DUNE MIGRATION AND AEOLIAN TRANSPORT ALONG CEARÁ STATE, BRAZIL: DOWNSCALING AND UPSCALING AEOLIAN INDUCED PROCESSES

Migração de dunas e transporte eólico no Estado do Ceará, Brasil: escalonamento dos processos eólicos induzidos

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ABSTRACT

Dune evolution and aeolian sediment transport have been studied along the coast of Ceará State, Brazil. Barchan dune fields were found to be in equilibrium, with morphometric relationships such as H/W and W/L being constant in the area. Dune migration rates depend on dune size, with migration rates decreasing as dune size increases. Barchans in Jericoacoara beach migrate at an average rate of 17.5 $m.yr^{-1}$ whereas sand-sheets do it at 10.0 $m.yr^{-1}$. This dependence stresses the existence of equilibrium in the dune field, i.e. a constant aeolian transport exists and dunes migrate according to their sand volume. Aggregated sediment transport obtained from dune migration was in the order of 78 m^3/m/yr for barchan fields in Jericoacoara beach and 89 m^3/m/yr in Pecém beach and it was found to be uncorrelated with dune size. When the aeolian transport was calculated by using a predictive model as a function of a power of the wind velocity and results were integrated at a yearly scale a maximum difference of 30% was obtained. This agreement between the two approaches to estimate yearly aeolian transport was associated with specific climatological conditions in the area, i.e. wind direction restricted to easterly components and rainfall concentrated in few months.

Key words*: dune migration, aeolian transport, wind direction, rainfall, Ceará State (Brazil).*

RESUMO

Evolução das dunas e transporte eólico de sedimentos foram estudos ao longo da costa do Estado do Ceará. Campos de dunas barcanas se encontram em equilíbrio, sendo constantes relações morfométricas tais como "altura da crista/largura" e "largura/comprimento". A migração de dunas depende do seu tamanho, variando numa relação inversa. Dunas barcanas na praia de Jericoaoara migram a uma taxa de 17,5 m/s, enquanto os lençóis de areia o fazem a 10,0 m/s. Esta dependência ressalta a existência de equilíbrio no campo de duna, isto é, através de transporte eólico constante e migração de acordo com seu volume. O transporte agregado de sedimento obtido com a migração das dunas barcanas foi da ordem de 78 m^3/m/ano na praia de Jericoacoara e 89 m^3/m/ano na praia de Pecém, não apresentando correlação com o tamanho da duna. Verificou-se uma diferença de 30% entre o valor do transporte calculado usando-se um modelo preditivo como função de uma potência da velocidade do vento e aquele calculado por integração numa escala anual. A concordância entre os dois enfoques para estimar transporte eólico foi associada com condições climatológicas específicas na área de estudo, quais sejam componentes orientais da direção do vento e pluviosidade concentrada em alguns meses do ano.

Palavras-chaves*: migração de dunas, transporte eólico, direção do vento, pluviosidade, Estado do Ceará.*

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INTRODUCTION

Aeolian sediment transport and dune migration in coastal zones are key issues in coastal management due to the potential role of dunes in the coastal sediment budget (Illenberger & Rust, 1988) as well as due to the potential interaction of mobile dunes with coastal infrastructures. Such topics can be studied using either one of two different approaches: a top-down approach whereby 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 to forecast its geomorphological consequences. Although both approaches seek similar final results, they commence from different spatial and temporal scales. Moving through temporal and spatial scales in geomorphological process poses a number of open questions: (i) how to downscale geomorphology response to assess sediment transport patterns responsible of such as a response; (ii) 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 (iii) how to aggregate these small scale processes for use at longer time scales (see discussion *in* de Vriend, 1997 on scales in coastal morphodynamics).

