

Determining the Nearshore Wave Climate between Galinhos and Guamaré – Brazil

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ABSTRACT

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This paper applies two numerical models, REFDIF and SWAN, to characterize the wave climate near the coastal stretch between Galinhos and Guamaré, Brazil. This region is exposed both to incoming swell from North Atlantic Ocean and to local seas generated by steady SE Trade Winds, tidal currents are strong, and beach morphology is very dynamic. Both models were applied to the propagation of different wave conditions, from offshore to the coastline of Galinhos-Guamaré. The following incident wave conditions were considered: periods between $T=5$ s and 13 s, deep water heights between $H=0.8$ m and 2.4 m, and off-shore directions between N-60-W (60°) and N-60-E (60°). A total of 1053 simulations were performed for the incident wave conditions for each model. The results consist on the wave heights and wave directions of study area. It is also analyzed the results at points over the bathymetric line of -8 m (CD). A comparative analysis of the results obtained with each model permit to assess their suitability for this area and evaluate their limitations and potentialities.

ADDITIONAL INDEX WORDS: *wave refraction, wave diffraction, REFDIF, SWAN,*

INTRODUCTION

The region of Galinhos-Guamaré, located at the northern coast of the state of Rio Grande do Norte, Brazil (Figure 1) is a very scenic area with high touristic potential. However, oil exploitation and transportation, both offshore and in coastal locations, salt ponds and fish farms are the main economic activities in this region, leading to high environmental risks.

The area presents a diversified morphology (estuaries, tidal flats, river-marine terraces, bars and sand dunes) continuously shaped by the joint action of several factors (currents, waves, wind, etc.), thus vulnerable to sea level and climate changes. Local bathymetry is very complex, characterized by a gentle slope with submerged linear longshore dunes.

For these reasons, the area has been the focus of several environmental studies and monitoring programs, which contribute to the understanding of coastal processes and evolution.

Castro et al. (2009), Vital et al. (2006, 2010), Stattegger et al. (2004), Grigio et al. (2006), among others, have pointed out to the need of better knowledge on waves, tides and winds, as well as on the hydrodynamic circulation at the area of study. As a matter of fact, the complex bathymetry and tidal circulation make wave propagation not a trivial exercise and the correct estimate of the wave field becomes of fundamental importance for sediment dynamics, coastal morphodynamic studies, and coastal engineering design.

However, existing information regarding the waves and their propagation in the Galinhos-Guamaré region are insufficient as a basis for any study of coastal and port engineering. To overcome this problem, numerical models of wave propagation constitute a viable alternative for estimating the wave climate.

REFDIF (Dalrymple and Kirby, 1991) and SWAN (Booij et al., 1999) are two examples of wave propagation models that can simulate the nearshore wave climate. REFDIF propagates regular waves in mild slope areas, taking into account the effects of refraction and diffraction, wave dissipation energy (by friction or by wave breaking) and the presence of currents. It is a phase-resolving model based on the parabolic approximation of the mild slope equation. It is essentially adapted to model coastal areas with dimensions on the order of tens of kilometers.

The SWAN model is a nonlinear spectral model that includes wave generation, propagation and dissipation effects. It is a phase-averaged model, based on the conservation of the wave action equation. This model allows for the generation of waves by wind and considers various phenomena involved in the propagation of waves and directional spread - refraction, diffraction, wave breaking and generation of harmonics (non-linear wave-wave interaction). It is adequate for large coastal areas (hundreds of kilometers). However, since it is a phase-averaged model, it cannot describe the wave shape transformation, especially in shallow depths. Moreover, due to computational limitations, the

