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Long- and Short-Term Coastal Erosion in Southern Brazil

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ABSTRACT

Rio Grande do Sul is the southernmost state in Brazil. Open sandy beaches dominate the 630-km long shoreline that is 76% still undeveloped. Less than 5% of the state's population (totalling 9.7 million people) live in coastal cities. However, the coastal population is growing faster than the state's average since 1990. Although intense erosion is widely accepted along the beaches of Conceição lighthouse and Hermenegildo, the extent of erosion along the Rio Grande do Sul shoreline is still a controversial issue. Discussions arise from the contrasting results presented by studies addressing coastal erosion in Rio Grande do Sul. Recent DGPS monitoring indicates that about 80% of the Rio Grande do Sul shoreline is eroding; wave refraction studies indicate that it is mainly stable, and long-term coastal evolution modelling reveals a predominantly prograding shore for the last 5 ka. This work critically evaluates published data on long- and short-term causes of coastal erosion in Rio Grande do Sul, in an attempt to highlight the unanswered questions that could minimize the debate. The analysis includes sea-level rise, concentration of wave energy due to large-scale coastal topography, sand deficit as the long-term causes of erosion, storm surges, concentration of wave energy due to small-scale submerged features, interference in the longshore sediment transport, and human activities as the short-term causes. Discrepancies in shoreline change results are a matter of the temporal scale in question and what are the causes that play a significant role in it. For coastal management purposes short-time events represent a far greater hazard than long-term trends. It is therefore reasonable to state that in order to support decision-making mechanisms in Rio Grande do Sul a better understanding of the relationship of storms, sand budget, and beach erosion is necessary.

ADDITIONALINDEXWORDS: *Shoreline change, beach erosion, coastal evolution, Rio Grande do Sul.*

INTRODUCTION

Rio Grande do Sul is the southernmost state in Brazil (Figure 1) and its 630-km long shoreline is one of the least-developed in the country. In 1999, about 430,000 people were living in coastal cities, representing 4.4% of the state's population (9.9 million). However, the coastal population has grown about 1.5% per year since 1991 with six of the ten cities that had the greatest population growth in the last decade situated on the coast. Thus, a new trend of coastal occupation is evident and undeveloped areas will probably give way to new settlements in the near future. To avoid unplanned development along hazardous coastal segments, it is necessary to identify such areas and to understand the effects and interactions of coastal processes in different time scales, particularly those related to shoreline changes.

As the Rio Grande do Sul shoreline is mainly undeveloped (except for the northern sector) and beaches are used only in the summer months when calm weather prevails, coastal studies have not attracted the attention of community, government, or indeed researchers until recently. Only in the late 1980s, did published works started to focus on coastal processes, including those addressing beach erosion in Rio Grande do Sul (VILLWOCK and TOMAZELLI, 1989; TOMAZELLI, 1990), before that articles on coastal studies were mainly descriptive. Since then, several studies have addressed coastal erosion in Rio Grande do Sul indicating natural and human-induced contributing factors in the long-term (i.e. TOMAZELLI *et al*., 1998; TOMAZELLI and DILLENBURG, 1998; DILLENBURG *et al*., 2000) and the short-term (i.e. CALLIARI *et al*., 1998a,b; ESTEVES *et al*., 2000a; TOLDO *et al*., 1999). The increasing interest in coastal processes and shoreline changes reflects the intensification of coastal occupation and beach use, as well as the growing economic importance of beach-related tourism. Although knowledge about coastal processes in southern Brazil is improving, it is still incipient, and many unsolved issues need to be addressed. At present, there is an ongoing discussion on whether the Rio Grande do Sul shore is mainly eroding, prograding or if it is stable.

