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Climate teleconnections and indicators of coastal systems response

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ABSTRACT

This article surveys secular urban sandy beaches erosion – accretion and its relationship with climate teleconnections, e.g., El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), and extreme events, e.g., storm surges, great rivers' floods, and heavy rains in adjacent basins. The paper aims to discuss these issues and the expected coastal retreat as a consequence of manmade climate changes, e.g., sea level rise (SLR) and increased storminess in the coming decades. Several beaches (Buceo, Malvín, Pocitos, Ramírez) and two tidal creek sandy mouths (Carrasco and Pando), with different characteristics but all constrained by coastal linear infrastructure were studied. These sites are located along the urbanised coast of the middle region of Río de la Plata microtidal river estuary. All of them show a more or less strong retreat trend with alternated fluctuations, e.g., weak retreat likely due to sea level rise, significant erosion very likely due to storm surges, and processes of loss of sediment stock, as well as episodes of sand recovery. Therefore, these beaches require interventions to preserve their beach prism and dry sand surface. In search for answers to better understand why and under what conditions the process of advance and retreat of the coastline occur, we have analysed different teleconnections and carried out reanalyses for wind anomalies during ENSO events from 1951 to 2010. Both weak and moderate erosion–accretion periods are likely related to atmospheric anomalies, e.g., wind direction changes and the consequent swell and littoral drift changes, related to El Niño and La Niña events. The former associated with accretion and the latter with erosion. In the past most interventions have been reactive. Increased knowledge of climate and weather relationship with the sedimentary balance provides an approach that would allow developing beach risk-management, pro-active strategies and climate adaption measures focused on the generation and recovery planning based on the analysis of the occurrence and prediction of El Niño/La Niña events.

1. Introduction

The growing threat that hangs over coastal systems due to global change is induced primarily by forcings such as changing land use and climate change, especially sea level rise (SLR) (Masselink and Gehrels, 2014). Socioeconomic, cultural and environmental importance of beaches make it necessary to create as accurate as possible scenarios of their evolution in the medium and long term (Dias et al., 2013; Ledoux and Turner, 2002), in order to develop mitigation and adaptation plans and measures against these threats (Luisetti et al., 2014).

Ecosystem resilience is a clear objective of modern science (Holling and Gunderson, 2002). For coastal environments this involves analysing the capacity to generate the necessary conditions for maintaining ecosystem functions that support the services provided by beaches (Flood and Schechtman, 2014).

In order to build resilience in an ecosystem subject to fast and

Abbreviations: AMO, Atlantic Multidecadal Oscillation; AMSL, above mean sea level; ENSO, El Niño Southern Oscillation; MSL, mean sea level; NCEP/NCAR, National Center for Environmental Prediction/National Center for Atmospheric Research; PDO, Pacific Decadal Oscillation; PHTH-WL, high tide high – water level; RdlP, Río de la Plata; SLR, sea level rise; SSTA, Sea Surface Temperature Anomalies; WDL-RM, wet/dry line or run-up maxima; WSA, wind speed anomalies.

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slow drivers of change, e.g., extreme events and gradual climate change respectively, there is a need to identify them, particularly the fast ones and their trends in the mid-term (months to years), since they may produce undesirable and irreversible shifts. These threats are very important in urban beaches constrained by linear infrastructure.

World's beaches are threatened not only by the increase in mean sea level (MSL), with a recent trend of +3.26 mm/year (average rate 3.3 ± 0.4 mm/year) measured by high-precision altimetry satellites (Nicholls and Cazenave, 2010), but also by other natural forcings as subsidence, depletion of underwater sand reserves, changes in atmospheric circulation and possible increase in wind speed due to global warming. In addition, attention should be given to local human forcings, such as construction or resizing of harbours, building walls, breakwaters, jetties or breakwaters, sand mining, or urbanisation of exchanging sand dune systems (Gutiérrez and Panario, 2005; Gutiérrez et al., 2015; Marshall and Banks, 2013; Panario and Gutiérrez, 2005; Panario and Piñeiro, 1997; Stevens et al., 2005).

As a result of these actions, most of the Uruguayan beaches are showing evidence of degradation e.g., the loss of the primary dune, and/or the decrease in the area of dry sand and/or the height of the beach prism, which makes them vulnerable. Typically these beaches have their land limit constrained by the presence of coastal linear infrastructure. Several experiences of primary dune reconstruction carried out by our team have been successful while others have failed due to storms that destroyed the installed soft works. The chances of success of these initiatives on these beaches could be fostered if we had better knowledge of both the causality and prognosis of increased storms, and the periods of increased beach prism, hence of the availability of aeolian sand.

From our experience it should be noted that the reconstruction of dunes in long stretches of coastline requires adequate economic, human, and material resources, and logistics to perform the task. Since failures discourage funding sources of these activities, it is of paramount importance to anticipate preparedness for when these activities are most likely to occur and in sufficient time to have the human and material resources for execution.

This article focuses on four beaches Pocitos, Ramírez, Buceo and Malvín of Montevideo city, and two tranches with mouths included (Carrasco and Pando creeks) on the Uruguayan coast of the large Río de la Plata (from now on RdlP) river estuary (38,000 km^2, 100–230 km wide) (Fig. 1). The northern Uruguayan coast of the estuary is characterised by the presence of wave-dominated sandy beaches. This coast and its beaches are subject to the action of tides (<0.5 m amplitude), wind climate patterns, episodic river floods and storm surges events, and gradual sea level rise (SLR) (Gutiérrez et al., 2015; Nagy et al., 2014a, 2014b; Verocai et al., 2015).

The selected beaches have notable differences, e.g., orientation, bathymetry, exposure length, profile, presence/absence of primary dune, as well as in the mineralogical composition. Human interventions have also contributed to the observed differences and long-term evolution of the studied coastal systems (Gutiérrez, 2016; Gutiérrez et al., 2015). Due to all these differences it is very likely the existence of diverse sources of sediment for the studied beaches and creek mouths.

Among the fast climate stressors on the Uruguayan coast, the wave climate change stands out. This change is associated with: i) atmospheric circulation changes likely attributable to global warming (Young et al., 2011); ii) the Atlantic Multidecadal Oscillation - AMO (Ortega et al., 2013) and the Pacific Decadal Oscillation – PDO (Nagy et al., 2014a, 2014b); and iii) oscillations associated with El Niño Southern Oscillation – ENSO teleconnections (Bidegain et al., 2015, 2014; Nagy et al., 2014a, 2008a, 2008b, 2002). It is not always clear whether these variables are linked to global climate change or natural variability. It is therefore necessary to isolate seasonal, annual, decadal and multi-decadal fluctuations occurring in atmospheric circulation and wind climate over the RdlP basin and estuary (Bidegain et al., 2005; Ortega et al., 2013; Simionato et al., 2005; Verocai et al., 2015).

The aims of this article are: i) to review the background of long-term accretion–erosion processes at urban sandy beaches focused on case studies at the Uruguayan coast of the middle region of the RdlP river estuary; ii) to focus on climate teleconnections, mainly ENSO, extreme storm surges, and their relationship with coastline retreat; iii) to update the analysis of ENSO-related wind anomalies; iv) to give insight on the need of fostering the analysis, forecast and impacts of fast climate stressors of sandy beaches changes in the light of very likely future sea level rise and likely increased storminess; v) to provide further evidence to develop beach management planning and implement climate adaptation measures.

2. Background

The two main observed wind patterns related to the purpose of this article are synthesised as follows:

1. An increasing trend of the occurrence of south-eastern (SE) winds over the RdlP (Bischoff, 2005; Escobar et al., 2004; Nagy et al., 2013; Ortega et al., 2013; Simionato et al., 2005).
2. A relationship between ENSO events and anomalies of atmospheric circulation and winds, e.g., an increase in E-SE-SSE-N and decrease in SW winds (called *Pamperos*) during El Niño, and increase in SW winds during La Niña from 1954 to 1998 (Gutiérrez, 2010).

