REVISTA Mundi
Engenharia, Tecnologia e Gestão
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WIND DRIVEN WAVES' ENERGETIC POTENTIAL ASSESSMENT ON BRAZILIAN SOUTH-SOUTHEASTERN COAST

ANÁLISE DO POTENCIAL ENERGÉTICO DAS ONDAS GERADAS POR VENTO NA COSTA SUL-SUDESTE BRASILEIRA

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Abstract: The electrical energy demand is constantly growing, making the study of new energy sources necessary. The worries about climate change make it almost mandatory that these sources are renewable. The ocean is a vast source of energy that is not yet fully exploited. With this in mind, for this paper, wind generated waves were simulated along the Brazilian South-Southeastern shelf to evaluate the existence of places with appropriate potential for conversion into electrical energy. The simulations were run using the spectral wave model TOMAWAC, for the time between January and December 2006. The preliminary results have shown two places on the continental shelf near the coastal zone, with potential for wave energy exploitation. The first location, around the island Ilhabela, has a higher energetic potential than the second location, around Florianópolis; yet, on the other hand, the first location's energetic potential has a higher variability. The location around Florianópolis has a lower average potential (10 kW/m to 20 kW/m) than the location around Ilhabela (18 kW/m to 25 kW/m); however, its potential is more stable, since its temporal variability is half the one seen on Ilhabela.

***Keywords*:** Wave energy. TOMAWAC. Spectral modelling. Wave climate.

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Abstract: A demanda por energia elétrica está constantemente crescendo, tornando necessário o estudo de novas fontes de energia. As preocupações com as mudanças climáticas tornam quase mandatório que estas fontes sejam renováveis. O oceano é uma fonte de energia renovável ainda pouco explorada. Nesse sentido, no presente trabalho foram realizadas simulações de ondas geradas pelo vento ao longo da costa Sul-Sudeste do Brasil de forma a avaliar a existência de regiões próximas à costa e com potencial adequado para a conversão de energia elétrica. O estudo foi realizado com o modelo espectral TOMAWAC para o período compreendido entre Janeiro e Dezembro de 2006. Os resultados indicaram dois locais na plataforma continental próximos à zona costeira com potencial para a extração de energia das ondas. A primeira região, localizada próximo à Ilhabela detém um potencial energético maior que o da segunda região, localizada nas proximidades de Florianópolis, entretanto esta região possui uma maior variabilidade do potencial energético. A região de Florianópolis possui uma potência média mais baixa (entre 10 kW/m e 20 kW/m) que a região de Ilhabela (entre 18 kW/m e 25 kW/m), porém é uma região com o potencial mais estável, visto que sua variabilidade é da ordem da metade da observada na região de Ilhabela.

***Palavras-chave*:** Energia das ondas. TOMAWAC. Modelagem espectral. Clima de ondas.

1 Introduction

The utilisation of new energy sources is one of the most discussed subjects on the last few years. These discussions arise due to the technological advances, which depend mainly on electricity. The concerns with climate changes and sustainability turn these discussions into clean and renewable energy sources, which may be used in sustainable ways.

The majority of ancient civilisations sought to settle near fresh water sources to harness this resource for transportation and irrigation. Modern civilisations keep this same habit, though the main goal changed specifically to coastal and oceanic zones due to the ease of transportation of great volumes of cargo between continents (MILLER, 2015). Currently another reason for the population growth along the coastline is the tourism. However, population growth demands an equivalent increase on the electric energy supply. On the last few decades, the energy demand near the ocean led to many researches on the many forms of ocean energy harvesting (MILLER, 2015).

Mørk et al. (2010) made a theoretical study of the wave energy potential around the world. These authors showed that the Brazilian South-Southeastern coastline presents an average energy potential between 20 kW and 30 kW per metre of wave crest length, with a small variability rate across the year. This result shows an advantage compared to west European countries like England that, in spite of having a potential over 60 kW/m, also shows a higher variability rate, which makes the energy potential almost null in the summer. Moreover, Mørk et al. (2010) concluded that waves with higher potential have periods between 7 s and 14 s and heights between 1.5 m and 5.5 m.

Arinaga e Cheung (2012) went further into the wave power issue and used 10 years of hindcast data from WW3 to address the wave power resource and provide an overview of the order of magnitude of wave heights on Earth. Their results presented a cyclic pattern of bigger wave heights hence, wave power, in the winter. This is true for both hemispheres.