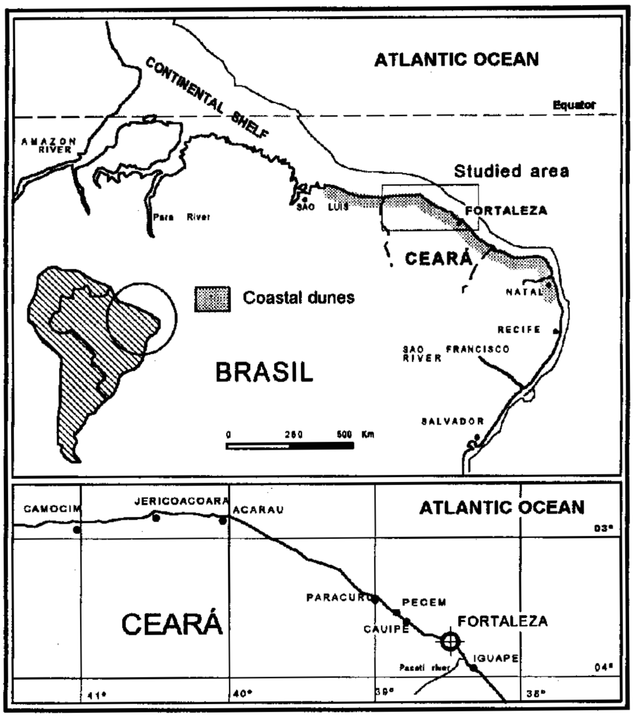

Figura 1 - Study area.

In this respect, this paper covers both approaches to characterise aeolian transport and dune evolution along the coast of Ceará State, Northeastern Brazil. Firstly, dune dynamics along the coast is studied to assess the intensity of geomorphological response at decadal scale and, at the same time, to estimate bulk transport rates responsible for such as evolution. Secondly, aeolian transport rates are estimated from the small-scale standpoint by using predictive models after site-specific calibration by using short-term measurements. The so-calibrated model is used to estimate long-term transport rates by using annual climatological (wind and precipitation) regimes. Although theoretically, both transport rates should be similar, it is usually recognised the limitations of existing aeolian sediment transport models when compared to field data even at the small scale (Davidson-Arnott & Law, 1996; Sherman *et al.*, 1998). Finally, the degree of success in the comparison of both methods is discussed and some guidelines on how to address the problem are given.

STUDY AREA

Ceará State is located in northeastern Brazil (figure 1) and its coastal zone is approximately 572 km long, and consists mainly of long sandy beaches, occasionally interrupted by small rivers and rocky headlands. The local wave climate can be roughly described by a yearly averaged significant wave height, H_s, of 1 m, a mean period, T_z, of 5 sec with a full dominance of easterly waves. Very large longshore transport rates (up to 700,000 $m^3.yr^{-1}$) are common along the coast due to the steadiness of wave climate which usually approaches to the coast with a large angle (Maia, 1998). It is a mesotidal environment, with a diurnal tide with a maximum range of 3 m.

Practically the entire Ceará coast is backed by extensive dune fields. Three to four dune generations have been identified: paleodunes, parabolic dunes, eolianites and mobile dunes (from the oldest to the youngest dunes) (Maia, 1998; Jiménez *et al.*, 1999). The last dune generation comprises the currently *active dunes*, and these are the object of the work presented here. These dunes extend along a stretch about 6 km wide following the coastline (figure 1), and comprise barchans, barchanoids and sand sheets, with the dominant form depending on the available sand stock. At present, the active dunes are detached from the coast by between 600 m and 2,000 m, and are migrating on top of older dune generations.

Regional Climate

The regional climate of Northeastern Brazil is governed by the intertropical convergence zone (ITCZ), which is a convergence region for northeasterly and southeasterly Atlantic trade winds. Seasonal latitudinal positioning of the ITCZ determines both the presence of dominant winds and the rainfall regime (Philander & Pacanowski, 1986). Thus, when the ITCZ is located in its northernmost position, normally from August to September, intense southeasterly winds and low rainfall dominates in the area. Conversely, when the ITCZ is in its southernmost position, from March to April, weak southeasterly winds and high rainfall prevail.

The rainfall regime in the are is strongly seasonal (figure 2), with a wet period from January to July in which almost the yearly rainfall is concentrated (about the 93%) and a dry period from August to December, when virtually no rain falls. Additionally, a large interannual variability is also present due to the appearance of droughts and floods associated with El Niño (Markham & McLain, 1977; Nobre & Shukla, 1996).

