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Winter Sedimentology and Morphology of the Maçambaba Beach–Foredune System, SE Brazil

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ABSTRACT

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The Maçambaba Holocene coastal barrier and dune system in Rio de Janeiro state, Brazil, is located immediately west of an abrupt orientation change from SW-NE to W-E on the SE Brazilian coastline. The eolian deposits are formed by winds from the SW, associated with polar air masses advancing in austral winter, and winds from the NE, associated with summer monsoon and upwelling intensification. The active beach–foredune system consists of intermediate reflective beaches and ramp incipient foredunes in the western (km 0–km 14) and central (km 15–km 35) sectors of the barrier and intermediate to dissipative beaches with more common ridge incipient foredunes in the eastern sector (km 36–km 48). This pattern from W to E indicates a change in the beach–foredune system from a more erosional regime with lower sand supply in the west to a more depositional setting in the east. Measured at the swash line, winter mean grain size fines and granulometric sorting increases from W to E, evidence of a net longshore drift in this direction. The increase in eolian sand supply toward the east favors sand reworking by SW (onshore) winds in the winter; consequently, coastal dunes are well developed in this sector. Overwash processes frequently develop where eolian deflation favors marine inundation during winter swell events. After their formation, washover fans are typically reworked by reverse winds from the NE (offshore) in austral summer. Throughout the entire barrier system, seasonal shifts in both swell orientation and wind direction are dominant climatic factors determining the development of washover fans, blowouts, and parabolic dunes with opposing migration directions. Investigating the effect of this climatic seasonality on the beach–foredune system is critical to understanding coastal response to storm events and climatic variations on longer timescales.

ADDITIONAL INDEX WORDS: *Coastal barrier, eolian sand deposits, coastal processes, climatic factors, washover fans, opposite winds.*

INTRODUCTION

Maçambaba beach is a W-E–oriented, 48-km-long coastal barrier (Figure 1) located in the Cabo Frio region, Rio de Janeiro state, SE Brazil. The barrier is situated immediately west of an abrupt change in coastline orientation, from SW-NE to W-E. This change promotes deviation of the Brazil Current from the coast and is one of the factors responsible for the coastal upwelling system known as Cabo Frio (Figure 2). Upwelling on the Brazilian shelf is also induced by winds from the NE (Albuquerque *et al.*, 2014; Campos, Velhote, and da Silveira, 2000) and favored by seasonal intensification of the South Atlantic Subtropical Anticyclone (SASA), originating from the Intertropical Convergence Zone (ITCZ) during austral summer (Garreaud *et al.*, 2009; Melo, Cavalcanti, and Souza, 2009). Another major climatic element acting in this region is the Polar Marine Anticyclone (PMA), whose migration to the north induces the passage of cold fronts associated with predominant winds from the SW mainly during austral winter (Valentin, 2001). The PMA shift to the north can be associated with the Southern Westerly Wind (SWW) belt expansion in the same direction over long timescales (centuries to millennia; Voigt *et al.*, 2015).

Cooling of coastal waters by upwelling is responsible for relatively low local precipitation rates (<1000 mm/y). The semiarid microclimate (Biassi, 1975; Martin *et al.*, 1997; Valentin, 1984) keeps sand cohesion low throughout the year and favors alternating sand deposition by opposing winds (Andrade and Giannini, 2016; Andrade *et al.*, 2015). This climatic context shapes the regional dune system, which is notable because the Cabo Frio region is the only area of dune fields in SE Brazil under the influence of the South Atlantic Convergence Zone (Giannini *et al.*, 2005). Active eolian features that are close to the beach comprise foredunes, SW blowouts, and NE parabolic dunes. These are best developed in the eastern part of the barrier.

The development of an eolian depositional system depends on the accumulation of eolian sediments, meaning a positive balance between influx and efflux of eolian sediment. Three fundamental factors control this balance. The first factor is wind strength and its capacity for sediment transport (Kocurek and Lancaster, 1999). The second factor is eolian sediment supply, which can be classified as external or internal (Kocurek and Lancaster, 1999). In a coastal system, the external supply

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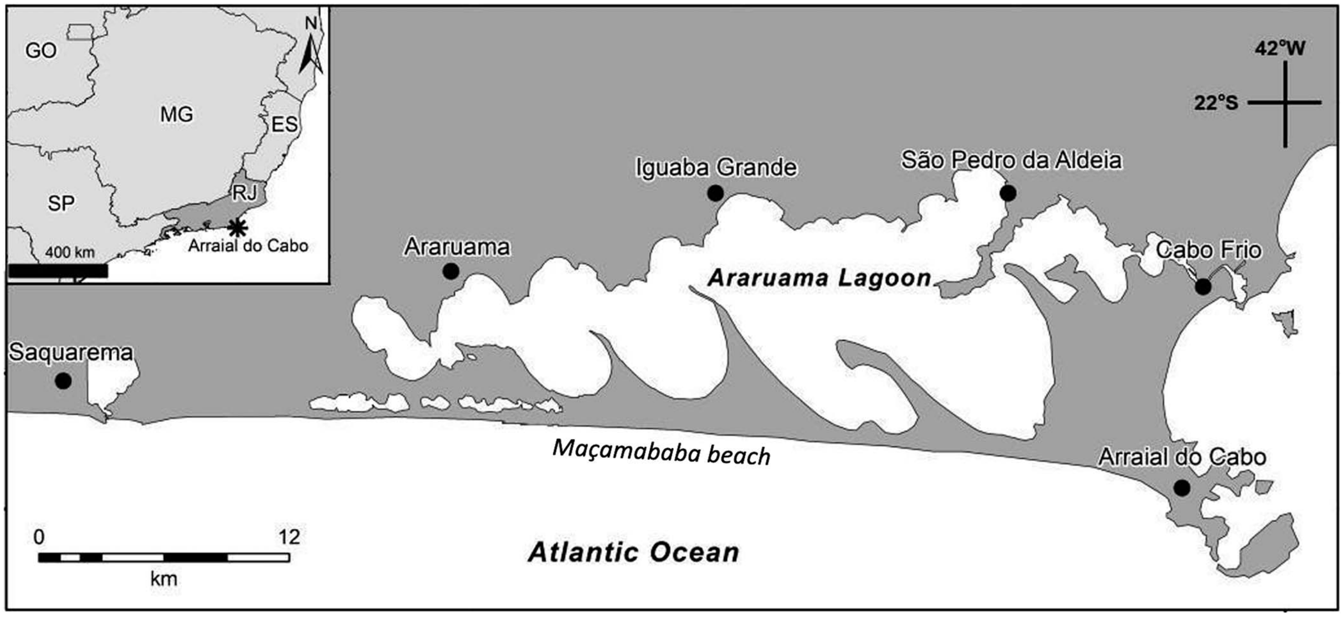


Figure 1. Location of the Maçambaba coastal barrier in Rio de Janeiro state (RJ).

corresponds to the sediment present in the neighboring depositional system on the sea side, particularly within the intertidal prism. The internal supply refers to the sand within the eolian system, starting with the primary dunes commonly represented by foredunes (Giannini *et al.*, 2014). The third factor is the availability of sand, which refers to the susceptibility of surface sediment to be transported by the wind (Kocurek and Lancaster, 1999).

Variations in the development of blowouts associated with foredunes and washover fans along Maçambaba beach indicate changes in the balance of influx and efflux and can be related to wind transport capacity, eolian supply, and/or sand availability. Wind capacity varies seasonally: SW winds are more active in winter, whereas NE winds and upwelling intensify during summer. Eolian supply can be influenced by longshore coastal drift, eolian fetch, and grain size. Foredunes work as sand suppliers during periods of intense erosion of the coastline. When there is constructive imbalance in the foredunes (eolian influx exceeds eolian efflux), the exceeding sand forms other types of eolian features, such as blowouts and parabolic dunes (Giannini *et al.*, 2014). Finally, eolian availability is influenced by sand cohesion at the source area, influenced by storm and overwash processes. It also has a seasonal pattern, because these processes are more common and intense in the winter. Storm waves and overwash have ambiguous effects on the system. They immediately impede eolian transport because of flooding and increased cohesion of sands at dunes and backshore. But in the end, they deposit or expose, through erosion, sand without vegetation cover, which is liable to be reworked by the wind when dry.