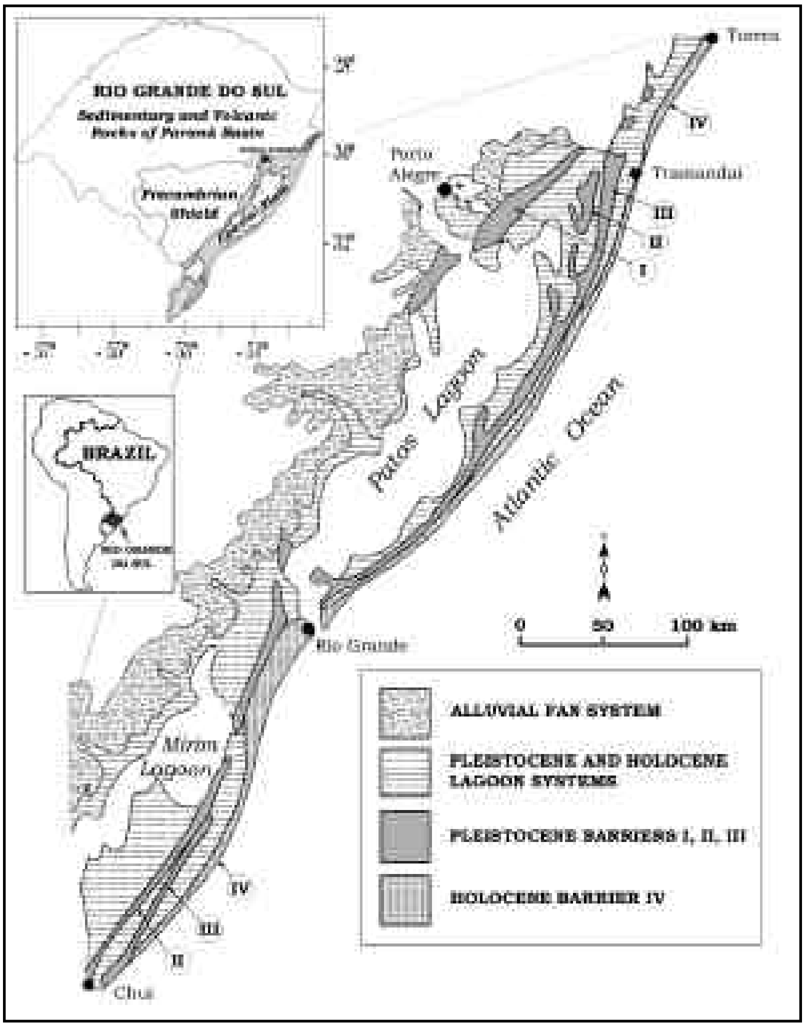

Figure 1. Location and simplified geologic map of Rio Grande do Sul coastal plain (modified from TOMAZELLI *at al*., 2000).

This paper compiles available shoreline change data at different time scales, critically analysing them to help determine which logical step should be taken in the study of coastal changes in the state. Additionally, present shoreline monitoring results are discussed in an attempt to establish the present extension of beach erosion or at least identify shoreline change trends in Rio Grande do Sul.

STUDYAREA

The Rio Grande do Sul shore is part of a large coastal plain that extends between the granitic headlands of Cabo Polonio (Uruguay) in the south and Cape Santa Marta in the north. It is remarkable the presence of a well developed lagoon system formed by two large ones (Mirim in the south and Patos in the middle coastal sector) and several small others in the northern littoral. The Rio Grande do Sul shoreline is 630-km long mainly consisting of exposed fine sandy beaches that have a NE-SW general orientation. It is one of the longest sandy beach coastlines in the world, made up of only two permanent discontinuities (Tramandaí and Patos lagoon inlets). Innumerous permanent and temporary washouts discharge water accumulated behind the dunes, influencing the local sand balance.

Waves are the main hydrodynamic process along the Rio Grande do Sul coast, as the maximum tidal variation is less than 0.5 m (TOMAZELLI *et al*., 1998). Winds from NE prevail and are mainly active during summer and spring, southerly winds are the strongest and more frequent during winter and fall. As southerly waves have higher energy, the net longshore sediment transport is to the north. Mean significant wave height is 1.5 m and mean period is 9 s. Storms associated to the passage of cold fronts frequently strike the coast in fall and winter months, mainly April and July (CALLIARI *et al*., 1998b).

Generally, the Rio Grande do Sul coast can be subdivided into three sectors: (1) the northern sector comprised of 136 km of developed beaches extending from Torres (at the state border) to Dunas Altas in the south; (2) the central sector, 266-km long and includes the undeveloped beaches from Dunas Altas to the Patos Lagoon inlet, and (3) the southern sector made up of the shoreline from the Patos Lagoon inlet to the Chuí creek (at the border with Uruguay), a 225-km long shoreline with only 7.6 km of urbanized beaches (ESTEVES *et al*., 2000b).

Well-sorted fine quartz sands dominate in the Rio Grande do Sul beaches (MARTINS, 1967), except in three areas: (1) south of the Conceição Lighthouse (central sector), where mean sizes are coarser and less sorted due to the presence of shell fragments; (2) in Cassino Beach, fine sediments from the Patos Lagoon cause a slightly decrease in the mean size, and (3) between Albardão lighthouse and Hermenegildo (southern sector) there is a 30-km long segment (Concheiros do Albardão) that presents bimodal sediments composed by quartzose fine sands and bioclastic gravel (SIEGLE, 1996; CALLIARI and KLEIN, 1993). Morphodynamically, beaches vary from intermediate to dissipative stages, except along Concheiros do Albardão which was classified as reflective to intermediate according to CALLIARI and KLEIN (1993).

QUATERNARY COASTAL EVOLUTION

The geologic evolution of the Rio Grande do Sul coastal plain was described by VILLWOCK *et al.* (1986) and detailed in several following studies (i.e. VILLWOCK and TOMAZELLI, 1989, 1998; TOMAZELLI *et al*., 2000). As the Quaternary coastal evolution was a key factor for the present shoreline configuration, this section summarizes the main findings of those studies.

