An overview of the Brazilian continental shelf wave energy potential

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Abstract. *Wave energy studies have received high attention in the last few years due the increasing exploitation of alternative energies, as a result of the urgency in reducing the consumption of fossil fuels. However, a characterization of this resource has extreme importance due its elevated temporal and spatial variability. Parallel to this development on the renewable energy field, there is a wide range of studies of Wave Energy Converters (WEC's) which has brought with them a number of important analysis that contribute to the development of these technologies. The viability of the implementation of wave energy farms highly depends on the wave energy power of the intended location. In this way, this study explores the evaluation and characterization of the wave energy potential on the Brazilian coast. Numerical simulations were carried out in order to determine, amongst other factors, Significant Wave Height (*H_s*) and Wave Power Rate (*P_w*), of the studied region. The two-dimensional spectral model TOMAWAC was used to conduct the simulations, which were calibrated and validated using wave data measured by buoys along the Brazilian coast. The surface boundary was forced using wind velocity data, and the oceanic boundaries were forced by *H_s*, Peak Period (*T_p*), and Peak Direction (*D_p*) data, both provided by Era-Interim project. A 5 year wave hindcast was developed, and the annual averages were analyzed in different locations over all the Brazilian continental shelf, aiming to explore the potential implementation of WEC farms. In near shore areas the mean *P_w* reached values of* $15\ kW.m^{-1}$*, while offshore values reached from* 18 *to* $20 kW.m^{-1}$ *being most frequent in the South-Southeastern Brazilian Shelf (SSBS). A great variability of the wave power was also identified when comparing the SSBS and the North-Northeastern Brazilian Shelf (NNBS), which demonstrate that the* P_w *tends to increase at higher latitudes. The results of this study could be used to seek specific areas which demonstrate available wave power for conversion in electric power.*

Keywords: *Wave, Energy, TOMAWAC, WEC*

1 INTRODUCTION

The growing interest in recent years over renewable energy resources has brought in company the increase amount of studies upon all different energy sources. The recurrent need of energy has become a harder problem to solve, one of the biggest reasons is that the current energy resources not only are becoming limited but also due the genuine pollution issues, governmental institutions have increased the sanctions over the use of those.

To work around this problem, there are several new studies on renewable energy sources, and one of the most not highly exploited resource, is the ocean wave energy, which by the currents, tides and waves can easily be an important component to build a country's energy network. Although to implement energy conversion sites, the chosen location has to be previously studied in order to avoid misplacement of the conversion structures or unexpected output.

Numerous wave energy resource studies have been developed in the last years. Gunn et al., (2012) quantified the global wave power resource, analyzing NOAA (National Oceanic and Atmospheric Administration) WaveWatch III data and calculating the energy flux across a line 30 nautical miles offshore. These authors concluded that the global wave power resource is $2.11 \pm 0.05\, TW$.

Cornett (2008) also assessed the global wave energy resource using WaveWatch III data. The author analyzed a 10 year period from 1997 to 2006 describing the spatial and temporal variations. The results showed that the annual mean wave power is greatest in the higher latitudes of the southern hemisphere and in some areas of the North Atlantic and Pacific ocean.

Reguero et al., (2012) generated a global ocean wave (GOW) reanalysis from 1948 onwards, which the authors intend to periodically update it. Lately, Reguero et al., (2015) assessed the global wave power using his GOW dataset. The conclusion was that the global wave power offshore is estimated at $32.000\, TWh/yr$, but considering the direction of the energy this value is reduced to $16.000\, TWh/yr$.

Even though the global resource has been widely studied, local assessments are still of a small number. Since the implementation of WEC's depends directly on the site energy consistency and variability, research similar to that of Oleinik et al., (2017 and 2017a) have a high level of importance. These authors studied the wave climate of the most energetic locations of the SSBS, and found that Farol island (RJ) has the highest mean wave power of the studied locations. They also showed the variability patterns for the studied locations enabling the scaling of the turbines for the site.

