POTENTIAL CONSEQUENCES OF CLIMATE CHANGES ALONG A TROPICAL COASTAL REGION OF BRAZIL

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RESUMO. Potencias consequências das mudanças climáticas ao longo de uma região costeira tropical do Brasil. O presente estudo avalia qualitativamente os potenciais impactos induzidos pelas mudanças climáticas ao longo de uma faixa litorânea do estado da Bahia, a qual apresenta grande diversidade geomorfológica e exuberante beleza cênica. Entre esses impactos salientamos: um ganho significativo da energia das ondas podendo acelerar processos erosivos na linha das praias; intrusão de água salgada nos aquíferos costeiros; rápido recuo das falésias ativas; mudanças nas zonas baixas como terras úmidas e manguezais; represamento de sedimento nos estuários e aumento da turbidez e sedimentação sobre os recifes de corais. Estes efeitos irão gerar enormes prejuízos econômicos nas áreas urbanas. A aproximação de primeira ordem referente às avaliações feitas no presente estudo, crivado de incertezas, requerem, ainda, estudos posteriores que venham a refinar os cenários perspectivos quanto às mudanças climáticas na área de estudo. Todavia, mesmo com incertezas, essas avaliações podem vir a serem úteis como um instrumento válido para o planejamento e gerenciamento das zonas costeiras.

Palavras chave: Mudanças climáticas; zonas costeiras; nível do mar; impactos ambientais, Brasil.

ABSTRACT. The present study has a qualitative assessment of potential impacts induced by climate changes along a coastal region from the State of Bahia, which presents great geomorphological diversity and exhibits lush scenic beauty. Among these impacts we include: a significant increase of wave energy that will accelerate erosion processes along the beaches; intrusion of seawater into shallow coastal aquifers, a rapid retreat of active cliffs, changes in low-lying areas, such as wetlands and mangroves and turbidity and sedimentation around coral reefs. These impacts will generate enormous economic losses in urban areas. The first-order approach for the assessments made in the present study, which is riddled with uncertainties, still requires further study to refine its prospects with regard to climate change scenarios along Brazilian coastal regions. However, even with these uncertainties, these evaluations can be useful as valid instruments for coastal zones planning and management.

Key words: Climate change; coastal zone; sea-level; environmental impacts; Brazil

INTRODUCTION

Whether humanity has been promoting an increase in the temperature of the planet in recent decades through the mechanism commonly described as the release of greenhouse gases remains controversial; nevertheless, a large number of studies have reached a consensus that the sea level may rise significantly during this century (e.g., Scor, 1991; French et al., 1995; Neves & Muehe, 1995; Camfield & Morang, 1996; Zhang et al, 1997; Church, 2001; Douglas & Peltier, 2002; Fletcher, 2009; IPCC, 2014). As a result of the acceleration of global warming, the expansion of ocean waters and the melting of glaciers, the sea level could rise by approximately 1 m or, according to the IPCC (2014), by an average of 74 cm by the end of this century with a 95% confidence interval (between 52 and 98 cm) in the worst-case scenario (RCP 8.5). However, as suggested by Sanchez-Arcilla et al. (2008) and Fletcher (2009), we must always consider that sea level rise will have significant variability at both the regional and the local scale.

Along the Brazilian coast, the available time-series of sea level data are limited to less than 50 years and exhibit many gaps (Muehe & Neves, 1995). However, despite these limitations and numerous uncertainties, these records suggest a trend of sea level rise (Aubrey et al, 1988; Muehe & Neves, 1995; Dominguez & Bittencourt, 1996; Mesquita, 2003; Muehe, 2010).

Additionally, there is an expectation that global warming will promote significant changes in the climatology of storms and waves, increasing their magnitudes and frequencies (Hughes & Brundit, 1995; Douglas & Pertier, 2002; Tronis, 2004; Walsh et al., 2004; Ferreira et al., 2008).

Beaches worldwide are strong attractions for leisurely activities, and they carry economic implications associated with tourism and recreational activities (Breton et al., 1996; Silva et al., 2003; Muehe, 2004; Coriolano & Silva, 2005); consequently, they attracted a great human migration to coastal regions during the twentieth century (Charlier & Bologa, 2003; Small & Nicholls, 2003). Currently, approximately 50% of the world's population lives fewer than 6 km from a beach, and it has been conjectured that this number will rise to 75% by the year 2020 (Charlier & Bologa, 2003). This has caused considerable economic pressure for construction to occur even closer to the active profiles of beaches, as this construction is intrinsically related to the great value that beaches have (Wicker, 1966; Domurat, 1987; Appendini & Fisher, 1998; Hall, 2001; Calliari et al., 2003; Griggs, 2005; Santos et al., 2007; Bittencourt et al., 2008; Silva et al., 2008, 2012). These construction projects accompany a highly vulnerable exposure of sceneries and a wide variety of risks due to climate changes (Klein et al., 2001).