The coastal plain comprises two major depositional systems formed by sea-level fluctuations in the Quaternary: the alluvial fan deposits that mark the western limit of the coastal plain and the barrier-lagoon systems developed seawards (TOMAZELLI *et al.*, 2000). The alluvial fan system consists of coarse-grained clastic deposits (gravel, sand, and mud) originated from gravity flows and accumulated at the base of highlands (sedimentary and volcanic rocks of the Paraná Basin to the north and the igneous and metamorphic rocks of the Precambrian shield in the south). Formation of these deposits probably date from the late Pliocene regression to the Holocene and was controlled by climate changes. Arid periods might have intensified the formation of gravity flows, while water flows during the humid phases reworked the conical shape of individual fans into a continuous apron gently dipping seaward. Deposits at the edge of coalescent fans were eroded by higher sea levels in the Pleistocene resulting in marine and lagoon terraces that are particularly well developed and preserved to the south.

Four barrier-lagoon depositional systems were identified in the Rio Grande do Sul coastal plain, each representing the sedimentary record of a marine transgression, three during the Pleistocene and one in the Holocene. Each barrier represents the landward limit of the respective maximum transgressive event (VILLWOCK and TOMAZELLI, 1998; TOMAZELLI *et al.*, 2000). VILLWOCK *et al.* (1986) named the four barrier-lagoon systems as Barrier I (the oldest) to IV (the youngest). Absolute ages of the pleistocenic barriers are still unknown (TOMAZELLI *et al.*, 2000). An attempt to correlate the last major peaks of the oxygen isotopic record and barrier formation indicates that they were probably formed in the last 400 ka (TOMAZELLI *et al*., 2000). Barrier I, II, and III correlate with oxygen isotopic stage 11 (about 400 ka), stage 9 (325 ka), and sub-stage 5e (approximately 125 ka), respectively. Barrier IV was formed in the Holocene and corresponds to oxygen isotopic stage 1. About 18 ka ago, sea level was near the present shelf break and rose steadily up to 2-4 m above the present level at the maximum of the last transgression (about 5 ka BP). The following regression favoured the progradation of Barrier IV through the formation of beach/foredune ridges that were mainly developed in the smooth embayments in between Torres and Tramandaí and in Rio Grande (TOMAZELLI and DILLENBURG, 1998). The onshore sand transfer from the shelf was the main source for barrier progradation, as fluvial sands were retained in the lagoon system.

Figure 1 shows the location of the preserved barrier deposits. Barrier I is preserved in the northwestern part of the coastal plain as a 150 km-long and 10-km wide strip of aeolian sands at the top of basement highs. Barrier II is better preserved to the south, where it was responsible for the initial formation of the Mirim lagoon. Barrier III is preserved along most of the coastal plain extension and is formed by beach deposits covered by aeolian sands, demonstrating its regressive nature. Its beach deposits are rich in Callichirus sp. burrows, indicating an ancient high sea level at 6-8 m above the present. The Pleistocene lagoon systems (I, II, and III) developed in between the respective barrier (I, II, or III) and mainland (the previous barrier or the alluvial fan deposits). Barrier IV consists in the present shore deposits. The large lagoon system was developed in between Barrier IV and Barrier III at the maximum Holocene transgressive event. However, the last marine regression favoured the infilling of some lagoons that have evolved into lakes, swamps and floodplains.

EVIDENCE OF BEACH EROSION

The extent of erosion along Rio Grande do Sul beaches is a controversial issue. Some studies suggest that most of the coast is stable (i.e. CALLIARI *et al.*, 2000) and others indicate that it is mainly eroding (i.e. TOMAZELLI *et al*., 1998; TOLDO *et al*., 1999; ESTEVES *et al*., 2001). However, intense erosion is widely accepted at the localities of Conceição lighthouse and Hermenegildo beach (CALLIARI *et al*., 1998a, 2000; TOMAZELLI *et al*., 1998).

Back-barrier lagoonal deposits and peat have been exposed at the beach along (a) the northern developed coastal sector in Jardim do Éden, (b) for more than 60 km continuously along the undeveloped shorelines of the central sector (in front and adjacent to Conceição lighthouse), and (c) in Hermenegildo beach in the southern sector (TOMAZELLI *et al*., 1998). These lagoonal deposits show radiocarbon ages of 5.76 ka in Jardim do Éden (DILLENBURG, 1994), 3.49 ka close to Conceição lighthouse (DILLENBURG, personal communication), and 4.33 ka in Hermenegildo (TOMAZELLI *et al*., 1998).

Foredune scarps in front of the Conceição lighthouse have retreated in an average rate of 2.5 m/yr in the period 1975-1995 (TOMAZELLI *et al*., 1998). The analysis of beach profiles from 1996 to 1999 shows an average retreat rate of 3.6 m/yr for the same area and 1 m/yr for Lagamarzinho beach, about 70 km north of Conceição lighthouse (BARLETTA and CALLIARI, 2000). This lighthouse actually fell under wave attack during a storm in 1993. Destruction of coastal structures during storms has been a strong source of evidence of erosion in Hermenegildo. Beachfront owners have built seawalls and revetments to protect their properties from wave attacks and storm surges and yet have seen destruction not only of the armouring but also of the houses that were supposedly protected (ESTEVES *et al*., 2000a).

