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BLUFF RETREAT INDUCED BY WAVE ACTION ON A TROPICAL BEACH, IN ESPÍRITO SANTO, BRAZIL

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ABSTRACT. Interest in understanding sea bluff erosion along the coasts around the world has grown in recent years, especially when in proximity to urban expansion. To prevent economic, social and environmental losses, it is necessary to understand the factors behind the sea bluff erosion. This study analyzed temporal and spatial changes in wave exposure over 60 years (1948-2008) and the corresponding impacts of these variations on three sea bluffs with similar lithology over 55 years (1953-2008). Erosion distances and annual erosion rates were obtained from aerial and satellite images for the time intervals 1953-1970, 1970-1995 and 1995-2008. Analysis of bluff retreat and wave exposure compared annual wave behavior, extreme wave occurrences and modeled spatial and temporal variations in wave energy to yearly retreat rates obtained from imagery analysis and assessed for each of the three intervals. For the three bluffs, the total erosion distance decreased northward – 51, 43 and 18 m, resulting in recession rates of 0.8, 0.69 and 0.43 m/year, respectively. Overall, annual erosion rates appear to slow down during long periods (63 years) compared to the short-term (8-25 years). The shift in modeled wave energy distribution is mainly in accordance with the longshore variability of erosion rates. However, the relationship between bluff recession and wave energy shows that periods of high energy are not necessarily related to intense bluff recession. The erosion process induces debris deposition, which may be able to protect the bluff toe from wave action for a while. The bluffs in our study receded at different rates, despite proximity, in response to spatial and temporal differences in wave energy distribution. Based on results, we propose a bluff erosion cycle model for the studied area and infer current erosion vulnerability.

Keywords: short-term events, decadal mobility, wave exposition, bluff cycle model.

RESUMO. Nas últimas décadas, questões relativas à erosão de falésias marinhas têm sido importantes ao longo das costas ao redor do mundo, especialmente devido à expansão urbana nessas áreas. Torna-se, portanto, necessário entender os fatores por trás do processo de erosão destas falésias, a fim de evitar perdas econômicas, sociais e ambientais. Este estudo analisou como o grau de exposição às ondas muda ao longo do tempo, no espaço entre 1948 e 2008, e também os impactos desta modificação sobre três falésias com mesma litologia, durante o intervalo de 1953-2008. Distâncias erodidas e taxas de erosão anual foram obtidas através da análise de imagens de satélite e aérea para os intervalos de tempo de 1953-1970, 1970-1995 e 1995-2008. A correlação entre o recuo das falésias e a ação das ondas foi baseada no comportamento das alturas significativas médias anuais, ocorrência de onda extremas e modelagem da variação espaço/temporal da energia de onda de 1953 a 2008. O recuo das três falésias estudadas apresenta um incremento no sentido norte-sul, variando de 51, 43 e 18 m, resultando em taxas erosivas anuais de 0,8; 0,69 e 0,43 m/ano, respectivamente. Em geral, taxas de erosão parecem menores durante longos períodos (63 anos) em comparação com taxas de curto prazo (8-25 anos). Além disso, a mudança na distribuição de energia de onda modelada se mostra de acordo com a variabilidade espaço/temporal das taxas de erosão. No entanto, os resultados mostram que as fases de alta energia de ondas não estão necessariamente relacionadas com o intenso recuo das falésias. Discute-se que processo de erosão induz a deposição de detritos na base da falésia, que podem ser capazes de proteger da ação de onda até que sejam transportados para o mar. Portanto, conclui-se que falésias homogêneas mostram ritmos diferentes de recessão que respondem a alterações espaciais e temporais em distribuição de energia de onda. Além disso, a partir do modelo esquemático do ciclo de erosão no pé de falésias proposto neste estudo, é possível inferir a atual vulnerabilidade de erosão das falésias estudadas com base nos resultados obtidos.

Palavras-chave: eventos a curto prazo, mobilidade decadal, exposição às ondas, modelo evolutivo de falésias.

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INTRODUCTION

Bluff erosion is a natural process, but interest in understanding the mechanics and rates of that erosion has been growing in recent decades when urban expansion efforts are nearby, focused on preventing economic, social, and environmental losses. The bluff erosion process depends on boundary conditions such as geology, sea level, climate, tides and waves, which affect processes behind bluff retreat, such as rainfall, seismicity and wave attack (Kennedy et al., 2014).

Marine bluff erosion is mainly controlled by wave attack (Sunamura, 2015). Waves reaching the toe (base) region promote erosion, leading to steep slopes, hence mass movement (Carter & Guy Jr, 1988). The relationship between wave energy and bluff recession has been discussed in several studies, for example, Valentin (1954), Robinson (1980) and Ruggiero et al. (1997). One bluff evolution model states that erosion begins when the force of incident waves overcomes the resistance of bluff material (Sunamura, 1983).

