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Alongshore Patterns of Shoreline Movements in Southern Brazil

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ABSTRACT

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Rio Grande do Sul has a 618-km long shoreline dominated by mostly continuous, exposed sandy beaches that are often described as straight and homogeneous. From 1997 to 2002, the state shoreline was mapped five times using the kinematic Global Positioning System method, showing regional differences in the dynamics of shoreline displacements. This study compares short-term changes with long and medium-term trends in coastal evolution. Generally, patterns of annual shoreline displacements are distinct for the three coastal sectors. Similar magnitudes and directions of changes occur along the southern sector, while displacements are in opposite directions in other areas. The effects of the high-energy winter conditions are evident in the landward displacements registered from Nov/1999 to Jun/2000. Similarly, the changes observed from Jun/2000 to Apr/2002 represent the recovery of the beach width from a winter to a post-summer condition. A mirror image has been observed in between displacement lines of different time intervals for distinct coastal sectors, indicating that the return to a previous shoreline configuration and, perhaps, to its original position, is just a matter of time. Although these findings refer only to short-time scales, in the longer term, shoreline shapes may be continually recurrent while moving landward or seaward. Shoreline change rates obtained from aerial photographs show that the northern beaches are mainly prograding in the medium-term, with rates decreasing southwards, similarly to the changes registered during the Holocene. Shifts in the short-term trends are spatially coincident with changes observed in the dynamics of the transgressive dune fields.

ADDITIONAL INDEX WORDS: *Beach erosion, DGPS, Rio Grande do Sul.*

INTRODUCTION

The knowledge of beach and shoreline changes in Rio Grande do Sul is generally limited in time and space. Coastal data have been obtained in few places that are distant from each other, and are, at best, discontinuously available in the last 10 or 15 years. The coastline of Rio Grande do Sul is 618-km long and comprises one of the longest continuous sandy shores in the world. The visual similarity of its beaches and the lack of data to continuously represent long segments lead researches often to describe this coast as straight and very homogeneous. However, recent studies have linked changes in shoreline orientation with alongshore gradients of wave energy, differences in the potential of longshore sediment transport, and in the dynamics of shoreline movements at various time scales (e.g. DILLENBURG *et al*., 2000, 2003; ESTEVES *et al*., 2002, 2003a; LIMA *et al*., 2001).

From 1997 to 2002, the Rio Grande do Sul shoreline was mapped five times using the kinematic Global Positioning System (GPS) method in an effort to follow the trends in recent shoreline change studies, which have focused in gathering continuous data at a regional scale. Although only 20% of the state shoreline is developed, the coastal population has grown faster in the last decade and some pristine areas are already under threat of unplanned occupation (ESTEVES *et al*., 2003b). A better understanding of the shoreline dynamics at various time-scales is needed urgently to support regional and local coastal management plans. This study describes magnitudes and patterns of short-term shoreline changes, focusing in the regional alongshore differences. Additionally, the short-term patterns are compared with medium-term rates obtained from aerial photos (from 1974, 1989, and 2000) and from evidence of the Holocene evolution of coastal barriers in an attempt to better understand shoreline changes in Rio Grande do Sul.

STUDY AREA

Rio Grande do Sul is the southernmost state in Brazil, sited around latitudes 27S to 34S and longitudes 50W to 57W (Figure 1), presenting a humid temperate climate with warm to hot temperatures in summer (mean of 26ºC) and cool temperatures in winter (mean of 12ºC). About 450,000 people live in coastal cities, or less than 4.5% of the state's population. The majority of the developed areas are concentrated along the northernmost 120 km, comprised mainly by second houses that are occupied only in the summer months, when about 2 million people move to the coast (ESTEVES *et al*., 2003b). The study area consists in the Rio Grande do Sul shoreline, where only two permanent discontinuities occur (Tramandaí and Patos lagoon inlets). The coast is usually divided into three major sectors: (1) the southern sector extends 220 km from the Chuí creek (at the Uruguayan border) to the Patos lagoon inlet (2) the central sector is a 275 km-long and mostly undeveloped shore, and (3) the northern sector, a 123-km long urbanized shoreline, extending from Quintão beach to the border with Santa Catarina state (Figure 1).