For instance, Ortega et al. (2013) have shown in Atlantic ocean beaches near the RdlP, the existence of two variables correlated in time, the anomalies of sea surface temperature (SSTA) and wind speed (WSA) as well as an increase in S, SSE and SE wind directions for the last few decades. Whereas Codignotto et al. (2012) observed an increase in wave energy from the East, which affects the erosion of ocean beaches in the province of Buenos Aires (Argentina). Recent research (Nagy et al., 2015a) on the current (1979–2014) and future climate scenarios (centred in 2030) confirm a slight increase of SE winds along the Uruguayan coast.

During the successive El Niño and La Niña events from 1998 to 2002 the following observations have been reported:

- The frequency of days with winds greater than 8 m/s during October–March varied from 7.2 days per month from 1977–86 to 11 days in 2001–02 and 17.6 days per month during the moderate to strong El Niño event in 2002–03, an increase of 57 and 150 per cent respectively (Nagy et al., 2008a),
- the wind speed yearly variability varied from 5.8 m/s to 6.2 m/s during El Niño and La Niña respectively (Nagy et al., 2003), and
- the prevailing anomalies' modes were fresh (8.6 m/s) ESE winds and strong (10.9 m/s) W winds (Nagy et al., 2008b).

With regard to waves, Dragani et al. (2010) reported a possible increase in wind wave heights and relatively high inter-annual variability in the south-eastern South American continental shelf between 32°S and 40°S, including the RdlP estuary, based on short-term series of *in situ* (1996–2006) and Topex satellite (1993–2001) data. The authors suggested that this possible increase would be able to produce changes in the littoral processes and, consequently, in the erosion of the coast. The possible link between this inter-annual variability and ENSO was investigated but no apparent relationship was found.

Pereira and Klumb-Oliveira (2015) found for the coastal zone of

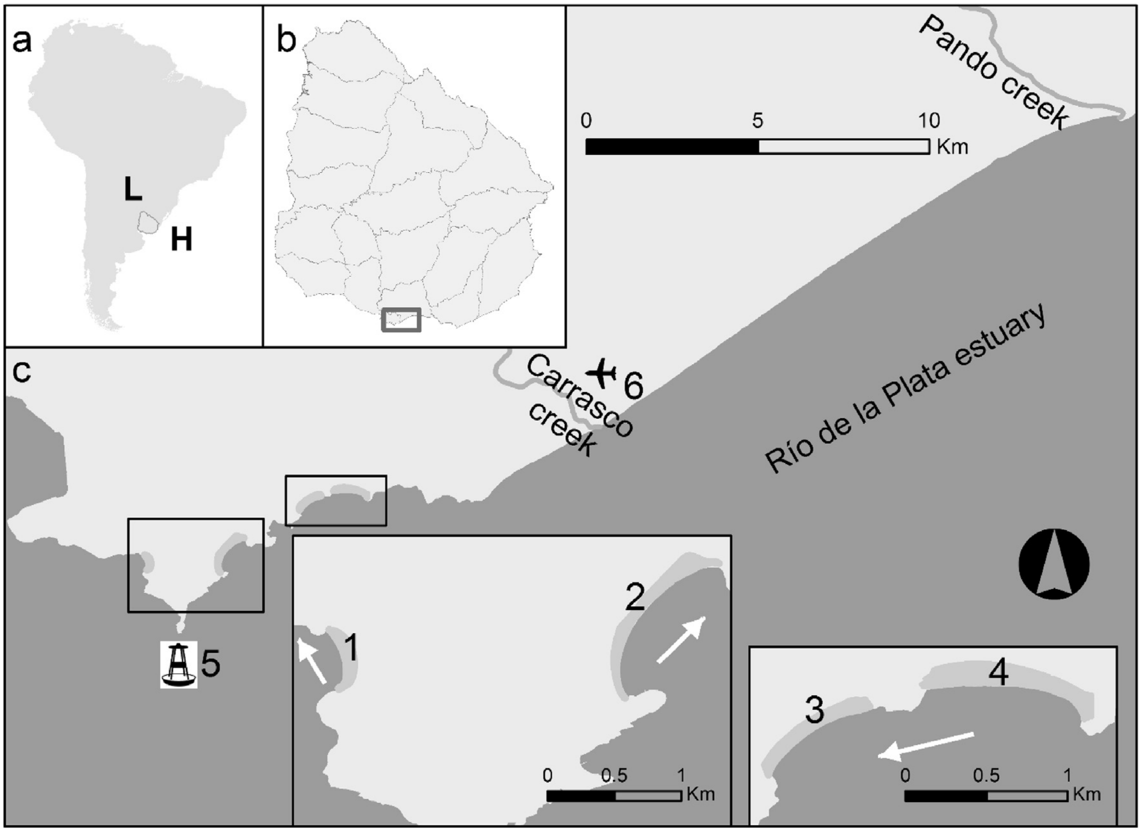

Fig. 1. Study area: a) South America, L and H indicate low and high atmospheric pressure. b) Uruguay. c) Beaches: 1) Ramírez, 2) Pocitos, 3) Buceo, 4) Malvín; and Carrasco and Pando creeks. 5) Indicates the location of the Punta Brava wave sensor. 6) Carrasco airport meteorological station. The white arrow indicates the drift direction.

Rio de Janeiro, Brazil, a slight reduction in significant wave height during strong El Niño years caused by the attenuation of the frequency of events from the S quadrant. The opposite pattern was observed during strong La Niña years, caused by an increase in wave incidence from the S and SW quadrants, especially in boreal winter from 1979 to 2013. The decrease could be attributed to the intensification of the South Atlantic High with a corresponding increase in the occurrence of subtropical jets during periods of El Niño. This weather change causes the blocking of southern cold fronts and the consequent reduction in the percentage of waves from the south.

According to our systematic observations of the Uruguayan coast of the RdlP river estuary and Atlantic Ocean since the 1990s, the southern winds play a key role on water and coastal dynamics, but with dissimilar effects depending on the synoptic conditions and fetch associated with wind speed (EcoPlata, 1999; Gutiérrez et al., 2015; López Laborde and Nagy, 1999; MTOP/PNUD/UNESCO, 1979; Nagy et al., 2014a, 2013, 2008a, 2008b, 2007, 2005, 2002; Verocai et al., 2015).

Southerly wind called "Pampero" is associated to the entry over the RdlP of dynamical high pressure system with two different types. The first called "dry Pampero" is formed with air masses from the south-eastern Pacific Ocean, which lose their moisture by passing the Andes and whose entry over the RdlP determines a rapid decrease in cloudiness and rainfall. Its mass air origin is mainly from the W-WSW, and the fetch is weak over shallow RdlP, causing only a slight to moderate increase in water-level along the Uruguayan coast. The other type is called "wet Pampero" characterised by the trajectory over the southern Atlantic Ocean producing rainfall after its entry into the region. Associated winds in the frontal zone can exceed 100 km/h and its origin can be both S-SSW and SSE. The fetch over the Atlantic Ocean generates a sharp rise in sea level associated with downwelling at beach level. Its prevalence is mostly during winter season (Simionato et al., 2007) including May to September, and its frequency was dominant during dry and cold periods of the Holocene (Iriondo et al., 2009; Piovano et al., 2009 and references therein).

The wind rose of tri-hourly average speeds between December 1997 and August 2008 (data from Instituto Nacional de Meteorología-InUMet, Uruguay) at Carrasco airport (Fig. 2) shows that ESE direction prevailed up to 6 m/s (which is about 7 m/s at the coast), that is to say for most observations, whereas for greater speeds SW and WSW directions prevailed (Panario et al., 2008). The former were mainly related to the austral spring and summer months and the latter to mid-winter (July–August) strong "pamperos" winds, which is supported by the high frequency of storm surges greater than 1.69 m above mean sea level (AMSL) reported by Verocai et al. (2015).

Wave rose (Dec 2003–May 2006), available for the studied region (Fig. 3) generated from the wave sensor data of the Municipal Government of Montevideo closely matches the prevailing ESE to SE and S wind and swell directions: SE 35%; E 24%; S 20%; W and SW <10%; NW, NE and N <5% (Panario et al., 2008).