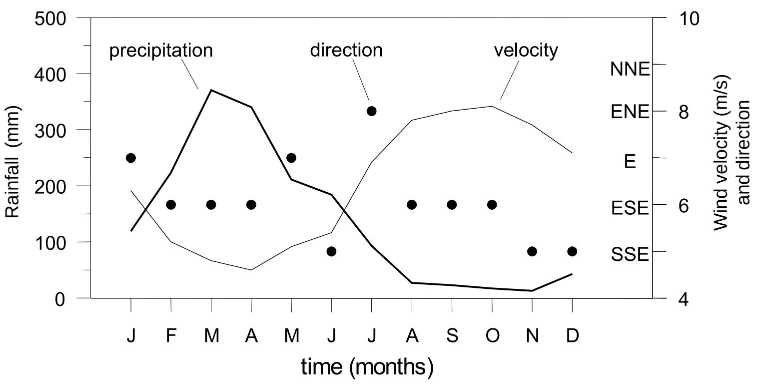

Figure 2 - Top: monthly distribution of wind intensity and rainfall. Bottom: spatial distribution of mean wind intensity along the coast of Ceará State, Brazil.

The wind regime is also strongly seasonal with low wind velocities prevailing during the wet season (average velocity of 5.47 $m.s^{-1}$), whereas higher wind velocities occur during the dry season (average velocity of 7.75 $m.s^{-1}$). Wind direction does not show a clear seasonal pattern, but it is mainly easterly all year round due to the full dominance of the trade winds. As to the spatial distribution of dominant winds along the Ceará coast, wind velocity increases towards the Northwest, with directions slowly varying from SE to NE towards the north (figure 2). These variations may be due to the latitudinal position of each site with respect to the average ITCZ position (Jiménez *et al*., 1999).

METHODS

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. In addition to this, three dimensional dune parameters, i.e. height, width and length, were characterised by field data obtained by topographic levelling taken in the various dune fields. This method was complemented by other field techniques to characterise dune evolution (Maia, 1998; Jiménez *et al*., 1999).

Measurements of aeolian transport were made by using sediment traps developed by Maia (1998) modifying those proposed by Leatherman (1978). Simultaneously, wind characteristics (velocity and direction) were recorded during each experiment. These short-term experiments were done in different dune fields and beaches along the Ceará coast, covering the locations where dune evolution was analysed. Experiments were conducted during different seasons to cover variations in wind regime.

DUNE GEOMETRY AND MIGRATION

Dune geometry

The dune geometry for barchans was characterised by using two dimensionless parameters, *H/W* and *W/L*, which have been used by Howard *et al*. (1978) to propose an equilibrium model for barchans. Main geometric variables are the crest height, *H*, the wing-to-wing width transverse to the flow, *W*, and the dune length *L* (distance from the tip of the windward edge to the crest). For the studied dune field, the average barchan is 31 m high, 260 m wide and 133 m long.

The ratio between crest height, *H*, and width, *W*, is shown in Figure 3 where a linear fit by the least-square method is included. According to the results of the fit, the data present a linear relationship (significant at the 95% level), i.e. the wider the dune, the higher it will be. The functional relationship here estimated is of the same order of magnitude as those obtained in other barchan fields (Hesp & Hastings, 1998), although dunes analysed here are in the upper size range.

The ratio between width (W) and length (L) can be seen in Figure 3, where a linear relationship is also detected, i.e. the longer the dune, the wider it will be (in general, the width of a barchan is about twice its length).

The outlier in Figure 3 corresponds to the largest monitored dune (56 m high, 808 m wide and 377 m long). 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 that of Howard *et al.* (1978), i.e. they evolve preserving their relative dimensions. On the other hand, its **H/W** value significantly departs from that of the other dunes monitored, i.e. although the dune width is much greater than the others, its height is not. A possible explanation to this behaviour would be that dune height in the region is limited to a maximum value, which would be a function of factors such as the natural atmospheric scale determined by the regional climate (Cooke *et al*., 1993), surface roughness determined by vegetation and sediment characteristics (Wilson, 1972).