SHORELINE CHANGE MONITORING

Shoreline changes in southern Brazil have been monitored through beach profiles that were obtained in few places, distant from each other, and for a short-time interval. As a result, available data might be useful to show short-term seasonal changes, but a longer-time dataset is needed to reveal long-term trends. Since 1997, the 630-km long Rio Grande do Sul shoreline has been mapped in a yearly basis using the kinematic Global Positioning System (GPS) method (MORTON *et al*., 1991). A GPS is installed in a vehicle moving along the water line in an average velocity of about 50 km/h to register positions every 3 s. The 630 km-long shoreline can be surveyed in a 3-days long field trip and costs less than U$1,000. It is a fast and economic way to monitor the entire state's shoreline. Errors due to the GPS positions are less than 1 m for the method used. Additionally, the spatial and temporal water line oscillations along the smooth slope of the Rio Grande do Sul beaches (1/30 in average) are a major source of error. At present, changes between mapped shorelines can only be interpreted as a result of short-term events. Although the GPS solves the lack of data alongshore, it still does not eliminate the time-scale problems. It is expected that trends in shoreline movements can only be observed after decades of continued monitoring.

Adequate sources from where to obtain ancient shoreline positions in the state (e.g. historic maps, aerial photographs) are scarce and cover mainly urbanized shores (less than 20% of the total shoreline extension). In an attempt to determine longer-term changes, the GPS lines have been compared to a digitized shoreline of 1975 obtained from topographic maps printed in a scale of 1:50,000 (TOLDO *et al*., 1999; ESTEVES *et al*., 2001). Although the scale of the base maps is inadequate to this type of study, it was the best available source for a statewide analysis in a time period of more than a couple of years. A large error range was used to qualitatively classify shore segments in three classes: eroded, stable, and accreted. The comparative analysis of the 1975 digitized shoreline and the 2000 GPS line indicates that approximately 81% of the beaches are eroding, 12% are stable, and the remaining 7% are accreting (ESTEVES *et al*., 2001). Similarly, TOLDO *et al*. (1999) identified erosion along 84% of the shoreline and accretion along about 8% for the 1975-1997 interval. At present, shoreline position in the Rio Grande do Sul coast from different sources (beach profile, aerial photos, GPS lines) and for the available time frames started to be compiled into a database. As more data are obtained, more reliable results are provided. Shoreline change classes according to ESTEVES *et al*. (2001) are presented in Figures 2, 3, and 4.

LONG-TERM CAUSES OF EROSION

Relative Sea-level Rise

Geomorphological, sedimentological, and geochronological available data indicates that a sea-level fall has promoted progradation of the Rio Grande do Sul coast since the maximum of the last post-glacial marine transgression. Sea-level curves established for the Brazilian coast show a marine regression for the last 5 ka (SUGUIO *et al*., 1985; ANGULO and LESSA, 1997). However, according to TOMAZELLI *et al*. (1998), the relative sea-level trend might have reversed at some point when progradation stopped and coastal retreat started. Although there is not enough data to build a consistent Holocene sea-level curve for the Rio Grande do Sul, the authors support their idea making an interesting statement that in this paper will be posed as a question. Where are the barrier deposits that associated with the (lagoon) peat and organic mud layers exposed at the present shoreline? Additionally, they conclude that short-term erosion due to storms is significant but can only result in long-term shoreline retreat if superimposed onto a longer term mechanism, such as a sea-level rise.

The hypothesis of a rising sea level along the Rio Grande do Sul coast would be in agreement with the global trend of an eustatic rise in the order of about 1-2 mm/yr (e.g. DOUGLAS, 1991). Unfortunately, a long-term record of tidal levels along the Rio Grande do Sul coast does not exist. The nearest longer tidal record is from Puerto Quequén (Argentina), from where 64 years (1918-1981) of hourly tidal levels were analysed resulting in an average relative rise of 1.6 ± 0.1 mm/yr (LANFREDI *et al*., 1998). Considering that this coast is part of a passive margin and there are no neotectonic movements, it is likely that the relative sea level is similar to the global trend. In the other hand, three studies show evidence that may conflict with this theory: the possibility of neotectonic activities in the Rio Grande do Sul during the Quaternary (FONSECA *et al.*, 2001), and vermetid tubes ^{14}C dates for nearby states which show a continuous regression for the last 5 ka with no evidence of levels below the present (ANGULO and LESSA, 1997; ANGULO *et al*., 2001).