The effect of waves post eroding bluff is unknown (Kamphuis, 1987). Talus deposition results from bluff retreat (Sunamura, 2015) and has been related to different stages of bluff stability (Carter & Guy Jr, 1988; Hapke et al., 2009). Stability of a bluff may be maintained until the talus deposit is removed by waves and coastal currents (Kamphuis, 1987; Sunamura, 2015). Talus mobility determines the velocity and the intensity of the bluff retreat (Castedo et al., 2013). Talus acts as a barrier protecting the bluff toe against the assailing waves (Amin, 2001; Wolters & Müller, 2008).

Seen through the relationship between the rates of mean erosion and extreme wave erosion, bluff recession occurs due to brief periods of high energy (Collins & Sitar, 2008). Storm duration and surge level control the amount of energy reaching the bluff toe (Carter & Guy Jr, 1988). However, despite strong correlation between waves and bluff retreat, severe waves are not necessarily related to intense bluff erosion (Kline et al., 2014). Bluff retreat alternates between short erosion periods and long periods of no erosion, demonstrating that the retreat rate of bluffs under normal and extreme wave attack was the same over a 100-year span (Castedo et al., 2013). Higher and milder bluff backing rates have been observed in the short- and long-term (70 and 100 years, respectively) for moderate to high-relief sandstone cliffs impacted by waves ranging from 1 to 4 meters at their largest with 3 to 10 second periods (Griggs & Savoy, 1985; Carter & Guy Jr, 1988; Hapke et al., 2009; Hapke & Plant, 2010).

Given the recent trend of sea level rise and increasingly severe storms due to climatic changes (PBMC, 2013) bluff erosion episodes may accelerate. Bluff erosion is already considered a devastating process, with England, for example, estimating a cost of one million pounds per year spent on maintenance and improvement of coastal defenses (Lee, 2005). Along the Espírito Santo coast, particularly the narrow Maimbá beach backed by sea bluffs, current bluff retreat has required government investment to try to stop the erosion process after the destruction of an important coastal road (Albino et al., 2001; Machado et al., 2003; Albino et al., 2016b).

The erosion process has not been uniform along Maimbá beach (Albino et al., 2016b), where outcrops and islands present along the beach arc may affect wave dissipation. Bluffs undergo spatial retreat fluctuations (Griggs & Savoy, 1985; Carter & Guy Jr, 1988) primarily due to the degree of exposure to incident waves Valentin (1954); Fleming (1986); Ruggiero et al. (2001). Bathymetric changes and the resulting wave dissipation controls the degree of wave exposure (Robinson, 1980), highlighting the importance of geomorphology. Given that bluffs along Maimbá beach are all composed of the same materials (Albino et al., 2016a), this study approached bluff retreat along this beach as a process induced mainly by the temporal and spatial distribution of wave series, examining the last 60 years. A schematic model is proposed for the evolution cycle of the Maimbá beach bluff, which may allow predictions of future bluff evolution.

STUDY AREA

Maimbá beach is located in Guarapari, Espírito Santo, Brazil (40º 35’26“, 4037’56”W; 20º 44’31”S, 20º 47’27” S), (Fig.1). The beach is 6 km long, surrounded by the Meaípe crystalline headland to the North and Port of Ubu to the South. Small crystalline islands, concentrated near the beach’s center, modify the wave incidence patterns along the beach. The NE-SW coastline is exposed to intense E and SE winds, related to trade winds and frontal systems, respectively (Albino et al., 2016b). Examining waves from the WaveWatch III model, Pianca et al. (2010) reported that mean wave peak direction is predominantly from the east over the entire year except during fall when southern waves prevail. Average significant wave height ranges from 1 to 2 m with 6 to 8 s peak periods, during summer and spring. During fall and winter, mean significant wave heights vary between 2 and 3 m with 8 to 12 s peak periods. Annual events with mean waves higher than 2 m occur especially in fall and winter (Pianca et al.,