In Maçambaba, eolian features are key components of the coastal sand-sharing system, because they work as sediment sources and sinks when wind direction and wave energy fluctuate seasonally.

Geological Setting

The Maçambaba barrier is located between the communities of Saquarema and Arraial do Cabo in the Lakes Region on the Rio de Janeiro central coast. The adjacent inner continental shelf is a smooth, wave-swept surface characterized by moderately to well-sorted medium sands and rare outcrops of crystalline and sedimentary rocks (Muehe and de Carvalho, 1993). The Maçambaba coastal plain has been described as having two terraces (Martin *et al.*, 1997). The older terrace is a last interglacial Marine Isotopic Stage (MIS) 5e stranded barrier located landward of the modern barrier–dune complex (Dias and Kjerfve, 2009; Muehe, 2006). The younger terrace developed over the late Holocene as sea level stabilized and sedimentary processes contributed to a general pattern of coastal accretion (Andrade and Giannini, 2016; Andrade *et al.*, 2015; Dias and Kjerfve, 2009; Fernandez and Muehe, 2004; Martin *et al.*, 1997; Turcq *et al.*, 1999).

Tides and Waves

Maçambaba beach is a microtidal system with an average tidal range of 1 m. Southern swell waves generated in the southern ocean are present throughout the year with periods of 8 to 12 s and heights of 1 to 2.5 m and are found seasonally in combination with three other wave regimes: (1) locally generated summer–spring NE wind waves with periods of 5 to 8 s and heights of 1 to 2.5 m, (2) locally generated winter–autumn east wind waves with periods of 6 to 12 s and heights of 1 to 3 m, and (3) SW swell waves with periods of 6 to 16 s and heights of 2.5 to 5 m associated with cold front passages in the South Atlantic induced by the PMA from April to June (Cotrin, Semedo, and Lemos, 2022; Lourenço and Siegle, 2012).

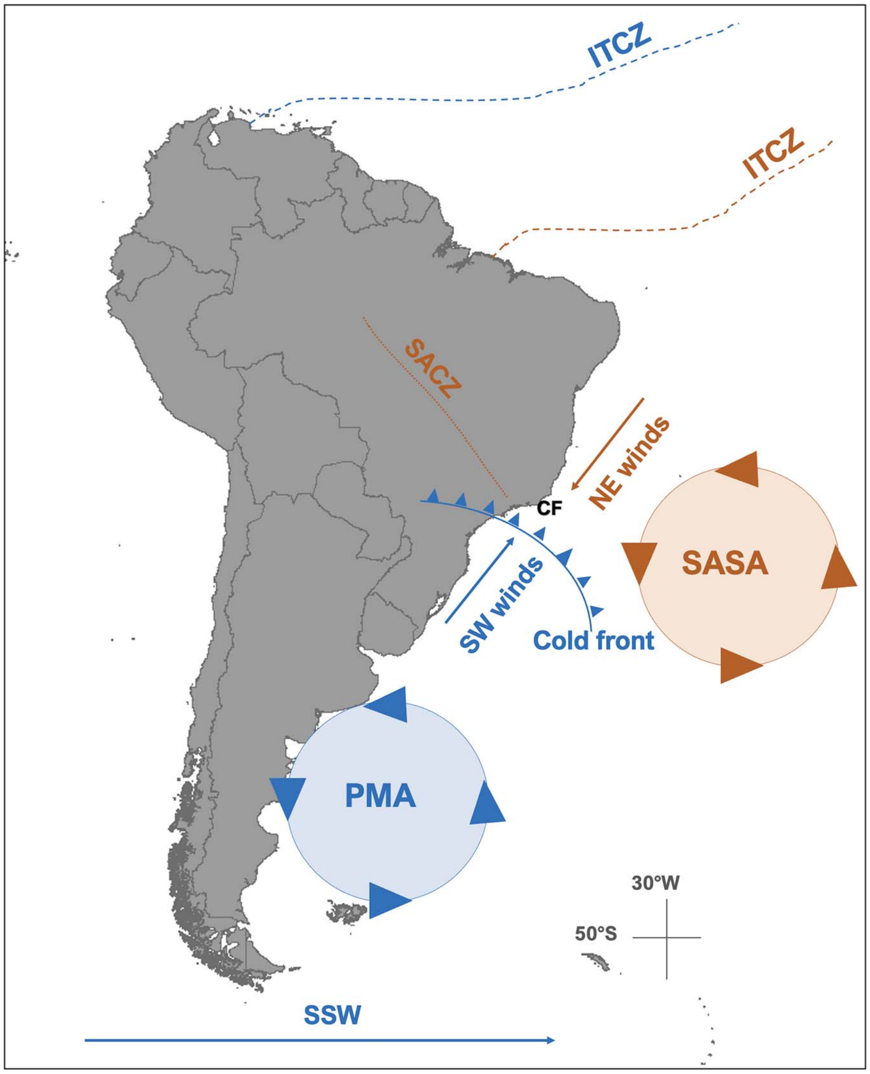


Figure 2. Atmospheric features and predominant climatic elements acting on the Maçambaba coastal barrier during summer (orange) and winter (blue). The morphology of eolian features is governed by seasonally reversing winds, a unique feature of the study area controlled by regional climatology. CF = Cabo Frio upwelling system, ITCZ = Intertropical Convergence Zone, SACZ = South Atlantic Convergence Zone, SASA = South Atlantic Subtropical Anticyclone, PMA = Polar Marine Anticyclone, SWW = Southern Westerly Wind.

Geomorphology

The main eolian features found along Maçambaba beach are incipient and established foredunes, blowouts, and parabolic dunes. Foredunes are defined as shore-parallel dune ridges formed by eolian deposition within the vegetated backshore and/or upper foreshore (Martinho *et al.*, 2006). Foredune formation depends on the presence of vegetation, sand supply, and then various other elements, such as wind patterns, surf zone–beach type, plant species present, and the density, distribution and frequency of storms (Hesp, 2002; Hesp *et al.*, 2021).

Hesp (1983) classified foredunes as either incipient or established based on their morphological and phytoecological complexity and evolution. According to Hesp (1988), foredunes begin as incipient and evolve to become established with increasing height, width, age, morphological complexity, and botanical diversity. Incipient foredunes are distinguished from established foredunes by the prevalence of active eolian deposition, plant colonization age, and geomorphological complexity. Established foredunes develop from incipient foredunes. Established foredunes are characterized by lower sand deposition rates and can be intensively reshaped by erosion (Hesp, 1988).

Hesp (2002) identified three morphological types of incipient foredunes: ramp, terrace, and ridge. In many cases, an evolutionary sequence occurs in which ramps become terraces, which in turn may become ridges. Each of these types is formed under specific conditions. Ramps are typically newly accreting features, prograding seaward, that form on the seaward stoss slope of an established foredune. Terraces evolve from ramps and are typically found in association with rapidly accreting beaches. Ridges form where either beach accretion has slowed or the incipient foredune is older (Hesp, 2002).

A blowout is a saucer-, cup-, or trough-shaped depression or hollow formed by wind erosion on a preexisting sand deposit (Hesp, 2002; Martinho *et al.*, 2006). These erosional eolian features are common in coastal dune environments, particularly where beaches and foredunes are occasionally eroded and/or receding, but they also occur in stable and accreting environments where wind and wave energy is high (Hesp, 2002). Coastal blowouts often form in the foredune, especially where there is low vegetation cover that might occur naturally or because wave erosion or human or animal traffic is common (Hesp and Walker, 2021).

Parabolic dunes are similar to blowouts but present more elongated arms. These dunes have a U or V shape. In coastal settings, they often form when wind erodes a section of the backbeach area and pushes sediment leeward while vegetation stabilizes (holds) the arms.

