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6 Geomorphological significance of wind flow patterns over a Namib linear dune

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Abstract

This paper reports that part of a wider study of the dynamics of a linear dune in the Namib sand sea which is concerned with the wind flow patterns over the dune. Results of wind speed measurements using anemometers and flow visualization using smoke flares demonstrate that the dune's intrusion into the boundary-layer creates a pattern of wind flow change over the dune cross profile. By assuming that increasing wind speed causes erosion of the dune surface and decreasing wind speed causes sand deposition, a simple, qualitative model of linear dune dynamics is postulated. Without invoking secondary wind flows as previous theories have done, maintenance of linear dune form is seen as a response to the pattern of wind speed change alone.

Introduction

Despite the dominance of dunes with a linear form in the world's sand seas (Fryberger & Goudie 1981), they remain "perhaps the most controversial type of dune" (McKee 1979), the subject of a number of highly speculative interpretations and relatively few careful field studies. In recent years, however, single dune studies, notably those of Knott (1979) and Tsoar (1978), have greatly extended our knowledge of processes on aeolian dunes. Furthermore, at the same time as geomorphologists studying the development of desert dunes have become interested in wind flow over dunes, meteorologists have become concerned with the parallel problem of the effect which the intrusion of low hills into the boundary-layer has on wind fow, and Lancaster (1985) and Tsoar

(1985) have recently made use of formulae provided by meteorologists to model wind flow over dunes. There has consequently been some progress towards empirical modelling of linear dune dynamics.

Against this background an investigation has been undertaken of the dynamics of a single, complex linear dune in the Namib Desert in southern Africa (Livingstone 1985). This paper reports that part of the study concerned with wind flow patterns over the dune, and seeks to propose a simple qualitative model of linear dune dynamics.

Past theories

In the past, a number of theories have been proposed to explain linear dune origin, evolution and maintenance. There has been a difference of opinion between those believing in the role of prevailing winds blowing parallel to the dunes and those invoking necessarily bi-directional wind regimes. Much has been made of the importance of antecedent dune forms such as barchans, zibars and parabolic dunes. There has also been some discussion, reviewed in Lancaster (1982), between those invoking an erosional 'wind rift' origin and those proposing a depositional origin for linear dunes.

Two theories in particular, however, have attempted to explain the actual mechanism by which linear dunes form and advance, and it is of value to consider these theories further. The first of these, and the one which appears most often in textbooks, is the helical roll vortex theory of Bagnold (1953). In support of his theory, Bagnold cites laboratory experiments by Brunt (1937) in which polygonal cells were created by heating a metal plate. When a glass plate was then moved above the heated metal plate a shear in the boundary-layer was caused and the polygonal cells were moved laterally producing spiral roll vortices. The two essentials, therefore, for the creation of roll vortices are thermal convection and a strong geostrophic wind, conditions often found in desert areas, and Bagnold tentatively suggests this as a possible mechanism of linear dune genesis.

While this theory is attractively simple, a number of objections have been raised. There is no doubt that roll vortices do exist, but they have yet to be described from linear dune fields, and those which have been reported from other areas appear to display transverse velocities well below that required to move sand. Additionally, while Kelly (1984) reports roll wavelengths between 1.5 and 13.7 kilometers, linear dune spacing varies between 0.15 and around 3.5 kilometers (Breed & Grow 1979). Given that roll vortices are paired, dune wavelengths of between 3.0 and 27.4 kilometers could be inferred, and clearly there is little overlap between the two size distributions. The theory also requires that winds blow parallel to the dune trend. This occurs rarely in the

Namib Desert, and Besler (1980) overcomes the problem by viewing the dunes as relics of a much windier episode of winds parallel to the dune alignment at the time of the Last Glacial maximum. Yet the fact that roll vortices have still to be demonstrated creating linear dunes in any dune field, when coupled with the circumstantial evidence outlined above, suggests that it is necessary to entertain the possibility of some other mechanism of formation for linear dunes.