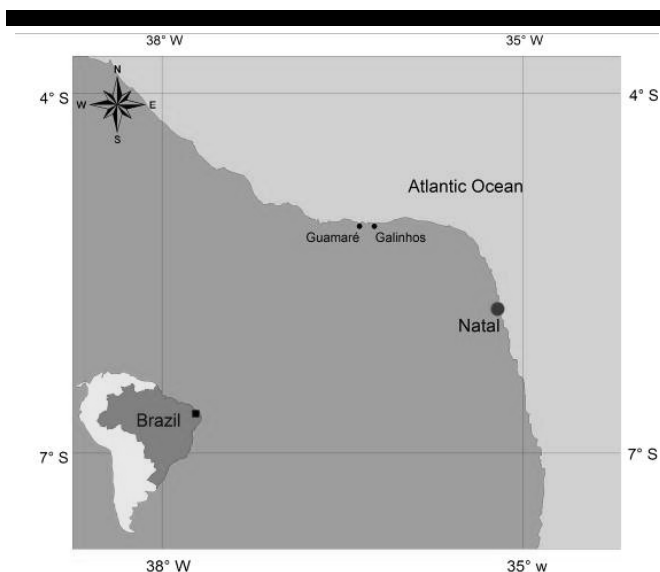


Figure 1. Location of the study area.

discretization of the studied area is coarse and does not represent well the bottom bathymetry. This leads to unrealistic changes in wave propagation, mainly in shallow water where diffraction becomes more relevant.

In the present study, the behavior of these two models is analyzed and their results (wave heights and direction) are compared to each other for several wave conditions, offshore Galinhos-Guamaré. Results at selected points along the bathymetric contour of -8 m (Chart Datum) are also analyzed. From this comparative analysis it is possible to assess the models' suitability for this area.

After this introduction, a brief characterization of the existing wave climate and tide level is made. It follows a description of REFDIF and SWAN models and their applicability conditions. Next, the results are compared, and finally the discussion and conclusions are presented.

STUDY AREA, WAVE CLIMATE AND TIDAL LEVEL

The target area extends over approximately 15 km. The continental shelf is wide, average width of 40 km, with a sandy bottom. The bathymetry is very complex, large areas with gentle slope but also submerged shore parallel dunes may exist.

Due to the lack of wave measurements at that region, significant wave periods and heights were obtained from the Global Wave Statistics (Hogben, 1986). Such information should be used very carefully since it corresponds to observations made by different sources (ships, buoys, wave buoys, visual observation) at different points in a much wider area that includes for instance Natal region, 140km away, where the shoreline runs North-South (Figure 1). Moreover, wave directions are inferred from data and observations of local winds.

The incident wave conditions considered correspond to wave periods (T) between 5 s and 13 s, wave heights (H) between 0.8 m and 2.4 m and wave directions between N-60°-W (-60°) and N-60°-E (60°). Tidal level information was obtained from the Brazilian Hydrographic Service (DHN), and corresponds to +1.3 m in relation to chart datum (CD) for both models.

MODEL'S APPLICATION

The REFDIF and SWAN models were applied to study the propagation of waves along the maritime area between Galinhos and Guamaré (Figure 2). The preparation of data, execution and display of the results of the models were made with the tool SOPRO (Fortes et al., 2006, 2007). The next sections present the adopted computational conditions and the results obtained from both models at the Galinhos-Guamaré coastal area.

Computational conditions for REFDIF model

The following incident wave conditions were selected in the calculations with the model REFDIF:

1. direction: from N-60°-W (-60°) to N-60°-E (60°), spaced by 10° (13 directions);
 2. period: $T=5$ s to 13 s, spaced by 1 s (9 periods);
 3. height: $H_0=0.8$ to 2.4 m, spaced by 0.2 m (9 heights).
- These conditions total 1,053 simulations (9 periods \times 13 directions \times 9 heights).

The grid used for the calculations is shown in Figures 2 and 3.

Three different domains (D1, D2, D3) were used by REFDIF, according to the incident wave directions (-60° to 60°), so that the wave propagation direction should not exceed $\pm 45^\circ$ of the incident wave condition anywhere within the domain. For each domain, three different meshes (M1, M2, M3) were created, (Figure 2) whose dimensions and number of nodes are given in Table 1. The 1st mesh of each domain was extended until the deep water limit for the longest period and the 3rd mesh included the area of interest. The grid spacing was set to ensure a minimum of 5 points per wavelength for the chosen wave condition, taking into account the computational capacity available (Workstation AMD Athlon™ Dual Core Opteron 1.7GHz with 2.00GB of RAM).