Beach Morphodynamics and Beach–Foredune Interaction

Seasonal dune development in Maçambaba is tied closely to beach profile response to wave forcing. Therefore, the variety and degree of development of eolian features are related to the beach morphodynamics. Wright and Short (1984) classified beaches into six morphodynamic states to imply a complete assemblage of depositional forms and coupled hydrodynamic processes. Reflective beaches are characterized by steep beach faces and narrow swash zones. Dissipative beaches have low gradients and wide multibarred surf zones. Four intermediate states represent complex morphologies where dissipative and reflective elements coexist and vary significantly in both cross-shore and alongshore directions and where rips are common.

Assuming minimal longshore sediment transport and adequate sediment availability, Hesp (1983) and Short and Hesp (1982) proposed a model for beach and dune interactions suggesting that the dynamics, morphology, and evolution of foredunes and dune fields are strongly influenced by the beach morphodynamic state. The sediment transport from the surf zone to the beach and from the beach to the foredune is controlled mainly by the surf zone and beach type, which are determined by the morphological characteristics of the beach face and backshore (Hesp, 1988, 1999). This model is fundamentally based on the dynamic relationships of waves, beach, and surf zone morphologies and eolian sediment transport in foredune development. The morphodynamic state of the beach and type of surf zone are determined by waves, which control the amount of sediment that is transported from the shoreface and inner shelf to the beach. Miot da Silva, Mousavi, and Jose (2012) expanded this model through a pioneering study on wave refraction, wave-driven sediment transport, and foredune dynamics along a beach to the south of Maçambaba, in Santa Catarina state, South Brazil, showing that in headland bay systems, gradients in wind exposure, wave energy, and longshore sediment transport can overrule the control of the beach and surf zone morphodynamic state in dune development and evolution.

METHODS

Observational data were collected and analyzed to describe variations in morphology and grain size along the length of the beach–foredune system.

Remote Sensing

A remote sensing analysis was carried out to try to recognize geomorphological sectors along the Maçambaba coastal sand barrier as a whole. This analysis was done using DigitalGlobe and the National Centre for Space Studies (CNES) Airbus satellite images from 2004 to 2018.

The main criteria adopted for subdividing the barrier were as follows: the presence or absence of a high sandy terrace (Pleistocene barrier) and an associated lagoon on its outer margin (south), the existence of active or fossil blowouts and parabolic dunes, the presence and configuration of washover fans, and the continuity of the foredune alignment.

Topography

Topographic surveys of the Maçambaba beach–foredune system using a CST/Berger 24x automatic level were obtained over the period of 6 to 8 September 2013. The autolevel has an instrument resolution of 0.16 cm. Repetitive surveys were used to define a standard error of ±3.6 cm. A total of 48 topographic profiles spaced 1 km alongshore between Saquarema and Arraial do Cabo were collected. The spacing between each transect is considered representative of the morphological variability along the length of the beach–foredune system.

Profiles extended from the swash line (0 elevation) to the crest of the incipient foredune. Beach width is defined as the distance between the swash line and the toe of the adjacent incipient foredune. Although swash line variability resulting from tide change could be considered a negligible uncertainty in beach width measurements because of the microtidal regime, the tidal effect on the width was corrected by trigonometry based on the tide table. All profiles were oriented normal to the trend of the shoreline. Foredune width is defined as the distance from the seaward dune toe to the first crest.

During each survey, the beach morphodynamic state was described on the basis of the surf zone width, beach-face steepness, and presence of berms and cusps (Wright and Short, 1984). Foredunes were classified according to the nomenclature proposed by Hesp (2002): ridge, terrace, and ramp.

Sampling and Grain Size Analysis

One sediment sample from the swash zone and one from the incipient foredune crest were collected on each topographic profile for grain size analysis. Particle-size distribution was measured on a Malvern Mastersizer Granulometer by laser diffraction in a Hydro 2000MU. The sample mean size, sorting, and skewness were calculated using Pearson's moments from data grouped into 0.125-phi class intervals.

RESULTS

This section contains a proposal of geomorphological division of the barrier into three sectors, based on observation of satellite images; it also contains data obtained from a winter field survey along Maçambaba beach, including morphometric measurements, description of morphological characteristics, and grain size results.

Geomorphology

Based on geomorphological features, the Maçambaba barrier can be divided into three sectors. In the western sector (Figure 3A), both Pleistocene and Holocene barriers are continuous in the alongshore direction and separated by an interbarrier lagoon system. The Pleistocene barrier (up to 10 m in elevation) prevents overwash processes from flooding farther landward, thus confining washover deposition to the interbarrier lagoon and other locations between the two barriers. The interbarrier lagoon is characterized by small (approximately 1 km^2) and shallow (less than 2 m deep) basins that accumulate sediment and water during overwash events.

In the central sector (Figure 3B) past erosion of the Araruama lagoon shoreline released sediment to a system of now-stabilized parabolic dunes formed by predominant NE winds (Andrade and Giannini, 2016). These eolian deposits formerly migrated toward the SW and over the interbarrier lagoon, which in this sector is now partially buried.

The eastern sector is characterized by a relatively wide zone of coalescing washover fans deposited on a large paleospit that lies landward of the modern beach–foredune system. The washover deposits are reworked by well-developed parabolic dunes formed by NE winds and active blowouts associated with SW winds (Figure 3C). Individual washover fans are associated with the SW blowouts and interrupt an otherwise well-developed foredune ridge in the backbeach area. Blowout basins act as preferential channels for overwash processes. Typically, the flooding associated with overwash processes brought by storm waves from the SW is absorbed by eolian sand deposits landward of the active beach. Hence, in the eastern sector, there is no morphological evidence of the interbarrier lagoon system. In this way, these washover fans remain dry most of the time; they are reworked by NE winds to form parabolic dunes that migrate toward the beach and are seasonally subject to blowout development by SW winds. Thus, the eastern sector is characterized by a complex mosaic of seasonally active eolian features and overwash processes.

Morphometric Measurements and Morphological Features

Topographic surveys of beach width varied between 11.6 and 96.2 m (Figure 4A) and averaged 52.8 m. The incipient foredunes varied in width between 0.2 and 90 m (Figure 4A) and in height between 0.2 and 4.4 m (Figure 4B). Beach-face steepness (Figure 4C) ranged from 1.1 to 11.0° and averaged 3.7°. Beach width and steepness showed great variability (Figure 4D) across the length of the barrier, with the largest variations occurring in the eastern sector (km 27–km 48).

The western sector (km 1–km 14) was classified as high-energy reflective, with breaking wave heights between 0.7 and 1.5 m (Table 1). In the central sector (km 15–km 36), beach morphodynamics changed from reflective to intermediate dissipative, with intermediate energy and breaking wave heights between 0.4 and 1.2 m. In the eastern sector, the beach state was intermediate to dissipative, with low energy and breaking wave heights between 0.4 and 0.6 m.

Incipient foredune morphology varies along the entire Maçambaba beach–foredune system. In the western and central sectors (km 1–km 31), incipient foredunes were continuous with almost no erosional interruptions. East of km 31, incipient foredunes were interrupted by blowouts (Figure 5) associated with washover channels. Blowouts were best developed between km 35 and km 36. The observed variation in incipient foredune width (Figure 4A) and height (Figure 4B) are related to blowout and overwash processes. In the western and central sectors (up to km 31), foredune width and height averages were 29.1 and 1.3 m, respectively. From km 31 onward, width and height averages increased to 32.3 and 2.6 m, respectively. Similar to beach width distribution, foredune width maximum (96.4 m) and minimum (2.5 m) values were found on the easternmost 17 km.

In the western sector (Figure 6A–C), incipient foredunes usually occurred as ramps anchored on established foredune terraces. In the central sector (Figure 6D–F), incipient foredunes occurred as ramps, although in this sector they were anchored on established ridges. In the eastern sector (Figure 6G–I), both incipient and established foredunes appeared as asymmetric and discontinuous ridges.