Eastern and south-eastern winds (E, ESE, and SE) have different impact on the coast. For instance, floodings due to ESE and SE winds varies from + $\approx$0.2 m AMSL for average wind speed (5 m/s or 18 km/h) to + $\approx$1 m AMSL for strong winds of 20 m/s (72 km/h), whereas MSL (102 cm) matches weak winds speed of 2 m/s (Verocai et al., 2015). Their destructive effects are caused by a strong atmospheric low pressure to the north of Argentinean

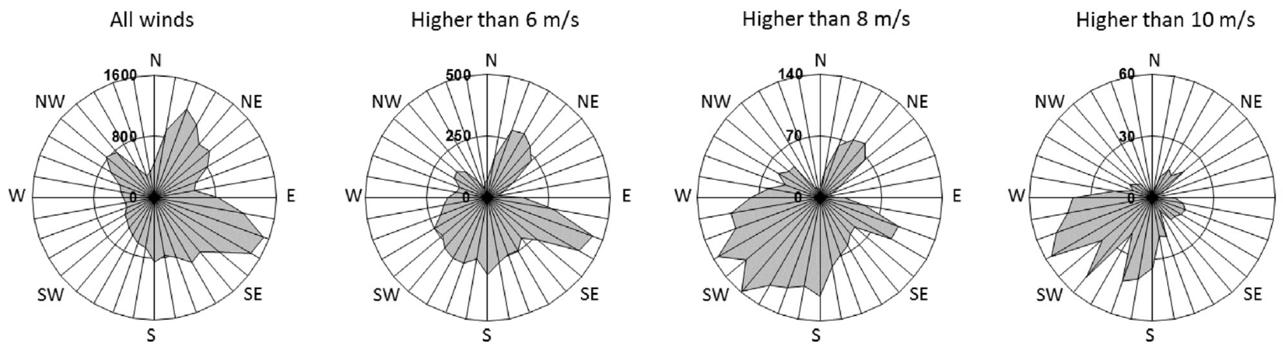

Fig. 2. Carrasco wind rose 1998–2008. The frequency of directions is shown for all winds (left), and for those higher than 6 m/s (center left), higher than 8 m/s (center right), and higher than 10 m/s (right) from 1998 to 2008 (Panario et al., 2008).

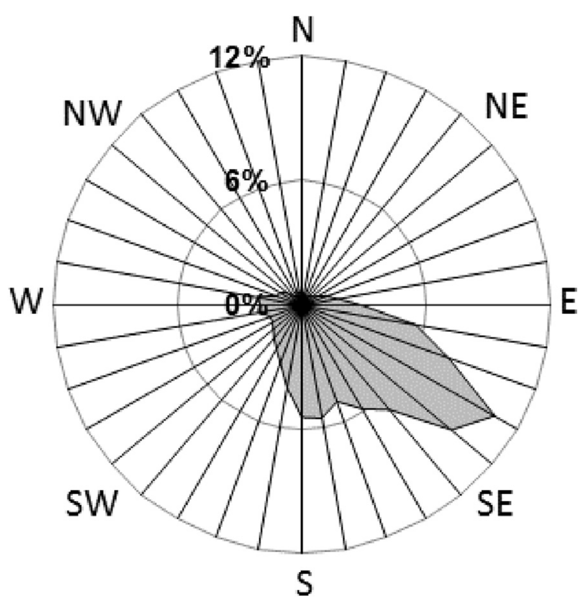

Fig. 3. Punta Brava wave rose from 2003 to 2006 (between Pocitos and Ramírez beaches, see Fig. 1). The prevailing direction related to swell matches quite well the prevailing E–SE winds, particularly during the austral summer (Panario et al., 2008).

Mesopotamia (between the great Paraná and Uruguay Rivers), which fetch raises the level of RdlP and adjacent sea. These very destructive events are infrequent (Barros et al., 2005; Bischoff, 2005), only 2 or 3 per year in the Uruguayan coast (Simionato et al., 2007; Verocai et al., 2015) and tend to occur mainly during the summer (Simionato et al., 2007) and mid-winter (Verocai et al., 2015).

ESE winds are largely sea breeze prevailing from October to March. Their intensity is usually weak to moderate therefore produce no significant downwellings or storm surges as they only raise water height a few centimetres AMSL. These winds are associated with rebuilding of the beach prism because they generate waves that reinforce the action of the swell (Fig. 3), which is the main builder of the beach prism on the Uruguayan coast. Thus, an increase in light ESE and ENE winds, prevailing from October–April and April–September respectively (Nagy et al., 2015a) can result in cushioning the effects of SLR, while an increase in meridional winds (+) may have the opposite effect.

Assuming that current response of the winds to air temperature variations are similar to what happened during the Upper Holocene (Iriondo et al., 2009; Piovano et al., 2009 and references therein), hypotheses can be developed on the basis of trends which forces are known, to the extent that their effects on coastal systems are verified. This approach would allow establishing midterm scenarios. Sedimentological evidences indicates that during the cold periods of the Holocene, including the Little Ice Age (from 1550 to 1850), there was predominance of dry weather, low temperatures and low rainfall in the pampean region and surrounding areas (Bracco et al., 2011; del Puerto et al., 2013; Iriondo et al., 2011, 2009; Piovano et al., 2009 and references therein). There is also geomorphological evidence, expressed in longitudinal dunes fields, suggesting the dominance of southern winds during the cold period of the Holocene (Iriondo and Garcia, 1993; Iriondo et al., 2011, 2009).

Observations over the last century show a sea level rise (SLR) of 11 cm in Montevideo (Bidegain et al., 2005; Magrín et al., 2007; Nagy et al., 2005) and 17 cm in Buenos Aires as a result of global climate change and the regional effects of river discharge and winds (Barros et al., 2005; Magrín et al., 2007). Periods of acceleration and stabilisation have been recorded at Montevideo from 1971 to 2003 and 2004–2013 respectively (Nagy et al., 2014a, 2005; Verocai et al., 2015). The latter was mainly attributed to lower river discharges which could have masked the global trend.

Sea level along the Uruguayan coast fluctuates ±0.1–0.2 m (superimposed on SLR) due to ENSO-related anomalies in precipitation, river flow and winds. Wind-induced flooding reaches 1, 2, and 3 m AMSL on yearly, decadal, and historical timescale basis, respectively (Nagy et al., 2015b; Verocai et al., 2015).

While it is recognised that the input of fresh water can produce yearly time-scale differences in MSL of up to 20 cm (Verocai et al., 2015) the effects of atmospheric circulation is a key factor in the behaviour of most estuarine and coastal variables (Gutiérrez et al., 2015; Simionato et al., 2007, 2005; Verocai et al., 2015). For instance, the retreat of pocket beaches of Montevideo seems to fit the Bruun Rule, without negative fluctuations associated with the freshwater input (Gutiérrez et al., 2015).

The well-known El Niño/La Niña – Southern Oscillation (ENSO) linked variability at the Uruguayan coast (Nagy et al., 2014a, 2008a, 2008b), and medium-term trends have been analysed, resulting in seasonal and biennial variability (Ortega et al., 2013; Simionato et al., 2005) linkable to Rossby waves (Simionato et al., 2007), and another one with a rate of return of 8–12 years, in addition to long cycles of between 70 and 80 years linked to the AMO (Ortega et al., 2013).

Gutiérrez et al. (2015) have suggested for pocket beaches of Montevideo, a possible relationship between ENSO and fluctuations of beach area. From all the information and assumptions presented here, it is arguable that the trends observed on the beaches of Montevideo and perhaps partly for the whole Uruguayan coast, should be analysed in terms of atmospheric circulation anomalies with effects and variations over time, likely associated with both natural variability and manmade climate change.

3. Materials and methods

This article is based on data compiled and generated by Gutiérrez (2010), as amended by Gutiérrez et al. (2015). A long-term analysis of a dense series of high definition remote sensing was performed since 1927 for four urban beaches (located in Montevideo city), and since 1937 for two tidal creek sandy mouths located few tens of km to the East of downtown.

