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Variations in wind velocity and sand transport on the windward flanks of desert sand dunes

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ABSTRACT

The magnitudes of increases in wind velocity, or speed-up factors, have been measured on the windward flanks of transverse and linear dunes of varying height. On transverse dunes, velocity speed-up varied with dune shape and height. For linear dunes, speed-up factors varied principally with wind direction relative to the dune, with dune shape and dune height. The main effect of velocity speed-up on the windward flanks of dunes is to increase potential sand transport rates considerably in crestal areas. This is greatest for large dunes, with winds of moderate velocity blowing at a large angle to the dune. Changing ratios of base to crest sand-transport rates on transverse dunes tend to reduce dune steepness as overall wind velocities increase. On linear dunes, the tendency for crestal lowering is counteracted by deposition in this area when winds reverse in a bi-directional wind regime.

INTRODUCTION

The factors which control the equilibrium morphology of desert sand dunes are imperfectly understood. Recent work (e.g. Ash & Wasson, 1983; Lancaster, 1983; Wasson & Hyde, 1983) has suggested that sand availability and wind-regime characteristics are the most important factors, with sand-grain size and sorting and vegetation cover locally significant (Lancaster, 1983).

Fundamentally, the equilibrium morphology, particularly the size, of desert dunes is a function of their sediment budget, which may be expressed as the balance between erosion and deposition, or sand supply and removal at each point on the dune, summed for the dune as a whole. In turn, the sediment budget for each part of the dune will depend upon sand-transport rates and thus on the velocity of the wind, and through application of the sediment continuity equation (Rubin & Hunter, 1982), whether sand transport rates are increasing or decreasing. The presence of vegetation may additionally play a role in modifying sand transport and deposition patterns. Although attempts have been made (Howard *et al.*, 1978) to study and model dunes in this way, they have been hampered by the lack of empirical observations of variations in wind velocity and sand-transport rates on dunes.

It has often been observed (e.g. Lewis, 1936; Madigan, 1946; Wopfner & Twidale, 1967; Ash & Wasson, 1983) that, particularly on dunes of linear (longitudinal, seif) form, sand movement is active in crestal areas, whilst the base or plinth of the dune remains stable. Frequently, this has been attributed to the presence of vegetation on the lower parts of the dune. An alternative explanation is to be found in the increase of wind velocity with height on the dune, in the manner noted by Ash & Wasson (1983). Thus crests are more active and vegetation unable to establish itself because wind speeds and sand transport are much greater in these zones.

The acceleration of wind up the windward flanks of natural hills has been widely noted by meteorologists. It apparently results from the compression of streamlines in the boundary layer and has recently been the subject of further measurement (Mason & Sykes, 1979; Bradley, 1980) and numerical modelling (Jackson & Hunt, 1975; Taylor, 1977). The 'speed-up factor'

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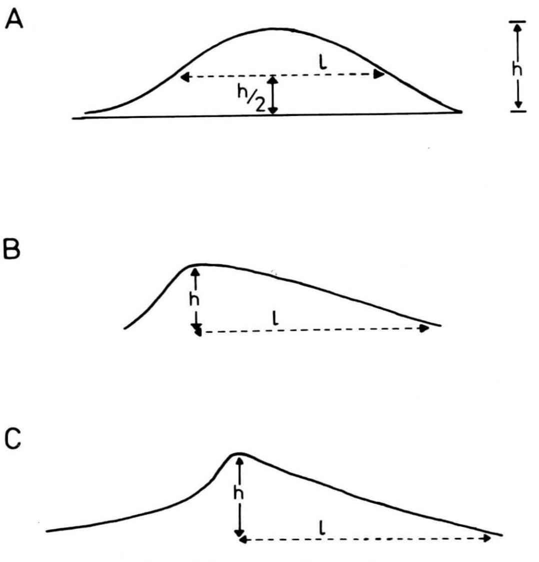

Fig. 1. Explanation of dune morphometric parameters. (A) Isolated hill (after Jackson & Hunt, 1975). (B) Transverse dune ridge. (C) Linear dune (note that l is measured parallel to the wind direction).

