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Brazilian coastal vulnerability to climate change

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Abstract. The coastal zone of Brazil includes a variety of coastal forms, such as wide occurrence of sedimentary cliffs, large and deeply incised estuaries, crystalline headlands and low-lying coastal plains. These forms will respond in different ways to the expected climate changes and associated sea level rise. The potential vulnerability of the distinct coastal types along the Brazilian coast to climate change is evaluated. Due to the low occupation of large sectors of the coastline, the risks are concentrated in the urbanized areas. The largest impacts are expected to be caused by floods. The absence of long-term observations of oceanographic data or detailed altimetric maps presents a major difficulty for the evaluation of different risk scenarios at the local level and consequently for the application of measures to minimize these impacts over the population.

Key words: Coastal vulnerability, climate change, coastal classification, Brazil

Resumo: Vulnerabilidade da costa brasileira a mudanças climáticas. A zona costeira brasileira se caracteriza por amplos domínios de falésias sedimentares e de rochas do embasamento com alternância de baixadas costeiras e margens ao longo de estuários inseridos nos relevos elevados. Considerando os distintos compartimentos geomorfológicos é apresentada uma avaliação da vulnerabilidade potencial em face de uma mudança climática e associada elevação do nível do mar. Os resultados indicam que a baixa ocupação de grande parte da zona costeira faz com que as áreas de risco se concentram nas cidades costeiras, sendo os riscos de inundação os de maior impacto sobre a população. A ausência de observações contínuas de longa duração, assim como a falta de mapeamentos altimétricos de detalhe, representa a maior dificuldade na construção de cenários de risco a nível local e consequentemente para o desenvolvimento e aplicação de medidas de minimização dos impactos sobre a população.

Palavras-chave: Vulnerabilidade costeira, mudança climática, classificação costeira, Brasil

Introduction

The climate changes forecasted by the Intergovernmental Panel on Climate Change (IPCC) will necessarily depend on the time and place being considered.

One of the forecasts for the evolution of the average surface temperature of the planet under different greenhouse gas emission scenarios (IPCC 2007) is that the temperature increase along the Brazilian coast will be less than 1 °C until 2030. But, this increase may be as high as 2 °C or 3 °C for the last decade of this century (Fig. 1). The predicted increase in temperature at higher latitudes is more significant and suggests that ice will melt in Greenland and Antarctica, resulting in rising sea level rates. Sea level rates will already be increasing because of thermal expansion. The most direct result of coastal geomorphological processes will be the adjustment, usually by erosion, of the coastline and the increased vulnerability of low-lying areas to flooding.

This first approximation regarding the climate evolution already allows us to affirm that, from a geomorphic viewpoint, the changes brought about by sea level rise will be small in the next 20 years, and the current trends will be more or less maintained. However, because of the significant rise in temperature forecasted for the end of the century, geomorphic processes are expected to intensify, starting in the middle of the century, as a result of both the sea level rise and the intensification and frequency of subtropical cyclogenesis. This cyclogenesis is associated with an increase in the sea water temperature, changes in sea level, increased wind transport and destabilization of dune fields.