The RS coast is characterized by a complex system of coastal lakes and lagoons formed during the Quaternary sea-level

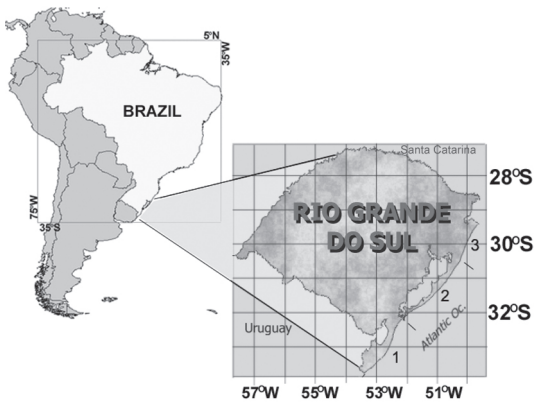

Figure 1. The Rio Grande do Sul shoreline is 618-km long and is usually subdivided in three major coastal sectors: (1) southern, (2) central, and (3) northern.

fluctuations. In the last 5 ka, no new sand has been supplied to the shore from inland as the lagoon system retains the sands transported by the rivers (TOMAZELLI *et al*., 1998). According to DILLENBURG *et al*. (2000), sand budget in the RS coast has been controlled by alongshore gradients of wave energy resulted from the concentration of wave rays in large-scale coastal projections and dissipation along smooth embayments. Northeast winds blow constantly along the shore, although southerly winds are the strongest and more frequent from April to July (fall and winter). Alongshore currents are bi-directional, but there is a net sediment transport to the north due to the strong southerly waves associated to the passage of cold fronts. This is a microtidal coast with tidal variation less than 0.5 m; consequently, waves are the main hydrodynamic process.

Intermediate beaches composed by well-sorted fine quartzose sands dominate in the RS (*e.g.* TOLDO Jr. *et al*., 1993; CALLIARI and KLEIN, 1993; BARLETTA *et al*., 1999), except along (a) the reflective to intermediate beaches of the *Concheiros do Albardão*, a 30-km long segment between Albardão lighthouse and Hermenegildo (southern sector), where bioclastic gravels are added to the quartzose fine sands forming a bimodal sediment, and (b) the dissipative beaches from Cassino Beach to Sarita Lighthouse (southern sector), where there is a slightly decrease in the mean grain size caused by the suspended sediments carried through the Patos Lagoon mouth (CALLIARI and KLEIN, 1993).

METHODS

From 1997 to 2002, the Rio Grande do Sul shoreline was mapped five times using the kinematic Global Positioning System (GPS) method (*i.e.* TOLDO Jr. *et al*., 1999; MORTON *et al*., 1993). The state beaches are flat, dissipative, continuous, and undeveloped, characteristics that favor the application of the kinematic GPS method to map the 618-km long shoreline in a fast and economic way. This study aims to compare shoreline positions mapped in 1997 (Nov/26-28th), 1998 (Nov/17-19th), 1999 (Nov/10-11 and 19th), 2000 (June/26-28th), and 2002 (April/15-17th) to determine regional differences in alongshore patterns of shoreline changes. Additionally, shoreline change rates were estimated from sets of vertical aerial photographs, and the long-term evolution of coastal barriers (during the Quaternary) are analyzed to better understand coastal changes in the RS.

The aerial photographs used in this study were obtained in Jan/1974 and Feb/1989 (scale of 1:20.000) by the state *Departamento de Estradas e Rodagens* (DAER), and in 2000 low altitude, small format, digital photographs were obtain by the Fundação Universidade Federal do Rio Grande (FURG) using the ADAR-1000 system (FONTOURA and HARTMANN, 2001). Distances between control points (at least 6 in each photograph) were measured to establish the error due to distortions and also due to the accuracy in identifying the exact points from where the measures were taken. Then, beach widths were measured every 150 m or 200 m in front of stable points along at least 2 km in five different beaches and the average rate of change was estimated for each one of the beaches.