For each area, the extreme incident directions are also shown in Figure 3. Since the REFDIF model is based on the mild slope equation, the bathymetry in the zone between 0 and -20 m was smoothed, in order to avoid computational instabilities.

Table 1. Grid dimensions for the meshes and number of nodes.

		mesh		
		M1	M2	M3
spacing		6 m	3 m	3 m
domain	D1	25,920m \times 33,600m	25,920m \times 24,000m	25,920m \times 16,080m
		4,320 \times 5,600 nodes	4,320 \times 8,000 nodes	4,320 \times 5,360 nodes
	D2	12,960m \times 36,000m	12,960m \times 24,000m	12,960m \times 16,080m
		2,160 \times 6,000 nodes	2,160 \times 8,000 nodes	2,160 \times 5,360 nodes
	D3	12,960m \times 36,000m	12,960m \times 24,000m	12,960m \times 16,080m
		2,160 \times 6,000 nodes	2,160 \times 8,000 nodes	2,160 \times 5,360 nodes
		along wave propagation \times normal to wave propagation		

The range of incident wave directions is for D1 (-60° to -20°), for D2 (-20° to 20°) and for D3 (20° to 60°). Notice that in the domains D1, D2 and D3, the mesh M1 is the most distant from the area of interest and mesh M3 is the one which surrounds that area.

Computation conditions for SWAN model

The input data for the SWAN model is a directional spectrum. Since no spectral data was available for the site, a JONSWAP spectrum with a coefficient $\gamma = 3.3$ and a cosine directional spread function was adopted. The peak period and main direction of the spectrum were the same as those of the monochromatic waves used for REFDIF. The spectral resolution consisted of 31 intervals from 0.02 to 0.4 Hz, according to a logarithmic distribution. The resolution in direction was 2°.

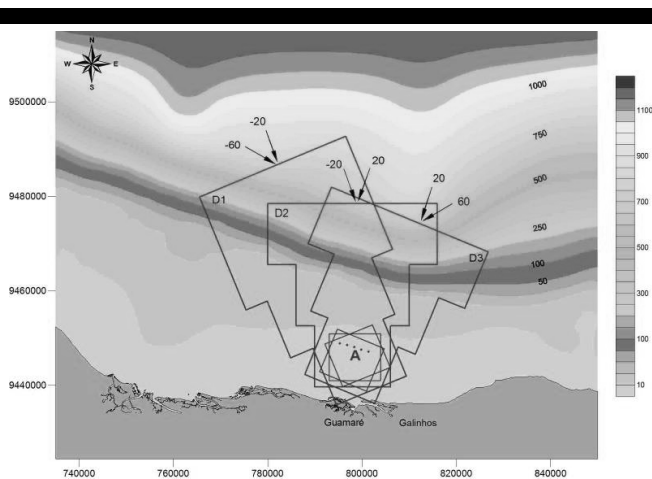


Figure 2. Bathymetry of Galinhos-Guamaé region. REFDIF domains (D1 to D3) and meshes. Representation of the range of incident waves to be considered, at each domain.

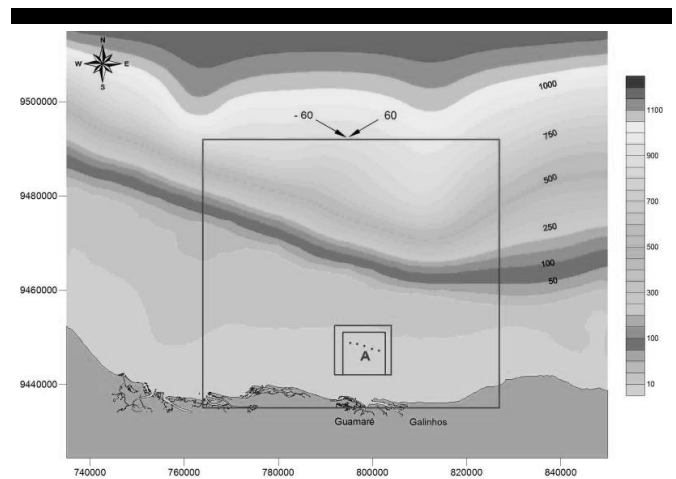


Figure 3. SWAN model: Domain and meshes used. Representation of the range of incident waves to be considered, at the domain.

