UNIVERSIDADE FEDERAL DO PARÁ
CAMPUS UNIVERSITÁRIO DE BRAGANÇA
INSTITUTO DE ESTUDOS COSTEIROS
FACULDADE DE CIÊNCIAS BIOLÓGICAS

REMO LUAN PEREIRA MARINHO DA COSTA

The effects of tidal modulation of breaking wave in a macrotidal beach in the Amazon coast (Ajuruteua-PA): climatic patterns and unplanned territorial occupation

BRAGANÇA-PARÁ
2022

REMO LUAN PEREIRA MARINHO DA COSTA

The effects of tidal modulation of breaking wave in a macrotidal beach in the Amazon coast (Ajuruteua-PA): climatic patterns and unplanned territorial occupation

Trabalho de Conclusão de Curso, apresentado como requisito parcial para obtenção de grau de Licenciatura em Ciências Biológicas, Faculdade de Ciências Biológicas, Instituto de Estudos Costeiros, Universidade Federal do Pará.

Orientadora: Prof.ª. Drª. Luci Cajueiro Carneiro Pereira

Coorientador: Prof. Dr. Cesar Mösso Aranda (UPC, Barcelona, Espanha)

BRAGANÇA – PARÁ

2022

REMO LUAN PEREIRA MARINHO DA COSTA

The effects of tidal modulation of breaking wave in a macrotidal beach in the Amazon coast (Ajuruteua-PA): climatic patterns and unplanned territorial occupation

Trabalho de Conclusão de Curso, apresentado como requisito parcial para obtenção de grau de Licenciatura em Ciências Biológicas, Faculdade de Ciências Biológicas, Instituto de Estudos Costeiros, Universidade Federal do Pará.

Orientadora: Prof.ª. Drª. Luci Cajueiro Carneiro Pereira

Coorientador: Prof. Dr. Cesar Mösso Aranda (UPC, Barcelona, Espanha)

Data de aprovação: ___/___/_______

Banca Examinadora

____

Professora Drª Luci Cajueiro Carneiro Pereira

Orientadora – UFPA

____

Professora Drª. Marcela Cunha Monteiro

Examinador externo – UFRA

____

Professor Dr. Nils Edvin Asp Neto

Examinador interno – UFPA

AGRADECIMENTOS

À Universidade Federal do Pará por me ajudar a dar os primeiros passos ao meu sonho de conquistar o mundo.

Ao CNPq pela bolsa de Iniciação Científica que foi fundamental para despertar a vontade em continuar na área de pesquisa.

Ao Prof. Dr. Marcelo Vallinoto por ter sido meu primeiro orientador e por me guiar nesses primeiros passos ao mundo científico.

Ao Laboratório de Evolução e a todos os seus participantes, principalmente ao Dr. Yrlan Oliveira por me ensinar tudo que sei sobre técnicas de laboratório.

À CAPES pela oportunidade de sair do país e conhecer o mundo, através da bolsa de Ciências sem Fronteiras e ao meu orientador na Universidade de Barcelona, Dr. Alejandro Gracia por me receber e orientar durante o estágio em Barcelona.

À minha mainha e orientadora, Profa. Dra. Luci Pereira, pelos ensinamentos e por sempre acreditar em mim e estar ao meu lado, por ser o meu chão quando tudo parece estar perdido. Ao meu coorientador Prof. Dr. Cesar Mösso Aranda por me ajudar a realizar parte do meu sonho.

À minha família por sempre acreditar, torcer por mim e mesmo estando a milhares de quilômetros sei que sempre estiveram e estão ao meu lado. Obrigado ao meu pai. À Renata, Nayara, Murilo, Ricardo e Natalícia, por fazerem parte da minha vida e me mostrar que família não é só sangue. À minha Bubu por sempre me amar, a minha madrinha Luise por sempre me inspirar e a minha irmã Raíssa por sempre estar ao meu lado.

À Andrea por ser minha pessoa, sempre me escutar e sempre se preocupar por mim. À Xavi por sentar-se do meu lado no primeiro dia de aula em Barcelona e desde então ser meu amigo. Às minhas amigas, Brenda, Carla e Lídia e amigo, Arthur, pelos melhores rolês.

À minha casa por me fornecer um refúgio tranquilo nesse caos que é o mundo.

Em especial à Dani que sempre me consegue fazer sorrir e feliz independentemente do mal ou triste eu esteja.

Ignorance more frequently begets confidence than does knowledge: it is those who know little, and not those who know much, who so positively assert that this or that problem will never be solved by science.
—Charles Robert Darwin, *The Descent of Man* (1871)

RESUMO

O objetivo deste estudo foi conhecer os efeitos da modulação das ondas em função da variação das marés em uma praia de macromaré no litoral amazônico, considerando diferentes padrões climáticos. O estudo foi dividido em duas abordagens, uma com série de dados obtidos em médio prazo (2006-2018) de tempo de instituições nacionais e internacionais, e outra com dados obtidos *in situ* de marés e ondas, na praia de Ajuruteua, entre 2012 e 2014. Imagens obtidas por Digital Globe foram extraídos usando o *software* Google Earth (GE). Essas imagens foram utilizadas para monitorar o litoral em diferentes períodos (05/06/2007, 28/04/2013 e 07/09/2021) na área de estudo. As forçantes *offshore* - ventos e ondas - sopraram de nordeste para sudeste (45°<θ< 120°N) durante a maior parte do estudo. Tempestades severas foram registradas em 2007, 2009, 2011 e 2017 (La Niña) com velocidades médias e de rajadas de vento acima de 20 m s^{-1}. Durante o mesmo período, H_{os} alcançou alturas acima de 5 m associados a períodos de 16 a 23s. As descargas fluviais também foram relacionadas à precipitação com valores extremos registrados durante os eventos climáticos, como os de 2008-2009 (La Niña), 2010 (El Niño e Seca), 2011 (La Niña), 2012-2013 (Seca) e 2015 -2016 (El Niño). As alturas e períodos de ondas nearshore foram moduladas pela flutuação semi-diurna das marés, assim como pelas condições *offshore* e do clima local. Um recuo progressivo da praia foi registrado ao longo dessa costa. Comparando 2007 e 2021, foi possível registrar uma redução de 0,15 km^2 e um recuo de 0,360 km na parte mais ao norte da praia de Ajuruteua. A ocupação territorial não planejada e a falta de planejamento intensificaram os processos erosivos nesta praia de macromarés que recebe ondas de energia moderada. O planejamento e a regulação costeira são urgentemente necessários para a área de estudo. Diante disso, este estudo sugere que as autoridades governamentais devem controlar a ocupação territorial local, bem como devem considerar os processos físicos de curto a longo prazo para os futuros projetos de contenção.

ABSTRACT

The objective of this study was to know the effects of tidal modulation of breaking waves in a recreational macrotidal beach on the Amazonian coastline, considering different climatic patterns. The study was divided in two approaches, one with medium-term data series (2006-2018) acquired by National and International institutions, and other with *in situ* short-term data of tides and waves at Ajuruteua beach between 2012 and 2014. Images obtained by Digital globe were extracted using Google Earth (GE) software. These images were used to monitor the coastline in different periods (05/06/2007, 28/04/2013 and 07/09/2021) in the study area. Offshore forces - winds and waves - blew from northeasterly to southeasterly (45°<θ< 120°N) during most of the study period, Severe storms in 2007, 2009, 2011 and 2017 with average and gust wind speeds above 20 m s^{-1}, coinciding with the La Niña event. During the same period, H_{os} were above 5 m associated with periods of 16 to 23s. Riverine discharges also were related to rainfall levels with extremes ranges recorded during climatic events, such as those of 2008-2009 (La Niña), 2010 (El Niño and Drought), 2011 (La Niña), 2012-2013 (Drought) and 2015-2016 (El Niño). Nearshore wave heights and periods were modulated by the semi-diurnal tidal fluctuation and variability depends of offshore condition and local climate. A progressive beach retreat was recorded along of that coastline. Comparing 2007 with 2021, it was possible to register a reduction of 0.15 km^2 and a beach retreat of 0.360 km in the most northern part of Ajuruteua beach. Unplanned territorial occupation and the lack of beach planning have intensified the erosive processes in this macrotidal beach that expect waves of moderate energy. Coastal planning and regulation is urgently required for the study area. Given this, this study suggests that the governmental authorities must control the local territorial occupation, as well as must consider physical processes from short to long term for the future contention projects.