In 1997, shoreline mapping was conducted using two Garmin GPS 100 Personal Surveyor; one was installed in a vehicle moving along the waterline in an average velocity of 50 km/h to register positions every 5s, and the other was set in static mode every 100 km to enhance the horizontal accuracy to 3 m. In the following years, position data were corrected using a fixed GPS antenna. In 2000 and 2002, a Trimble GPS 4600 was used to register positions every 3s, resulting in an accuracy of 1 m. A major source of error in this study consists in the spatial and temporal waterline oscillations along the smooth slope of the RS beaches (1/30 in average). Such errors were minimized as mapping was always conducted on similar conditions (*e.g.* tidal levels, fair weather, no storms or passage of cold fronts in the weeks before field work). The waterline was chosen as the reference feature as it could be followed throughout the length of the study area and could be easily identified while driving along the beach. Dune crest or scarp, vegetation line, and berm crest are not continuous along the entire coast; then cannot be used to compare beach segments that are distant to each other. The high waterline was the reference feature mapped in 2002, therefore a correction was necessary to allow this shoreline to be compared with the others. The correction consisted in displacing the shoreline mapped in 2002 seaward based on the distance from the high waterline to the waterline measured on aerial photos obtained in 2000 and 1989. Such distances were measured every 200 m along several beaches, and the mean values were applied for segments with similar characteristics.

The ArcView GIS 3.2 program was used to display and organize the shoreline position data from where the ArcView extension Digital Shoreline Analysis System 2.0, developed by the U.S. Geological Survey (THIELER *et al*., 2003), was applied to measure distances between mapped lines and to estimate shoreline change rates every 1 km alongshore for the regional analysis and every 250 m for the detailed analysis of the northern sector. Identification of regional patterns of shoreline displacement was based on line graphs of alongshore distance *vs*. shoreline change where a landward movement (shore retreat) was represented as negative values, and seaward movements (beach accretion) as positive values. Alongshore distance was measured from south to north, starting at the jetty of the Chuí creek (at the border with Uruguay) and ending at the beach of Itapeva in Torres. Although shoreline change rates are presented, they should not be interpreted as long-term trends as the time frame of the available data is too short. Rates were estimated to allow comparison between short and longer-term trends.

ALONGSHORE PATTERNS OF SHORELINE MOVEMENTS

Graphs of shoreline changes (Figure 2) indicate that shoreline movements occur differently along the three major coastal sectors of Rio Grande do Sul, including the maximum amplitude of displacements and the effects of seasonal and interannual changes (ESTEVES *et al*., 2003a). Alongshore patterns of annual and seasonal changes are described below.

Annual Changes

Figure 2a represents annual changes in shoreline position as it shows displacements between Nov/1997-Nov/1998 and Nov/1998-Nov/1999. In general terms, magnitudes of changes and trends presented by both lines are similar along the southern sector, and to opposite directions in the central and northern sectors. Magnitudes of changes and shoreline mobility are greater along the central sector, where shoreline positions oscillate up to 140 m. Less variability is observed along the southern and northern sectors, where shoreline positions vary up to 50 m.

From Nov/1997 to Nov/1998, shoreline movements were exclusively seaward along the southern sector, indicating beach accretion with mean shoreline displacement of 25 m. From Nov/1998 to Nov/1999, similar behavior was observed, except in the southernmost 60 km where erosion was registered. Along the southern sector, the shoreline tends to move further seaward from south to north, oscillating around 20 m along the southern 90 km and reaching 50 m northwards (Figure 2a). This is partly due to the shoreline orientation, as the northern part of this sector is characterized by an embayment (*i.e.* favors deposition), and partly due to the long-term progradation of this coastal barrier (*i.e.* DILLENBURG *et al*., 2000; ESTEVES *et al*., 2003a). In the central sector, both annual lines (Nov/1997-Nov/1998 and Nov/1998-Nov/1999) show a rhythmic pattern alongshore (Figure 2a). They move seaward and landward to opposite directions and show regularly spaced peaks that do not always have same amplitudes. Magnitudes of changes are greater for the Nov/1997-Nov/1998 period, mainly for the seaward movements, resulting in a mean displacement around 22 m, while the mean for the Nov/1998-Nov/1999 line is 2.8 m. The cause of such rhythmic pattern is unknown, but preliminary analysis indicates that it might be associated with smooth bulges and embayments on the shoreline configuration.