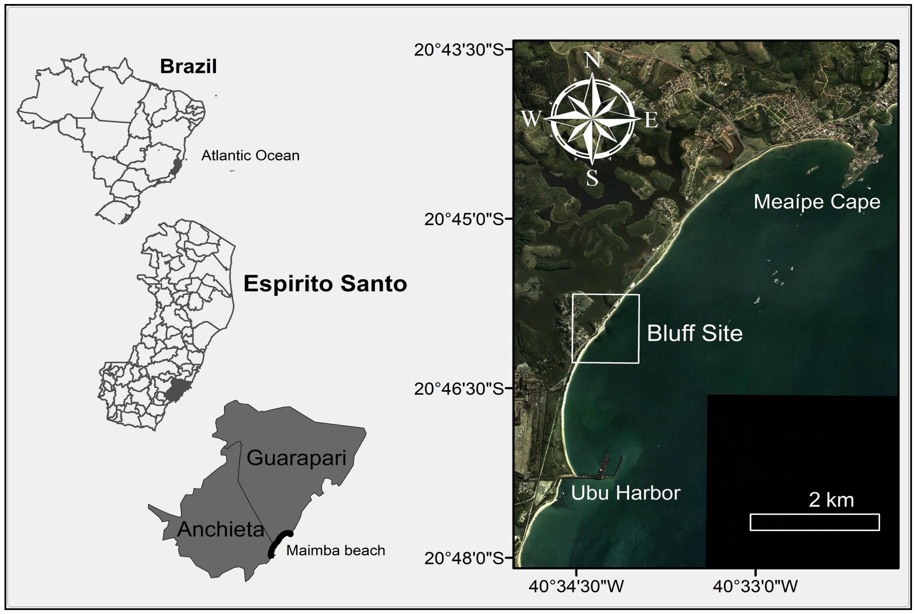

Figure 1 – Study area and bluff site.

Figure 2 – Road sign explaining the destruction triggered by bluff erosion. "Stabilization of marine eroded slope on the Meaipe-Anchieta stretch of the ES-060 road." Photograph source: Labogeo – 12/28/2007.

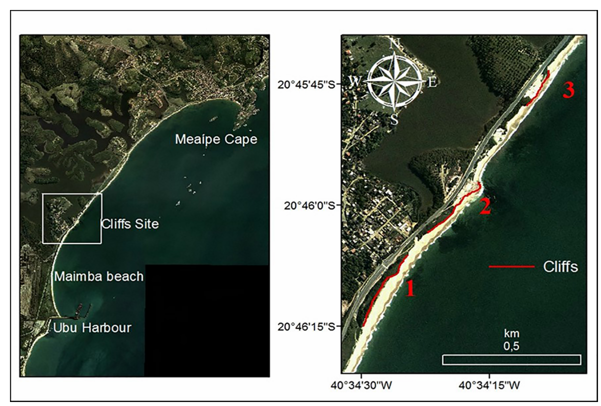

Figure 3 – Maimbá beach, with delimitations and the studied bluff site area illustrated.

2010). Maimbá beach has a microtidal regime with a mean tide level of 0.82 meters (Albino et al., 2016a).

Albino et al. (2016b) discussed the presence of a coastal southward longshore current, able to transport 400.00 m^3 of sediment per year, while emphasizing an active cross-shore sediment transport, especially in the central portion. According to Albino et al. (2016a), Maimbá beach has narrow beaches ranging from intermediate to reflective, backed by soft sedimentary bluffs. These beaches are completely eroded during major storms, allowing waves to attack the bluff toe. The bluffs are deposits from the Barreiras Formation, composed of heavy minerals; they are layered beds composed of white-grayish, reddish-purple sandy and muddy grains, associated with a fluvial environment. Albino et al. (2016b) state that after storm conditions, heavy minerals comprise up to 45% by weight of the surface of the beach face, especially in the central and north portion, highlighting the erosive process on the bluffs (Machado et al., 2003; Albino et al., 2016a), (Fig 2).

The bluff section in this study is divided into three sections, each extending approximately 50 m and differing in coastline orientation and consequent degree of wave exposure: 1 (South), 2 (Central) and 3 (North)(Fig. 3). All three bluff segments have the same composition. Bluffs 1 and 2 have mean heights of 8 meters while the bluff 3 face averages 5 meters. The presence of debris deposited at the base of bluff 3 is currently absent or minimal. In contrast, bluff 1 and 2 have a substantial quantity of material at their bases.

METHODS

Bluff retreat

Bluff retreat data were collected by comparing images of each from the following years: 1953, 1970, 1995 and 2008 (Table 1). Bluff toe was adopted as a proxy to determine shoreline, which according to Boak & Turner (2005) is an adequate indicator for coastal erosion as it does not show accretion. The chosen shoreline presents uncertainties in terms of identification, given that along the coast some bluffs may have debris at their toe and/or a prominent top, which could lead to variations in shoreline position. Taking image resolution into account, the authors designated the shoreline as every discernible segment that provides continuity to the bluff toe line (Fig. 4). Bluff retreat between the 1953-1970, 1970-1995 and 1995-2008 intervals was determined according to the methodology applied by Thieler et al. (2005), Araújo (2008) and Hapke et al. (2009). It consists of analyzing aerial and satellite images using the Digital Shoreline Analysis System (DSAS), developed for ArcGIS software (ESRI).