LISTA DE FIGURAS

Figure 1. Study area, showing (A) South America, (B) Brazilian Amazon coast, (C) Bragantinian Peninsula detaching Caeté and Taperaçu estuaries and Bragança city, (D) Ajuruteua beach, (E) Unplanned territorial occupation on intertidal zone of Ajuruteua beach and (F) Destruction of the waterfront of Ajuruteua beach…………………………**5**

Figure 2. Wind (A) and wave (B) directions (θ °N) and histogram (%) of the wind speed classes (m s^{-1}) from NOAA (station 41041) for the period 2006-2018............................9

Figure 3. Offshore wind (intensity, m s^{-1}) and wave (height-m and period-s) conditions between 2006 and 2018..10

Figure 4. (A) 3-Month Oceanic *Niño* Index, (B) Annual rainfall levels between 2006-2018, highlighting climate events (LN: La Niña, EN: El Niño and D: Drought) and the average of the historical data (red line). Search: NOAA, figure A and INMET, figure B.11

Figure 5. Monthly river discharge (m^3s^{-1}) and rainfall level (mm) between 2006 and 2018. (Search: Riverine discharge, ANA, and rainfall level, INMET)………………………...12

Figure 6. Water level from DHN (Fundeadouro de Salinópolis station) between 2006 and 2018……………………………………………………………………………13

Figure 7. Water level (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2012 at Ajuruteua beach. …………………………………...14

Figure 8. Water level (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2013 at Ajuruteua beach……………………………………15

Figure 9. Water level (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2014 at Ajuruteua beach……………………………………16

Figure 10. Google earth satellite image, with 3 colored lines representing the study area in 2007 (*green line*), 2013 (*blue line*) and 2021 (*red line*), comparing the effects of erosion in the study zone…………………………………………………………………...17

Figure 11. Relationship between riverine discharge and maximal values of significant wave heights in six field campaigns……………………………………………………..19

Figure 12. Unplanned territorial occupation on intertidal beach zone (A-C), mangrove (D, E) and dune (F) areas, and debris of houses in front of the seawalls (G, H)……………21

SUMÁRIO

1. INTRODUCTION…………………………………………………………………..01

2. STUDY AREA…………………………………………………………………03

3. METHODOLOGY……………………………………………………………06

4. RESULTS………………………………………………………………………08

4.1. Forcing Mechanisms……………………………………………………...08

4.2. *In Situ* measurements…………………………………………………..13

4.3. Satellite Image……………………………………………………………16

5. DISCUSSION…………………………………………………………………17

6. CONCLUSION………………………………………………………………..22

LITERATURE CITED

1. INTRODUCTION

Coastline processes are controlled by different physical drives, such as tides, waves, currents, riverine discharges, winds, rainfall levels, etc. under local, regional, or global scales (Aagaard, 2002). So, a standardized understanding of these processes and their variability is important for the recognition of both - spatial and temporal changes (Short, 1991; Levoy, 2001).

On a global scale, studies on these processes have given more attention on microtidal (tidal range < 2.0 m) followed by mesotidal (tidal range between 2.0- 4.0 m) beaches (Wright et al., 1982; Masselink., 1993). However, on macrotidal (tidal range > 4.0 m) beaches, the physical processes need more attention, as those related to tidal modulation of break waves (Pereira et al., 2020).

Given this, over the tidal cycle, breaking waves might be modulated by the tides when - for example - extensive sub or intertidal sandbanks/flats or coral reefs are exposed in the nearshore area (Kroon and Masselink, 2002; Pereira et al., 2020). At the low tide, the waves break on the sandbanks and bars or reefs, and only locally generated short-period wind waves might reach the coast. When the tide is rising, by contrast, offshore waves with a longer period start to propagate over the now deeper sandbanks and move towards the shoreline, with maximum wave heights and periods being recorded during the high tide (Haquette and Aernouts., 2010; Pereira et al., 2016a, 2020).

The Brazilian Amazon has a macrotidal coastline, at the same time that is protected by nearshore sandbanks throughout the low tide, whereas during the high tides of spring tides (occurring when the difference between high and low water is the greatest, after the new moon or full moon), the wave energy (with significant wave height of around 1.7 m) causes destruction of edifications and degradation of dunes and mangrove forest (Souza-Filho et al., 2006; Pereira et al., 2016a, 2016b, 2018). In addition, this coastal area is particularly sensitive to climatic events such as El Niño, Drought and La Niña events. These events cause intense drought or strong rains, as a consequence of lower or higher temperatures of the surface waters of the Tropical Atlantic Ocean (Drought event, drier condition) or of the Tropical Pacific Ocean (El Niño, drier condition and La Niña, flooding condition), (Marengo et al., 2012, 2013a, 2013b; Pereira et al., 2013a, 2017; Andrade et al., 2016; Cunha et al., 2019 and Costa et al., 2022).

Due to the local high hydrodynamic energy and climatic events, erosion episodes have been recorded in some Amazonian beaches, mainly in areas with unplanned territorial occupation (Pereira et al., 2007, 2014, 2018). Among the recreational oceanic Amazonian beaches, Ajuruteua is one of the most visited and problems related to erosion processes have been recorded since 90's (Souza-Filho and El Robrini, 2000; Monteiro et al., 2009; Santos et al., 2019). Despite the efforts to mitigate or avoid the destruction of edifications and degradation of local coastal environments none of them have been efficient, and unfortunately there is no beach management plan for the study area. In the last two years, erosion contention structure (e.g., seawalls) have been constructed on the waterfront of Ajuruteua beach, but the erosion problems are still clearly evidenced, mainly during the equinoctial spring tides (i.e., largest tidal range in March and September when the moon and sun are aligned with the equator).

In this context, this study includes hydrodynamic and meteorological data from national and international institutions. In addition, field campaign (wave and tides, focusing on the modulation of breaking wave) data and satellite images from Google Earth were obtained to better understand how climatic and hydrodynamic patterns affect a beach with unplanned territorial occupation. Given this, the objective of this study was to know the effects of tidal modulation of breaking waves in a recreational macrotidal beach on the Amazonian coastline, considering different climatic patterns.

As no data or information about tidal modulation in this zone has been taken by the decision makers, this study will bring important information that can be considered in future beach management plans elaborated in the study area or in other beaches that have similar characteristics on the Amazon coast.

2. STUDY AREA

The study area is located in northeastern Pará state, specifically in Bragança municipality - between Maiaú and Caeté bays (00°46'–1°00' S and 46°36'–46°44' W) - in eastern Brazilian Amazonia. This coastline holds five beaches (Pescadores, Ajuruteua, Farol, Chavascal and Busucanga beaches) located on a coastal island, which is bordered by the Caeté River estuary and Taperaçu estuary, by the presence of dunes and about 25 km of mangrove forest dominated by three mangrove tree species, *Rhizophora mangle* L., *Avicennia germinans* L., and *Laguncularia racemosa* (L.) C.F. Gaertn (Cohen et al., 1999; Menezes et al., 2008), saltmarshes, and several other coastal environments which are cut by creeks and tidal channels (Souza-Filho and Paradella, 2002).

The local climate is equatorial humid, with mean annual rainfall of approximately 2,500 mm, of which, 75–85% of the annual rainfall occurs during the rainy season i.e., from January to June, being the rainiest months normally between March and May (INMET, 2022). Conversely, the other six months encompass the dry season, being from September to November the driest period. Wind directions and speeds also vary seasonally, with relatively strong northeasterly winds occurring during the dry season (mean monthly speeds of 2.5–4.5 m s^{-1}, with a maximum of 7.0–9.5 m s^{-1}). Winds are weaker during the rainy season, coming from all directions, with mean monthly speeds normally of 1.5–3.0 m s^{-1}, increasing to a maximum of 4.0–7.0 m s^{-1} (INMET, 2022).

The main local hydrodynamic features are tidal elevations varying from 4 m (neap tide) to 6 m (spring tide) over semi-diurnal cycles (DHN, 2022). The macrotides are responsible for intense tidal currents with velocities reaching normally of 1.5–2.0 m s^{-1}, following bi-directions, depending on the tidal cycles - the flood tide or the ebb tide (Pereira et al., 2012a, 2012b, 2013b). With respect to wave features, the height is attenuated from 3–4 m in deep water to 1–2 m in nearshore waters, and the modulation of wave energy occurs due to the presence of local nearshore sandbanks (Pereira et al., 2016a, 2020).

Specifically Ajuruteua has a barrier-beach ridge and forms an arc along NW-SE direction with two different sectors (Northwestern and Southeastern), presenting erosive characteristics mainly in the NW sector (Figure 1). The Caeté-Taperaçu Marine Extractive Reserve includes four of Bragança’s beaches, but Ajuruteua beach is excluded from the strict protection of the conservation unit of sustainable use of natural resources. In the latter, the main economic sectors are based in fishing and tourism, however the lack of planning and any effective municipal management initiatives have generated a series of environmental and social problems, including the destruction of edification and the degradation of dunes and mangrove areas (Pereira et al., 2014, 2018).