or 'fractional speed-up ratio' has been shown by Jackson & Hunt (1975) to follow the relationship

$$\Delta_s = 2h/l$$

with h being the height of the hill and l the length parallel with the wind at half-height (Fig. 1). Similar velocity increases should occur over desert sand dunes and have indeed been predicted by Bagnold (1941) and Wilson (1972). They were measured, but not commented upon, by Howard *et al.* (1978) and Tsoar (1978). Ash & Wasson (1983) have applied the formula of Jackson & Hunt (1975) to dunes in Australia, but no measurements of velocity speed-up have been made on desert dunes.

In this paper, I report the results of measurements of wind velocity at the crest and base of transverse and linear dunes in the Namib Desert and discuss some of the implications of these observations for sand-transport rates and the evolution of an equilibrium morphology for dunes. This study should be seen as complementary to detailed studies of individual dunes, such as those carried out by Tsoar (1978) and Livingstone (in preparation).

METHODS

Wind velocities were measured using cup anemometers exposed at 1 m above the bare sand surface. The instruments were sited at the upwind base and crest of transverse and linear dunes of varying heights (Table 1). Additional anemometers were at times deployed on the middle and upper flanks of the dunes at approximately 0·25 and 0·5 dune height. The anemometers were read simultaneously at 30-min intervals, and the readings converted to average wind velocities in metres per second. Cross-calibration of the anemometers with each other was carried out under field conditions. In most instances, at least 10 readings were made on each dune during the afternoon period of moderate to strong winds. At transverse dune sites, dune crests were approximately perpendicular to oncoming winds from the SSW and SW. During the period of observations on linear dunes, winds often changed direction systematically from the WSW or the west through to the SSW and occasionally the south. This enabled the effects of changing angles of incidence between winds and the S–N trending dunes to be observed. Unfortunately, it was not possible to make measurements for all wind directions which affect the dunes. The observations cover the dominant sand-moving winds (for further details see Lancaster, 1983), but do not include the infrequent, but high velocity east to NE winds of winter months.

Dune morphology (Fig. 1, Table 1) was described by dune height (h) and width (l), with l being measured parallel to the wind direction. Dune shape was characterized by the dimensionless ratio $2h/l$ of Jackson & Hunt (1975). Thus, in the case of linear dunes, $2h/l$ varies with wind direction, tending to zero with a wind blowing parallel to the dune.

In this paper, the term 'speed-up factor' of S is used in the sense of Mason & Sykes (1979) so that

$$S = \frac{\text{wind velocity at dune crest}}{\text{wind velocity at base or plinth of dune}}.$$

It is preferred to the fractional speed-up ratio (Δ_s) of Jackson & Hunt (1975). Potential sand movement rates were calculated using the general formula of Bagnold (1953).

$$Q = \frac{1{\cdot}0 \times 10^{-4}}{(\log 100z)^3} \times t \cdot (v - v_t)^3$$

where Q = potential sand-transport rate in tonnes per metre width; t = the number of hours of wind blowing with a velocity v; v_t = the threshold velocity for sand movement (4·5 m s^{-1}) and z = the height of the wind recorder (1 m). Where necessary, correction was made for effects of the slope on Q, using the formula

Table 1. Dune morphometric parameters

		Dune height (m)		$2h/l$	
Transverse dunes					
Skeleton Coast					
Isolated dunes					
	a	9		0·41	
	b	2		0·25	
	c	9·7		0·28	
Paired dunes					
	a	8		0·53	
	b	8		0·18	
	c	11·4		0·24	
Sandwich Harbour		18·5		0·22	
Linear dunes					
			WSW	SW	SSW
Narabeb	a	93	0·32	0·24	0·13
	b	58	0·31	0·23	0·12
	c	30	0·20	0·14	0·05
	d	27	0·30	0·19	0·07
	e	32	0·28	0·19	0·08
	f	38	0·32	0·22	0·11
Rooibank		50	0·43	0·38	0·25
Dune 7	a	102	0·34	0·26	0·14
	b	83	0·36	0·27	0·14
Dune 8		115	0·34	0·23	0·08
Immigration	a	6	0·37	0·41	0·29
	b	5	0·42	0·29	0·24
Gobabeb South	a	5	0·42	0·32	0·17
	b	3	0·22	0·17	0·09

