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Accelerated Dune Migration and Aeolian Transport During El Niño Events along the NE Brazilian Coast

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ABSTRACT

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Dune migration response to regional inter-annual climate variability in Ceará, Northeastern Brazil was investigated. Dunes along the study area are mainly barchans and sand-sheets and they migrate at an averaged rate of 17 m/yr although this value depends on dune dimensions, the larger the dune the lower the migration. This is explained by the existence of a representative regional aeolian transport rate that is almost constant along the region inducing different dune response depending on dune size, which is a common feature of barchans fields. Estimated yearly transport rates from dune migration were compared to the values obtained by using the calibrated aeolian transport formula when fed by regional wind climate data. The results obtained differ by about 20% (100 m^3/m/yr) from actual aeolian transport measurements (80 m^3/m/yr) from dune evolution, which can be considered as a good agreement between both approaches. We show a relationship between dune displacement and strength of the dry season in the region. With larger displacements occurring in drier years, coincident with a more northern position of the Intertropical Convergence Zone (ITCZ), which occurred during strong El Niño periods. This relationship serves to link the dune migration in Northeastern Brazil with El Niño events. As El Niño Southern Oscillation (ENSO) supposes a major climatic perturbation, its effects will be transferred to all the dynamical processes controlled in a direct or indirect manner by the regional climate. These findings should be incorporated into Integrated Coastal Zone Management (ICZM) strategies for the region.

ADDITIONAL INDEX WORDS: *Dune crest marks, sedimentary dynamics, climatic changes, barchans.*

INTRODUCTION

Dunes are continually distributed along the 573 km of Ceará state coast, NE Brazil, although their penetration inland is limited to the first six kilometers. These deposits cover the most important area of the current urbanization and tourism development, being of significant economic importance to the State and requiring urgent Integrated Coastal Zone Management (ICZM) plans for its proper development. The alterations induced on the dunes by their use and occupation generates instability of older dunes that then may migrate over houses and urban infrastructure. Associated to the impacts of the induced migration on older dunes should be added the impacts from the natural migration of young "active" dune systems witch might also cause calamitous results for many coastal communities.

Aeolian sediment transport and dune migration along the coastal zone is a key issue in coastal geomorphology due to their potential role to contribute to the coastal sedimentary budget as well as due to the potential interaction of mobile dunes with coastal infrastructures. Its study can be conducted from two approaches: *top-down* where the aeolian sediment transport is derived from dune evolution and *bottom-up* where by estimating the aeolian sediment transport due to wind action, the derived geomorphological consequences (*i.e.* dune evolution) are foreseen. Both approaches try to quantify the process starting from different bands in time and space of the geomorphological spectra. From the theoretical standpoint, moving through temporal and spatial scales in geomorphological processes present a number of open questions such as the validity of using small scale approaches to reproduce the long-term geomorphological development (*e.g.* dune field evolution); how to aggregate these small scale processes to be used at longer time scales (MAIA *et al.,* 1999); or how climate variability controls the dune evolution. Although some debate about up-scaling aeolian transport to estimate dune evolution exists (DAVIDSON-ARNOTT and LAW, 1996; SHERMAN *et al.,* 1998), climate and geological conditions in North-eastern Brazil make this area ideal to do this time integration to respond to some open questions (MAIA, 1998).