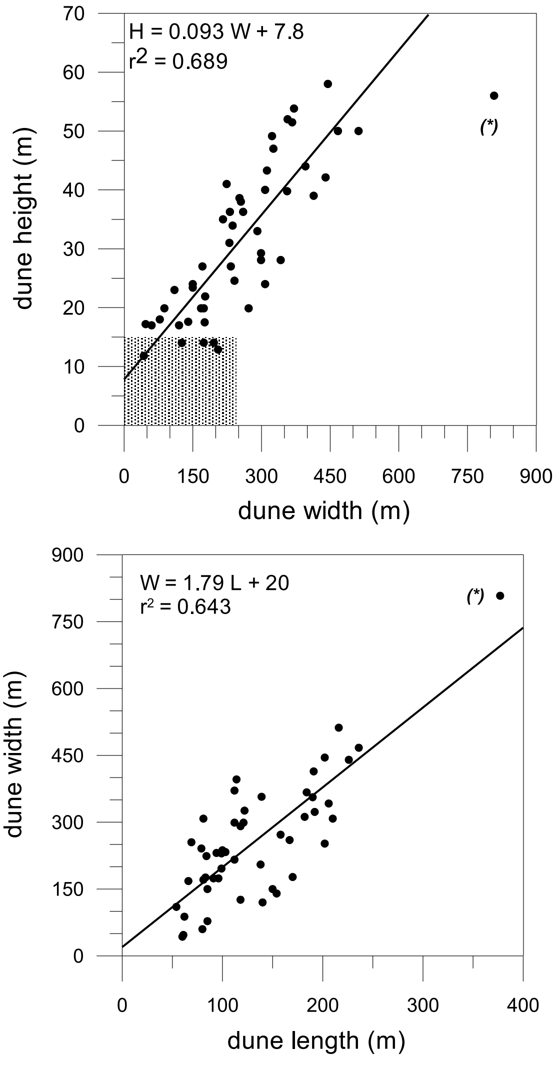

Figure 3 - Barchans morphometric relationships in Jericoacoara, Ceará State. (*) Largest monitored dune in the area (not included in the fit for *H/W*). Shadow area represents the range of compiled dune size data by Hesp & Hastings (1998).

Dune migration

Barchan migration rates for different dune classes of dune size as a function of dune height and volume can be seen in Figure 4. To make this analysis, it is assumed that dunes are in equilibrium, i.e. they have not suffered any change in volume. This is a reasonable assumption according to the results presented before and taking into account that they are mature dunes and that no changes in the sand-supply conditions have not occurred during the considered the time range (1958-1988).

Results show a strong dependence of migration rates on both dune height and volume, i.e. the larger the dune is, the lower the migration rate will be. Data were fitted to a linear and to a logarithmic law by least squares (figure 4), with *r* - values of 0.992 and 0.934, respectively, when volume was used as the independent variable and *r*-values of 0.999 and 0.988 when the dune height was used. This inverse relationship between dune size and migration rates can be used as an indicator of the existence of an equilibrium state in the dune field, i.e. the regional climate induces similar transport rates in the dune field and, dunes migrate at rates proportional to their size.

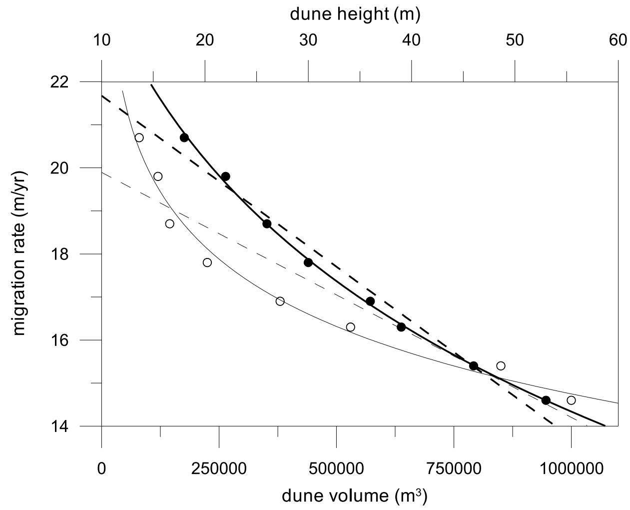

Figure 4 - Barchan migration versus dune size (solid dots: height; open dots: volume).