Annual lines also move to opposite directions along the

northern sector. However, they do not oscillate from shoreward to landward displacements, as the Nov/1997-Nov/1998 line shows only beach accretion, and the Nov/1998-Nov/1999 line presents mainly erosion (Figure 2a). Shifts in the direction of the longshore current might be the main factor driving those lines to move to opposite direction in the period. The direction of the littoral drift has been visually registered three times a day at the fishing pier of Tramandaí since 1996 (NICOLODI *et al*., 2000). The data show that the longshore current was dominantly flowing to SW in 1996 and 1997, shifting to NE in 1998 and 1999, returning to flow to SW in 2000, 2001, and 2002. Considering that the NE winds dominate along the Rio Grande do Sul coast, it is expected that the longshore currents flow in the NE-SW direction most of the time. However, the net longshore sand transport has been from SW to NE as the southerly waves are higher and more energetic. Taking into account that the net longshore transport is to the NE even when the main direction of the littoral drift is to SW, it is likely that sediment transport to the NE is more intense when the littoral drift flows dominantly to the same direction (*i.e.* 1998 and 1999). According to the data collected since 1996, in normal years, the longshore current flows to SW more than 60% of the time. It is assumed that, for such conditions, there is a balance in the volume of sediment transported alongshore as currents from the south are less frequent but stronger. When currents from south are dominant, a greater volume of sediment is probably mobilized from the areas with a shoreline orientation more exposed to the SSE waves where potential longshore transport is greater (LIMA *et al*., 2001). These sediments are then transported north and deposited in the areas of less potential sediment transport, such as smooth embayments or along a segment of less exposed shoreline angle. Thus, the accretion registered in the northern sector from Nov/1997-Nov/1998 might be due to deposition of sediments eroded from beaches further south where alongshore sediment transport is more intense. The erosion registered in the following year is likely to represent the return of the shoreline to a more stable position as the ratio of SW and NE currents were already returning to normal. The reversal in the net direction of longshore currents is coincident with the strong El Niño event of 1997/1998. However, at this moment, no further investigation was conducted to evaluate the possible effects of El Niño in the coastal currents of Rio Grande do Sul.

Seasonal Changes

Seasonal effects on the patterns of shoreline movements were observed through the analysis of the changes registered between the shorelines mapped in November (1997, 1998, and 1999) and the ones mapped in June/2000 and April/2002. The effects of the higher energy conditions dominant in the fall and winter seasons can be observed in figure 2b. As expected, shoreline displacements in the period Nov/1999-Jun/2000 are mainly shoreward, indicating that an eroded condition prevails at the end of fall/beginning of winter along the three sectors. There is no evident rhythmic pattern alongshore in the Nov/1999-Jun/2000 line but a mirror image with the Nov/1998-Nov/1999 line is clear along the northern 130 km of the southern sector (Figure 2b). The spatial coincidence of peaks with similar magnitudes in opposite directions suggests that the shoreline returns to a pre-existing position along this segment. It implies also that the accretion registered in a one-year interval (from Nov/1998 to Nov/1999) was balanced by retreat in the following 7 months (or the next fall/winter season). Figure 2a shows that similar accretion was observed in the previous year (from Nov/1997 to Nov/1998). This raises the question whether such accretions are always balanced by retreat in the following winter or whether there is a net accretion in the short term that corroborates with the long-term progradation of the barrier.

Apart from the northern part of the southern sector, a mirror image was not observed in other areas for the period Nov/1998 to Jun/2000 (Figure 2b). However, such effect occurs along the northern sector when a longer period is considered (Figure 2c). The mirror image observed between the lines Nov/1997-Nov/1998 and Nov/1998-Jun/2000 indicates that the accretion over a period of one year was balanced by erosion 19 months