Table 1 – Imagery information. All images contain a pixel size of approximately 1 m and scale 1:7800. IJSN – Instituto Jones dos Santos Neves. GEOBASES - Sistema Integrado de Bases Geoespaciais do Estado do Espírito Santo.

Year	Source	RMS error (m) between images	Image type	Sensor
1953	IJSN	3.8	Aerial	x
1970	IJSN	3.8	Aerial	x
1995	GEOBASES	2.0	Satellite	Geoeye 1
2008	GEOBASES		Satellite	Geoeye 1

Waves

Wave data were obtained from the hindcast model Global Ocean Wave (GOW), which is a reanalysis of global data that provides hourly significant wave heights, peak directions and peaks period from 1948 to 2008. This study used data from the coordinates 20º 50'S and 40º 25'W (25 m depth). The GOW results have been calibrated from satellite altimetry data and buoy measurements throughout the world (Reguero et al., 2012). Albino et al. (2016b) calibrated and validated the numerical results using *in situ* wave data from a 25 m-deep Acoustic Doppler Current Profiler (ADCP) at Maimbá beach (20º48'S and 40º33'W) during the following intervals: i) 01/31/2007 to 04/04/2007; ii) 09/29/2007 to 10/25/2007; iii) 11/23/2007 to 12/18/2007; and iv) 11/23/2007 to 03/06/2008.

The prevailing wave condition was determined from the most recurrent peak direction, peak period and significant height between 1948-1953, 1953-1970, 1970-1995 and 1995-2008, retrieved from GOW data. A monochromatic wave representing each interval was used to force the Sistema de Modelagem Costeira (SMC-Brasil) model to propagate deep water waves to the coast using bathymetry digitalized from CEPEMAR (2008), (Fig. 5).

More specifically, this study applied the monochromatic wave propagation model (Oluca-MC), which is part of the integrated model of wave propagation, currents and beach morphodynamics (Mopla). Open boundary conditions were used for the limit between the grid and ocean, while closed boundary conditions were used for the shoreline limit. To determine the boundary conditions along the shoreline, Oluca-MC applies the parabolic approximation for a mild slope equation (Tsay & Liu, 1982; Kirby & Dalrymple, 1983). Linear wave theory was applied to calculate the energy of waves for each scenario (Muehe, 1996) (Eq. 1). The energy variation during the 1953-1970, 1970-1995 and 1995-2008 intervals was obtained by subtracting the mean wave energy of every notch of the model grid between the current and prior intervals as illustrated in Figure 6.

$$E = 0.5 * \rho g A^2, \qquad (1)$$

where E is the wave energy (J/m^2), ρ is water density (kg/m^3), and A is wave amplitude (m).

The annual mean significant wave heights between 1953 and 2008, from the GOW database, were compared to the total mean significant wave height over intervals matching each of our periods of available bluff retreat data, identifying wave intensity fluctuation over time.

Extreme wave records were based on the frequency that the wave height exceeded twice the mean height over time (1953-2008), according to You & Lord (2008). The authors defined extreme wave height as waves exceeding 3 m for at least 1 hour, considering a mean wave height of 1.5 m (Short & Trenaman, 1992; Lord & Kulmar, 2001). De Souza et al. (2016) and Bulhões et al. (2016) successfully applied this height limit to tropical South Atlantic coasts. In this study, this criterion may be suitable since it considers that higher waves can reach the bluff toe while the high frequency accelerates bluff retreat.

Figure 4 – Adaptation to extract bluff toe as a shoreline proxy from images. Satellite photos from Google Earth.

RESULTS

Bluff retreat rates

Results presented in this section refer to shoreline position variations extracted from imagery using DSAS. The three bluffs along the beach had different retreat rates. Bluff 1 (Southern section) retreated 50.8 m between 1953 and 2008 (Table 2), eading to a long-term rate of 0.8 m/year. However, the short-term rates were higher; 1.05 and 0.99 m/year for time spans between 1953-1970 and 1970-1995, respectively. The calculated rate was 0.19 m/year for the 1995-2008 period, below the long-term rate (Table 3).

Bluff 2, in the Central region, receded 43 m, resulting in an erosion rate of 0.70 m/year for the 1953-2008 interval (Tables 2 and 3). Meanwhile, the retreat rates for shorter periods were 0.83, 0.64 and 0.45 m/year for 1953-1970, 1970-1995 and 1995-2008, respectively (Table 3).

In the northern area, bluff 3 retreated the least among the studied bluffs, 18.3 m, with an erosion rate of 0.43 m/year over 55 years (1953-2008). The short period analyses revealed low rates: 0.03, 0.24, and 0.07 m/year for the intervals 1953-1970, 1970-1955, and 1995-2008, respectively.

