Spatiotemporal Variability of Longshore Sediment Transport on the Brazilian Coast

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SPATIO-TEMPORAL VARIABILITY OF LONGSHORE SEDIMENT TRANSPORT ON THE BRAZILIAN COAST ☆

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Abstract

The lack of planning and management regarding the transport of sediments along the coast can alter the existing equilibrium in coastal regions, causing or accelerating erosive processes and resulting in economic and environmental damage. Thus, it is important that the characteristics of the coastal drift be investigated, serving as source of information for future projects involving the coastal environment management. Within this context, the present work aims to identify the annual sediment transport averages along the Brazilian coast, the dominant direction of the coastal drift and its spatial variability. For this, a wind-generated wave modeling was considered, with 37 years of data (1979 to 2015), as well as four sediment transport formulations. For the spatiotemporal variability, the analysis of wavelets was applied, relating the effect of cycles of variability over the behavior of longshore sediment transport. The results showed that the largest annual volumes of sediment transport occurred in the northeastern Region of Brazil, reaching approximately $850\,000\,\mathrm{m^3\,year^{-1}}$. On the other hand, the smallest transport averages occurred in the southern region, in the state of Santa Catarina, reaching the value of $13\,497\,\mathrm{m^3\,year^{-1}}$. In the northeast region, annual and interannual cycles were more frequent and more energetic than in the southern Region, where short cycles presented similar importance to longer cycles, during 37 years of the study. However, in the overall context of the analysis, the long period cycles are more significant for longshore

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sediment transport, since this is a long term process. In this way, the present article contributes with information on longshore sediment transport, highlighting the annual means and the dominant drift, and deals with important questions about the influence of cycles of variability in the study region, emphasizing the importance of longer period events for the control of sedimentary transport in the Brazilian coast.

Keywords: Brazilian Coast, CERC, Kamphuis, Wavelets, Sediment Transport.

1. Introduction

Sandy beaches present it own dynamic due to the mobility of sediments transported by the constant effects of waves, coastal currents, tides and winds, resulting in processes of beach accretion and/or erosion (Klein et al., 2006). The movement of sediments transported along the coast, either by natural causes or anthropogenic, can change the existing balance in certain environments, causing or accelerating erosion processes and resulting in economic and environmental damages (CERC, 1984).

The waves play a substantial role in coastal landscape, influencing the coastal features, inputting morphological differences in space and time scales, according to (Holthuijsen, 2007). In addition, the study of coastal dynamics involves the evaluation of the distribution of wave energy, the patterns of sediment dispersion and the balance of sediment along the coast (Silva et al., 2007).

The longshore sediment transport is a conditioning factor for the occurrence of morphological changes in coastal environments. Therefore, prior knowledge of the local wave climate and coastal sediment transport represents an essential source of information for the design of projects, coastal management plans and applications in erosion risk analysis.

Several studies were carried out at national and global level to analyze the patterns of dispersal of the longshore sediment transport. For example, Giosan et al. (1996) on the Black Sea coast, in Romania, Kumar et al. (2000) along the coast of Kannirajapuram, India, and Oliveira et al. (2004) in the Portuguese west coast. In all studies the results obtained improve the knowledge of the variation of the longshore transport along the beach profile, its average annual value, and a way to quantify other parameters that characterize the coastal zone where the sediment transport induced by waves is significant.

Considering researches in Brazil, once there are hundreds of coastal areas where the process of environmental change became very sharp and harmful, it is important highlight Bittencourt et al. (2005), Moura and Morais (2011), Oliveira et al. (2015) and Silva et al. (2016), which estimated the pattern of sediment

dispersion in different regions. Recently, Trombetta et al. (2020) studied the potential of longshore sediment transport by the action of waves considering all Brazilian coast, showing that there are many studies associated with this issue.

The space-time variability in sediment transport is able to predict the effects of the passage of short and long-term phenomena, such as cold fronts, changes in the seasons, El Niño events, for different regions. However, this analysis is little studied, and has no applications along the Brazilian coast. Within this perspective, the present work has as main objective to investigate the effect of short and long period cycles (intra-seasonal, seasonal, annual and interannual weekly) in the sediment transport along the entire Brazilian coast, considering a period of 37 years.

1.1. Study Area

The study area involves all Brazilian coast, extending for approximately 9000 km, between 4° N, near Cabo Orange in Amapá state, and 34° S, at Arroio Chuí in Rio Grande do Sul state (Figure 1). The Brazilian continental margin has a substantial physic and environment diversity, being a challenge for the coastal management. This diversity is characterized for heterogeneity in relation to the coastal morphology and hydrodynamics components.

According to Short and Klein (2016), the long extension of the Brazilian coast, climates variety and coastal processes requires that the littoral be divided em different sectors, with the purposes to understand the impacts of these aspects on the coast and beach systems. In addition, Tessler and Goya (2005) explained that Brazil has many climatic, oceanographer e geomorphological elements that condition certain processes in different coastal segments.

In this paper, the longshore sediment transport will be presented in some points of the study area, followed by the analysis of the spatiotemporal variability throughout the Brazilian coast. Again, some places will be chosen to further the discussion.

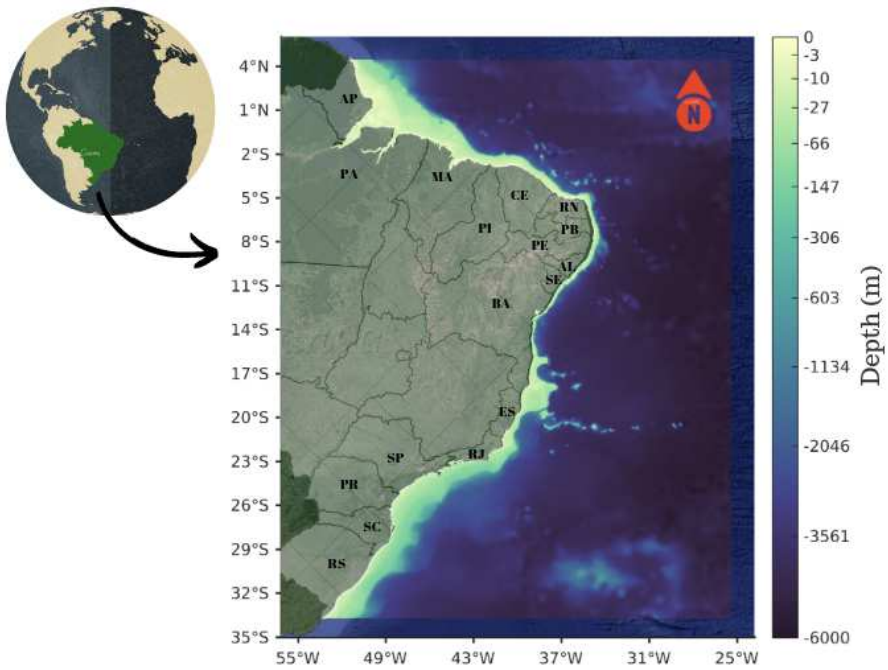

Figure 1: Representation of the study area, with bathymetric data and pointing coastal states - Amapá (AP), Pará (PA), Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE), Bahia (BA), Espírito Santo (ES), Rio de Janeiro (RJ), São Paulo (SP), Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS). The colorbar represents the depth in meters.

2. Methodology

This study involves the analysis of sediment transport throughout the Brazilian coast, considering mathematical formulas and numerical simulations. A third generation wave model was applied to simulate the sea state, for a period of 37 years (1979 to 2015). The numerical domain was represented by an unstructured mesh composed of 547 479 nodes, with a distance between 500 m on the coastline (region of interest in the study) and 55 km near the oceanic boundary, according to Figure 2.

The wave model TOMAWAC (TELEMAC-Based Operational Model Addressing Wave Action Computation[2]) was used to simulate the sea state on the Brazilian coast. This model is maintained by the consortium open TELEMAC-

[2]www.opentelemac.org

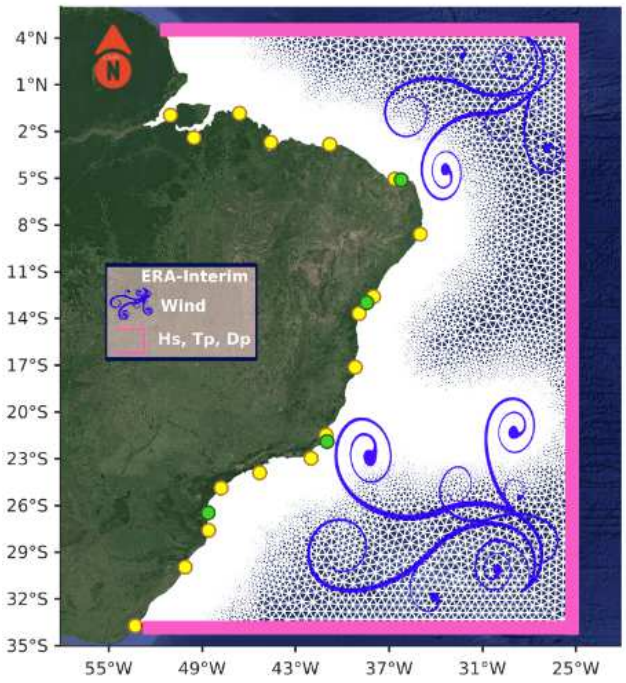

Figure 2: Figure of the computational domain with surface and boundary conditions. The points represent the areas used to analyze the spatial (in yellow) and temporal (in green) variability. The pink lines and the blue symbols represent wave and wind data, respectively.

MASCARET, and was developed by Benoit et al. (1996).

TOMAWAC is a spectral wave model that calculates the sea state by solving the Wave Action Density Conservation Equation (Hasselmann et al., 1988; Holthuijsen et al., 1998). As reported by Awk (2017), this wave model is able to calculate the changes in the wave energy spectrum generated by the wind and also the wave agitation for applications in the ocean and coastal domains.

In order to carry out the simulations, the surface of the TOMAWAC model has been forced with wind data, interpolated at all points of the numerical mesh (blue symbols in Figure 2). The oceanic contour was forced with significant height data (H_s), peak period (T_p) and average wave peak direction (D_p), inserted in mesh oceanic boundary (pink lines in Figure 2).

The wave and wind data of boundary conditions were obtained from the

ERA Interim Reanalysis Project[3] from ECMWF (European Centre for Medium-Range Weather Forecasts), for the time period ranging from 1979 to 2015. The data used as initial and boundary conditions were interpolated and prescribed for each point of the finite element mesh, with a spatial resolution of 0.75° of latitude and longitude, and temporal resolution of 6h.

The longshore sediment transport was calculated using mathematical formulas, which was proposed by the Coastal Engineering Research Center (CERC, 1984) and by Kamphuis (1991). These methodologies are widely used for researches and presents coherent results when compared with *in situ* data.

Wave parameters, beach profiles and sedimentary characteristics were considered in the calculations to estimate the sediment transport. In addition, in the CERC (1984) formula, there is an dimensionless coefficient (K) that directly relates the longshore sediment transport with the waves energy flow (Lima et al., 2002). The value recommended by CERC (1984) for this coefficient is 0.39, considering American beaches. In this way, for the expression becomes more reliable, other values of K were analyzed, considering the formulas proposed by Kamphuis et al. (1986) and Mil-Homens et al. (2013), according to Table 1.