The study area, located along the eastern coast of Brazil, extends from the town of Belmonte in the north, to the boundary with the State of Espírito Santo (Ponta dos Lençóis) in the south (Fig. 1). This area primarily comprises the Discovery Coast—considered by UNESCO as a Natural

Heritage of Humanity site—so named by the fact that it was the first place where the Portuguese made first contact with the Brazilians in 1500 in the town of Porto Seguro (Fig. 1).
In general, the coastal zone of the study area is sparsely occupied, while most of the population is concentrated within the larger urban centers, which are the municipalities located along the seafront (Fig. 1). The most populous city is Porto Seguro (Fig. 1) (Fig. 4A) with approximately 70,000 inhabitants and the highest density in the region (28.12 inhab/km^2), and the remaining municipalities represent populations ranging between 15,000 and 35,000 inhabitants (Carneiro, 2011).
Currently, tourist activities in the Discovery Coast and its vicinity are intense, especially in the municipalities of Porto Seguro and Santa Cruz de Cabrália (Fig. 1), due to the amenities offered by the implementation of accessible roads. In addition, the natural potential of the area, which is characterized by the presence of rain forest remnants, a dense drainage network, a coastline with diverse landscapes and a colonial urban environment, ensures that the study area has a rich scenic beauty. In addition, the Discovery Coast has large reserves of the Atlantic Forest, within which there are three large national parks and protected native Indian villages.
With the rapid development of new coastal segments for residential and recreational activities, the study area has become the subject of great economic pressure for extensive construction projects (e.g., hotel complexes and resorts) along the coast and immediately adjacent to the beaches. With regard to climate change, and in the absence of local regulations, these conditions will certainly encourage a considerable increase in damage-prone properties.
While recognizing the uncertainties inherent in attempts to predict the behaviors of dynamical systems (De Vriend, 2003), the present study aims to present a preliminary qualitative evaluation of the possible impacts—without chronological connotations—induced by climate changes in their course, which may be caused during rises in sea levels or by the increased magnitudes and frequencies of weather events along the Discovery Coast and its vicinity. In this way, it is also expected that the prospective scenarios produced from our evaluation will be useful for subsidizing management policies that are formulated for the coastal region of the study area.

MATERIALS AND METHODS

CHARACTERISTICS OF STUDY AREA

Density of urbanization along the coastline

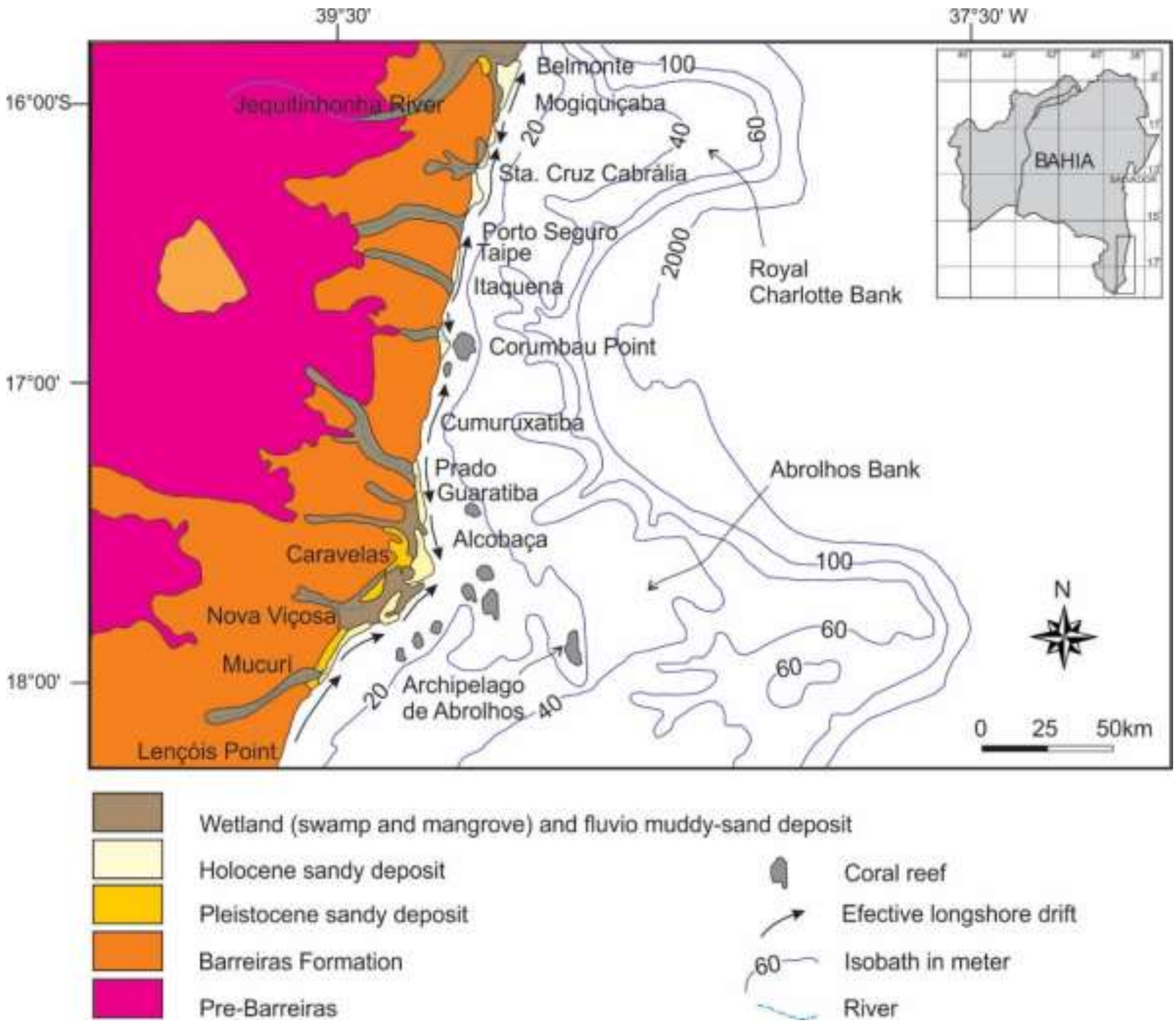
The levels of urbanization, which are described in terms of the stabilization of construction, were defined by walking along the beaches and the tops of the cliffs within an arbitrary range of 50 m inland from the coastline. Aerial photographs and pictures taken during scenic overland flights (Silva et al., 2007; Santos et al., 2007) were also used for this purpose.
In relation to the coastal section from Guaratiba to Belmonte (Fig. 1), Silva et al. (2007) divided the coastline into 5 km by 5 km segments and adopted the criteria of Esteves et al. (2003) to classify them as follows: a) low urbanization, which includes the 5 km stretch from the coastline where there is fixed construction that occupies less than 30% of its extent, b) medium urbanization, which includes construction between 30% and 70%, and c) high urbanization for construction above 70%. According to these criteria, 70% of this section of the studied area represents a low level of urbanization, 10.3% represents a medium level and 19.7% represents a high level (Fig. 2B) (Silva et al., 2007).
For the section between Guaratiba and Ponta dos Lençóis (Fig. 1) Santos et al. (2007) divided the coastline into 1 km by 1 km segments and utilized the criteria of the Projeto Orla (MMA, 2002) to rank them as follows: a) low urbanization, including the stretch within 1 km from the coastline with less than four fixed construction projects, b) medium urbanization, including 5