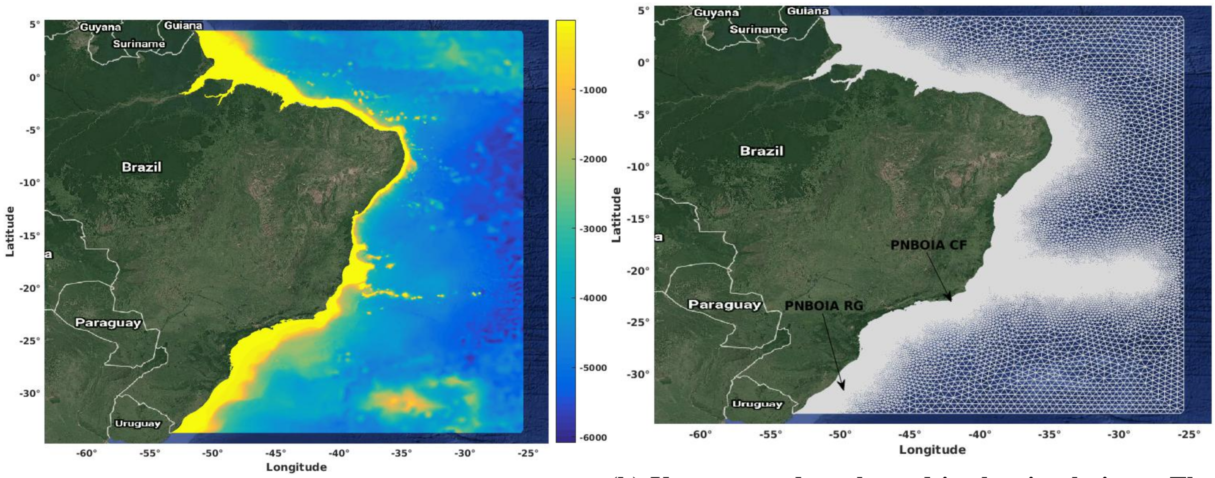
To better understand the Brazilian wave climate, this work aims to analyze the H_s and P_w along the entire Brazilian coastline, in order to understand the behavior and the potential of the different areas along the Brazilian shore. In order to accomplish that, a sea state modeling software was used to simulate the waves over the Brazilian coast and part of the Atlantic ocean during a 5 year period. Then the H_s and P_w were mapped and a set of locations were chosen to carry on a comparison between the time series.

2 MATERIALS AND METHODS

This study uses the third generation wave model TOMAWAC (TELEMAC-Based Operational Model Adressing Wave Action Computation) to simulate the sea conditions over the

Brazilian continental shelf (Fig. 1a) in the 5 year period, between 1979 and 1983. Then the H_s and the P_w were assessed, which led to the choice of four locations. Santa Marta cape (SC) and Cabo Frio (RJ) were chosen as a comparison to the works of Oleinik et al., (2017 and 2017a), while Rio Grande (RS) and Recife (PE), were chosen to widen the range of the study to better distribute the studied locations over the Brazilian coast.

An unstructured mesh composed of $547\,479$ nodes with varying relative distance between them, from $55\ km$ at the oceanic area to $1\ km$ at the regions closer to the shore was used to represent the domain (Fig. 1b). The temporal resolution for each computation is 7.5 minutes, even though the temporal resolution for the output result is considerably bigger, being $24\ h$.



(a) Bathymetry of study region.

(b) Unstructured mesh used in the simulations. The arrows point to the location of the wave buoys.

2.1 Numerical Model

The third generation wave model TOMAWAC is a part of the TELEMAC-MASCARET (www.opentelemac.org) modeling suite. The model computes the sea state by solving the equation of the conservation of wave action density Eq. (1), for the wave directional spectrum:

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

where N is the directional wave spectrum, k_x and k_y are the x and y directional components of the the wave number vector, and t is the time. The Eq. (1), represents that the density of the wave action action is preserved within the source and sink terms, characterized by Q, for a general situation of waves propagating at a non-homogeneous and unsteady environment.