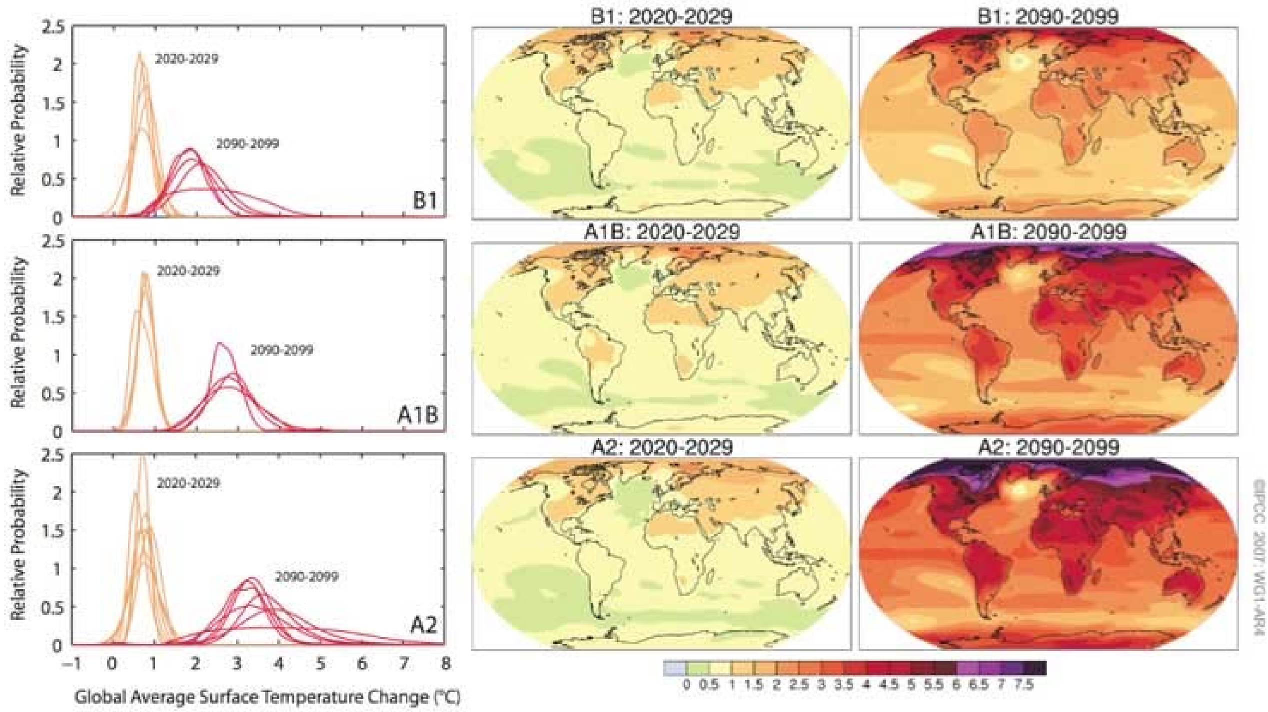

Figure 1. Evolution of the average surface temperature projected by the IPCC in 2007.

Nobre *et al.* (2007) produced climate projections for the next 30 years of the century in South America for various emission scenarios. In terms of precipitation these predictions show discrepancies in the forecasted anomalies in terms of either increase or decrease. Although the discrepancies between the results are small they will affect negatively or positively areas that are already experiencing water deficit as in the Northeast Region of Brazil, where the projections for the coastal zone indicate anomalies varying from very small to an increase and even decrease in the amount of precipitation. However, even with no significative change in rainfall, the augmented evaporation caused by the temperature increase will result in augmented water shortages in the semi-arid regions.

The temperature forecasts by Nobre *et al.* (2007) for the coastal zone are similar to the scenario forecasted by the IPCC (2007) and indicate a temperature increase in the range of 2 ºC to 3 ºC.

The perception of risk from sea level rise was incorporated into the ORLA Project of the Ministry of Environment (Ministério do Meio Ambiente 2004) through the establishment of set-back lines of 50 m in urban areas and 200 m in rural areas. This distance would be measured landward either from the backshore limit or from the dune toe of the reverse side of foredunes when present. The establishment of the width of these set-back lines resulted from a conciliation between the results of the application of the Bruun rule (Bruun 1962, 1988), for an increase of an 1 m sea level rise (Muehe 2001, 2004), and the impossibility of its practical application in areas of very low gradient of the shoreface and inner shelf as in the north and northeast regions where the results of the model indicate very large recession of the coastline (Fig. 2).

The adopted limits represent a first minimum restriction to be considered in the urbanization of coastal areas, and can be expanded according to local geomorphic characteristics such as the known erosion rate and landscape conservation.

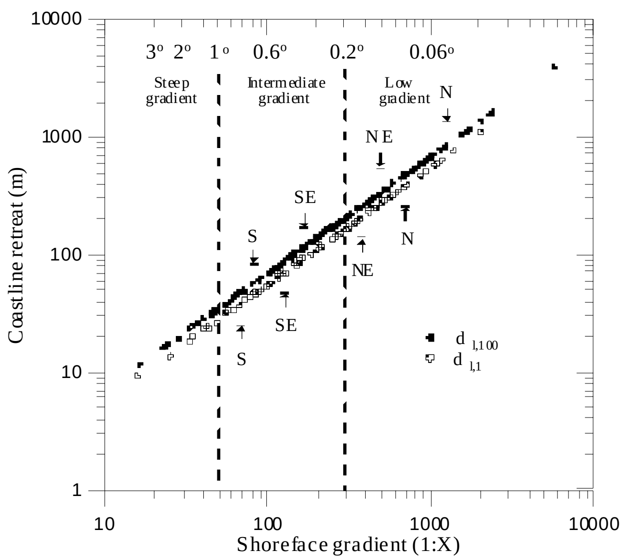

Figure 2. Coastline retreat in response to an elevation of 1 m of relative sea level and a closure depth of the beach profile of 5 m (dl, 1) and 10 m (dl, 100)), (Muehe 2001).