employed by Howard *et al.* (1978). Thus

$$q = \frac{Q}{\cos\theta'\,(\tan\alpha + \tan\theta')}$$

where Q = sand transport rate on a flat surface, q = the equivalent rate on a surface with a slope of θ' in the direction of transport, and α = the dynamic friction angle $\approx$ the angle of repose, in this case 33°. Tan $\theta' = \tan\theta \cos\chi$, where θ = the slope angle and χ = the angle between the slope direction and wind direction.

RESULTS

Transverse dunes

Wind velocities were measured over isolated and pairs of adjacent transverse ridges on the eastern edge of the Skeleton Coast dunefield in the northern Namib (site 2E of Lancaster, 1982), and over pairs of large, compound transverse dunes inland from Sandwich Harbour on the north-western margins of the main Namib Sand Sea (site XI of Lancaster, 1983). A total of four transects was measured across pairs of adjacent dunes, separated by narrow interdunes, and across three isolated dunes. Dune height ranged from 2 to 18·5 m (Table 1). Crest-to-crest spacing of the pairs of compound ridges was 240 m, whilst that of simple ridges ranged from 120 to 140 m. The results of the measurements are presented in Table 2. In all cases, wind velocities increased steadily up the windward flanks of the dunes, from a minimum on the upwind base of the dune. The velocity speed-up calculated for paired dunes ranged from 1·79 to 2·25 and from 1·35 to 1·46 for isolated dune ridges.

Whilst the wind velocity on the upwind base of isolated dunes can be regarded as representative of the mean wind in that area, the wind at the same position on a pair of ridges is strongly affected by the separation of flow in the lee of the upwind dune. Whilst no actual flow reversal was observed in this

Table 2. Mean speed-up factors

Transverse dunes				
Skeleton Coast				
Isolated dunes				
A		1·41		
B		1·35		
C		1·37		
Dune—interdune units				
Interdune—crest			Flanks to crest	
			Lower	Mid
A	2·24		1·38	1·15
B	1·99		1·79	1·27
C	1·79		1·62	
Sandwich Harbour				
Interdune—crest			Mid-flank to crest	
	2·36		1·46	

Linear dunes

	Wind direction				
	W	WSW	SW	SSW	S
Site					
Narabeb					
a	1·90	1·60	1·52	1·46	
b	2·04	1·74	1·53	1·32	1·16
c	1·90	1·74	1·34	1·07	
d	1·71		1·47	1·32	
e		1·65	1·48	1·37	
f		1·77	1·65	1·49	
Dune 7					
a		1·89	1·48	1·32	
b		1·63	1·59	1·49	
Dune 8		2·01	1·65	1·47	
Rooibank			1·68	1·65	
Immigration					
a			1·46	1·30	
b				1·37	
Gobabeb South					
a			1·49	1·30	
b				1·11	

zone, wind velocities in the interdune were highly variable in strength and direction. In view of this, the velocity increase down wind of the re-attachment of the separated flow, i.e. between the central and upper parts of the stoss slope and the crest of these dunes, was also measured. Values of the speed-up factors between these points ranged from 1·15 to 1·62.

Linear dunes

Wind velocities were measured on the western, or windward, flanks of linear dunes of simple and complex form at 14 sites in the northern parts of the Namib Sand Sea. Dune height varied from 3 to 115 m. The results are presented in Table 2. In every case, the wind on the plinth was regarded as representative of that in the interdune as a whole, as no significant variations in wind velocity or direction were observed across their 1–2 km width. Wind velocities increased steadily up the windward side of the dunes. There was some evidence to suggest that the rate of increase in wind velocity increased towards the dune crest, but it was not possible to confirm this. Mean speed-up factors varied from 1·11 to 2·04. It was found that velocity speed-up was greatest when winds were blowing at a large angle to the dune and for large dunes.