Taking the path of seasonal variability, Neill e Hashemi (2013) conducted an analysis of monthly variability of wave power around the British Isles. Their study shown that on the months that comprise the winter (December to March), the wave power availability is remarkably higher than the remaining months.

This is mainly due to the passage of severe cold fronts that add up to the waves energy. Neill e Hashemi (2013) also found greater variability associated with the higher wave energies, as well as, interannual variations within the 7 years of data they addressed.

Contestabile, Ferrante e Vicinanza (2015) used wave hincast data from the WAM wave model at the ECMWF (European Centre for Medium-range Weather Forecasts) to assess the wave energy availability near the coast of the state of Santa Catarina, Brazil. The authors found that most of the wave energy in this region comes from southeast and ranges from 8 kW/m to 14.5 kW/m, associated with significant wave heights between 1.5 kW/m and 2.5 kW/m and peak periods between 8 s and 10 s. The authors conclude that the low temporal variability found in this location, the state of Santa Catarina is one of the most suitable regions in the Brazilian coastline for wave energy exploitation.

A similar conclusion was drawn by Oleinik, Marques e Kirinus (2017a) and (2017b), who studied the temporal variability of wave energy on three of the most energetic locations of the Brazilian shelf. These authors also found that the state of Santa Catarina has the steadiest wave climate when compared to other locations with higher energetic potential.

Seeking to make good use of this available energy source, for this paper, wind generated waves were simulated along the Brazilian South-Southeastern shelf (figure 1), in order to evaluate the existence of places with appropriate potential for conversion into electrical energy.

2 Materials and Methods

The model used for the numerical simulations was TOMAWAC (TELEMAC-Based Operational Model Addressing Wave Action Computation), part of the TELEMAC–Mascaret modelling system[4]. The next paragraphs present the most important concepts about TOMAWAC, and for further information the author is referred to Benoit, Marcos e Becq (1996) and to Awk (2017). TOMAWAC is a third generation sea state solving wave model based on the equation 1 of wave

[4]<www.opentelemac.org>

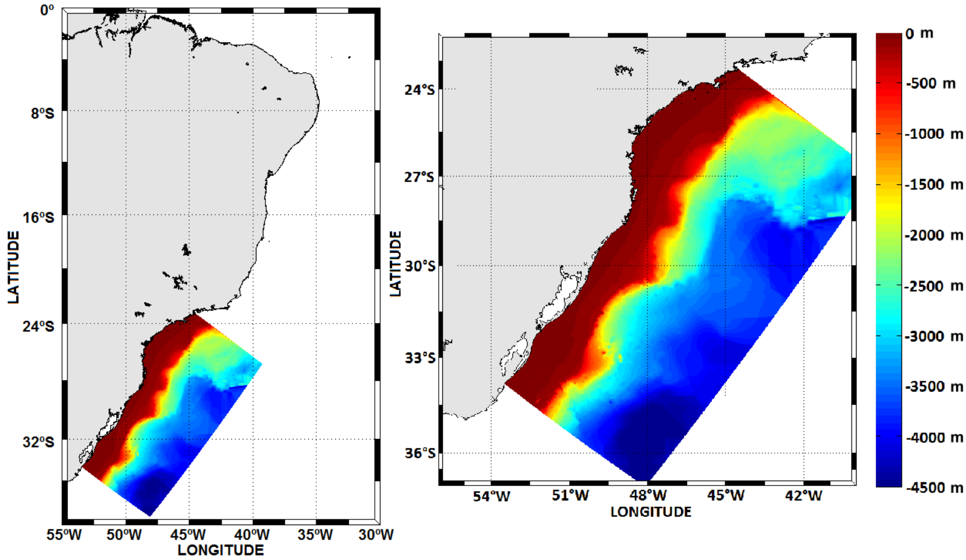


Figure 1: Location and bathymetry (m) of the studied location on the Brazilian coast.

action density conservation:

$$\frac{\partial N}{\partial t} + \frac{\partial(\dot{x}N)}{\partial x} + \frac{\partial(\dot{y}N)}{\partial y} + \frac{\partial(\dot{k}_x)}{\partial k_x} + \frac{\partial(\dot{k}_y)}{\partial k_y} = Q(k_x, k_y, x, y, t) \qquad (1)$$

where: N is the directional spectrum of wave action density, x and y are the coordinates of the Cartesian coordinate system, K_x and K_y are the components, on x and y, of the wave number vector and t is the time. Equation 1 shows that in a general situation of propagating waves in a non-homogeneous and non-stationary environment, *e.g.* an environment under the action of currents and/or sea level variation, the wave action is preserved within the source term, defined by Q (AWK, 2017).

