DYNAMICS OF COASTAL DUNES AT CEARÁ STATE, NORTHEASTERN BRAZIL: DIMENSIONS AND MIGRATION RATE

Dinâmica das dunas costeiras no Estado do Ceará, Nordeste do Brasil: dimensões e taxa de migração

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RESUMO

As dunas da região costeira do Estado do Ceará estão formadas por acumulações do tipo lençol de areia e barcana, cujas dimensões, relações geométricas e taxas de migração foram estudadas a partir de dois tipos de aproximação. Como principal resultado, se observa que as dunas barcanas apresentam uma relação geométrica de equilíbrio, caracterizada pelos parâmetros adimensionais H/W e W/L. As dunas são altamente móveis, com taxas média de migração de 17,5 m/ano para as barcanas e 10 m/ano para os lençóis de areia. As taxas de migração calculadas para esses dois tipos de dunas apresentam uma relação inversa com suas. Esta relação está associada à existência de uma taxa de transporte comum ao longo dos campos de duna, que induz uma resposta geomorfológica diferenciada e dependente das dimensões das dunas. A partir da evolução multitemporal das dunas foi possível estimar a taxa de transporte eólico de sedimentos para a região, cuja magnitude é da ordem de 90-100 m^3/m/ano. Ao final, destaca-se algumas implicações da migração das dunas para a área de estudo.

***Palavras-chaves**: dunas costeiras, migração, relações geométricas, barcanas, Estado do Ceará.*

ABSTRACT

Dimensions and migration rates of mobile dunes, along the Ceará State's coast, currently composed of sand sheets and barchans, are analysed. The results show that barchans maintain an equilibrium form which can be characterised by values of dimensionless shape parameters H/W and W/L. Dunes are highly mobile, with average migration rates of 17.5 m.yr^{-1} for barchans and 10 m.yr^{-1} for sand sheets. The calculated migration rates were found to depend strongly on dune dimensions for both barchans and sand sheets, i.e., the larger the dune is, the lower the migration rate will be. This was associated with the existence of a representative common transport rate along the dune fields which induces a differential geomorphologic response velocity dependent on dune size. Finally, from the observed dune evolution, an aggregated-scale aeolian sediment transport was inferred. This transport rate, in the order of 90-100 m^3/m/yr, is only valid for a time scale from years to decades, which is the one scale used in dune evolution analysis. Finally, some implications of dune migration in the study area are also highlighted.

***Key words**: coastal dunes, migration, morphometric relationship, barchans, Ceará State, Brazil.*

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INTRODUCTION

Aeolian sediment transport and dune migration in coastal zones are key issues in coastal geomorphological studies, since the potential role of dunes in the coastal sedimentary budget is well known (Goldsmith, 1985; Illenberger & Rust, 1988). Such studies can be carried out using either one of two different approaches: a top-down approach whereby the aeolian sediment transport is derived from dune evolution, and a bottom-up approach, in which the aeolian sediment transport due to wind action is estimated in order to forecast its geomorphological consequences. Although both approaches seek similar final results, they start out from different bands in time and space geomorphological spectrum. From the theoretical standpoint, moving through temporal and spatial scales in geomorphological processes poses a number of open questions such as the validity of using small scale approaches (e.g., aeolian sediment transport rates calculated via a deterministic model fed by detailed wind intensity and direction time series) to reproduce long-term geomorphological development (e.g., dune field evolution); and how to aggregate these small-scale processes to be used at longer time scales (see discussion *in* de Vriend, 1998).

In this respect, the study of dune dynamics is a matter of upscaling (time and spatial integration) because they reflect the aggregated effect of a microscale process, i.e., wind action on sediment grain sizes. Thus, if dune evolution in a specific location in the long term (years to decades) is characterised, it will be possible to infer a net aeolian sediment transport rate which will represent the aggregated wind action at the studied time scale. Theoretically, this transport rate should be similar to one obtained by time-integration of the transport rates associated with each wind condition over the period considered, although from the practical standpoint most works recognise the limitations of existing aeolian sediment transport models when compared to field data even at the small scale (Davidson-Arnott *et al*., 1996; Sherman *et al*. 1998).

Within this context, the main aim of this paper is to analyse dune field characteristics along Ceará State's coast from a dynamical standpoint. This is done by characterising dune dimensions and migration rates in the study area, and using them to determine the aggregated aeolian transport rates responsible for this dune development. Finally, some consequences of the studied dune dynamics are also presented, in terms of interactions with other physical processes taking place along the Ceará State's coast and in terms of interactions for land use/planning.

STUDY AREA

Ceará State, located in Northeastern Brazil (Figure 1), has a coastal zone which is 573 km long, consisting mainly of long sandy beaches, interrupted only by small river mouths and rocky headlands determining changes in the coastal orientation. This area is a mesotidal environment, with a diurnal tide with a maximum astronomical range of 3 m. The local wave climate can be roughly described by a yearly averaged significant wave height, Hs, of 1 m, a mean period, Tz, of 5 sec and full dominance of easterly waves. The wave characteristics and the coastal orientation determine a large angle between waves and coastline, which potentially induces very large longshore transport rates (Maia, 1998).

Practically the entire Ceará coast is backed by extensive dune fields. Thus, three to four dune generations have been identified (see sketch in figure 2) and although it is difficult to establish whether they were formed in one or more episodes, Maia (1998) made an indirect estimation through an analysis based on stratigraphic, sedimentological and pedologic criteria, and associated them with different sea levels during the Quaternary. This was done by considering dune position and pedogenesis, and by interpreting the required conditions for their development and taking into account the sea level curve for the Brazilian coast as calculated by Martin *et al*. (1979).

