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SANTOS BEACH MORPHODYNAMICS UNDER HIGH-ENERGY CONDITIONS

MORFODINÂMICA DA PRAIA DE SANTOS FRENTE A EVENTOS ENERGÉTICOS

Luiza Paschoal Stein
Instituto Oceanográfico, Universidade de São Paulo
Praça do Oceanográfico, 191, São Paulo, São Paulo. CEP: 05508-120. Brasil
ORCID: 0000-0002-7843-8622
E-mail: luiza.stein@usp.br

Eduardo Siegle
Instituto Oceanográfico, Universidade de São Paulo
Praça do Oceanográfico, 191, São Paulo, São Paulo. CEP: 05508-120. Brasil
ORCID: 0000-0003-3926-1710
E-mail: esiegle@usp.br

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Abstract:

The city of Santos is located in southeastern Brazil. It is a densely urbanized area with touristic and economic importance, including the largest harbor in Latin America. Such activities are related to the sea and they impact and are impacted by erosional processes of the city's beach. Here we assess the morphodynamics of Santos Beach as a response to energetic wave conditions. Since the Santos Bay coastline is facing south, it is exposed to storm waves generated by cold fronts. Therefore, our aim was to analyze Santos Beach morphologic data during the period of energetic conditions from April to August. Morphological surveys were conducted at approximately 20-days intervals. The wave data for the study period were extracted from the global wave generation model, WaveWatch III (NOAA) and used as boundary conditions for the wave propagation model Delft3D-WAVE. The results of the study show the direct relationship between the incidence of higher waves during a period of two or more days (associated with cold fronts) with the loss of beach sediment volume. The beach dynamics varies from east to west. Even with higher waves reaching the exposed western part of the beach, its volume varies less than the more protected eastern part of the beach. Areas with slightly steeper profiles and usually subjected to less energetic conditions (eastern portion) have higher morphological variability; therefore they are more unstable and susceptible to higher wave energy than the highly dissipative areas (western portion).

Resumo:

A cidade de Santos está localizada no sudeste do Brasil. É uma região de alta densidade demográfica, alta importância turística e inclui o maior porto da América Latina. Tais atividades estão relacionadas ao mar e impactam e são impactadas pelos processos erosivos da praia local. Aqui, avaliamos a morfodinâmica da praia de Santos como resposta às condições de ondas energéticas. Como a Baía de Santos está voltada para o sul, o arco praial está exposto a ondas de tempestade geradas por frentes frias. Portanto, nosso objetivo foi analisar os dados morfológicos da Praia de Santos durante o período das condições energéticas de abril a agosto. A coleta de dados morfológicos foi realizada em intervalos de aproximadamente 20 dias. Os dados de onda para o período estudado foram extraídos do modelo global de geração de ondas, WaveWatch III (NOAA) e usados como condições de contorno para o modelo de propagação de ondas Delft3D-WAVE. Os resultados do estudo mostram a relação direta entre a incidência de ondas com maiores alturas durante um período de dois ou mais dias (associado a frentes frias) com a perda do volume da praia. A dinâmica da praia varia de leste a oeste. Mesmo com ondas mais altas atingindo a parte mais a oeste exposta da praia, seu volume varia menos que a parte leste mais protegida da praia. Áreas com perfis ligeiramente mais inclinados e que normalmente são menos energéticas (porção leste) apresentam maior variabilidade morfológica, sendo, portanto, mais instáveis e sensíveis a altas energias de onda quando comparadas às áreas altamente dissipativas (porção oeste).

Introduction

Beaches are depositional environments formed by the accumulation of sediments due to wave action. Such dynamic systems, in their natural state, become important and most efficient coastal protection elements. The main processes controlling the coast are the currents, tides and waves. In the case of waves, the energy that reaches the coastal zone is defined by the wave climate of the region. The energy balance of good weather waves and storm waves that arrive on the coast is the process responsible for controlling the deposition or removal of sediment on the beach, causing changes in the topographic profile (Komar, 1998).

Waves propagating nearshore undergo several transformation processes and when they reach the coast and break, they dissipate energy, generating coastal currents that define sediment transport and control the beach morphodynamics. Other important factors in coastal evolution are high-energy events associated with storms and storm surges (Stone and Orford, 2004). Such energetic events present varying results as a function of the different wave transformation processes as they propagate to coastal areas (e.g. Regnauld *et al.*, 2004). Along the southern Brazilian coast, such events are the cause of substantial morphological and sedimentary changes (e.g., Calliari *et al.*, 1998; Tessler and Mahiques, 1998; Siegle and Calliari, 2008). Most energetic waves that reach the eastern Brazilian coast are the result of strong winds associated to the passage of cold fronts. These polar front systems result in more wave power reaching the southern and southeastern coast of Brazil, decreasing as they move northwards (Pianca *et al.*, 2010).

Urbanized beaches are complex environments due to the interaction of occupation and coastal processes. In many cities, coastal construction can affect the local sediment balance and hydrodynamics, thereby increasing the demand for morphodynamic studies of beaches that are important for coastal management (Muehe, 2001). According to Souza (2009), anthropogenic interference in the environment can modify the natural factors, which in turn are related to oceanographic and hydrological factors, such as currents, waves and tides. Therefore, human intervention can be the direct cause of the sedimentary processes that influence the sediment balance of a beach.

The growing and disordered human occupation causes concern and direct impacts with regard to coastal erosion, requiring additional studies to better manage coastal areas (e.g. Serafim *et al.*, 2019; Andrade *et al.*, 2019; Sousa *et al.*, 2013; Silva *et al.*, 2016; Silveira *et al.*, 2016; Sallenger, 2000; Ruggiero *et al.*, 2001). Thus, our aim is to better understand the morphodynamic behavior of the urbanized Santos Beach area under energetic conditions.

The city of Santos is located on São Vicente Island in the central portion of the coast of São Paulo State (Figure 1). Estuarine channels that influence the beach dynamics surround the island. The channel on the east side of the beach is also used as an entrance for the harbor. This is a region with high population density and includes the largest harbor in Latin America. It is, therefore, of great touristic and economic importance for the region. Santos Beach is narrower in its eastern portion and wider in its central portion. The western beach limit is a large groin that is part of the submarine sewage outfall.