The source term accounts for the physical of energy exchange that the waves are subject to when propagating. The physical processes taken into account by Tomawac include: wind driven generation and propagation; bottom-friction induced dissipation; wave breaking; bathymetry and current induced refraction; shoaling; whitecapping dissipation; and nonlinear triad and quadruplet[5] interactions between waves. Tomawac, however, does not take into account phase-dependent processes like diffraction and reflection, so its usage is not recommended where these processes prevail (AWK, 2017).

To solve equation (1), Tomawac splits the directional spectrum of wave action (N) into a finite number of wave frequencies (f_i) and directions (θ_i) and solves equation (1) for each component (f_i, θ_i). The directional spectrum of wave energy, denoted by $E(f, \theta)$, can be associated with $N(f, \theta)$ by:

$$E(f, \theta) = \rho g \sigma N(f, \theta) \qquad (2)$$

where ρ is the specific mass of water, g is the gravity acceleration and σ is the angular frequency of the waves given by $\sigma = 2\pi f$. The integration of $E(f, \theta)$ along the discretised frequencies and directions yields the energy per unit area of the random multi-directional waves (equation 3):

$$\sum_{f}^{f+df} \sum_{\theta}^{\theta+d\theta} \frac{1}{2}\rho g a^2 = E(f, \theta) df d\theta \qquad (3)$$

2.1 Initial and Boundary Conditions

The spatial domain of the model was set by an unstructured mesh that encompasses the Brazilian coastline between the states of Rio Grande do Sul and São Paulo, with an extension of approximately 700 km towards the sea (figure 2). The mesh has a total of 111 742 nodes and 220 831 triangular elements. The distance between the mesh nodes is approximately 3500 m in deep ocean, reducing to 2500 m on the coastal area, and 300 m in areas of interest.

The mesh was generated using the pre and post processment tool Blue Kenue[6], which has built-in support for Telemac's file format and is the mesh generation tool recommended by the developers.

The numerical model was initialised from the rest and forced on its boundaries by the imposition of a wave spectrum and on the surface by the

[5]Triad wave–wave interaction is the phenomenon where two waves, travelling at different angles, resonate, and the combined action of both generates (or adds energy to) a third direction. This process is predominant in shallow waters. Quadruplet wave–wave interactions is when two *pairs* of waves resonate and transfer energy to another wave direction and frequency. This process is predominant in deep water. See Holthuijsen (2007, pp. 183–188).