Furthermore, the waves energy spectrum, $E(f,\theta)$ can be associated with $N(f,\theta)$ trough Eq. (2):

$$E(f,\theta) = N(f,\theta)\rho g \tag{2}$$

where ρ and g are the specific mass of the water and the gravity acceleration, respectively. The integration of $E(f,\theta)$ along the discretized frequencies and directions leads to Eq. (3), returning the energy per unit of area of the random multi-directional waves:

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

2.2 Superficial and Boundary Conditions

To perform the simulations the numerical model TOMAWAC was initialized from the rest. H_s, T_p, and D_p were imposed at the oceanic boundaries, while the superficial boundary was forced by winds. Both wind and wave data were acquired from the ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-Interim reanalysis (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim), having a spatial resolution of $0.75° \times 0.75°$ and a temporal resolution of $6\ h$.

2.3 Validation

To verify the efficiency of the numerical model a comparative study between the model output and buoy data from the Programa Nacional de Boias (PNBOIA) was held. A simulation for the year of 2012 was chosen taken into account the high quantity of accurate data in this period. H_s values were compared at two locations, Rio Grande and Cabo Frio, being the data acquired from the buoys at $200\ m$ depth.

The measured buoy data underwent a treatment to remove spikes and outliers, and then the model output was interpolated to fit the buoy data. Figure 2 shows the measured and simulated time series. The Fig. 2 a shows a good fit between the modeled and measured H_s. Both high and lower values were characterized by the model, even though the quick changes from peaks to depressions were often hard to represent by the model. One factor that might influence this problem is the relatively small output resolution.

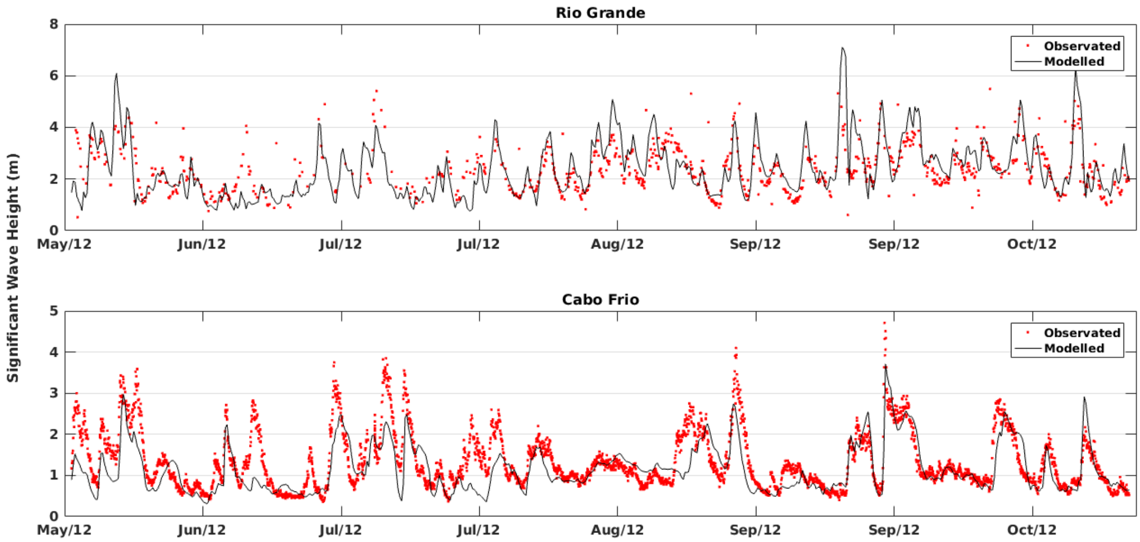


Figure 2: Model and buoy data comparison.

In order to quantify the comparison, different error metrics previously used in this field (Melo et al., 2008; Chawla et al., 2013) were tested. The Eq. (4) and Eq. (5) show the used parameters:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(m_i - b_i)^2}{N}} \tag{4}$$

$$V = \frac{\sum_{i=1}^{N}(m_i - b_i)}{N} \tag{5}$$

where m_i is the modeled and b_i is the buoy data. The RMSE (4) expresses the magnitude of the error in module of the model, and the Bias (5) measures the mean deviation between the modeled and the buoy data. Table 1 shows the computed values of the parameters for both Rio Grande (RG) and Cabo Frio (CF).