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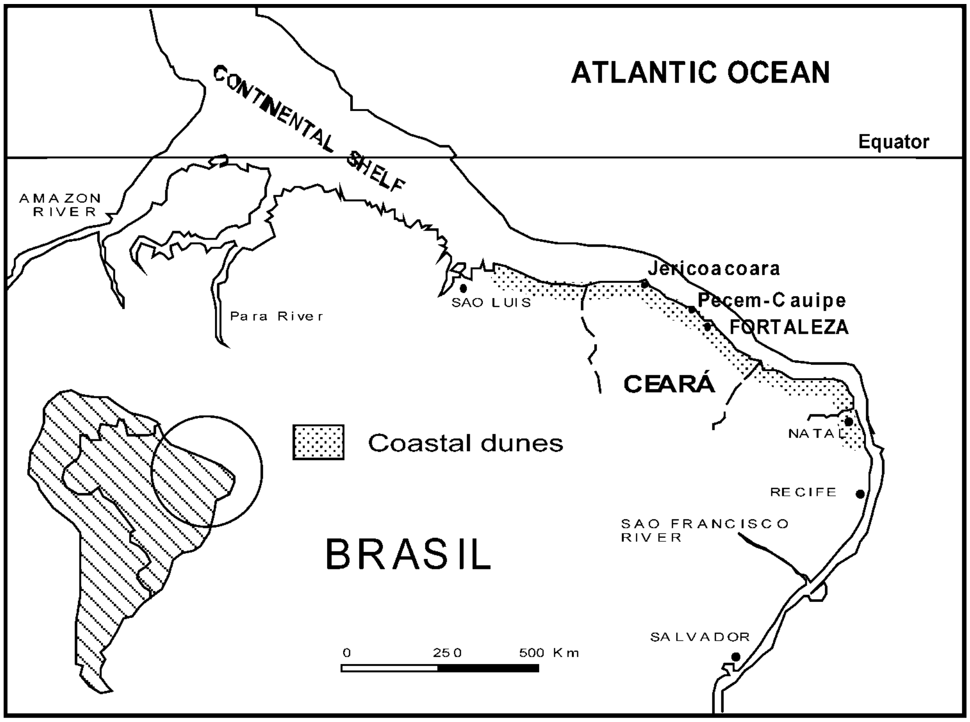

Figure 1. Map showing the northeastern coast of Brazil and location of the studied area at the Ceará state.

STUDY SITE

Ceará State is located in northeastern Brazil (Figure 1). Its coastal zone consists mainly of long sandy beaches, occasionally interrupted by small rivers and rocky headlands. Very large long-shore transport rates of up to 700,000 m^3/yr are common along the coast due to the steadiness of wave climate, which usually approaches the coast with a large angle (Maia *et al.,* 1998).

Practically the entire Ceará coast is backed by extensive dune fields. Three to four dune generations have been identified: paleodunes, parabolic dunes, aeolianites and mobile dunes (from the oldest to the youngest dunes) (Maia, 1998; Jimenez *et al.,* 1999). The last dune generation comprises the currently *active dunes,* and these are the object of the present work. These dunes extend along a stretch about 6 km wide following the coastline, and comprise barchans, barchanoids and sand sheets, with the dominant form depending on the available sand supply. At present, the active dunes are detached from the coast by between 600 m to 2,000 m and are migrating on top of older dune generations (Figure 2).

METHODS

Measurements of aeolian transport were made by using sediment traps developed by Maia (1998) modified from those proposed by Leatherman (1978). Simultaneously, wind characteristics (velocity and direction) were recorded during

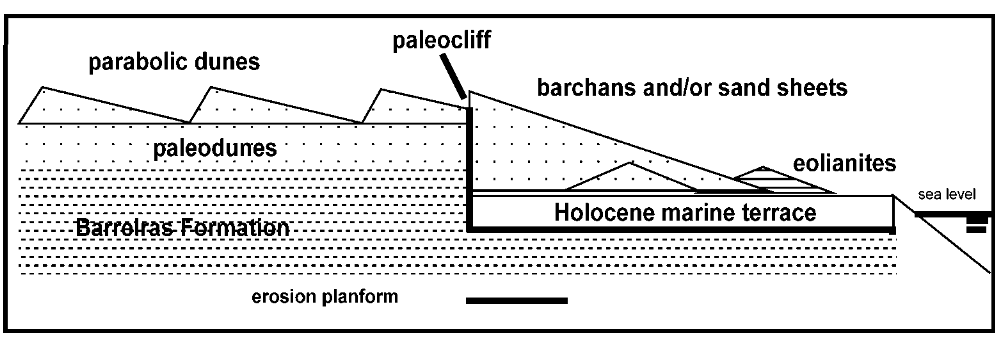

Figure 2. Schematic representation of dune generations at the Ceará state coast showing progression of present, active dune over older dunes generations.