During the topographic survey, berms and cusps were observed throughout the barrier. Double berms or scarps carved on berms were found at some sampling locations, and scarps were more frequent in the eastern portion, indicative of a more dissipative state. Based on this evidence, and considering the increasing breaker zone width, less steep beach face, and less pronounced berms eastward, the morphodynamic state was qualitatively described as intermediate to reflective in the western part (km 1–km 14) and as transitioning to intermediate to dissipative toward the east (from km 15 onward).

Grain Size Analysis

Statistics of granulometric distribution (mean size, standard deviation, and skewness) show decreasing variability from W to E (Figure 7). There is similarity between beach and foredune mean grain size and standard deviation distribution along the barrier (Figure 7A,B). In contrast, beach and foredune skewness values are similar only in the eastern part of the barrier (Figure 7C).

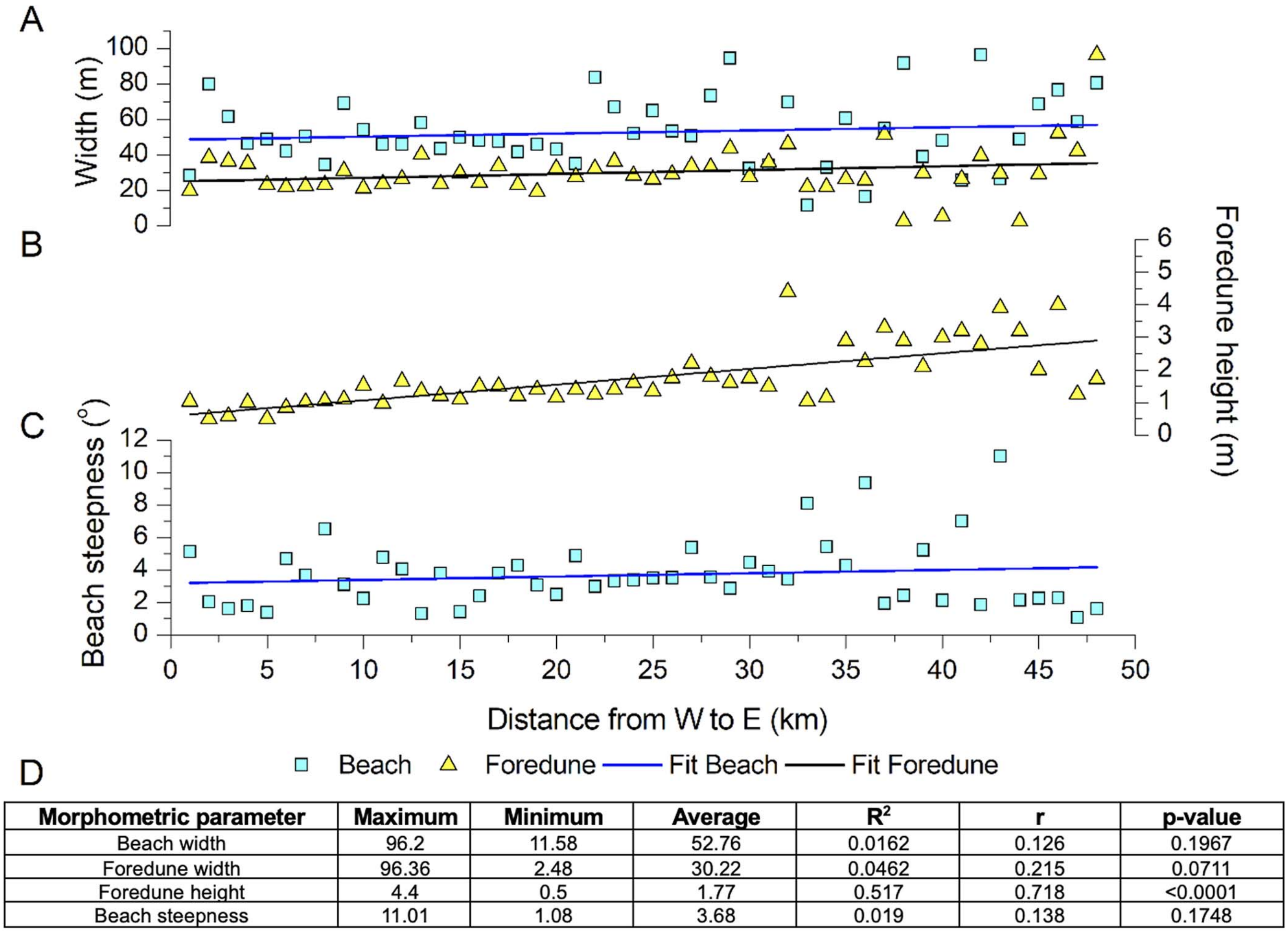
Mean grain size tends to fine (with increasing phi values) eastward (Figure 7A). Granulometric results permit division of the beach–foredune system into two segments: from km 1 to km 26 and from km 27 to km 48. Mean grain size at the swash line and at the foredune crest show poorer correlation with distance ($r = 0.348$, $p = 0.00407$, to beach samples; $r = 0.482$, $p = 0.0063$, to foredune samples) and greater variability between km 1 and km 26 than in the eastern section (km 27–km 48; $r = 0.946$, $p < 0.00001$, to beach samples; $r = 0.864$, $p < 0.00001$, to foredune samples). There is a decrease in the standard deviation of grain size values from 0.7 to 0.4 between km 1 and km 26 that stabilizes around 0.35 from km 27 to km 48 ($r = -0.940$, $p < 0.00001$; Figure 7B). For the

Figure 3. Western (A), central (B), and eastern (C) sectors of the Maçambaba barrier, according to Andrade and Giannini (2016).

beach samples, skewness values decrease from W to E between km 1 and km 26 (r = -0.301, $p = 0.0657$; Figure 7C). In the eastern sector, skewness values show reduced variability, with slightly increasing eastward trend in beach samples (r = 0.539, $p = 0.0034$).

DISCUSSION

This section consists of a discussion of the winter season environmental dynamics of the Maçambaba beach–foredune system, followed by analysis of granulometric, morphodynamic, and climatological parameters.



Morphometric parameter	Maximum	Minimum	Average	R^2	r	p-value
Beach width	96.2	11.58	52.76	0.0162	0.126	0.1967
Foredune width	96.36	2.48	30.22	0.0462	0.215	0.0711
Foredune height	4.4	0.5	1.77	0.517	0.718	<0.0001
Beach steepness	11.01	1.08	3.68	0.019	0.138	0.1748

Figure 4. Variation along the beach–foredune system of measurements taken during a topographic survey in September 2013. (A) Beach and foredune width. (B) Dune height. (C) Beach-face steepness. (D) Maximum, minimum, and average values and respective coefficients of linear regression (r) and confidence levels (*p-value*).

Environmental Dynamics

The physical dynamics of the Maçambaba beach–foredune system are influenced by three major factors that are partly related to one another and contribute to the mobilization of eolian features that migrate in opposing directions: (1) climatic seasonality, (2) regional geomorphological setting inherited from the barrier's previous Quaternary history, and (3) variation of sedimentological characteristics along the barrier, especially grain size, that is largely determined by the two previous factors.