DISCUSSION

The magnitude of speed-up factors

Two major factors may influence the magnitude of velocity increase on the windward side of desert dunes: the shape of the dune profile presented to the wind, as measured by $2h/l$, which is dependent on the angle of incidence between the wind direction and the dune; and dune height. These factors are considered separately for transverse and linear dunes.

Transverse dunes

As Fig. 2(A) shows, there is a clear relationship ($r = 0{\cdot}91$ for paired dunes; $r = 0{\cdot}61$ for isolated dunes), despite the small sample, between mean speed-up factors and dune shape, as expressed by the ratio $2h/l$, for both isolated and paired dunes, although the magnitude of speed-up factors is much greater in the latter case. This accords with the predictions of theory and confirms empirical evidence for wind flow over natural hills (Jackson & Hunt, 1975; Bradley, 1980). In addition, there is a statistically significant (at the 0·05 level) relationship ($r = 0{\cdot}78$) between mean speed-up factors and the height of transverse dunes, as indicated by Fig. 2(B). The slope of the regression line is similar for both isolated and paired dunes, but the magnitude of the speed-up factors is much greater for the latter group, probably because wind velocities at the base of the stoss slope are reduced by flow separation in the lee of the upwind dune.

Linear dunes

The most important influence on the velocity increase on the windward slopes of linear dunes is the angle of incidence between the wind and the dune. A very strong linear relationship (Fig. 3) exists between mean speed-up factors and wind direction ($r = 0{\cdot}99$). Mean speed-up factors averaged 1·80 for westerly winds, those for WSW winds 1·68, for SW 1·51 and 1·33 for SSW. Thus, as the wind blows more nearly parallel to the dune, so its acceleration up the windward flanks becomes progressively less.

Although wind direction is important in determining speed-up factors, this variable can be eliminated if $2h/l$ is calculated with l measured parallel to the wind direction. As Fig. 4 shows, a good correlation exists between mean speed-up factors and dune shape as described by $2h/l$, for all wind directions ($r = 0{\cdot}67$, significant at the 0·05 level).

Much of the variability in speed-up factors for given values of $2h/l$ can be explained by the relationships between mean speed-up factors and dune height (Fig. 5). The best correlations are obtained for WSW winds ($r = 0{\cdot}71$), with progressively poorer correlation coefficients for SW ($r = 0{\cdot}62$) and SSW winds ($r = 0{\cdot}47$).

It is difficult to sort out the varying effects of dune shape and height on speed-up factors. Clearly, as the wind direction relative to the dune changes, the effective shape of the dune is altered, but its height remains the same. Further, for a given wind direction, dune shape tends to be very similar, yet the height varies. However, the effects of dune height on velocity speed-up are such that, as winds blow more nearly parallel to the dune, the effects of dune height are less important and the effects of dune shape become dominant. This is probably the result of decreasing streamline compression as wind direction and dune trend become more nearly parallel.

Effects of velocity speed-up on the effective wind regime

One consequence of the acceleration of winds by 1·2–2 times as they cross the windward flanks of both