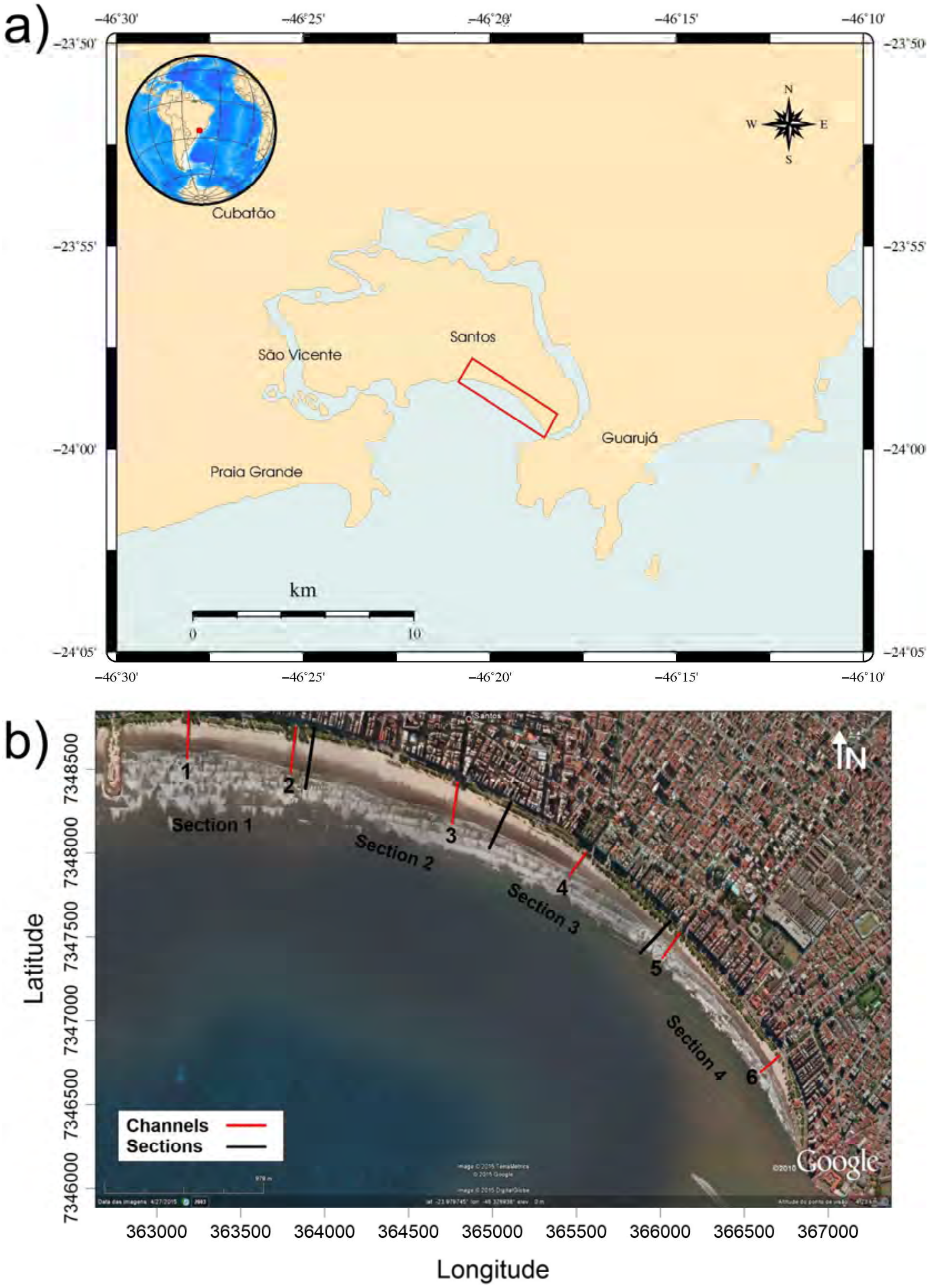

Figure 1 - a) Map indicating the study area location. b) Image of Santos Beach from the Ponta da Praia (near the port channel) to the outfall (near Urubuqueçaba Island), showing the drainage channels of the beach in red and the sections we used to analyze the beach are shown in black (Image: Google Earth).

According to Pianca *et al.* (2010), it is from April to September (autumn and winter) that the greatest significant wave heights (2-3 m), associated to higher wave periods (10-12 s), reach the region coming from the southern quadrant. Since the Santos Bay is facing south, its coastline becomes exposed to such high energy waves. A wall that protects the boardwalk and extends along the entire beach defines the upper limit of the beach. The beach is also segmented by six drainage channels that cross the beach and reach the surf zone (Figure 1).

Methods

The methods used in this study combine in situ beach morphology data with the application of a numerical wave propagation model, thereby assessing variations in beach morphology as a function of incoming waves characteristics.

Beach morphological surveys

Beach morphology has been surveyed at approximately every 20 days from April to August, 2015, totaling six surveys that cover the entire Santos Beach. The surveys were conducted using Differential Global Positioning System (DGPS) technology in kinematic mode to obtain data continuously throughout the surveys. The method consists of using two or more GPS units, with one of the receivers stationed at a point with known coordinates, while the mobile unit collects data from unknown points. We used the Trimble 5700 L1/L2 as the fixed base station and a Trimble R4 with a GNSS antenna as the mobile receiver. The GPS data were recorded in ellipsoidal height (h), converted to orthometric height (H), and corrected with the geoid heights (N) using the IBGE MAPGEO2010 program (IBGE, 2015).

The converted data were analyzed using the software Surfer 11 (Golden Software). Surfer 11 was used to create the digital terrain maps with a resolution of 49 lines and 100 columns, interpolated using the Kriging method. After comparing different interpolation methods with the measured profiles, Kriging has presented the best results for the interpolated grid. Altimetry maps showing the differences between the surveys were generated for the evaluation of erosion/deposition in the region of interest. The volume was calculated using the integration from a surface f (x, y), parameterized from the interpolated mesh and a plane surface Z, and based on the dimension -0.8. A standard mask, representing the smallest surveyed area, was established for all the grids allowing the comparison of volumes between the surveys.

In addition to analyzing the beach as a whole, the beach was divided into four sectors for a more detailed analysis (Figure 1). Section 1 is located farthest west, starting at the outfall groin and ending near Channel 2. This section is approximately 180 m wide. The central part of the beach arch was divided in two sections (Sections 2 and 3). Section 2 comprises the portion of the beach between Channels 2 and 3, approximately. It is the widest section, reaching up to 210 m. Sector 3, approximately from Channel 3 to Channel 5, is narrower with a width of approximatly100 m. Finally, Section 4 covers the eastern end of the beach, from Channel 5 to the end of the beach defined by the estuarine channel seawall. This is the narrowest part of the beach and is mostly inundated at high tide.