The coastal vulnerability investigations conducted by research groups associated to the Program of Marine Geology and Geophysics (PGGM) (Muehe 2006) indicate that, in general, erosion is more prevalent than accretion, which is restricted to sites with a significant input of fluvial sediments.

Coastal morphology and its response to sea level oscillations

Horizontal adjustments of the coastline are the result of an intricate relationship between the oscillations in the sea level, changes in wave incidence, sediment availability, coastal morphology and rock strength. Accretion of the shoreline may occur locally even during a period of sea level rise, provided there is sufficient sediment supply. Such areas include coastal plains or terraces associated to a fluvial outlet. Nevertheless, large-scale marine transgressions cannot be accompanied by a positive sediment balance and consequently result in coastline erosion. For example, during the last marine transgression, the coastline receded tens of kilometers over the course of about 10,000 years.

The relative sea level elevations of the Brazilian coast 120,000 years BP and 5,600 years BP were on the order of 8 m and 5 m higher than the current level, respectively. During these transgressions, marine sands were deposited in the form of beach barriers and beach ridge coastal plains. The higher sea level, that the present one, of the last transgression resulted, according to Pirazzoli (1996, cited in Bird 2008), from the postglacial isostatic compensation, which was limited, in Brazil, to the coast between Cape Calcanhar and the southern extremity of South America and excluded the Amazonian Coastal Region (Fig. 3).

Curves of relative sea level variation were established by Martin *et al.* (1979, 2003 among others) for Salvador (Fig. 4) and several locations in southern and southeastern Brazil. These curves confirm a sea level elevation of up to 5 m, despite disagreements about the oscillations after the maximum transgression (Angulo & Lessa 1997).

The development of coastal barriers during each of the marine transgressions led to the formation of lagoons at the lee of the barriers and the subsequent formation of coastal plains through sediment infilling of the lagoons. The low altitude and topography of these plains results in difficulty of water discharge, amplified during storms due to the blocking of the channel outlets by waves and tides. Therefore, these plains represent an area with potential risk of flooding due to sea level rise (Fig. 5). The response of a barrier to a sea level rise is to adjust by landward translation, a process that involves wave overwash, the formation of overwash fans and even localized barrier rupture. Overwash does not occur when the barrier was formed during a period of higher sea level or had their height increased by the development of dunes. In any case there will be erosion on the ocean side of the barrier as also at its backside in contact of a lagoon, if present.

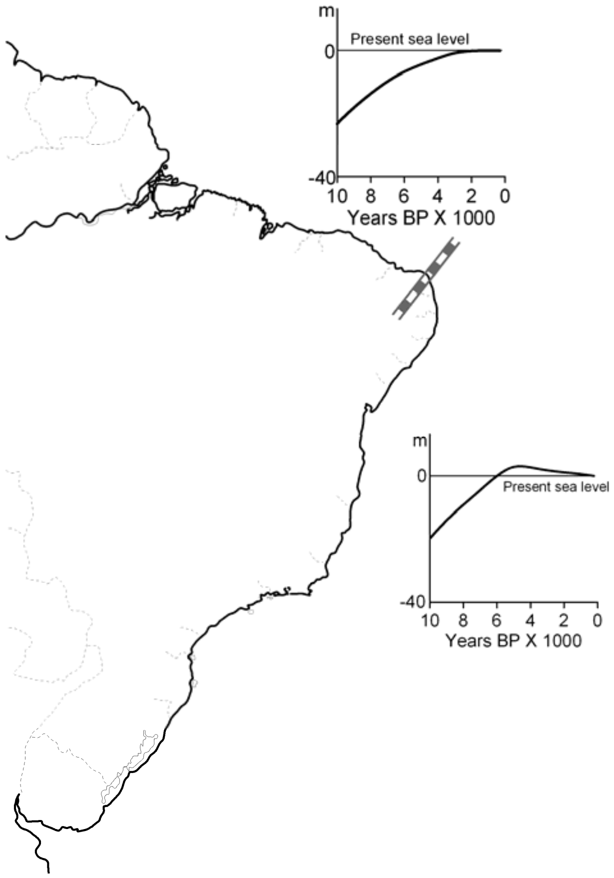

Figure 3. Relative sea level variations during the Holocene. Adapted from Pirazzoli 1996, cited in Bird 2008.