More recently, though, there has been a challenge to this first theory from Tsoar (1978, 1983) whose own theory describes the importance of the separation and deflection of flow in lee side eddies on linear dunes. Following the study of a simple linear dune in the Negev Desert, Israel, Tsoar proposed that,

> "The basis of the dynamics of the longitudinal dune is the phenomenon that the path of the wind flow when crossing the crest at any angle whatsoever is deflected on the lee flank in the direction parallel to the crest line". (Tsoar 1978, p. 133).

In other words, Tsoar's proposal is that once formed, the intrusion of the linear dune into the boundary-layer creates eddies condusive to its own self-perpetuation, such that sand is prevented from leaving the lee side of the dune. Two conditions must be fulfilled for this mechanism to operate: there must be a bi-directional wind regime, and the dune must have a sharp crestline so that flow separation occurs in the immediate lee of the crest. Clearly, the theories of both Bagnold and Tsoar invoke some form of secondary flow, but the attraction of Tsoar's theory is that the secondary flow is caused by the dune itself rather than by atmospheric conditions.

The study dune

The study site lies at the northern edge of the Namib sand sea in Namibia, approximately eight kilometers southeast of the Namib Desert Research Station at Gobabeb (23° 34'S 15° 03'E). The dune here is aligned roughly north-south, and is approximately 350 m wide and 50 m high. The study dune displays the asymmetry typical of dunes in this part of the Namib sand sea, with a relatively uniform west flank, but a series of secondary ridges and barchanoid features on the east flank.

The central Namib Desert is subjected to a seasonal wind regime so that, broadly speaking, the dunes are attacked by low to moderate winds from the southwest and northwest in summer, and by high magnitude, low frequency easterly winds in winter (Lancaster *et al.* 1984). Under the influence of this regime the crest of the dune moves laterally back and forth some fourteen meters each year (Livingstone 1985), while northward extension of the dunes into the Kuiseb River valley has been measured by Ward at between 0 and 1.85 m yr^{-1} (Ward 1984).

Wind flow measurements

In order to monitor the pattern of wind flow near the dune surface two techniques were employed. Smoke flares were used to enable visualization of the flow patterns, and rotating-cup anemometers of the 'wind run' type were used to measure wind speed near the dune surface. All anemometers were mounted on posts one meter above the ground surface, and readings were usually made every 30 minutes, although during periods of relative calm, readings were made every hour. Because there were never more than five anemometers available at any one time, different dune or interdune elements were monitored at different times, but on each occasion when anemometers were located on the dune, an anemometer was placed at the crest of the dune, thereby enabling the formulation of a relationship between the wind speeds at various points over the dune cross-profile.

A total of 69 readings of winds originating from the west side of the dune and 23 readings in easterly winds were recorded at the study dune. Forty-five readings were recorded for wind speeds on the interdune corridors adjoining the study dune in both easterly and southwesterly winds. From these data it has been possible to

Table 1 Wind speeds on the study dune in south-westerly winds: correlation and regression with the speed at the crest.

y	n	r	t	p	m	c
Widc	47	0.8743	12.1	0.001	0.72	−0.42
B	19	0.9981	66.8	0.001	0.65	−0.16
E	23	0.9969	58.2	0.001	0.80	−0.24
H	23	0.9940	41.6	0.001	0.68	+0.44
M/N	21	0.8237	6.3	0.001	0.70	−2.38
O	21	0 8986	8.9	0.001	0.95	−3.34
P	24	0.7648	5.6	0.001	0.58	−0.44
Q	21	0.9620	15.4	0.001	0.93	−2.55
S	21	0.9459	12.7	0.001	0.84	−2.22
Eidc	24	0.6077	3.6	0.001	0.64	−0.59

y point on the dune (Widc = West interdune corridor, Eidc = East interdune corridor)
n sample size
r Product Moment Correlation Coefficient
t Student's t value
p significance level expressed as probability that the distribution is random
m gradient of regression equation
c intercept of regression equation

calculate the 'Product Moment Correlation Coefficient' and 'Least Squares' regression equations indicating the relationship between wind speeds at the dune crest and the speed on other parts of the dune, and thereby providing a simple linear regression model of wind speed change at the surface of a linear sand dune (Tables 1 & 2). The letters denoting location of the anemometers use the notation of a simultaneous erosion pin project.