Wave climate

The wave climate for the region was defined based on results extracted from the global wave generation model WaveWatch III (NWW3) database. NWW3 is developed by the National Center for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) (Tolman *et al.*, 2002). Wave information (significant wave heights and peak periods) was extracted offshore at coordinates 26°S, 45°W, close to the shelf break. These data provided the boundary conditions for the nearshore wave propagation model.

Numerical modeling

The numerical model Delft3D-WAVE (developed by Deltares) was applied to the region to analyze the wave transformation as waves propagate nearshore. The Delft3D-WAVE model uses the SWAN model (Simulation Waves Nearshore) and simulates the propagation of waves over arbitrary depths for specific wind, flow and water level conditions. SWAN is based on the conservation equation for spectral action density (Holthuijsen *et al.*, 1993; Booij *et al.*, 1999; Ris *et al.*, 1999). The physical processes include wind wave generation, non-linear wave interactions, dissipation due to whitecapping, bottom friction and wave breaking. The effects of refraction, diffraction, shoaling and wave setup in coastal areas are also considered.

Boundary conditions used in Delft3D-WAVE are the offshore significant wave height (Hs), peak period (Tp) and direction (Dp), derived from NWW3 covering the period of the field surveys. The model grid defined for the Santos Beach simulations is shown in Figure 2. The model domain comprises the studied area located in the central part of the domain and extends to the continental shelf. Santos Beach is located in the more refined area, with an average resolution of 60 m.

To better understand the changes caused by the occurrence of cold fronts, four wave propagation scenarios were prepared, with each scenario covering one month of the 5-month sampling period (April, May, June, July and August). We could observe the cold front signals based on the wave information for each period. Wave height results from the numerical model wave propagation were extracted at the 3 m isobath from 5 points representing each sector and one additional point representing the eastern end of the beach (Ponta da Praia).

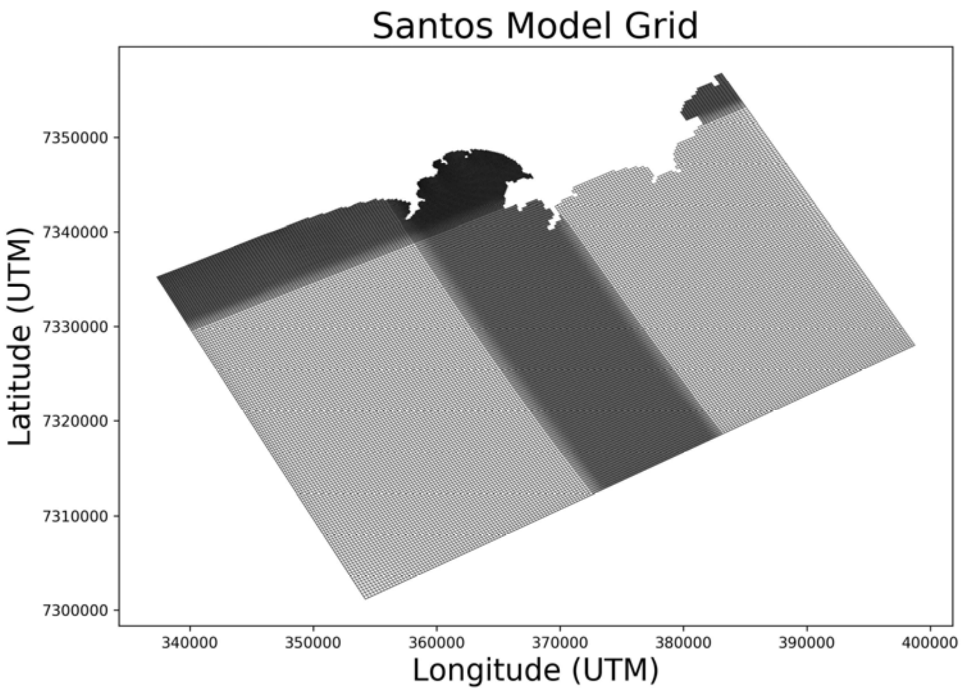

Figure 2 - Grid generated to model simulations encompassing the Bay of Santos, with 250 m average resolution in less detailed regions and 60 m resolution in the most refined area.

Wave Power

The wave power was estimated for each sector of the beach from the wave characteristics (Hs and Tp) extracted from the numerical model results. Wave power takes into account the wave period and height and can be related to the beach volume changes. Temporal wave power variations can lead to changes in beach stages (Short, 1978). According to the linear wave theory presented in Holthuijsen (2010), the wave energy flux can be determined by multiplying the power per unit area times the wave group velocity. We can estimate the value of the wave power through Equation 1, where ρ is the water density (1,027 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), H is the wave height (m) and T is the wave period (s). P is given in W/m:

$$P = \rho g^2 H^2 T / 32\pi \quad (1)$$

Results and Discussion

The incidence of frontal systems on the southeastern coast of Brazil influences wave formation and the dynamics of coastal processes, resulting in beach morphological changes. We observed the passage of several frontal systems during the 2015 study period based on the daily synoptic analysis provided by CPTEC/INPE: 4

in April; 7 in May; 6 in June; 4 in July and 4 in August.

During the studied period, in April, May and June, waves approached the area mainly from the south and southeast, with Hs mostly between 1 m and 2.5 m but reaching heights of up to 3.5 m (Figure 3). These were the months with the highest frequency of frontal systems. July presented the smallest Hs and incoming waves were mainly from the east. Similarly, waves were also mainly easterly in August, although higher, with Hs values of up to 3 m. The wave data were consistent with the overall wave climate for the region described in Pianca *et al.* (2010).