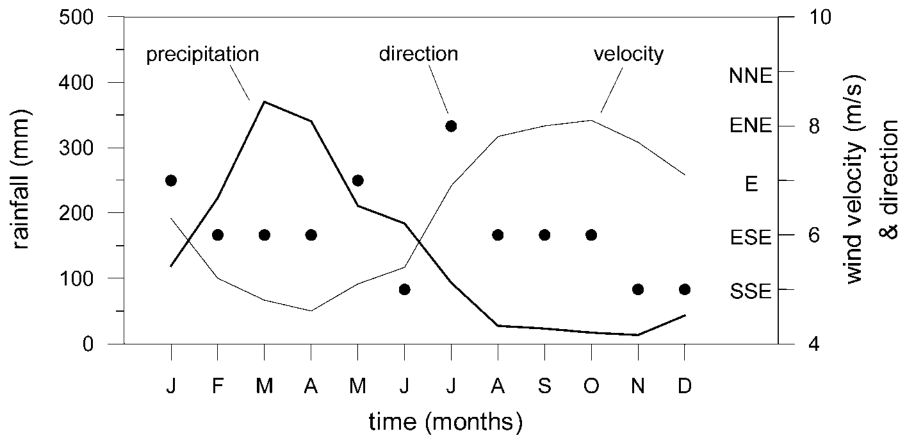

Figure 3. Monthly distribution of wind velocity, direction and rainfall along the Ceará coast.

each experiment. These short-term experiments were done in different dune fields and beaches (Jericoacoara and Pecén-Cauipe) along the Ceará coast (see Figure 1), covering the locations where dune evolution was analyzed. Experiments were conducted during different seasons to cover variations in wind regime.

Dune migration was estimated by using vertical aerial photographs taken in 1958 and 1988. Individual dunes were identified in the photos and displacements were measured at several points along dune fronts to obtain a representative mean displacement for each dune. Dune displacement was considered as the distance between consecutive dune edge marks left by the dune progression of the previous years (MAIA, 1998). In addition to this, another dune feature, *i.e.* sinuous (cuspidate) vegetation marks (similar to geigenwalle ridges) were characterized by field data obtained by topographic leveling taken in the various dune fields. This method was complemented by other field techniques to characterize dune evolution (MAIA, 1998). Annual displacement of barchans was compared to the Southern Oscillation Index (SOI) for the Central Pacific Ocean available from the United States National Oceanographic and Atmospheric Agency (NOAA, 2001).

RESULTS AND DISCUSSION

The climate of NE Brazil is part of the Tropical Atlantic area and is governed by the Intertropical Convergence Zone (ITCZ). Seasonal latitudinal position of the ITCZ determines the presence of dominant winds and the rainfall regime in the region (PHILANDER and PACANOWSKI, 1986; NOBRE and SHUKLA, 1996). When the ITCZ is in its southernmost position, normally in March–April, weak Southeast winds and highest rainfall prevail. On the opposite, when the ITCZ is located in its northernmost position, August–September, intense Southeast winds and low rainfall dominates in the area (Figure 3). This results in a regional climate with only two seasons per year characterized in terms of precipitation and wind regime. The wet season normally extends from January to July contributing about 93% of the total yearly rainfall (average about 1500 mm). It is characterized by the weakest winds of the year (average about 5.5 m/s). During the dry season, from August to December, virtually no rain exists ($<$130 mm) whereas wind velocities are highest average (7.8 m/s). Wind direction does not show any clear seasonal pattern, with Eastern winds blowing on the region during all the year due to the full dominance of trade winds, those with a Southern component being the most frequent in particular during the dry season (MAIA, 1998).

This seasonal climate results in a pulsating dune evolution pattern in which dunes behave differently depending on the season (MAIA, 1998). During the wet period, high rainfall reduces aeolian transport rates due to an increase in sand humidity (SHERMAN, 1990; VAN DICK and STROOSNIJDER, 1996) and the above mentioned low wind velocities, resulting in the reduction of dune mobility. Simultaneously, higher soil humidity and, occasionally high water tables, largely promotes vegetation growth that temporarily fixes the dune edge by plant colonization. On the opposite, during the dry season with the increase in wind intensity and the sharp decrease of sand humidity due to the absence of any precipitation together with the effects of evaporation, wind action is very effective to drive aeolian sediment transport resulting in a free dune migration.