The average migration rate for barchans in Jericoacoara, Ceará State, during the 30 year period rate was estimated in 17.5 $m.yr^{-1}$, ranging from 14.6 $m.yr^{-1}$ to 21 $m.yr^{-1}$. On the other hand, for sand sheets, the average migration rate in Pecem amounted to 10 $m.yr^{-1}$ (ranging from 9 $m.yr^{-1}$ to 11 $m.yr^{-1}$), whereas in Cauipe migration rates ranged from 6 $m.yr^{-1}$ to 8 $m.yr^{-1}$. Because the sand sheets in Cauipe are larger (in terms of both dune front and dune volume) than those in Pecém, these results are consistent with those obtained for barchans, i.e. migration rates decrease as dune size increases. Moreover, when comparing with these rates with those obtained for barchans, this dependence is also stressed because sand-sheets comprise a larger volume of sediment than barchans.

The obtained results are in the upper range of dune sizes in comparison with other published data shown and they confirm the trend already noted in previous analyses in which this size dependence is weaker as dune size increases (Jiménez *et al*., 1999). Moreover, they also serve to discard previous assumptions Cooke *et al*. (1993) among others that assume the existence of a limit dune size beyond that the rate of movement is not affected, at least for the dune size range analysed here (Jiménez *et al*.,1999).

AEOLIAN SEDIMENT TRANSPORT

Aggregated aeolian transport rates

Dune evolution results were used to estimate the aeolian transport rates along the study area, because they must be considered as the aggregated-scale sediment response to wind action. Thus, aggregated rates were calculated by estimating the time that each dune will take entirely to migrate (its overall volume) at the calculated migration rates, this being normalised by the respective wing-to-wing width (Maia,1998; Jiménez *et al*., 1999), i.e.

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

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. This approach differs of the usual one, i.e. making an analogy between the dune field and migrating bedforms (Simons *et al*., 1965), because the studied dunes do not present a well defined spacing.

Aggregated transport rates for the different dune fields can be seen in Table I. It must be stressed that these values are only representative at the decadal scale because they have been obtained from dune migration at this temporal scale and are uncorrelated to dune size, which validates the assumption of the existence of a dynamical equilibrium of dunes in the area. This uncorrelation can be also seen directly from Equation 1 if we consider the observed dependence of migration rates on dune size (Jiménez *et al*., 1999). Thus, if the dune volume, **V**, is defined as the product of the three basic dune dimensions (L, W, H) and a dimensionless shape factor, φ, i.e. $V = L\,W\,H\,\varphi$, (1) can be re-written as

$$Q = H\,\varphi\,m \qquad (2)$$

Because the migration rate, **m** was found to be inversely dependent on dune height, i.e. $m \sim 1/H$, (2) indicates that **Q** does not depend on any dune dimension (L, W, H). Equation 2 also formalises the concept of dynamical equilibrium, i.e. for a given constant bulk transport rate, the larger the dune is, the lower the migration will be.

Table I - Aeolian transport rates along the coast of Ceará State, Brazil.

Location	Aggregated† ($m^3/m/yr$)	Short-term‡ ($m^3/m/yr$)
Jericoacoara	78	102
(barchans)	(64-98)	(74-125)
Pecém-Cauipe	89	79
(sand-sheets)	(65-115)	(55-102)

Remarks: average rates and ranges: † estimated from dune evolution; ‡ calculated by model calibrated with trap measurements.

At the most aggregated level, the transport rate can be calculated for an idealised 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 the estimated average rate ($17.5\ m.yr^{-1}$). This yields an aggregated aeolian sediment transport rate of 98 $m^3/m/yr$ for the barchan field in Jericoacoara.

Short-term aeolian transport rates

Another way to estimate transport rates induced by wind action is to use some of the large number of proposed aeolian-induced sediment transport models (Sherman *et al*., 1998). This approach means that a short-term process-oriented model is used to estimate a short-term integrated transport rate (where the time integration scale is usually very short, i.e. a wind event), and to upscale it to a longer period by simple integration of all the wind events occurring during that period, e.g. a year.