The climatic seasonality is related to the interchange between PMA and SASA. During winter, the PMA shifts to the north, bringing higher swells and stronger winds coming from the S-SW. Since these swells drive longshore sediment transport to the east, favoring a larger eolian sand supply in this part of the beach, the wind forms blowouts preferentially in these sectors

Table 1. *Beach morphodynamics, foredune morphology, and grain size distribution for the western, central, and eastern sectors along the Maçambaba barrier.*

Characteristic		Sector		
		Western (km 0–km 14)	Central (km 15–km 35)	Eastern (km 35–km 48)
Foredune morphology	Established	Terrace	Ridge	Ridge
	Incipient	Ramp	Ramp	Ridge
Mean grain size (phi)	Foredune	1.08 (km 0–km 26)		1.38 (km 26–km 48)
	Beach	0.91 (km 0–km 26)		1.32 (km 26–km 48)
Beach morphodynamic state		High-energy reflective	Reflective to intermediate dissipative	Dissipative

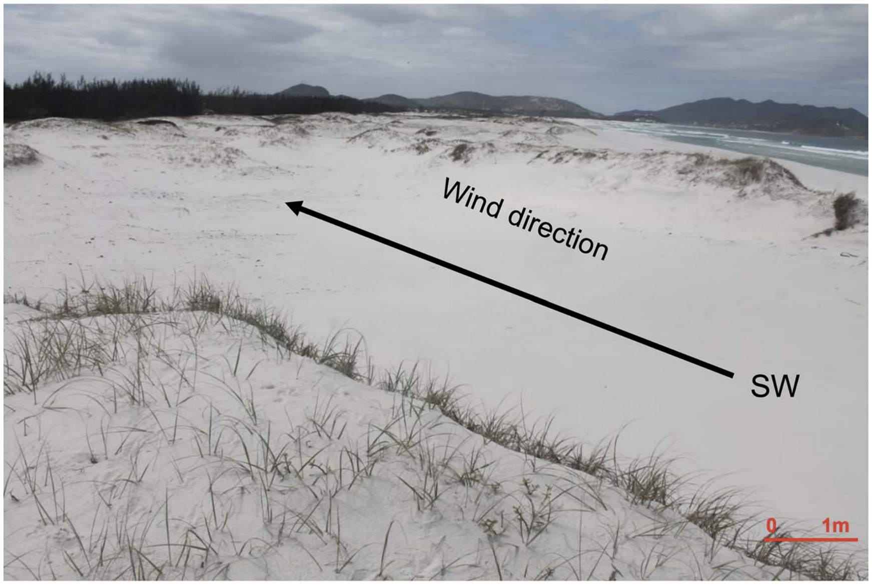


Figure 5. Blowout from the SW eroding ridge incipient foredune on the eastern part of Maçambaba.

with more sand supply. However, higher wave runup related to storm waves deposits washover fans and partially erodes these blowouts. During summer, SASA intensifies, creating conditions in which NE waves and winds are predominant and favor coastal upwelling. The presence of cold water near the coast is responsible for low precipitation rates in the area, keeping sand cohesion low in the washover fans deposited in winter. These sand deposits are then reworked by NE winds, forming parabolic dunes and blowouts that migrate toward the beach. Thus, the climatic seasonality (NE wind in summer and S-SW swell and wind in winter) is responsible for depositing eolian features that migrate in opposing directions.

The main influence of the geomorphological inheritance factor on recent coastal dynamics is the discontinuity of the Pleistocene barrier (Figure 3; Martin *et al.*, 1997). In the western part of Maçambaba, both Pleistocene and Holocene barriers are continuous in the alongshore direction and separated by an interbarrier lagoon system; however, only the Holocene barrier is present in the east. Because of this geomorphological configuration, flooding and deposition associated with overwash processes are confined between those two barriers in the west, but not in the east, where water is quickly absorbed by unconsolidated washover fan deposits. NE winds (predominant in summer) blow unimpeded in the eastern region and actively form eolian deposits where there is sediment availability. Thus, these NE winds produce parabolic dunes that migrate SW from the erosional coast of Araruama lagoon in the central part of Maçambaba, and they rework washover fan deposits, forming the blowouts and parabolic dunes that migrate toward the beach of the eastern part.

This climatological and geomorphological setting governs physical processes that determine the third factor, beach–foredune sedimentology. Mean grain size for both swash zone and foredune samples fines toward the east, ranging from 0.5 phi in the west to 2.0 phi in the east (Figure 7A). The average winter wind velocity measured at Arraial do Cabo Station (Instituto Nacional de Meteorologia - winter 2007–13) is 5 m s^{-1}, with 10 m s^{-1} gusts. These wind velocities are not strong enough to transport the coarse sand (Yang *et al.*, 2019) found in the west; however, they can transport the medium sand found in the east. This factor helps to explain why foredunes in the eastern part are frequently interrupted by the association of blowouts and washover channels formed by S-SW winds and swells predominant in winter. Therefore, this association in the east can be explained by three main factors: (1) grain size fining toward the east, making eolian reworking possible given the averages of grain size and wind speed; (2) increase of eolian sand supply by the longshore drift toward the east; and (3) absence of the Pleistocene barrier and the interbarrier lagoon, allowing water from overwash processes to be absorbed and the NE winds to reach farther toward the beach, where they rework the dry washover fan deposits.

The climatic seasonality and geomorphological heritance, associated with grain size fining toward the east, set up a pattern of geomorphological characteristics of the beach–dune system from W to E: (1) foredune morphology transitioning from ramp to ridge and (2) beach morphodynamic state transitioning from reflective to dissipative (Figure 8). In summary, the western sector exhibits a coarser grain size, high-energy reflective beach, lower eolian sediment supply, and incipient foredunes in ramps. Conversely, the eastern sector is characterized by a finer grain size, dissipative beach, higher sediment supply, and larger incipient foredunes in ridges. This pattern is consistent with the model proposed by Short and Hesp (1982): on narrower, steeper reflective beaches (western sector of Maçambaba), the eolian sediment transport from the beach to the foredune is lower than on flatter, wider, and less mobility dissipative beaches (eastern sector). It is also consistent

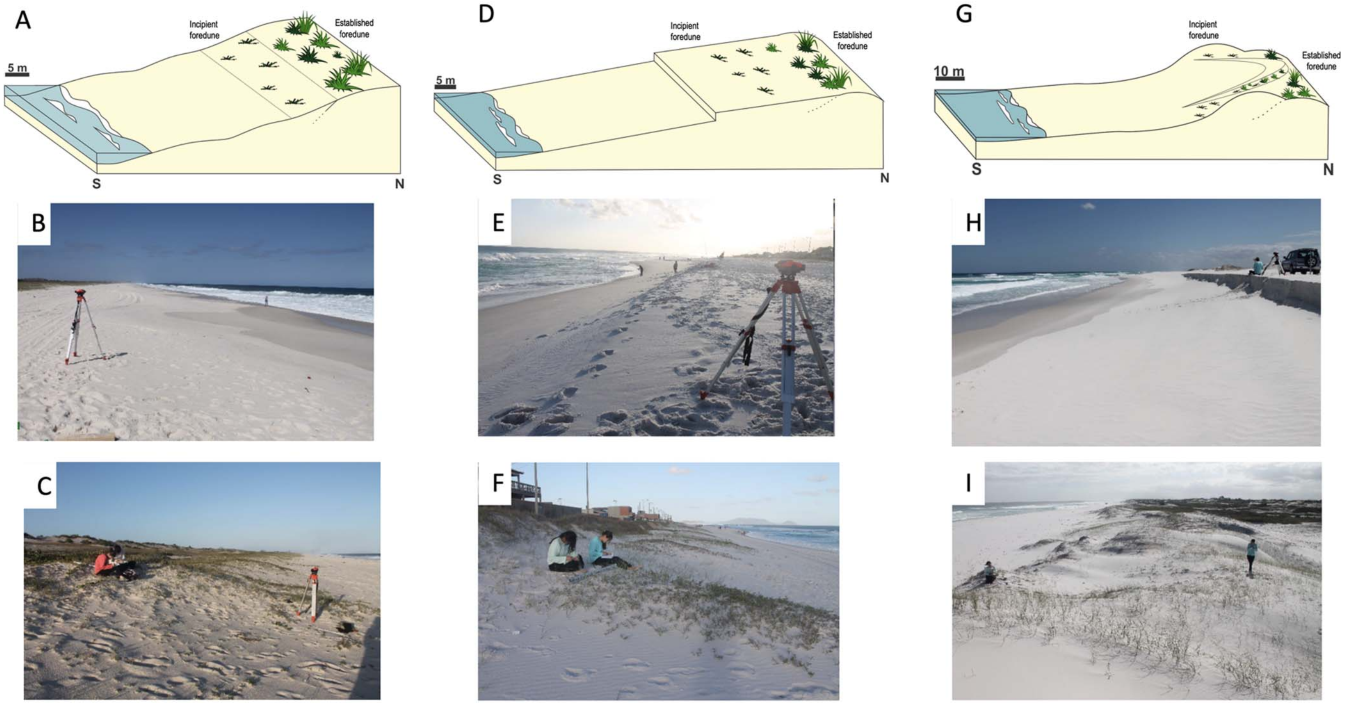


Figure 6. Western sector. (A) Schematic of the beach–foredune system. (B) Intermediate reflective beach at km 8. (C) Incipient foredune ramp over an established foredune terrace at km 14. Central sector at km 31. (D) Schematic of the beach–foredune system. (E) Intermediate beach with a scarp carved on a berm. (F) Incipient ramp foredune on an established foredune ridge. The eastern sector at km 35. (G) Schematic of the beach–foredune system. (H) Dissipative beach with a scarp carved on a berm. (I) Incipient foredune as an asymmetric and discontinuous ridge, and established foredunes as ridges extensively reshaped by blowouts.