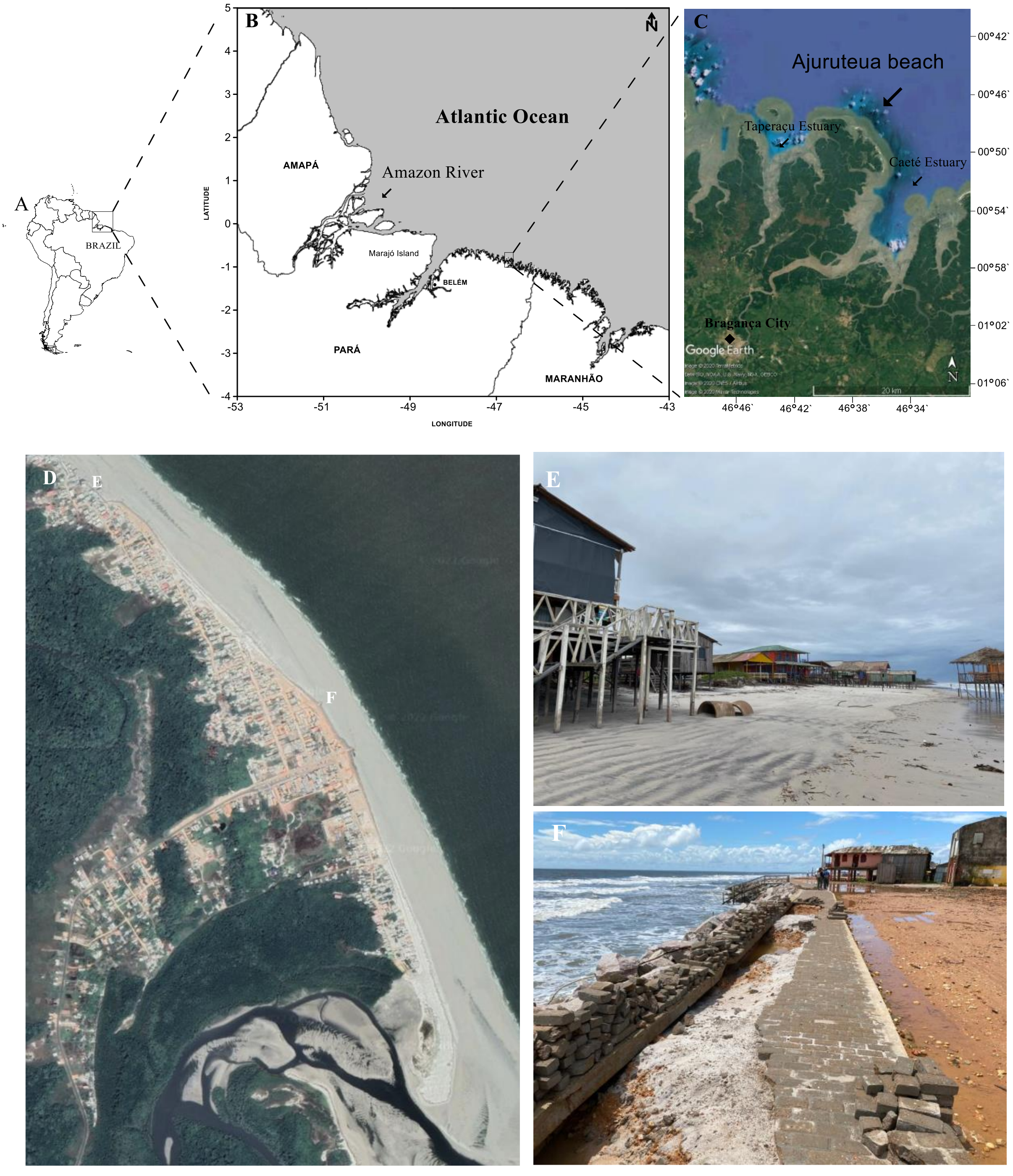

Figure 1. Study area, showing (A) South America, (B) Brazilian Amazon coast, (C) Bragantinian Peninsula highlighting Caeté and Taperaçu estuaries, and Bragança city, (D) Ajuruteua beach, (E) Unplanned territorial occupation on intertidal zone of Ajuruteua beach, and (F) Destruction of the waterfront of Ajuruteua beach.

3. METHODOLOGY

This study was divided in two approaches, one with medium-term data series (2006-2018) acquired by National (Brazilian Institute of Meteorology-INMET, National Waters Agency-ANA and Hydrographic and Navigational Department of the Brazilian Navy-DHN) and International (National Oceanic and Atmospheric Administration - NOAA and Google Earth) institutions, and other with *in situ* short-term data of tides and waves in Ajuruteua beach between 2012 and 2014.

Offshore hourly wind intensities (average and maximum) and directions, as well as offshore significant wave heights-H_{os} (average height of the highest one-third of all waves measured), periods-T_p (defined as the wave period associated with the most energetic waves in the total wave spectrum at a specific point) and directions-θ were obtained from National Data Buoy Center - NDBC which holds data from NOAA (station 41041). Correlations between offshore wind and wave conditions were made between 2006 and 2018, in order to characterize seasonal variations. Monthly Oceanic Niño Index-ONI, highlighting El Niño and La Niña intensities were also acquired from NOAA during the same period. The events were classified according to Cunha et al. (2019) and government websites (INMET, 2022; Golden Gate Weather Service, 2022).

Monthly precipitation data from 2006 to 2018 were provided by the INMET (meteorological station located at Tracuateua at 36 m above the ground and approximately 17 km west of the town of Bragança). The records of the fluvial discharge of the Caeté River were provided from 2006 to 2018 by the ANA gauge station at Nova Mocajuba, located approximately 23 km upstream from the upper sector of the estuary (ANA, 2022).

Hydrodynamic (tide elevation and significant wave height—H_s and wave period-T_p) data were obtained in situ during 10 campaigns from 25 h to 168h duration, which were carried out between 2012 to 2014, including four different scenarios (Table 1).

Table 1. Natural characteristics during field campaigns.

SEASONS	**NATURAL CONDITIONS/MONTHS**
Rainy	when it is increasing river discharge and coinciding with equinoctial tides - March and April
	when the high river discharge attain the maximum values - May and June
Dry	when it is decreasing river discharge and coinciding with equinoctial tides - September and October
	when the discharge of the local rivers is at its lowest level - November and December

Hydrodynamic data were collected using a bottom-mounted mooring at a depth of 4.7 m below MWL, to which a wave and tide data loggers (TWR 2050) were attached. Wave sampling was based on 512 samples at a burst rate of 4 H_z with sampling periods of 10 min duration. Tidal water level data were obtained every 2s and mean values were measured every 10 min. The correction of tidal elevation was made according to the level of water over the Reduction Level, which is 2.75 for the Salinópolis station, according to the DHN.

Images obtained by Digital globe were extracted using Google Earth (GE) software. These images were used to monitor the coastline in different periods (05/06/2007, 28/04/2013 and 07/09/2021) in the study area. Vegetation, dunes and/or edifications were considered as reference line through visual interpretation to define the shoreline at each image. Polygons were also plotted in the GE and the eroded areas and beach retreat were estimated among the years (2007-2013, 2007-2021 and 2013-2021).

4. RESULTS

4.1 Forcing Mechanisms

This section described the data on wind intensities and directions, offshore significant wave heights and periods, rainfall levels, ONI (Oceanic Niño Index), fluvial discharges and tidal oscillation

Figure 2 shows offshore forces - winds and waves - blowing from northeasterly to southeasterly (45°<θ< 120°N) during most of the study period, i.e., 90% for winds and 70% for waves. For the winds blowing in these directions, the average and gust wind speeds were 6.8±1.8 m s^{-1} and 8.3±2.1 m s^{-1}, respectively. These winds generated H_{os} of 2.0±0.5 m associated with periods of 9.0±2.0 s. Seasonally, mean and gust winds were 11% stronger during the rainy season (7.6±1.7 m s^{-1} and 9.2±2.0 m s^{-1}, respectively) than the dry season, and consequently H_{os} were 10% larger during the rainy season associated to periods of 9.4±2.4 s. Figure 3 shows severe storms in 2009, 2011 and 2017 with average and gust wind speeds above 20 m s^{-1}, coinciding with the La Niña event. During the same period, H_{os} were above 5 m associated with periods of 16 to 23s.

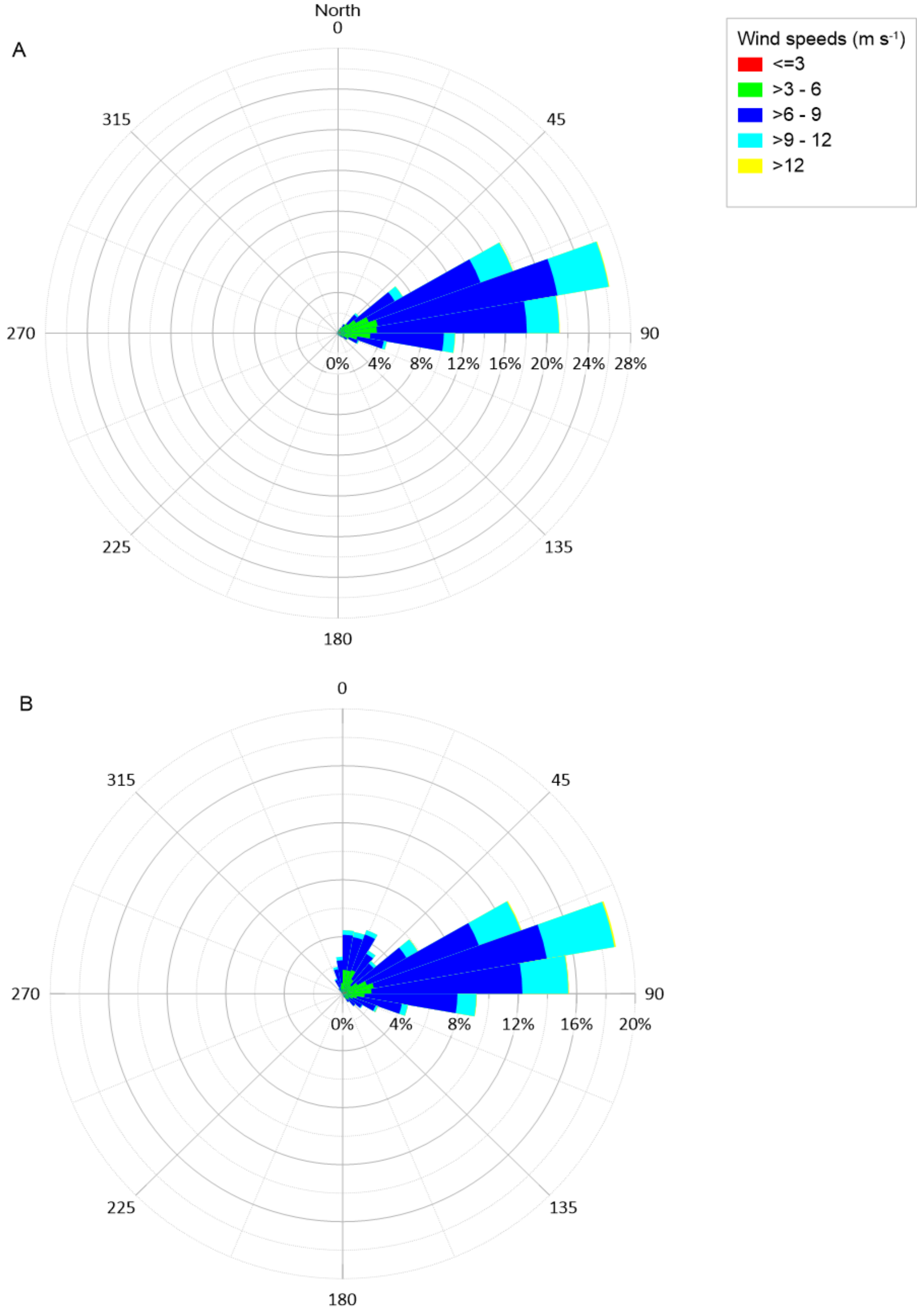

Figure 2. Wind (A) and wave (B) directions (θ °N) and histogram (%) of the wind speed classes (m s^{-1}) from NOAA (station 41041) for the period of 2006-2018.