For the definition of the domains and meshes, the same bathymetry was used as for model REFDIF (Figure 2, Figure 3). The first mesh covers the entire offshore region of Galinhos and Guamaé with dimensions of 63 km by 57 km and spacing of 300 m. The 2nd mesh, a more refined one within the first one, had a resolution of 150 m, a total of 12 km by 10.5 km. The 3rd mesh, the most refined and embedded in the second one, had a resolution of 25 m and dimension of 9 km by 9 km.

The offshore incident wave spectrum boundary conditions are imposed on two sides of the 1st mesh, which depend on the incident wave direction. The results of the global mesh provide the boundary conditions for the 2nd mesh, and the results of that mesh provide the boundary conditions for the 3rd mesh.

In the present calculations, neither currents nor winds were considered. On the 1st mesh, only the variation of water depth along the domain was considered. For the 2nd and 3rd meshes, diffraction and nonlinear effects were included.

PRESENTATION AND DISCUSSION OF RESULTS

Values of wave heights and wave directions for all 1,053 simulated conditions at were compared on the entire area along the coastline between Galinhos and Guamaé and a limited area centered on the area of interest, Figure 2 and 3. Results were also obtained along the bathymetric contour of -8 m (line A), at 5 selected points about 800 m apart from each other.

Based on those results, the following figures were chosen:

- Wave characteristics (wave height and wave direction) in 3rd mesh of the domain of calculation, for incident waves $\theta = -40^\circ$, 0° and 40° , $T=7$ s and $H=2$ m;
- Wave agitation characteristics (height and direction) along the bathymetric contour of -8 m (CD), for incident waves with $\theta \in [-60^\circ, 60^\circ]$, $T=7$ s and $H=2$ m.

Note that the wave condition, $T=7$ s and $H=2$ m, as concluded from the results, corresponds to the most frequent one.

Wave characteristics along the domain

From the analyses of wave characteristics along the domain, it appears that, in general, with both models, the incident wave with $T=7$ s and $H=2$ m, suffers a progressive rotation as the wave propagates shoreward. The waves hit the coast with greater

intensity as the incident wave directions turn from -40° to 0° or 40° to 0° . The changes occur both in wave height (increase or decrease) and in wave direction, depending on the offshore wave considered. Changes in wave height are more significant than the ones in wave direction, especially for REFDIF model results.

For REFDIF model, there is more variability in the values of wave height along the domain leading to areas of convergence/divergence of wave energy. This variability is more significant for the directions of -40° and 40° . For the SWAN model, there are much less areas of convergence/divergence of energy. The wave characteristics is maintained unchanged (less variability in the values of wave height along the domain) or is reduced slightly for directions between -40° to 40° .

The differences between results from the two models can be explained by the much higher spatial resolution (3 m) of REFDIF than that of SWAN model (25 m) at the 3rd mesh. Moreover, REFDIF is a regular wave propagation model and does not consider the scattering of waves in frequency and direction, as SWAN does. These two differences lead to a smoother wave height values by SWAN.