Table 2 Wind speeds on the study dune in easterly winds: correlation and regression with the speed at the crest.

y	n	r	t	p	m	c
Widc	19	0.8718	7.3	0 001	0.50	−1.29
A	5	0.1814	0.3		not statistically significant	
D	6	0.7594	2.3		not statistically significant	
F	5	0.7637	2.0		not statistically significant	
I/J	6	0.1558	0.3		not statistically significant	
N	5	−0.0690	−0.1		not statistically significant	
O	3	0.6032	0.8		not statistically significant	
Q	5	0.5828	1.2		not statistically significant	
R	14	0.8630	5.9	0.001	0.60	+0.55
S	7	−0.2470	−0.6		not statistically significant	
Y	9	0.9714	10.8	0.001	0.47	−0.57
Eidc	14	0.9847	19.6	0.001	0.38	+0.98

y point on the dune (Widc = West interdune corridor, Eidc = East interdune corridor)
n sample size
r Product Moment Correlation Coefficient
t Student's t value
p significance level expressed as probability that the distribution is random
m gradient of regression equation
c intercept of regression equation

Considering summer winds originating on the west side first, there are very strong, positive, linear relationships between wind speeds at one point on the dune and speed at another (Table 1), and from these empirically formulated linear relationships it has been possible to calculate the wind speed over the study dune's cross-profile for given initial winds speeds on the interdune corridor (Fig. 1). From these calculations a distinctive pattern of changing wind speed on the linear dune emerges. This pattern shows a very obvious, progressive increase of wind speed from the interdune corridor to the dune crest due to a compression of streamlines, and a similar decrease from the crest to the lee side interdune corridor as the streamlines diverge. However, there is some finer detail on this overall trend for there is a very rapid drop in wind speed in the immediate lee of the crest where the slip face is formed. This is the result of the separation of the flow from the ground surface described by Tsoar (1978), and is discussed in the following section on 'Flow Visualization'. The wind then

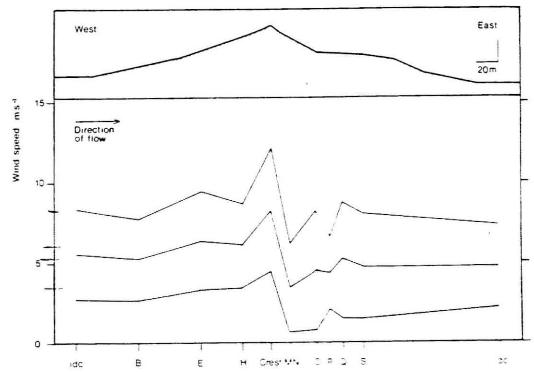

Figure 1 Wind speeds calculated from the regression equations for flow over the study dune in south westerly winds.

recovers speed away from the base of the slip face, represented by readings from point M/N, to the secondary dune crest, represented by readings from Q and S. Between M/N and Q, there is again a slightly anomalous pattern introduced by the series of troughs and barchanoid forms in this area of the east slope of the study dune.

Unfortunately, the strong relationships between speeds at different points on the dune found for westerlies are not repeated in the results for easterly winds (Table 2). This may well be because the easterly winds, as well as being stronger, are also 'gustier' than the southwesterly winds, and there is therefore likely to be far greater variability in their readings. In addition, there are fewer readings from easterly winds, so that the effect of variability on the calculations is increased. Furthermore, poor correlation is associated with zones where there are turbulent eddies on the lee side, west slope, and in the lee of the secondary dune ridge.

Despite the lack of significant statistical relationships between points on the dune surface in easterly winds, it is possible to present five individual transects from winter, 1981, and to describe qualitatively the pattern they show (Fig. 2). Again, the speed at the crest is very clearly greater than the speed in either interdune corridor. There are, however, very sharp decreases in speed in the lee of the main dune crest and the lee of the east slope secondary dune. At the crest, the difference is between 17.5 m s^{-1} at the crest and 1.7 m s^{-1} ten meters downwind on one transect, and between 22.8 m s^{-1} and 3.9 m s^{-1} on another. This represents a very great decrease in the competence of the wind to transport sand. The greater variations of the speeds recorded on the lee slope compared with the range of initial speeds at the windward base are a manifestation of the turbulence and the existence of