Table 1: Mathematical formulas used in the calculation of the longshore sediment transport.

CERC (1984)	$Q_v = 0.0625 K \rho_a g^{0.5} H_{s,b}^{2.5} [\sin(2\alpha_b)] (\gamma_b)^{-0.5} (\rho_s - \rho_a)^{-1} (1-p)^{-1}$
Recommended to American Beaches	$K = 0.39$
Kamphuis et al. (1986)	$K = 0.022 (\gamma_b H_{s,b})^{0.5} (D_{50})^{-0.5}$
Mil-Homens et al. (2013)	$K = [2237.7 (H_{s,b})^{1.45} (L_0)^{-1.45} + 4.505]^{-1}$
Kamphuis (1991)	$Q_v = 6.4 \times 10^4 (H_{s,b})^2 (T_p)^{1.5} (m_b)^{0.75} (D_{50})^{-0.25} [\sin^{0.6}(2\alpha_b)]$

In these equations, K is the dimensionless coefficient, ρ_a is the sea water density ($1025\,\mathrm{kg\,m^{-3}}$), g is the acceleration of gravity ($9.81\,\mathrm{m\,s^{-2}}$), $H_{s,b}$ is the significant wave height at the breaker (m), α_b is the wave incidence angle at the breaker (°), γ_b is the breaker parameter (typically 0.78), ρ_s is the sediment

[3] www.ecmwf.int

density (typically 2650 kg m^{-3}), p is the sediment porosity (typically 0.4), D_{50} is the median particle diameter of sediments, L_0 is the wavelength (m), T_p is the wave peak period and m_b is the slope of the beach profile at the breaker.

The sedimentological data of the study region (Table 2) were obtained by the expeditions of the ReviZEE Program and prepared by the *Diretoria de Hidrografia e Navegação* - Brazil. The formulations proposed by CERC (1984) and Kamphuis (1991) consider only a sedimentary fraction, so the distribution of sediments throughout the study region has been simplified.

Table 2: Distribution of sedimentological data along the Brazilian coast based on the ReviZEE Program.

Sediment Fraction	D_{50} (mm)	**Stretch**
Muddy sand/Very fine sand	0.06	Cabo Orange (AP) to Parnaíba (PI)
Coarse sand	1	Parnaíba (PI) to Maceió (AL)
Medium sand	0.5	Maceió (AL) to Cabo Frio (RJ)
Muddy sand/Very fine sand	0.06	Cabo Frio (RJ) to Chuí (RS)

Amapá (AP), Piauí (PI), Alagoas (AL), Rio de Janeiro (RJ) and Rio Grande do Sul (RS).

The spatiotemporal variability of the longshore sediment transport was investigated through the wavelet analysis, following the methodology proposed by Torrence and Compo (1998) and rectified by Liu et al. (2007) and Veleda et al. (2012). The spatial variability was analyzed for a transect (which connects the yellow dots in Figure 2), towards the usage of the wavelet analysis. In the two-dimensional analysis, a DOG wavelet (known as Mexican Hat) was considered.

At first, all the formulas used in the calculation of sediment transport were investigated, resulting in similar patterns in relation to spatial variability's for cycles between 100 and 1000 days. Thus, for this article, the formulation of CERC (1984), with the parameter K calibrated by Kamphuis et al. (1986), was chosen to compose this analysis, since it represented one of the formulas considered most suitable for the calculation of sedimentary transport in several sectors of the Brazilian coast.

The wavelet method also allowed the analysis of the temporal variability

of longshore sediment transport along the Brazilian coast. For this analysis, four points were selected located in Galinhos - Rio Grande do Norte, Salvador - Bahia, Praia do Açu - Rio de Janeiro and Balneário Barra do Sul - Santa Catarina, which are indicated by the green dots in Figure 2. For each point, the sediment transport formula considered more adequate was used with the application of one-dimensional DOG wavelet.

2.1. Validation

The validation of the numerical model TOMAWAC was realized comparing the main wave characteristics of the Brazilian continental shelf with measured data by four buoys from the *Programa Nacional de Boias* - Brazil (PNBOIA[4]). These buoys are located in Recife - Pernambuco, Cabo Frio - Rio de Janeiro, Santos - São Paulo and Rio Grande - Rio Grande do Sul, at 200 m depth, covering the period from 2010 until 2015.

Validation is important to properly reproduce the main wave characteristics of the Brazilian continental shelf in the model. Thus, the significant height (H_s) and the peak period (T_p) of the waves were analyzed through Statistical metrics, as show in Table 3.

Table 3: Statistical metrics calculated by comparing modeled data and measured data.

	RECIFE - PE		**CABO FRIO - RJ**		**SANTOS - SP**		**RIO GRANDE - RS**	
	Modeled	**Measured**	**Modeled**	**Measured**	**Modeled**	**Measured**	**Modeled**	**Measured**
HS (m)	1.6476	1.6054	1.5863	1.2322	1.6264	1.9586	1.6512	1.9979
ER (m)	0.0262		0.2874		0.1696		0.1735	
MAE (m)	0.0421		0.3541		0.3322		0.3467	
RMSE (m)	0.2902		0.7305		0.5977		0.7482	
Bias (m)	-0.0421		-0.3541		0.3322		0.3467	
	Modeled	**Measured**	**Modeled**	**Measured**	**Modeled**	**Measured**	**Modeled**	**Measured**
Tp (s)	8.5713	8.5713	8.4079	10.5817	8.4096	9.6381	8.6140	8.9654
ER (s)	0.0174		0.2054		0.1274		0.0391	
MAE (s)	0.1520		2.1738		1.2285		0.3514	
RMSE (s)	2.2249		3.5947		2.7904		2.4992	
Bias (s)	0.1520		2.1738		1.2285		0.3514	

Pernambuco (PE), Rio de Janeiro (RJ), São Paulo (SP) and Rio Grande do Sul (RS).
Relative Error (ER), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).

The comparison of the statistics showed a good correlation between the modeled data by TOMAWAC and measured data by PNBOIA, as shown by the similarity in the values of H_s and T_p in all sites. Besides that, all statistical

[4]http://www.goosbrasil.org/pnboia

metrics resulted close to zero, highlighting the Relative Error (ER) and the Mean Absolute Error (MAE) presented in Recife, with the lowest values.

In addition, the Root Mean Square Error (RMSE) resulted close to zero for H_s in all sites, representing a low magnitude of the error. This metric resulted near to 2.5 for the T_p, but is important explain that this parameter is less important than H_s in the sediment transport formulas considered in this study.

The Bias values were considered to indicate whether the model is overestimating (positive values) or underestimating (negative values) the *in situ* data. As shown, the values of H_s in TOMAWAC model are underestimated for Cabo Frio and Recife, unlike the other sites.

In this way, it was possible to verify a good correlation between the modeled and measured data, verifying the reliability of TOMAWAC model for the purposes of this study. Besides, TOMAWAC model was also validated along the Brazilian coast in the studies of Kirinus et al. (2018), Guimarães et al. (2019) and Trombetta et al. (2020).

The verification of the longshore sediment transport was carried out by comparing the annual rates calculated with the formulations presented previously and the results of Brazilian studies related to the theme. Thus, the study area was divided into different sectors and all formulas were tested, according to Table 4.

Table 4: Longshore sediment transport rates in $m^3\,year^{-1}$. Negative values indicate that the liquid transport direction is towards South.

	CERC (1984)			Kamphuis (1991)	Previous Studies
Localização	**0,39**	**Kamphuis et al. (1986)**	**Mil-Homens et al. (2003)**		
Galinhos - RN	322 640	14 549	**86 275**	52 690	**185 839**
Natal - RN	846 680	44 473	134 430	**160 560**	**250 000**
Aracaju - SE	- 1 392 600	- 101 320	- 208 830	**- 500 590**	**- 355 600**
Salvador - BA	- 101 430	- 9 397	- 45 048	**- 166 430**	**- 194 500**
Linhares - ES	- 2 123 900	**- 162 390**	- 364 410	- 107 610	**161 000**
Vila Velha - ES	- 2 709 700	**- 218 040**	- 465 840	- 1 378 900	**- 205 588**
Itapemirim - ES	1 049 700	**66 431**	215 650	295 105	**69 313**
Barra do Açu - RJ	2 159 600	**165 480**	316 010	289 090	**182 500**
Cibratel - SP	- 1 654 000	**- 356 760**	-296 940	- 521 410	**- 400 000**
Matinhos - PR	625 580	**142 240**	115 010	118 500	**188 496**
Baln. Barra do Sul - SC	1 767 500	**402 970**	314 490	1 109 300	**459 900**

RN - Rio Grande do Norte; SE - Sergipe; BA - Bahia; ES - Espírito Santo; RJ - Rio de Janeiro; SP - São Paulo; PR - Paraná; SC - Santa Catarina.

The first site tested was in Galinhos - Rio Grande do Norte, where the

longshore sediment transport rates calculated with the four formulations were compared with the study of Marcelino et al. (2018). These authors found 185 839 $m^3\,year^{-1}$ for the analyzed area, with a predominant direction westward.

The results of the formulas considered in the present study indicated the same predominant direction, and the formulation proposed by CERC (1984), with the parameter K by Mil-Homens et al. (2013), was the one that best approached the rate found by Marcelino et al. (2018), resulting in 86 275 $m^3\,year^{-1}$. In this way, this formulation was chosen to represent the sectors close to Galinhos, more precisely between Parnaíba - Piauí and Touros - Rio Grande do Norte.

Another site tested was in Natal - Rio Grande do Norte, where the study of Araújo (2015) was considered in the analysis. The results of longshore sediment transport calculated for these authors showed the predominant direction northward, with a rate of 250 000 $m^3\,year^{-1}$. In the present study, the predominant direction also resulted northward for the four formulas, and the methodology proposed by Kamphuis (1991) was the most similar to the study of Araújo (2015).

At Aracajú - Sergipe, the average sediment transport rate of 500 590 $m^3\,year^{-1}$ was obtained by Kamphuis (1991) formulation, with predominant direction toward the south. This site was compared with the study results of Bittencourt et al. (2005), which found rates of approximately 355 600 $m^3\,year^{-1}$ with southward direction, validating the results of the present study.

Bittencourt et al. (2005) also found rates of 194 500 $m^3\,year^{-1}$ with dominant direction southward, in Salvador - Bahia, which is similar to the rate of 166 430 $m^3\,year^{-1}$ calculated in the present work using the Kamphuis (1991) formulation. Thus, this formula was considered to represent the sectors between Carnaubinha - Rio Grande do Norte and Canavieiras - Bahia.

The last sector defined involves Linhares - Espírito Santo, where Oliveira et al. (2015) found an average of 161 000 $m^3\,year^{-1}$, which is similar to the

result calculated using the CERC (1984) formulation, with the parameter K by Kamphuis et al. (1986). The result reached 162 390 $m^3\,year^{-1}$, and the transport was northward in both studies, showing that the data is validated.