The oldest generation is composed of paleodunes without defined dune forms and placed directly on top of the Barreiras Formation. These paleodunes consist of unconsolidated quartz sand varying from moderately to well sorted fine to medium grains of a deep red colour. The thickness of the layer is variable, decreasing inland, and they present a high degree of pedogenesis with well developed soils. Maia (1998) associated their formation conditions with sea level during the Pleistocene for they lie on top of the Barreiras Formation and its alteration level is very high.

The second generation is composed of stabilised parabolic dunes formed by medium to fine sand of unconsolidated quartz, from moderately to well sorted grains and colours varying from orange to grey. They have U and V plan shapes with heights from 20 m to 40 m, lengths from 1200 m to 2000 m and widths from 320 m to 460 m. They can be found as isolated dunes or grouped in complex systems, although in all cases they are fixed at present by bush type vegetation. Maia (1998) assumed that they must be older than the highest sea level during the Holocene transgression because they are separated from the coast by a paleocliff and a Holocene erosion surface (Figure 2).

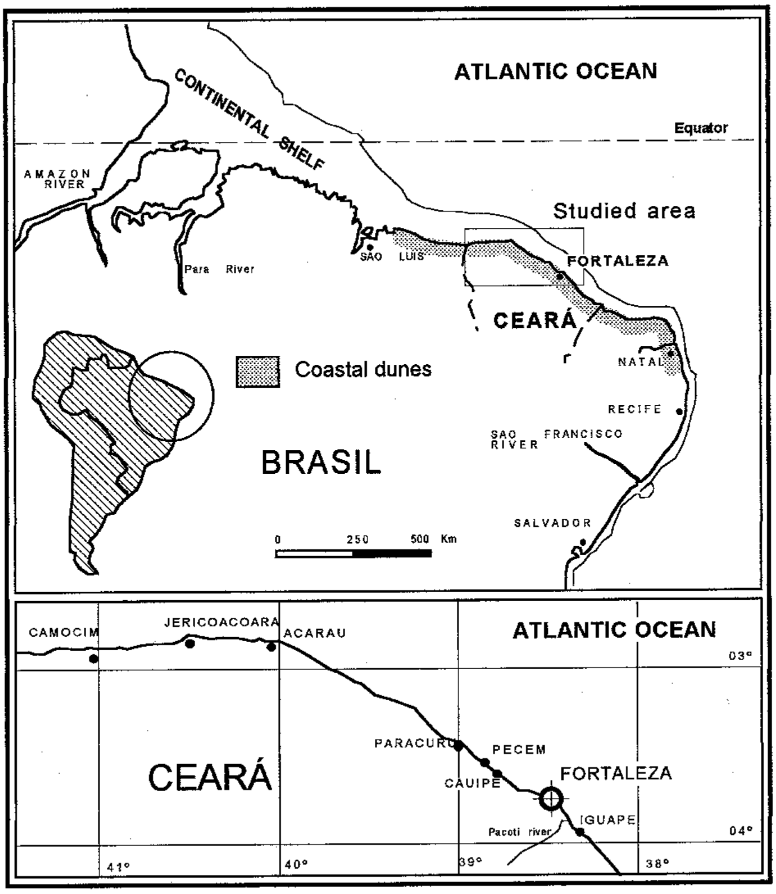

Figure 1 - Map of the study area.

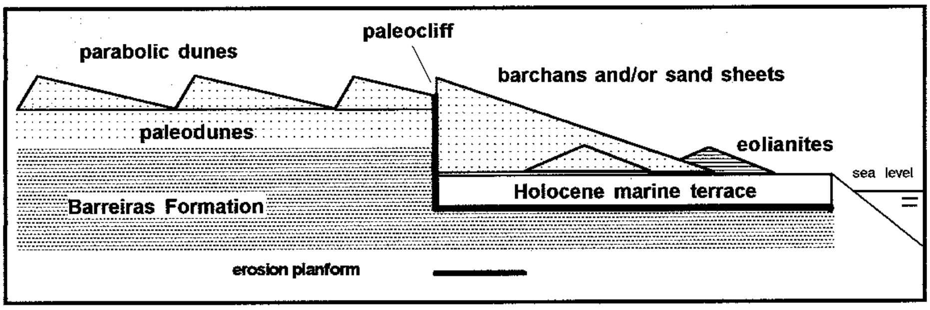

Figure 2 - Sketch of the basic stratigraphy of the existing dune systems.

The third dune generation is composed of eolianites, which are placed above the Holocene marine terrace and below the present mobile dune system. They are of the quartzeolianite type (with a quartz content between 48% and 51%), with a mean grain size between 100 mm and 600 mm, in which the dominant cement is of the low-Mg calcite type, with values of Ca (CO3) higher than 95% and Mg (CO3) lower than 4%. Cement geometry varies between isopachous and meniscus types. According to Yaalon (1967) the formation of this type of eolianite requires a rainy season with sufficient rainfall for the calcium carbonate from the shell fragments in the sand to form a solution and a warm dry season, during which the calcium carbonate precipitates and forms the cement. These environmental requirements are clearly fulfilled by the regional climate in the study area. Maia (*op. cit.*) associated the formation conditions with the minimum sea level, when carbonate rich sands were available on the continental shelf to form those dunes.

The last dune generation comprises the currently active dunes, and these are the object of the work presented here. It extends along a stretch about 6 km wide following the coastline, and is composed of barchans, barchanoids and sand sheets, with the dominant form depending on the original available sand stock (figure 3). At present, the dunes are detached from the coast (between 600 m and 2000 m from the coastline), and they are migrating on top of older dune generations. Maia (*op. cit.*) estimated that the original conditions for dune formation occurred during the last 1,000 years.