During the 1953-2008 interval, the bluff mobility results show that the three bluff sites exhibited receding periods followed by a stable pattern when erosion rates decreased.

Extreme wave records and variation of the yearly mean wave height

All results in this section regard significant wave height from the GOW database at 20º 50'S and 40º 25'W between 1953-1970, 1970-1995 and 1995-2008.

During the 1953-1970 period, storm events occurred 4.4% of the time. Likewise, the 1970-1995 interval shows extreme events 4.6% of the time. The 1995-2008 period had a higher frequency of storms, 5.6% of the period. The results suggest storm event intensification over the years (Table 4).

Wave Modelling

Results in this section describe the outputs from SMC-Brasil forced with three different monochromatic waves using the GOW dataset. The model used prevailing conditions between 1953-1970, 1970-1995 and 1995-2008, determined as the peak period and significant height associated with the most recurrent peak direction (Table 5).

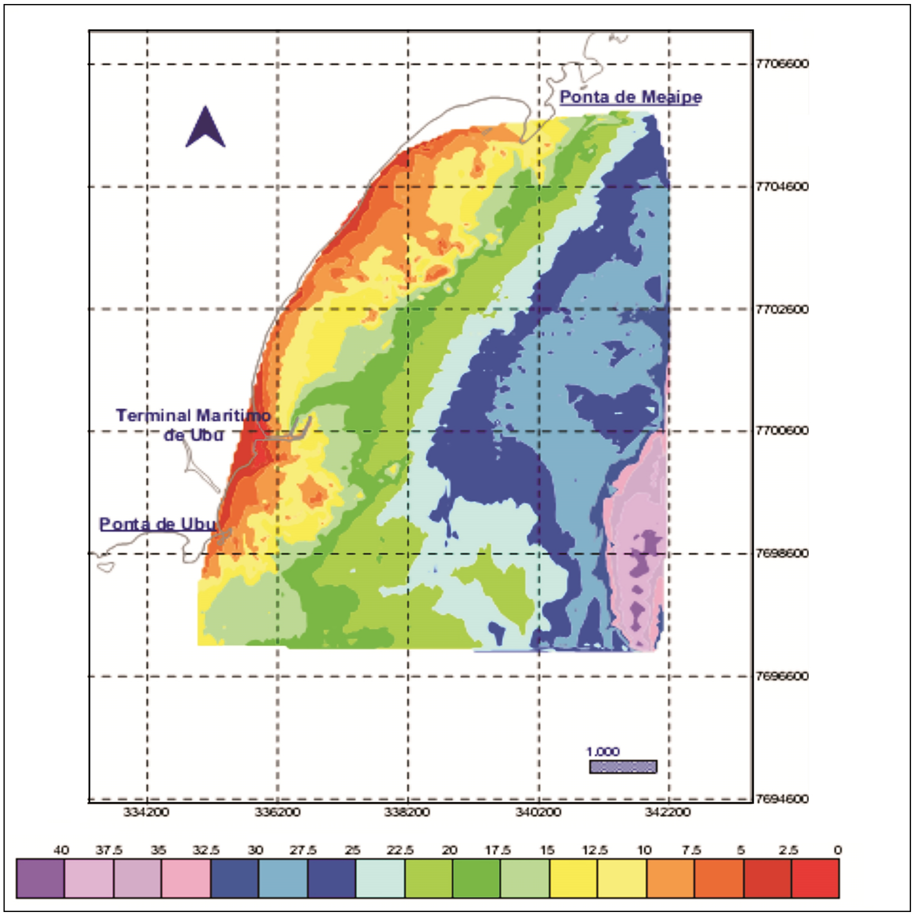

Figure 5 – Bathymetric input used to run the SMC model. Source: CEPEMAR (2008).

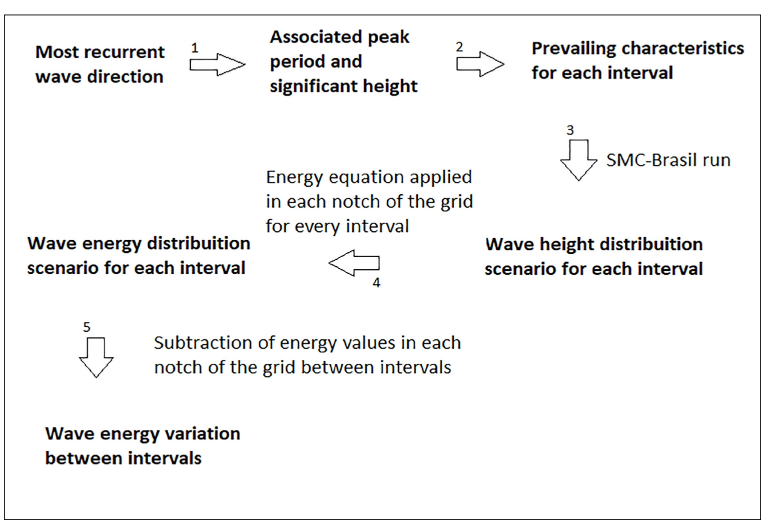

Figure 6 – Schematic diagram illustrating the steps (1 to 5) involved in determining wave energy variability within each selected time interval.

