are close to those obtained for the Asturias by Iglesias and Carballo (2010). At almost all the studied locations, during all the months of the year, the energy flux was consistently estimated within the 10 to 30 kW/m range, the most appropriate one for the installation of such devices, showing that the Atlantic coast of Brazil is a source of moderate wave power. Therefore, future studies would need to identify hot spots for developing a more detailed evaluation that considers other aspects related to the feasibility of wave energy converters. For this purpose, interactions between the energy devices with human activities in the target area, including physical and ecological aspects, and between the living organisms and energy converters need to be included and evaluated. Also, economic aspects, such as market demand and governmental support, should be considered. Also, the wave energy potential should be considered in providing energy for the oil platforms and related activities, once there is, already, a local infrastructure for maintenance and the need of a lean energy transmission structure.

Finally, WW3 and PNBOIA have, in general, a good agreement for significant wave height and peak period, mainly at the south and southeastern coasts. At the northeastern coast, more *in-situ* measurements are necessary for a better comprehension of the wave models. However, both data sets, the PNBOIA and WW3, present similar results in terms of energy fluxes.

ACKNOWLEDGMENTS

We thank the PNBOIA program for providing the buoy data. Camila Pegorelli and João Flesch Fortes were funded by the NAP-OceanoS project.

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