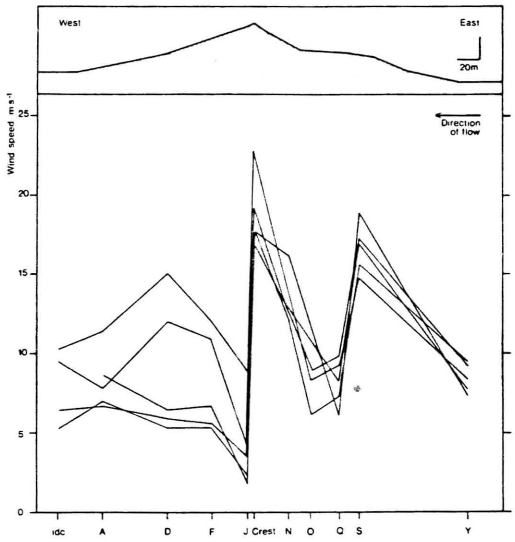

Figure 2 Five sets of readings of wind speeds over the study dune in easterly winds.

eddying on the lee slope. The data from the interdune corridors for winds from a variety of directions indicate that wind speed across the corridors at one meter above the ground surface is more or less constant.

Flow visualization

To support the data collected from the anemometers, smoke flares were used to visualize the flow pattern over the dune. The release of smoke flares of the kind used as ground targets for parachutists provides a qualitative impression of wind flow patterns which can be recorded photographically. The technique has proved highly successful for the visualization of eddies, and a summary of the results of the flow visualization investigation are presented in diagramatic form in Figure 3.

While Tsoar (1978) found that the lee side eddy covered the entirety of the lee slope of his study dune, it is clear from the smoke flares that this is not the case on the study dune of the present project. Figure 3 represents the situation in a southwesterly wind and shows that, while a lee side eddy does exist, the eddy covers only the upper part of the east slope. On the lower slope the flow appears to have re-attached to the surface of the dune so that flow on the lower lee slope is also southwesterly. The clear consequence of this observation is that