Sediment accumulation may occur in the form of coastal terraces or plains developed through accretion of a succession of beach ridges. This type of accumulation occurred in the delta-shaped plains of the São Francisco, Jequitinhonha, Doce and Paraíba do Sul Rivers (Fig. 6), which were studied in detail by Dominguez *et al.* (1983, 1987, 1989), and Martin *et al.* (1984). Reversals of the longshore sediment transport direction is revealed by the changing alignment of beach ridges as a consequence of

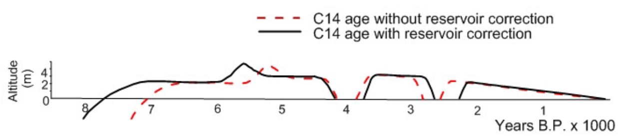

Figure 4. Relative sea level curve for Salvador (adapted from Martin, 2003).

Figure 5. Highly developed double coastal barriers and enclosed lagoons in Barra da Tijuca, Rio de Janeiro. Photo D. Muehe.

Figure 6. Beach ridges of the Doce River coastal plain. Image from Google Earth.

changes in the wave incidence in response to climate changes, and those changes are reflected in adjustments of the shoreline through the process of beach rotation.

In areas of high relief, as represented by the sedimentary deposits of the Barreiras Group and other morphologically similar areas which occur discontinuously from the coast of Amapá up to Rio de Janeiro, the result of transgressions were the formation of coastal cliffs, in some places still active, preceded by narrow beaches and a nearshore and inner shelf of low gradient (Fig. 7). A rising sea level will increase the erosion of the cliffs, a slow process whose speed depends on the cohesion of the material and the amount of sediment released and maintained in the profile. Many of the cliffs that are still active probably represent an incomplete adjustment related to the post-glacial transgression rather than the result of a recent rise in sea level.

The erosion of sedimentary cliffs left vestiges of their past position in the form of lateritic concretions deposited on the continental shelf, and the released sediments represented an important source of sand for the formation of beaches, dunes and coastal terraces.

Figure 7. Active cliffs in sedimentary deposits of the Barreiras Group. Buzios, Rio Grande do Norte. Photo D. Muehe.

Coastal Compartments and Associated Vulnerabilities

Physiographic coastline classifications, for the Brazilian coastline, have been proposed by several authors. The most largely known was proposed by Silveira (1964) who considered geological, geomorphological, climatic and oceano-graphic aspects. More recent studies (Muehe 1998, 2005, 2006, Muehe & Neves 1995, Dominguez 2004, 2007) are in many aspects coincident with the classification scheme of Silveira but are differentiated by their objectives and level of detail.

The following classification (Fig. 8) is based on the literature mentioned above, with emphasis placed on the prevailing geomorphological aspects and potential vulnerabilities associated with climate change and its consequences (*e.g.*, sea level rise and flooding):

Figure 8. Coastal compartments.

The tide and mangrove dominated coast of the North region

With a wide continental shelf, highly influenced by the water discharge and mud deposition of the Amazon, the coastal zone is submitted to a macro tidal regimen with tidal ranges of locally up to 10 m associated to strong tidal currents.

Mangroves occur widely and correspond about 76% of this formation of the whole Brazilian coastline (Muehe, 1998). They represent an important ecosystem for the maintenance of fishery as also for the protection of the coast. A rise in sea level may be compensated by a backward and lateral expansion of the mangroves, but this expansion is frequently limited by the presence of cliffs along the open coast and estuaries. Depending of the rate of sea level rise the adaption may not be sustained under rates higher that 7 mm a^{-1} as reported by Reed *et al.* (2008) for the Mid-Atlantic coast of the USA.

Coastal erosion has been reported by El Robrini *et al.* (2006) in Mosqueiro in the estuarine coast to the north of Belém and along the Atlantic Coast in the region of Salinópolis, one of the principal resorts of the coast of Pará, and near Ajuruteua, whose beaches are in high demand on weekends and holidays.