to 10 projects, and c) high urbanization, including more than 10 projects. Based on these criteria, 81.9% of this section represents a low level of urbanization, 6.8% represents a medium level and 11.3% represents a high level (Fig. 3B).

Geological-physiographic setting

The study area (Fig. 1) is bounded internally by a line of fossil cliffs within tablelands from the Miocene and Pleistocene (Martin et al., 1980; Suguio & Nogueira, 1999; Dominguez et al., 2009) of the so-called Barreiras Formation, which consists of semi-consolidated sandy-clayey deposits (Martin et al., 1980; Rosseti & Dominguez, 2012). In general, these tablelands are slightly inclined to the east and, in some places, end in active cliffs (Figs. 2A and 3A) with heights of 15 to 30 m (Fig. 4B, C). Many of these cliffs present suspended valleys (Fig. 4D), which may be indicative of relatively rapid erosion that does not allow the streams to converge at its base level (Silva, 2004). Most of the stretches at the top of the active cliffs are anthropomorphized with different types of vegetation reaching already their edges. In some locations, such as between Coqueiros and Ponta dos Lençóis (Fig. 3A), there are even fixed construction projects that are already threatened by the receding cliffs (Fig. 4E).

Figure 1. Geological map of the study area, including the continental shelf, rivers, coral reefs (in the Abrolhos Bank and along the coast), cliffs, and longshore drift.



The Quaternary plain is characterized by the presence of Pleistocene and Holocene marine sandy terraces covered by beach ridges, fluvio-lagoon deposits and, near the coastline, sandy beaches and mangrove deposits (Martin et al., 1980; Dominguez et al., 1987; 2009; Andrade et al., 2003) (Fig. 1). Locally, beachrock banks are found both on the beach and at the foreshore (Martin et al., 1980) (Fig. 4F) and are also found on the truncated surfaces of coral reefs (Fig. 2A) (Fig. 4G). Coral reefs are also found offshore (Leão & Kikuchi, 1999) in the section between Ponta do Corumbau and Nova Viçosa. They are located along a large internal arc roughly following the coastline and locally along an external arc around the eastern shores of the Abrolhos Archipelago islands (Fig. 1). The reefs located inshore near the beach system are characterized by isolated bank reefs of varied shapes and dimensions and have their tops exposed subaerially during low tides. The offshore reefs are coral pinnacles with the shapes of mushrooms (the Brazilian chapeirões) that reach heights of up to approximately 25 m or are bank reefs with extents that range from hundreds to thousands of meters. The tops of the chapeirões are generally below the level of low tide, but the extensive bank reefs may be exposed during low spring tides (Leão et al., 2003).

The studied region is also characterized by a very large continental shelf in front of both Mogiquiçaba (100 km) and Caravelas (200 km); meanwhile, in the section between Porto Seguro and Prado, the shelf is relatively narrow (50 km) (França, 1979) (Fig. 1). The so-called Royal Charlotte and Abrolhos Banks are striking physiographic features within the continental shelf. The above mentioned reefs in the Abrolhos Bank are considered as the most significant reefs of the entire Southwestern Atlantic Ocean (Laborel, 1969; Castro & Pires, 2001; Leão et al., 2003).

The rivers that flow into the study area, with the exception of the Jequitinhonha River (Fig. 1), present very low average annual flows (CEPLAB, 1979) and have drainage basins with small expressions that develop estuarine areas and ebb tidal deltas in their mouths. The Jequitinhonha River which has a mouth in the form of a wave-dominated delta (Dominguez et al., 2009), drains an area of 70,315 km^2 with a sediment discharge of 7.89 x 10^6 tons/year.

The tidal regime in the region is semi-diurnal and, considering the classification of Davis & Hayes (1984), is a mesotidal type with spring tides that reach a maximum amplitude of 2.5 m (DHN, 1999).

Atmospheric circulation on the surface, wave climate and longshore drift

The studied area is entirely located within the trade winds belt in the South Atlantic (NE-E-SE), which is related to one high-pressure cell in this region (Bigarella, 1972; Kousky & Chou, 1978; Martin et al., 1998). Another important element of the atmospheric circulation in this region is the periodic advance of the Atlantic Polar front during the autumn and winter, which generates SSE winds (Kousky,1979; Dominguez et al., 1992; Martin et al., 1998; Molion & Bernado, 2002). It should be emphasized that, on a year-to-year basis, the high-pressure cell typically presents a tendency to remain relatively stationary. Seasonally, however, this cell tends to expand and contract. In the coastal region, this movement of the high-pressure zone controls the position of the divergence zone (DZ) between the trade winds *sensu stricto* (SE) and the return trade winds (NE). During winter, the DZ is located at approximately 20°S, while in the summer the position changes to approximately 13°S (Bigarella, 1972; Dominguez et al., 1992; Martin et al., 1998), which affects the entire area of study.