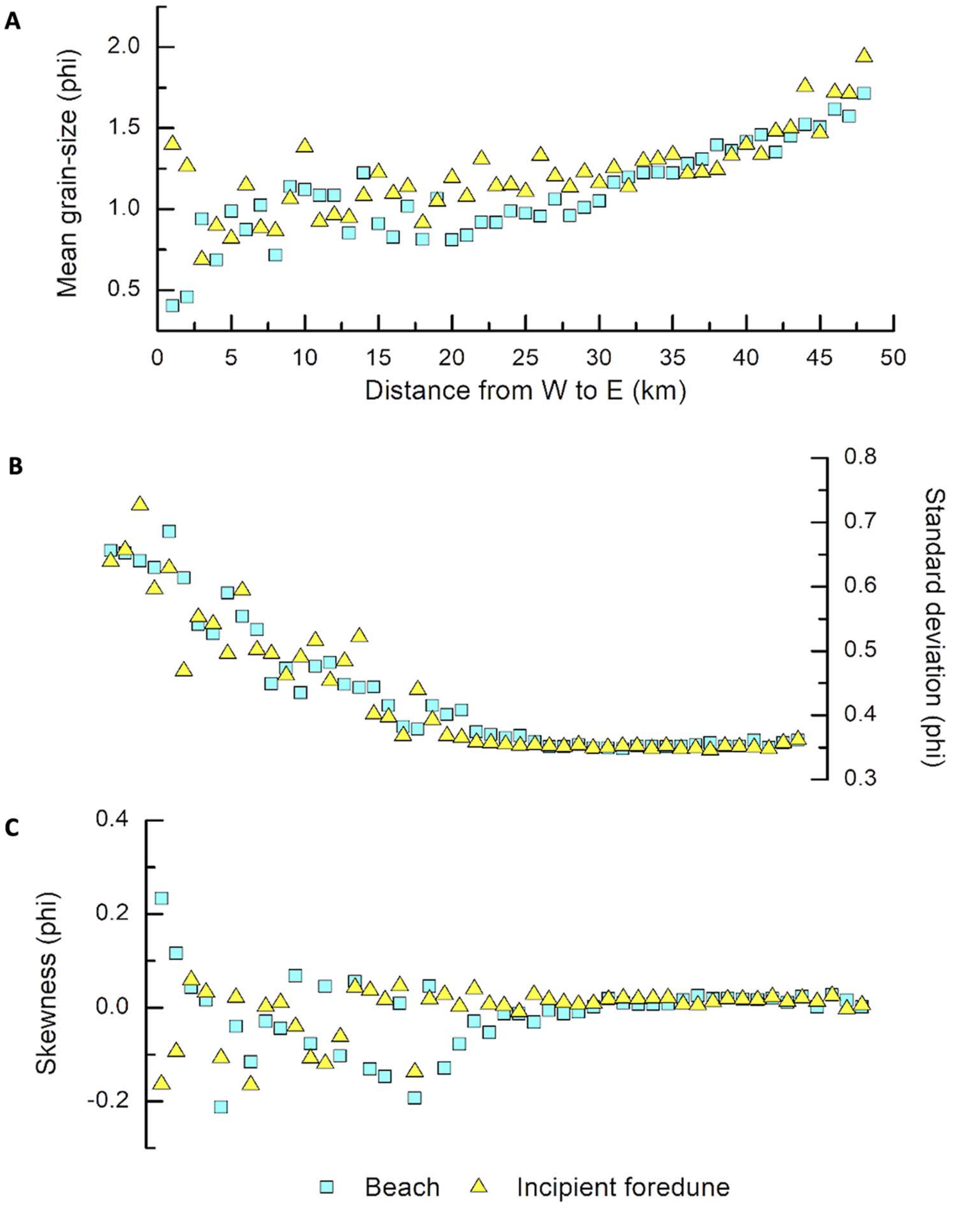
with the effect on the coastal eolian system of increasing eolian sand supply to the east—that is, formation of more voluminous and complex eolian systems to the east, according to the model proposed by Giannini *et al.* (2014). This is represented in the transition from low ramp foredunes in the west to higher ridge foredunes with blowouts in the east.

Beach–Foredune Grain Size

Mean grain size of both foreshore and foredune samples ranges from coarse sand (0.5 phi) in the west to medium sand (2.0 phi) in the east. Similar longitudinal variation has been observed by Muehe and de Carvalho (1993) in the inner continental shelf (to 75-m isobaths) between Saquarema and Arraial do Cabo. From the beach to the 45-m isobath, grain size is predominantly medium sand, with the exception of fine sand on the easternmost part of the shelf. On the adjacent inner shelf, Muehe and de Carvalho (1993) assigned the eastward fining grain size to a greater distance from the primary source, a rocky massif north of Araruama lagoon.

Finer, better sorted, and more negative grain size distribution from km 1 to km 26 (western and central sectors) is evidence of sedimentary transport to the east, according to the McLaren and Bowles (1985) method. From km 27 to km 48 (central and eastern sectors), there is progressive grain size fining toward the east accompanied by stabilization of the standard deviation and skewness. This stabilization might be related to the granulometric sorting effect exerted by blowouts and parabolic dunes, combined with the action of longshore drift to east and winds from the NE. Blowouts from the SW remove finer grains and leave a residual concentration of coarser fractions in the foredunes. This sorting action is evidenced by the foredune samples being coarser than the adjacent beach samples (Figure 7A). The residual concentration of coarse material (lag deposit) should be characterized by increased sorting and more negative skewness. However, sorting and skewness stabilize along the eastern sector (Figure 7B,C), suggesting that the lag deposit is offset by the enrichment in fine grains brought by longshore drift to the eastern part. On Maçambaba beach, the fining trend is more prominent in the eastern half (Figure 7A) and is probably related to the addition of fine grains by the NE winds that are responsible for forming parabolic dunes and blowouts migrating toward the ocean.