In Vila Velha and Itapemirim beaches, also in Espírito Santo, Contti Netto (2013) found transport rates similar to those obtained in the present study by applying the CERC (1984) formulation, with K calibrated by Kamphuis et al. (1986). The author found values of 205 588 $m^3\,year^{-1}$ directed southward and 69 313 $m^3\,year^{-1}$ directed northward, respectively. The rates are similar to the rate calculated by the present study, respectively 218 040 $m^3\,year^{-1}$ and 66 431 $m^3\,year^{-1}$.

In the southeastern region, in Barra do Açu - Rio de Janeiro state, the formulation of CERC (1984), with K calibrated by Kamphuis et al. (1986), was the one that better approximated the results obtained by Bastos and Silva (2000). The values calculated in both studies reaches 165 480 $m^3\,year^{-1}$ and 182 500 $m^3\,year^{-1}$, respectively, with predominant direction northward.

In São Paulo state, the transport rate was validated at Cibratel beach based on the proximity of the results given by the CERC (1984) formulation, with K calibrated by Kamphuis et al. (1986) and the outcomes obtained by Araújo and Alfredini (2001). The average transport was similar in the studies, reaching 356 760 $m^3\,year^{-1}$ and 400 000 $m^3\,year^{-1}$, respectively, and dominant direction toward the south, which validates the results.

At Matinhos beach - Paraná, Wosiacki and Gobbi (2012) found an average of 188 500 $m^3\,year^{-1}$, with a predominant direction toward the north. This result is similar to the transport calculated using the CERC (1984) formula, with K calibrated by Kamphuis et al. (1986), which gives a rate of 142 240 $m^3\,year^{-1}$, also northward.

In the Southern region, Castilhos and Gré (2006) found a transport rate of 459 900 $m^3\,year^{-1}$ at Balneário Barra do Sul - Santa Catarina. This rate is similar to the one calculated using the CERC (1984) formula, with K calibrated by Kamphuis et al. (1986), which resulted in 402 970 $m^3\,year^{-1}$. Moreover, the

transport direction toward north validates the analyzed site. In this way, this formulation was chosen to represent the sectors between Belmonte, in Bahia, and Meia Praia, in Santa Catarina.

The annual averages calculated for the longshore sediment transport were orders of magnitude similar to existing studies in the literature. Hence, for the present article, the rates were calculated in eleven sites along the Brazilian coast, considering a specific method for each sector, according to Table 5.

Table 5: Definition of the methodology used in each stretch along the Brazilian coast in comparison with past studies.

Stretch	**Methodology**
Parnaíba (PI) to Touros (RN)	CERC (1984) - K calibrated by Mil-Homens et al. (2013)
Carnaubinha (RN) to Canavieiras (BA)	Kamphuis (1991)
Belmonte (BA) to Meia Praia (SC)	CERC (1984) - K calibrated by Kamphuis et al. (1986)

Piauí (PI), Rio Grande do Norte (RN), Bahia (BA) and Santa Catarina (SC)

In addition, as expected, the dominant direction of littoral drift also had a good agreement within the analyzes, since it is highly influenced by the waves climate already validated. In this way, the formulas considered for the calculation of the longshore sediment transport proved to be adequate in different sectors of the Brazilian coast, with the exception of the CERC (1984) formulation, with the K equal to 0.39, which overestimated the results in all situations.

A fraction of the South region and in the North region of Brazil were not considered in the calculation of the longshore sediment transport. This occurs due to the possibility of these sectors being influenced by the boundary conditions imposed into the numerical domain of TOMAWAC Model, which possibly caused variations in the results. In addition, the southern region has been subject of many studies, for example Calliari and Klein (1993), Barletta (2000), Lima et al. (2002), Siegle and Asp (2007), Martinho et al. (2009) and Silva et al. (2016).

3. Results and Discussions

This section presents the results obtained from the analysis of the waves generated by wind behaviour, over 37 years (between 1979 and 2015). These results were applied in the calculation of the longshore sediment transport and, consecutively, an analysis of the spatiotemporal variability was performed.

Results obtained for the averages of significant height (H_s, in meters), peak period (T_p, in seconds) and direction of incidence of waves (M_d, in degrees) are derived from a simulation of waves generated by the wind. Figure 3 shows a schematic representation of the mean values obtained over all years simulated.

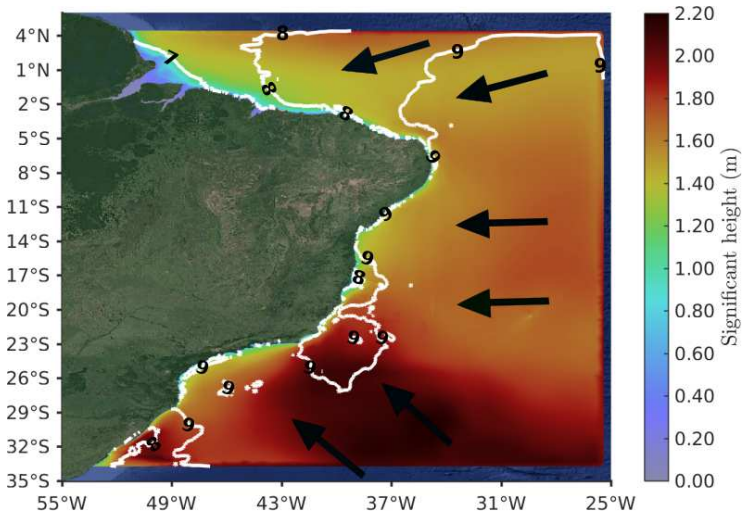

Figure 3: Results of the Brazilian Continental Shelf, overlapping image by Google Maps, Landsat/Copernicus, 2018. Frame shows H_s (m) in the surface, T_p (s) in the isolines and M_d in the arrows.

The results show that the distribution of the significant wave height over the entire Brazilian continental shelf is highly variable, with considerable variability between the northern and southern regions. The highest averages occurred in the South region, with values close to 1.2 m in the coastal zone of Rio Grande do Sul and Santa Catarina, decreasing to 0.8 m in Paraná.

In the Southeastern region, the averages remained at approximately 0.8 m in the coastal zone. An exception occurs in Cabo Frio and Cabo de São Thomé, both in Rio de Janeiro, where maximum values of 1.8 m are observed in the

offshore, once reflexive beaches characterize the region.

Finally, the north and northeast regions of Brazil presented smaller mean significant wave height when compared to the South. The values reached approximately 0.6 m in the coastal zone, and in the adjacencies of the Amazon River mouth presented even smaller significant wave height.

For the M_d, from the state of Amapá to Ceará, in the Northern Region, prevail the waves incidents of East and Northeast. The atmospheric system of the Brazilian equatorial region is related to the Intertropical Convergence Zone, which generates the trade winds from Northeast and Southeast that converge in the region (McGregor and Nieuwolt, 1998).

In the sector between the Rio Grande do Norte and the Espírito Santo, the predominant direction of incidence is East, with variations in specific regions of this passage. Dominguez (2009) showed that the main atmospheric circulation of this sector is determined by the South Atlantic Subtropical Anticyclone, with small variability linked to the seasonal cycles.

Finally, between Rio de Janeiro and Rio Grande do Sul, the waves come from East and Southeast. The atmospheric circulation pattern varies according to seasonal oscillations and the intensity and position of the South Atlantic Subtropical Anticyclone, according to Oliveira (2002). The passage of cold fronts over the region can interrupt this behavior, turning the wind direction to the Southern quadrant. These results showed a high discrepancy in the averages of H_s and M_d, in all the Brazilian continental shelf, mainly in relation to the northern and southern regions.

On the other hand, the wave T_p showed values similar throughout the area analyzed, varying between 7 and 9 s. The most frequent values are near 9 s, which is typical of swell waves generated by distant storms. The waves with shorter periods are classified as seas, and usually, they are caused by the effect of the local wind blowing on the sea surface.

The results presented in this section are in agreement with previous studies carried out by Pianca et al. (2010); Espindola and Araújo (2017); Guimarães

et al. (2019) and Trombetta et al. (2020). These authors analyzed the wave climate along the Brazilian coast from a combined approach, using data analysis and numerical modeling.

3.1. Longshore Sediment Transport Rates

Regarding the longshore sediment transport rates, some sites in the Brazilian coast were chosen to the calculation, considering a specific methodology for each region, with the corresponding diameter of sediments, as shown in Tables 6, 7 and 8. It is valid to emphasize that due to the proximity of the regions north and south of Brazil to the boundary conditions of the numerical model, these regions where excluded to the analysis of this study.

Table 6: Representation of longshore sediment transport rates (LST) in $m^3\,year^{-1}$, considering D_{50} equal to 1 mm.

Diameter	**CERC (1984) Coefficient K calibrated by Mil-Homens et al. (2013)**	**LST** ($m^3\,year^{-1}$)	**Kamphuis (1991)**	**LST** ($m^3\,year^{-1}$)
1 mm	Parnaíba – PI	48 200	Carnaubinha – RN	39 470
	Praia de Atalaia – PI	133 800	Maxaranguape – RN	86 014
	Praia de Maramar – PI	66 054	Ceará-Mirim – RN	102 290
	Praia de Barra Grande – PI	120 310	Natal – RN	160 560
	Barroquinha – CE	150 690	Parnamirim – RN	126 630
	Camocim – CE	89 247	Tibau do Sul – RN	261 560
	Acaraú – CE	43 188	Barra de Camaratuba – PB	138 860
	Itarema – CE	110 440	Balneário Lucena – PB	37 123
	Itapipoca – CE	88 403	Cabedelo – PB	154 000
	Paracuru – CE	397 610	Costa do Sol – PB	259 170
	Caucaia – CE	52 516	Praia do Amor – PB	124 650
	Fortaleza – CE	442 670	Pitimbu – PB	172 440
	Beberibe – CE	225 630	Pontas de Pedra – PE	215 650
	Aracati – CE	277 690	Olinda – PE	418 600
	Icapuí – CE	57 962	Pina – PE	765 810
	Porto do Mangue – RN	52 412	Sirinhaém – PE	325 960
	Galinhos – RN	86 275	Maragogi – AL	708 720
	Touros – RN	387 750	Barra de Santo Antônio – AL	342 330

Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE) and Alagoas (AL).

The mean liquid sediment transport behavior, over the 37 years simulated, can be explained due the wave climate, which is the main variable in the short and medium term coastal processes. As demonstrated in the Table 6, the formula of CERC (1984), with the coefficient K calibrated by Mil-Homens et al. (2013), was the most suitable for the calculation of the longshore sediment transport between Parnaíba (Piauí) and Touros (Rio Grande do Norte), where it was considered an average diameter of 1 mm, corresponding to a sedimentary fraction of coarse sand.

In this sector of the Northeast Region of Brazil, the waves are generated by the action of the trade winds (Tessler and Goya, 2005), resulting in the whole movement (atmospheric or oceanic) directed from East to West (Muehe, 1998). Thus, in this coastal segment, the drift has dominant sense to the West, as indicated by the positive averages in Table 6.