Table 2 – Bluff recession in meters between 1953-1970, 1970-1995 and 1995-2008 obtained using DSAS, also noting the associated error in meters.

Interval	Bluff			Error
	1	2	3	
1953-1970	17.9	14.1	0.4	3.8
1970-1995	22.4	16.0	5.9	3.8
1995-2008	2.5	5.9	0.9	2
Total	50.8	43	18.3	

Table 3 – Annual rate in meters/year of bluff retreat, determined by dividing recession distance by the time, along with its associated error in meters/year.

Interval	Bluff			Error (m)
	1	2	3	
	Retreat Rates (m/year)			
1953-1970	1.05	0.83	0.03	0.22
1970-1995	0.99	0.64	0.24	0.15
1995-2008	0.19	0.45	0.07	0.15
Average	0.78	0.70	0.43	

Table 4 – Frequency of wave heights registering above storm threshold.

Interval	Storm records frequency (%)	Mean significant wave height (m)	Maximum significant wave height (m)
1953-1970	4.4	2.25	3.44
1970-1995	4.6	2.38	3.61
1995-2008	5.6	2.20	2.83

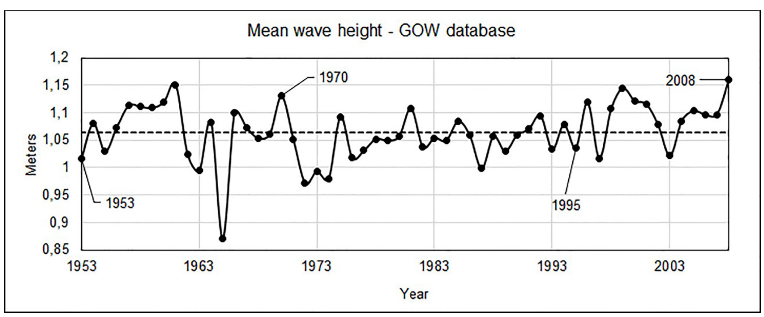

Figure 7 – Annual mean wave height (solid line) and total mean wave height (dashed line) from the GOW dataset.

Figure 7 shows yearly mean significant wave height, calculated from the GOW database, compared to total (1953-2008) mean significant wave height (1.05 m). Yearly mean was higher than the total mean in the 1953-1970 interval, especially in the 6-year interval between 1956 and 1961, which happened to be the longest uninterrupted period above the mean. During this interval, waves were above total mean height for the period 61.1% of time. However, the 1953-1970 time interval is also marked by short periods of yearly means below the total mean significant wave height (38.9%) over the 55-year period.

In contrast, between 1970 and 1995, yearly heights were below the total mean 73.1% of the time.

In the 1995-2008 interval, significant wave height behaved similarly to the 1953-1970 period, where short intervals with yearly heights below the total mean (21.4%) alternated with long periods of waves above the 55-year mean (78.6%).

Figure 8 shows a comparison between two different scenarios modelled from SMC-Brasil in terms of increasing (positive/black) and decreasing (negative/white) wave energy. Wave energy values oscillated from 133 to -352 J/m^2 over the 1953-1970 interval, revealing that bluffs 1 and 2 are slightly more exposed to it than bluff 3. The 1970-1995 results displayed maximum of 283 J/m^2 and minimum of -383 J/m^2 , with a different pattern of energy increase compared to 1953-1970. Dark

Table 5 – Frequency of wave heights registering above storm threshold.

Interval	Significant height (m)	Peak period (s)	Peak direction (°)
1948-1953	1.25	7.37	110
1953-1970	1.18	7.31	89
1970-1995	1.15	7.08	91
1995-2008	1.20	7.08	112

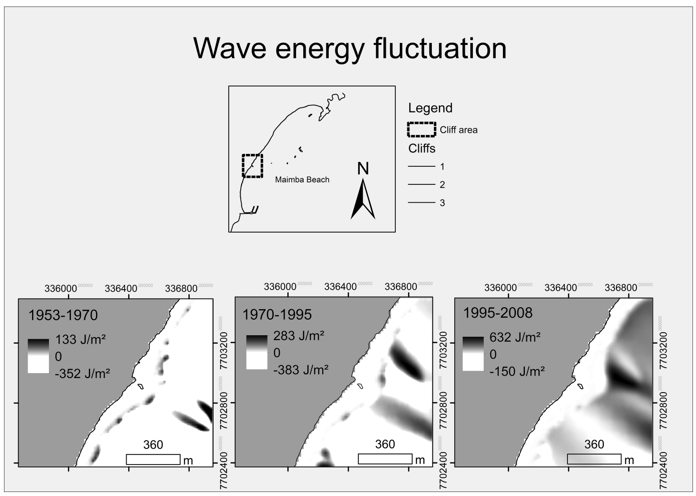

Figure 8 – Wave energy intensification (black) and decrease (white) at the bluff sites.