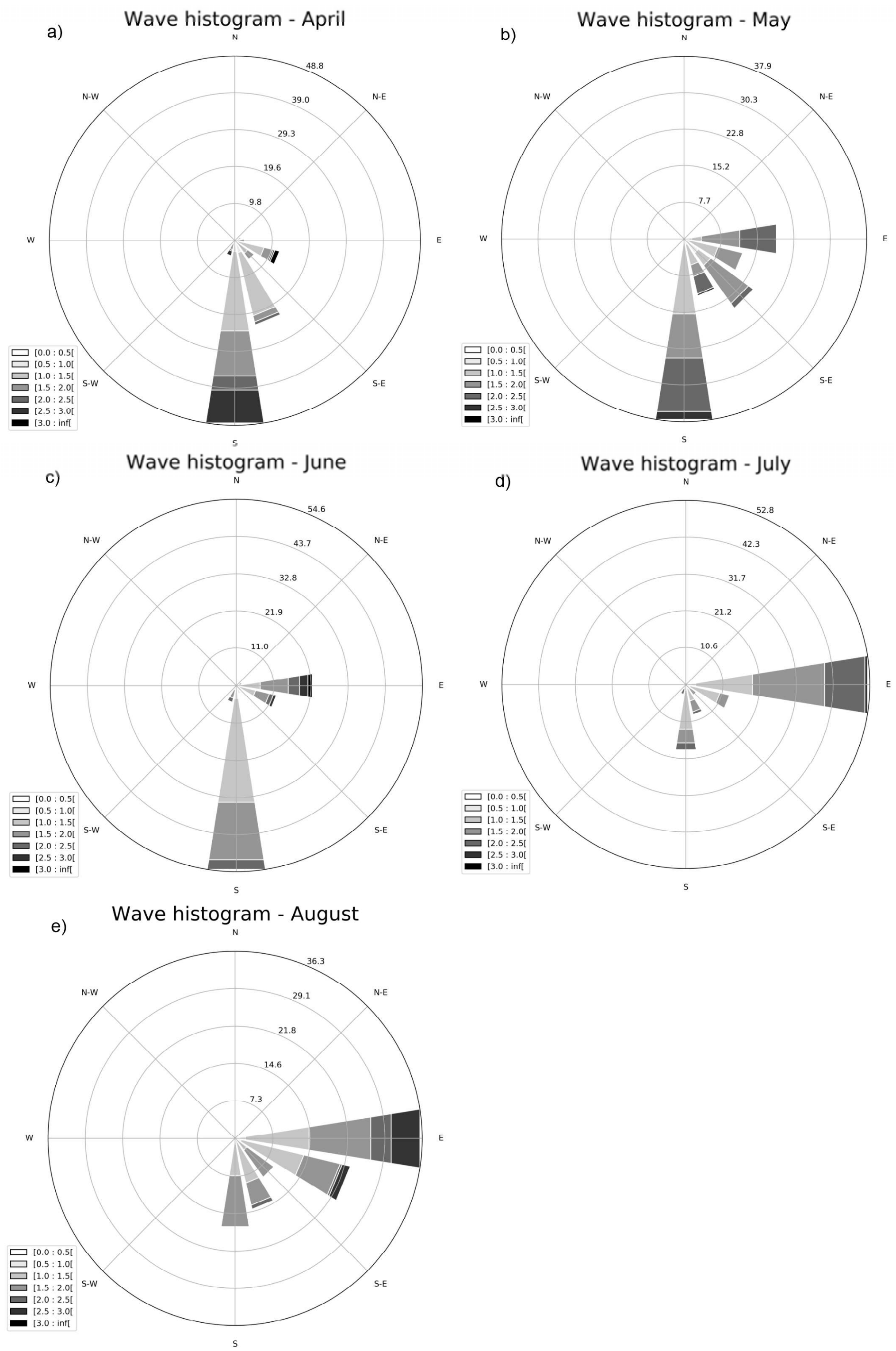

Figure 3 - Directional histograms for significant wave height during the period of study in 2015 (April, May, June, July and August).

Based on the numerical modelling results, estimates of wave power (P) have been made for each sector of the beach (Figure 4). As expected, the results for May and June, with higher cold fronts frequency, indicate more energetic waves. During July and August, when fewer frontal systems reach the region and the offshore waves come from the eastern quadrant, the wave power was lower than in previous months.

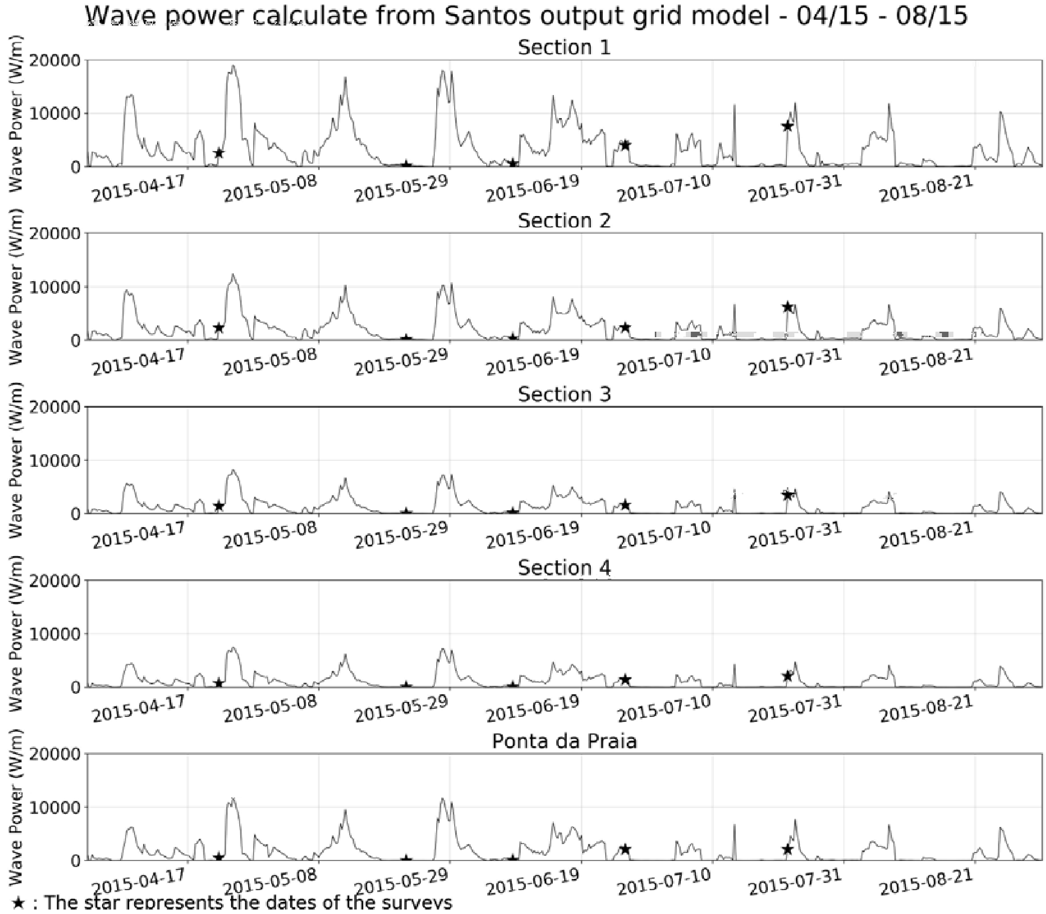

Figure 4 - Wave time series during the period of field surveys indicating the wave power of the incident waves for each studied sections and Ponta da Praia.

It is interesting to highlight the variation of wave intensity between sections. Sections 1 and 2 exhibited waves with higher wave power than Sections 3 and 4. Therefore, lower wave energy was observed at the east side of the beach. However, although it is located at the eastern end of the beach, Ponta da Praia exhibited wave power values similar to those of Section 2.