Trombetta et al. (2020) corroborates with these results, showing values of angles of incidence greater than 0° in this region, indicating that the waves are derived from East and Northeast and, therefore, at all points, the dominant drift is directed to the West. In addition, the same results are indicated in the Figure 3, where the arrows demonstrate the dominant direction of incidence of waves. The average annual sediment transport do not present large variations between Parnaíba and Touros, reaching maximum of $442\,000\,\mathrm{m^3\,year^{-1}}$ in Fortaleza, Ceará, and at least $43\,188\,\mathrm{m^3\,year^{-1}}$ in Acaraú, in the same state.

Analyzing the other points of the Table 6, it is possible to observe that between Carnaubinha - Rio Grande do Norte and Barra de Santo Antônio - Alagoas, the formulation of Kamphuis (1991) was defined as the most appropriate for the estimation of the longshore sediment transport. In addition, for this segment, the average diameter of sediments remained equal to 1 mm, corresponding to a coarse sand.

In the sector that involves the coast of Alagoas and Rio Grande do Norte, the study of Trombetta et al. (2020) demonstrated that the incidence angles are smaller than 0°, indicating that these come from Southeast and, therefore, becoming the dominant drift to the North. The studies of Bittencourt et al. (2005); Araújo (2015) and Gurgel (2017) corroborate these results, as well as Tessler and Goya (2005) that point out that in this region receives only waves generated from the Trade winds, indicating a transport resulting Northwards.

Regarding the average rates calculated for the longshore sediment transport, it is observed a high diversity among the values, highlighting the greatest averages that occurred in Pina - Pernambuco and in Maragogi - Alagoas, reaching $765\,810\,\mathrm{m^3\,year^{-1}}$ and $708\,720\,\mathrm{m^3\,year^{-1}}$, respectively. On the other hand, in

the sector further north there was a significant decrease of mean transported, resulting in 37 123 m^3 $year^{-1}$ in Balneário Lucena - Paraíba, and 39 470 m^3 $year^{-1}$ in Carnaubinha - Rio Grande do Norte.

Table 7 presents the stretch between Maceió - Alagoas and Farol de São Thomé - Rio de Janeiro, where was considered the sediment fraction equal to 0.5 mm, corresponding to medium sand. In the first sector, the formulation of Kamphuis (1991) proved to be the most appropriate, while in the second, the formulation of the CERC (1984), with the coefficient K calibrated by Kamphuis et al. (1986), had a more satisfactory result.

Table 7: Representation of longshore sediment transport rates (LST) in m^3 $year^{-1}$, considering D_{50} equal to 0.5 mm.

Diameter	**Kamphuis (1991)**	**LST** (m^3 $year^{-1}$)	**CERC (1984) Coefficient K calibrated by Kamphuis et al. (1986)**	**LST** (m^3 $year^{-1}$)
0.5 mm	Maceió – AL	-769 200	Belmonte – BA	127 780
	Jequiá da Praia – AL	-844 320	Santa Cruz – BA	121 150
	Feliz Deserto – AL	501 200	Trancoso – BA	142 110
	Piaçabuçu – AL	-450 320	Prado – BA	-61 034
	Pacatuba – SE	159 760	Alcobaça – BA	-31 069
	Barra dos Coqueiros – SE	-269 940	Mucurí – BA	-22 577
	Aracaju – SE	-500 590	São Mateus – ES	132 590
	Itaporanga d'Ajuda – SE	-262 610	Linhares – ES	162 390
	Jandaíra – BA	-133 280	Comboios – ES	-29 853
	Conde – BA	-382 930	Praia Formosa – ES	-169 030
	Entre Rios – BA	-672 790	Vila Velha – ES	-218 040
	Salvador - BA	-166 430	Nova Guarapari – ES	-154 500
	Valença – BA	-148 870	Itapemirim – ES	66 431
	Maraú – BA	604 100	Alto Lagoa Funda – ES	-82 975
	Itacaré – BA	648 340	São Francisco de Itabapoana - RJ	-71 836
	Ilhéus – BA	646 810	Atafona – RJ	-76 607
	Una – BA	293 640	Praia do Açu – RJ	165 480
	Canavieiras – BA	-54 035	Farol de São Thomé – RJ	122 460

Alagoas (AL), Sergipe (SE), Bahia (BA), Espírito Santo (ES) and Rio de Janeiro (RJ).

In these coastal sectors it is observed that the drift varies towards South and North on several points, due to the predominant incidence of the East waves, according to the Figure 3. This occurs because the wave climate in this region is maintained by the winds generated by the South Atlantic Anticyclone, according to Tessler and Goya (2005), with waves coming from the East, Northeast and Southeast. This behavior is also demonstrated in Trombetta et al. (2020), since variations in the direction of incidence of waves, interfering with the dominant pattern of littoral drift.

In the northern sector of Bahia, the drift is directed, in the majority of the

points analyzed, towards South, agreeing with the study of Bittencourt et al. (2002, 2008). While between Maraú and Trancoso, within the same state, the transport has dominant direction towards North (Bittencourt et al., 2000, 2008), with the exception of Canavieiras.

In the south of Bahia, the drift return its direction pattern Southwards. The patterns of sediment dispersion along the coast of Bahia vary according the general orientation of the coastline and the system of atmospheric circulation, therefore, this inversion occurs in the littoral drift along throughout the whole state.

In the coastal segment between the state of Espírito Santo and the Farol de São Thomé, the more effective waves for sediment transport are generated by the winds of Northeast and East quadrants (Tessler and Goya, 2005), explaining the directed drift, in most cases, towards South. In Linhares, the fact that the drift outcome is towards North is in agreement with the study of Oliveira et al. (2015), which demonstrated that the sediments provided by Rio Doce are transported preferentially to North due to the action of the waves.

For the Rio de Janeiro littoral, the study of (Bastos and Silva, 2000) demonstrated the occurrence of convergence in the littoral drift between Atafona and the Praia do Açu, among with other authors (Cassar and Neves, 1993; Bastos and Silva, 2000; Machado et al., 2018) that stated that the dominant direction of sediment transport in the vicinity of the Cabo de São Thomé is Northward. Thus, these studies are in agreement with the results presented in Table 7.

The calculated averages on the stretch between Maceió and Canavieiras presented the greatest values of longshore sediment transport in relation to any other points analyzed on the Brazilian coast, reaching $844\,320\,\mathrm{m^3\,year^{-1}}$ in Jequiá da Praia - Alagoas and $769\,200\,\mathrm{m^3\,year^{-1}}$, in the neighbor city, Maceió. The lower average occurred in Bahia State, at Canavieiras, reaching values of $54\,035\,\mathrm{m^3\,year^{-1}}$.

Among Belmonte and Farol de São Thomé, the rates of average sediment transport resulted not too considerable, reaching a maximums of $218\,040\,\mathrm{m^3\,year^{-1}}$

in Vila Velha - Espírito Santo. In Bahia, the values were quite discrepant, ranging from 142 110 $m^3\,year^{-1}$ in Trancoso towards 22 577 $m^3\,year^{-1}$ on Mucurí. In Espírito Santo the variations were also high, 218 040 $m^3\,year^{-1}$ in Vila Velha until 29 853 $m^3\,year^{-1}$ in Comboios. Rio de Janeiro, for instance, kept the averages on the order of 100 000 $m^3\,year^{-1}$.

Moving southwards, in the Table 8, which presents the stretch among Saquarema - Rio de Janeiro and Meia Praia - Santa Catarina, the CERC (1984) formula, with the K coefficient calibrated by Kamphuis et al. (1986), was the best fit. For this segment, it was considered an average grain diameter of 0.06 mm, corresponding to a sedimentary fraction of muddy sand/very fine sand.

Table 8: Representation of longshore sediment transport rates (LST) in $m^3\,year^{-1}$, considering D_{50} equal to 0.06 mm.

Diameter	**CERC (1984) Coefficient K calibrated by Kamphuis et al. (1986)**	**LST** ($m^3\,year^{-1}$)
0.06 mm	Saquarema – RJ	690 670
	Barra da Tijuca – RJ	625 670
	Praia de Maresias – SP	153 390
	Cibratel – SP	- 356 760
	Iguape – SP	320 430
	Ilha Comprida – SP	24 067
	Guaraqueçaba – PR	237 710
	Matinhos – PR	142 240
	Itapoá – SC	56 895
	Balneário Barra do Sul – SC	402 970
	Balneário Piçarras – SC	-317 580
	Balneário Camboriú – SC	-172 650
	Meia Praia – SC	-13 497

Rio de Janeiro (RJ), São Paulo (S), Paraná (PR) and Santa Catarina (SC).

From the Cabo Frio region to southern Brazil, Pianca et al. (2010) stated that, overall, the waves generated by high South Atlantic storms are the most frequent, being the most energetic originated from the South and Southeast, which makes the dominant pattern of littoral drift towards Northeast. Figure 3 demonstrated that the main direction of waves are from Southeast, thus agreeing with the results.

In the São Paulo coast, in Cibratel, it is observed that the transport has

dominant pattern for Southwest, in accordance with the study of Araújo and Alfredini (2001). This exception occurs due to the change in the alignment of the coast, along to the possible temporal predominance of the Atlantic Tropical Anticyclone (source of waves of Northeast and East). However, it is valid to emphasize that, in normal conditions where mobile Polar Anticyclones predominate, the waves are coming from the South and Southeast directions, changing the drift towards Northeast.

For the states of Paraná and Santa Catarina, some authors (Gobbi, 1997; Veiga et al., 2004; Castilhos and Gré, 2006; Thoaldo, 2011; Abreu, 2011; Wosiacki and Gobbi, 2012) stated that the direction of littoral drift is preferably to the North, due to the incident waves climate in the region. Regarding the Piçarras, Camboriú and Meia Praia beaches, in Santa Catarina, which showed dominant drift towards the South, this can be explained due to the morphology of the region, which alters the standard alignment of the coast and, consequently, modifies the intensity and direction of action of the waves.

For this last stretch, the annual mean sediment transport was lower in Meia Praia (Santa Catarina), reaching 13 497 $m^3\,year^{-1}$, in addition to Ilha Comprida - São Paulo, with 24 067 $m^3\,year^{-1}$. On the other hand, in Saquarema and Barra da Tijuca, both in Rio de Janeiro, presented the highest averages occurrence, reaching 690 670 $m^3\,year^{-1}$ and 625 670 $m^3\,year^{-1}$, respectively.

The variations in the coastal drift observed in all of the analyzed sections from the Brazilian coast can be explained due to the spatial changes in the alignment of the coastline or by the temporal variations of the wave climate itself. Bittencourt et al. (2000) also stated that the presence of coral reefs can act as a barrier, causing in some stretches changes in the drift pattern induced by less intense waves, provoking a reversal in the dominant direction of transport. In order to conclude the evaluation of the longshore sediment transport, the cycles of variability simulated over 37 years was investigated for the entire Brazilian coast, and in order to enforce these results, the wavelet analysis was applied.