3.1. Geomorphological analysis

Polygons were plotted on all analysed beach surfaces as proposed by Gutiérrez et al. (2015), Gutiérrez and Panario (2005) to overcome the uncertainty associated with estimating changes by random transect method. This procedure allows reducing uncertainty since the surface is equivalent to infinite transects (method commonly used for these studies), and ultimately, the beach area is the parameter of greatest management interest. In order to standardise the process, the digitalisation of shorelines was conducted at a scale of 1:3,000, as proposed by Armaroli et al. (2006), Ciavola et al. (2003), and Gutiérrez and Panario (2005). To select indicators of the shoreline, only those identified in the entire time-series of records were used. These were:

i) The *previous high tide high – water level – PHTH–WL* (Boak and Turner, 2005) is used because relatively large differences between tides produce a minimal error in the horizontal cartographic translation of the coastline. This is because the segment of the beach above the high tide level is the one with greater slope in the cross section thereof (Gutiérrez et al., 2015).
ii) Another indicator called *wet/dry line or run-up maxima – WDL–RM* (Boak and Turner, 2005) was used. This line indicates the erosive – constructive limit set within the maximum range of the wave, which is neatly identifiable by the difference in tone on aerial photographs. It is found where the beach changes from a concave profile to a convex one, with a clear break in the slope's angle.

Univariate statistical analyses were developed for the data sets obtained for each study site. The selected statistical indicators were: central tendency and data dispersion: mean, median, mode, standard deviation, variance, coefficient of variation and R^2. Deviations from the trend line, the R^2, the existence (or not) of climatic anomalies and their forcing atmospheric circulation were also analysed.

3.2. Climatic and oceanographic analysis

Meteorological, hydrological and oceanographic databases were used to establish possible correlations of the observed changes in the position of the coastline, with series of events that could explain them. This approach seeks to analyse coincident responses in all or most of the analysed shores despite the noticeable differences in the physical parameters of the beaches and the mouths of this study.

Positive changes (accretion) of coastlines in both creeks' mouths were correlated with periods of heavy rainfall. During these periods, the ideal conditions for transporting sandy sediments to RdlP estuary and the ocean are generated. These sediments were introduced into the mouths by the tidal flow or wind where there are dunes next to the mouth, or due to inputs from the watershed, as analysed by Gutiérrez and Panario (2006, 2005).

This analysis was based on maximum rainfall events (>80 mm/24 h) in the basins of the Pando and Carrasco creeks using the precipitation rate and precipitation database (data provided by InUMet from the local rainfall network).

The positions of the coastlines, particularly the negative changes (retreats) were compared with the elevations of the RdlP caused by the great floods of the rivers Paraná and Uruguay, together or separately (Camilloni and Barros, 2003, 2000; Menéndez and Berbery, 2006; Nagy et al., 2002). These floods are able to increase the water height of the RdlP by 10–20 cm or plus (Bidegain et al., 2005; Nagy et al., 2005; Verocai et al., 2015). Therefore, Nagy et al. (2007) raised the hypothesis that river floodings could be a cause of the retreat of the coastline.

The historical series of decadal average and yearly maximum storm surges from 1921 to 2008 recorded in Montevideo were also analysed focussing on the search for matches from aerial photographic surveys occurred after (from months to a year) SSE and SSW wind-storms producing significant rise in sea levels (storm surges).

In turn, the effect on the response of the coastline (retreat or accretion) was analysed for years with ENSO events through composites of wind anomalies.[1] Two methods were used: i) atmospheric reanalysis of the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research), NOAA-CIRES Climate Diagnostics Center, Kalnay et al. (1996) based on the NOAA Global Circulation Model to estimate the zonal[2] (from the West: + and from the East: -) and meridional[3] (from the South: + and from the North: -) winds from 1948 to 2012, and ii) the Twentieth Century Reanalysis Project dataset (Version V2) lead by the Physical Sciences Division at the NOAA/ESRL (National Oceanic and Atmospheric Administration, Earth System Research Laboratory), and the CIRES at the University of Colorado, to estimate the wind vector anomaly from 1950 to 2010 and vector wind components anomalies at surface level from 1948 to 2011.

Tri-hourly average wind speed data from 36 directions were used, as well as the time-series of significant wave height and direction (Panario et al., 2008) in order to analyse and integrate results from climatic data, models and reanalyses.

These analyses were performed for the period October–March because beaches usually recover after the winter S and SW erosive winds (from July–August) and the ENSO signal is expressed from October onwards over the RdlP (Pisciottano et al., 1994; Ropelewski and Halpert, 1987). For the period 2000–2008 images are available for most of the years, so the possible relationships between the observed coastline fluctuations with Rossby waves were explored, because according to Simionato et al. (2005) they modify the position of the South Atlantic anticyclone (SA High Pressure).

ENSO events, classified as weak, moderate, strong or very strong were determined according to Climate Prediction Center, NOAA (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) and to Severov et al. (2004) for the period before 1950.

[1] Climate anomaly – The difference between the average climate over a period of several decades or more, and the climate during a particular month or season. (http://glossary.ametsoc.org/wiki/Climate_anomaly).

[2] Zonal Wind – The wind or component of a wind along a particular parallel of latitude: It is positive if it blows from the West and negative if it blows from the East.

[3] Meridional Wind – The wind or component of a wind along a particular meridian: It is positive if it blows from the South and negative if it blows from the North.

4. Results and discussion

4.1. Joint analysis of the study cases

Pocitos and Ramírez beaches have almost opposite orientations; however, they have a similar mineralogical composition (originated from rocks of Montevideo Formation). On the other hand, their drifts are divergent, so these are two separate beaches different from each other and the other beaches of Montevideo (Gutiérrez et al., 2015) (see Fig. 1, Tables 1 and 2).

These beaches have statistically significant difference in the mineralogy of the sand ($p < 0.01$) with neighbouring Buceo and Malvín beaches, while the mouths of Carrasco and Pando creeks have similar sources of sediment as Malvín beach, but differ from the others by having a recirculation of sediment by wind action and contributions of their watersheds. In turn, these beaches have different gradients of depth, making them change their typology from intermediate beach to dissipative beach. Because of all these factors it is particularly important to analyse the causes of the similarities in their behaviour through time.

4.2. Wind, waves and storm surges

Not including hours without wind (calms), the hourly wind speed data at the Carrasco station (see Fig. 2) fit well to a Weibull distribution with a tail toward higher-energy events. The so originated positive asymmetry was associated with the fact that the mean was greater than the mode of the distribution, indicating that the average wind conditions were disturbed by strong rare events linked to disturbances such as the passage of cyclone systems and cold fronts (Panario et al., 2008).

The wave rose data (see Fig. 3) closely matches the prevailing wind and swell directions coinciding with modelled reanalyses. In turn, the exploratory analysis of the wave data in Punta Brava values showed that significant height (Hs, in meters) and period (T, in seconds) had a frequency distribution which fitted a log- Normal function ($p < 0.001$). The main parameters were: Average Hs (m) 0.539, T (s) 5.657427; median Hs (m) 0.46, T (s) 4.4; mode Hs (m) 0.35, T (s) 2.9; standard deviation Hs (m) 0.38121, T (s) 3.983412 (Panario et al., 2008).

Matches between records of aerial photos and previous storm surges were recorded in the years 1943, 1993 and 2005. Although there were no coincidence of storm surges occurrence with photos for all studied sites, the available superimposed trends suggest the existence of storm signs in all cases except Malvín, where the signal was only recorded in the dry sand surface, not in the full beach. This can be attributed to the fact that during strong southern wind storm surges Malvín beach receives sediments passing over the tombolo linking Malvín with Brava beach, since the height of waves exceed its maximum height, offsetting losses related to these extreme events. Three storm events coinciding with elevations of more than 2.11 m AMSL were found coinciding with average daily Southern winds (S) from 24 m/s (85 km/h) to 31 m/s (110 km/h). These events can overcome most of the prism beach in most of the study area. Their occurrence from 1921 to 2008 was six times (0.068), only once since 1950 (0.017). However, Verocai et al. (2015) found a slight increase of the occurrence of events greater than 1.69 and 1.89 m AMSL over the last decade.