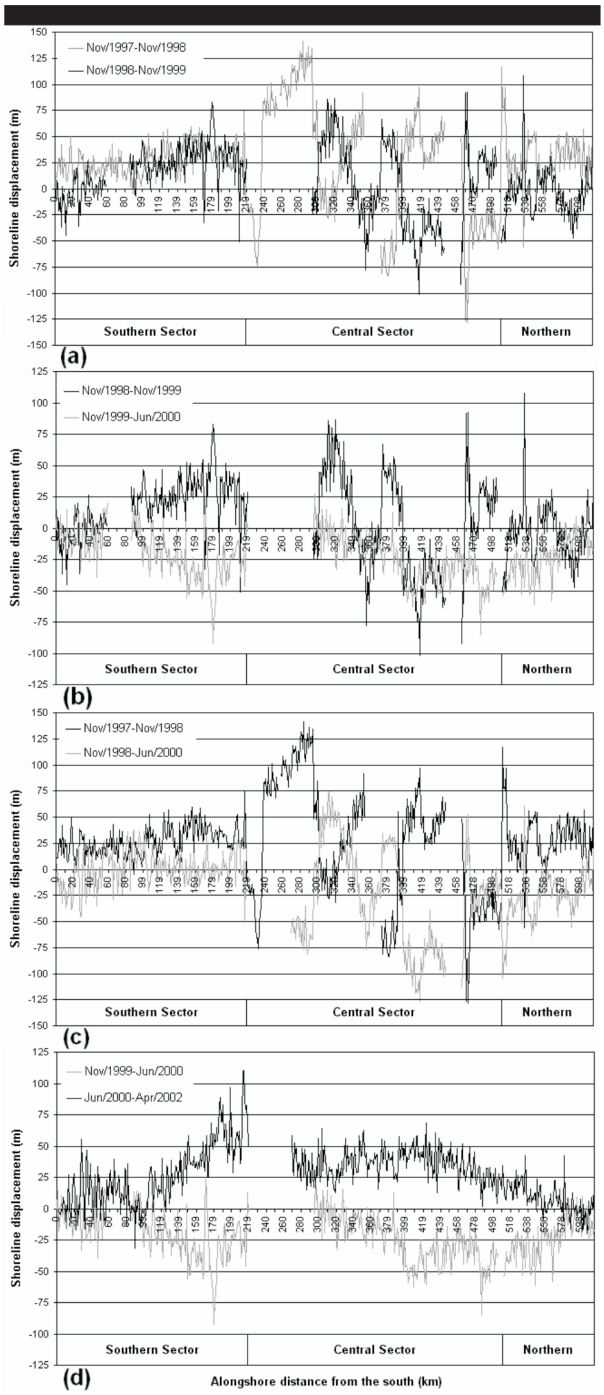

Figure 2. Line graphs comparing shoreline displacements to show alongshore differences in the patterns of annual change (a) and in the seasonal effect (b, c, and d). Positive values represent seaward shoreline displacement and negative values represent landward movements.

later along the northern sector. A mean line derived from those lines shows a total recovery of the previous shoreline position from the Tramandaí inlet to Xangrilá, with a slightly negative balance southwards and a positive balance northwards. In these areas, the beach width was not completely recovered because opposite peaks of displacements were not of the same magnitude. The mirror effect was also registered by List and Farris (1999) before and after a storm along the shores of Outer Banks (North Carolina, US) and Cape Cod (Massachusetts, US). The mirror image indicates that the shoreline has a memory of its original shape, to which it returns from time to time (LIST and FARRIS, 1999). Considering that the mirror image has been observed for different beaches on varied short-time scales (after passage of a storm, seasonally, and annually), the return to a previous shoreline configuration and, perhaps, to

its original position, is just a matter of time. Maybe, an important question is whether such shape and position are dominant in time or represent only transitory moments in between a highly dynamic state.

In contrast to the Nov/1999-Jun/2000-line, the June/2000-April/2002 line shows accretion throughout the study area (Figure 2d). Such accretion was expected as this line compares a retreated beach registered at the end of the fall (June/2000) and a beach accreted by the fair-weather conditions that prevail in the summer (January to March). As in the Nov/1999-Jun/2000-line, the June/2000-April/2002 line does not show the regular rhythmic pattern observed in the annual lines (see Figure 2a) and also do not form a mirror image with any of the displacement lines obtained in this study. Although out of phase, the shape of the line and the magnitudes of changes are similar and opposed to the Nov/1999-Jun/2000 line (Figure 2d). Possibly, peaks of maximum shoreline variation travel alongshore according to seasonal changes in energetic conditions up to the moment where previous shoreline configuration and/or positions are re-established.