According to data from the Brazilian Institute of Geography and Statistics (IBGE) interpreted by Strohaecker (2008), the population on the coast is relatively high in relation to the population of the state (89% in Amapá, 45% in Pará and 27% in Maranhão). However, this population is mainly concentrated in metropolitan areas, while the rest of the coast is almost empty. Over 80% of the coastal municipalities of Amapá and Pará have population densities of less than 50 inhabitants/km^2. Therefore, many erosion or flood events would only have localized socio-economic impacts.

According to a study by Tessler (2008), the flood risk varies from very high to high in the region around Macapá and in the northeast area of Marajó Island and from high to medium in the city of Belém and the coast of Bragança in Pará. The risk is high along the estuary on the island of São Luiz in Maranhão and medium to high in the Parnaíba Delta.

The Sediment Starved Coast of the Northeast

The coast is characterized by the dominance of sedimentary cliffs of the flat topped Barreiras group and can be sub-divided according the degree of water deficit into a semi-arid compartment in the north, including the States of Piauí, Ceará and the West Coast of Rio Grande do Norte and a more humid compartment in the south extending from the South Coast of Rio Grande do Norte to Salvador in Bahia.

Large dune fields occur widely and represent a sink of the sands which otherwise would lead to a progradation of the coastline. An increase in temperature or decrease in precipitation will amplify the eolian sediment transport and increase the vulnerability of the coastline due to the augmented transfer of sediments from the shore to the continent.

Beach rocks occur widely at some distance from the beach and acts like breakwaters, providing some protection against the waves but also avoiding sediments to be carried to the beach, increasing the vulnerability to erosion. The overtopping of these barriers under a higher sea level will increase the wave activity at the beach which will have to adjust morphodynamically to the new level of energy.

In the semi-arid sector the most impacted segments by erosion are in Ceará, to the north of the port of Pecém, and in Fortaleza. In Pecém because of the deposition of sediments at the lee of the port structure, and in Fortaleza because of the retention and diversion of the flow of sediment to the beaches of the city after the construction of a breakwater in order to protect the Port of Mucuripe (Morais *et al.* 2006). In Macau and Guamaré in Rio Grande do Norte, the recession of the coastline is endangering oil pumping stations (Vital *et al.* 2006). According to these authors the construction of structures perpendicular to the beach in Macau, Caiçara do Norte and Touros accelerates the erosion. Segments under erosion of the sedimentary cliffs of the Barreiras Formation are associated to a slow retreat of the cliffs and represent a risk for constructions when located too close to the edge of the cliff. Occasional swell from the Northern Hemisphere reach the coast of Ceará in the summer months triggering erosion (Melo Fo & Alves, 1993, Melo Fo *et al.* 1995). The frequency of these events may increase as a result of climate change, and will contribute to the general trend of coastline destabilization.

The population in the states of Ceará and Rio Grande do Norte is concentrated along the coast and represents almost 50% of the population of these states, with densities ranging from 50 to 200 inhabitants/km^2 (Strohaecker 2008). However, almost 40% of this population is concentrated in coastal metropolitan areas, therefore only 10% is distributed in the rest of the coastal municipalities.

According to Tessler (2008), the areas with the greatest risk of flooding are located in the Parnaiba metropolitan area in the State of Piaui, in the metropolitan region of Fortaleza in Ceará, and along the margins of the Apodi and do Carmo Rivers, between the localities of Areia Branca and Mossoró in Rio Grande do Norte.

On the coast of the sedimentary cliffs, the erosion is widespread and occurs almost along the whole coastline from the south of Rio Grande do Norte along the coast of Paraíba, Pernambuco and Alagoas. The opposite is true on the coast of Sergipe, where the abundant amount of sediment delivered by the rivers causes about 57% of the shoreline to be in equilibrium, while 21% is under erosion (Bittencourt *et al.* 2006).

In Paraíba State, the segments under erosion represents about 42% of the 140 km of beaches (Neves *et al.* 2006).

In Pernambuco, about 30% of the beaches are under erosion. The majority are experiencing severe erosion due to natural factors, such as coastal circulation and sediment deficit, while man-made interventions often intensifies this trend (Neves & Muehe, 1995; Manso *et al.* 2006). The occurrence of beach rocks and algae in the shoreface and innershelf increase the sediment deficit by preventing their transport in direction to the shore. Because of the proximity of buildings, the most critical areas are the beaches of Boa Viagem, Piedade, Candeias and Barra das Jangadas in Recife.