4.3. Exceptional rainfall

There was no evidence of clear trends associated with extreme rainfall in the basins of Pando and Carrasco microtidal creeks and in the beaches near them.

4.4. Floods of the tributaries of the Río de la Plata basin

The comparison between the events of river flooding and the morphodynamics of the studied beaches showed an opposite trend to what might be expected, given that the highest recovery in all the studied sites coincided with major river floods, and relatively high water level values. These results are not consistent with the hypothesis linking high flow and erosion.

4.5. General atmospheric circulation anomalies

The existence of relationships between the evolution of beaches and ENSO events was analysed, showing multiple matches of photogrammetric records with the latter (Figs. 4–6). Several papers (Nagy et al., 2008b; Severov et al., 2004; Simionato et al., 2005), suggest the existence of a signal of ENSO events in the South-western Atlantic Ocean at sea level pressure (SLP) and sea surface temperature (SST) with a weakening of the Malvinas Current and strengthening of Brazil current during El Niño, and vice versa during La Niña. It is arguable, in agreement with the findings of Iriondo et al. (2009 and citation therein) for the Holocene, the existence of a higher incidence of strong winds from the South quadrant and more specifically Meridional Wind (+) during La Niña, and increased Zonal wind (−) during El Niño events.

Due to the existence of coincidences between La Niña events with coastline retreats or loss of dry area in all analysed beaches, we decided to verify the hypothesis that ENSO-related circulation anomalies could explain the observed changes. For this, the NCEP/NCAR reanalysis (Kalnay et al., 1996) and the Twentieth Century Reanalysis were used to estimate the meridional and zonal wind anomalies, and the latter was also used to estimate vector wind components at surface level respectively. These reanalyses were applied for moderate and strong ENSO events, and even weak ones,

Table 1
Characterisation of four beaches.

Beach	Primary dune	Classification	Sand mineralogy	Slope	Coastal tipology	Orientation (normal to the direction tangent)	Exposure length (m)
Ramírez	No	Dissipative	Feldspathic quartz medium sands with amphibole and pyroxene	Smooth (1.9°)	Pocket	N68°E	500
Pocitos	No	Intermediate	Feldspathic quartz medium sands with amphibole and pyroxene as main accessory minerals	Smooth (1.8°)	Pocket	N43°W	1425
Buceo	Protodune	Dissipative	Feldspar quartz sands, with very little amphibole and pyroxene, very few points garnet points	Smooth (1.9 −2.2°)	Logarithmic spirals	N28°W	887
Malvín	Partially	Dissipative to intermediate	Medium feldspathic quartz sands, and very little amphibole and pyroxene, calcite, opaque, garnet points, zircon, tourmaline, andalusite and epidote	Smooth (1.9 −2.2°)	Logarithmic spirals	N3°E	1072

Table 2
Characterisation of two creek mouths.

Creeks' mouth	Primary dune	Classification	Sand mineralogy	Orientation (normal to the direction tangent)	Trench length (m)
Carrasco	Degraded	Dissipative to intermediate	Feldspar quartz medium sand with very little amphibole and pyroxene, calcite, opaque, garnet points, zircon, tourmaline, andalusite and epidote	N26.3°W and N36°W	1549
Pando	No	Dissipative to intermediate	Feldspar quartz medium sand with very little amphibole and pyroxene, calcite, opaque, garnet points, zircon and tourmaline.	N24°W and N17.3°W	3290

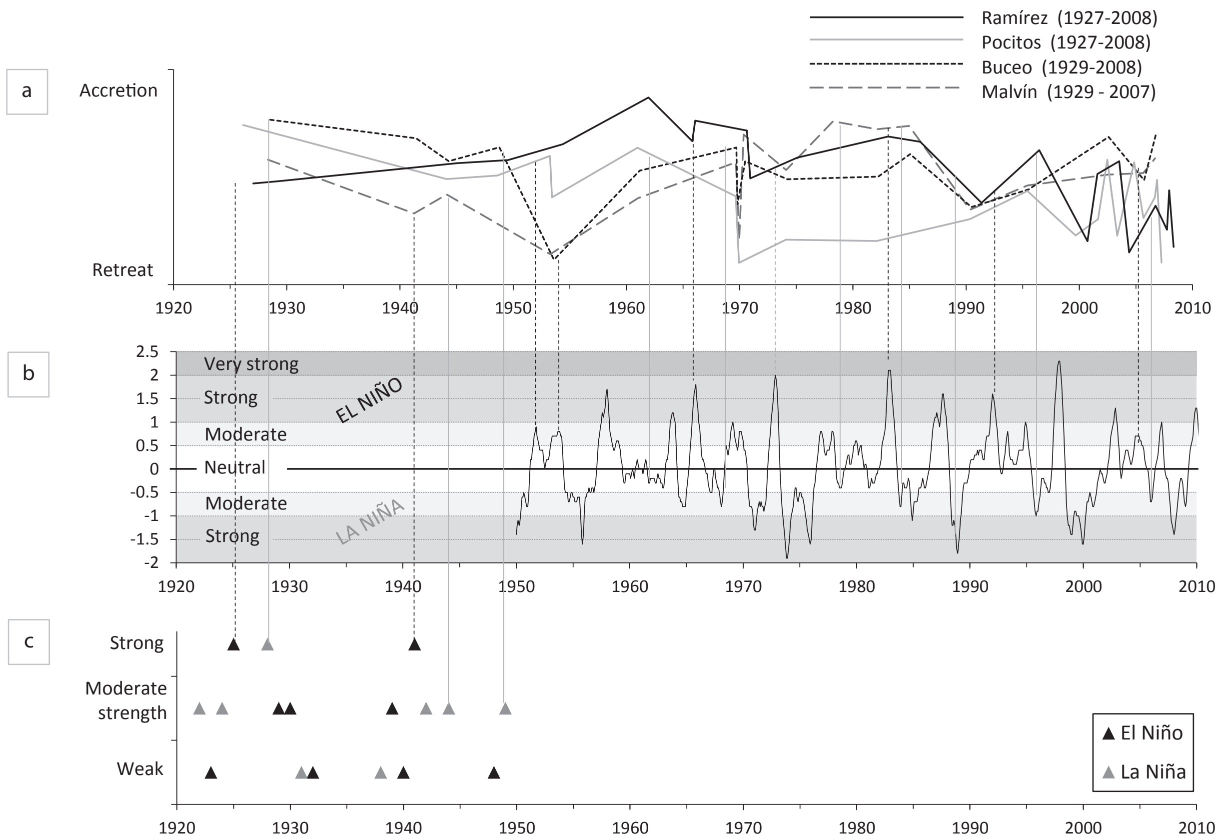

Fig. 4. a) Historical development of the beaches Ramírez, Pocitos, Buceo and Malvín, indicated as coastal accretion or retreat process. b) ENSO events, classified as weak, moderate, strong or very strong according to Climate Prediction Center, NOAA (period 1950–2010). c) ENSO events according to Severov et al. (2004) for events before 1950. The vertical gray lines (La Niña) and the vertical dashed black lines (El Niño) suggest the links between the coastal fluctuations and teleconnections.

if they occurred in the context of a multi-year event (e.g., from 1973 to 1975).

Due to the relatively low number of moderate and strong El Niño/La Niña events from 1950 to 2010 (less than 20) the results of wind anomalies are not conclusive yet but allow stating a working hypothesis to depict the relationship between ENSO-related wind anomalies and beach accretion–erosion processes.

The analysis focused on the anomalies of surface winds on the Uruguayan coast, showing a positive anomaly of SW winds associated with retreats of the coastline during La Niña events as suggested by Gutiérrez et al. (2015) for Ramírez and Pocitos. Nevertheless, if all La Niña events were considered, no significant correlation was found as either observed by Simionato et al. (2005), which could be attributed to the fact that the signal of weak ENSO events (+/−0.5 °C) is poor. For instance, from October–March ESE-SE winds usually increase and a light ENSO signal can be masked.

Wind anomalies were also recorded in neutral years, i.e., in 1961, 1970. In 1970 retreats were recorded in all beaches due to the observed increased frequency of southern winds.