We were able to observe the beach morphological variations and their relation to the varying waves through the use of digital terrain maps (DTMs) (Figure 5) and the numerical modeling of waves. The elevation differences between the first (April) and last (August) field surveys indicated that overall beach erosion could be observed, with the eastern end of the beach experiencing the largest variations and sediment loss (Figure 6). Such behavior is expected for the sampled period, which covered the most energetic conditions for the area. It also stresses how the beach portion near the harbor channel is more vulnerable to the passage of cold fronts and is subjected to higher erosion than the rest of the beach.

Figure 7 shows the elevation differences between the surveys. It is possible to observe that substantial loss of sediment with more concentrated erosion at the east side of the beach between the surveys of 22/04 and 22/05. Between 22/05 and 08/06, overall beach accretion is observed, with only the eastern limit of the beach indicating some sediment loss close to the harbor channel. However, the altimetry variation between 08/06 and 26/06 shows again a loss of sediment throughout the entire beach. In this period, further erosion occurred at the west side of the beach, while the central/east presents sediment gain at the lower portion of the beach. Between the surveys of 26/06 and 22/07, we noticed an accretion of sediment in the central and east portions of the beach, while the western portion indicated some sediment loss. In the two last surveys, the central/east portion experienced more erosion than the portion farther west, which shows sediment loss but also some accretion.

The volumes obtained from the digital terrain maps are shown in Figure 8. It is possible to observe that the surveys conducted in May and June have a relatively lower volume of sediment when compared to other months, which can be related to the higher Hs values and higher frequency of cold fronts. The survey conducted at the end of July indicates the highest sediment volume and corresponds to the month in which the waves came from the eastern quadrant with lower heights, demonstrating the ability of beaches to recover after a period of higher energy. The second largest volume was observed in April, the period with southerly waves but with lower heights.

Through the beach volume analysis we observe that there was erosion (-7.7%) between the first two surveys, a recovery between the second and third survey (7.0%), and erosion again (-2.4%) between the third and fourth survey. There is a clear relationship between the erosive behavior and wave incidence for Santos Beach, which are therefore related to the frequency of cold fronts and wave power. A volume increase of 9.6% was observed for the period of June to July, which is related to the lower waves reaching the region and allowing the beach to recover. We observed a loss of sediment (-5.8%) in the last survey, probably related to the incidence of some specific wave events with higher energy than in the previous month.

A more detailed behavior of the beach can be observed through the analysis of volume variations at each section in which the beach was divided (Figure 9). Only Section 1 followed the erosion/deposition pattern of the entire beach. For some periods, Sections 3 and 4 showed only small variations (lower than 3.5%), although Section 3 indicated a large volume loss (-8%) during higher wave conditions from June to July. In Section 4, we noticed that there was erosion during most of the studied period, with the only exception being between the surveys in July and August, which corresponds to the period of smaller waves when the beach recovered 8.7% of its volume.

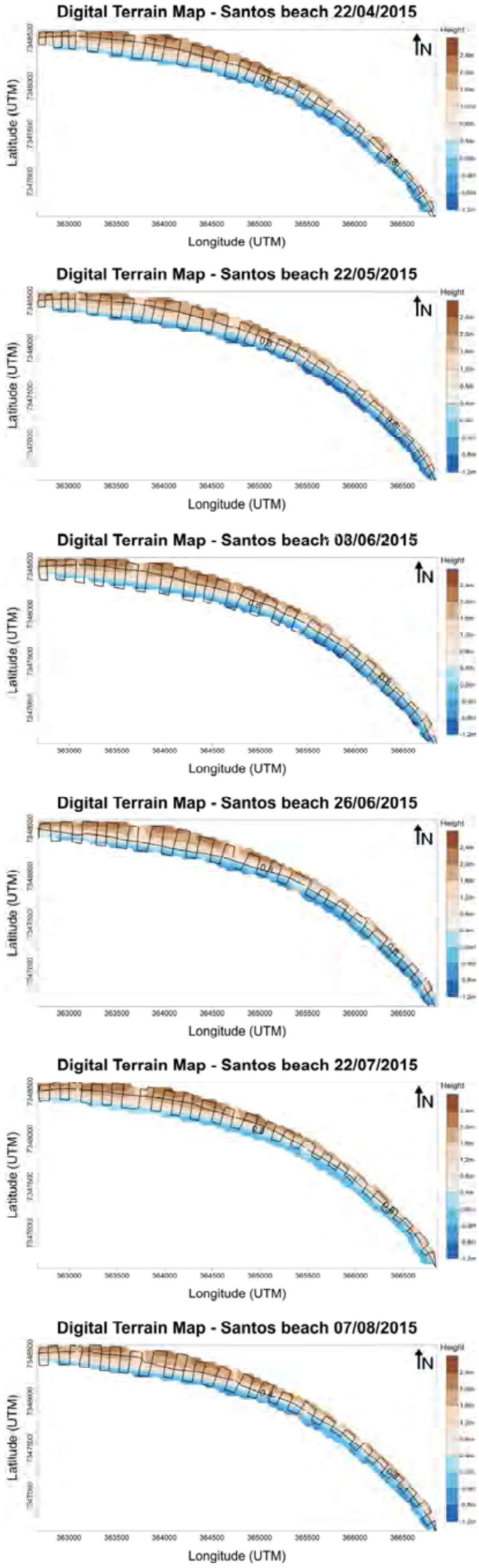

Figure 5 - Digital Terrain Model for each survey showing the DGPS survey coverage.

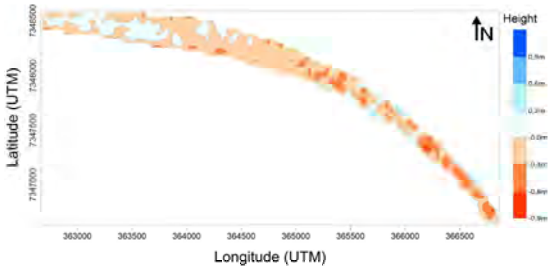

Figure 6 - Topographical beach variation between the first and last survey, indicating the difference in height (m) during the study period.