In Alagoas, the vulnerability to erosion is caused by the reduced delivery of fluvial sediments. Erosion is concentrated primarily on the northern coast of the state, where tourist activity is concen-trated (Araújo *et al.* 2006). According to Dominguez (1995), the susceptibility of the coast to erosion is demonstrated by active cliffs of the Barreiras group, the almost absence of coastal plains and Pleistocene terraces as also the occurrence of submerged beach rocks attesting the retreat of the coastline.

In Sergipe segments under erosion are located in Atalaia Nova, north of Aracaju, and to the south of the São Francisco River outlet, where the Vila do Cabeço was completely eroded. Areas of high shoreline variability are located near the outlets of the Real, Vaza Barris and Sergipe Rivers, where erosive episodes have caused significant material damage (Bittencourt *et al.* 2006).

In Bahia, the coast between Mangue Seco, at the outlet of the São Francisco River and Salvador, is in equilibrium (Dominguez *et al.* 2006).

According to Strohaecker (2008) based on IBGE data, the general trend of the State population is to concentrate in coastal municipalities. Around 40% to 50% in Rio Grande do Norte, Pernambuco and Alagoas, 30% to 40% in Sergipe and Bahia and 20 to 30% in Paraíba. The majority lives in metropolitan areas with only 10 % distributed along the remaining coastal municipalities.

The areas under greatest risk to flooding (Tessler 2008) are located in low-laying areas of João Pessoa and Recife, in the urban area of Aracaju, in the coastal plain north of the Vaza Barris River and in the low-lying areas of Salvador.

The Mixed Coast of Sedimentary Cliffs and Wave Dominated Deltas

The presence of the sedimentary cliffs of the Barreiras Group is still dominant but less continuous in the south. Beach ridge plains developed in front of the Jequitinhonha and Caravela Rivers, in Bahia, Doce River in Espirito Santo and Paraíba do Sul River in Rio de Janeiro State (Fig. 6). The changes in the alignment of the beach ridges associated to modifications in the longshore sediment transport indicate the occurrence of alternations in the dominium between waves generated by the trade winds and swell waves generated by cold fronts from the south. Therefore the compartment is located in a region highly susceptible to modifications in the dominium between tropical and subtropical climatic-oceanographic processes.

In Bahia, about 60% of the coast is in equilibrium, and 26% is under erosion, with intense erosion occurring in fluvial outlets. Sediment retention occur in Ilhéus and in unconsolidated capes such as the coastal plain of Caravelas. Long stretches of the cliffs in south Bahia, from Cumuruxatiba to the border of Espírito Santo State, are experiencing long-term negative sediment budget (Dominguez *et al.* 2006). Strong coastal erosion with destruction of houses occurs in Mucuri, in south Bahia near the border with Espírito Santo.

In Espírito Santo the coastline alternates between long stretches under erosion or in equilibrium with few segments of accretion. Accretion is occurring in the coastal plains of Doce River, in the north, and Itabapoana River, at the southern border between the States of Espírito Santo and Rio de Janeiro (Albino *et al.* 2006).

On the coast of Rio de Janeiro near the border between Espírito Santo and Cape Frio, significant erosion is occurring on the south margin at the outlet of the Paraiba do Sul River in Atafona where the sands are being trapped on the inner continental shelf by mud brought by the river and by the predominance of longitudinal transport of sediments towards the south, out of the affected area (Muehe *et al.* 2006). Other areas at risk of erosion in highly urbanized areas include the coast of Macaé and Rio das Ostras (Muehe *et al.* 2006).

The population density of this compartment is low except along the northern coast of Rio de Janeiro, where oil exploration on the continental shelf led to migration to the cities of Macaé and Campos. Other cities with strong growth due to tourism are Armação dos Búzios, Rio das Ostras and Cabo Frio (Strohaecker 2008).

According to Tessler (2008), the critical areas at risk of flooding are the cities of Valença and Ilheus in Bahia, São Mateus and Vitória in Espírito Santo and Campos dos Goytacazes, Macaé and Cabo Frio in Rio de Janeiro.