In the western part of the system, there is almost no sand available to form blowouts from either wind direction. On the beach, the grain size is too coarse for the average wind velocities to transport, and because the washover deposits are mainly confined in the shallow interbarrier lagoon system between the Pleistocene and Holocene barriers (Figure 3A), there is no dry sand on the washover fan deposits available to be reworked. In the eastern part of the barrier, blowouts and parabolic dunes are formed by both SW and NE winds. This is because of an increase in fine sediment supply by longshore



D

Type of sample	Beach				Incipient foredune			
Sector	km 1 to km 26		km 27 to km 48		km 1 to km 26		km 27 to km 48	
Number of samples	26		22		26		22	
	r	p-value	r	p-value	r	p-value	r	p-value
Mean diameter	0.348	0.0407	0.946	<0.0001	0.482	0.0063	0.864	<0.0001
Standard deviation	- 0.94	<0.0001	0.296	0.0905	-0.883	<0.0001	0.09	<0.3462
Skewness	-0.301	0.0657	0.539	0.0034	0.291	0.0746	0.062	0.3820

Figure 7. Variation of grain size distribution statistics along the Maçambaba beach–foredune system. (A) Mean grain size. (B) Standard deviation. (C) Skewness. (D) Respective coefficients of linear regression (r) and confidence levels (*p-value*).

drift and the presence of dry washover fans acting as a sediment source. Thus, eolian processes and grain size differences over the beach–foredune system in the eastern half can be attributed to the withdrawal of fine grains by blowouts from the SW and to the addition of fine grains by the NE winds and longshore drift toward the east. This causes the observed pattern of progressive fining toward the east with no significant change in the standard deviation and skewness values along this segment. Therefore, the trend to finer, more sorted, and more negative sands, which would be expected according to

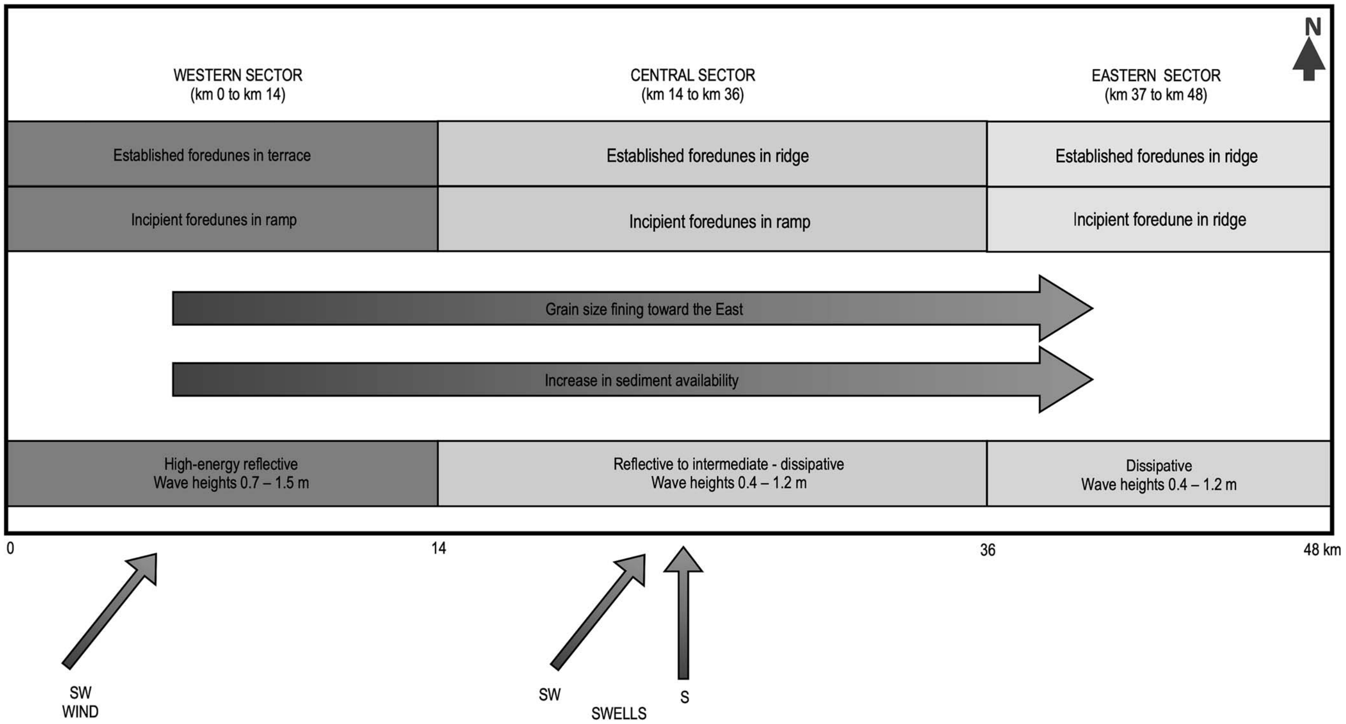


Figure 8. Seasonal climatic factors set up a pattern of sedimentological and geomorphological characteristics from W to E: grain size fining toward the east, incipient foredune morphology transitioning from ramp to ridge, and beach morphodynamic state transitioning from reflective to dissipative.

the McLaren and Bowles (1985) rule in the direction of the longshore drift (to east), is not observed in the eastern part of the barrier, because there is more than one sedimentary source to the sand of the beach–foredune system in this sector. This means that one of the assumptions or boundary conditions for the use of the McLaren and Bowles (1985) method, provided by the authors themselves, is not met in the eastern part of the beach.

Beach–Foredune System Morphodynamics

The morphodynamic transition from the reflective to the dissipative state from W to E is evidence of longshore drift toward the east. Sediment transport mainly occurs in the submerged area of the beach prism, and sandbars develop as the concentration of sediment increases (Wright *et al.*, 1979). Because the water is shallower on these sandbars, wave energy dissipation increases. The coarser grain size in the west is also consistent with the pattern described by Wright *et al.* (1979), in which reflective beaches tend to be made of coarser sand.

The increase in beach width is indicative of longshore drift (Jacobsen and Schwartz, 1981), although beach width does not increase toward the east in Maçambaba, as expected. Instead, beach width has greater variability in the eastern half, possibly related to the occurrence of SW blowouts, given that foredune height and width also vary in this part. Short and Hesp (1982) proposed that eolian sand supply is related to the beach morphodynamic state and dissipative beaches and/or sediment accumulation contribute to eolian sand supply. In Maçambaba beach, blowouts occur in the eastern sector (beginning at km 31), indicating more eolian sand supply in this direction (Giannini *et al.*, 2014). Incipient foredunes are higher in the eastern half (2.6 m) compared with the western half (1.5 m; Figure 4C), which is further evidence of eolian sand supply increasing from W to E. According to Short (1988), waves control sediment supply and foredune stability, and as wave energy increases, foredune size increases.

Beach width, sediment supply, and wind velocity act as three of several factors controlling or influencing foredune development (Davidson-Arnott and Law, 1996). Beach width and sediment supply are related to surf zone–beach type in some regions, especially where sediment supply is not a major limiting factor (Hesp, 1988; Short and Hesp, 1982). Foredune height and volume are related to surf zone–beach type: larger foredunes occur on dissipative beaches (widest beaches and maximum potential sediment supply) and smaller ones occur on reflective beaches (narrowest beaches and minimum potential sediment supply; Hesp, 1988; Ruz and Allard, 1995; Sherman and Bauer, 1993; Sherman and Lyons, 1994). Other evidence of the increase in sand supply from W to E is incipient foredune morphology transitioning from ramps in the west to ridges in the east. According to Hesp (2002), ramp incipient foredunes represent accretion and are mostly anchored on older dune scarps. When a ramp foredune accumulates sand for an extended period, it covers the scarp height and becomes a ridge foredune. The presence of ramp foredunes in the western part of the barrier is evidence of an erosional beach–foredune system with relatively

Figure 9. Washover channels (dashed red), oriented SW-NE and subparallel to blowouts (dashed black).

low sand supply, whereas ridge foredunes, more common in the east, indicate more deposition and greater sand supply.

According to Muehe (2006), given that Maçambaba beach is oriented W-E, it is equally exposed to both SW and SE waves and the longshore drift could be in both directions. Lourenço and Siegle (2012) published wave data on the Rio de Janeiro shelf (1997–2010) that indicate dominant waves arrive from the S, S-SW, and NE. Storm waves (up to 5.7 m in height with a period of 16.4 s) come from the S-SW (42%) and S (18%). These storm waves have a greater impact on beach dynamics, especially when associated with episodic overwash processes, which can reshape the coast and interrupt foredune ridges (Moulton *et al.*, 2013). The preferential NE-SW washover channel orientation (Figure 9) is evidence that waves from the SW and S-SW dominate overwash processes. Washover deposits also have their orientation controlled by preexisting NE and SW blowouts.