Concentration of Wave Energy Due To Large-Scale Coastal Topography

Shoreline configuration contributes to variations in the distribution of wave energy along the coast in a macro-scale (TOMAZELLI and DILLENBURG, 1998). Applying a coastal evolution model, DILLENBURG *et al.* (2000) suggested that antecedent topography was a key-factor for the definition of the present Rio Grande do Sul coastal shape that in turn have controlled the type of barrier that was developed. Steeper topography resulted in coastal projections and milder gradients originated embayments. Thus, concentration of wave energy in large protruding shore segments favoured development of retrogradational barriers, while progradational barriers were formed in smooth embayments. This mechanism explains why sedimentary records of progradation are evident only in parts of the coast and not evenly distributed, as it should be if a change in sea level was the only cause of shoreline changes. Classification of long-term shoreline changes based on DILLENBURG *et al.* (2000) is displayed in Figures 2, 3, and 4. Progradational barriers occur along about 40% of the state's coast, receded barriers along 34%, and 26% are classed as stable barriers.

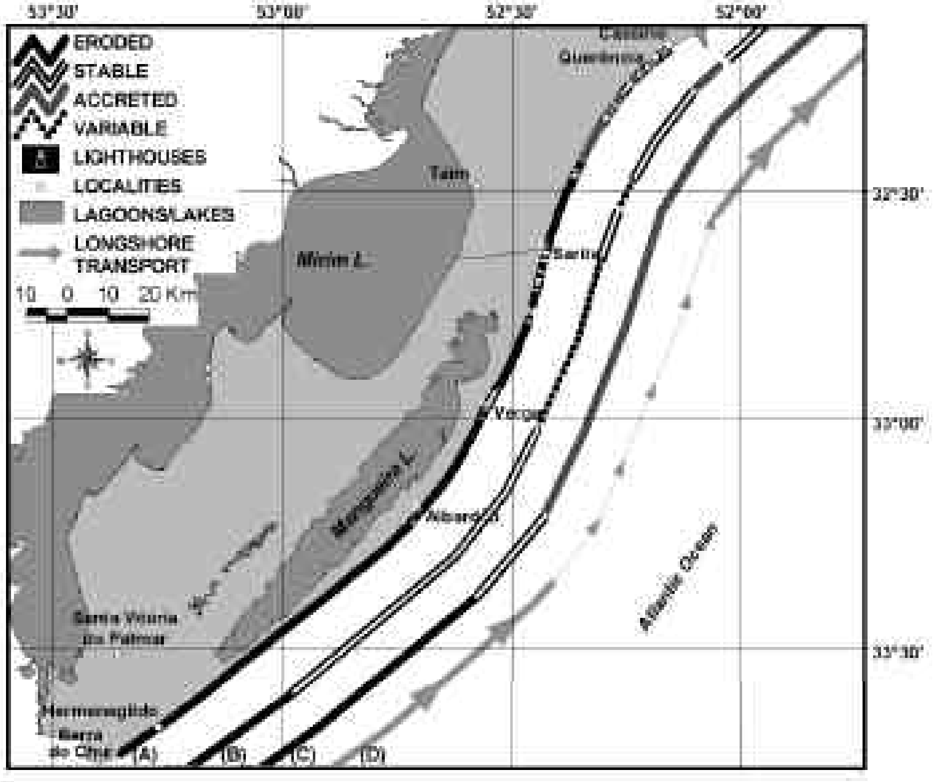

Figure 2. Shoreline changes in the southern RS littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES *et al.*, 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al*., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al*., 2000). Arrows show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDA *et al*., 2001) are indicated by changes in arrows width.

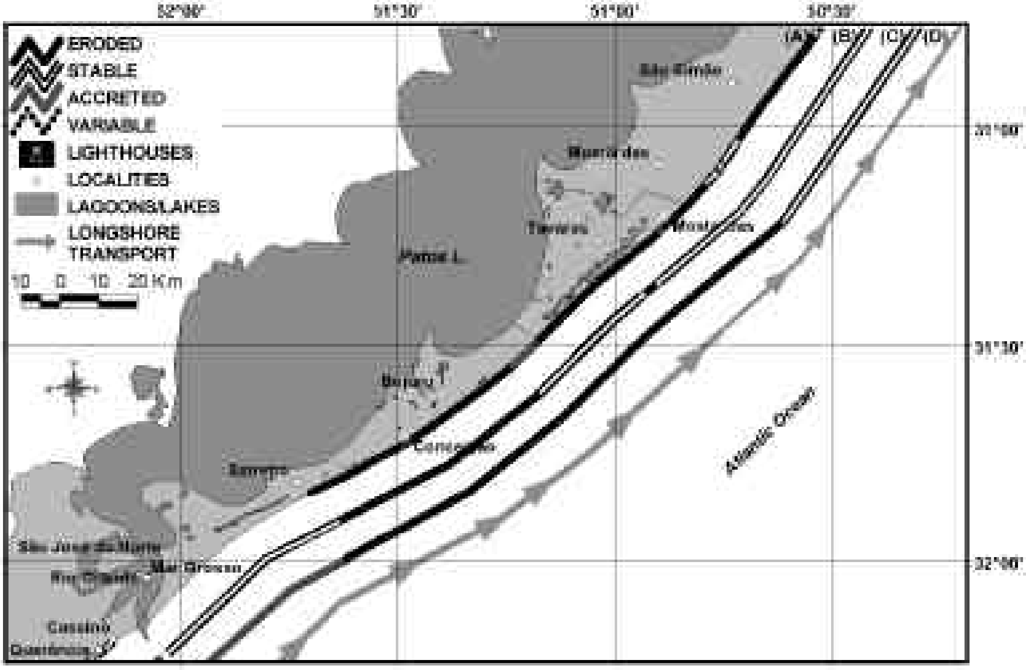

Figure 3. Shoreline changes in the central RS littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES et al., 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI et al., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG et al., 2000). Arrows show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDAet al., 2001) are indicated by changes in arrows width.