Table 1: Statistical parameters calculated comparing TOMAWAC output and buoy data

PARAMETER	TOMAWAC RG	PNBOIA RG	TOMAWAC CF	PNBOIA CF
Height Average (m)	2.3808	2.3588	1.1544	1.3505
Standard Deviation (m)	1.0809	0.8439	0.5831	0.6936
RMSE	0.8008		0.5171	
BIAS	0.0054		0.1959	

With the statistical parameters some conclusions could be presented. The close to zero Bias values shows that the model does not tend to under or overestimate the model in comparison to the observed data. The RMSE values showed that the differences of the compared data is considerable acceptable, because the difference between the model and the buoy data is squared, what would cause higher RMSE values.

3 RESULTS AND DISCUSSION

Two different analysis were conducted. Initially, the H_s and P_w were averaged for the entire Brazilian shelf and the previously cited locations had their time series evaluated. Furthermore, a deeper study at the Santa Marta cape was carried out.

Figure 3 shows the mean H_s for the entire Brazilian shelf. This result highlights the greater values at south, being in agreement with Pianca et al., (2010), who also demonstrated the lower H_s values in the northern areas of Brazil. While some coastal areas at south reached almost $2\ m$ of wave height, the northern areas revealed values around $1\ m$.

When the wave power magnitude was analyzed (Fig. 4) the discrepancy of the north and south of Brazil is even greater. While at the south the coast values reach up to $11\ kW.m^{-1}$ at north the values are around 5 to $8kW.m^{-1}$. This greater difference of magnitude may be explained by the incidence direction of the swell, which in the southern regions is predominantly south oriented.

After the extraction of the time series (Fig. 5), which were created using the mean values of each day along the 5 simulated years, for the formerly mentioned locations, some observations could be made. Although Santa Marta cape displayed the highest H_s values, Rio Grande was the spot with the highest mean of the four points analyzed, with 1.82 m. Recife showed the lowest standard deviation for the studied period, meaning that it has the most stable H_s values along the year. Cabo Frio demonstrated a situation completely different from the others, being the mesh node used to extract the time series closer to the coast, the mean value was the lowest recorded of all of them, with $0.84\ m$.

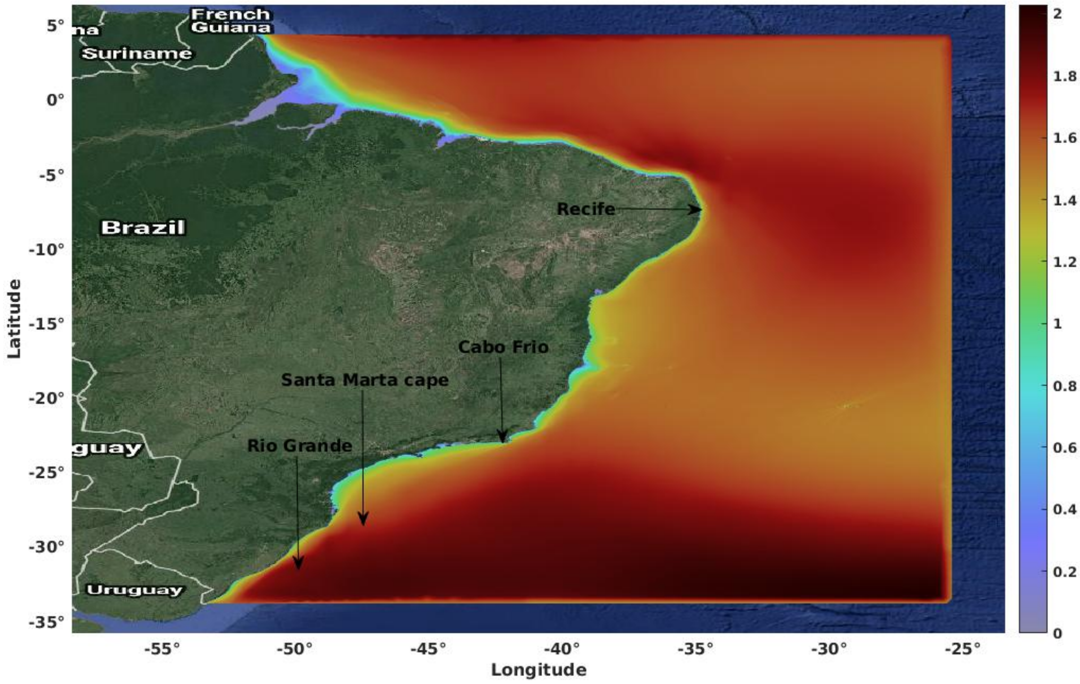


Figure 3: Mean significant wave height (m), with the 4 studied locations pointed.