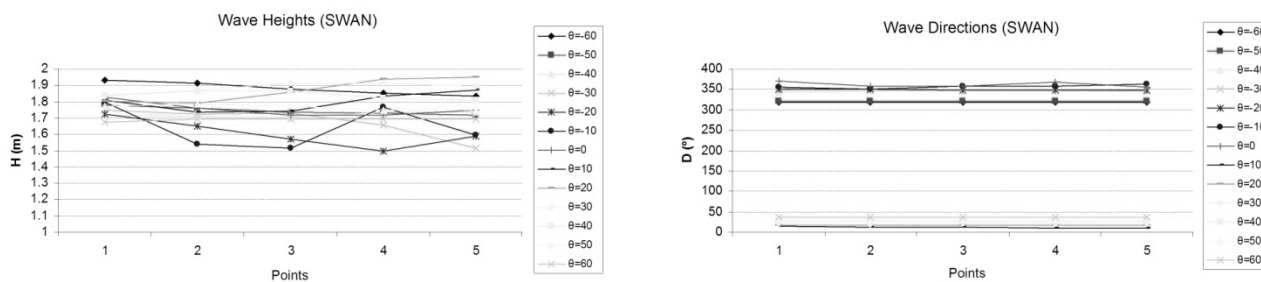
Wave properties along the contour -8m

Figures 4 to 6 present the SWAN and REFDIF results for wave height and direction at 5 points along the bathymetric contour -8m (CD), spaced by 800 m, for incident waves with $T=7$ s and $H=2$ m and wave directions between -60° and 60° .

Regarding the variation of wave height with the incident wave direction, it can be seen that, with the model REFDIF:

- For incident wave directions between 60° and 30° , wave heights vary from 1.5 to 2.1 m, reaching the coast with a slight reduction or without major changes in height;
- For the incident wave direction between -40° and -50° , wave heights are always less than the deep water values, showing greater variability over the bathymetric points;
- For the incident direction of -60° , wave heights increase, what seems surprising because it is a very oblique incidence. It seems that maybe the model REFDIF is used outside its domain of validity.

With the SWAN model, it was observed that for all wave directions, wave heights vary from 1.5 to 2.0m, reaching the coast without significant changes. For most directions, there is no



a) b) Figure 4. – SWAN model. Significant wave height (a) and mean wave direction values (b) along the bathymetric line of -8 m (CD), for incident waves of $T_p=7$ s, $H_s=2.0$ m and $\theta=[-60^\circ, 60^\circ]$.

variability in the wave height values over the points of bathymetric contour, except for wave directions of -10° and -20° .

Regarding the variation of local wave direction with the incident wave direction, D_0 , one can see that, in general, with the two models:

- There seems to be a linear relation between incident wave directions and wave directions at points in the bathymetric contour;
- For incident wave directions between 0° and 20° do not change along the domain, which is expected since they are almost parallel to the direction of the gradient of the bathymetry;
- For wave direction values higher than 20° the calculated values of the wave direction near the coast are lower than the incident wave (spin-wave to the left, to align with the gradient of the bathymetry);
- For values below 0° the calculated values of the wave direction near the coast are higher than the incident wave (spin-wave to the right, to align the gradient of the bathymetry).

The differences between results from the two models are more evident for wave height than for wave direction. Although the bathymetries used in both models are similar in terms of the orientation of the contour lines, there are significant differences in shallow areas because of different grid spacings.

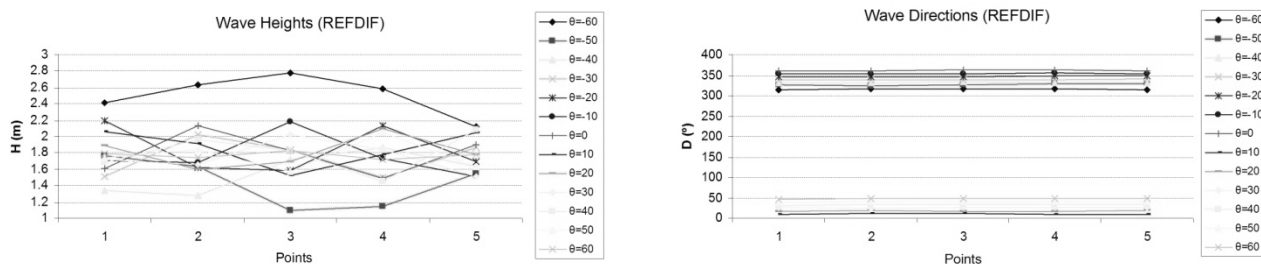
In addition, diffraction in the SWAN model is considered approximately as a directional dispersion which is not the case of REFDIF model. In the other way, REFDIF model only propagates regular waves, and so does not take into account the spectral dispersion (direction and frequency) and changes on the wave period by transfer of energy between spectral components such as

the model SWAN models. In addition, it was admitted that the wave heights, periods and directions, resulting from calculations with regular waves REFDIF model, are equivalent to the values of significant wave heights, peak periods and peak directions of a wave spectrum, which is also an approximation.