Figure 2. Coastal stretches under erosion, cliffs, beach typology, and the density of urbanization (excerpt of Belmonte/Guaratiba).

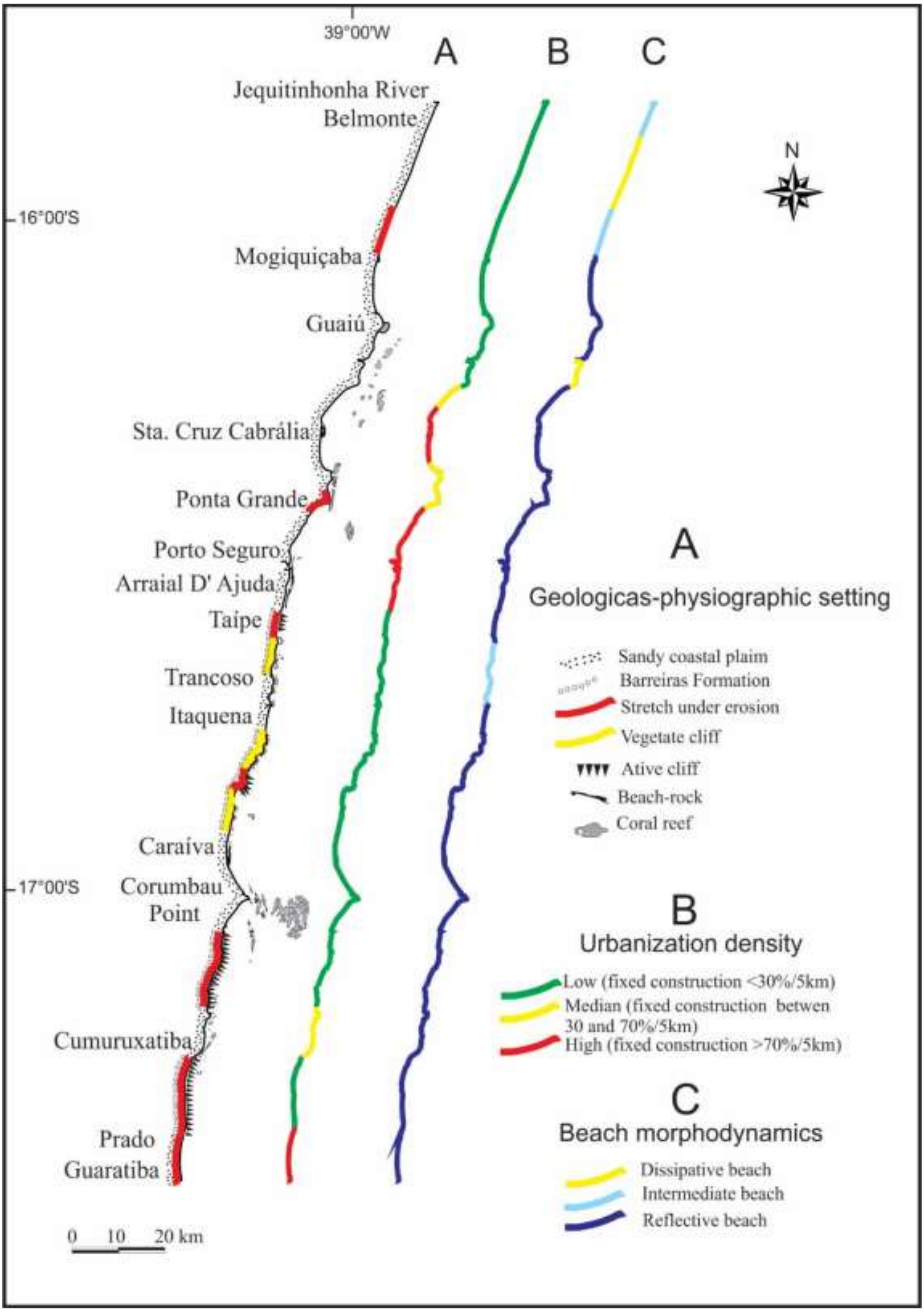
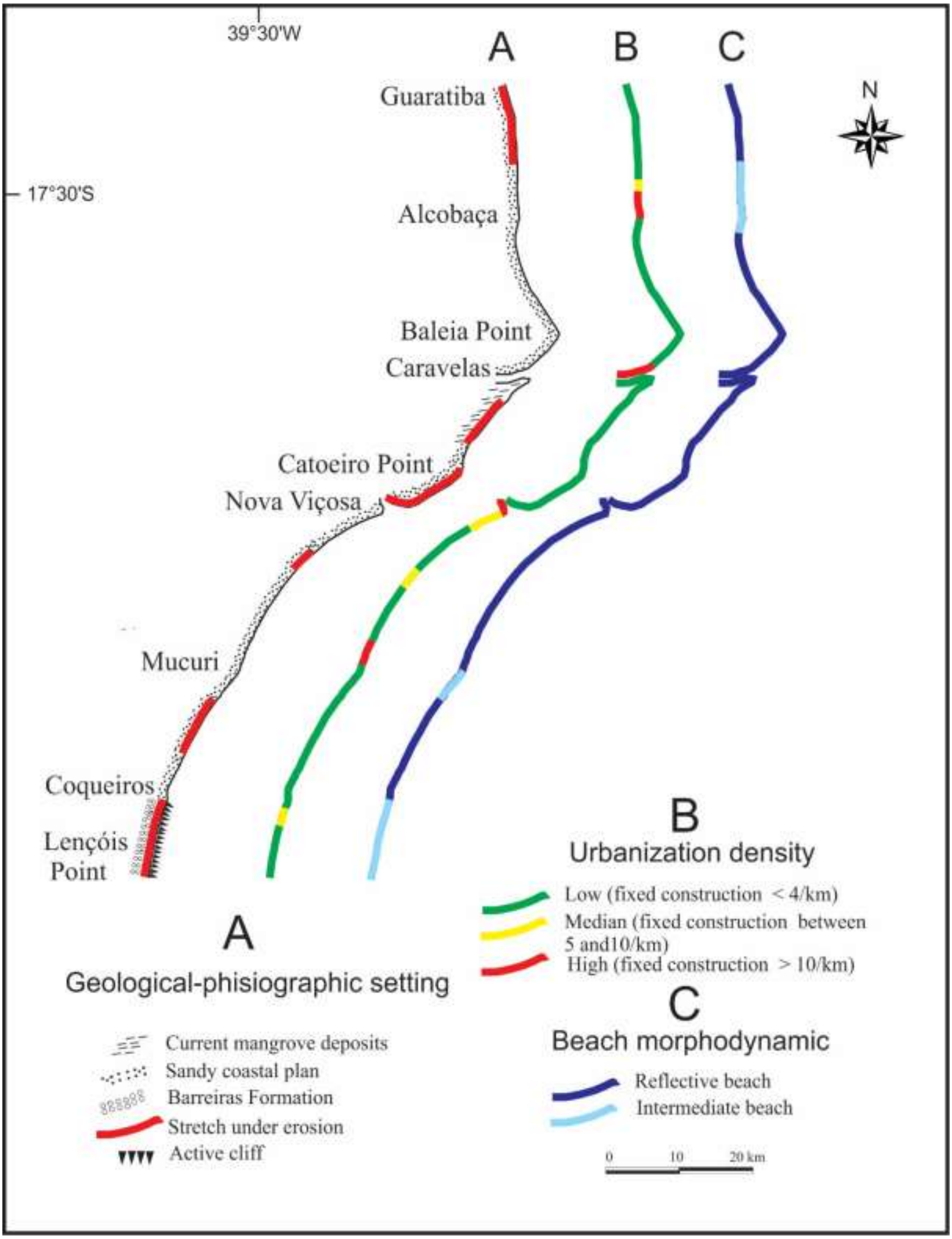