REGIONAL CLIMATE

The regional climate of Northeastern Brazil is influenced by the Intertropical Convergence Zone (ITCZ) which is a convergence region for northeasterly and southeasterly Atlantic trade winds, and is characterised by an intense cloud presence and the quasi-permanent action of low atmospheric pressure centres. Seasonal latitudinal positioning of the ITCZ determines both the presence of dominant winds and the rainfall regime (e.g., Philander and Pacanowsky, 1986). Thus, when the ITCZ is located in its northernmost position, normally from August to September, intense southeasterly winds and low rainfall predominate in the area. Conversely, when the ITCZ is in its southernmost position, from March to April, weak southeasterly winds and high rainfall prevail.

Figure 4-a shows monthly rainfall statistics obtained from records for a 22 year period (1974 to 1995) at a meteorological station in Fortaleza, which if averaged give a yearly rainfall of 1,663 $mm.yr^{-1}$. However, the pluviometric regime is strongly seasonal, with a wet period from January to July in which almost the entire yearly rainfall is concentrated, with an average yearly cumulative contribution of 1,540 mm (92.6% of total rainfall) and a dry one from August to December, when virtually no rain falls, with an average yearly cumulative contribution of 123 mm (7.4% of total rainfall). Additionally, a large interannual variability can also be observed, which is indicated by maximum and minimum monthly values. This interannual variation is due to the appearance of droughts and floods associated with large scale climatological phenomena, mainly El Niño teleconnections. This factor alters the "normal" latitudinal displacement of the ITCZ, resulting in earlier northward movement during El Niño years, although the interaction mechanism has not yet been satisfactorily explained (Markham & McLain, 1977; Hastenrath & Greischar, 1983; Nobre & Shukla, 1996).

The monthly distribution of the wind intensity obtained from data recorded over a 4 year period (from 1993 to 1996) at a meteorological station in Praia do Futuro beach, on the Fortaleza coast, is shown in Figure 4-b. Records of wind data in Fortaleza city for longer periods were discarded because they are biased, showing a systematic decrease in wind intensity with respect to the coastal zone due to urban development (Maia, *op. cit.*).

As it can be seen, wind regime is also strongly seasonal, with lower wind velocities prevailing during the wet season (average velocity of 5.47 m/s), whereas higher wind velocities occur during the dry season (average velocity of 7.75 m/s). Wind direction does not show a clear seasonal pattern, eastern winds blowing in the region all year round (Figure 4-b) due to the full dominance of the trade winds. Throughout the year there is a frequent southern component, especially during the dry season (from August to December).

Finally, Figure 5 shows the spatial distribution of the dominant winds, characterised by mean yearly velocity and most frequent direction, in the coastal zone of Ceará State on the basis of data recorded over a 4-year period (from 1993 to 1996) in several meteorological stations on the coast. It can be seen that in general wind velocity increases towards the northwest, and at the same time a change in direction is also detected from SE to NE winds. These changes may be related to the latitudinal position of each place with respect to the average ITCZ position in such a way that locations north of it are subjected mainly to NE trade winds, whereas those south of it are subjected to SE trade winds.

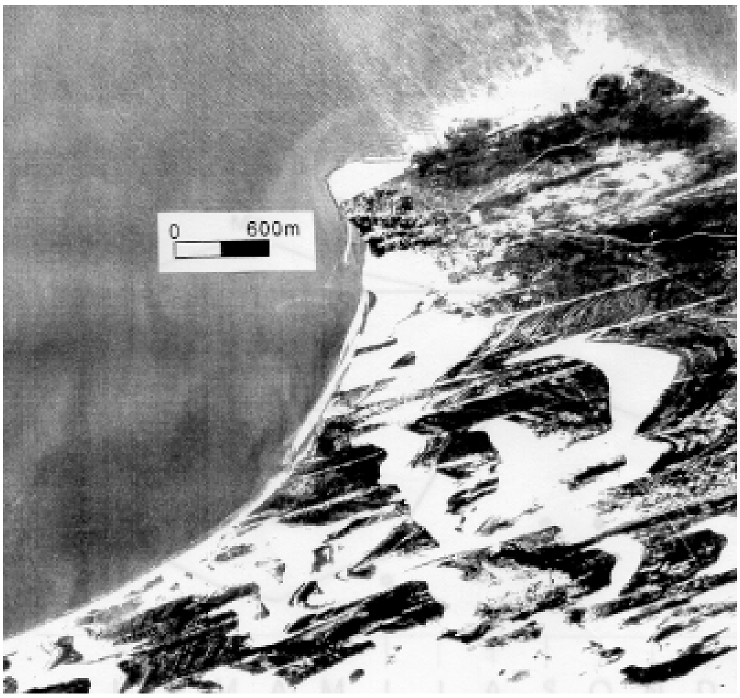

Figure 3 - Aerial photograph of mobile dune systems in Jericoacoara.