The average dune migration rates during the 30 years period under study for the three sites studied (see Figure 1) were dependent on dune size. For the dunes at Jericoacoara, where barchans could reach 60 m in height and over 500 m in length, average migration rates reach 17.5 m/yr, ranging from 14.6 m/yr to 21 m/yr. The associated aeolian transport rates in this area based on short term experiments, calculated by model calibrated with trap measurements averages 102 m^3/m/yr, varying from 74 to 125 m^3/m/yr, similar to the values obtained by aggregated values estimated from dune evolution (Table 1). On the other hand, for sand sheets, the average migration rate in Pecém amounted to 10 m/yr (ranging from 9 m/yr to 11 m/yr), whereas in Cauipe migration rates ranged from 6 m/yr to 8 m/yr. Because the sand sheets in Cauipe are smaller (in terms of both dune front and dune

Table 1. *Aeolian transport rates along the Ceará coast, Brazil. a)-Estimated from aggregated dune evolution and b)-Calculated by model calibrated with short-term trap measurements. Mean rate and range in m³/m/yr.*

Location	a)-Aggregated Dune Evolution	b)-Trap Experiments
Jericoacoara (barchans)	78 (64–98)	102 (74–125)
Pecém-Cauipe (sand sheet)	89 (65–115)	79 (55–102)

volume) than those in Pecém, these results are consistent with those obtained for barchans, *i.e.* migration rates decrease as dune size increases. The associated aeolian transport rates in this area based on short term experiments, calculated by model calibrated with trap measurements averages 79 m^3/m/yr, varying from 55 to 102 m^3/m/yr, similar to the values obtained by aggregated values estimated from dune evolution (Table 1).

At the most aggregated level, the transport rate can be calculated for an idealized dune representing the average dune field characteristics, *i.e.* with dimensions equal to the average width, length and height of existing dunes, which migrates at an estimated average rate (17.5 m/yr). This yields an aggregated aeolian sediment transport rate of 98 m^3/m/yr for the barchan field in Jericoacoara. A detailed study of transport rates based on the two approaches can be found in MAIA (1998).

The alternating pattern in dune mobility leaves on the land surface upwind the dunes, clear signatures of former dune edge positions in the form of cuspidate marks, which were fixed during the previous wet season by vegetation (Figure 4). Once the dry season commences, the entire dune, but not the fixed edge, migrates, resulting in low sinuous dune marks (the cuspidate vegetation marks) which are maintained by vegetation. Dominant plant species are typical representatives of primary dune colonization such as *Remirea maritima, Ipomoea pres-caprae, Cenchrus echinatos.* Due to the very well defined seasonal climate in the region, it is reasonable to assume that each mark should correspond to the position of the dune upwind edge one past wet period and then, they can be used to reconstruct previous year to year dune positions (MAIA, 1998). At the same time, distances between consecu-

Figure 4. Oblique aerial photograph of barchans in Jericoacoara dune field, NE Brazil, during the wet season. Low vegetation dunes or marks (arrows) each corresponding to the position of the upwind edge of the dune during one past rainy season is seen behind the front dune. Front dune is about 60 m high and 500 m wide. Upper left: Location of the Jericoacoara dune field at the coast of Ceará State (02°50′S; 40°30′W).

tive marks should indicate inter-annual variability in climatic conditions governing dune migration, with the distance between marks being increased for years with low rainfall and higher intensity winds.

The main inter-annual climate variability in the Tropical Atlantic and, specifically in North-eastern Brazil, has been associated to El Niño teleconnections, although the interaction mechanism has not yet been satisfactorily explained (MARKHAM and MCLAIN, 1977; SERVAIN, 1991; HASTENRATH and GREISCHAR, 1993). Several authors have analyzed changes in sea surface temperature (SST) in the tropical Atlantic Ocean and related them to El Niño Southern Oscillation (ENSO) events (SERVAIN and LEGLER, 1986; TRENBERTH and HOAR, 1997). These SST changes drive the latitudinal position of the ITCZ. As a result, they alter the "normal" regional rainfall and wind patterns. Thus, the presence of El Niño results in an earlier displacement of the ITCZ towards the North anticipating the dry season with respect to a normal year and then droughts prevail in Northeastern Brazil which are accompanied by an increase in wind velocity above normal levels (TRENBERTH and HOAR, 1996). During El Niño events, the wet season experiences a rainfall decrease and a wind velocity increase with respect to "normal" levels. On the other hand, during La Niña (negative ENSO episodes), rainfall increases and wind velocity decreases with respect to the "normal" levels. As regional climate has been identified as the aggregated forcing term for dune evolution, it should be expected that one could identify signatures of such variability in the dune migration history.