3.2. Spatial Variability Analysis

The spatial variability of the longshore sediment transport was analyzed for a transect (which connects the yellow dots in Figure 2), towards the usage of the wavelet analysis. In the two-dimensional analysis, a DOG wavelet (known as Mexican Hat) was considered, following the methodology proposed by Torrence and Compo (1998) and rectified by Liu et al. (2007) and Veleda et al. (2012).

At first, all the formulas used in the calculation of sediment transport were investigated, resulting in similar patterns in relation to spatial variability's for cycles between 100 and 1000 days. Thus, for this article, the formulation of CERC (1984), with the parameter K calibrated by Kamphuis et al. (1986), was chosen to compose this analysis, since it represents one of the formulas considered most suitable for the calculation of sedimentary transport in several sectors of the Brazilian coast.

Figure 4 (a) shows the local energy spectrum averaged for cycles of variability ranging from 100 to 1000 days, observed over the 37 years simulated and the distance of the Brazilian coast. The average behavior of these cycles is represented by the Hovmöller plot, with the yellow color highlighting the higher energy and frequency of the cycles, while the blue color, shows the situations in which these cycles are less significant and, therefore, do not cause great influence in the longshore sediment transport.

The position along the Brazilian coast is indicated on the vertical axis, where the distance of 0 km is related to Arroio Chuí, in the southernmost region of South Brazil, while 6000 km are on Cabo Orange, at the northern end of the Northern Region. The simulation time is shown on the horizontal axis, varying from the year of 1979 to 2015. The mean-integrated variance along space, Figure 4 (b), and over time, Figure 4 (c), are also presented.

Analyzing the spatial variability along the entire Brazilian coast, Figure 4 (a), it can be seen that the cycles of variability between 100 to 1000 days, which are correspondent to annual and interannual cycles of variability, are the most frequent and well defined in some regions, and occur in a transient way in others.

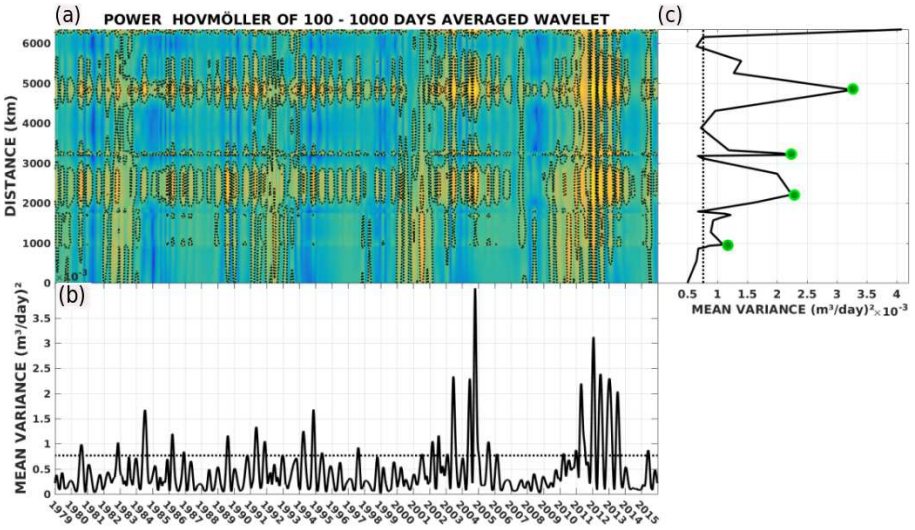

Figure 4: (a) Local energy spectrum for cycles of variability between 100 to 1000 days, observed over time on the Brazilian coast, using the DOG wavelet. Dotted lines indicate the regions with statistical confidence of 95%. (b) Time series of integrated mean variance for all points on the Brazilian coast. The dotted horizontal line represents the level of 95% confidence. (c) Spatial series of mean variance integrated towards the simulation period. The dotted vertical line represents the confidence level 95% while the green points represent the locations where the time variability will be analyzed.

At the distances between 2000 and 3000 km, as well as in the stretch of 4500 and 5500 km, these cycles are strongly relevant, indicating a high frequency of occurrence and higher intensities over the simulated years. These distances are equivalent to the stretches between the state of Rio de Janeiro and the southern sector of Bahia, as well as between the western sector of Rio Grande do Norte and Maranhão.

However, in the other stretches, the blue color suggests that the longshore sediment transport suffers greater influence of the variability cycles shorter than 100 days, being related to the passage of meteorological systems and variations in the seasonal patterns. For the distance between 0 and 1000 km, corresponding to the section between Rio Grande do Sul and Paraná, 3500 and 4500 km, between Sergipe and the southeastern sector of Rio Grande do Norte, in addition to the proximity of 6000 km, in the state of Pará, it can be observed that the longest cycles are less frequent occurring with greater energy only in some periods.

The spatial integrated mean variance, Figure 4 (b), demonstrates the regions where the occurrence of annual and interannual cycles of variability are most significant across the Brazilian coast, with peaks above the dashed horizontal line having statistical reliability of 95%. The integrated variance over time on the Brazilian coast, Figure 4 (c), confirms the behavior observed in the analysis of the local variability, with peaks at the points where the long period cycles are more intense and frequent, agreeing with the locations shown in Figure 4 (a). It is important to note that, to the right of the dashed vertical line, the reliability of the results are approximately 95%, statistically proving the high influence of annual and interannual cycles at these locations.

The annual cycles are associated with changes in the pattern of winds related to the changes of seasons, a fact that is better characterized in some regions the Brazilian coast, as can be observed in the Figures 4 (a) and (b). On the other hand, it stands out the years of 1980, 1982, 1984, 1986, 1989, 1991, 1994, 1997, 2002 to 2006, 2010 to 2013 and 2015, when cycles are more intense and energetic.

According to data available from National Oceanic and Atmospheric Administration (NOAA[5]), these years are characterized by the occurrence of the El Niño-Southern Oscillation (ENSO) phenomenon, which is defined as the main source of interannual variability in scales of a few years, which represents global impacts as well (Trenberth, 1997; Almeida et al., 2017; Oliveira et al., 2017).

A greater disparity is observed, in the year of 2004, in comparison to the other periods, being able to be related to the passage of a tropical cyclone coming from the South Atlantic, known as "Hurricane Catarina" (Dias et al., 2004; Menezes and Dias, 2004), that reached the coast of South Region of Brazil in March, producing winds above $30\,\mathrm{m\,s^{-1}}$ (Menezes and Dias, 2004). Another extreme event, known as the "Ribeirão Preto Case", occurred in May 1994, when severe convective storms formed over the state of São Paulo, causing strong winds and hail, with gusts reaching velocities higher than $28\,\mathrm{m\,s^{-1}}$ (Menezes

[5] http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

and Dias, 1998, 2004).

In this way, it is important to emphasize that cyclones are the atmospheric systems that produce the most extreme winds where they are, being their influence in the South Atlantic Ocean quite common (Dereczynski and Menezes, 2015), in addition they are able to cause, directly and indirectly, significantly variations in the sediment transport. Additionally, the severity of events can be intensified over the years influenced by interannual events.

Another factor related to the integrated energy towards time, refers to the intensification and propagation of the cycles of 100 to 1000 days after the 90^{th} decade, standing out the period from 2010, that is clearly the most energetic. Such occurrence might be addressed in a future study proposal, in which the causes of the intensification of the long period cycles in the last years shall be enlighten.

3.3. Temporal Variability Analysis

The wavelet method also allowed the analysis of the temporal variability of longshore sediment transport along the Brazilian coast. For this analysis, four points were selected located in Galinhos - Rio Grande do Norte, Salvador - Bahia, Praia do Açu - Rio de Janeiro and Balneário Barra do Sul - Santa Catarina, which are indicated by the circles of green color in Figures 2 and 4 (c).

The longshore sediment transport formula considered more adequate for each site was used with the one-dimensional DOG wavelet, following the methodology proposed by Torrence and Compo (1998) and rectified by Liu et al. (2007) and Veleda et al. (2012). Figures 5 and 6 demonstrated the time series of sediment transport (in $m^3\,d^{-1}$) during the simulated 37 years.

The predominance of positive values indicates that the coastal drift is dominant to the West or North, depending on the position of the point, while the negative values represent the drift towards East or South. In addition, the local spectrum measures the amount of energy over the time for the cycles of vari-

ability occurring between 8 and 4096 days, the most energetic situations being those in which the red color and the black outline become more evident. The global spectrum complements the results visualized, indicating the cycles that most influence the longshore sediment transport in an integrated way.

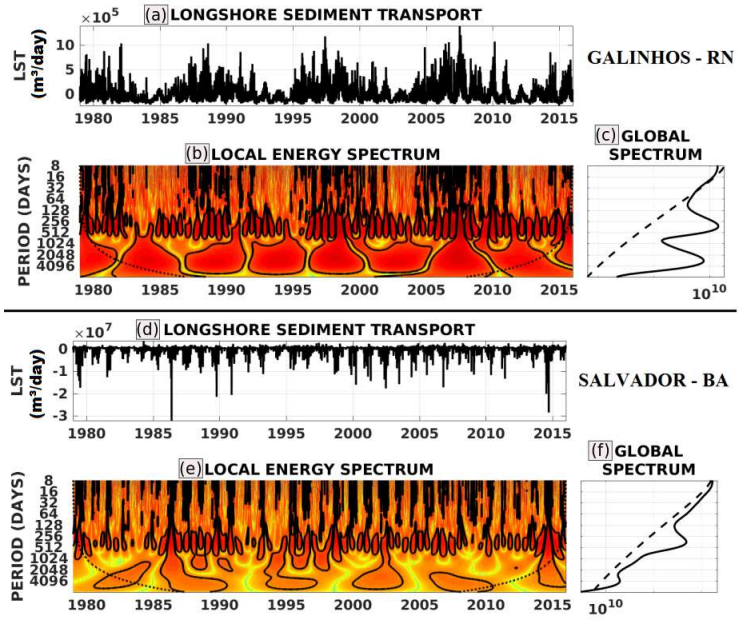

Figure 5: (a) and (d) Analysis of the Wavelet Method represented by the time series of longshore sediment transport in Galinhos - Rio Grande do Norte and Salvador - Bahia. (b) and (e) The local energy spectrum, and the black outlines represent the confidence level of 95% and the black dotted line represents the cone of influence. (c) and (f) The overall energy spectrum, and the black dotted line indicates the level of 95% confidence.

Figure 5 (a) presents the time series at Galinhos - Rio Grande do Norte, and it is observed peaks in sediment transport throughout the period, being the largest between years 2005 and 2010. It may also be noted that there is a variation between peaks, which increase and decrease approximately at every 5 years. In addition, the predominance of positive values in the series confirms the western direction of the coastal drift, as discussed above.

The local energy spectrum is represented by the red color and the black outline, presented in Figure 5 (b), and it shows that the highest energy concentrations occurred between 256 and 2048 days. These cycles can be associated with annual and interannual cycles, which are characterized by ENSO. This

dominance of the longest cycles in longshore sediment transport has also been demonstrated for this point.