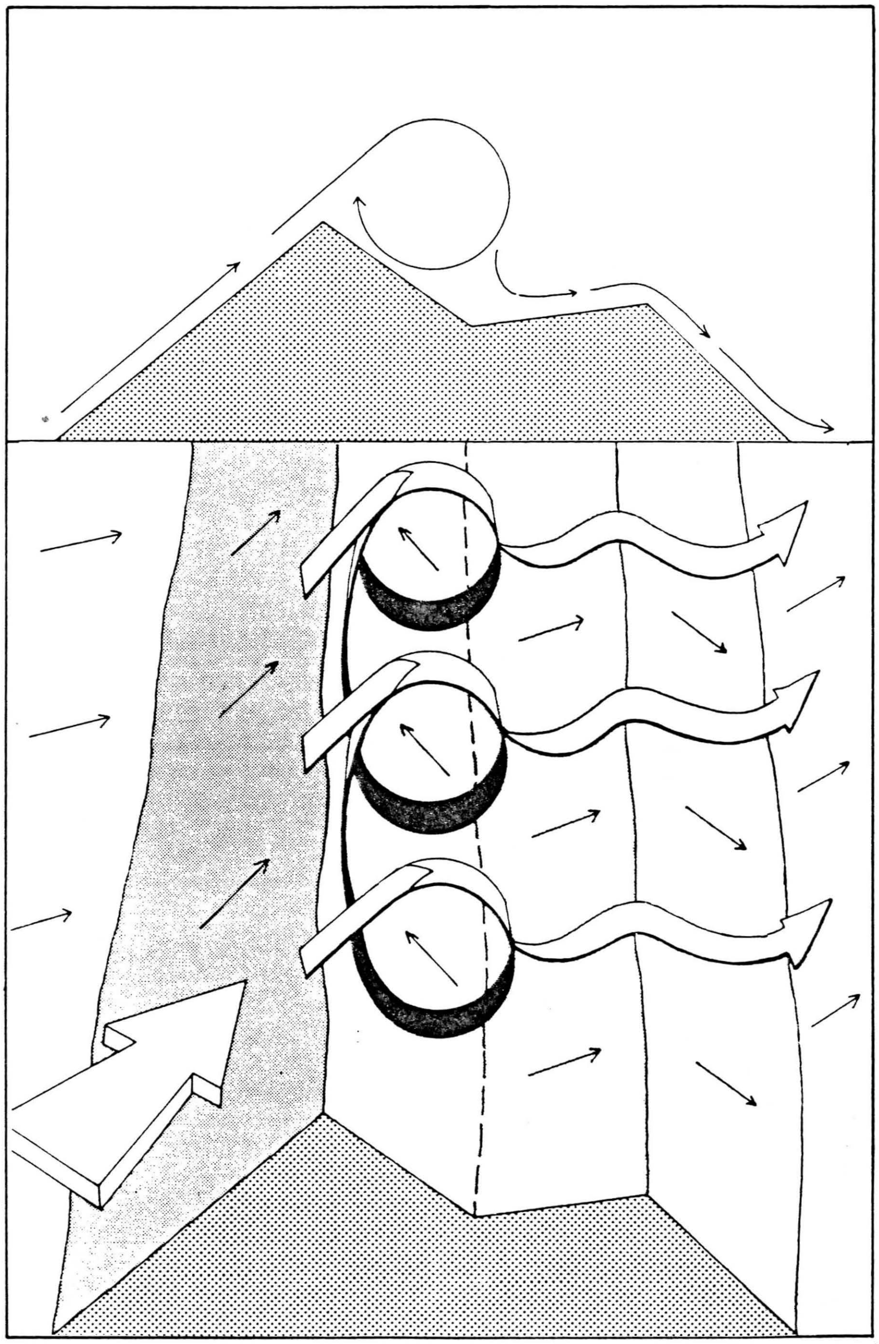

Figure 3 Summary of the wind flow pattern over the study dune visualized using smoke flares.

on a 'complex' dune the size of the present study dune, the lee side eddy does not prevent sand from leaving the dune and crossing the interdune corridor. In other words, Tsoar's postulated mechanism for linear dune maintenance of a lee side eddy in which net movement of sand is longitudinal does not seem to be universally applicable.

Towards a model of linear dune dynamics

It has proved possible to demonstrate, then, that there are significant changes in the speed of the near-surface wind over a linear dune cross-profile, and to provide an empirically derived model of patterns of wind speed change for westerly winds on the study dune. Naturally, it would be of considerable advantage to both pure and applied studies of dune dynamics to be able to model the relationship between the wind flow patterns outlined above and the dynamics of sand transport at the dune surface. Wind speed alone, however, is a measure only of the capacity of the wind to carry sand. Landform change - erosion and deposition - is effected by variations of that capacity related to changes of wind speed in both time and space, and a simple intuitive model can be proposed whereby positive acceleration gives erosion, negative acceleration gives depositon, and zero acceleraton gives no net change in the dune form (Cooke & Warren 1973, Holm 1960).

The changes in the wind's speed and direction on an individual dune are caused by effects at two scales superimposed one on the other. In both cases, it is the role of converging or diverging airflows which have been emphasized. At the macro-scale of an erg, the regional wind changes speed and direction in response to the regional pressure gradient. However, in a single dune study such as this covering a relatively small area, a constant regional wind speed can be assumed. At the second scale, which is more important to the behaviour of individual dunes, there is a pattern of wind speed change across the dune profile. Wind speed varies as a response to the convergence and divergence of streamlines caused by the intrusion of the dune into the wind flow. It should also be noted, however, that there exists an important inhibition to sand movement on the windward slopes where the increased gradient of the dune flank will increase the effective force due to gravity countering upslope movement, and a greater wind speed would be required to entrain the sand (Howard 1977).