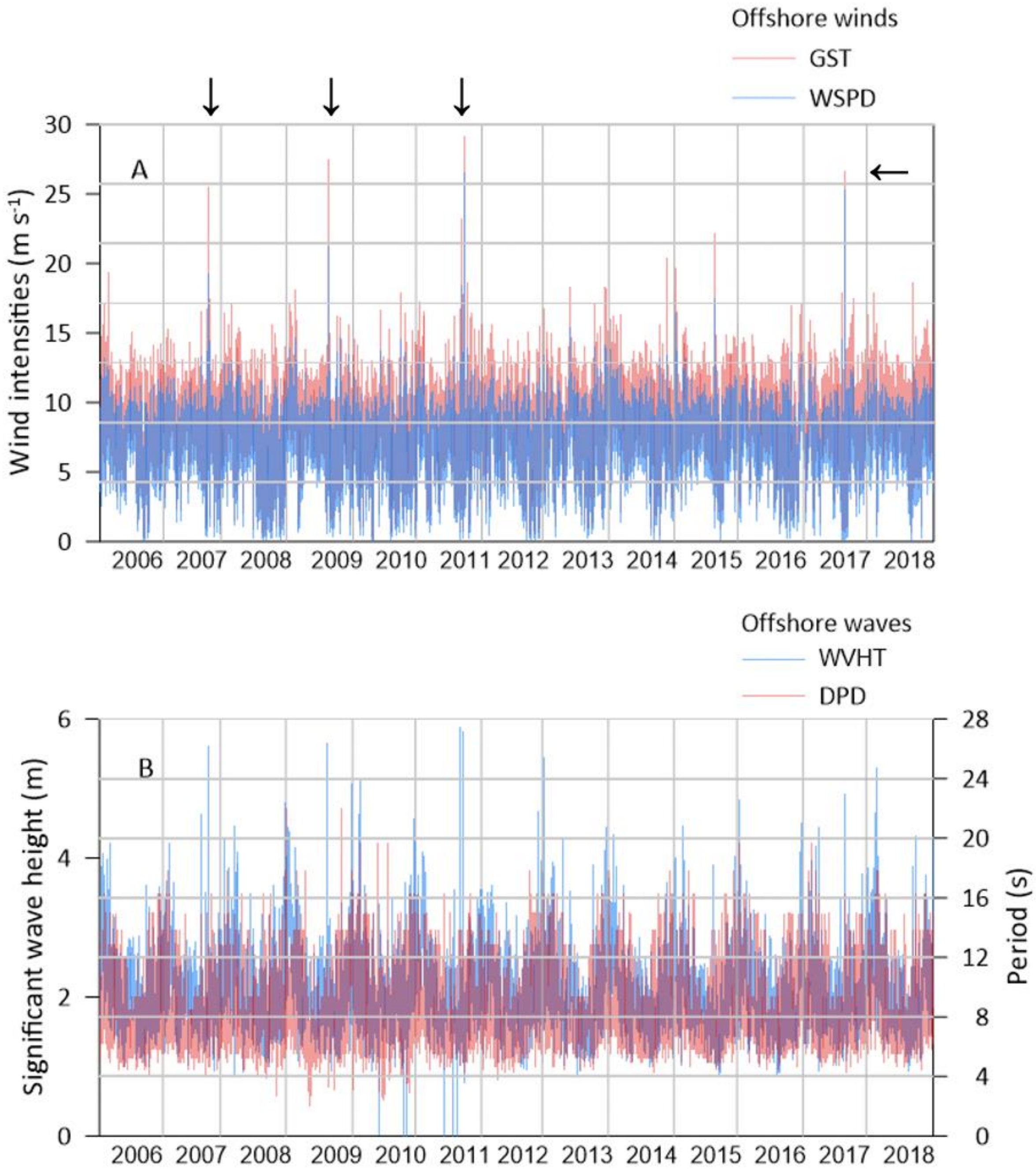

Figure 3. Offshore wind (intensity, m s^{-1}) and wave (height-m and period-s) conditions between 2006 and 2018.

An intense La Niña episode was recorded in 2008 and 2009 (Figure 4), reaching rainfall levels of 3284.3 mm in 2009 (i.e., 31.34% above 2006-2018 rainfall average). In 2010 there was a moderated El Niño event which coincided with the Drought event, resulting in a 13.44% reduction in rainfall when compared with the 2006-2018 rainfall average. In 2011, a moderate

La Niña was recorded, leading to an increase of 14% in the rainfall level in the region. In 2012 and 2013 an intense and resilient Drought event was recorded. This event resulted in a 45% reduction of rainfall levels in 2012 and 40% in 2013, when compared with 2006-2018 rainfall average. A strong El Niño event between the second half of 2015 and November 2016 was recorded in the study area, resulting in a 14% and 21% rainfall deficit for 2015 and 2016, respectively (Figure 4).

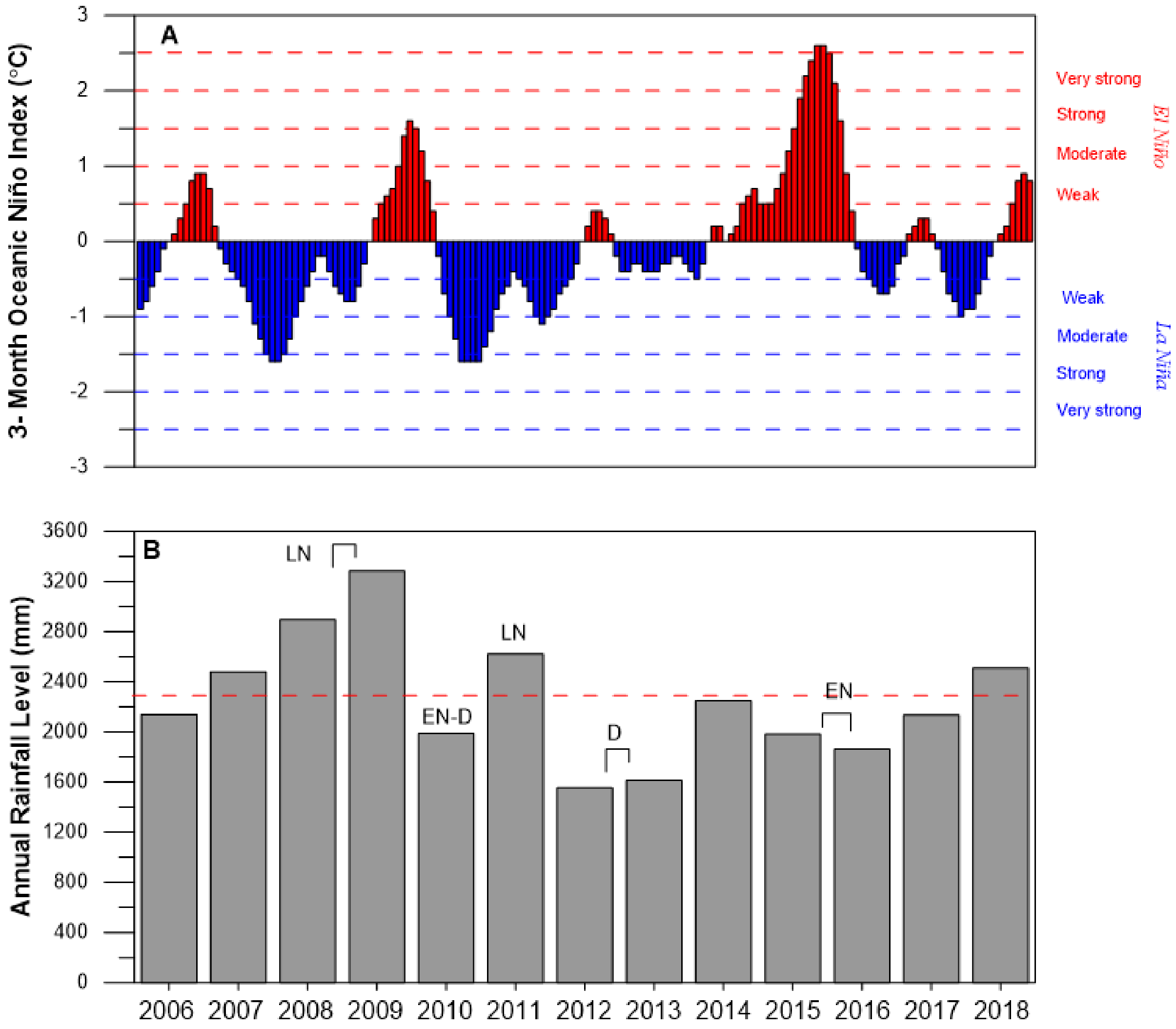

Figure 4. (A) 3-Month Oceanic *Niño* Index, (B) Annual rainfall levels between 2006-2018, highlighting climate events (LN: La Niña, EN: El Niño and D: Drought) and the average of the historical data (red line). Search: NOAA, figure A and INMET, figure B.