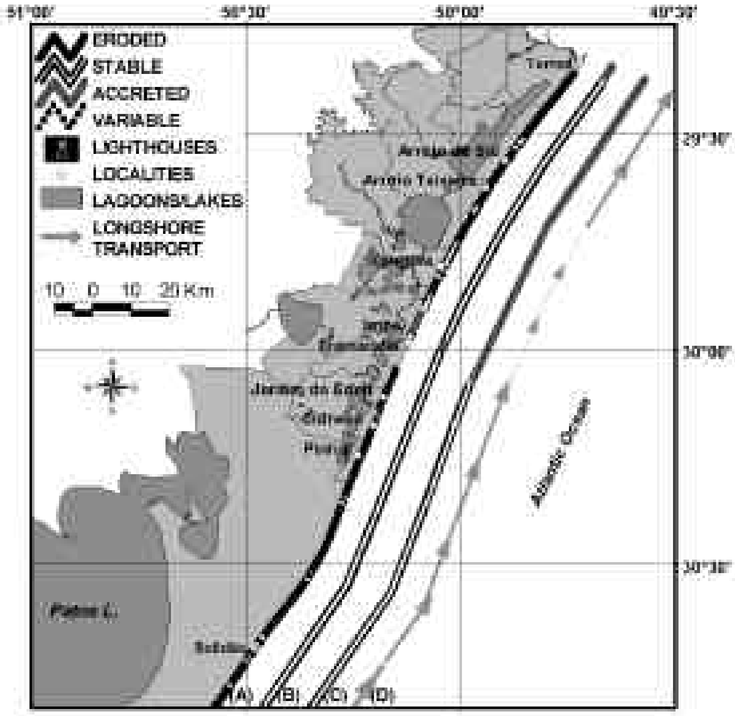

Figure 4. Shoreline changes in the northern Rio Grande do Sul littoral based on: (A) shoreline variations between 1975-2000 (ESTEVES *et al*., 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al*., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al*., 2000). Arrows show direction of littoral drift, and variations of longshore transport rates (as estimated by ALMEIDA *et al*., 2001) are indicated by changes in arrows width.

Sand Deficit

The Rio Grande do Sul coast presents two large lagoons along the central (Patos lagoon) and southern coastal sectors (Mirim lagoon) and several other small lagoons and lakes along the northern littoral. This lagoon system traps sediment from fluvial discharge, reducing the sand volume reaching the shore (TOMAZELLI *et al*., 1998). As such conditions exist since the formation of Barrier IV(last 5 ka), inland sand did not contributed to barrier growth. Two sources provided sand for progradation in the embayments: erosion of existing coastal landforms and onshore transport from the shelf. In the last 5 ka, the sand budget on the Rio Grande do Sul coast has been controlled by alongshore gradients of wave energy resulting from the concentration of wave rays in large-scale coastal projections (DILLENBURG *et al*., 2000). Thus, a link between coastal morphology, wave energy gradients, and imbalances on sand budget is evident.

SHORT-TERM CAUSES OF EROSION

Storm Surges

Storm surges are described as an elevation in tidal level on top of the expected astronomical tide. In southern Brazil, they occur when S-SE winds force water onshore during the passage of intense cold fronts (forming cyclogenesis). Although storm surges are about 1-m high along the Rio Grande do Sul coast, the higher water level intensifies the erosive capacity of storm waves, causing severe damage at the coast mainly when coincident with high spring tides (CALLIARI *et al*., 1998b). This catastrophic combination is more frequent in April and May and is more destructive the longer it lasts (CALLIARI *et al*., 1998b). It is also known that the frequency of storms is a factor that influences beach erosion.