Nonetheless, setting aside considerations of gradient, and assuming a regional wind of constant velocity, this qualitative model in conjunction with the regression equations for wind speed over the study dune presented in Table 1 outlines a two-dimensional description of surface change across the linear dune profile. Figures 4 and 5 show a schematic representation of the topography of the study dune, the inferred patterns of wind

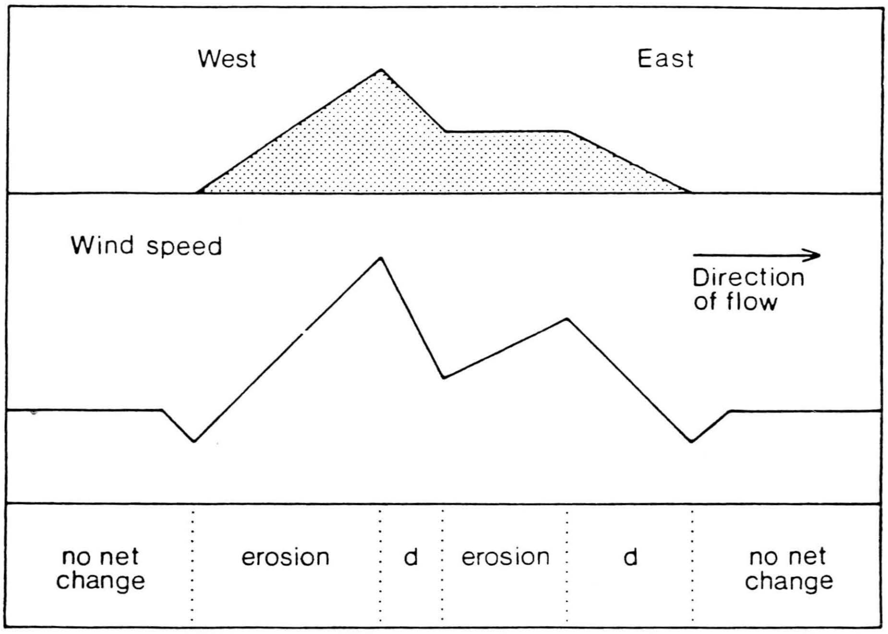

Figure 4 Relationship between wind speed and surface change in winds originating from the west side of the study dune.

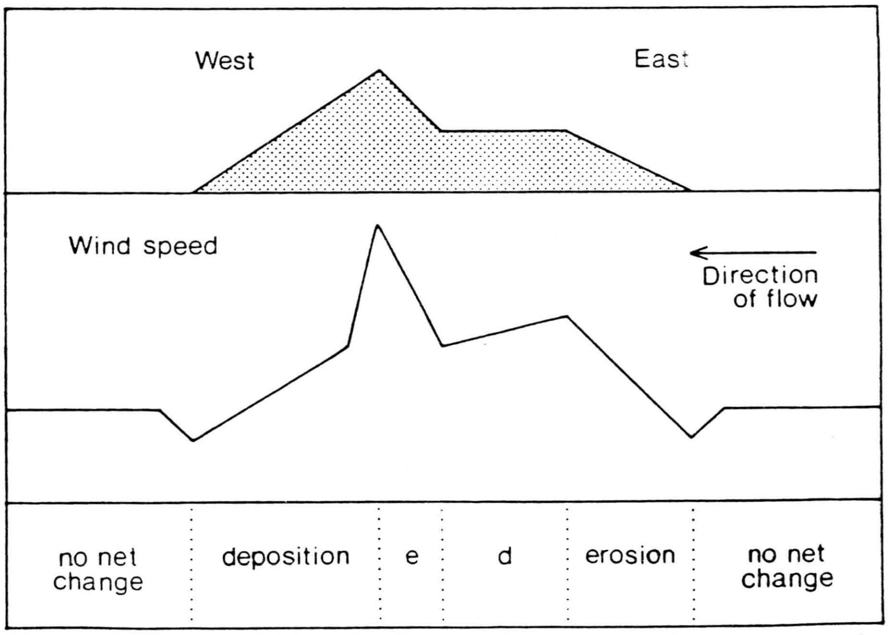

Figure 5 Relationship between wind speed and surface change in winds originating from the east side of the study dune.

speed, and surface changes in south-westerly winds (Fig. 4) and easterly winds (Fig. 5). Without recourse to any indication of wind flow direction, the model of wind speed over the dune cross-profile can be extended to predict the salient dynamic features of the dune. It shows erosion of the windward flank, deposition on the slip face, erosion of the zone to the lee of the slip face, deposition on the lee flank, and no net change on the interdune corridor. When these deduced patterns of surface change are compared with the actual patterns recorded from erosion pin data, a very good correlation of the overall trends is apparent (Livingstone 1985). From these patterns it is possible to propose a model of linear dune dynamics whereby the dune's intrusion into the atmospheric boundary-layer leads to its own self-perpetuation.