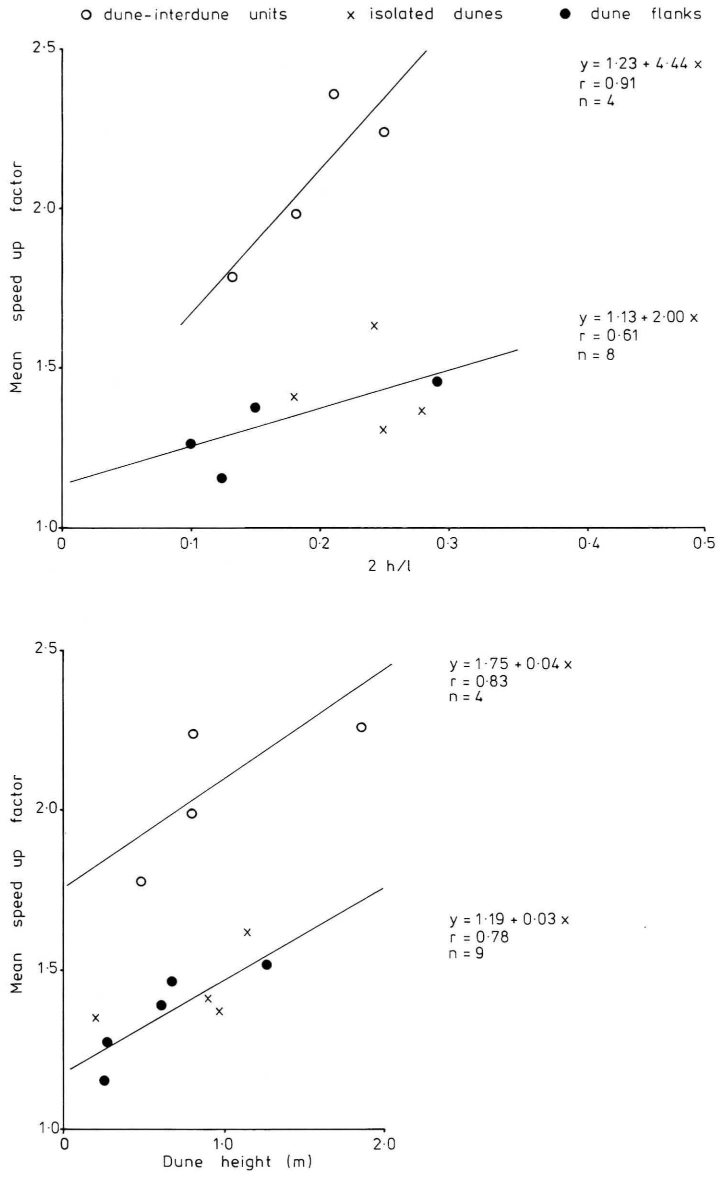

Fig. 2. (A) Relationship between mean speed-up factors and dune shape ($2h/l$) for transverse dunes. (B) Relationship between mean speed-up factors and dune height for transverse dunes.

transverse and linear dunes is that winds which are below the threshold velocity for sand movement in interdune areas, and in the basal areas of dunes, are able to move sand in crestal areas. This may result in a change in the effective, or sand-moving wind regime, between interdune and dune-crest areas. For example, at Narabeb, in the northern part of the Namib Sand Sea, an average speed-up factor of 1·5 for the 90–100 m high dunes in this area results in an increase in wind velocity of 3·1–4·2 m s^{-1} in the interdune areas to velocities which are capable of moving sand at dune crests, assuming a threshold velocity of 4·5

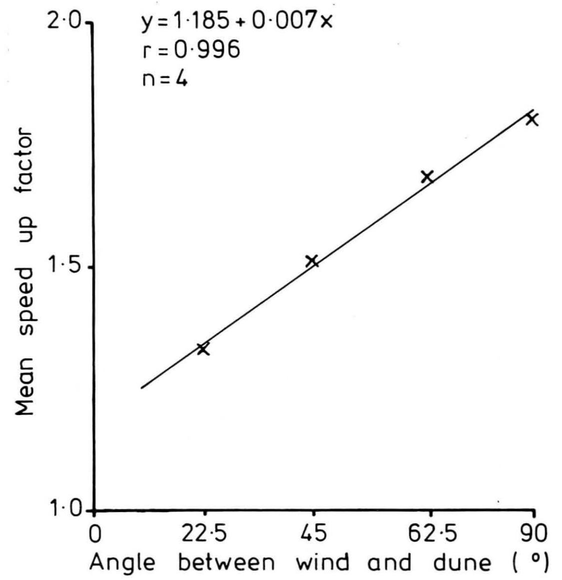

Fig. 3. Relationship between mean speed-up factors and angle of incidence between wind and dune for linear dunes.

m s^{-1}. This has the effect of increasing total potential sand movement (Q) by 300%, and changes the resultant direction of sand movement from 197° to 208°, although the total amount of the time the wind is above threshold velocity for sand movement increases by only 23%, from 30 to 53% of the time.