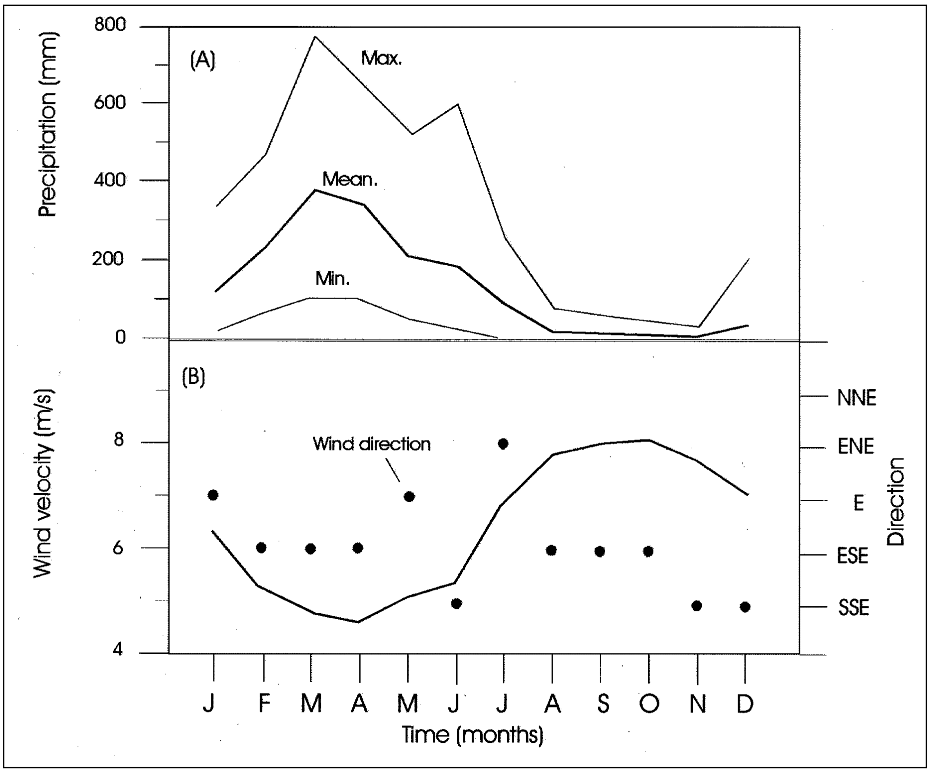

Figure 4 - (a) Monthly averaged, maximum and minimum rainfall in Ceará (obtained from 22 years of data recorded in Fortaleza city); (b) Monthly averaged wind velocity in Praia do Futuro beach (obtained from 4 years of data recorded in a meteorological station placed on Fortaleza coast). Monthly representative wind direction in Praia do Futuro beach obtained as the most frequent wind direction each month.

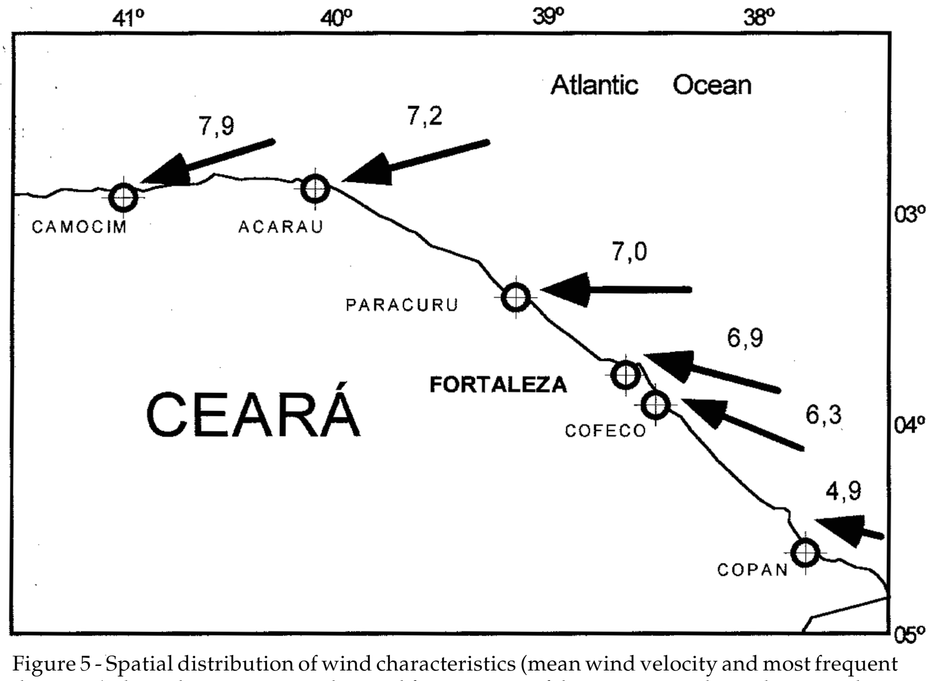

Figure 5 - Spatial distribution of wind characteristics (mean wind velocity and most frequent direction) along the Ceará coast obtained from 4 years of data in meteorological station along the coast.

METHODS

Dune forms and migration in the study area were monitored using different methodologies depending on the targeted objective and each variable was measured by different means whenever possible. Dunes were characterized three-dimensionally as to height, width and length through field data obtained by standard topographic measurements taken in the dune fields.

Dune migration was estimated by using vertical aerial photographs taken in 1958 and 1988. Individual dunes were identified in the two photos and displacements were measured at several points along dune fronts to obtain a representative mean displacement for each dune.

In addition to the direct comparison of dune position in aerial photographs, a new method of estimating the dune migration history was developed. In Figure 3 a series of marks on the land surface upwind of the dunes can be observed which are composed of vegetation (the dominant plant species are beach-star, *Remirea maritima*, beach-bramble, *Ipomoea pres-caprae* and sea-grasses *Cenchrus echinatos* and *Dactyloctenium algyptium*) and, theoretically, each of them should correspond to the position of the upwind edge of the dune during one past rainy season. During that period, the high rainfall promoted vegetation growth and reduced aeolian transport rates and consequently dune mobility, due both to an increase in the humidity of the sand (Sarre, 1988; Jackson & Nordstrom, 1998) and also to the drop in wind intensity during the wet season, as described above. This results in a temporary fixing of the dune edge by plant growth (Figure 6-a). During the dry season, the wind intensity increases, the sand humidity strongly decreases and wind action is efficient as regards sediment transport, resulting in the dunes migrating freely (Figure 6-b). However, the dune edge occupied by vegetation remains in place due to the stabilising effect of the plants (Goldsmith, 1985) leaving a cuspidate mark which indicates the previous position of the dune (Figure 6-c).