Figure 3. Coastal stretches under erosion, active cliffs, beach typology, and the density of urbanization (excerpt of Guaratiba/Ponta dos Lençois).



The general pattern of sediment dispersion along the Discovery Coast (Silva et al., 2001) shows that the effective longshore drift has a predominant direction from south to north with three significant coastal segments that exhibit backward directions (Fig. 1). As a result, these inversions give rise to three coastal stretches with convergence and three stretches with divergence in the direction of the drift (Fig. 1). However, we cannot disregard the possible effects of local variations induced, for example, by the dynamics of tidal inlets and of the river mouths, which can locally change the direction of a drift cell (see e.g., Linch-Blosse & Kumar, 1976; Fitzgerald, 1984).

Beach typology

Considering the coastal morphodynamics, the beaches represent features dominated by reflective characteristics (Fig. 4H) with a few stretches of intermediate (Fig. 5A) and dissipative beaches (Fig. 5B). The particle sizes are markedly dominated by medium to coarse sand and are locally formed by fine sand (Silva, 2004; Santos, 2006).

Coastal stretches under erosion

Several coastal stretches under erosion are spread out along the coastline between Belmonte and Ponta dos Lençois (Figs. 2A and 3A) (Silva, 1999; Dominguez et al., 2000; Silva et al., 2007; Santos et al., 2007; Dominguez et al., 2008) (Fig. 5C to H). Between Guaratiba and Belmonte, stretches under erosion occur throughout 34.16% of the coastline, while 38.85% of the coastline between Guaratiba and Ponta dos Lençóis is being eroded (Silva, 1999).

Figure 4. Illustrated photos of: (A) Aerial view of the city of Porto Seguro; (B) Active cliffs at Taípe Beach; (C) Active cliffs between Coqueiros and Ponta dos Lençois; (D) Active cliffs with suspended valleys between Cumuruxatiba and Guaratiba; (E) A building threatened by collapse on the top of an active cliff between Coqueiros and Ponta dos Lençois; (F) Beach rock in Santa Cruz Cabrália; (G) Coral reef in front of the Corumbau Point; (H) Reflective beach in Santa Cruz Cabrália. For location see figures 2 and 3.

It should be emphasized that the above authors did not have the means to differentiate between their observations as evidence of erosion referring to medium- or long-term processes. They did manage, however, to ensure that their evidence were not indicative of seasonal processes. However, where active cliffs were observed (Figs. 2A and 3A), they were considered to be affected by medium- to long-term erosive processes.

Figure 5. Illustrated photos of: (A) Intermediate beach in Alcobaça; (B) Dissipative beach between Guaiú and Santa Cruz Cabrália; (C) A building suffering from erosion atop an active cliff between Corumbau Point and Cumuruxatiba; (D) A destroyed house on the beach of Guaratiba; (E) Remains of a house in Nova Viçosa; (F) A tree with exposed roots and an erosive slope in Cumuruxatiba; (G) A tent precariously protected from erosion by the trunks of coconut trees in Prado; (H) Micro-cliffs in a Holocene terrace and coconut trees that have fallen on the beach a little above Mogiquiçaba. For location see figures 2 and 3.