However, the most important effect of velocity speed-up is to increase the sand-moving power of the effective wind regime in the crestal region of the dunes. As the rate of sand transport is proportional to the cube of the excess of wind velocity over the threshold velocity for sand movement (Bagnold, 1941), the effects are very marked. By applying an appropriate speed-up factor determined by the angle of the wind to the dune, it is possible to calculate the potential sand transport for each wind direction at the crest of the dune (Table 3). At Narabeb, this results in an eight-fold increase in total potential sand movement compared to the interdune, with an average speed-up factor of 1·5. The increase in potential sand transport varies with wind direction from 3 to 22 times. The effect of velocity speed-up appears to be greatest for winds which blow at a large angle to the dune and for those directions which include a high proportion of low to moderate velocity winds. In this case, the effect on the total sand transport regime is to change one which is complex, low to moderate kinetic energy in the interdune, with a dominant SSW–WSW mode and minor N–NNW and NE–E modes, to a moderate to high kinetic energy, bimodal regime in crestal areas. The SSW–WSW mode is still dominant, but decreased in importance, whilst the NE–E mode becomes much more important. However, in this situation, the effects on the direction of resultant sand movement are small. Although much more sand is

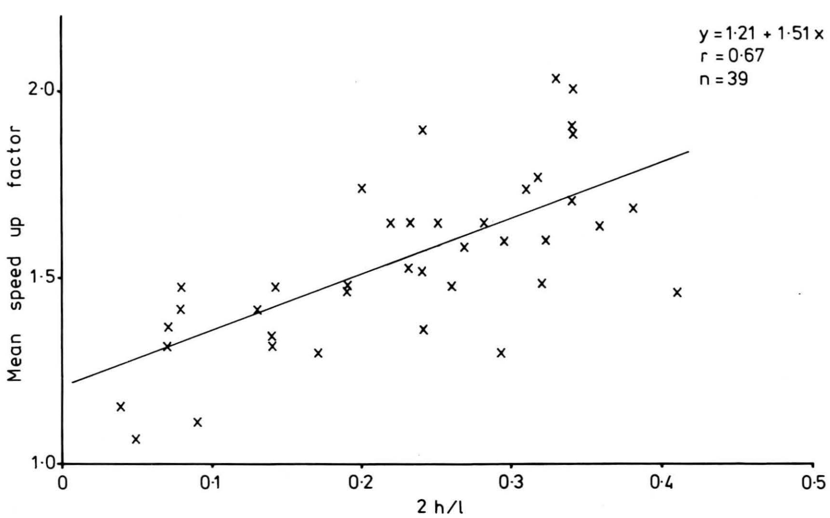

Fig. 4. Relationships between mean speed-up factors and dune shape ($2h/l$) for linear dunes.

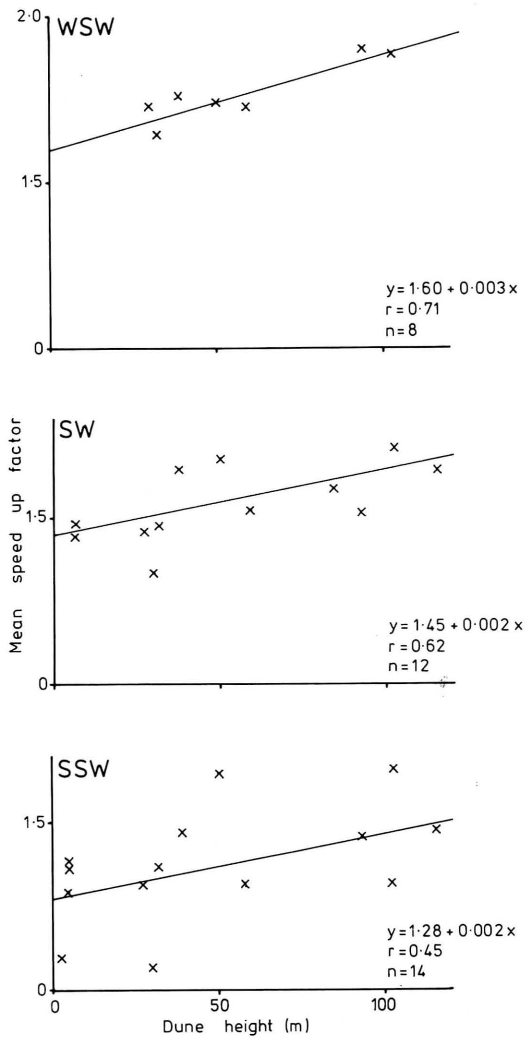

Fig. 5. Relationship between mean speed-up factors and linear dune height for different wind directions.