Thus, despite the strong association between El Niño and increased river discharges, beach area was recovered during several of these events (Gutiérrez et al., 2015).

During strong ENSO events yearly sea levels (SL) at Montevideo lie outside the long-term trend line. For instance, during La Niña SL is −5 to −15 cm below MSL and during El Niño it lies +5 to +20 AMSL (Nagy et al., 2005; Verocai et al., 2015).

The observed behaviour of the coastline could be interpreted as follows: The SW winds -associated with both winter period and La Niña variability-produce short period waves, change the direction of long shore drift in the analysed beaches (except Ramírez), raise the water level (although to a lesser extent than the S and SSE winds), and also cause the retreat of the coastline. These effects are likely to be compensated during austral spring and summer, or during El Niño events, when winds anomalies are reverted intensifying the spring-summer time usual recovery. Wind climatology show that the strongest wind velocities occur in August associated with SW-WSW winds and October associated with ESE-SE winds (Nagy et al., 1997).

The NCEP-NCAR composites of meridional and zonal wind anomalies over the RdlP and the Atlantic coast for moderate and

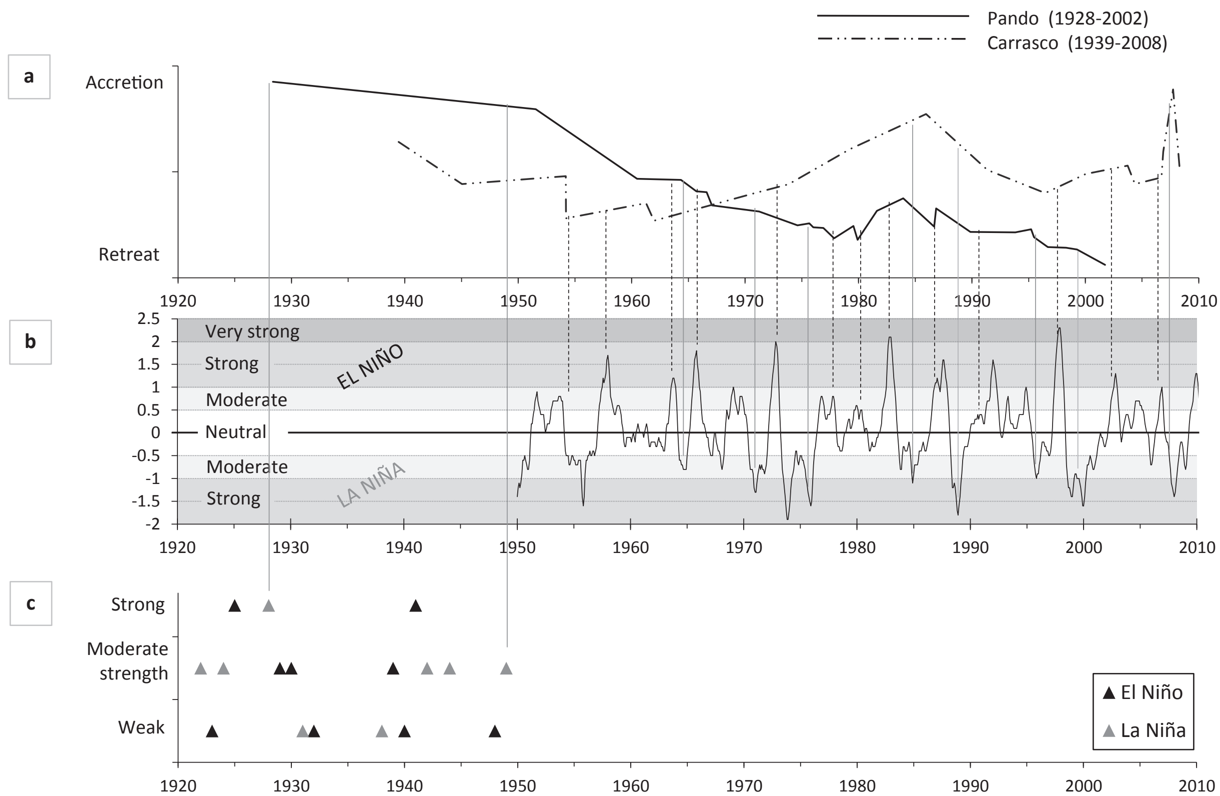

Fig. 5. a) Historical development of the Carrasco and Pando tidal creeks mouths, indicated as coastal accretion or retreat process. b) ENSO events, classified as weak, moderate, strong or very strong according to Climate Prediction Center, NOAA (period 1950–2010). c) ENSO events according to Severov et al. (2004) for events before 1950. The vertical gray lines (La Niña) and the vertical dashed black lines (El Niño) suggest the links between the coastal fluctuations and teleconnections.

strong ENSO events from 1950 to 2010 confirmed that the most important anomaly was the meridional component from October to March. During this period an increase of northerly winds (warm, moist and weak winds) expressed by an anomaly of −0.2 m/s (Fig. 7) was observed. During La Niña southerly winds increased (positive anomaly of +0.2 m/s on the Atlantic coast). The zonal component showed positive anomalies in both phases although somewhat higher during El Niño when the zonal circulation, particularly the easterlies, slightly increased. Results obtained with 20th century reanalysis for the Uruguayan coastal areas were very similar.

The reanalysis of the fields of vector wind anomalies (speeds) from October–March for all moderate and strong events showed anomalies from SW of 0.8 m/s during La Niña, and 0.4 m/s from W-WNW during El Niño (Fig. 8).

Summarising, climate analysis of joint frequency of wind speed and direction indicates higher mean speeds, e.g., in August and October with WSW-SW and ESE-SE winds respectively. The La Niña events increase the frequency of SW to WNW, which typically prevail during fall-winter (April–September). The El Niño increases ESE-SE ones during spring-summer (October–March). Therefore, it is arguable that it is very likely that the effect of the La Niña reinforces climatic winter beach sand losses (July–August), whereas El Niño reinforces and/or extends summer beach sand accretion from October onward.

Results of vector field anomalies' are closely associated with strong southern to western directions (WSW and SW) > 8 and > 10 m/s, whereas the meridional-zonal anomalies are closely associated with the prevailing south-eastern frequencies. The similar field anomalies during La Niña (SW to WNW) for both methods are the resultant of the coincidence of frequency and speed, whereas the differences for El Niño are related to the increased frequency of typically fresh to strong eastern to south-eastern winds (<8 m/s) and of the far less frequent but stronger (>8 m/s and >10 m/s) western winds (see Fig. 2). Therefore, the increased frequency of fresh SE winds (>6 m/s) is masked by the small increase of strong W winds (>8 m/s).

This result coincides with previous observations about ENSO influence on atmospheric circulation anomalies from October–March as well as with the observed and projected increase in eastern to south-eastern winds over the Uruguayan coast. Therefore, it could serve as an analogy to foresee coastal evolution and management scenarios.

The evolution of decadal mean of the maximum yearly storm surges (Fig. 9) and of the AMO (Ortega et al., 2013) showed a similar development trend which was not reflected in the evolution of the studied beaches, except partially in Ramírez. However, this effect is likely to have occurred and should be explored at lower prism height beaches in some sections of both inner and outer estuary, with cliffs that have actively retreated in the past and which nowadays are stabilised or receding more slowly.

Since 2000 yearly available images show a bi-annual variation in neutral years (see last few years of Fig. 4). This could be associated with the Rossby wave signal in SST and SLP in the South Atlantic reported by Simionato et al. (2005). Nonetheless, this hypothesis should be analysed using a denser and longer series of images and/or land monitoring.