It appears that wind velocities on the corridors on either side of the dune are more or less the same. Assuming an equal supply of sand, the volume of sand carried across the two adjacent interdune corridors is therefore the same, and the volume of sand arriving at the upwind base of the dune is matched by the volume of sand leaving at the downwind base. The total volume of sand in the dune therefore remains (roughly) constant. Sand may be eroded from the windward flank and deposited on the lee flank thereby leading to lateral movement, but there is no net loss or gain of sand, and all changes of form occur as a result of sand budget variations on the dune itself. This deduction of no net erosion or deposition on the interdune corridors is important, for if there is no net change, interdune corridors once formed are maintained. As a result there is no necessity in this model to invoke any aerodynamic control of the interdune corridors as, for instance, Tsoar (1978) has done. While Tsoar's model seeks to prevent sand leaving the dune, the present model allows sand to leave the dunes to cross the interdune corridors, but because of the constant wind velocity, there is no net change of the interdune surface.

The wind speed measurements from the interdunes also have some significance for the 'windbreak' theories of linear dune spacing proposed by Tsoar (1978) and Twidale (1972). Twidale's argument is that on the lee side, separated flow covers the entire interdune corridor, and that a neighbouring dune forms at the point of re-attachment of flow. Neither the present study nor Tsoar's provide support for lee side eddies of this size (although it is possible that some mechanism of this sort might be responsible for the 'compound' linear dunes described by Lancaster (1982)). Tsoar's theory proposes that the spacing between dunes is a function of the distance required for the wind to recover its initial speed, and that dunes form at the point when this initial speed is regained. It is not clear how this mechanism might operate, and the data from the present study of wind speeds on the interdune corridors provide no evidence to support a theory proposing gradual recovery of speed across the interdune corridors. Rather, it seems that wind speed recovers near the downwind base of the dune and is constant across the interdune corridor. Based on these results, a 'windbreak' hypothesis of linear dune spacing cannot be supported.

A model in which it is the intrusion of the dune into the boundary-layer which leads to its own self-perpetuation and in which the interdune spaces are geomorphologically by-passed is not exclusively applicable to linear dunes. Indeed, were the wind regime unidirectional, erosion on the upwind slope and deposition on the downwind slope would lead to a downwind migration of the dune with the crest normal to the incident wind direction: the dune would be developing as a transverse dune. But as a result of the bi-directional wind regime (or more accurately a non-uni-directional wind regime) zones of erosion in winter become zones of deposition in summer and vice versa, and the dune does not progress like a transverse dune, but oscillates about a central position.

Both the present study and the study of Tsoar (1978) have shown that as the wind crosses the crest there is a deflection of the flow direction along the dune causing some longitudinal sand movement, and this is the dynamic process which Tsoar invokes to explain the maintenance of linear dune form and the absence of lateral movement. According to Tsoar, the separation of flow and the lee side eddy are the key to linear dune dynamics. Yet on a dune of the size of the present study dune, it has been demonstrated that this may not be entirely applicable. There is clear evidence, both from smoke flares and from the present author's observations of surface sand movement, that the lee side eddy does not cover the entire east slope in the moderate winds originating from the west side. Because lee side eddies do not cover the entire lee flank of a dune of the size of the study dune, a model which emphasizes the importance of wind speed in dune development has advantages over a model, such as Tsoar's (1978), which emphasizes the role of wind direction, particularly of the diversion of flow in lee side eddies. A model based on wind speed is applicable to dunes of any size.