The rainfall regime in the study area is strongly seasonal, with two very well defined periods, a wet season from January to July and a dry season from August to December (Figure 4). This pattern allows us to assume that each mark corresponds to the position of the dune during the wet period each year, and in this sense acts as a kind of "tree ring" indicating the yearly dune migration. Additionally, and depending on the steadiness of the wind regime for a particular length of time, large variations in the distance between vegetation marks reflect interannual variability in the pluviometry, and could potentially be used to monitor long-term climatic changes.

Finally, a short-term experiment to monitor sand-sheet migration in Cauípe was also set up by means of a bench-mark line of coconut trees planted along a sand-sheet front. Migration of the dune along its entire front was measured with respect to the trees during the dry season. Unfortunately, the trees were pulled up during the third month of the experiment and its duration was therefore restricted to this time span.

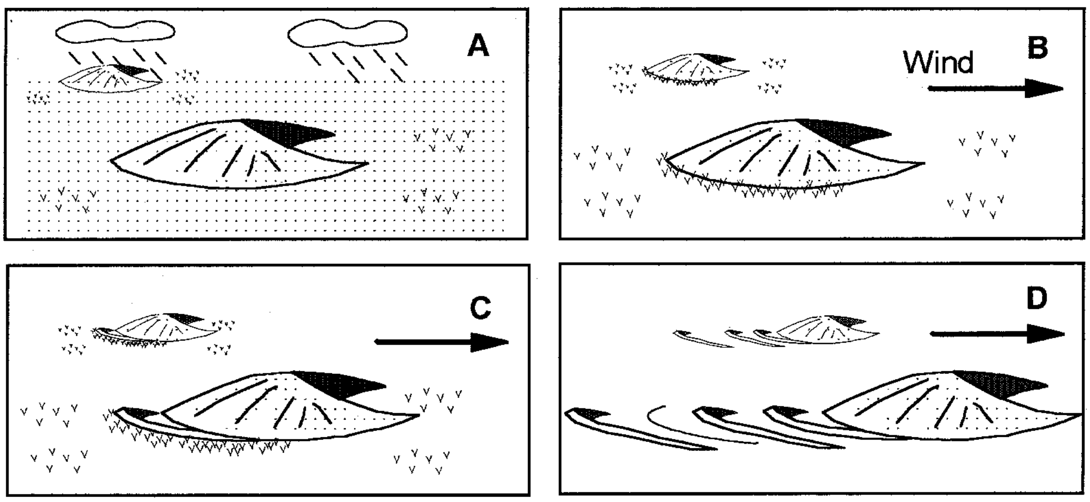

Figure 6 - Conceptual model of cuspated vegetation marks.

RESULTS

Dune dimensions

The dune geometry for barchans in Jericoacoara was characterised by using two dimensionless parameters, H/W and W/L, where **H** is the crest height, **W** is the wing-to-wing width transverse to the flow, and **L** is the dune length, the distance from the tip of the windward edge to the crest. Howard *et al.* (1978) characterised the side geometry of a barchan using these two parameters and proposed an equilibrium model in which the dune evolution is related to variations in H/W and W/L. Table I shows the basic statistics of dune dimensions (H, W and L) obtained for 50 monitored barchans in the Jericoacoara region. In general terms, the "average" barchan is 31 m high, 260 m wide and 133 m long, although these dimensions vary throughout the dune field.

Table I - Descriptive statistics of barchan dimensions (n = 50) in Jericoacoara.

Dimension (m)	Mean	St. Dev.	Max.	Min.
Height (H)	31	13	58	12
Width (W)	260	138	808	43
Length (L)	133	62	377	54

Figure 7-a shows the wing-to-wing width versus length for the monitored barchans, a linear fit by the least squares method also being included. According to the results of the fit (Table II), the data have a linear relationship, i.e., the longer the dune, the wider it will be. In general terms, the width of a barchan is about twice its length, indicating a triangular plan shape of nearly equal long edges.

Table II - Main relationships between dune dimensions by least squares method.

Relationship	R^2
W = 1.91 L	0.92
W = 1.79 L + 19.9	0.64
H = 0.12 W	0.95
H = 0.09 W + 7.8	0.70

Figure 7-b shows the corresponding crest height versus dune width. Again, a linear relationship is detected (Table II), i.e., the wider the dune, the higher it will be. The estimated relationship is of the same order of magnitude as others obtained in various barchan fields around the world (Finkel, 1959; Hastenrath, 1967 adn 1978; Hesp & Hastings, 1998).

The outlier observed in Figures 7-a/b corresponds to the largest dune to be monitored, which was 56 m high, 808 m wide (from wing to wing) and 377 m long. The relative dimensions of this dune in comparison with the others vary depending on which of the dimensionless shape parameters is analysed. Thus, its W/L value follows the general pattern of the dune field, indicating that all monitored dunes in the region are in equilibrium according to existing conceptual models such as in Howard *et al.* (1978) and Tsoar (1985) as regards plan shape, i.e., they evolve preserving their relative dimensions. However, the H/W value of this dune departs significantly from that of the other dunes monitored, in that the dune width is much greater than the others but its height is not. A possible explanation to this different behavior would be that dune height in the region is limited to a maximum value, which would be a function of the regional wind regime determining the natural atmospheric scale (Cooke & Warren, 1973), typical surface roughness (e.g., determined by vegetation) and sediment characteristics (Wilson, 1972; Howard *et al.*, 1978). This maximum crest height would be about 60 m, and even in the case of very large dunes formed by a large original sand stock, dunes can be "unlimited" in plan but "limited" to this maximum height.