Studies addressing the occurrence and impact of storm surges in Brazil are scarce and limited to the monitoring of individual events. A few examples are the storms of July 14, 1993 and April 19-21, 1995 (CALLIARI *et al*., 1998b), April 3-5 and 24-26, 1997 (BARLETTA *et al*., 1999), and April 16, 1999 (ESTEVES *et al*., 2000a). The 1993 and the 1999 storms were very similar and consisted of extratropical cyclones formed after the passage of a cold front striking the Rio Grande do Sul coast with average wind velocities of about 75 km/h, resulting in a storm surge of 1.3m and 0.8 m (measured at the Rio Grande Port), respectively. Beach profile measurements showed that the 1993 and 1999 storms caused subaerial beach erosion in Hermenegildo of up to 60 m^3/m and 45 m^3/m, respectively. TOZZI and CALLIARI (2000) observed that maximum changes in sand volume occur when the first Fall storms (from March to June) erode the accreted profile built during the Summer months (from December to March). According to Tozzi's results, the storm of April 1999 was a typical example of the high-energy events that threaten Hermenegildo at least once a year. From the data presented in BRITTO and SARAIVA (1999), the number of cold fronts passages along the Rio Grande do Sul coast in the winter months (June to August) from 1988 to 1998 varied from 6 to 14, with a mean of 10 for that period. However, there is still a lack of studies that examine storm distribution and frequency, related storm surges and beach profile responses in a longer term (i.e. do they fully recover?).

Concentration of Wave Energy Due to Submerged Small-Scale Features

Recent studies have shown that convergence of wave rays due to refraction on small-scale changes in bathymetry concentrates wave energy along the coast and is a probable cause of erosion in the areas of Conceição lighthouse and Hermenegildo (CALLIARI *et al*., 1998a, 2000). According to these studies, convergence patterns in those two areas were identified for waves with periods longer than 9 s approaching from SSE-SW while a divergent pattern is observed in the northern shores. SPERANSKI and CALLIARI (2000) suggest that wave 'focus' is the major cause of erosion in the Conceição lighthouse area and in Hermenegildo. However, this mechanism could not explain erosion in Lagamarzinho, where BARLETTA and CALLIARI (2000) have estimated a retreat rate of 1m/yr. This 'unexplained' erosion indicates that other factors are actively contributing to erosion along the Rio Grande do Sul shoreline. Distribution of eroded, stable, and accreted shorelines according to the wave refraction patterns (CALLIARI *et al*., 2000) is presented in Figures 2, 3, and 4. About 75% of the Rio Grande do Sul coast would be stable, 15% under erosion, 2% accreting, and 8% show a variable response to wave refraction.

Longshore Sediment Transport

Sedimentary and geomorphologic evidences indicate that net longshore transport is towards the north (i.e. accretion of beaches south of jetties). However, measures of longshore transport rates are still lacking for the Rio Grande do Sul coast. A recent study applied the Energy Flux Method (USACE, 1984) to estimate the potential littoral drift based on wave measurements in deep water (ALMEIDA *et al*., 2001). Results indicate that that highest rates occur in the areas where intense erosion was observed. While the average rate for other coastal sectors is about 700,000 m^3/yr, they are in the order of 1.8 million m^3/yr from Hermenegildo to Albardão lighthouse and 1.6 million m^3/yr from Cassino Beach to Solidão lighthouse (ALMEIDA *et al*., 2001). Thus, highest longshore transport rates are expected exactly along the most intensely eroded beaches in the state, as can be observed in figures 2 and 3.

According to the results of ALMEIDA *et al*. (2001), it is evident that shoreline orientation has an important role on the littoral drift along the Rio Grande do Sul shoreline, where highest rates occur in the southern half of coastal projections (shoreline orientation close to N45°E). Thus, long-term erosion in coastal projections may have resulted from higher wave energy due to wave focusing and steeper gradients, as pointed by DILLENBURG *et al*. (2000), and also due to appropriate angles of wave attack.

Human Activities

Despite the long and undeveloped coastal segments, almost one-third of the state shorelines have been impacted by human activities, such as urbanisation in active dune areas, shore armouring, sand mining, and construction of jetties (ESTEVES *et al*., 2000b). Anthropogenic changes might be affecting local sand balance in a way that intensifies natural shoreline changes. For example, fixation of the Patos lagoon inlet by two 4-km long jetties resulted in accelerated accretion of the southern beaches due to obstruction of the longshore sediment transport. This coastal sector has shown long-term progradation (DILLENBURG *et al*., 2000). In Hermenegildo, urbanization in the active beach/dune system and coastal armouring appears to have aggravated erosion along a long-term retreating shoreline. Coastal development did not leave much space for natural beach dynamics to take place, which has increased the risk of structural damage during storms (e.g. Cidreira, Pinhal, Hermenegildo). The artificial closure of natural washouts might be another anthropogenic change that interfers with the local sediment balance. In many coastal communities, washouts were artificially closed for road construction and tend to reopen temporarily during high rainfall events. Sand from the dune/beach system has been used for landfill and civil engineering purposes for a long time and, in some places, resulted in the removal of entire dunes. Although the impact of human activities on the sediment balance is still unknown, it seems to play a role largely at a local level, enhancing natural trends rather than reverting them.