Although this seems a straightforward technique, when applied the results usually have not been satisfactory. Sherman *et al*. (1998) evaluate the performance of several of the most used models and found large deviations between measured and modelled transport, which in most cases were associated with intrinsic "inaccuracies" of the models. Moreover another source of inaccuracy was found to lye in the inability to adequately consider the soil moisture content in such models.

To estimate the aeolian transport rates by using this approach, several transport models were analysed by comparing their performance against a data set obtained in different dune fields and beaches along the study area (Maia, 1998). The analysed models were of two types: (i) including a threshold velocity (Bagnold, 1951; Kawamura, 1951; Lettau & Lettau, 1977 and White, 1979); (ii) not including a threshold (Bagnold, 1951; Hsu (1971); Borowka, 1980; O'Brien & Rindlaub 1936).

From the analysed models including a threshold velocity the best performance was obtained for Bagnold (1951) and Lettau & Lettau (1977) models. In the case of models without a threshold velocity, tested models gave similar results but the Borowka's one due to the different power dependence on velocity.

The larger difference between both approaches was found to derive, as expected, from low wind velocities, whereas the second group of models gave an over-prediction of transport rates. However, due to regional climatology these conditions are not too relevant because during the dry season, wind velocities significantly exceed threshold velocities. This would mainly be related to wind conditions during the wet season when wind velocity decrease which. is accompanied by a drastic increase in rainfall and thus, in soil moisture. In practical terms, these two factors, decrease in wind velocity and increase in soil moisture makes aeolian transport during the wet season to be negligible.

Due to this constraint in effective wind velocities to the upper range, it was decided to use the simplest model, i.e. transport rate is a function of a power of the wind velocity. Figure 5 shows the averaged transport rates measured in the different areas against measured shear velocity. This regional comparison can be done because no significant differences in sediment grain size were found in the analysed areas. The objective to include all areas into the same analysis was to obtain a simple formula valid for the region, which includes the possible local sources of variability or specificity's.

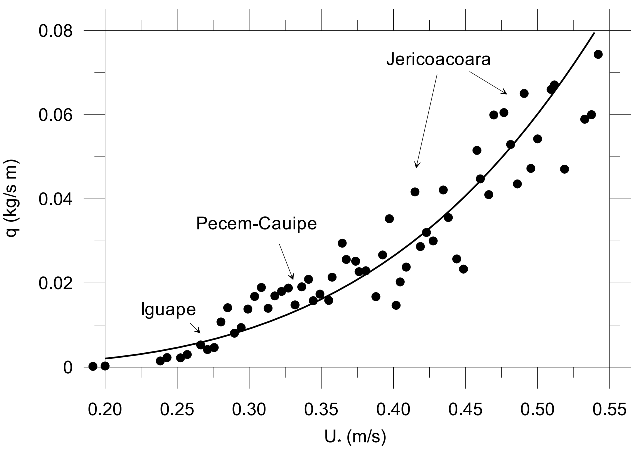

Figure 5 - Measured transport rates versus shear velocity in the study area.

The best-fit empirical model obtained by using all the measured aeolian sediment transport data (Figure 5) was:

$$q = 0.77\ u_*^{3.8} \qquad (3)$$

Once the model was fitted/calibrated against field data, this was used to calculate yearly aeolian transport rates in Jericoacoara and Pecém regions. To take into account the interannual variability in regional climatology, estimations were done by using four years of meteorological records. The potential aeolian transport rate was calculated for every day except when large rainfall existed (the used criterion was that those days with rainfall larger than evaporation rates did not experience significant aeolian transport).