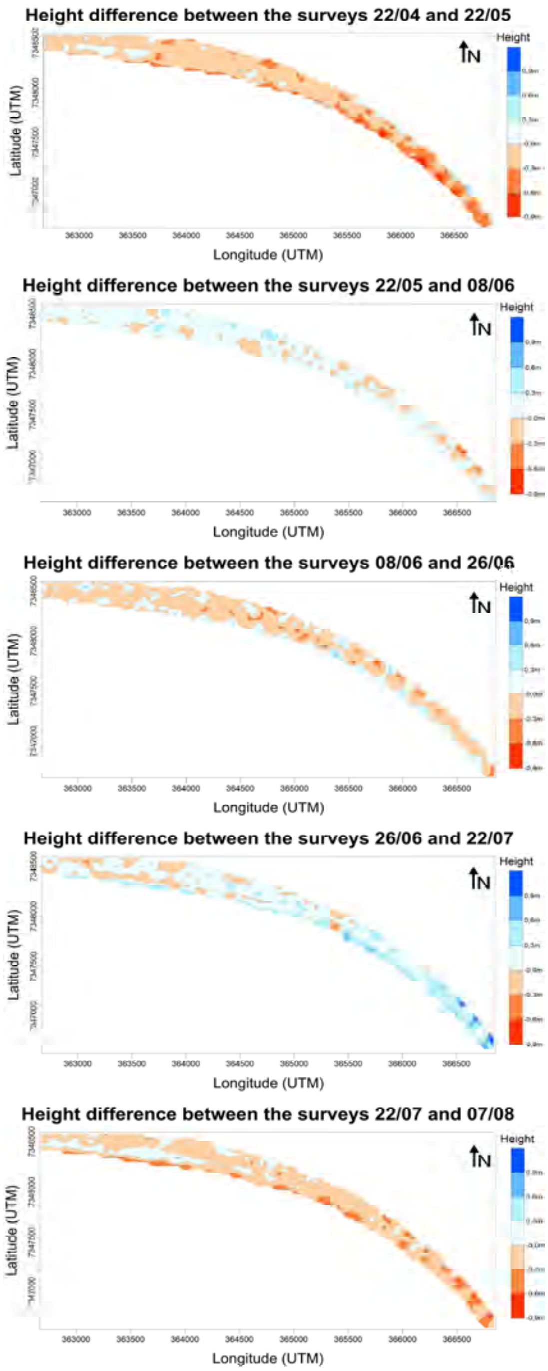

Figure 7 - Topographical beach variations between consecutive surveys, indicating the difference in height (m) during the study period.

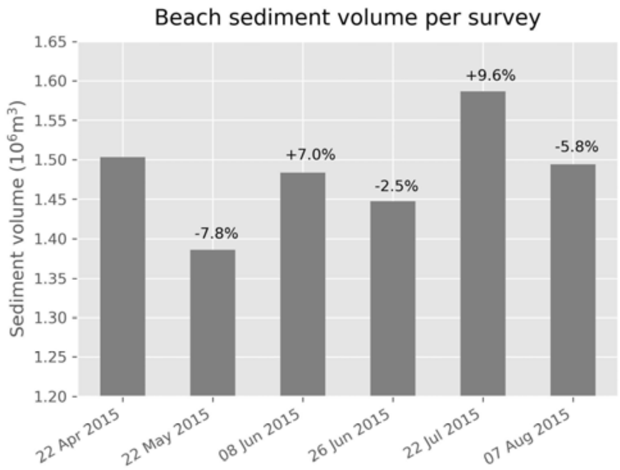

Figure 8 - Sediment volume along Santos Beach calculated for each survey.

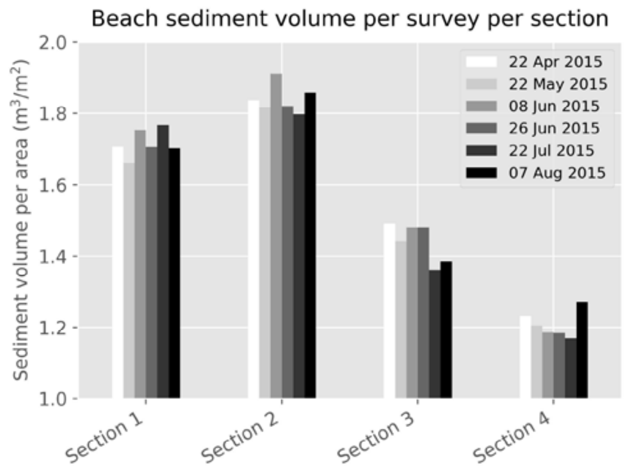

Figure 9 - Graph of sediment volume normalized per area in each section of Santos Beach for each day of the conducted survey.

The loss of a larger amount of sediment in Section 4, when compared to the other sections, reinforces the idea that this area is more susceptible to the action of cold fronts. This result is consistent with the results obtained by Magini *et al.* (2007). Based on their assessment of the sedimentation in the channels during storms, these authors observed that there is a greater volume of sediment being deposited in Channels 1, 2 and 3, while Channel 6, the closest to the harbor channel, did not exhibit any sedimentation during the event, only sediment loss.

Profiles extracted from each beach section allow the assessment of the slope and variability of the beach (Figure 10). The overall steepness and variability of the beach increases from Section 1 to Section 4 (profiles 1 to 4). Profiles 1 and 2 indicate the most stable slopes with mean *tanβ* values of 0.009 and 0.010, respectively. Both profiles showed only small variations between surveys. These two profiles indicated that their corresponding sections have dissipative characteristics, which is in agreement with the results of previous studies by Elliff *et al.* (2013) and Farinnaccio *et al.* (2009) that indicate that the beach portion located between Channels 2 and 3 present a dissipative profile, with low slope and fine sand.