DISCUSSION

According to TOMAZELLI *et al*. (1998), TOLDO *et al*. (1999), and ESTEVES *et al*. (2001), the Rio Grande do Sul shoreline is mainly eroding. CALLIARI *et al.* (2000) has stated that most of the Rio Grande do Sul coast is mainly stable and does not show evidence of permanent natural erosion. It is possible that all these studies are correct under certain aspects. Figures 2, 3, and 4 display shoreline changes in the northern, central, and southern coastal sectors, respectively, according to: (A) shoreline variations between 1975-2000 (ESTEVES *et al*., 2001), (B) concentration of wave energy due to short-term storm events (CALLIARI *et al*., 2000), and (C) concentration of wave energy due to large-scale coastal topography (DILLENBURG *et al*., 2000). Additionally, it shows variation in the longshore transport rates estimated by ALMEIDA *et al*. (2001).

Although these studies represent short (A and B) and long-term (C) changes resulting from different variables, all have shown erosion along the shoreline of the Conceição lighthouse (Figure 3) and Hermenegildo (Figure 4). There is also a reasonable agreement about the stable condition of a short segment north of Mostardas (Figure 3). Apart from that, results differ for one or all three studies, as in C the coast is dominantly prograding (40% of the shoreline length), in B is mainly stable (75%), and in A is mostly eroded (80%). These contrasting results can be explained by the difference in time scales and in the variables analysed. Short-time oscillations can be superposed to long-term trends, masking them when only a few years of data are analysed. Thus, shorelinesthat have been prograding for thousands of years may retreat in shorter intervals. In a life-long period, the effects of short-term events are easily observed while long-term trends might not be evident, unless change rates are extremely high. In this time frame, variables with slower reaction times (glacioeustasy, tectonoeustay, geoidal variations, isostasy) are not significant, leaving mainly hydrodynamic changes to be considered (FAIRBRIDGE, 1989). In the other hand, for longer-time intervals (e.g. 500 years), glacioeustasy and steric effects can cause a fluctuation of up to 30 cm in the sea level, besides the effects of isostasy (FAIRBRIDGE, 1989). Differences in the amplitude of changes caused by each variable in different time scales may explain the contrasting results of shoreline change studies in Rio Grande do Sul.

Coastal changes result from the interaction of several processes, natural and human and are of long and short duration. When major variables act in the same direction (accretion or erosion), they enhance each others effects and net variations are clearly identified. This is the probable scenario for the intensely eroded areas of Hermenegildo and the Conceição lighthouse, where concentration of the wave rays occur at a long-term receded barrier, the shoreline orientation is highly susceptible to the southerly storm waves, and high longshore transport rates may have contributed to a local sand deficit, in addition to a probable rise in sea level. In places where major factors operate in opposition to each other, changes are variable and are a function of the time interval analysed. As might be the case for the northern coastal sector, where human activities and a relative sea-level rise oppose the spreading of wave energy along a long-term prograding shore. So, some factors can be of major importance to shoreline changes in some areas and be indistinct in others. According to FAIRBRIDGE (1989), in places of adequate sand supply, without human interference, and where neotectonics is positive or neutral, beach equilibrium will be maintained in a scenario of a mean sea-level rise as high as 5-10 mm/yr. In contrast, the same rise in sea level and neotectonic settings in a low-relief shore without adequate sand supply will result in significant coastal retreat. This might be the case of the receded barriers developed along the large-scale coastal projections simultaneously to the shore progradation along the embayments suggested for the last 5 ka in Rio Grande do Sul (DILLENBURG *et al*., 2000).

Short-term shoreline changes affect beach uses and can be potentially destructive in developed areas. Short-time events that last few days and have a frequent recurrence (within several months) represent a far greater hazard than long-term trends (FAIRBRIDGE, 1989). Therefore, knowledge of long-term trends is necessary to establish adequate coastal management plans, although they can only be efficient when maximum variations of short-term changes are properly incorporated. For management purposes, much needs to be done to evaluate the influence of different causative factors in the short and long time frame. It is evident that storms (strong winds, high energy waves, and storm surges) erode Rio Grande do Sul beaches. However, how long does beach profiles take to recover? Do storms cause long-term local negative sand balance? Is it true that destructive storms strike the Rio Grande do Sul coast once a year or is that abnormally occurring only in the last years? How much sand is actually transported alongshore? Is sea level really rising in southern Brazil? If so, when did it start to rise and what are the rates?

CONCLUSIONS

All studies indicate erosion of the beaches of Conceição lighthouse and Hermenegildo, while diverse results are observed along most of the Rio Grande do Sul shoreline. Where long- and short-term causes lead to shoreline changes to the same direction, the net result is evident at all temporal scales. However, in places where at least one variable results in movement to the opposite direction, the net variation is reduced and might not be observed in different time scales. Thus, results obtained from shoreline change studies vary according to the temporal scale in question and the causes that are significant in that period. Although there is strong evidence of short- and long-term erosion spread along the Rio Grande do Sul shore, more data is necessary to define and quantify shoreline change trends. For coastal management purposes short-time events represent a far greater hazard than long-term trends. Hence, it is necessary to better understand the relationship between storms, sand budget, and beach erosion in Rio Grande do Sul to support proper decision-making processes.

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