Transport rates are of the same order of magnitude that those obtained from dune evolution (table I) and, thus if differences between both estimations are measured as

$$\xi = \frac{Q - \int q}{Q} 100 \qquad (4)$$

where $\boldsymbol{\xi}$ is the deviation in percentage, $\boldsymbol{Q}$ is the aggregated transport obtained from dune evolution and $\int q$ is the yearly integrated aeolian transport rate calculated by using (3), a difference of 30% is obtained for the barchan fields in Jericoacoara, whereas in the sand-sheets of Pecém-Cauipe a deviation of the 11% is found. The obtained deviations can be considered as reasonable, especially when considering the simplicity of the approach. Moreover, when they are compared with the usually found in other studies, even working at time scales much shorter than the one used here, they are in the upper range of agreement (Bauer *et al*., 1990; Sherman *et al*., 1998).

DISCUSSION AND CONCLUSIONS

The analysis done along the coast of Ceará State to characterize aeolian sediment transport and its geomorphodynamic consequences, i.e. dune evolution, has permitted to quantify the system functioning from different standpoints.

Firstly, the analysed dune fields, specially the ones formed by barchans, present characteristics that seems to suggest the existence of an equilibrium state as that described by Howard *et al*. (1978) and Tsoar (1985), among others, for barchan development. This is reflected in the morphometric dune relationships, i.e. ***H/W*** and ***W/L***, which present constant values for the entire dune field. This means that they evolve preserving their dimensions and without a significant variation in shape. In this sense, it has to be stressed that in most of the cases these dune fields are detached from the coast and they are not receiving more sand. On the other way round, they act as sediment sources for the littoral dynamics since in most of the cases, the sea is in the final pathway of the mobile dunes.

The existence of such equilibrium state is also stressed in the observed dependence of migration rates with dune size, i.e. the larger the dune is the lower the migration will be. Moreover, since the analysed dunes are quite large, this behaviour let to increase the range of validity of previous observations of Cooke *et al*. (1993), based on the analysis of smaller dunes, according to which large dunes should not conform to this pattern.

Aggregated aeolian transport rates were calculated from dune migration and they do not show any dependency on dune dimensions. This also validates the assumption of the existence of a dynamical equilibrium of dunes in the area, i.e. wind induces a common aeolian transport along the dune field and dune migrates at a speed proportional to its size (volume of sand).

Finally, the aeolian transport was also calculated by using a predictive model as a function of some power of the wind velocity. Several models were tested against field data acquired by using sediment traps. Although models including a threshold velocity seem to give better results in general, due to the relative steadiness in the wind regime during the dry season (with wind velocities much larger than the required threshold velocity), it was not necessary to including such parameter. The best-obtained model was a simple power function of the velocity (equation 3) and it was validated against data measured along the entire coast.

When comparing aggregated transport rates obtained from dune dynamics with those calculated by using the calibrated deterministic aeolian sediment transport model fed by the wind climate, results show a good agreement, i.e. they differ between 30% and 11% (table I). This agreement between the two approaches has been associated with the specific climate conditions. Thus, the strong persistence of wind direction during the year with slight variations from southeasterly to northeasterly winds, reduce one of the major source of uncertainty in the evaluation of aeolian sediment transport, i.e. the wind direction (Nordstrom &Jackson, 1993). Moreover, the existence of a well defined rainfall pattern (with all the rain concentrated in few months and virtually no rain in the rest of the year), reduces uncertainties associated with the soil moisture content which is an important parameter controlling models' predictability (Sherman *et al*., 1998).

From the practical standpoint, this work has permitted to validate different ways to estimate the contribution of aeolian sediment transport along the Ceará coast where the major sediment source for littoral dynamics are the dunes, whereas in most cases this role is mainly played by the rivers. Moreover, the large dune mobility with migration rates of more than 17 $m.yr^{-1}$ for dunes with volumes of several hundred thousands cubic meters of sand can significantly interfere with other geomorphological processes or with land planning (e.g. Maia, 1998; Jiménez *et al*., 1999).

REFERENCES

Bagnold, R.A. *The physics of blown sand and desert dunes*. Methuen, London, 265 p, 1954.

Bauer, B.O.; Sherman, D.J.; Nordstrom, K.F. & Gares, P.A. Aeolian transport measurement and prediction across a beach and a dune at Castroville, California, p. 39-53, *in* Nordstrom, K; Psuty, N. & Carter, R.W.G. (eds.), *Coastal dunes: form and processes*. Wiley, New York, 1990.