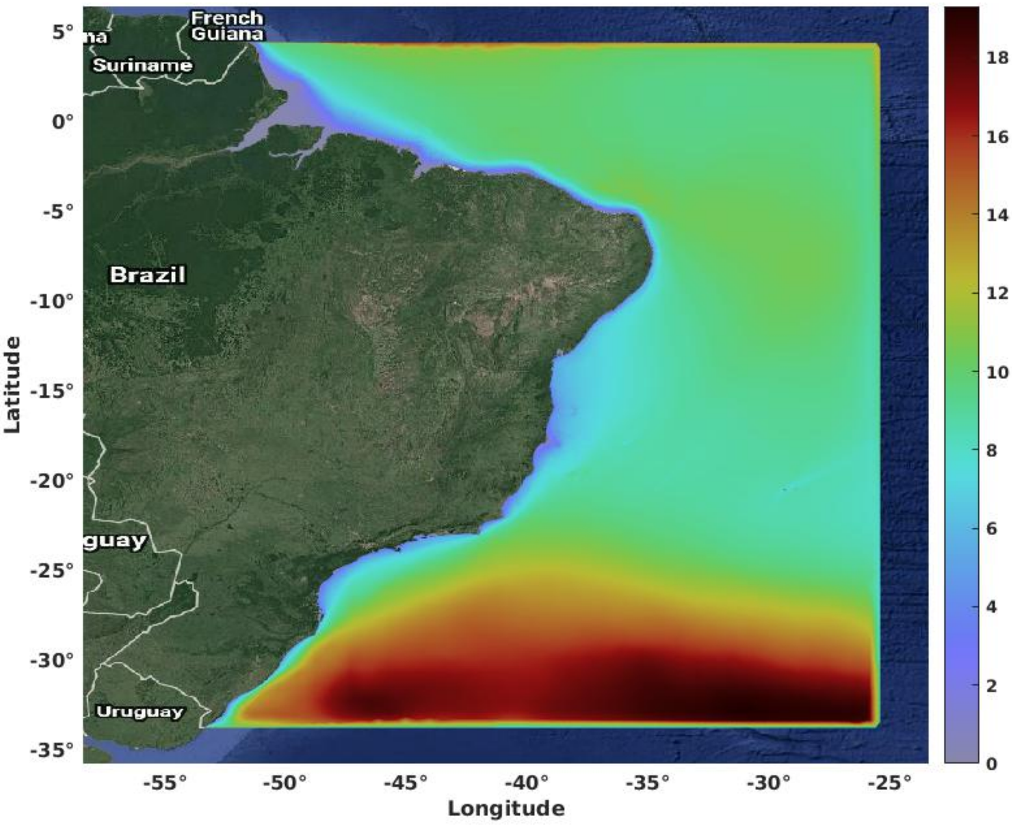


Figure 4: Mean wave power rate ($kW.m^{-1}$)**.**

Moreover, Fig. 6 shows the time series for all 5 simulated years. The chosen place was Santa Marta cape which evidences the greater number of H_s peaks, alongside greater mean