When foredunes are exposed to wave erosion and revegetation processes are slow, these foredunes become narrower and are eroded by overwash processes and blowout formation (Hesp, 2002). In the western and central sectors of Maçambaba beach (km 1–km 28), overwash processes happen when waves overcome the foredune height, transporting water and sediment into the interbarrier lagoon (Figure 3A,B). From km 28 onward (Figure 3C), overwash processes occur associated with blowout deflation basins formed by the SW winds. These washover fans are then reworked by wind from the NE, forming blowouts and parabolic dunes migrating toward the beach. The association between overwash processes with blowout deflation basins and these reverse dunes in the eastern part is related to the increase in eolian sand supply and grain size fining toward the east, making eolian reworking easier.

Signals in Beach–Dune Morphodynamics and Sedimentology as an Archive of Climatic Variability

The dynamics of the beach–foredune system in Maçambaba are controlled by seasonal S-SW winds and swells in winter and NE winds and swells in summer. These govern the deposition of eolian features with opposing migration directions.

The development of these eolian features also depends on the eolian sediment supply and availability, which are similarly controlled by climatic seasonality. The eolian sediment supply for the blowouts formed by SW winds is represented by the accumulation of coastal sand in the eastern part of the barrier, brought *via* longshore drift; eastward net longshore drift is driven by SW swell waves and therefore is also favored in winter. The eolian sediment supply for parabolic dunes and blowouts from the NE is represented by the dry washover deposits favored by SW waves, which are predominant in winter. The availability of eolian sand increases because of the semi-arid microclimate favored by coastal upwelling, intensified by the regional winds from the NE that are predominant in summer.

The development of eolian features and washover fans on the Maçambaba coastal barrier directly depends on three factors controlled by this seasonality: the intensity of the upwelling, the range of the PMA's northward migration in winter, and South American Monsoon System (SMAS) southward migration range in summer. Understanding the seasonal context of atmospheric features and climatic elements is key to comprehending storm events, climatic variability, and development of sedimentary eolian features during the late Holocene.

If upwelling intensity and precipitation levels remain stable, the development of washover fans and SW blowouts is favored by strengthening of the PMA. Over longer timescales (centuries to millennia), the PMA may shift to the north depending on the SWW belt. During austral winter, the SWW belt expands northward; as a consequence, the intensity of the wind decreases in the core of the belt and becomes stronger on its northern margin (Jenny, Wilhelm, and Valero-Garcés, 2003; Lamy *et al.*, 2010). Lamy *et al.* (2010) proposed that during the late Holocene, winds were weaker in the SWW belt core and stronger in its northern margin, similar to the modern winter condition. Hence, modern seasonality may have a late Holocene history characterized by environmental conditions that favored development of washover fans and coastal eolian features formed by SW winds.

This late Holocene atmospheric framework is supported by oceanographic evidence described by Voigt *et al.* (2015). The Brazil–Malvinas Confluence (BMC) is a dynamic oceanic feature in which the warm, saline waters of the Brazil Current meet the colder, less salty waters of the Malvinas Current. Voigt *et al.* (2015) suggested that the BMC is highly sensitive to changes in the position and strength of the SWW belt and therefore can be used as an indicator of the PMA position. Interpreting planktonic foraminifera $\delta^{18}O$ records with high temporal resolution from the western South Atlantic, the authors suggest that the BMC migrated to the north approximately 1000 years BP and stayed more northward from 2000 to 500 years BP than today. This would have favored the development of cold fronts in southern South America (Gilli *et al.*, 2005; Lamy *et al.*, 2010; Stuut and Lamy, 2004). Intensification of the SWW northern margin during the late Holocene was followed by a northward shift of cold front systems (PMA and BMC), which would be recorded in coastal depositional systems of S and SE Brazil by intensification of SW wind and swell wave activity (Zular *et al.*, 2013).

Additional evidence for strengthened seasonality in the region is found in sedimentary records from the outer lagoon system. In Maçambaba, the development of eolian features migrating SW results from strengthening of NE winds that also intensify coastal upwelling in the Cabo Frio region. Barbosa *et al.* (2003) and Sylvestre *et al.* (2005) interpreted increased aridity and/or NE winds and upwelling intensification in this area over 2500 years BP. Dias *et al.* (2013), Lessa *et al.* (2016), Mahiques *et al.* (2005), and Nagai *et al.* (2009) found similar paleoconditions recorded in sediment archives from the continental shelf. Therefore, both SW and NE winds would have intensified in the middle of the late Holocene, and the climatic seasonality responsible for the development of washover fans and eolian features of opposing migration direction likely occurred in 2000 years BP in the Maçambaba barrier.

CONCLUSIONS

The climatic factors that lead to the development of washover fans, blowouts, and parabolic dunes with opposing migration directions on the Maçambaba barrier are seasonal changes in wind and swell orientation, as well as local semiaridity caused by coastal upwelling. Although storm waves from the S and SW are not as frequent as other wave regimes, they are responsible for longshore transport and an increase in sediment supply toward the east during austral winter. NE winds, predominant in austral summer, rework noncohesive and dry sediments brought by longshore drift and overwash processes. In the western sector of the Maçambaba beach–foredune system, overwash processes predominate over eolian processes as the sediment gets confined in the interbarrier lagoon. This climatic seasonality in Maçambaba results in an overall trend of increased sorting and decreased grain size from W to E. This is reflected in the transition of the beach morphodynamic state from reflective (W) to dissipative (E) and incipient or established foredune morphology association from (1) ramp incipient foredunes anchored on terrace established foredunes in the western sector, (2) ramp incipient foredunes anchored on terrace established foredunes in the central sector, and (3) ridge incipient and established foredunes in the eastern sector. These ramp incipient foredunes indicate scarce sand availability and constant reconstruction of eolian deposits after recurrent erosion. Over the late Holocene, the climatic seasonality favorable to current eolian features is driven by migration of the PMA and SWW belt to the north during austral winter and NE wind intensification during austral summer. Some evidence from different kinds of proxies suggests that this seasonality may have been present in the Maçambaba region for approximately 2000 years BP.

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ABSTRACT IN NATIVE LANGUAGE

A barreira costeira holocênica de Maçambaba localiza-se no estado do Rio de Janeiro, Sudeste do Brasil, imediatamente a oeste de uma mudança abrupta de orientação na costa, de sudoeste-nordeste para oeste-leste. Os depósitos eólicos são formados pelos ventos de sudoeste, associados às massas de ar polar que avançam no inverno austral, e pelos ventos de nordeste, associados à monção de verão e à intensificação da ressurgência. Nos setores central e oeste da barreira, o sistema praia-duna ativo consiste em praias intermediárias refletivas e dunas frontais incipientes em rampa. No setor leste, ele é composto por praias intermediárias dissipativas e dunas frontais incipientes em cordão. A passagem de dunas frontais em rampa, na parte oeste da barreira, para dunas frontais dominantemente em cordão, na parte leste, indicam que o aporte de areia eólica é maior a leste que a oeste. Nas amostras coletadas no espraiamento, a seleção granulométrica melhora e o tamanho médio de grão diminui de oeste para leste, o que é sugestivo de transporte longitudinal de sedimentos nesse rumo. O crescimento do aporte sedimentar para leste aumenta o retrabalhamento eólico pelos ventos de sudoeste (onshore) no inverno, e consequentemente as dunas costeiras são melhor desenvolvidas no setor leste, incluindo a formação de rupturas de deflação (blowouts). Neste setor, processos de sobrelavagem costeira frequentemente se desenvolvem onde a deflação eólica favorece a inundação marinha durante eventos de swell no inverno. Após sua formação, os leques de sobrelavagem são geralmente retrabalhados pelos ventos reversos de nordeste (offshore) no verão austral. Na barreira como todo, mudanças sazonais na orientação do swell e na direção do vento são fatores climáticos dominantes que determinam o desenvolvimento e deposição de leques de sobrelavagem, blowouts e dunas parabólicas com direções de migração opostas. Investigar o efeito dessa sazonalidade climática no sistema praia-duna ativo é fundamental para entender a resposta costeira a eventos de tempestade e variações climáticas em escalas de tempo mais longas.