Figure 4 shows the dune field of Jericoacoara with typical cuspidate vegetation marks at the backside of a moving dune fixed by vegetation. A between-marks distance variability factor (the difference between the actual and the averaged distance between marks) was obtained by comparing aerial photographs over a period of 29 years (1968 to 1996) for one barchan (dimensions: 60 m high, 500 m wide transverse to the wind flow and 260 long from upwind edge to the crest). The averaged yearly displacement rate estimated from vegetation marks was 19 m/yr, varying from 9.5 to 37 m/yr. This is comparable to the historical average migration rates for barchans in this area of 17.5 m/yr.

Figure 5 compares the fluctuation of the SOI and the yearly displacement rate measure at the studied barchan. Dune displacement and SOI showed an inverse weak, but significant correlation ($r_{Spearman} = -0.383$; $P<0.05$). Largest positive variations occurred from 1981 to 1983. This period was characterized by a continuous negative rainfall anomaly and with the highest wind velocities during the wet season and has been considered as the severest El Niño of this century (TRENBERTH and HOAR, 1996) until the recent 1997–1998 event. Amongst other induced climate signatures such as a prolonged drought in NE Brazil, an increase in trade winds intensity in the western Tropical Atlantic Ocean has been reported (CARLTON and SHULKA, 1991).

The second important period for positive displacement was observed in 1990/93. This period also coincides with the El Niño presence (1990–1995) which has been classified as the longest warm ENSO event on the record. Again, negative rainfall anomalies and increasing wind velocities dominated this period during the wet season. On the other hand, negative dune vegetation marks variation, *i.e.* lower than "normal" dune migration rates occurred during years with high rainfall and low wind velocity as for instance, years 1985 and 1986. For the monitored period, highest migration rates (33.2 m/yr) were measured during the El Niño 1982–83 event and were found to be threefold the lowest rates (9.5 m/yr) measured during the La Niña 1985–86 event.

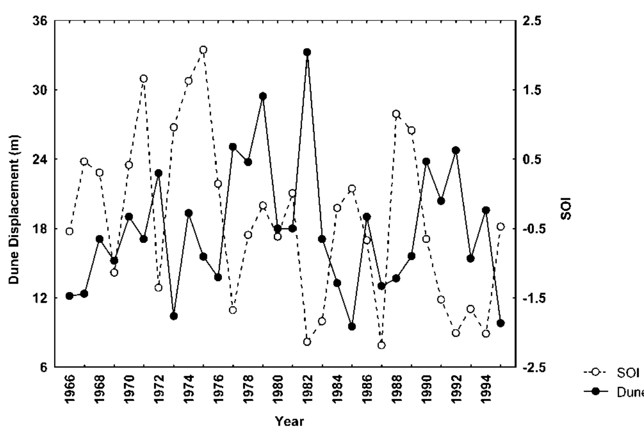

Figure 5. Time series (1966–1995) of the Southern Oscillation Index (SOI) using data from USNOAA (2001) and corresponding displacement variations measured in Ceará dunes.

CONCLUSION

The relationship described here serves to link the dune migration in Northeastern Brazil with El Niño events. As ENSO supposes a major climatic perturbation, its effects will be transferred to all the dynamical processes controlled in a direct or indirect manner by the regional climate. Because mobile dunes respond to the actual rainfall and wind regimes, El Niño years will result in faster than normal dune migration whereas La Niña years will result in lower than normal dune migration. Although our data on sand transport rates are not sufficiently frequent to compare with SOI, sand transport will respond to ENSO events in a manner similar to dune displacement rates.

The potential effect of dune migration and sand transport upon coastal structures, including antropic developments, strongly suggests that these results should be considered wherever ICZM is being undertaken.

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