Therefore, the key climatic teleconnections factor of accretion–erosion processes seem to be the occurrence of moderate to strong La Niña which are pulses of severe events, while El Niño events allow partial or full sand recovery on the short- and mid-term scales. The quantitative balance of this superimposed

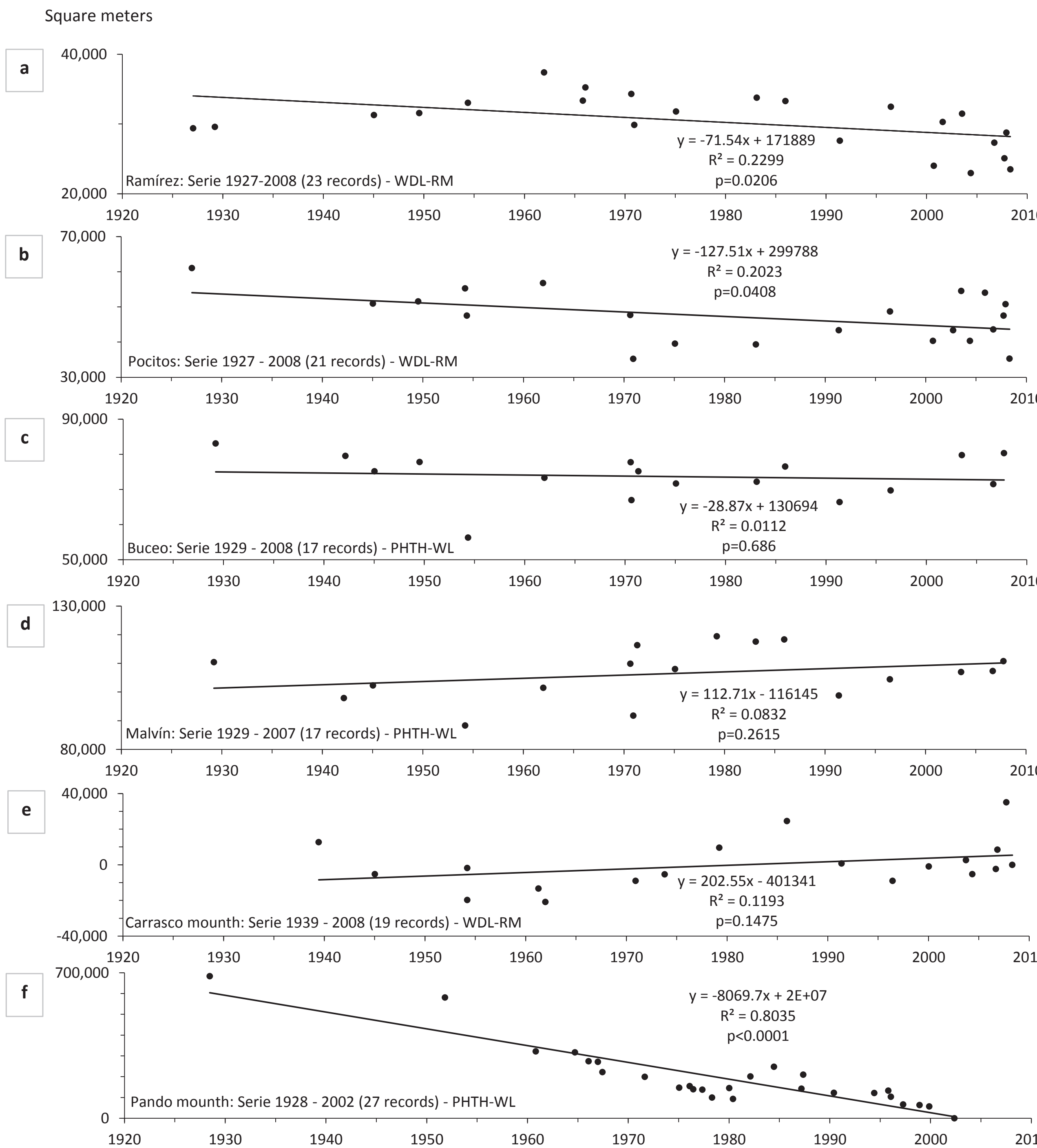

Fig. 6. Historical trend-line of study sites. Beaches: a) Ramírez, b) Pocitos, c) Buceo, d) Malvín. Creeks' mouths: e) Carrasco, f) Pando. The series of remote sensing observations have a minimum of 17 records and a maximum of 27. Different proxy records were explored as indicators of coastline in order to interpret the responses of the system, wet/dry line or run-up maxima (WDLRM) or previous high tide high water level (PHTH-WL).

seasonal and interannual sedimentary budget is difficult to be made due to the parallel effects of gradual sea level rise, storm surges and human interventions.

Fisher et al. (2015) identified three specific challenges in climate change and resilience monitoring and evaluation: i) assessing attribution, ii) creating baselines, and iii) monitoring over long time horizons. This paper addressed the attribution of urban sandy beaches accretion–erosion processes, baselines, long-term series of climate teleconnections and weather extremes, and developed an approach to monitoring and evaluation, aiming to increase beach resilience to SLR and storminess.

Coastal management and adaptation to climate threats have been mostly based on reactive responses to date. In order to achieve practical management implications of ENSO impacts, as well as of other climatic modellers and threats to coastal systems, i.e., storm surges and SLR, it is necessary to foster continuous prognosis, monitoring and modelling of both climatic threats and coastal responses on monthly to seasonal basis. Soft measures such as

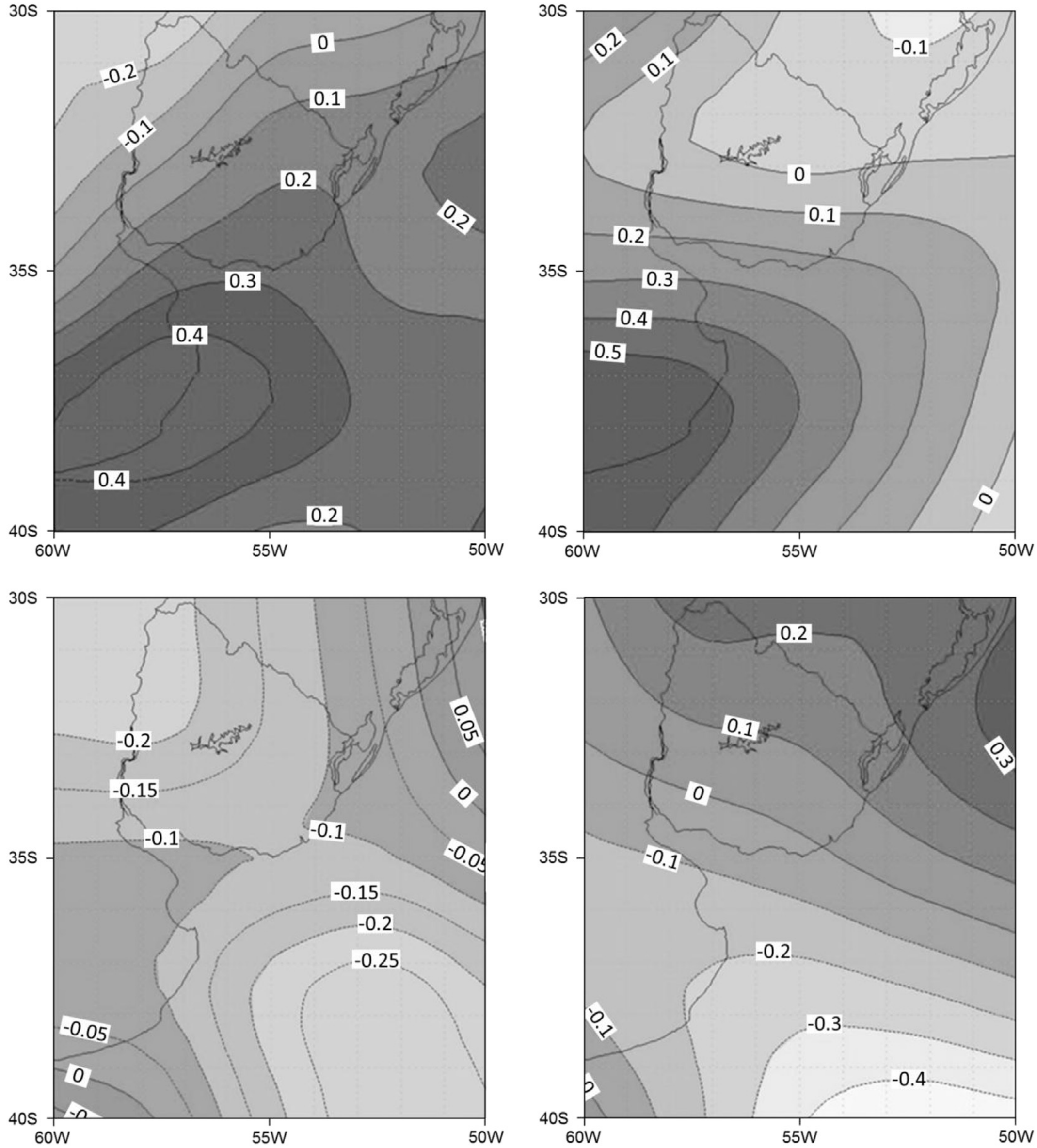

Fig. 7. Composite of zonal and meridional wind anomalies for moderate and strong ENSO from 1950 to 2010 (NCEP-NCAR reanalysis). Zonal anomalies: El Niño (above left), La Niña (above right), and meridional anomalies: El Niño (below left) and Niña (below right).