In addition, it can be observed that the seasonal and intra-annual cycles, between 128 and 256 days, also influence the transport, representing the variations caused by the passages of the seasons. The black color also highlights the high energy related to the short period cycles, between 8 and 128 days, however, in the global context of the long period analysis, these cycles are the less energetic.

The high energy rate associated with the medium and long-term phenomena is in agreement with the result presented in the global spectrum, in the Figure 5 (c). This result also shows that the shorter cycles do not exert a great influence on the longshore sediment transport when compared to the longer cycles.

The time series of longshore sediment transport in Salvador - Bahia are presented in the Figure 5 (d). This result demonstrates that isolated peaks have occurred in transport over the years, with the largest of them between 1985 and 1990 and around 2015. In the other years, the series remained practically constant, with coastal drift permanently dominant towards South, as expected, due to the predominance of negative values.

The local spectrum is presented in the Figure 5 (e), and it s observed that highest energy concentrations for the cycles occured between 128 and 512 days, over the 37 years simulated. This result demonstrate that seasonal and annual cycles effects are the ones that most influence the longshore sediment transport towards this region. In this way, this fact is corroborated by the global energy spectrum, presented in the Figure 5 (f).

In addition, the interannual cycles are well defined in some periods such as the years 1989, 1995, 2003 and 2007, which according to NOAA are years influenced by ENSO. In relation to the short period cycles, these were energetic and frequent throughout all years, losing their relevance due to the amount of energy associated with the longer cycles.

For the point in Praia do Açu - Rio de Janeiro, it is observed a high discrepancy of peaks along the time series, according to Figure 6 (a). The 90's is

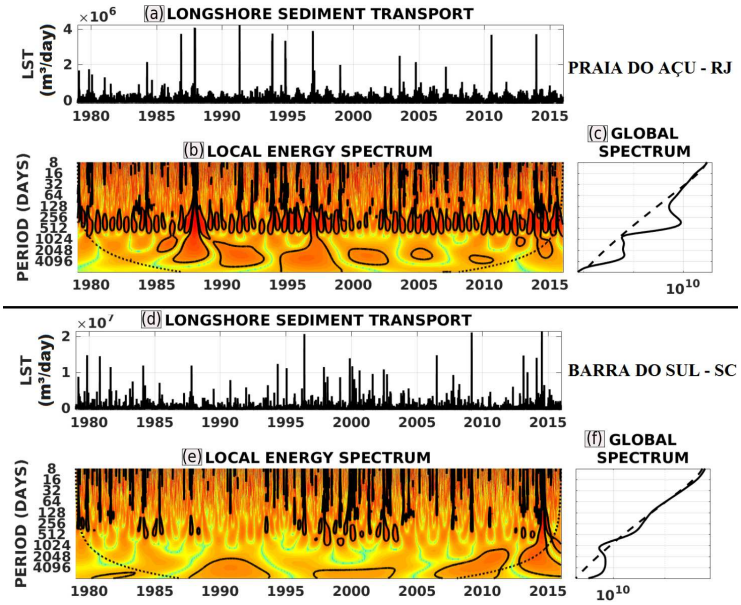

Figure 6: (a) and (d) Analysis of the Wavelet Method represented by the time series of longshore sediment transport in Praia do Açu - Rio de Janeiro and Balneário Barra do Sul - Santa Catarina. (b) and (e) The local energy spectrum, and the black outlines represent the confidence level of 95% and the black dotted line represents the cone of influence. (c) and (f) The overall energy spectrum, and the black dotted line indicates the level of 95% confidence.

highlighted because the peaks were higher and with a higher frequency. Coastal drift was dominant for the North, since positive values prevailed in the series.

The local spectrum is presented in the Figure 6 (b) and it shows that the most energetic cycles refers to the period between 128 and 512 days, with predominance over the 37 years analyzed. The cycles greater than 512 days are also energetic and influence the longshore sediment transport.

Starting from 1985, highlighting the period between 1995 and 2000, it is possible to observe the occurrence of a well-defined interannual phenomenon, according to the time series. The shorter cycles show few relevance for this point, although they also occur over the years.

Finally, the global spectrum presented in the Figure 6 (c) highlights that annual and interannual cycles are the most important in longshore sediment transport and that shorter cycles are not significant at this time scale. It is important to emphasize that local and global energy spectra showed a similar behavior that occurred in Salvador, as shown previously in Figure 4.

For the last point, located in the Balneário Barra do Sul - Santa Catarina, the time series demonstrated a high variability of the peaks along the 37 years, not following any pattern. This result can be observed in the Figure 6 (d).

Nearby the years of 1996, 2009 and 2015, the highest values occurred, being these associated to the occurrence of El Niño and La Niña events, according to NOAA. In addition, the predominance of positive values in the series represents that the coastal drift is towards the North.

The local and global energy spectra are presented in the Figures 6 (e) and (f), and its show an extremely different behavior in relation to the other points analyzed. In the local spectrum is observed that cycles greater than 128 days do not present an amount of energy so different when compared to smaller cycles between 8 and 32 days.

The intensity of shorter cycles is greater because in the southernmost regions of Brazil the passage of meteorological systems occurs more frequently and intensely than in other regions, significantly affecting sediment transport and interfering with the pattern of variability on a seasonal and annual scale. It can also be observed that the interannual cycles are more energetic in the years 1990, 2000 and 2010, reflecting their relevance in the global spectrum, according to Figure 6 (f).

Thus, the shorter cycles always occur and are energetic as the others, however, it is possible to conclude that for the global context of the analysis, the annual and interannual cycles are the most important for the control of longshore sediment transport. In addition, it can be emphasized that the interannual cycles contribute to a more frequently and well defined longshore sediment transport in the northeast and north of the Brazilian coast.

4. Conclusions

Considering the numerical modeling of the waves generated by the wind during a period of 37 years, it was possible to estimate the annual means of sediment transport for 85 points along the entire Brazilian coast. The four

methodologies applied in the calculations proved to be satisfactory, with the exception of the formulation of CERC (1984), with the parameter K equals to 0.39, which was not suitable for any region. The formulation of Kamphuis (1991) was applied in most of the points, however, the formulation of CERC (1984), with the K calibrated by Kamphuis et al. (1986), covered most of the Brazilian coast.

In relation to the obtained sedimentary rates, the highest occurred in the Northeast Region of Brazil, emphasizing the sector between Pina (Pernambuco) and Piaçabuçu (Alagoas), with averages up to $844\,320\,\mathrm{m^3\,year^{-1}}$. Another sector that presented high transport values refers to Maraú and Ilhéus, both in Bahia, with an average of approximately $650\,000\,\mathrm{m^3\,year^{-1}}$.

In the state of Rio de Janeiro, Saquarema and Barra da Tijuca stood out, with values closer to $690\,000\,\mathrm{m^3\,year^{-1}}$. On the other hand, the lowest averages occurred in different analyzed regions, the lowest in Meia Praia (Santa Catarina) with $13\,497\,\mathrm{m^3\,year^{-1}}$, followed by Mucurí (Bahia) with $22\,577\,\mathrm{m^3\,year^{-1}}$, and Ilha Comprida (São Paulo) with $24\,067\,\mathrm{m^3\,year^{-1}}$.

Although only three sedimentary fractions were considered to characterize the sedimentology of the study region, these were appropriate for each stretch, since they did not affect the results very significantly. In fact, it is suggested that in future studies a more refined sedimentological data set should be used, further improving the results. In addition, the choice of other formulas to calculate sediment transport can also be considered, allowing a comparison with the results presented in this article.

The spatial and temporal variability analysis presented important aspects in relation to the influence of variability cycles in the longshore sediment transport. For the northern regions of Brazil, the interannual cycles were more frequent and energetic than in the southern regions of Brazil, where shorter cycles were significant also.

The high frequency of the annual and interannual cycles during the 37 years occurred in the sector between Maranhão and Rio Grande do Norte, as well

as between Bahia and Rio de Janeiro. In the other stretches of the Brazilian region, these cycles of long period occurred transiently, being masked by cycles of shorter period.

In addition, the high intensity and energy of the long period cycles were also observed in the years of 1980, 1982, 1984, 1986, 1989, 1991, 1994, 1997, 2002 to 2006, 2010 to 2013 and 2015, being related to the occurrence of the ENSO phenomenon. After the 90^{th}, the intensification and the increase in the frequency of these cycles can also be verified, highlighting the year of 2010, when it becomes evident that these events have become more energetic. This fact also makes possible a future study to clarify the causes of the intensification and increase in the frequency of occurrence of the interannual cycles in recent years.

The temporal variability analysis of the transport also allowed the conclusion that the short period cycles, related to the passage of meteorological systems, are always present throughout the year in the different regions, especially the south region that is strongly affected by the action of low pressure atmospheric features. However, such cycles lose their relevance as mechanisms to promote sediment transport when compared to annual and interannual cycles, which carry a greater amount of energy and, therefore, become more significant in the scale of variability of this study.

Thus, the present article contributes with relevant information about longshore sediment transport, highlighting the annual averages and the dominant drift, along the entire Brazilian coast. In addition, important questions about the influence of cycles of variability in the study region are discussed, emphasizing the importance of the longer period events for the control of sedimentary transport in the Brazilian coast.