RESULTS AND DISCUSSION

SOME CONSIDERATIONS REGARDING THE POTENTIAL CONSEQUENCES IN THE STUDY AREA

Waves, climate and longshore drift

a) In the study area, Silva (1999) and Bittencourt et al. (2000) estimated that wave fronts that originate from the NE and E begin to interact with the ocean bottom at a depth of 20 m, while those from the SE and SSE begin this interaction at 35 m. It is possible that this process occurs in the stretch of the continental shelf between Prado and Porto Seguro (Fig. 1), which is generally relatively narrow with an average gradient of 1/333 according to França (1979). Such conditions will tend to induce the waves to present any significant gain of energy along the coastline. Meanwhile, it does not appear that this will occur along the Royal Charlotte and Abrolhos banks (Fig. 1) because they are very wide with average gradients of 1/2500 (França, 1979), and thus, the waves will tend to demonstrate a great loss of energy during their spreading due to friction with the ocean bottom.

b) With a rise in sea level, the reflective beaches that dominate the study area (Figs. 2C and 3C) will impose a slight reduction in wave energy along almost all of the beaches. In contrast, an increase in the wave energy will occur along the few intermediate and dissipative beaches, because they present a surf zone that causes significant wave energy dissipation due to friction with the ocean bottom (see e.g., Komar & Shinh, 1993).

c) Eventual exacerbations due to weather conditions may also occur as a consequence of climate changes, which may massively impact the coastline of the study area by generating tropical storms with frequent and severe meteorological tides. Such events, as suggested by Spencer (1995), Chen (1997), Leatherman et al. (2000) and Williams & Gutierrez (2009), should provide a considerable increase in wave heights that can overlap the upper limits of the beach. In this sense, according to Carter & Woodroffe (1994), wave energies during an intense storm can compel beach sediments to enter into a liquefaction state, which significantly enhances the process of beach erosion. In such circumstances, beach sediments can be transported offshore to depths that will prevent their return to the beach via moderate wave action, leading to a loss of material that can become permanent (Héquette et al., 2001; Flick & Ewing, 2009).

d) The waves that travel atop the intertidal coral reefs, including both the reefs adjacent to the coastline as well as those located on the continental shelf, are assumed to incur a great loss of wave energy by friction with the ocean bottom (Silva, 1999; Bittencourt et al., 2000). Although there is no available data in the study area in relation to this subject, it can be considered in the pretext of comparison with other similar circumstances, e.g., the data obtained by Roberts & Suhayda (1983) and Costa et al. (2016). In the first case, there was a wave energy loss of approximately 95% and an energy loss of 67% to 99.9% in the second. With rising sea levels, such scenarios should change significantly since wave heights will increase due to the reduction of friction with the ocean bottom, which will consequently increase the transmission of energy to the coastline (See, e.g., Neves & Muehe, 1995; Storlazzi et al., 2011). Leão & Kikuchi (1999, 2001) and Leão et al. (2003) showed that the coral reefs in this region grow at an average rate of 3 mm/year, which is well below the rates of sea level rise projected for the years 2000-2100 by Nicholls & Cazenava (2010) of approximately 8-16 mm/year. Such circumstances may therefore result in an increase in the water level over the reef tops on the order of 0.45 to 1.25 m during the 21st century with a consequent increase in the energies of waves on the beaches located in the backs of the bank reefs. For the beachrock banks, it is also expected that a considerable part of the wave energies will be transmitted to the backs of the banks with a rise in sea levels (See e.g., Neves & Muehe, 1995).

Ebb tide deltas associated with the mouths of small rivers may also lead to a reduction in the wave energies before they reach the coastline. As noted by Fitzgerald & Nummendal (1983), the sandbars in an ebb tide delta effectively act as natural breakwaters. However, with a rise in sea levels, the waves will break closer to the coastline, thus increasing their energy.

e) In the present-day scenario, the refraction diagrams for the main wave fronts directed into the study area (Fig. 4A, B, C, D) (Silva, 1999; Bittencourt et al., 2000) show that the coral reefs, which act as barriers to the propagation of waves, create multiple and extensive regions of shadow zones in their back regions along the coastline. With the prospective scenario of sea level rise, the waves will act directly upon the coastline and distribute the available sediments produced by erosion processes along various beach stretches that are scattered along the adjacent coastline, thereby softening the coastal morphology by filling the re-entrances. In this sense, a striking reconfiguration of the coastline can be expected during sea level rise in the coastal stretches corresponding to the great cuspidate feature of Caravelas (Fig. 1) between Prado and Mucuri, wherein large stocks of sand from the marine Quaternary terraces are protected by the coral reefs of the Abrolhos Bank. In the same sense, although at a smaller scale, this can also be expected to occur along the tombolo of Corumbau Point (Fig. 2A).

Coral Reefs

The coral reefs of the study area, which are located within the coastal stretch between Cumuruxatiba and Guaiú (Fig. 2A), are both adjacent to the coastline and far away from the coast (approximately 1 to 10 km). However, the reefs in front of the coastal zone between Prado and Mucuri are approximately 10 to 30 km away from the coastline. In both types of reefs, living corals exist inside intertidal pools and in the reef walls. Meanwhile, the reefs adjacent to the coastline commonly have their tops partially covered with siliciclastic sands (Leão et al., 2003).