potentially being moved in crestal areas, and resultant sand transport increases by 5·5 times, the resultant direction only changes from 214° in the interdune to 211° in crestal areas.

It appears that the effects of velocity speed-up on the effective wind regime are much less pronounced in unidirectional wind regimes. Near the coast of the central Namib, in a high energy unimodal wind regime, potential sand movement on the crests of typical transverse dunes 7·5 m high increases by 2 times, with a mean speed-up factor of 1·5.

Effects on sand transport rates on dunes

The major effect of the velocity speed-up on the flanks of dunes is to increase the amount of potential sand movement towards the dune crest. The amount of increase varies with the velocity of the incident wind on the dune base or plinth, and the height of the dune. For linear dunes, the wind direction relative to the dune is also an important factor.

Variations with plinth wind velocity

At low wind velocities, it can be observed that, while there is no sand movement in interdunes and on dune plinths, sand is moving at the crest of the dune. There is thus an infinite increase in sand transport between these points. Just above threshold velocity on the upwind base of the dune, when the amount of sand movement is small, there is a very large increase in the amount of potential sand movement between the plinth and the crest. As Fig. 6 shows, the ratio between dune base and crest sand movement declines exponentially as wind velocity on the base of the dune increases. For example, on a typical isolated transverse dune, with a dune base wind velocity of 5·0 m s^{-1},

Table 3. Comparison of potential sand transport rates in interdune and crestal areas, Narabeb

Percentage of annual potential sand transport from:

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Interdune	7·8	3·1	3·6	2·6	2·5	2·2	0·7	0·01	3·8	49·1	14·1	0·6	0·3	0·2	2·6	6·9
Crest	3·0	3·8	4·9	7·2	9·7	3·5	1·3	0·1	1·6	22·8	23·4	6·1	3·9	2·6	3·3	2·9

	Total potential sand transport (tonnes m^{-1} yr^{-1})	Resultant sand movement (tonnes m^{-1} yr^{-1})	
Interdune	171	4·78	211°
Crest	1379	26·29	214°

Crest sand transport rates calculated after application of appropriate speed-up factor for 98 m high dune for each wind direction and corrected for the effects of slope on sand transport rates.

potential sand movement is 0·001 tonne m^{-1} hr^{-1} in basal areas and 0·158 tonne m^{-1} hr^{-1} at the crest. The ratio between base and crest sand movement is thus 158. However, when wind velocity at the base of the dune is somewhat greater, at 7·0 m s^{-1}, potential sand transport here rises to 0·086 tonne m^{-1} hr^{-1} and 1·191 tonnes m^{-1} hr^{-1} at the crest, giving a ratio between basal and crest potential sand movement of 13.

A similar situation occurs on linear dunes (Fig. 6), where the ratio between plinth and crest sand movement is infinite when the wind on the plinth is below threshold velocity for sand transport, and falls from 200 just above threshold velocity on the plinth to 4·5–15 at 11·1 m s^{-1}. Thus, as the incident wind velocity increases, the overall magnitude of sand transport increases and becomes more uniform over the whole dune, although even at relatively high wind velocities there is still a significant difference in the amount of sand movement between crestal and basal parts of the dune.

It is important to note, however, that at all times the magnitude of sand transport in the basal areas of dunes tends to remain small compared to that in crestal areas, where sand movement is absolutely and relatively larger at all times, when the wind is above threshold velocity.