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Figures

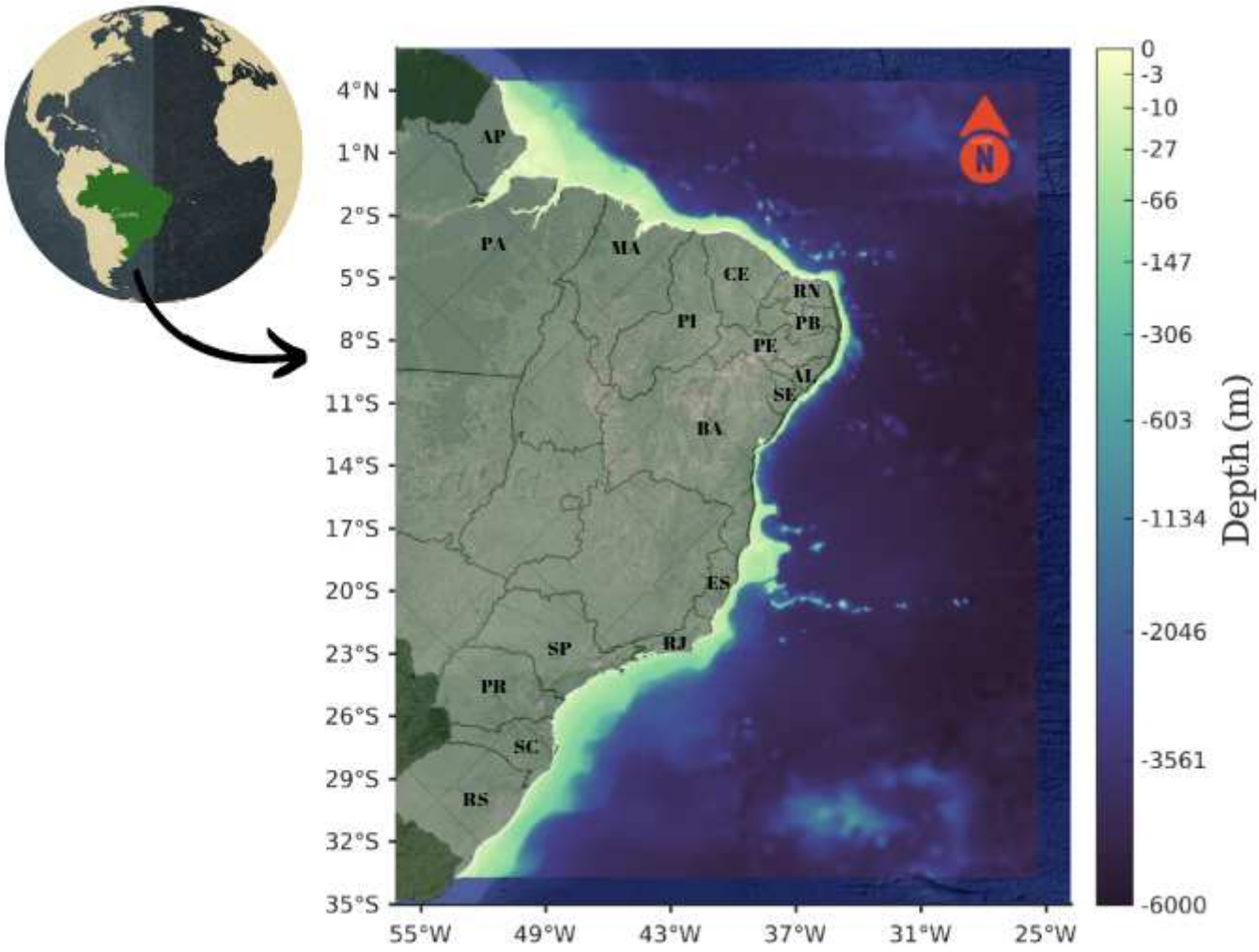

Figure 1

Representation of the study area, with bathymetric data and pointing coastal states - Amapá (AP), Pará (PA), Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE), Bahia (BA), Espírito Santo (ES), Rio de Janeiro (RJ), São Paulo (SP), Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS). The colorbar represents the depth in meters.

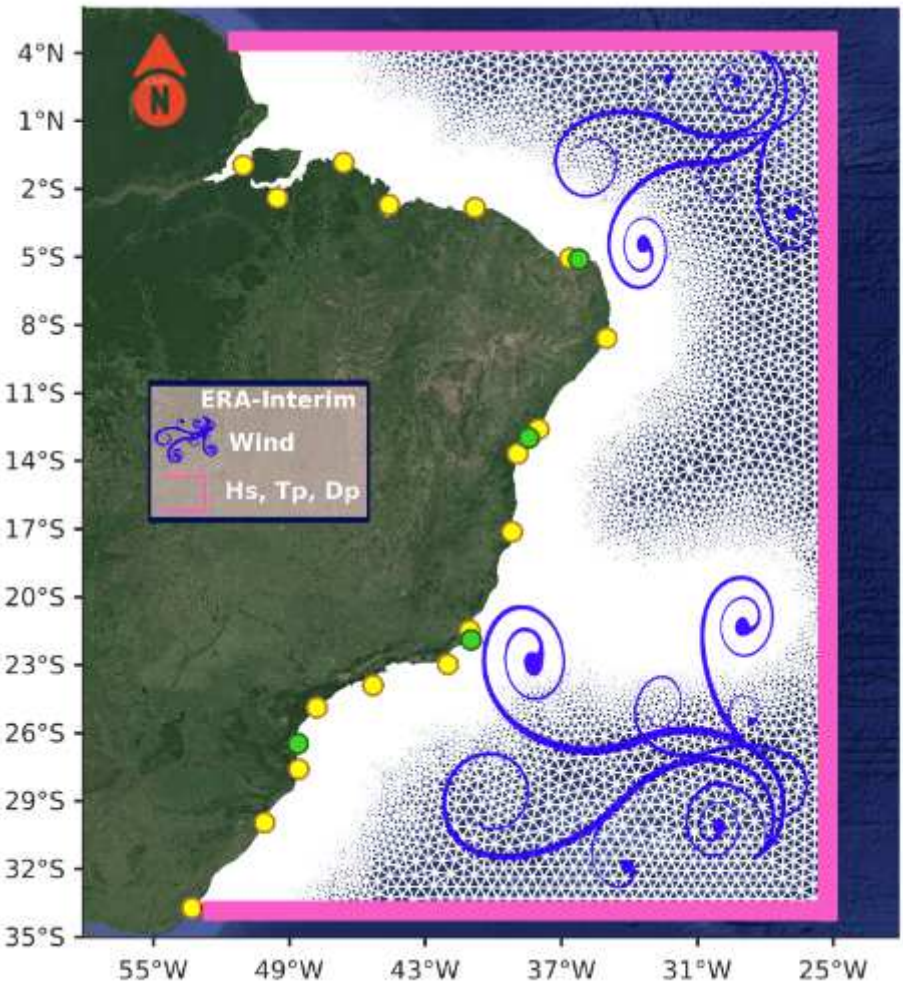

Figure 2

Figure of the computational domain with surface and boundary conditions. The points represent the areas used to analyze the spatial (in yellow) and temporal (in green) variability. The pink lines and the blue symbols represent wave and wind data, respectively.

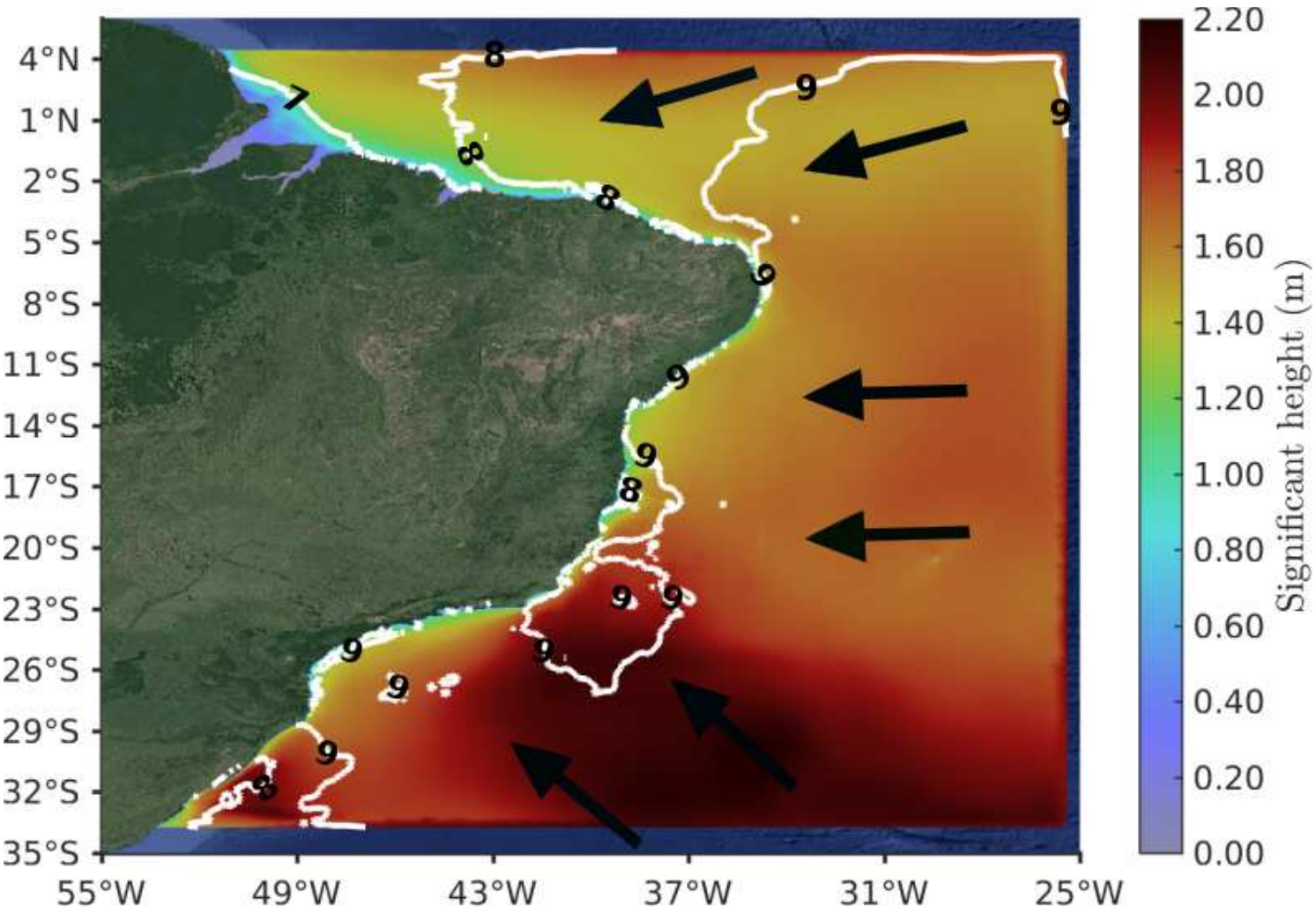

Figure 3

Results of the Brazilian Continental Shelf, overlapping image by Google Maps, Landsat/Copernicus, 2018. Frame shows Hs (m) in the surface, Tp (s) in the isolines and Md in the arrows.