[6]<https://www.nrc-cnrc.gc.ca/eng/solutions/advisory/blue_kenue_index.html>

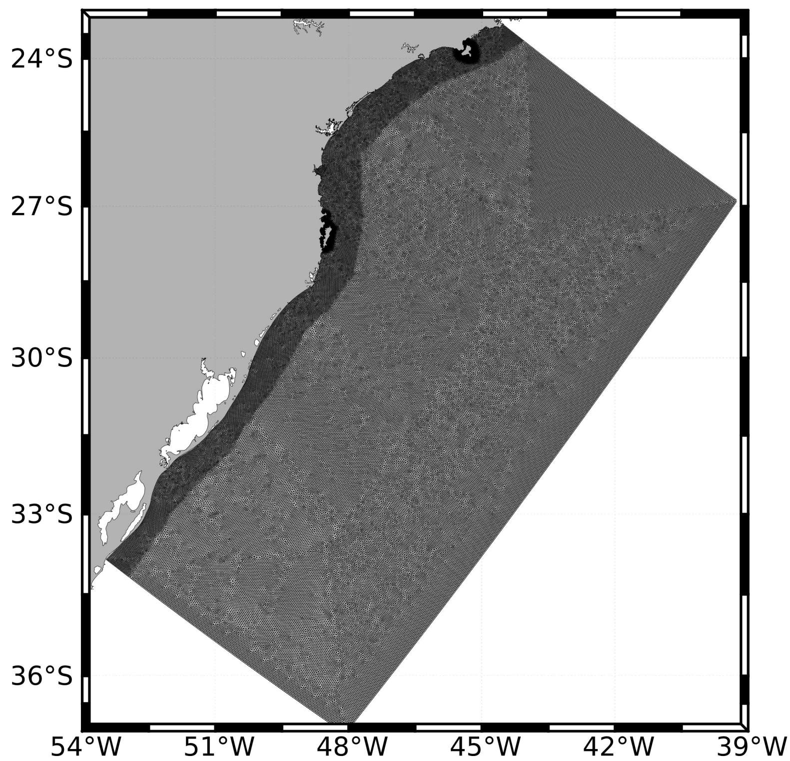


Figure 2: Unstructured mesh used as spatial domain for the simulation.

imposition of the wind action. The period studied comprehends the whole year of 2006. On the oceanic boundaries, Tomawac was forced with values of significant wave height, peak period, and mean direction, obtained from the history archive of the global wave model WAVEWATCH III (WW3)[7]. On the superficial boundary, the space-time variations of the wind were represented by data from NOAA's Reanalysis project, acquired from NOAA's web page[8], then interpolated and applied to the unstructured mesh.

3 Results

The study was performed for the time between January and December 2006. Since the model was forced from the rest, January was not taken into

[7] <ftp://polar.ncep.noaa.gov/pub/history/waves/>

[8] <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>

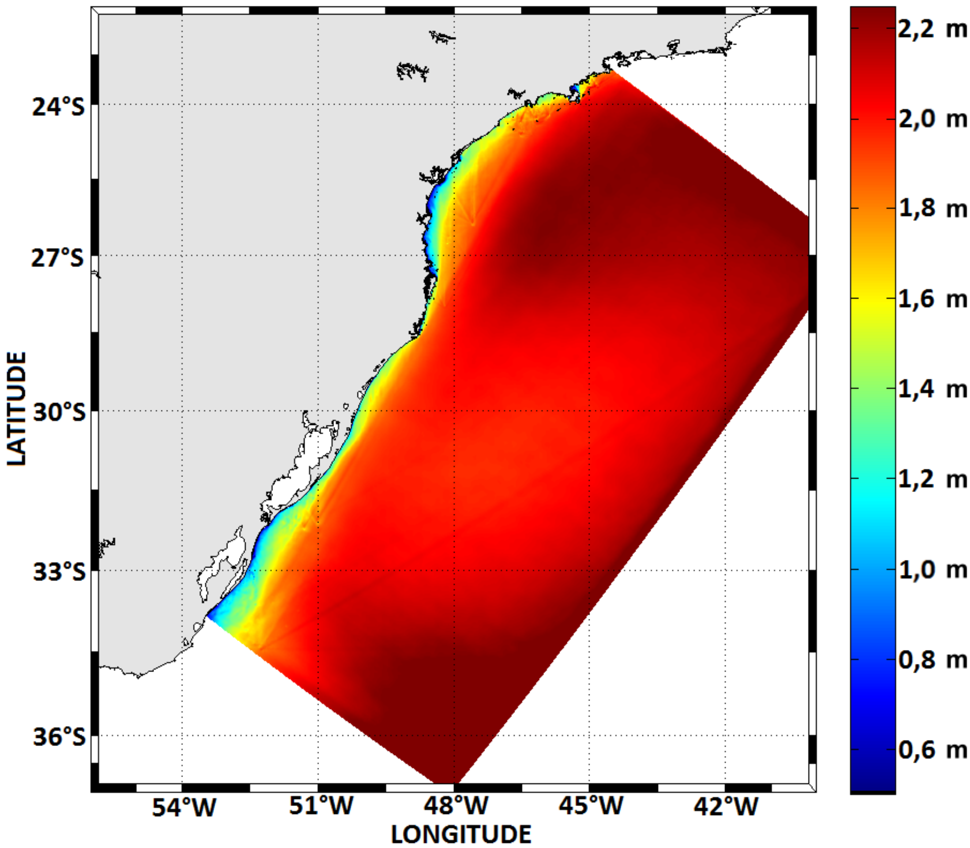
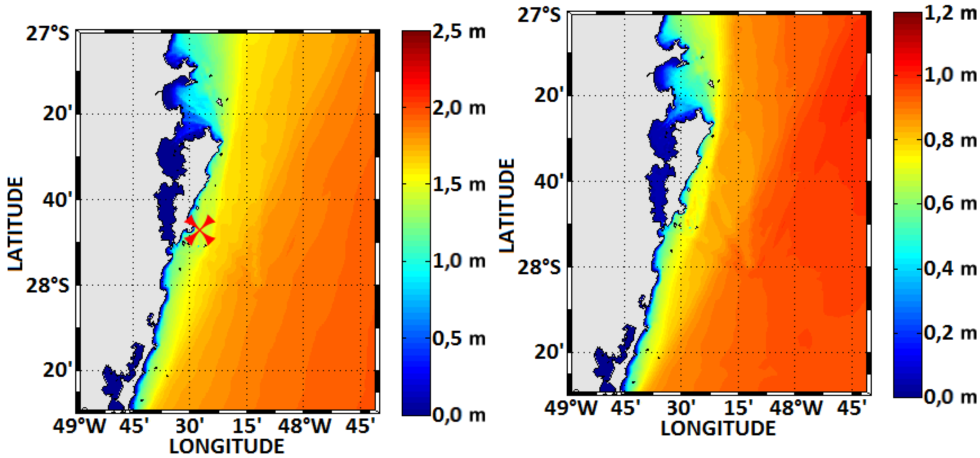