The Double Barrier-Lagoon Coast

This compartment due to its almost east-west alignment of the coastline is highly exposed to storm waves from the south. The longshore sediment transport tends to be in equilibrium along a year, with the less frequent high energy waves (swell) from south and southwest being compensated by the more frequent waves from the southeast. Seasonally this equilibrium is frequently disrupted by the predominance of one of these wave incidences resulting in short term beach rotation with erosion at one of the beach extremities and accumulation at the other as in the Ipanema-Leblon Beach in the Metropolitan area of Rio de Janeiro.

From Cape Frio to the Marambaia Island, the coastline of this compartment shows signs of instability, with wave overwash and backshore scarp retreat (Muehe *et al.* 2006). Backshore retreat on the order of 10 to 15 m were recorded in several places and resulted largely from an exceptional storm that occurred in May 2001. This storm destroyed houses, kiosks and streets, mainly in the municipalities of Maricá and Saquarema. Erosion also occurs at the lagoon side of the more landward located Pleistocene barrier in contact with the Araruama lagoon, a long lasting geomorphological process that has gradually reduced the width of this barrier associated to an increase in the width of the lagoon.

The extreme west of the compartment is characterized be a long and narrow barrier separating the large Sepetiba Bay from the ocean. Localized overwash and gradual erosion of the lagoon shore of the barrier may result in temporary disruption of the barrier during exceptional storms and sea level rise. This disruption, in turn, will lead to the propagation of waves into the bay, with possible effects on the port of Sepetiba.

The occupation of the coastal barriers are concentrated in the towns of Maricá, Saquarema, Figueira and Monte Alto and in the metropolitan area of Rio de Janeiro. The expansion of the urbanization in these areas is moving very close to the beach, increasing their vulnerability to erosion.

In the metropolitan area of Rio de Janeiro, which includes the coast of Niterói, the increased population density makes the oceanic and estuarine coast more vulnerable against erosion, flooding and landslides. The expansion of urbanization over low lying areas of previously existing lagoons (*e.g.*, Barra da Tijuca) with limited drainage capacity represents risks that will significantly increase under a raised sea level and increased storm activity (Muehe & Neves 2008). Other critical areas identified in the municipality of Rio de Janeiro are located next to the Meriti and Pavuna Rivers and in the Sepetiba Bay.

The Rocky Coast of the Southeast

This compartment, which extends from Ilha Grande Bay in Rio de Janeiro to the Cape Santa Marta in Santa Catarina is characterized by the proximity of the Serra do Mar mountain range which extends up to the coastline between Ilha Grande Bay in Rio de Janeiro and São Vicente in São Paulo resulting in a drowned landscape with a sequence of high cliffs of Precambrian rocks and small coves. Coastal plains are small and sometimes absent. From São Vicente to the North of Santa Catarina, therefore including the coast of Paraná, the coastline is formed by long beaches and wide coastal plains with important estuaries as in Santos and Cananéia in São

Paulo, Paranaguá and Guaratuba in Paraná and São Francisco do Sul in Santa Catarina. From the north of Santa Catarina to the south of Santa Catarina Island the coastline becomes irregular with outcrops of the crystalline basement and small coastal plains. Southward of Santa Catarina Island and cape Santa Marta, in Santa Catarina, the coastline is formed by a sequence of beaches limited by rocky promontories with wide coastal plains and lagoons.

Longshore sediment transport tends to be directed to the north. The occurrence of extra-tropical cyclones with strong winds, heavy rain and high waves has been a main threat and seems to increase in frequency. Associated to an increase in temperature of the ocean water their occurrence will increase and may also affect the coastline up to Rio de Janeiro.

Modifications of the coastline due to erosion are, in São Paulo, usually isolated and associated with natural or artificial obstacles that interrupt the flow of sediments (Tessler *et al.* 2006).

In Paraná, the most significant modifycations of the coastline occur on the estuarine outlets (*e.g.*, the Superagui channel, Peças island, Mel island, Pontal do Sul, Ponta de Caiobá and Guaratuba). These modifications include both retreat and advance of the shoreline and occurred on the order of hundreds of meters in less than a decade (Angulo *et al.* 2006). The ocean coastline is presently stable. Areas most impacted by erosion are the beach resorts of Flamengo and Riviera and the central beach of Matinhos, restored through beach nourishment.