The river discharges were directly related to rainfall levels and figure 5 shows the effects of both, seasonal variation, and climate events. During the first semester, the high rainfall levels contributed with the high discharges of the Caeté River, whereas an opposite pattern was recorded during the second semester, when the rainfall levels were lower resulting in lower river discharge. With respect to climate events, the intense episode of La Niña of 2008 and 2009 resulted in strong rains. In May 2009, rainfall level attained 849.7 mm and riverine discharge of the Caeté River was 127.7 $m^3 s^{-1}$. The effect of this event was also recorded in 2011, when river discharge reached 109.4 $m^3 s^{-1}$ under a rainfall level of 503.1 mm, in April of 2011. The drier events (Drought and El Niño) occurred in 2010 and lead a lower monthly river discharge, when maximal value was of 68.8 $m^3 s^{-1}$ in May (i.e., a reduction of 54.17% when compared to May 2009) under rainfall level of 379.5 mm. The 2015-2016 El Niño also lead a lower rainfall levels and river discharge, and maximal values were recorded in April (2015: 84.4 $m^3 s^{-1}$ and 621.3 mm, and 2016: 87.2 $m^3 s^{-1}$ and 389.1 mm).

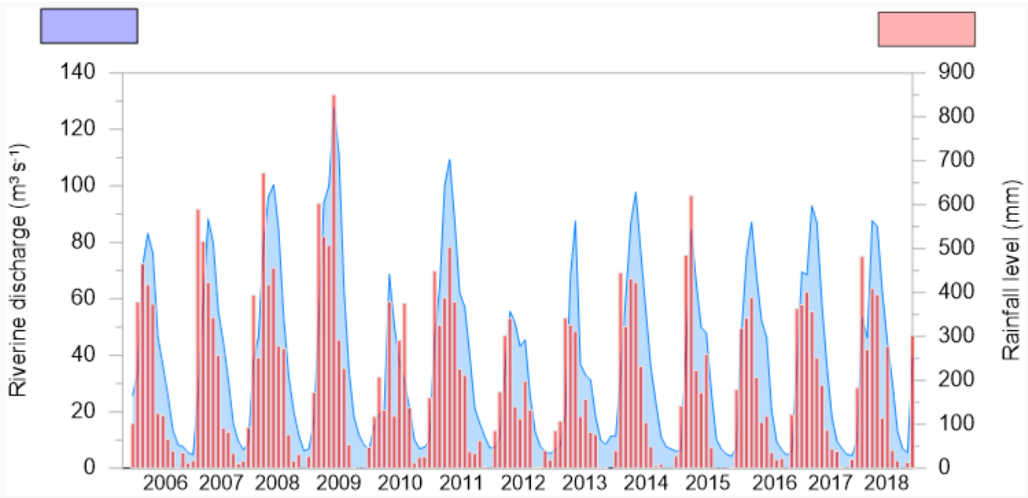

Figure 5. Monthly river discharge (m^3s^{-1}) and rainfall level (mm) between 2006 and 2018. (Search: Riverine discharge, ANA, and rainfall level, INMET).

With respect to tidal elevation, macrotides dominate the study area with spring tides varying from 4.0 to 5.5 m, and neap tides commonly ranging from 3.5 to 4.5 m. Figure 6 was based on DHN data and does not represent the effects of the climate oscillation.

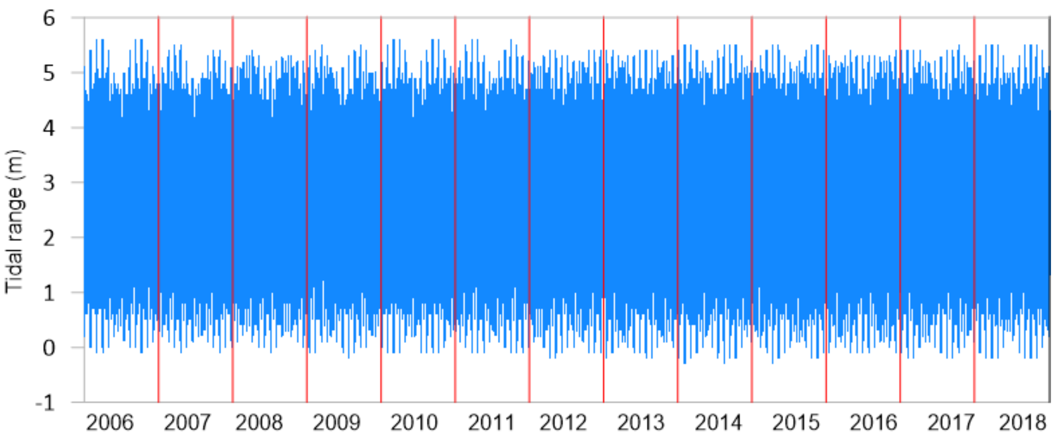

Figure 6. Water level from DHN (Fundeadouro de Salinópolis station) between 2006 and 2018.

4.2 *In Situ* measurements

Wave heights and periods were modulated by the semi-diurnal tidal fluctuation. Figures 7-9 show the effects of semi-diurnal spring and or neap tides at study area. Water depth across the beach increases by up to 6 m at spring high tide (as recorded in April 2014), allowing the longer period ocean waves to cross the sandbanks and surf zone reaching the beach, while at low tide exposure of the sandbanks dissipates ocean waves and only permits short fetch limited waves to reach the base of the low tide beach. As a consequence, breaking wave height varied from a 1–1.8 m at high tides to a of 0.1–0.5 m at low tides, with the lowest heights being recorded during spring low tides when the sandbanks were most exposed, resulting in a considerable range in wave heights (Figures 7-8). The highest significant wave heights with values from 1.5 to 1.8 m were normally associated to wave periods between 0.8 to 11 s. June

2012 (Figure 7) and July 2013 (Figure 8) were the months with the lowest values of both - wave heights (< 1.0 m) and periods (< 8s).

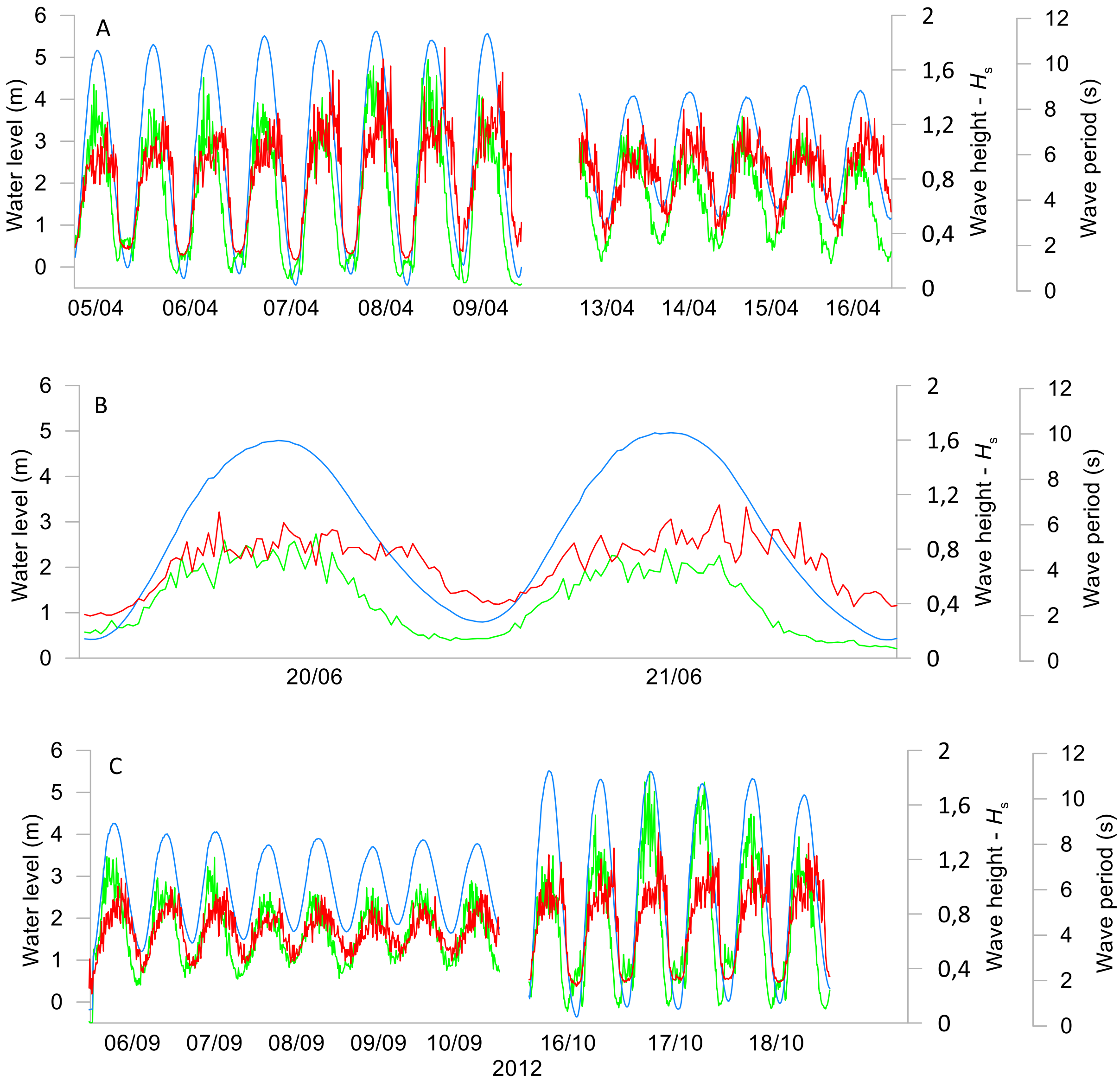

Figure 7. Water level (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2012 at Ajuruteua beach.