SHORELINE CHANGES IN THE LONGER TERM

To better understand changes along the state shoreline, a more detailed analysis was conducted for the northern sector, combining data of short-term changes (DGPS lines), rates estimated from aerial photos taken in 1974, 1989, and 2000, and evolution of coastal barriers in the Holocene. According to DILLENBURG *et al*. (2000), the coastal barrier had prograded from Torres to Tramandaí and remained stable from Tramandaí to Mostardas (central sector) during the Holocene (see Figure 3). Although the time interval of the DGPS monitoring is too short to provide consistent rates of changes, they were estimated just to compare the general alongshore trends with the ones observed in the Holocene. The shoreline change rates obtained for the period Nov/1997 to Apr/2002 show accretion from Torres to Xangrilá, stability to mild accretion from Xangrilá to Tramandaí, and erosion southwards up to Mostardas (Figure 3). Table 1 shows mean rates of changes estimated by linear regression that corroborate with these general trends. Cidreira is located south of Tramandaí and has been subjected to erosion (-4.5 m a^{-1}), Xangrilá has slightly accreted (0.7 m a^{-1}), and the other beaches located north of Xangrilá have accreted considerably (>1.0 m a^{-1}) from 1997 to 2002.

It is worth to note that Xangrilá is the place where there is a remarkable change in the width of the modern transgressive dune fields, which are narrow to the north and wider southwards, covering the Holocene barrier (DILLENBURG *et al*., 2000; 2003). From Tramandaí to Mostardas, the transgressive dune fields are much wider and extend also on top of the Pleistocene barrier (DILLENBURG *et al*., 2003), indicating a recent process of beach retreat (Hesp, personal communication). Thus, trends of shoreline change obtained from the short-term data are more or less in accord with the observed behavior of present transgressive dune fields (Figure 3).

Comparison of aerial photographs for five urbanized beaches along the northern sector suggests that rates of change in the medium-term are highly variable alongshore, but agree well with the short-term trends (Figure 3). Measurements of shoreline positions were taken along 3 km in the area of Arroio do Sal, 5 km in the area of Curumim and Arroio Teixeira, 2 km in the area of Xangrilá, and 2 km in the area of Cidreira. Note that Cidreira is about 50 km south of Xangrilá that is 20 km south of Arroio Teixeira (distance less than 1 km from Curumim), which is about 15 km south of Arroio do Sal. Rates of changes will be presented as a range when the uncertainties of measurements affect the meanvalue estimated for each area. Shoreline change rates estimated from aerial photos and from the DGPS monitoring are presented in table 1.

It seems that the alongshore variability of shoreline changes is due to long-term gradients of wave energy caused by the shape of the shoreline and the steepness of the inner shelf

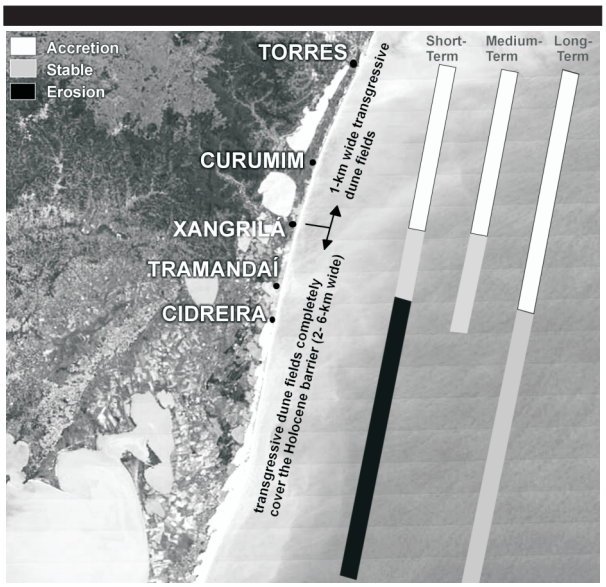

Figure 3. Shoreline changes in the short-term (1997-2002), medium-term (1974-2000), and long-term (Holocene) along the northern coastal sector of the Rio Grande do Sul. Aspects of the transgressive dune fields and the Holocene evolution were based on DILLENBURG *et al*. (2000, 2003).