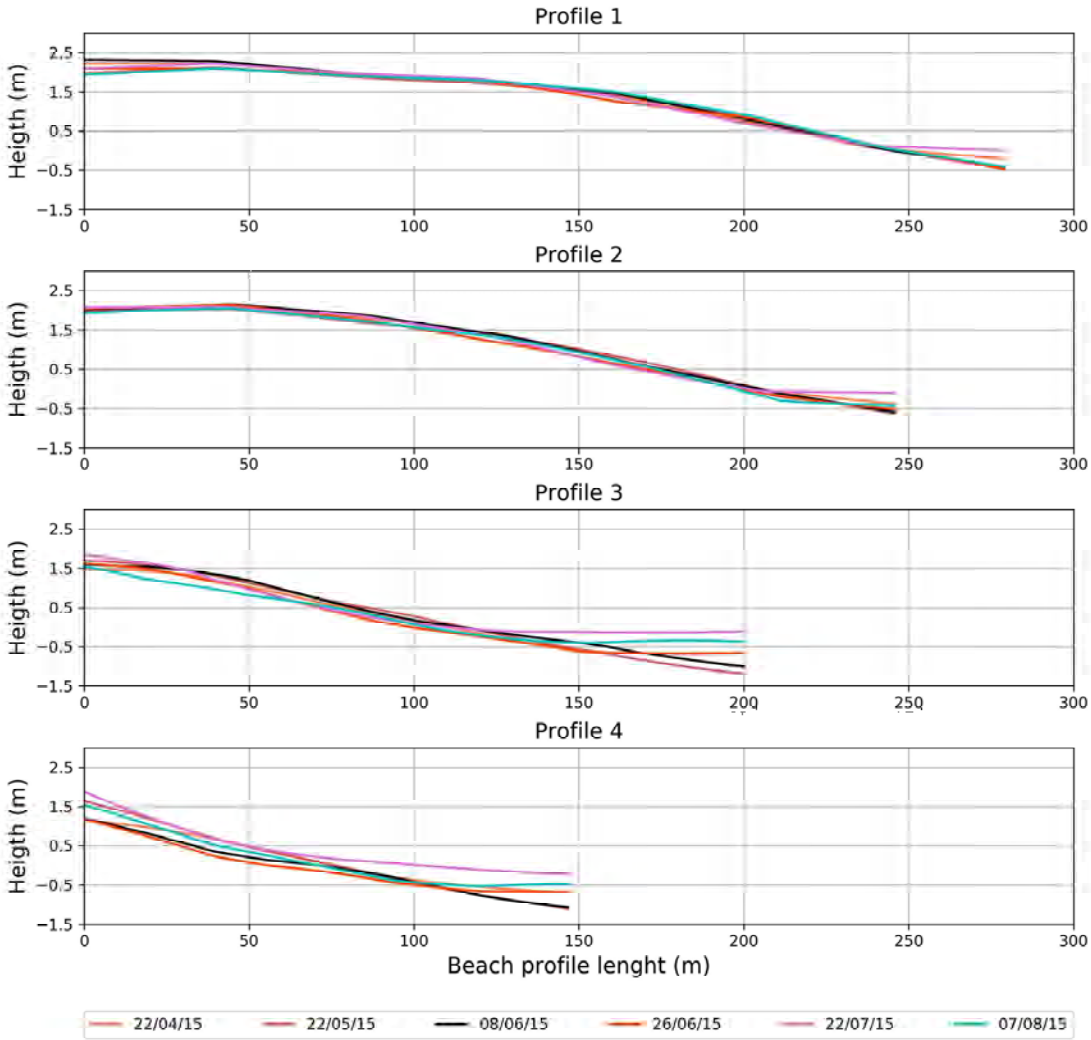

Figure 10 - Variation of the beach profile from each section of beach for all surveys conducted in the study.

However, profiles 3 and 4 are shorter and steeper when compared to profiles 1 and 2. These profiles also proved to be unstable for both the backshore and the shoreface. Profile 4 is the most variable profile. It was subjected to large changes between surveys and it is the most unstable and steepest profile. The steepness (*tanβ*) varies at approximately 0.011 in profile 3 and 0.015 in profile 4. In May, *tanβ* is 0.014 for profile 3 and 0.019 for profile 4, indicating the higher steepness and the variation of the profiles during the studied period. Thus, it is observed that the characteristics of the two corresponding sections (Sections 3 and 4) are relatively less dissipative, although being composed by similar grain size than the rest of the beach (fine sands, according to Farinnaccio *et al.* (2009) and Italiani (2014)). Steeper beaches are indicative for the influence of extreme events and are more susceptible to erosion (e.g., Shih and Komar, 1994; Komar, 1998), as observed in these sections, mainly in Section 4.

The study of Italiani (2014) assessed the effects of the artificial introduction of sediment at the Ponta da Praia, Santos Beach. Italiani (2014) also observed that Ponta da Praia continues to experience erosion even with the artificial introduction of sediment and retreats mainly during storm events. Farinnaccio *et al.* (2009) suggest that the erosion at Ponta da Praia may be related to the installation of the José Menino outfall at the western end of Santos Beach. The authors suggest that the cause for the retreat is the lack of sediment supply, which is likely retained in the exposed construction of the outfall that functions like a groin. Our results, however, indicate that the Ponta da Praia area is subjected to higher wave energy during storms, which could be the cause of intensified erosion in the area.

Additionally, the elevation differences observed throughout the surveys indicate overall beach erosion, with the eastern end of the beach exhibiting the largest variations and sediment loss. Such behavior is expected for the surveyed period, which was characterized by the most energetic conditions for the area. Our results also highlight how the beach portion near the harbor channel (Section 4) is more vulnerable to the passage of cold fronts and is subjected to higher erosion than the rest of the beach.

Conclusion

Based on morphological evolution and nearshore wave propagation, we assessed the behavior of Santos Beach under high-energy conditions. Our results show that the more energetic waves, associated with cold fronts that reach the region, have substantial influence on the local morphodynamics, resulting in a clear loss of beach volume. Such loss is still evident days after the exposure to more energetic conditions. The alongshore variability of the beach indicates that areas usually subjected to less wave energy are slightly steeper (eastern portion) than the more exposed areas (western portion). However, these slightly steeper areas are those that present higher morphological variability, being more unstable and susceptible to higher energy events than the highly dissipative areas. Since our aim was to assess the beach behavior under energetic conditions, overall beach erosion was observed throughout the surveyed period, as expected, with the eastern end of the beach experiencing the largest sediment loss. Wave modeling results indicate that the eastern portion of the beach (Ponta da Praia) is influenced by peaks of wave power during storm conditions. Our results, although limited in terms of temporal extension, provide important background information for the region, useful for the management of this highly urbanized stretch of the coast.

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REFERENCES

ANDRADE, T. S; SOUSA, P. H. G. O.; SIEGLE, E. Vulnerability to beach erosion based on a coastal processes approach. **Applied Geography**, v. 102, p. 12-19, 2019. DOI: 10.1016/j.apgeog.2018.11.003

BOOIJ, N. R. R. C.; RIS, R. C.; HOLTHUIJSEN, L. H. A third-generation wave model for coastal regions: 1. Model description and validation. **Journal of Geophysical Research: Oceans**, v. 104, n. C4, p. 7649-7666, 1999. DOI: 10.1029/98JC02622

CALLIARI, L. J.; TOZZI, H. A. M.; KLEIN, A. H. da F. Beach morphology and coastline erosion associated with storm surges in southern Brazil - Rio Grande to Chuí, RS. **Anais da Academia Brasileira de Ciências**, v. 70, n. 2, p. 231-247, 1998.

ELLIFF, C. I., MOTTA, N. de S., SCRICCO, I. M., de BARROS, M. O. Classificação Morfodinâmica da Praia do Gonzaga, Santos, São Paulo, Brasil. **Cadernos de Geociências**, v. 10, n. 2, p. 133-138, 2013.