Increasing water depths relative to the tops of the reefs in the light of rising sea levels may lead to various situations in different periods. Events in the short term, for example, can provoke an increase in the flow of water and sediment in the reefs adjacent to the coastline from their back zones to the reef fronts. This process may impact the corals as observed at the Trancoso and Itaquena beaches (Fig. 2A) (see e.g., Storlazzi et al., 2011). Furthermore, the simultaneous increase in wave energies can cause major turbulence within the reef banks, exacerbating the existing conditions involving the resuspension of fine siliciclastic sands from the beach, thereby increasing turbidity and sedimentation within the reefs (Field et al., 2011), which must also contribute to higher lapses of time in the tide cycle during which the reef will be submerged (Neves & Muehe, 1995). However, with the continuation of these processes, the regression of the coastline caused by erosion of the beach as well as increasing water levels will promote an improvement of conditions for reef growth, notably on the banks far away from the coast. From a stratigraphic point of view, there will be an increase in the area of accommodation because the greater water depth due to higher sea levels will be conducive for further growth of carbonate precipitation organisms (corals and coralline algae). In addition, a decrease in the efficiency of the resuspension of sediment at deeper sites and away from the coast is expected, thereby reducing the turbidity and/or sediment re-suspension events. It is worth mentioning that Dutra et al. (2006) found that the coral reefs of the Abrolhos Bank (Fig. 1) that are located less than 20 km from the coastline currently have high values of sediment accumulation rates with large percentages of siliciclastic that, according to these authors, appear to negatively influence the corals, as they probably cause choking and/or a reduction of their photosynthesis processes (see e.g., Storlazzi et al., 2011). Sea level rise and coastline regression should promote a drowning of the estuaries, thereby reducing the amount of fine sediments delivered to the coastal zone and possibly reducing the amounts of fine siliciclastic sediments for these coastal reefs.

Finally, we must also consider that coral reefs in the study area, which already show evidence of recurrent coral bleaching (Leão et al., 2006), can be affected by new episodes of bleaching with higher frequencies in scenery with increasing temperatures (see e.g., Spencer, 1995; Field et al., 2011), and this can affect coral growth and reef calcification rates (Oliveira, 2008). Another negative impact is the reduction of the water pH induced by increased CO_2 levels (Field et al., 2011; Kerr et al. 2015).

Flood

Floods in the study area as a result of sea level rise are expected to fill the low areas with wetlands, including the mangroves (Fig. 1). Flooding will more likely begin with the stretches along the river margins not far from the river mouth as well as in the intricate tidal channels on the large cuspidate feature of Caravelas (Fig. 1). It is reasonable to expect that the magnitude of flooding will increase following the exacerbating influences of the tides and the flooding will also act as a barrier along the seaside, thereby making runoff difficult, as pondered by Walsh et al. (2004). Muehe & Neves (1995) observed that flooding should increase the ability of the tides to behave as traps, thereby damming sediments and thus preventing them from reaching the coastline. As mentioned previously, this can cause erosive processes in the region due to a sediment deficit.

With a rising sea level, the wetlands (including the mangroves), which are considered as the most productive environments on Earth (Hooligan & De Boois, 1993, apud Nicholls & Leatherman, 1995), will be subjected to great pressures, significantly compromising the biodiversity of the coastal ecosystems as noted by Muehe & Neves (1995) and Nicholls & Leatherman (1995).

Another aspect to be taken into account is the possibility that the stretches of wetlands (Fig. 1) will grow vertically as a function of biomass/sediment nutrition, accompanying any slow rates during the beginning phases of sea level rise (Nicholls, 1995; Paskoff, 2004; William & Gutierrez, 2009).

It should also be considered that, as noted by Paw & Thia-Eng (1991), sea level rise could transpose the mangroves further inland during situations where land is available for colonization. This could be the case of the tidal flat that occupies the coastal stretch between Nova Viçosa and Caravelas (Fig. 1), part of which is located at the rear of the ocean shore colonized by mangrove vegetation, which is otherwise devoid of vegetation. Finally, one cannot disregard the possibility that incoming floods will impound high levels of salinity within the estuaries.

Groundwater

Sea level rise will cause the freshwater/seawater limits to increase as well, which would involve the intrusion of salt water into shallow coastal aquifers, thereby affecting the quality of drinking water (Paw & Thia-Eng, 1991; Muehe & Neves, 1995; Nicholls & Leatherman, 1995; Fitzgerald et al., 2008). Accordingly, such a prospective influence is a considerable threat particularly to small communities scattered along the coastal plains, which are normally served through water tanks.

Cliffs

With the exception of the coastal stretch comprised of active cliffs between Ponta dos Lençois and Coqueiros, which are combined with the intermediate beaches (Santos, 2006) (Fig. 3A, 3C), the remaining stretches are combined with reflective beaches, which offer little protection (Figs. 2A, 2C and 3A, 3C). As was mentioned earlier, reflective beaches are effectively dominated by the intense surging action of waves. Thus, it is expected that, during sea level rise, waves will begin to attack and more easily undermine the cliffs adjacent to these reflective beaches relative to the stretch between Ponta dos Lençois and Coqueiros. With a continually rising sea level, one possible trend is the disappearance of beaches at the base of the cliffs; the waves will strike them directly, giving rise to a faster retreat of the cliff faces, especially during the arrival of tropical storms.

As noted by Nicholls et al. (1995), another aspect to be considered is that lower cliff heights will generally lead to shorter required times for their retreat during sea level rise. As argued by Zenkovitch (1967), the cliffs will be more rapidly eroded since, at the beginning of their retreat, the amount of material that reaches the cliff base in a given unit of time will be shorter where the cliff is lower. This is taking into account that, with rare exceptions, the cliffs of the study

area are located in the Barreiras Formation. This can be expected for the cliffs at the southern end of Corumbau Point, where the heights are between 3 and 6 m (Fig. 2A), in comparison with larger cliffs, such as those located between Ponta dos Lençois and Coqueiros (Fig. 3A), which exhibit heights of approximately 15 m, and those between Cumuruxatiba and Prado (Fig. 2A), which have heights between 15 to 20 m (Bittencourt et al., 1999).
Finally, another significant process that contributes to the retreat of cliff faces is subaerial degradation, which involves the infiltration of rainwater into the sediments of the Barreiras Formation and the consequent landslides and disintegration of the material at the cliff base (Silva, 2004). Therefore, with the anticipated increase in the intensities and frequency of meteorological events, heavy rains will cause more landslides to occur along the cliffs, particularly because they are made up of semi-consolidated clayey and sandy deposits, as mentioned earlier.