Figure 3: Average wave significant height (m) on the studied area between February and December 2006.

account because it was considered as a stabilisation period for the model. The average values for significant wave height will be used to identify the higher potential zones along the coast. The time averaged values were calculated for each of the mesh's nodes.

Figure 3 shows that the average values for significant wave height are bigger in the ocean, reaching 1.75 m, while in the coastal zone they do not go over 1.25 m. The average results show also that the region of the Santos' basin and the coastal zone of Santa Catarina show higher values of significant wave height above the inner and medium continental shelf. Furthermore, the results of significant wave height show a narrow connection with the results shown by Pianca, Mazzini e Siegle (2010), who showed an average of 1.95 m, compared with 2.0 m in figure 3, for the Southern Brazilian shelf, and 2.3 m, compared with 2.2 m in figure 3, for the Brazilian Southeastern shelf.



(a) Average significant wave height (m)

(b) Standard deviation of significant wave height (m)

Figure 4: Statistical parameters for the significant wave height near the coastal area of Santa Catarina. The red × shows a spot for the later extraction of time series.

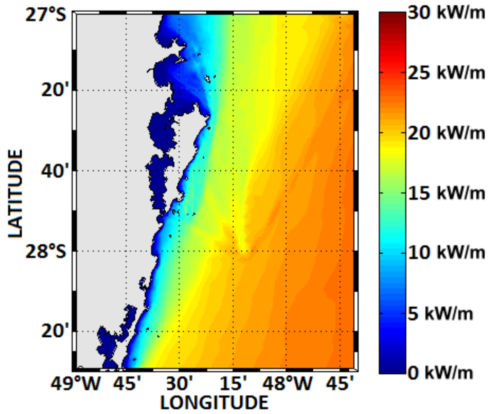
Figure 3 also shows that the highest averages near the coastline, where energy conversion devices can be installed more easily, are near the island of Florianópolis, in the state of Santa Catarina, and near the island of Ilhabela, in the state of São Paulo. For this reason, these two locations were chosen for the energetic suitability assessment along the studied time.

3.1 Coastal zone of Santa Catarina

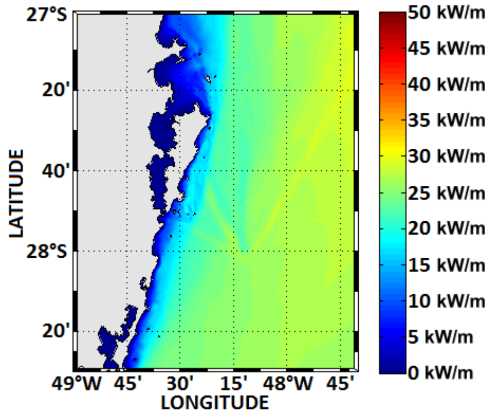
The area around the coast of Santa Catarina was chosen for study since the wave height averages are bigger in coastal zones compared to its adjacencies. The wave height averages on spots near the coast (around 10 km off the coastline) are around 1.3 m and 1.5 m (figure 4a) and the standard deviation is around 0.5 m and 0.8 m (figure 4b).