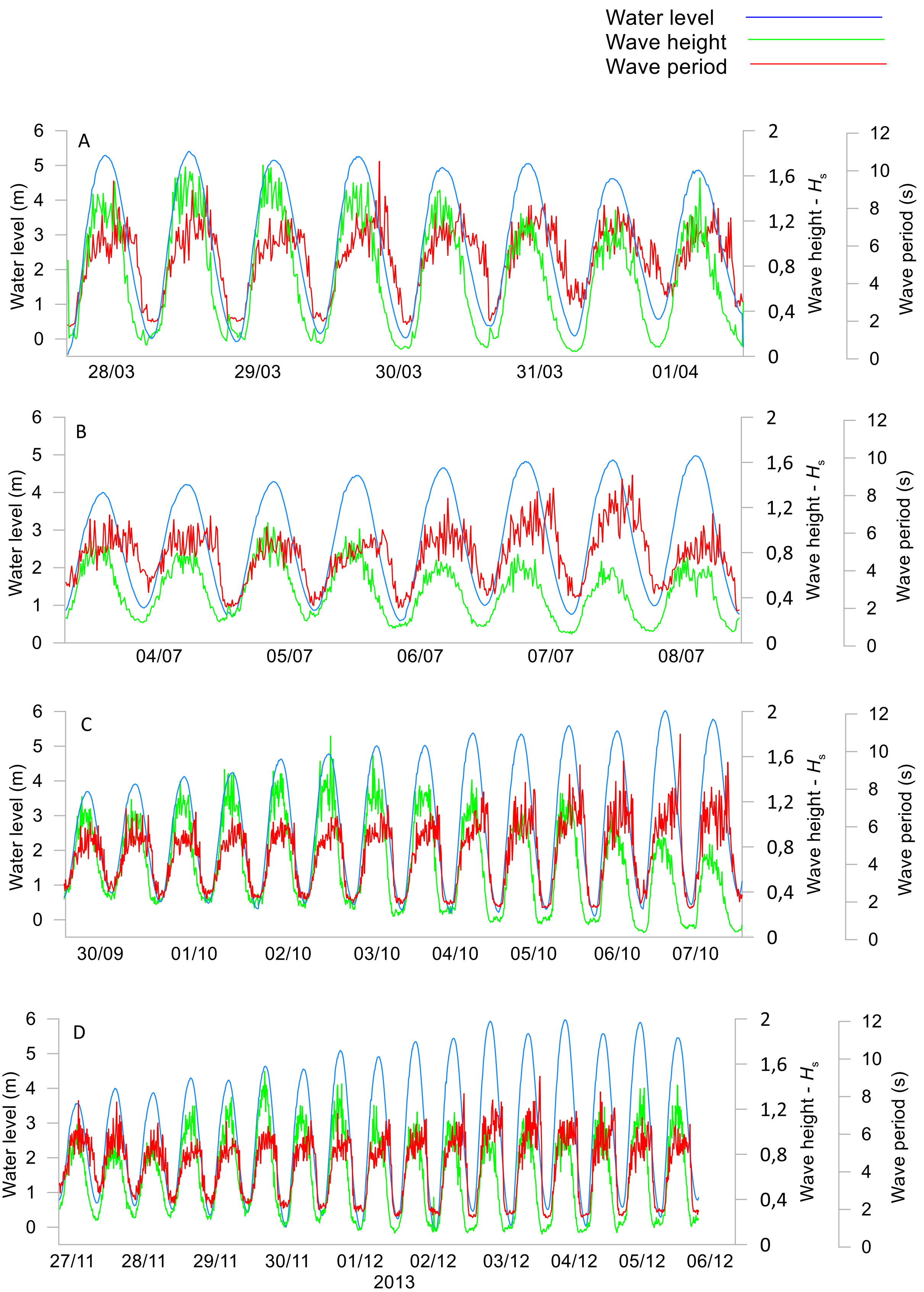

Figure 8. Water level (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2013 at Ajuruteua beach.

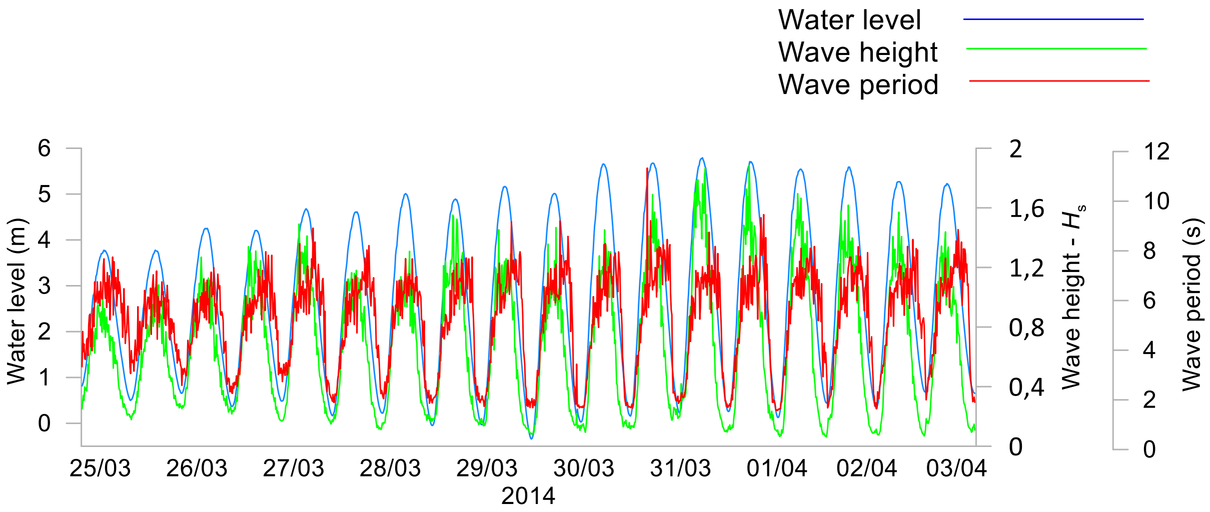

Figure 9. Tidal range (*blue* line), wave heights, *H*s (*green* line), and periods, *T* (*red* line), during different months in 2014 at Ajuruteua beach.

4.3 Shoreline analysis

Figure 10 shows a progressive beach retreat along the coastline. Comparing 2007 with 2021, it was possible to record a reduction of 0.15 km^2 and a beach retreat of 0.360 km in the most northern part of Ajuruteua beach. The NW sector of Ajuruteua beach has been the most affected by the erosion problems. Table 2 shows the beach retreat of the shoreline and the area eroded between 2007-2013, 2007-2021, 2013-2021. Between 2007 and 2013, it was recorded the highest erosion rate (80%) and beach retreat (68%) of the 2007-2021 period. Between 2007 and 2013 it was recorded two La Niña events (2008-2009 and 2011) and two drier events (2010 and 2012-2013), and between 2013-2021, the most intense event was the 2015-2016 El Niño event (Figure 4). Unfortunately, GE had no available good satellite images for each studied year and for this reason, it was not possible more detailed analyses on the effect of this event on the shoreline.