FARINNACCIO, A.; Y GOYA, S. C.; TESSLER, M. G. Variações da linha de costa nas baías de Santos e São Vicente. **Quaternary and Environmental Geosciences**, v. 1, n. 1, p. 42-48, 2009. DOI: 10.5380/abequa.v1i1.14389

HOLTHUIJSEN, L. H. **Waves in oceanic and coastal waters**. Cambridge university press. 2010. 387p.

HOLTHUIJSEN, L. H.; BOOIJ, N.; RIS, R. C. A spectral wave model for the coastal zone. In: **International Symposium on Ocean Wave Measurement and Analysis**. ASCE, 1993. New Orleans. p. 630-641.

ITALIANI, D. **Resposta morfodinâmica à alimentação artificial da Ponta da Praia, Santos, SP.** Dissertação (Mestrado em Oceanografia Geológica). Instituto Oceanográfico, Universidade de São Paulo, São Paulo. 2014. 81p.

KOMAR, P. D. **Beach processes and sedimentation**. 1998. 544p.

MAGINI, C.; HARARI, J.; ABESSA, D. M. de S. Circulação recente de sedimentos costeiros nas praias de Santos durante eventos de tempestades: Dados para a gestão de impactos físicos costeiros. **Geociências**, v. 26, n. 4, p. 349-355, 2007.

MUEHE, D. Critérios morfodinâmicos para o estabelecimento de limites da orla costeira para fins de gerenciamento. **Revista Brasileira de Geomorfologia**, v. 2, n. 1, 2001. DOI: 10.20502/rbg.v2i1.6

PIANCA, C.; MAZZINI, P. L. F.; SIEGLE, E. Brazilian offshore wave climate based on NWW3 reanalysis. **Brazilian Journal of Oceanography**, v. 58, n. 1, p. 53-70, 2010. DOI: 10.1590/S1679-87592010000100006

REGNAULD, H., PIRAZZOLI, P. A., MORVAN, G., RUZ, M. Impacts of storms and evolution of the coastline in western France. **Marine Geology**, v. 210, n. 1-4, p. 325-337, 2004. DOI: 10.1016/j.margeo.2004.05.014

RIS, R. C.; HOLTHUIJSEN, L. H.; BOOIJ, N. A third-generation wave model for coastal regions: 2. Verification. **Journal of Geophysical Research: Oceans**, v. 104, n. C4, p. 7667-7681, 1999. DOI: 10.1029/1998JC900123

RUGGIERO, P., KOMAR, P. D., MCDOUGAL, W. G., MARRA, J. J., BEACH, R. A. Wave runup, extreme water levels and the erosion of properties backing beaches. **Journal of Coastal Research**. v. 17, n. 2, p. 407-419, 2001.

SALLENGER JR, A.H. Storm impact scale for barrier islands. **Journal of Coastal Research**, v. 16, n. 3, p. 890-895, 2000.

SERAFIM, M. B.; SIEGLE, E.; CORSI, A. C.; BONETTI, J. Coastal vulnerability to wave impacts using a multi-criteria index: Santa Catarina (Brazil). **Journal of Environmental Management**, v. 230, p. 21-32, 2019. DOI: 10.1016/j.jenvman.2018.09.052

SHIH, S.M, KOMAR, P.D. Sediments, beach morphology and sea cliff erosion within an Oregon coast littoral cell. **Journal of coastal Research**, v. 10, p. 144-157, 1994.

SHORT, A. D. Wave power and beach stages: a global model. In: **International Conference on Coastal Engineering**, 16. Hamburg, 1978. ASCE. pp. 1044-1062.

SIEGLE, E., CALLIARI, L. J. High-energy events and short-term changes in superficial beach sediments. Brazilian Journal of Oceanography, v. 56, n. 2, p. 149-152, 2008. DOI: 10.1590/S1679-87592008000200008

SILVA, F. G., SOUSA, P. H. G. de O., SIEGLE, E.. Longshore transport gradients and erosion processes along the Ilha Comprida (Brazil) beach system. **Ocean dynamics**, v. 66, n. 6-7, p. 853-865, 2016. DOI: 10.1007/s10236-016-0956-9

SILVEIRA, T. M., TABORDA, R., CARAPUÇO, M. M., ANDRADE, C., FREITAS, M. C., DUARTE, J. F., PSUTY, N. P. Assessing the extreme overwash regime along an embayed urban beach. **Geomorphology**, v. 274, p. 64-77, 2016. DOI: 10.1016/j.geomorph.2016.09.007

SOUSA, P. H. G. O.; SIEGLE, E.; TESSLER, M. G. Vulnerability assessment of Massaguaçú beach (SE Brazil). **Ocean & coastal management**, v. 77, p. 24-30, 2013. DOI: 10.1016/j.ocecoaman.2012.03.003

SOUZA, C.R. de G. A Erosão nas Praias do Estado São Paulo: Causas, Conseqüências, Indicadores de Monitoramento e Risco. In: Bononi, V.L.R., Santos Junior, N.A. (Org.), Memórias do Conselho Cientifico da Secretaria do Meio Ambiente: A Síntese de Um Ano de Conhecimento Acumulado, Instituto de Botânica – **Secretaria do Meio Ambiente do Estado de São Paulo**, São Paulo, SP, Brasil. p. 48-69. 2009. ISBN 978-85- 7523-025-1

STONE, G. W., ORFORD, J. D. Storms and their significance in coastal morpho-sedimentary dynamics. **Marine Geology**. v. 210. p. 1-5. 2004. DOI: 10.1016/j.margeo.2004.05.003

TESSLER, M. G.; MAHIQUES, M. M. Erosional and depositional processes on the Southern Coast of the State of Sao Paulo: a case study of Cananeia-Iguape System. **Anais da Academia Brasileira de Ciências**, v. 70, n. 2, p. 267-275, 1998.

TOLMAN, H. L., BALASUBRAMANIYAN, B., BURROUGHS, L. D., CHALIKOV, D. V., CHAO, Y. Y., CHEN, H. S., GERALD, V. M. Development and implementation of wind-generated ocean surface wave Models at NCEP. **Weather and Forecasting**, v. 17, n. 2, p. 311-333, 2002. DOI: 10.1175/1520-0434(2002)017<0311:DAIOWG>2.0.CO;2

IBGE (2015). Instituto Brasileiro de Geografia e Estatística - Modelo de ondulação geoidal. http://www.ibge.gov.br/home/geociencias/geodesia/modelo_geoidal.shtm. Accessed: 1st Semester/2016.