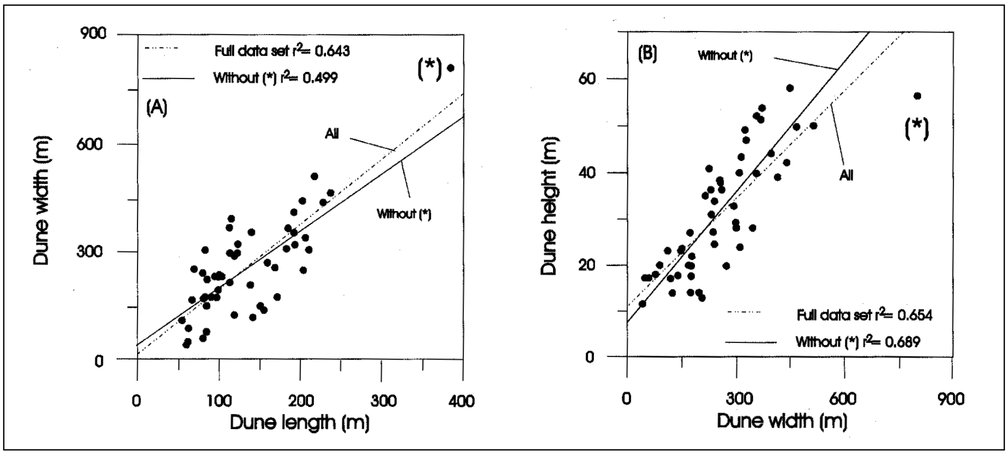

Figure 7 - (a) Dune wing-to-wing width transverse to the flow, W, versus dune length (from the tip of the windward edge to the crest), L; (b) Dune height at the crest, H, versus wing-to-wing width, W. Data set is composed by dimensions of 50 barchans in the Jericoacoara region (figure 1).

Dune migration

Figure 8 shows the estimated barchan migration rates for eight different classes of dune size as a function of dune height and volume obtained by comparing aerial photos from 1958 to 1988 in Jericoacoara, Ceará State. A strong dependence of migration rates on both dune height and volume is observed (data were fitted to a logarithmic law by least squares, yielding $R^2 = 0.98$ using volume as the independent variable and $R^2 = 0.99$ using dune height; in the latter case, a linear fit was also included, with $R^2 = 0.976$), i.e., the larger the dune is, the lower the migration rate will be. This inverse relationship between dune size and migration rate has previously been pointed out by Bagnold (1954) among others, and in fact it can be used as an indicator of the existence of an equilibrium relationship in the dune field, i.e., the regional climate induces similar transport rates along the entire dune field and, in consequence, dunes migrate at rates proportional to their volumes.

The estimated average migration rate for barchans in Jericoacoara during the 30 years covered by the aerial photographs was found to be 17.5 $m.yr^{-1}$, with minimum and maximum values of 14.6 $m.yr^{-1}$ and 21 $m.yr^{-1}$.

Dune migration rates in the region were also estimated by monitoring vegetation marks upwind of two dunes. Measuring the distance between 10 consecutive marks, corresponding to a period of 10 years (from 1987 to 1996), an average dune migration rate of 17.5 $m.yr^{-1}$ during the monitored period was obtained (Figure 9), which is in agreement with the rates obtained from aerial photographs.

Results obtained by comparing the aerial photographs from 1958 to 1988 show that sand sheets migrate at average rates from 9 $m.yr^{-1}$ to 11 $m.yr^{-1}$ in Pecém and from 6 $m.yr^{-1}$ to 8 $m.yr^{-1}$ in Cauípe. Because the sand sheets in Cauipe are larger than those in Pecém, these results are consistent with those obtained for barchans, i.e., the larger the sand sheet is, the lower the migration rate will be.

Sand-sheet migration was also estimated using vegetation marks for one dune in Pecém and through a short-term experiment using bench-marks in Cauípe. Results obtained by measuring the distance between 10 vegetation marks (10 years) in Pecém/Cauípe indicate that the sand sheet has been migrating at an average rate of 11 $m.yr^{-1}$ from 1987 to 1996 (Figure 9). Furthermore, the short-term experiment in Cauipe (2 months during the dry season, from September to November), gave an average sand-sheet migration rate of 0.95 $m.month^{-1}$. Assuming that the dune will effectively migrate during the dry season (5 months) at the calculated rate, this results in an average yearly migration rate of 4.75 $m.yr^{-1}$. The sand sheet migration rates obtained from vegetation marks and bench- marks are both consistent with those obtained from aerial photographs.

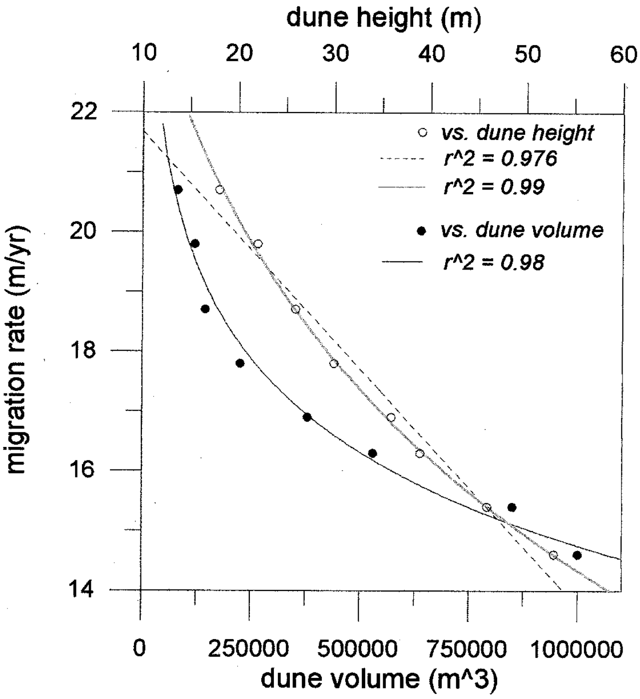

Figure 8 - Dune migration rates versus dune height and volume for barchans in Jericoacoara.