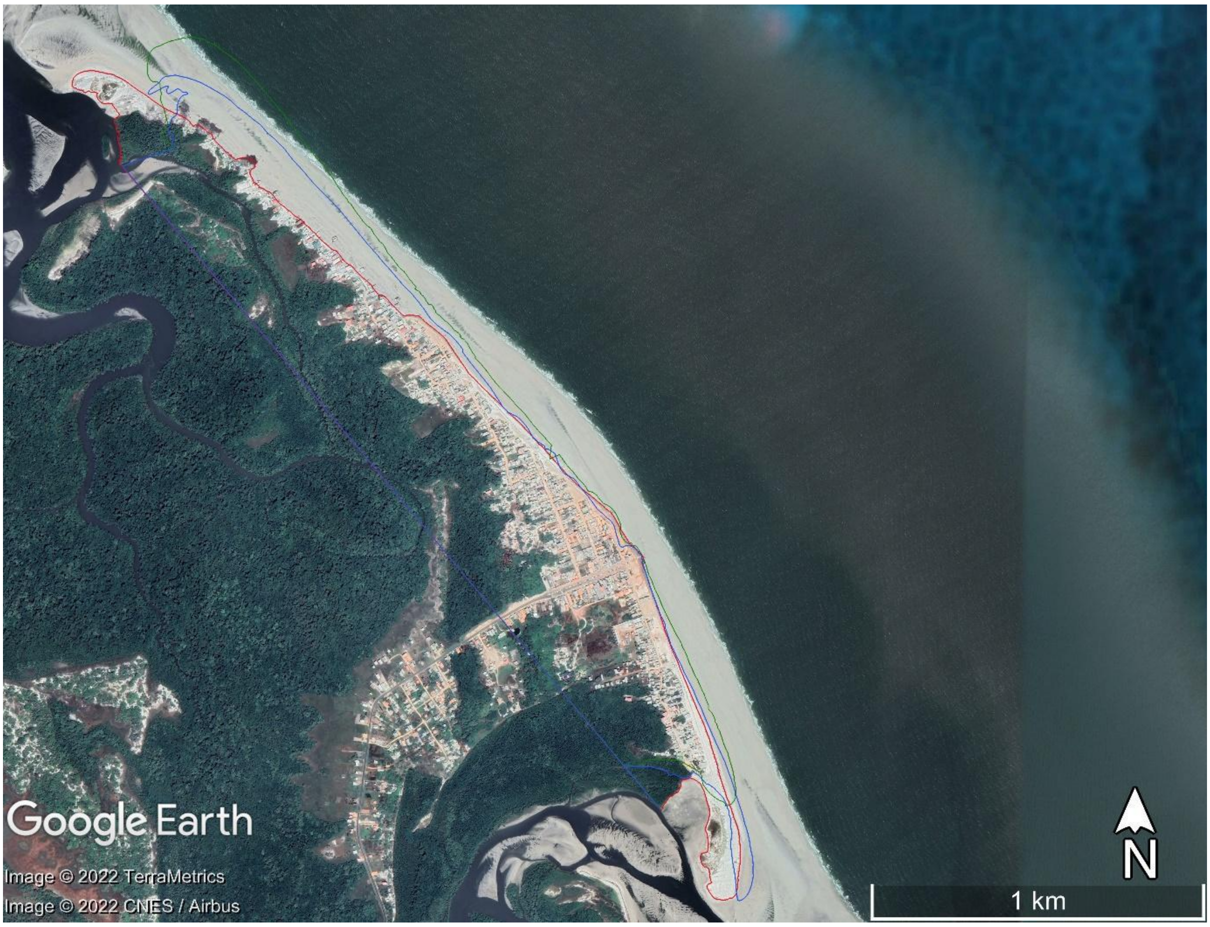

Figure 10. Google Earth satellite image, with three colored lines representing the study area in 2007 (*green line*), 2013 (*blue line*) and 2021 (*red line*), comparing the effects of erosion in the study zone.

Table 2. Beach retreat and eroded area between 2007-2013, 2007-2021, 2013-2021.

Features	**2007-2013**	**2013-2021**	**2007-2021**
Area	0.12 km^2	0.03 km^2	0.15 km^2
Maximal beach retreat in NW sector	0.245 km	0.119 km	0.360 km

5. DISCUSSION

Climate in the Amazon coast is characterized by two main seasons, the dry and the rainy season (Martorano et al., 1993). The normal rainfall pattern in this region is also subject to large-scale fluctuations (Pereira et al., 2013, 2017, 2022; Andrade et al., 2016) which can induce a decrease in rainfall, resulting in a drier than normal year under the influence of a El Niño or other types of drought conditions, as occurred in 2010, 2012-2013, 2015-2016, or a higher than normal rainfall levels typically associated with the influence of the La Niña, as occurred in 2008-2009 and 2011 (see Figures 4 and 5).

During this study there were recorded some of the most intense climatic events with global effects of the last decades, as those of 2009 (La Niña), 2010 (El Niño and Drought), 2012 (Drought) and 2015 (El Niño), according to Marengo et al. (2011, 2016), Barnard et al. (2017). These events resulted directly in offshore data showing peaks of gust wind speed, wave height and dominant wave period during the La Niña events of 2008, 2009 and 2011 (see Figure 3), and also in nearshore data with extreme values in rainfall level and riverine discharge in flooding and drier events with maximal and minimal peaks, respectively in 2009 and 2011 (La Niña) and 2010 and 2012 (drier events), as can be seen in Figures 4 and 5.

On local scale, the lowest wave heights were recorded during spring low tides because sandbanks are more exposed. Conversely, the highest values of wave heights (H_s) and periods were recorded during high tides, but depended of the offshore wind condition, as recorded on 02nd and 03rd October 2013 during a neap tide condition when in 28th-29th September of that year the offshore gust wind speeds reached intensities of around 13 m s^{-1} or 30th November and 01st December 2013 when maximal H_s were recorded between a neap to spring tide coinciding with maximal offshore gust wind speeds (15 m s^{-1}) in previous days (see Figure 8). Field campaigns did not cover all climatic events showed above, but it was possible to observe that in September-October 2012 (Drought event) were registered the highest wave heights, when compared to other studied months.

Riverine discharge also seems to have a relationship with wave height (H_s), prevailing lower wave heights when riverine discharge is maximal and higher wave heights when riverine discharge is minimal as shown in Figure 11, which considers a confidence level of 95%. So, maximal or minimal riverine discharge can cause respectively a higher or lower attenuation of the wave pattern in coastal environments such as that of the Amazon coast, and similar results were found by Trindade et al. (2017) in Vila dos Pescadores-PA (Brazil).

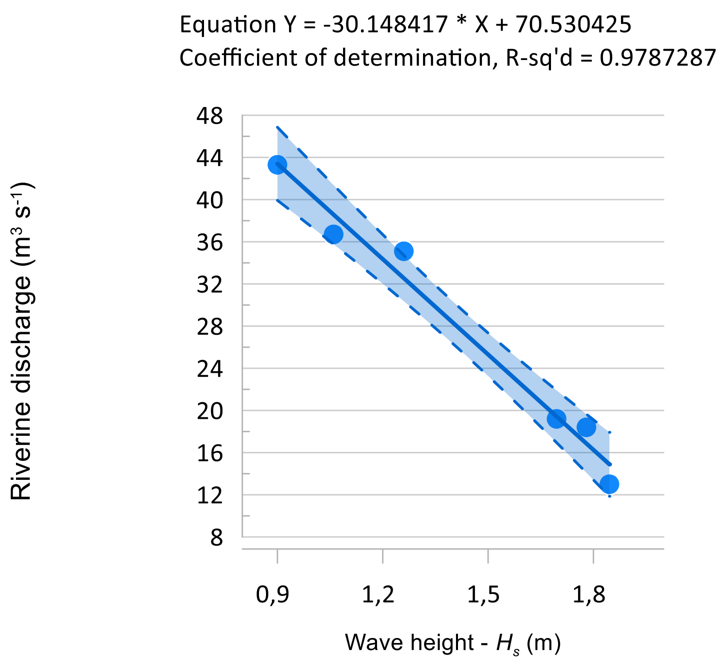

Figure 11. Relationship between riverine discharge and maximal values of significant wave heights in six field campaigns.

The effects of physical processes on Amazon beaches have been little studied (Pereira et al, 2016, 2020). Most of these beaches have a great potential for beach tourism and problems related to unplanned territorial occupation need more attention of the governmental authorities to guarantee the integrity of the local and associated environments, as well as the satisfaction of the visitors. At the study area, studies have showed the consequence of the erosion problems on the destruction of edifications, as that of Rodrigues et al. (2018), which reported that from 2014 to 2018 the erosion processes were responsible for the destruction of around 50 edifications (houses, bars, and hostel) and a total of 1,825 people were affected, resulting in an economical damage of $ 2,578,419.364 (1 USD$ = R$5.33).

At Ajuruteua, inappropriate beachfront development is dominated by a number of precarious wooden structures built on stilts on mangroves, dunes and the intertidal zone that intensify the local erosion processes. The construction of seawalls since 2018 has intensified the unplanned occupation because it has brought a sense of protection of the edification on the waterfront and consequently has attracted new edifications on dunes, mangrove and intertidal beach zones (Figure 12). In addition, the effects of tidal modulation of breaking wave, offshore wind-wave pattern and climatic events seem have been neglected by decision makers and outbrakes of erosion already can be verified in this new beachfront.

This study suggests that the governmental authorities must control the local territorial occupation to avoid environmental, social and economic risks and conflicts, as well as they must consider physical processes from short to long term for the future contention projects.

Figure 12. Unplanned territorial occupation on intertidal beach zone (A-C), mangrove (D, E) and dune (F) areas, and debris of houses in front of the seawalls (G, H).

6. CONCLUSION

The offshore wave heights were attenuated from 2-5 m in deep water to 1–2 m in nearshore waters, and a tidal modulation of the breaking waves is recorded due to presence of the sandbanks. Offshore conditions were affected by the La Niña event with severe storms being recorded in 2008-2009 and 2011. Riverine discharges were also related to rainfall levels with extremes ranges recorded during climatic events, such as those of 2008-2009 (La Niña), 2010 (El Niño and Drought), 2011 (La Niña), 2012-2013 (Drought) and 2015-2016 (El Niño). Nearshore waves have moderate energy and variability occurred due to offshore condition, tidal modulation and local climate. Unplanned territorial occupation and the lack of beach planning have intensified the erosive processes in this macrotidal beach that experience waves of moderate energy. Coastal planning and regulation is urgently required for the study area. Given this, this study suggests that the governmental authorities must control the local territorial occupation, as well as they must consider physical processes from short to long term for the future contention projects.

LITERATURE CITED

Aagaard, T., 2002. Modulation of surf zone processes on a barred beach due to changing water levels, Skalligen, Denmark. J. Coast. Res. 18 (1), 25–38.

ANA. Agência nacional de águas, 2022. https://www.gov.br/ana/pt-br

Andrade, M.P., Magalhães, A., Pereira, L.C.C., Flores-Montes, M.J., Pardal, E.C., Andrade, T.P. and Costa, R.M., 2016. Effects of a La Niña event on hydrological patterns and copepod community structure in a shallow tropical estuary (Taperaçu, Northern Brazil). Journal of Marine System. https://doi.org/10.1016/j.jmarsys.2016.07.006.