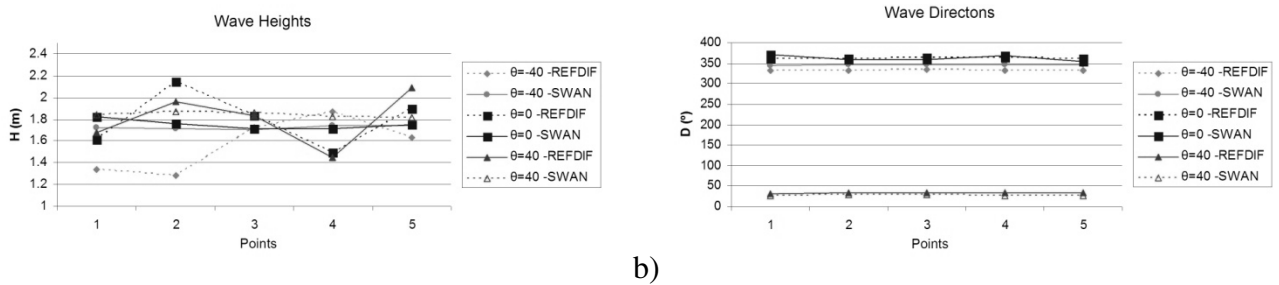
CONCLUSIONS

This paper presented the application of REFDIF (Dalrymple and Kirby, 1991) and SWAN models (Booij et al. 1991) to the wave propagation at the coastal zone between Guimarães and Galinhos, Rio Grande do Norte, Brazil, for different incident wave conditions. While REFDIF model is a phase-resolving model for monochromatic waves, SWAN is a phase-averaged model that propagates a wave spectrum.

Results from both models were compared at the entire domain and along the bathymetric contour of -8 m (CD), showing similar patterns. In fact, overall, for incident wave $T=7$ s and $H=2$ m, there is a gradual rotation of the wave direction, adjusting to the bathymetric contours (refraction effect). Changes in wave height, either increase (convergence areas) or decrease (divergence areas), depended on the incident wave direction. In general, higher waves reach the shore as the incident wave direction turns from -60° to 0° or 60° to 0° . With both models, the wave direction at various points is the result of combined refraction-diffraction and depends on the incident wave direction. In general, incident waves with a direction of about 0° and 20° suffer virtually no change in direction, whereas waves with directions outside this range have opposite variations.



a) b) Figure 5. – REFDIF model. Significant wave height (a) and mean wave direction values (b) along the bathymetric line of -8 m (CD), for incident waves of $T_p=7$ s, $H_s=2.0$ m and $\theta=[-60^\circ, 60^\circ]$



a) b) Figure 4. – Comparison of REFDIF and SWAN results. Wave height and direction values along the bathymetric line of -8 m (CD), for incident waves of $T=7$ s, $HS=2.0$ m and $\theta=-40^\circ, 0^\circ$ and 60° .

Significant differences between both models have been found with regard to wave height variation: SWAN results are smoother than REFDIF ones, especially in the shallower depths. There is greater variability in REFDIF wave height values along the domain because of areas of convergence/divergence of wave energy, which does not occur for SWAN. This may be partly due to the much larger spatial resolution adopted for the 3rd computational mesh used in the SWAN (25 m) compared to the REFDIF (3 m), leading to smoother bathymetry, but also results from the intrinsic mathematical models. Calculations should be made for this test case with the SWAN model using meshes with greater spatial resolution to obtain values closer to REFDIF.