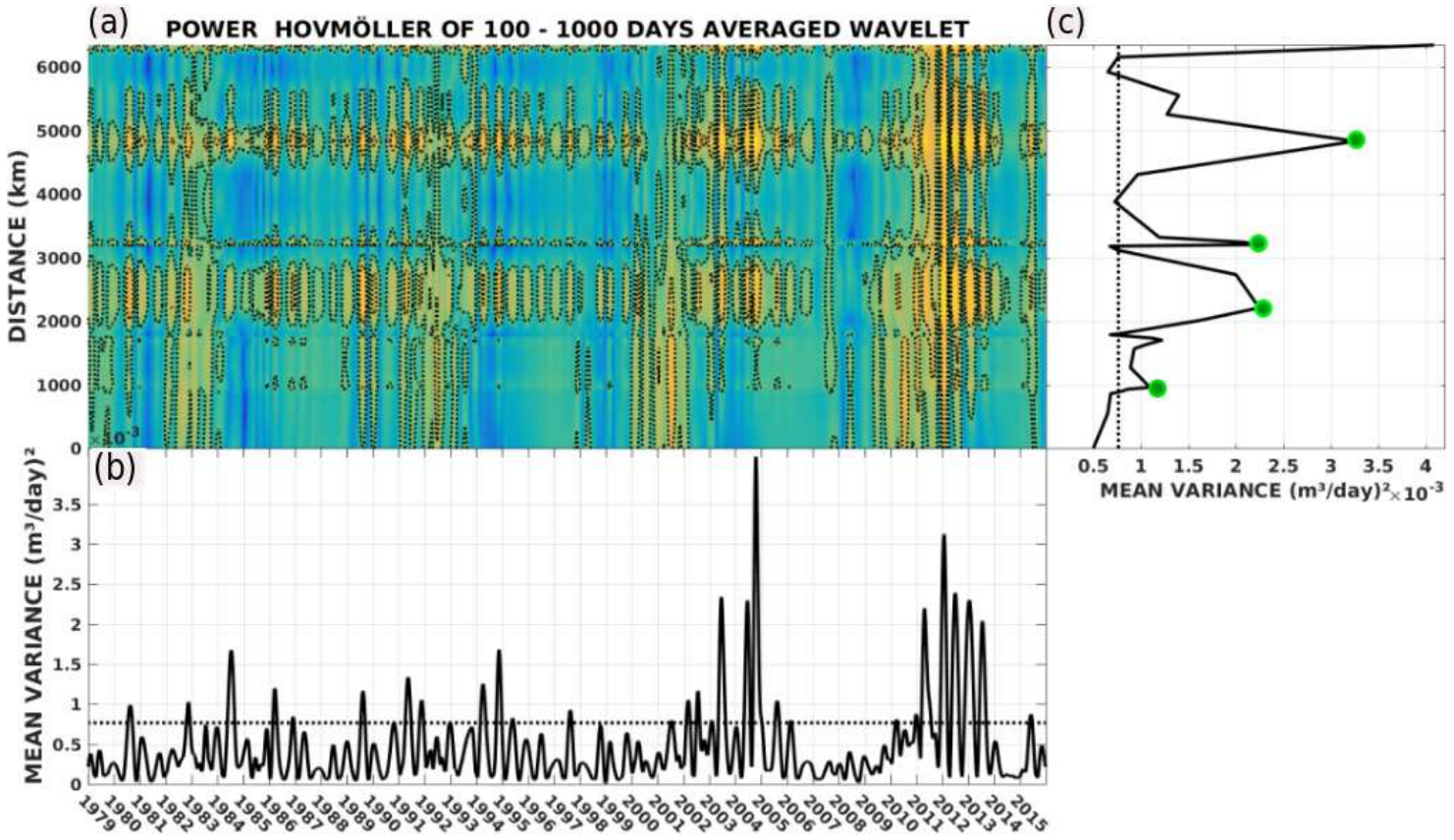

Figure 4

(a) Local energy spectrum for cycles of variability between 100 to 1000 days, observed over time on the Brazilian coast, using the DOG wavelet. Dotted lines indicate the regions with statistical confidence of 95%. (b) Time series of integrated mean variance for all points on the Brazilian coast. The dotted horizontal line represents the level of 95% confidence. (c) Spatial series of mean variance integrated towards the simulation period. The dotted vertical line represents the confidence level 95% while the green points represent the locations where the time variability will be analyzed.

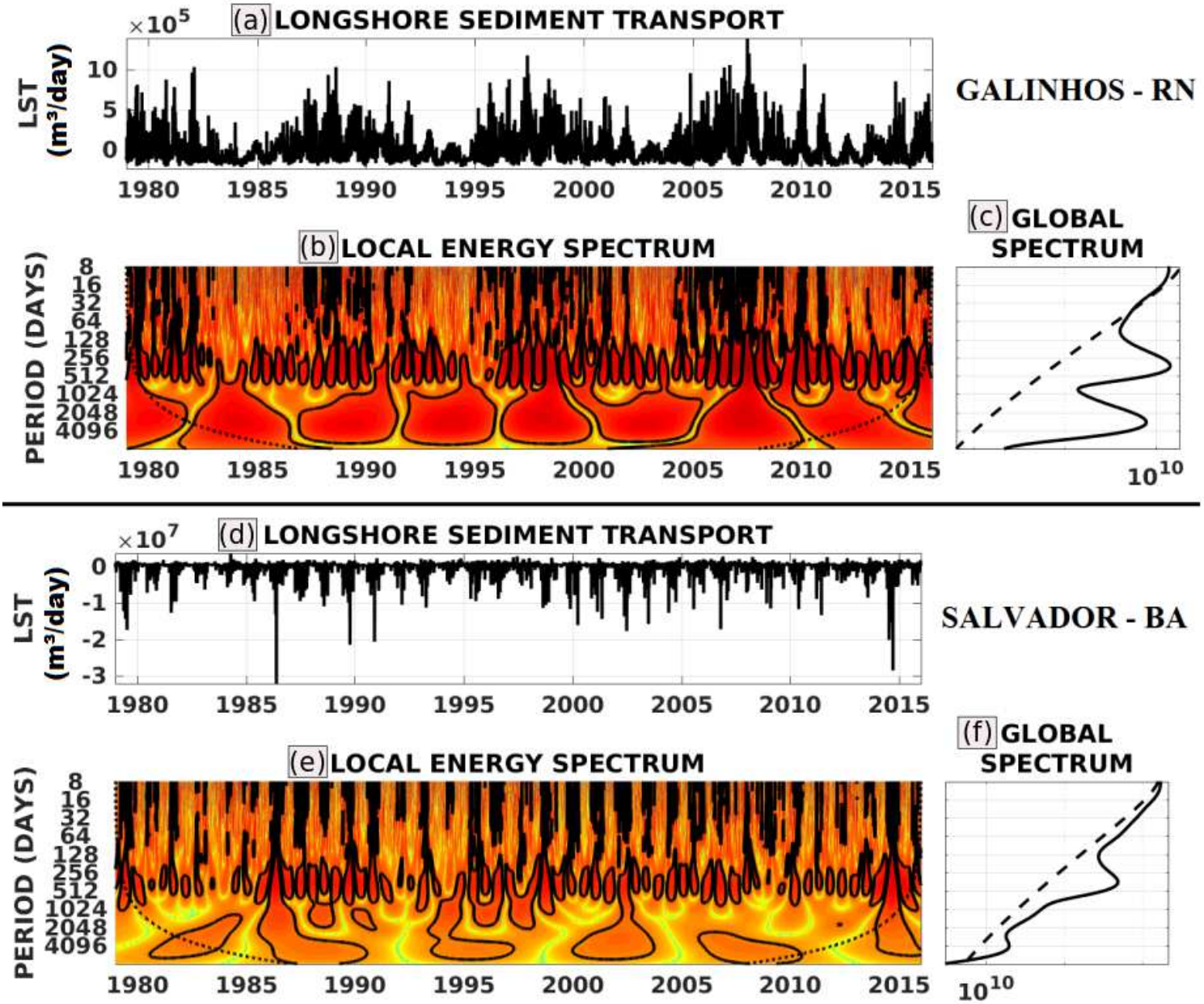

Figure 5

(a) and (d) Analysis of the Wavelet Method represented by the time series of longshore sediment transport in Galinhos - Rio Grande do Norte and Salvador - Bahia. (b) and (e) The local energy spectrum, and the black outlines represent the confidence level of 95% and the black dotted line represents the cone of influence. (c) and (f) The overall energy spectrum, and the black dotted line indicates the level of 95% confidence.

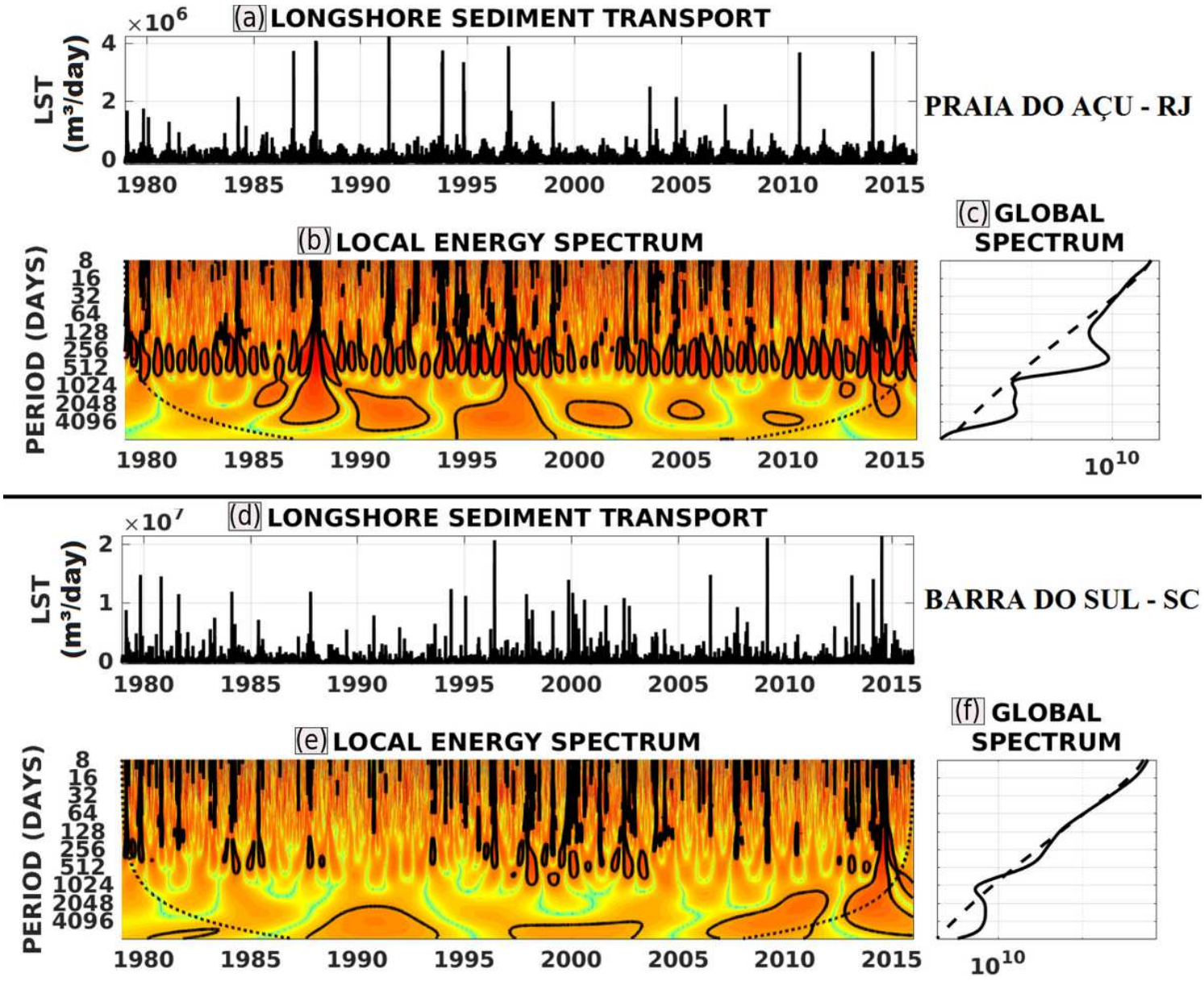

Figure 6

(a) and (d) Analysis of the Wavelet Method represented by the time series of longshore sediment transport in Praia do Açu - Rio de Janeiro and Balneário Barra do Sul - Santa Catarina. (b) and (e) The local energy spectrum, and the black outlines represent the confidence level of 95% and the black dotted line represents the cone of influence. (c) and (f) The overall energy spectrum, and the black dotted line indicates the level of 95% confidence.