Borowka, R.K. Present days process and dune morphology on the Leba Barrier, Polish coast of Baltic. *Geografiska Annl*., v. 62, p. 75-82, 1980.

Cooke, R.U.; Warren, A. & Goudie, A.S. *Desert geomorphology*. UCL Press, 521 p., London, 1993.

Davidson-Arnott, R.G.D. & Law, M.N. 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. *J. Coast. Res*., v.12, p. 654-663, 1996.

de Vriend, H.J. Prediction of aggregated -scale coastal evolution. *Proceedings of Coastal Dynamics'97*, ASCE Press, p. 644-653, 1997.

Hesp, P.A. & Hastings, K. Width, height and slope relationships and aerodynamic maintenance of barchans. *Geomorphology*, v. 22, p. 193-204, 1998.

Howard, A.D., Morton, J.B., Gad-El-Hack, M. & Pierce, D.B. Sand transport model of barchan dune equilibrium. *Sedimentology*, v. 25, p. 307-338, 1978.

Hsu, S.A. Computing aeolian sand transport from routine weather data. *Proceedings of the 14th Coastal Engineering Conference*, ASCE Press, p.1619-1626, 1974.

Illenberger, W.K. & Rust, I.C. A sand budget for the Alexandria coastal dunefield, South Africa. *Sedimentology*, v. 35, p. 513-521, 1988.

Jiménez, J.A.; Maia, L.P.; Serra, J. & Morais, J. Aeolian dune migration along the Ceará coast, northeastern Brazil. *Sedimentology, v.* 46, p. 689-701, 1999.

Kawamura, R. *Study of sand movement by wind*. Univ. Tokyo, Rept. Inst. Sci. & Technology, n. 5, 1951.

Leatherman, S.P. 1978. A new aeolian sediment trap design. *Sedimentology*, 25: 303-306.

Lettau, K. & Lettau, H. Experimental and micro-meteorological field studies of dune migration, in Lettau, K. & Lettau, H. (eds.), *Exploring the world's driest climate*. University of Wisconsin Press, 1977.

Maia, L.P. *Procesos costeros y balance sedimentario a lo largo de Fortaleza (NE Brasil): Implicaciones para una gestión adecuada de la zona litoral*. Tese de Doutorado, Facultad de Geologia, Universidad de Barcelona, 269 p., 1998.

Markham, C.G. & McLain, D.R. Sea surface temperature related to rain in Ceará, north-eastern Brazil. *Nature*, v. 265, p. 320-323, 1977.

Nobre, P. & Shukla, J. Variations of sea surface temperature, wind stress, and rainfall over the Tropical Atlantic and South America. *J. Clim.*, v. 9, p. 2464-2479, 1996.

Nordstrom, K.F. & Jackson, N.L. The role of wind direction in eolian transport on a narrow sandy beach. *Earth Surface Processes and Landforms*, v. 18. p. 675-685, 1993.

O'Brien, M.P. & Rindlaub, B.D. The transport of sand by wind. *Civ. Engin.*, v. 6, p. 325-337, 1936.

Philander, S.G.H. & Pacanowski, R.C. A model of the seasonal cycle in the tropical Atlantic Ocean. *J. Geophys. Res.*, n. 91, p. 14192-14206, 1986.

Sherman, D.J.; Jackson, D.W.T.; Namikas, S.L. & Wang, J. Wind-blown sand on beaches: an evaluation of models. *Geomorphology*, v. 22, p. 113-133, 1998.

Simons, D.B.; Richardson, E.V. & Nordin, C.F.Jr. Bedload equation for ripples and dunes. *Prof. Pap. US Geol. Surv.*, 462-H, H1-H9, 1965.

Tsoar, H. Profile analysis of sand dunes and their steady state signification. *Geogr. Ann.*, n. 67A, p. 47-59, 1985.

White, B.R. Soil transport by wind on Mars. *J. f Geoph. Res.*, v. 84, n. 4643-4651, 1979.

Wilson, I.G. Aeolian bedforms-their development and origins. *Sedimentology*, v. 19, n. 173-210, 1972.