Barnard, P.L., Hoover, D., Hubbard, D.M., Snyder, A., Ludka, B.C., Allan, J., and Serafin, K.A., 2017. Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. Nature Communications, 8(1), 1-8.

Cohen, M.C.L., Lara, R.J., Ramos, J.F.D. and Dittmar, T., 1999. Factors infuencing the variability of Mg, Ca and K in waters of a mangrove creek in Bragança, Nortrh Brazil. Mangroves and Salt Marshes. https://doi.org/10.1023/A:1009923513091.

Cunha, A.P.M., et al., 2019. Extreme drought events over Brazil from 2011 to 2019. Atmosphere. https://doi.org/10.3390/atmos10110642.

DHN. Diretoria de Hidrografia e Navegação MARINHA DO BRASIL., 2022. https://www.marinha.mil.br/dhn/

Golden Gate Weather Services., 2022. https://ggweather.com/enso/oni.htm

Haquette, A. and Aernouts, D., 2010. The influence of nearshore sand bank dynamics on shoreline evolution in a macrotidal coastal environment, Calais, northern France, Continental Shelf Research, 30 (12), 1349-1361. https://doi.org/10.1016/j.csr.2010.04.017.

INMET. Instituto Nacional de Meteorologia, 2022. Monitoramento das estações automáticas. http://www.inmet.gov.br/sonabra/maps/automaticas.php

Kroon A. and Masselink G., 2002.Morphodynamics of intertidal bar morphology on a macrotidal beach under low-energy wave conditions, North Lincolnshire, England, Marine Geology, 190, 3–4, 591-608. https://doi.org/10.1016/S0025-3227(02)00475-9.

Levoy, F., Monfort, O. and Larsonneur, C., 2001. Hydrodynamic variability on megatidal beaches, Normandy, France. Continental Shelf Research, 21 (6–7), 563–586. doi: 10.1016/S0278- 4343(00)00128-X.

Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., and Rodriguez, D.A., 2011. The drought of 2010 in the context of historical droughts in the Amazon region, Geophys. Res. Lett., 38, L12703, doi:10.1029/2011GL047436.

Marengo, J.A., Tomasella, J., Soares, W.R., Alves, L.M. and Nobre, C.A., 2012. Extreme climatic events in the Amazon basin: Climatological and hydrological context of recent foods. Theoretical and Applied Climatology. https://doi.org/10.1007/s00704-011-0465-1.

Marengo, J.A., Alves, L.M., Soares, W.R., Rodriguez, D.A., Camargo, H., Riveros, M.P. and Pabló., A.D., 2013a. Two contrasting severe seasonal extremes in tropical South America in 2012: Flood in Amazonia and drought in northeast Brazil. Journal of Climate. https://doi.org/10.1175/JCLI-D-12-00642.1.

Marengo, J.A., Borma, L.S., Rodriguez, D.A., Pinho, P., Soares, W.R. and Alves, L.M., 2013b. Recent extremes of drought and fooding in Amazonia: Vulnerabilities and human adaptation. American Journal of Climate Change. https://doi.org/10.4236/ajcc.2013.22009.

Marengo, J.A., Williams, E.R., Alves, L.M., Soares, W.R. and Rodriguez, D.A., 2016. Extreme Seasonal Climate Variations in the Amazon Basin: Droughts and Floods. In: Nagy, L., Forsberg, B., Artaxo, P. (eds) Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin. Ecological Studies, vol 227. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-49902-3_4

Masselink, G., 1993. Simulating the effects of tides on beach morphodynamics. Journal of Coastal Research, SI15, 180-197.

Menezes, M.P.M., Berger, U. and Mehlig, U., 2008. Mangrove vegetation in Amazonia: A review of studies from the coast of Pará and Maranhão States, north Brazil. Acta Amazônica.https://doi.org/10.1590/S0044-59672008000300004.

Monteiro, M. C. and Pereira, L. C. C., 2009 Morphodynamic change of a macrotidal sand beach in the brazilian Amazon Coast (Ajuruteua - Pará). Journal of Coastal Research, 56, 103-107.

Pereira, L. C. C., Costa, A. K. R., Costa, R. M., Magalhães, A., Jesus Flores-Montes, M. and Jiménez, J. A., 2018. Influence of a drought event on hydrological characteristics of a small estuary on the Amazon Mangrove Coast. Estuaries and Coasts, 41(3), 676-689.

Pereira, L., Concejo, A.V. and Trindade, W., 2020. Tidal modulation. In Sandy Beach Morphodynamics (pp. 87-101). Elsevier.

Pereira, L.C.C., Costa, A.K.R., Costa, R.M., Magalhães, A. and Flores-Montes, M.J.A., 2017. Influence of a drought event on hydrological characteristics of a small estuary on the Amazon Mangrove Coast. Estuaries and Coasts. https://doi.org/10.1007/s12237-017-0310-6.

Pereira, L.C.C., Oliveira, S.M.O., Costa, R.M., Costa, K.G. and Vila-Concejo, A., 2013a. What happens on an equatorial beach on the Amazon coast when La Niña occurs during the rainy season? Estuarine, Coastal and Shelf. Science, 135, 116–127, doi: 10.1016/j.ecss.2013.07.017.

Pereira, L.C.C., Pinto, K.S.T., Costa, K.G., Vila-Concejo, A. and Costa, R.M., 2012b. Oceanographic conditions and human factors on the water quality at an Amazon macrotidal beach. Journal of Coastal Research, 285, 1627–1637. doi: 10.2112/JCOASTRES-D-11-00032.1.

Pereira, L.C.C., Silva, N.I.S., Costa, R.M., Asp, N.E., Costa, K.G. and Vila-Concejo, A., 2012a. Seasonal changes in oceanographic processes at an equatorial macrotidal beach in northern Brazil. Continental Shelf Research, 43, 95–106. doi: 10.1016/j.csr.2012.05.003.

Pereira, L.C.C., Trindade, W.N., Silva, I.R., Vila-Concejo, A. and Short, A.D., 2016b. Maranhão beach systems, including the human impact on São Luís Beaches. In: Short, A.D., Klein, A.H.F. (Eds.), Brazilian Beach Systems. Springer International Publishing, AG Switzerland, pp. 125–152. doi: 10.1007/978-3-319-30394-9_5.

Pereira, L.C.C., Vila-Concejo, A. and Short, A.D., 2013b. Influence of subtidal sand banks on tidal modulation of waves and beach morphology in Amazon macrotidal beaches. Journal of Coastal Research, 65 (SI), 1821–1826. doi: 10.2112/SI65-308.1.

Pereira, L.C.C., Vila-Concejo, A. and Short, A.D., 2016a. Coastal morphodynamic processes on the macro-tidal beaches of Pará state under tidally-modulated wave conditions. In: Short, A.D., Klein, A.H.F. (Eds.), Brazilian Beach Systems. Springer International Publishing, AG Switzerland, pp. 95–124. doi: 10.1007/978-3-319-30394-9_4.

Pereira, L.C.C., Guimarães, D.O., Ribeiro, M.J.S., Costa, R.M., and Souza-Filho, P.W.M., 2007. Use and occupation in Bragança littoral, Brazilian Amazon. Journal of Coastal Research, SI 50, 1116–1120.

Pereira, L.C.C.; Vila-Concejo, A.; Costa, R.M., and Short, A.D., 2014. Managing physical and anthropogenic hazards on macrotidal Amazon beaches. Ocean and Coastal Management, 96, 149-162.

Rodrigues, H. D. S., 2018. Análise de perdas econômicas geradas pela erosão em ambiente praiano: caso da praia de Ajuruteua–Bragança/PA.

Santos, P.B.M., 2019. Variabilidade hidroclimática e sua relação com a erosão costeira na Praia de Ajuruteua (Bragança-PA). Trabalho de Conclusão de Curso (Graduação em Engenharia Ambiental e Energias Renováveis) – Universidade Federal Rural da Amazônia, Campus Belém, PA, 75 f..

Short, A.D., 1991. Macro-meso tidal beach morphodynamics -an overview. Journal of Coastal Research, 7, 417-436.

Souza-Filho P. W. M. and Paradell, W. R., 2002 Use of synthetic aperture radar for recognition of Coastal Geomorphological Features, land-use assessment, and shoreline changes in

Bragança coast, Pará, Northern Brazil. Earth Sciences, Anais da Academia Brasileira de Ciências, 75 (3). https://doi.org/10.1590/S0001-37652003000300007

Souza-Filho P.W.M., Martins, E. do S.F., Costa, F.R., 2006. Using mangroves as a geological indicator of coastal changes in the Bragança macrotidal flat, Brazilian Amazon: A remote sensing data approach, Ocean & Coastal Management, 49 (7–8), 462-475 https://doi.org/10.1016/j.ocecoaman.2006.04.005.

Souza-Filho, P.W.M., and Maâmar El-Robrini., 2000. Geomorphology of the Bragança coastal zone, northeastern Pará State. Revista Brasileira de Geociências, 30, 3, 522-526.

Trindade, W.N., Pereira, L.C.C., Vila-Concejo, A., 2016. Tidal modulation of moderate wave energy on a sandy tidal flat on the macrotidal Amazon littoral. Journal of Coastal Research, SI (75), 487–491. doi: 10.2112/SI75-098.1.

Trindade, W.N., 2017. Influência de forças físicas e atividades antrópicas em uma planície de maré equatorial (Vila dos Pescadores, Pará, Brasil). Tese (Doutorado em Biologia Ambiental) - Universidade Federal do Pará.

Wright, L.D., Nielsen, P., Short, A.D., and Greene, M.O., 1982. Morphodynamics of a macrotidal beach. Marine Geology, 50, 97- 128.