rebuilding of sandy dunes and planting of psammophyte vegetation among others, require financial resources and logistical planning for their implementation at appropriate times. Any failure due to a lack of foresight often discourage authorities to allocate resources for this purpose. This would allow to transform a threat into an opportunity by taking pro-active actions to increase coastal resilience, particularly in relation to sandy beaches and tidal creeks' mouths.

5. Conclusions

This article surveyed the behaviour of managed urban sandy beaches at a wave dominated coast of a large and unique microtidal system, the Río de la Plata's northern coast in Uruguay, and climate stressors such as wind extreme events and climate teleconnections, mainly ENSO-linked variability.

The working assumption of this article may be resumed as follows: The shape, size and characteristics of sandy beach and dune systems are the consequence of the particular interaction between the energy of waves and wind, with their grain size, equilibrium profile and roughness. Any change to any of these factors may result in a realignment of the beach. This flexibility and ability to work with pulses is the reason that the sandy beaches are considered the best coastal defence. Therefore, these systems are cyclical, with alternating periods of erosion and accretion, to give a type of position and geometry in the medium and long term.

Main key findings are: i) A relationship was found between the observed changes in urban beaches and teleconnections (ENSO), while it is arguable the existence of an effect of Rossby waves. ii) No correlation was found with water level variations attributable to river discharge. iii) The sand surfaces of the middle estuary beaches analysed in this article have varied due to atmospheric circulation anomalies such as exceptional storm surges associated with more frequent southern winds that erode beaches or zonal winds that enable their recovery. iv) The studied beaches are often more eroded during strong La Niña events due to a higher frequency of

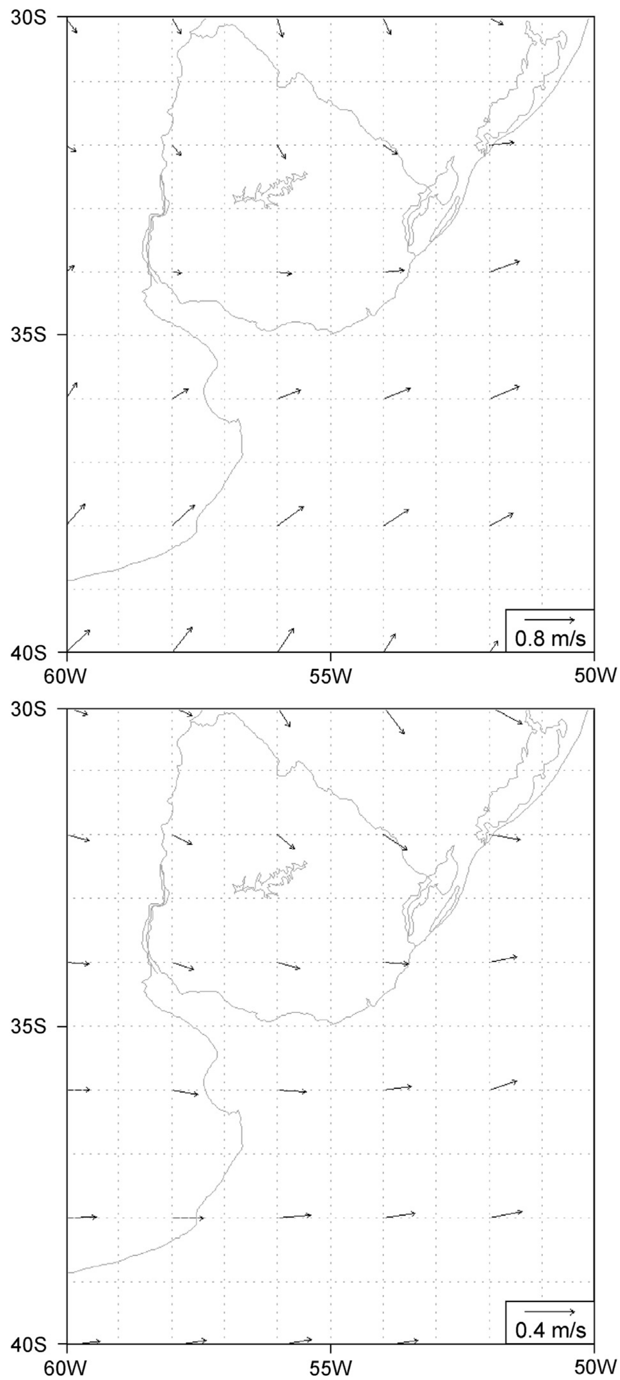

Fig. 8. Wind Vector Anomaly (m/s) for ENSO events during Oct–Mar, from 1950 to 2010 (NOAA 20th Century Reanalysis Project): La Niña years (above) and El Niño years (below).

typically strong SW winds than during neutral years, whereas during El Niño a decrease in the frequency of SW winds and a relative stabilisation or even gain in the exposed sand area is observed. This finding is supported by climatic reanalyses of wind anomalies for moderate and strong ENSO events from 1950 to 2008 besides field and remote sensing observations since 1921. v) The strong surface gain of Ramírez Beach in 1961 could be correlated to a light eastern winds anomaly, which would have strengthened the swell. This was also observed, although to a lesser extent, in Pocitos, Buceo, Malvín beaches and in the Pando and Carrasco creek tidal mouth.

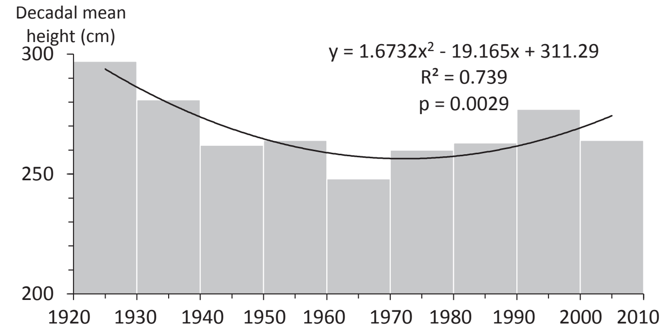

Fig. 9. Evolution of decadal mean of the maximum yearly storm surges for de RldP.

The main conclusion was that the results presented in this article highlight the likely existence of some degree of relationship between ENSO events and beach erosion–accretion processes.

The main questions to be explored in a further study are: i) Which is the response to other teleconnections e.g., Rossby waves and AMO? ii) Will the likely increase in the frequency and/or intensity of El Niño events be a risk or an opportunity for the studied beaches? iii) How was the relationship between ENSO wind-anomalies and beach accretion–erosion processes from 2009/10–2015/16 (when three moderate to strong events occurred).

Since ENSO seems to be a good descriptor of the status of sandy beaches of Montevideo during ENSO years and ENSO +1, there are practical implications in coastal erosion risk-management, climate adaptation, planning of sandy beaches conservation and restoration. The occurrence of El Niño events could become an opportunity to develop pro-active beach management plans to reduce risks provided an improvement of observational, forecasting and modelling tools and capacities are achieved. The implementation of this measure will also serve as an experience to adapt to both storm surges and gradual sea level rise.

Monitoring change within the coast and estuary play an important role in understanding the impacts of climate change.

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