In summary, both models showed to be appropriate for the study area. While SWAN is simpler to be applied, especially in regard to the preparation of the computational grids, it demanded higher computational time in comparison to REFDIF. In addition, SWAN can be applied to a larger region, but the resolution of the computational grid, especially in smaller water depths, needs special consideration since it may conduct to some mistakes in the local wave field. Otherwise, REFDIF is a monochromatic wave model and does not take into account the spectral dispersion (in direction and in frequency), or the change on the wave period due to energy transfer between spectral components, as it occurs in Nature and is modeled by SWAN.

So, in large coastal areas, SWAN model is a good alternative while for the propagation near the coast, where the bathymetry changes more significantly, REFDIF should be used.

In other applications of these models, it is advisable to assess what are the most important problems and, therefore, which model best simulates them. It is important to remember that, in addition to the physical phenomena that are decisive in choosing the model, there are other aspects to take into account, such as the size of the study area, the purpose of the study and the its urgency.

REFERENCES

- BOOIJ, N., RIS, R. C. and HOLTHUIJSEN, L. H., 1999. A Third-generation Wave Model for Coastal Regions, Part I, Model Description and Validation. *Journal Geophysical Research*, 104 (C4), pp. 7649-7666.
- CASTRO, A. F. ; AMARO, V. E. ; C.F. de Souza ; GRIGIO, A.M. 2009. Modeling and Development of a Computacional System to Create Environmental Sensitivity Index Maps for Oil Spill in High-Energy Coastal Enviroments. *Journal of Coastal Research*, v. 56, p. 1474-1478.
- DALRYMPLE, R. A. and KIRBY, J. T.; 1991. REFDIF 1, Version 2.3, Documentation Manual. Combined Refraction/Diffraction Model. CARC Report 91-91, University of Delaware, January.
- FORTES, C. J. E. M.; PINHEIRO, L.; PALHA, A.; 2007. O pacote SOPRO: Evoluções recentes. 5ªs Jornadas Portuguesas de Engenharia Costeira e Portuária” (JPECP), Lisboa, Outubro.
- FORTES, C. J. E. M.; PINHEIRO, L.; SANTOS, J. A.; NEVES, M. G. O.; CAPITÃO, R., 2006. SOPRO – Pacote integrado de modelos para avaliação dos efeitos das ondas em portos. *Revista da Tecnologia da Água*, Edição I, Março de 2006.
- GRIGIO, A. M., AMARO, V. E., VITAL, H., DIODATO, M. A., 2005. A method for coastline evolution analysis using GIS and Remote sensing - A case study from the guamare city, Northeast Brazil. *Journal of Coastal Research*, Florida, USA, v. 42, p. 412-421.
- GRIGIO, A. M., SOUTO, M. V. S, CASTRO, A. F. de, AMARO, V. E., VITAL, H., 2006. Use of remote sensing and geographical information system in the determination of the natural and environmental vulnerability of the Municipal District of Guamaré - Rio Grande do Norte - Northeast of Brazil. *Journal of Coastal Research*, Special Issue 39 (Proceedings of the 8th International Coastal Symposium). v. 39, p. 293-298.
- HOGBEN, N.; ,1986. Global Wave Statistics.
- STATTEGGER, K.; CALDAS, L. H. de O. and VITAL,H. , 2004. Holocene coastal evolution of the northern Rio Grande do Norte coast, NE Brazil. *Journal of Coastal Research*, SI39, proc. ICS2004.
- VITAL, H., GUEDES, I. M. G., 2006 . Erosion on areas of oil and gas exploration along the coast of northeastern Brazil: The Guamaré Hotspot. WIT Transactions on Ecology and The Environment, Inglaterra, v. 88, p. 175-182.
- VITAL, H. ; GOMES, M.P. ; TABOSA, W. F. ; FRAZAO, E. P. ; PLÁCIDO JUNIOR, J. S. ; SANTOS, C. L. A. 2010. Characterization of The Brazilian Continental Shelf Adjacent to Rio Grande do Norte State, NE Brazil. *Brazilian Journal of Oceanography* (Press) , v. 58, p. 43-54.

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