In Santa Catarina, investigations were concentrated on the central north coast (Klein *et al.* 2006) and on the island of Santa Catarina (Horn 2006). On the continental coast, the risks associated with coastal erosion result from inappropriate land use and frequent storms. The most critical points are located in Barra Velha, Piçarras and Penha. These areas are experiencing medium-intensity erosion, and Bombinhas is experiencing low-intensity erosion. On the island of Santa Catarina, erosion is occurring throughout the ocean coast. The greatest risk is to the urban areas on the north coast of the island (*e.g.*, beaches of Canasvieiras, Cachoeira and the Ingleses) and on the northwest coast in the Barra da Lagoa. Urbanized areas on the east and south coast with medium to high risk of erosion include Campeche, Armação and Pântano do Sul (Horn 2006).

Areas with the greatest risk of flooding are identified by Tessler (2008) and include the estuarine region of São Vicente and Santos in São Paulo, Paranaguá at the Bay of Paranaguá in Paraná, and in Santa Catarina at the southern shore of the Babitonga bay, at the estuary of the Itajaí-Açu River and at the localities of Palhoça and São José on the west shore of the South Bay and Florianópolis at the margins of the North and South Bay.

Strohaecker (2008) call attention to the high rate of population growth in the urban areas extending hundreds of kilometers along the coastline.

The Sandy Coast of Multiple Barriers of Rio Grande do Sul

From cape Santa Marta to Chui, at the border between Brazil and Uruguay, the coastline is formed by a long, wide, fine grained and monotonous beach in front of a multiple barrier-lagoon system, with the widest lagoons represented by the Patos and Mirim Lagoons. Active dune fields develop on top of the coastal barriers with dominant sand transport to southwest. Storm surges are frequently submitting the shoreline to a harsh wave climate.

The beach shows a high morphodynamic mobility alternating between long stretches of retreat and advance (Toldo *et al.* 2006) and reversal of this trend over time (Esteves 2008). This mobility has been in most cases limited to the beach without a definite retreat of the backshore. Very localized segments of coastal erosion were described by Calliari *et al.* (1998) and Speranski & Calliari (2006) and were related to wave convergence in Mostardas, to the south of the Mostardas lighthouse, between Bojurú and Estreito and at a small segment near Cassino and in the far south near Chuí.

The distribution of population along the coast is low and mostly concentrated in urban centers of second homes that attract nearly 100,000 visitors during the summer. The main urban center is located at the estuary near the mouth of the Lagoa dos Patos in Rio Grande. With about 200,000 inhabitants the city is located in low laying areas of the coastal plain and present the highest risk of flooding of the entire Brazilian coast (Tessler 2008). The port of Rio Grande is one of the most important in the country because its depth, its favorable location in relation to MERCOSUL countries and the presence of important industrial and petrochemical complexes.

Final Considerations

The Brazilian shoreline is experiencing erosion along the entire coast, but the erosion is irregularly distributed and often associated with river outlets. Large segments of the coast are formed by sedimentary cliffs in areas of low occupation where erosion is slow. On beaches the erosion becomes a risk when buildings are constructed to close to the shore. Numerous low-lying coastal plains formed by the sedimentary fill of old lagoons and estuaries are very susceptible to the effects of flooding and represent a risk to urban areas.

The already detected areas under risk will be magnified by rising sea levels and the increase in frequency and intensity of storms associated with an elevation in ocean temperature. These risks will be most significant in urban areas and especially in large coastal cities. In general flooding presents a greater risk than coastal erosion. Areas susceptible to flooding already have drainage problems, which will become more critical with a rise in sea level which in turn leads to groundwater contamination and the spread of diseases both through water as also due to the proliferation of mosquitoes and other transmittting agents. The implementation of appropriate actions by the various levels of government are difficult to make because of the uncertainty of the timing and magnitude of climate changes, the lack of observations of long-term temporal oceanographic variables and the absence of a well established observational network, the absence of detailed altimetric surveys required to model and identify the areas at greatest risk as also the small time window of the administrative mandate of each government in relation to the time required for the climate change to become effective. Nevertheless, the potential risk of erosion and flooding that will result from the expected climate change is significant. However, the situation in Brazil is less critical than in many countries in terms of the magnitude of potential impacts to the population due to the reduced occupation of large parts of the coastal area. Nevertheless, the establishment of integrated networks of continuous monitoring of oceanographic and climatic variables as also of the geomorphologic changes in response to coastal processes is crucial in order to build up convincing evidence of the direction and intensity of climatic-oceanographic changes which will give the justifycation to formulate appropriate actions for coastal management at the different levels of government.

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