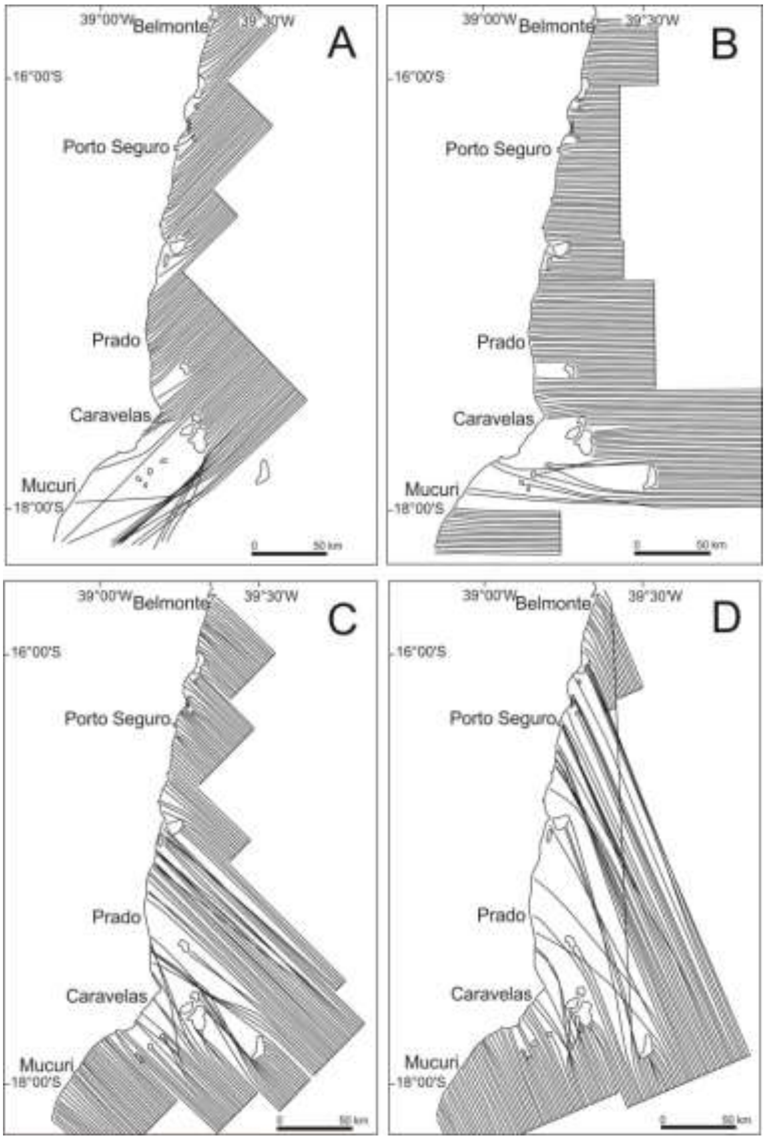
Socio-economic losses

The first areas that will be impacted by the rising sea levels and the increased frequency and intensities of meteorological events are the areas of coastal plains with fixed construction projects that are located in sections subjected to erosive processes (Fig. 5D to 5G). Additionally, such impacts may be expected in the cases of fixed construction projects located on the tops of the tablelands of the Barreiras Formation that are close to the active cliffs (Figs. 4E and 5C). On the other hand, the urban stretches are the most prone to considerable socio-economic losses, especially those with densities of medium to high urbanization rates (Figs. 2A, 2B and 3A, 3B). In this prospective scenario, the losses of properties, coastal infrastructure, improvements and modern hotel equipment, which also affect the qualities of recreational beaches, will result in a significant decrease of tourism along the Discovery Coast, which is one of the most visited coastal regions of Brazil and includes a long tradition of international attractions.
One should also expect that, with the consequent flooding due to rising sea level, the coastal stretches along the wetlands that are utilized for agricultural purposes would probably need to be abandoned over time.
The above mentioned impacts that can only be regarded as predictable within the shadow zones of different wave fronts (Figs. 6A, 6B, 6C, 6D) are not changed in a meaningful way during sea level rise. As discussed earlier, when the shadow zones begin to disappear with an increase in the sea level, the waves will reach increasingly greater heights over the barriers, and thus, they will attain increasing energy levels along the coastline. This will therefore create circumstances that are very different from the present-day circumstances with respect to the waves, longshore drift patterns and configuration of the coastline. Consequently, revealing the resulting coastal scenery is unpredictable with regard to socio-economic losses. For example, one cannot rule out the feasibility that the cliffs, as well as the eroded coastal stretches comprised of Holocene deposits, will be protected by sandy beaches from the drift of longshore sediments sourced from the erosion of the Caravelas cuspidate feature.

FINAL CONSIDERATIONS

A considerable spectrum of possible/likely impacts in the study area that may be generated by rising sea levels and by the exacerbation of meteorological events is constructed by the complex interactions between waves, wind action, tides and currents and is affected by the topography of the continental shelf, the characteristics of the beach system and the orientation of the coastline. As a result, such circumstances will give rise to considerable variations, even among adjacent beaches, wherein several individual segments of beaches will be characterized by different conditions of balance. In this sense, the first-order approach for the assessments made in the present study, which is riddled with uncertainties, still requires further study to refine its prospects with regard to climate change scenarios along the coastal region of Brazil. However, even with these uncertainties, these evaluations can be useful as valid instruments for the planning and management of coastal zones to establish the rules of occupation and their application.

Figure 6. Refraction diagrams for (A) waves from the northeast, (B) waves from the east, (C) waves from the southeast and (D) waves from the south-southeast.



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