On spots further away from the coastline, the wave mean height values surpass 2 m. These results for the significant wave height are similar to the ones observed by Peixoto (2005) in an analysis of the data gathered by the Federal University of Santa Catarina's (UFSC) wave rider buoy, placed south of Florianópolis island, comprehending the year of 2003.

Figure 5a shows the mean values of energetic potential per unit wave length (kW/m) in the same place in Santa Catarina. On spots near the coast, the



(a) Average energetic potential (kW/m)



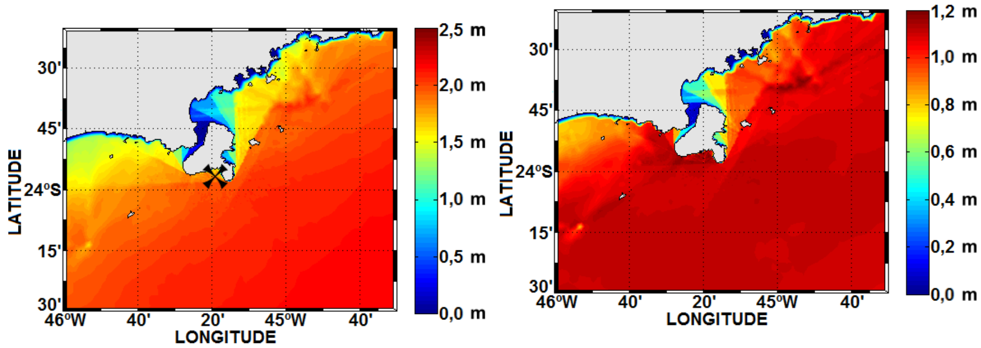
(b) Standard deviation of energetic potential (kW/m)

Figure 5: Statistical parameters for the energetic potential of waves near the coastal area of Santa Catarina.

averages are around 10 kW/m and 20 kW/m. Figure 5b shows the corresponding standard deviation values that, in the same places near the coast, admit values of the same magnitude. This result suggests a high variability of the wave height in this region, since these occur accordingly to the space-time variations of winds along the continental shelf. Tolmasquim (2003), analysing wave data acquired by the TOPEX-POSEIDON altimeter satellite, for the time between September 1992 and March 1996, and between February 1999 and September 2000, found an average energetic potential for Santa Catarina's coastal zone varying with the same magnitudes as the ones found in the simulations.

3.2 Coastal zone of São Paulo

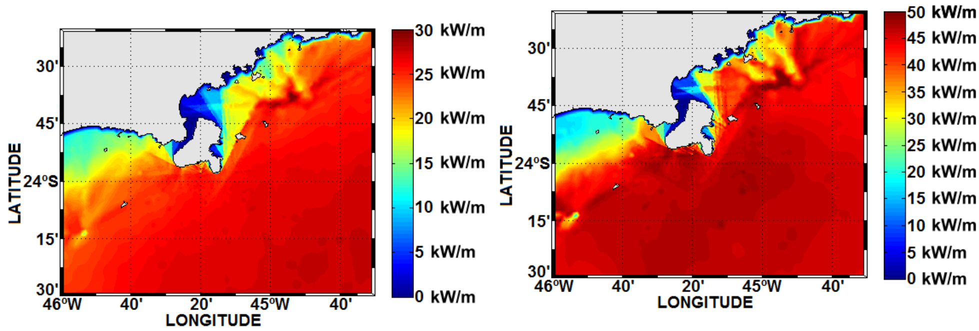
The area around Ilhabela was chosen to take part in this study for being prominent to the coast, this characteristic inserts it in water with higher energetic potential. Figure 6a shows the mean significant wave height near Ilhabela, where spots near the coastline have averages around 1.7 m on the southeastern side of the island, and 1.5 m on the northeastern and southwestern sides. The standard deviation (figure 6b) is almost the same around the island, with values around 0.7 m and 1.0 m. On spots further from the island, the mean significant wave height is around 1.9 m and 2.1 m and increases further away from the coastline. The study of the ondulatory patterns made by Pianca, Mazzini e Siegle (2010) for the region of the Santos' basin showed average significant



(a) Average significant wave height (m)

(b) Standard deviation of significant wave height (m)

Figure 6: Statistical parameters for the significant wave height near the coastal area of Ilhabela. The black × shows a spot for the later extraction of time series.