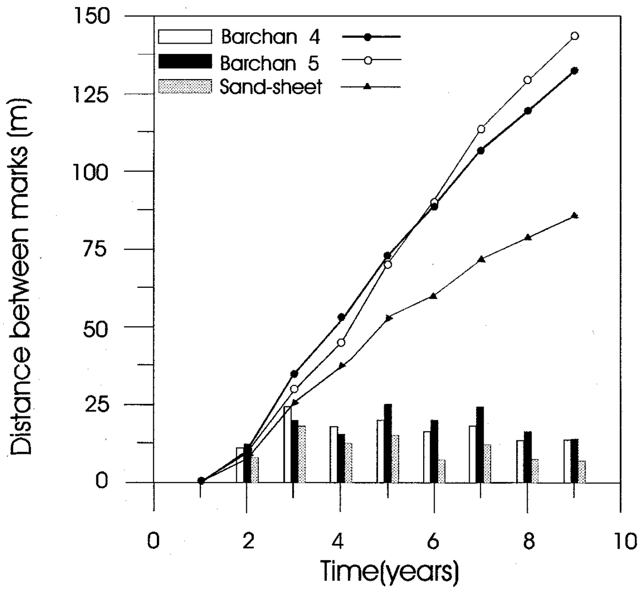

Figure 9 - Dune displacements obtained from distance between vegetation marks. Lines are cumulative displacements and bars are yearly displacements. Barchans are placed in Jericoacoara and sand-sheet in Pecém.

Aggregated aeolian transport rate

The estimated dune migration rates can be used to obtain an order of magnitude of aeolian transport rates along the dune field. In fact, dune migration should be considered as the response of the sand at an aggregated scale to wind action, and it should therefore be possible to estimate the magnitude of the transport rate causing this migration from the dune migration rate at the temporal scale determined by the dune evolution data.

Transport rates have been calculated differently from Illenberger & Rust (1988), who used the approximation of Simons *et al*. (1965) by making an analogy between dune field and migrating bedforms. As the studied dunes do not present a well defined spacing (figure 3) it is unrealistic to make an analogy with periodic bedforms.

The aggregated transport rate was calculated by estimating the time that each dune will take to entirely migrate (its overall volume) at the calculated migration rates, this being normalised by the respective wing-to-wing width. This results in the following expression:

$$q = \frac{V}{L/m}\,\frac{1}{W} \qquad (1)$$

where **q** is the aggregated aeolian transport rate per unit width, **V** is the total sand volume of the dune, **L/m** is the required time for a dune of length **L** to migrate at a rate of m a distance equal to its total length, and **W** is the dune width.

Results for the barchans in Jericoacoara give an average aeolian transport rate of 78 $(m^3/m).yr^{-1}$ with a maximum value of 98 $(m^3/m).yr^{-1}$ and a minimum of 64 $(m3/m).yr^{-1}$. It has to be stressed that these rates are representative at a decadal scale because they have been obtained from dune migration at this temporal scale. These transport rates are uncorrelated with dune dimensions, which is consistent with the previously estimated relationship between migration rates and dune dimensions. Thus, for a given constant aeolian transport rate along the dune field, the larger the dune is, the lower the migration rate will be.

At the most aggregated level, the transport rate can be calculated for an idealised dune representing the dune field characteristics, with dimensions equal to the average width, length and height of the dunes that constitute the dune field, which migrates at an average rate of 17.5 $m.yr^{-1}$ and at a resulting aggregated aeolian sediment transport rate of 98 $(m^3/m)yr^{-1}$.

If the long-term average transport rate thus estimated is compared to that obtained at a smaller scale using a deterministic aeolian transport model a reasonable agreement may be arrived at. Maia *et al.* (1998*a*) estimated for the Jericoacoara region an average rate of 102 $m^3/m/yr$ for the years 1993 to 1996, which is of the same order of magnitude as the "aggregated transport rate" of 98 $(m3/m).yr^{-1}$ calculated here and 30% higher than the mean of the estimated dune-to–dune rate, i.e., 78 $(m^3/m).yr^{-1}$.

It was not possible to estimate the aggregated aeolian transport rates associated with the sand sheets in the Pecém-Cauípe region by using the results of aerial photographs combined with field data as was done with barchans because of the great variation in height and the resulting cross-shore section of sand sheets along their front. However, during the short-term bench-mark experiment, volume changes for the monitored sand sheet were measured and from this an order of magnitude of the aeolian transport was obtained, yielding an average transport rate of 17.85 $(m^3/m).month^{-1}$ which, if integrated to the duration of the dry season (5 months), represents an average yearly transport rate of 89 $(m^3/m).yr^{-1}$ (between 65 $(m^3/m).yr^{-1}$ and 115 $(m^3/m).yr^{-1}$). Comparing these results with those obtained for the same region by Maia *et al*. (1998*a*) by using a deterministic model, a good agreement is also observed as shown by an average yearly transport rate of 79 $m^3/m/yr$, although for the year 1996 (during which the experiment was done) a rate of 96 m3/m/yr was estimated.

SUMMARY AND CONCLUSIONS

Results obtained in dune fields along the Ceará coast have enabled both the adequate characterisation of dune development and the inference of the net effect of wind action, i.e., aeolian transport rate.

The study area presents four dune generations associated with different prevailing conditions during the Holocene. At present, the youngest generation is formed by mobile barchans and sand sheets migrating across a 6-km wide fringe along the coast.