Figure 6a illustrates a simplified representation of the situation in the northern Namib sand sea. The deduced, seasonal movement of the dune tip is similar to the pattern described by Besler (1975, 1980) for the movement of a simple, linear dune close to the site of the present study, and to the pattern of advance of complex dune tips monitored by Ward (1984) in the Kuiseb River. In the hypothetical situation of a regime in which the angle between the modes is small (Fig. 6b) advance of the tip of the dune would be more rapid. This model can be extended. Were the volume of sand supplied to the two dunes in Figure 6 the same, because of the greater rate of advance in case b, a lesser volume of sand in the cross-sectional area could be deduced, and a smaller dune would be formed. It is proposed, therefore, that linear dune cross-sectional area (height and width) is a dynamic equilibrium response to the interaction of wind regime (direction and strength) and the volume of sand available. Thus in a regime in which sand supply is plentiful, but the modes of the wind regime are widely divided, the tendency will be for slow extension, and larger dunes will be built. In a model of this nature, once an equilibrium form is reached, time is irrelevant to the dune dimensions ofheight and width, but is relevant to the distance that the dune has extended from the source of sand.

This model of linear dune dynamics based on the pattern of wind speed change over the dune fails to elucidate two major problems. The first, common to all dune studies, concerns the mode of dune initiation. In his discussion of barchans Knott (reported in Warren & Knott 1983) has highlighted the role of converging air flow in thermally generated 'ground jets'. Clearly, further investigation is required to examine the conditions, both meteorological and topographic, by which the wind's capacity to carry sand drops and sand is deposited. The second major problem, which is particular to linear dune studies, is that of dune spacing (or wavelength). While the spacing in some linear dune fields displays a wide range of values and may therefore be some response to wind regime and sand supply, it is equally true that there are areas of linear dunes where spacing is outstandingly regular, and it is difficult to avoid the inference that this is a response to some secondary flow or wave pattern in the wind. If this secondary flow control of dune spacing exists, it remains to be discovered.

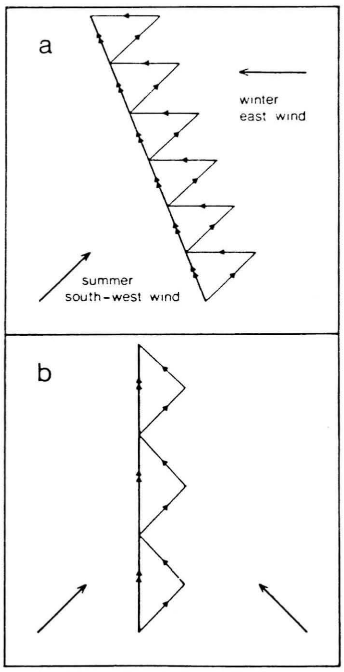

Figure 6 Inferred pattern of advance of linear dunes in two bi-directional wind regimes.

Conclusion

This paper has outlined the results of an investigation of wind flow patterns over a complex linear dune, and proposed a model of dune form maintenance based on the pattern of wind speed change over the dune cross-profile. Compression of streamlines on a rising, upwind slope leads to acceleration of the wind and consequently to erosion. Divergence of streamlines on the downwind slope leads to a decelerating wind and sand deposition. By this mechanism, dunes migrate downwind, yet the amount of sand arriving from the interdune corridor at the upwind base of the dune is matched by the sand leaving the downwind base, so that the net volume of sand in the dune is maintained. Linear dunes are viewed as essentially two or more transverse dune systems superimposed on the same sand body as a response to a non-uni-directional wind regime. Downwind advance in one direction is countered by movement in another and net dune advance is along some resolution of the vectors of wind speed and direction. In this model, linear dune form is seen as a response to the volume of sand supplied and the wind regime (Wasson & Hyde 1983). Unlike Bagnold (1953) and Tsoar (1978), no secondary wind flow is invoked and the only necessary condition for linear dune formation is seen as a non-uni-directional wind regime.

Clearly, this model is very far from being comprehensive. It fails, for instance, to take account of the linear dunes which appear to be related to regimes in which wind flow is predominantly from one direction parallel to the dune's alignment (Lancaster 1982),and it may well be that the linear dune represents an equifinal form. The problem of whether dunes are truly contemporary forms or are largely a response to antecedent conditions also remains to be tackled.

This study, along with those of Knott (1979) and Tsoar (1978), has shown that much can be discovered from process studies of individual dunes. There still exists, however, considerable scope for more information to be gleaned from careful field investigations of the relationship between wind regime and linear dune form in a variety of dune fields. When coupled with the formulae developed by meteorologists for wind flow over topographic barriers, this information will enable us to move closer to an understanding of linear dune dynamics.

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