(a) Average energetic potential (kW/m)

(b) Standard deviation of energetic potential (kW/m)

Figure 7: Statistical parameters for the energetic potential of waves near the coastal area of Ilhabela.

wave height values around 1.95 m in the reanalysis for the time between January 1997 and December 2007.

Regarding to the energetic potential, on places near Ilhabela, the average takes values between 18 kW/m and 25 kW/m (figure 7a), with standard deviations usually above 20 kW/m (figure 7b). On lines parallel to the coastline the average energetic potential is similar, reaching values above 25 kW/m on spots further away from the coastline. The result for this area is similar to the one seen in Santa Catarina, and suggests that the high variability on wave heights happen according to the space-time wind variations along the continental shelf.

This notable difference between Ilhabela and Florianópolis is possibly due to the different bathymetries of these locations. In Santa Catarina the bathymetry has a mild slope, and consequently a wide continental shelf so, as the waves propagate towards the coastline, they travel a long distance at “shallow waters”, making them lose a large amount of energy due to bottom friction. Thus, the waves that arrive at the coast of Santa Catarina have their properties mostly shaped by the bathymetry.

In Ilhabela, on the other hand, the bottom slope is much steeper, providing waves much less space to dissipate their energy by bottom friction, allowing deep-sea waves to arrive at the coastline with little energy loss. Thus the characteristics of the waves are shaped mostly by the offshore winds that generate the waves, and by waves that much longer distances, from other parts of the Atlantic Ocean.

3.3 Temporal variability analysis

The temporal variability study of the energetic potential was made by direct analysis of wave potential and mean direction time series for a spot near the coastline of Florianópolis and a spot near the coast of Ilhabela. The time series of mean wave direction and energetic potential near Florianópolis were extracted at the coordinates 48°28′49″S and 27°43′15″W (red × in figure 4a), and near Ilhabela at the coordinates 45°18′56″S and 23°57′8″W (black × in figure 6a).

The time series show the high variability of the energetic potential, as suggested by the high standard deviations presented previously, with variations that occur in the temporal scale of a few days, corresponding mainly to the variability of the wind action on the studied area. Many authors verified that ocean on the Brazilian south and southeastern shelf is strongly influenced by the passage of meteorological systems and changes in the winds direction and intensity (CIOTTI et al., 1995; FERNANDES et al., 2002; PIOLA et al., 2005; COSTA; Möller Jr, 2011; MARQUES, 2012).

The time series (figures 8 and 9) show that taller waves (consequently with higher energetic potential) are usually associated to events from around 330° (waves from southeast) in Santa Catarina and from around 13° (waves from southwest) on Ilhabela. The wave direction is measured using the nautical

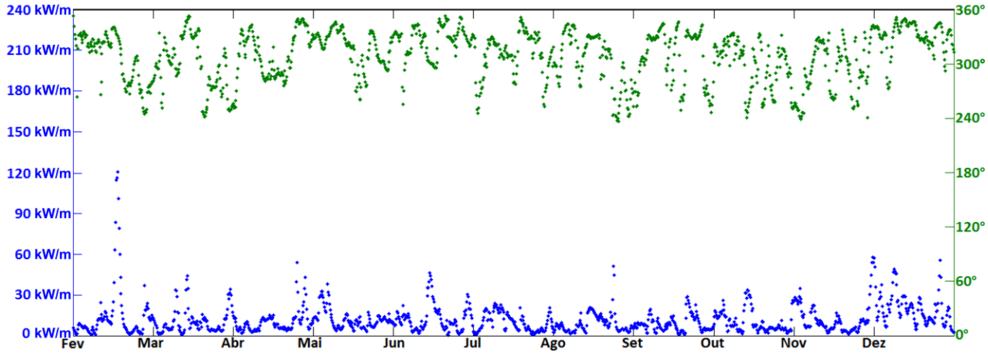


Figure 8: Energetic potential (kW/m) time series (blue) and mean direction (°) time series (green) for the spot chosen in Santa Catarina.