(DILLENBURG *et al*., 2003). Thus, higher energy (concentration of wave rays) tends to occur along convex shorelines adjacent to steeper inner shelf, and lower energy (dissipation of wave rays) is likely to occur along concave shores adjacent to a less steep shelf, favoring erosion and deposition, respectively. LIST and FARRIS (1999) have registered similar alongshore heterogeneity of shoreline changes along the Outer Banks (North Carolina, USA). It was observed that a complex pattern of accretion and erosion zones can be created as a result of high-angle waves approaching to the shoreline, *i.e.* when the angle that deep-water waves approach to the shoreline is greater than the one that maximizes longshore transport (ASHTON *et al*., 2003). Although this process is still to be verified along the state's shoreline, it is clear that the longshore sediment transport as a function of shoreline orientation is a major factor influencing alongshore variability of shoreline changes.

It is clear from these data that the northern beaches are mainly prograding in the medium-term (Figure 3), with a trend of decreasing rates southwards, in the same way it has been described for the long-term coastal evolution. The area of Curumim/Arroio Teixeira has presented one of the largest progradation in the Rio Grande do Sul coast during the Holocene with rates around 2 - 3 m a^{-1}, similarly to the values obtained from the aerial photos for the period 1974 to 2000 (3.0 - 3.4 m a^{-1} in Curumim, and 1.4 - 2.6 m a^{-1} in Arroio Teixeira). In Xangrilá and Cidreira, measurements indicate lower rates of accretion than in the areas further north (Table 1). The variability of the rates obtained for different periods in the area of Arroio do Sal illustrates the oscillation from accreted to eroded phases that seems to be characteristic of the intermediate beaches of the Rio Grande do Sul. The shoreline fluctuates back and forth in the short-term while the coast progrades or retreats in the longer-term. Such variability is probably due to a combination of factors, including interannual or decadal changes in wave climate, consequently in the volume and direction of longshore transport, and effects of cyclic events such as El Niño/La Niña.

A recent trend of shoreline retreat in a long-term prograding coast was also registered along the Brittany beaches, in the Atlantic coast of France (BATTIAU-QUENEY *et al*., 2003) and along part of the NW coast of England (PYE, 1990). The recent erosion along that part of the French coast is attributed to the depletion of sand reserves accumulated on the shoreface since the post-glacial marine transgression (PASKOFF, 1998 *in* BATTIAU-QUENEY *et al*., 2003). This might be a factor to be considered also for the Rio Grande do Sul coast, where sand deposited on the adjacent shelf have been reworked to form

Table 1. *Shoreline change rates estimated from aerial photos and DGPS shoreline monitoring.*

	Cidreira ($m\ a^{-1}$)	Xangrilá ($m\ a^{-1}$)	Arroio Teixeira ($m\ a^{-1}$)	Curumim ($m\ a^{-1}$)	Arroio do Sal ($m\ a^{-1}$)
1974-1989	na	0.4	2.5	na	1.0
1989-2000	na	na	[b]	na	-1.9 a -1.4
1974-2000	0.7 a 0.9	na	1.4 a 2.6	3.0 a 3.4	-0.2 a 0.0
1997-2002[a]	-4.5	0.7	3.5	3.0	1.3

coastal barriers in the last 5 ka (see DILLENBURG *et al*., 2000) and no new sand have been supplied to the shore since then (TOMAZELLI *et al*., 1998).

CONCLUSIONS

Data from DGPS monitoring of the shoreline indicate that shoreline movements respond differently to seasonal, annual, and interannual changes along the three major coastal sectors of Rio Grande do Sul. Differences include the amplitude of changes, the time frame in which beach widths are recovered, and the alongshore patterns of change due to seasonal and annual effects. From these findings, it is possible to conclude that, in a regional scale, the Rio Grande do Sul coast is neither straight nor homogeneous. The high alongshore variability of shoreline change rates is probably due to differences in the longshore sediment transport resulted from changes in the shoreline orientation. The analysis of short-term changes (5 years), medium-term average rates (26 years), and the trends of coastal evolution in the Holocene indicates that beaches along the northern coastal sector of Rio Grande do Sul are prograding north of Xangrilá, and stable to slightly prograding to the south, although a recent trend of erosion has been registered south of Tramandaí. It is interesting to note that the short-term changes reflect differences in the behavior of modern transgressive dune fields, and that the estimated medium-term rates of change agreed well with the long-term trend observed during the Holocene.

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