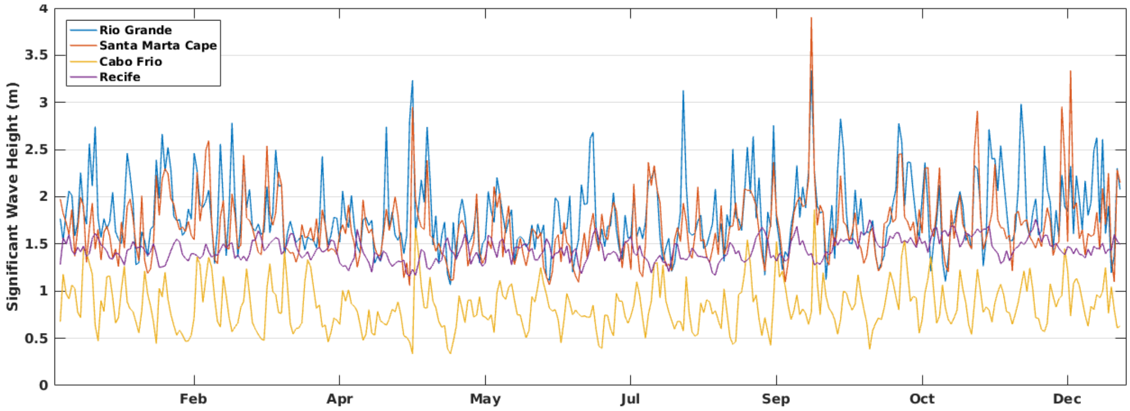


Figure 5: Mean significant wave height along the 5 simulated years of the four studied spots.

values at winter and spring seasons. Also, 1983 was the year with the most numerous peaks, what can be directed related to the strong El Niño event that happened over that year (Trenberth et al., 2001).

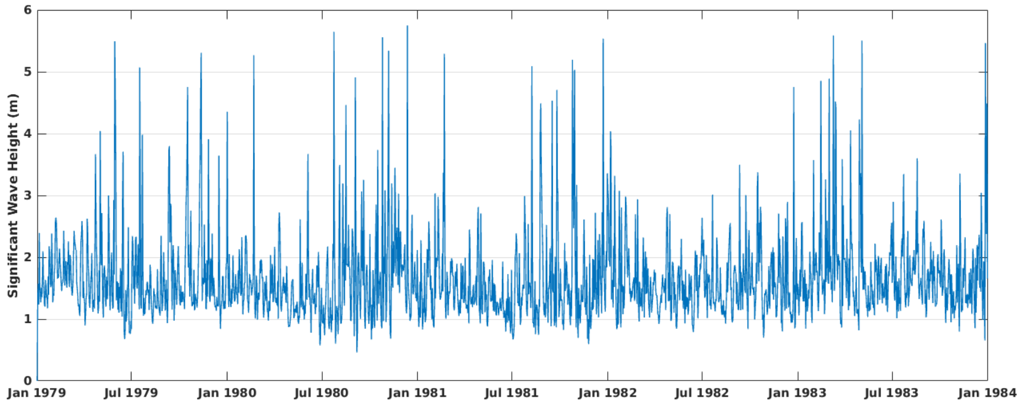


Figure 6: H_s time series for the 5 simulated years at Santa Marta cape.

In summary, the results showed good agreement with the literature, the north of Brazil represents a less wave energetic area then the south, which for future studies of WEC farms implementation can be a path to help the decision to start a study in a specific region of the Brazilian coast.

4 CONCLUSIONS

Aiming to analyze the P_w and H_s, the numerical model TOMAWAC has provided satisfactory results. The validation showed that the model presents good agreement with observed data, which also is in agreement with the literature. It was evidenced that the southern region of Brazil had the highest, both H_s and P_w values, which can lead to future studies in depth locations such as the Santa Marta cape. This site revealed a high H_s mean, despite the fact of a considerably high variability along the year, what can cause some problems in the scaling of WEC farms.

Also its important to emphasize that the lower values found at Cabo frio are due the location, near the coast, where the data was extracted, being it the same location of the buoy used in the validation. For a better understand of the wave potential in Cabo Frio the data should be extracted of a similar distance from the coast, as Santa Marta cape for example.

To conclude, this work opens space to a series of different analysis. A long term simulation can be done, to better understand the wave climate of the Brazilian shelf and understand the short and long term variabilities. Also, diverse locations can be chosen for a long term assessment. Using a greater refine of the mesh in the chosen spots, more accurate results can be reached, facilitating the interest of energy companies in the exploration of the areas.

Acknowledgements

The authors are grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ) for the fellowships. The authors are also grateful to CNPQ for sponsoring this research under the contract: 304227/2016-1 Additional knowledge goes to the Brazilian Navy for providing detailed bathymetric data for the coastal area, ECMWF for supplying the wind and wave data sets.

This research was developed with the support of the Centro Nacional de Supercomputação (CESUP) of the Universidade Federal do Rio Grande do Sul (UFRGS) and the Laboratório Nacional de Computação Científica (LNCC).

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