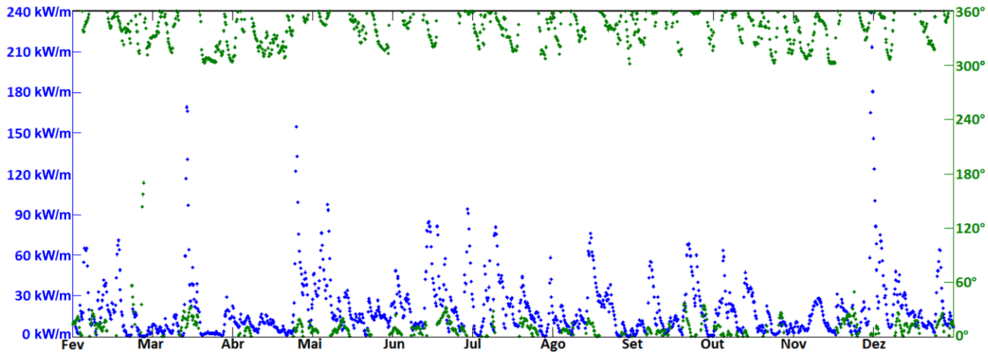


Figure 9: Energetic potential (kW/m) time series (blue) and mean direction (°) time series (green) for the spot chosen in Ilhabela.

convention (north at 0°, clockwise positive) indicating the propagation direction of the waves (AWK, 2017). On the graphs, the green dots represent the direction of propagation, in degrees, and the blue dots the energetic potential, in kW/m.

This shows that the waves with the highest energy are those that come from south, originated by the strong Antartic westerly winds, that generates the Antarctic Circumpolar Current in the water and a belt of high waves on the surface (KROGSTAD; BARSTOW, 1999; MØRK et al., 2010; GUNN; STOCK-WILLIAMS, 2012). These waves travel north reaching the Brazilian coast, prividing the highest energetic potentials.

Regarding average aspects, the spot in Santa Catarina (figure 8) shows that the mean propagation direction is 308° (waves from southeast) and the potential around 12 kW/m, with frequent events up to 20 kW/m and a occurrences of more than 40 kW/m. The mean value in Santa Catarina shows a behaviour similar to the maximum values, supporting the low variability found for that region (figure 4b).

Ilhabela, on the other hand, (figure 9) shows a mean direction of waves from 208° (waves from northeast) along the year. On this region, the potential is around 20 kW/m, with many events near 50 kW/m and some that surpass 70 kW/m. This shows that the mean behaviour is very different the maximum values, agreeing to the higher temporal variability presented earlier (figure 4b).

4 Conclusions

Comparing both studied places, one can realise that, at first sight, Ilhabela has a higher energetic potential than Santa Catarina. However this location has higher temporal variability too.

On both places the potential is higher compared to the rest of the nearby continental shelf. Ilhabela has a mean potential of 20 kW/m, with frequent extreme events going up to 70 kW/m. However, it is a region with a high standard deviation, of up to 45 kW/m. On this region, the extreme events associated with the highest energy potentials are usually also associated with waves from southwest. On the other hand, Florianópolis has slightly lower average, around 15 kW/m, with extreme events up to 30 kW/m. Its variability is reduced so that the standard deviation reaches an average 25 kW/m. On this location, the higher energy events are associated to waves from southeast.

The difference in the behaviour of these locations is partly due to the difference in the morphology of ocean floor. In Santa Catarina the bathymetry change is mild as the waves travel towards the coastline, making them lose a large amount of energy due to bottom friction, thus the waves that arrive at the coast have their properties mostly shaped by the bottom morphology. In Ilhabela, on the other hand, the bottom is much steeper, allowing deep-sea waves to arrive at the coast with less energy loss, thus the characteristics of the waves are more similar to the ones at deeper seas.

Locations with higher potential are mostly desirable due to the high energy events they can provide to power the wave energy conversion devices. But these devices are often capped to a maximum conversion rate and beyond that their efficiency reduces, thus the higher averages are compensated by the higher variability, making these locations less feasible for wave energy exploitation.

Locations with slightly lower averages, on the other hand, are more feasible if their variability is lower, because the devices can be tuned to capture the wave energy at the wave height and period bands that presents greater stability, providing a continuous energy source.

Giving sequence to this study, a wider numerical mesh shall be used, to cover a larger area and longer time span. From the results found in this paper one can conclude that the waves with the highest energy come from south so locations that have a west–east orientation should provide a higher potential, and prove themselves more suitable for wave energy conversion if their variability is not too large.

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Enviado em: 15/06/18

Aceito em: 11/07/18

Editor: Mateus das Neves Gomes