patches appear to be wider and able to reach deeper isobaths, especially associated with bluffs 2 and 3. The bluff 1 area shows an extensive energy decrease associated with an increase in the patch southward.

Extremely elevated values were found for the 1995-2008 scenario, with values reaching 632 J/m^2 and a minimum of only 150 J/m^3. This intense increase takes place essentially over bluff 3, where a consistent black patch is observed. Bluffs 1 and 2 areas had an insignificant energy increase and decrease during that same period.

In general, wave energy increased along Maimbá beach over the whole 1953-2008 period, particularly at bluff 3, which experienced higher exposure.

DISCUSSION

Bluff retreat by wave action

The differences between long- and short-term bluff retreat rates found along Maimbá beach are consonant with several previous studies. Short-term rates higher than long-term rates were also observed by Hapke & Plant (2010) and Hapke et al. (2009). This retreat rate difference between the short- and long-term is likely because recession can be accelerated by episodic high-energy events, such as storms (Sunamura, 1992; Carter & Guy Jr, 1988; Collins & Sitar, 2008; Castedo et al., 2013). The retreat, in meters, divided into short periods tends to increase retreat rate. Analysis of long-term rates has thus shown lower retreat rates, given that erosion distance is divided by a longer period of time.

Elevated annual retreat rates were found in this study in comparison to previously published worldwide data. For example, Zviely & Klein (2004) present an average retreat rate of 0.20 m/year based on an extensive review of cliff retreat rates along Israeli beaches. However, retreat rates found in the present study are similar to studies of soft cliffs composed by calcareous sandstones and chalk, exposed to mean significant wave height varying from 3 to 4 m during storms (Dornbusch et al., 2008; Moses & Robinson, 2011; del Río et al., 2016).

Over the 1953-1970 period, the lower wave energy observed at bluffs 2 and 3 resulted in lower recession rates compared to bluff 1, where wave energy was higher. Over the 1970-1995 interval, however, wave energy levels and recession rate decreased in bluff 1 and increased in bluff 2 (Fig. 8), which became the most eroded bluff. During 1995-2008, wave energy distribution changed again leading to the scenario where bluff 3 receded fast, triggering a road fall (Fig. 9). Wave energy distribution was mainly controlled by wave direction, given that SE waves (110º, 112º) was related to higher waves (1.25, 1.20 m) when compared to E waves (89º, 91º) and their correspondingly lower wave heights (1.18, 1.15 m). However it is important to consider how the waves interact with bathymetry contours and from which direction they approach the coast to determine erosive hotspots.

Thus, comparison between wave energy distribution and bluff retreat indicated that the energy of incident waves was highly related to the bluff erosive process, because bluff retreat is a function of wave attack (Kamphuis, 1987; Collins & Sitar, 2008) controlled by the degree of exposure (Robinson, 1980).

The 1953-1970 period represents a stage of intense erosion, which was preceded by a long period of wave heights above the 1953-2008 mean (61.1%). During the 1970 and 1995 interval, the relationship shows decreasing erosion processes; the wave height interval is below the total mean 73.1% of the time, reflecting a less energetic period. The 1995-2008 interval had low retreat rates and the highest number of annual mean wave heights above the period mean (78.6%).

A decrease in erosion rate appears to be in disagreement with the increasing storm frequency (Table 4). However, the occurrence of extreme waves does not necessarily induce bluff erosion (Kline et al., 2014) so it becomes important to take into account that bluff erosion is an episodic local process that follows a cycle. A decrease in bluff retreat under severe wave attack represents a period of bluff toe protection provided by a talus deposit, an outcome of previous erosions (Amin, 2001; Wolters & Müller, 2008).

Schematic model of bluff toe cycle

Based on the Amin schematic diagram (2001), it was possible to illustrate the evolution cycle of a general Cliff (Fig. 10), thus infer the cycle of Maimbá bluffs taking into account wave data and retreat rates. Bluffs 1 and 2 had an intense erosion process during 1953-1970, which was associated with high wave energy. Then, from 1970 to 1995, the wave height decreased; this allowed talus to deposit at the bluff toe, providing protection and decreasing retreat rates. Between 1995 and 2008, even under energetic wave conditions, bluff recession rates were moderate, which is represented by talus mobilization, when waves were transporting this material away from the bluff toe instead of eroding its base (Fig. 11A).