When barchan geometry is characterised by using two dimensionless parameters such as H/W and W/L, constant values are obtained for the dune field, as has been observed elsewhere (Hesp & Hastings, 1998). Thus, as a rule of thumb, the wing-to-wing dune width, W, is about twice the dune length (from the crest to the windward edge), L, and the dune width, W, is about 8 times the dune height, H. These relationships are valid for the entire dune field and they reinforce the widespread cited equilibrium-like development of barchan fields (Howard *et al*., 1978; Tsoar, 1985). However, the largest monitored barchan departs from the representative value of H/W, suggesting the existence of a maximum dune height development which will not only be a function of dune volume (in which case the regional H/W would be valid) but also of wind regime and sediment characteristics. This should result in a maximum dune height of about 60 m for the study area.

Calculated dune migration rates show a strong dependence on dune dimensions, suggesting the existence of a regional representative aeolian transport rate which is acting in a more or less uniform manner on the dune field, and induces a differential geomorphologic response as a function of size, i.e., the larger the dune is, the lower the migration rate will be. This dependence has been observed for both barchans and sand sheets throughout the study area, and representative migration rates are 17.5 $m.yr^{-1}$ for barchans in Jericoacoara, 10 $m.yr^{-1}$ for sand sheets in Pecém and 7 $m.yr^{-1}$ for sand sheets in Cauípe.

Dune migration rates calculated from vegetation marks agreed with those calculated from aerial photographs, and reflect the existence of a "pulsating" dune behavior, i.e., dunes are stabilised during the wet season and the dune's upwind edge is colonised by plants, whilst during the dry season dunes migrate freely, leaving a vegetated cuspidate mark. Due to the climatologically very well defined (in terms of rainfall and wind) seasons in the study area, long records of these marks can be used to reconstruct past climate conditions.

The observed dune evolution was used to obtain the aggregated aeolian sediment transport rate that is only valid at the temporal scale covered in this study, years to decades, and it represents the net transport rate induced by the regional climate at that scale, i.e., smaller scale wind action (fluctuations in wind intensity and direction resulting in a changing transport rate at a scale of hours, days and even months) is filtered out, and only the macroscale effect is retained. Thus, an "aggregated" aeolian transport rate of 98 $(m^3/m).yr^{-1}$ was calculated for the Jericoacoara barchan field and a transport rate of 89 $(m^3/m).yr^{-1}$ for the Pecém-Cauípe sand-sheet fields, although in the latter case few field data were available.

When comparing the transport rates thus obtained with those calculated using a deterministic aeolian sediment transport model fed by the wind climate, the results show a good agreement, i.e., they differ by less than 30% if all the cases are included in the analysis. This agreement may be due to the specific climate conditions, such as the strong persistence of a wind direction during the year with slight variations from southeasterly to northeasterly. Because wind direction is a key parameter for the proper evaluation of aeolian sediment transport (Nordstrom and Jackson, 1993) and direction remains relatively constant, the calculated (potential) transport rates will be closer to the net transport rates obtained from geomorphologic (real) observations.

Implications

The dune evolution characterized here in terms of migration and aggregated aeolian transport rates has several different implications on the Ceará State's coast. These can be classified as "natural" interactions, i.e., contribution to the sediment budget and interaction with other geomorphologic processes, and as "practical" ones, i.e., interference with human interests.

Although dune migration is usually recognised as a major contributor to the coastal sediment budget either as a source or as a sink, their real role has to be analysed taking into account the existing "boundary conditions". Although the calculated dune migration rates and the corresponding aggregated aeolian sediment transport seem to suggest that migration plays an important role in the evolution of Ceará State's coast, the fact that the dune field is actually detached from the coastal fringe leads us to conclude that it can only be considered as a contributor to the sediment budget in some specific cases, i.e., those in which dunes directly interact with the coastal zone. These cases occur in some specific stretches of coast, where the final pathway of dune migration reaches the sea as, for example, along the Pecém coast, where dunes behave as a source of sediment for the littoral dynamics. However, although the dunes were formerly developed from coastal sediments, at present they are evolving without a significant input of sediments from the coastal zone, and they are therefore not expected to actually play a significant role as a sediment sink.

Because these highly mobile dunes are migrating across the field, their evolution can interact with other physical processes and with the planning or use of the field itself. An example of the former is the potential interaction between dune migration and river courses in Ceará State where several rivers are in the pathway of some dune fields, what can result in the river course overlapping with dunes. The lower courses of all rivers undergo a change in their orientation due the dune migration, due to the filling of the original outlet with sand, making the river to divert towards a more hydraulically favourable course (Maia, 1998). In the present rivers courses it is possible to find sites where sand currently transported by the wind is being deposited. Moreover, sediment grain sizes with clear textural signatures of aeolian action have been found in the sediment transported by the river (Maia, 1998).

The other direct implication is the interaction between the natural process, i.e., dune evolution, and the use of the coastal zone. Like most of the world's coastal zones, that of Ceará State is subjected to an increasing use due to population migration from rural zones to the urban areas near the coast, and by the construction of new infrastructures related to urban needs. This usually results in a poorly planned coastal occupancy, since the existence of a natural dynamics is ignored, resulting in conflicts between natural resources and human interest (Maia *et al*., 1998*b*). Thus, some human infrastructures such as roads and small housing estates have been placed near or in dune fields. As the dunes are not stabilised, they have begun to interact with these infrastructures, with some drastic results. Another historical example occurred at town of Almofala, Ceará State where the church house was buried by a sand sheet for more than 25 years.

These minor examples clearly reflect that in order to properly plan land use along the Ceará State's coast it is necessary to consider the role of dune dynamics to avoid dune field degradation and reduce infrastructure damage/disablement due to undesired interactions.

Acknowledgements - We are grateful to FUNCEME and COELCE for making meteorological data available and to CPRM for logistic support during field campaigns. We are particularly indebted to José Orlando and Paulo Roberto for field data collection.

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