Figure 9 – Photograph showing road maintenance due to the present-day marine bluff erosion process taking place on Maimbá beach (March, 2015). The sea water color indicates the presence of fine sediment eroded from bluffs. Photograph source: Labogeo - 06/06/2016.

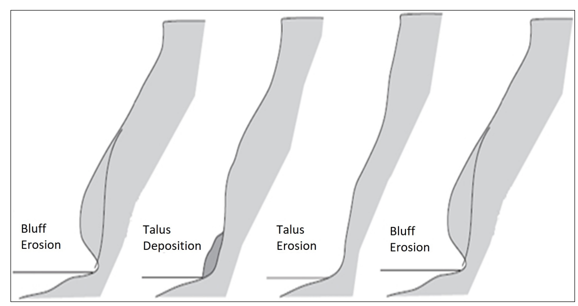

Figure 10 – General schema illustrating cliff erosion cycle due to wave attack.

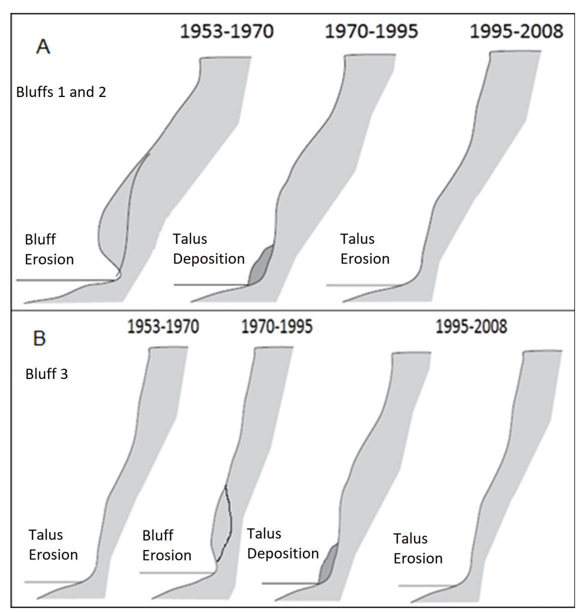

Figure 11 – The proposed model for bluff evolution based on the Amin (2001) schematic diagram, wave climate, degree of exposure and bluff toe deposition cycle. (A) model of bluffs 1 and 2; (B) model of bluff 3.

Figure 12 – Recent debris deposits present at the base of bluff 1 (upper) and 2 (lower), acting as protection to wave attack. Photograph source: Labogeo - 04/08/2016.

Figure 13 – Lack of material at bluff 3 toe as a result of recent wave transport. Photograph source: Labogeo - 04/08/2016.

Bluff 3 shows multiple evolution stages (Fig. 11B). During 1953-1970, a gentle recession dominated, thus talus deposition did not occur consistently. This suggests a remobilization period, with previously deposited material being removed from the bluff toe, given the intense wave regime. Despite the decreasing wave height from 1970 to 1995, erosion rates increased. Talus removal during 1953-1970 would increase the wave attack at the bluff toe. An outcome of this erosion process was the deposition of material at the bluff toe that formed a protective barrier from incident waves, resulting in a decreasing retreat rate from 1995 to 2008.

Future trends for Maimbá beach bluffs

Currently at the bluff 1 and 2 toes there are debris deposits that provide protection for the bluff toe. This suggests stability because this material acts as barrier preventing wave attack at the bluff toe (Fig. 12). In contrast, bluff 3 lacks a debris deposit at its base. Because it is the lowest bluff, the quantity of eroded material armoring its base is correspondingly reduced and can be easily removed by wave action. This dynamic leads to an unprotected bluff toe with current tendency to erode (Dornbusch et al., 2008; Sunamura, 2015), (Fig. 13).

CONCLUSION

Accumulated bluff retreat has spatial and temporal variations, indicating different rhythms in bluff evolution. External erosive agents, including wave exposure degree, control this discrepancy for a lithologic homogeneous bluff line.

Association between bluff retreat and waves shows that periods of high waves do not necessarily induce recession; it depends on the initial stage of the bluff evolution cycle at the time. Therefore, monitoring the bluff toe erosion/deposition pattern is necessary to completely understand its erosional behavior.

Geoprocessing methods applied in this study, together with spatial and temporal wave variability, enabled the identification of bluff retreat periods. Erosive hotspots were then determined along with the current evolutionary stage of the bluff. Based on the actual wave climate, regional meteorological and oceanographic fluctuations, it is possible to infer the vulnerability to erosion to guide coastal management.

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