Variation with wind direction

As the velocity speed-up for linear dunes of a given height varies with wind direction relative to the dune, the ratio between plinth and crest sand transport also varies with direction, for a given incident wind velocity. Thus, for a wind which has a velocity of 7·0 m s^{-1} on the plinth, sand movement will be 28 times greater at the crest if the wind is from the WSW, but only 8 times greater if the wind is from the SSW. Similar, but less marked, changes occur for progressively higher wind velocities, as Fig. 6 shows. Consequently, on linear dunes, for a given wind velocity, there will be much less variation over the dune in the amount of potential sand transport when winds are blowing more nearly parallel to the dune, providing that wind velocity on the plinth is above threshold velocity.

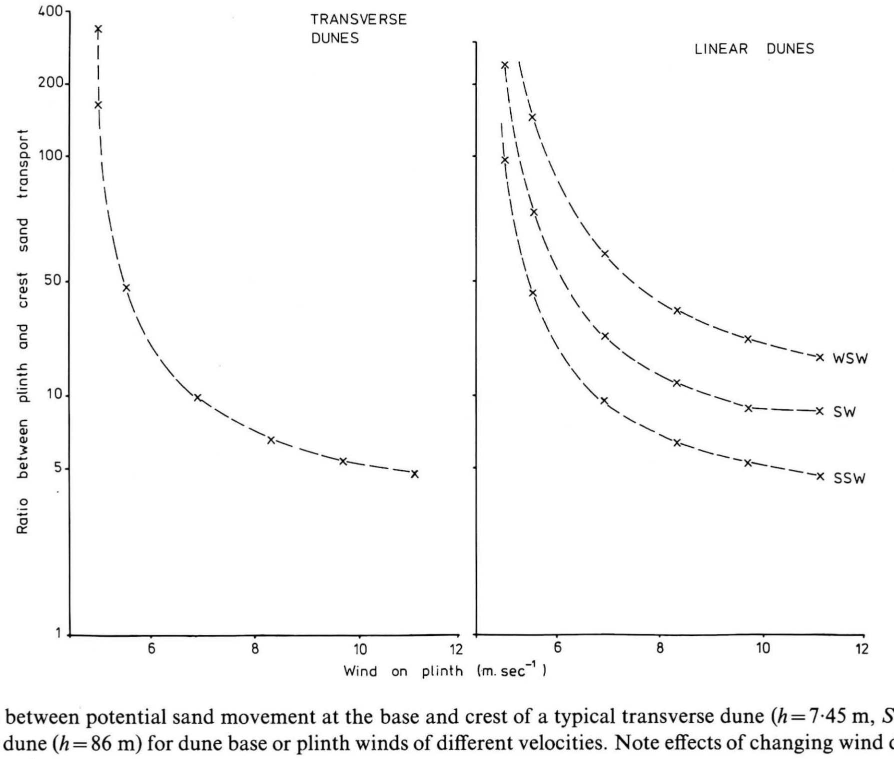

Fig. 6. Ratio between potential sand movement at the base and crest of a typical transverse dune ($h=7{\cdot}45$ m, $S=1{\cdot}5$) and a typical linear dune ($h=86$ m) for dune base or plinth winds of different velocities. Note effects of changing wind directions on ratios for linear dunes.

Variation with dune height

As speed-up factors vary with dune height, then the ratio between plinth and crest wind velocities and potential sand transport rates for a given direction will also vary with dune height, as Figs 7 and 8 demonstrate. Thus, with a 5·6 m s^{-1} wind, sand movement at the crest of a transverse dune will be 19·6 times greater than at the upwind base if the dune is 5 m high, and 121 times greater if the dune is 20 m high. Similar situations will occur on linear dunes of different heights, and increases in potential sand movement rates between the plinth and crest of large dunes can be considerable (Fig. 8). As both Figs 7 and 8 indicate, the ratio declines with increasing wind velocity. Thus the ratio between potential sand-transport rates is greatest for lower incident wind velocities and least for higher velocity winds. Again, as speed-up factors vary with wind direction relative to the dune, the ratio between plinth and crest sand transport rates is greatest when winds are blowing at a high angle to the dune, as examination of Fig. 8 will demonstrate.

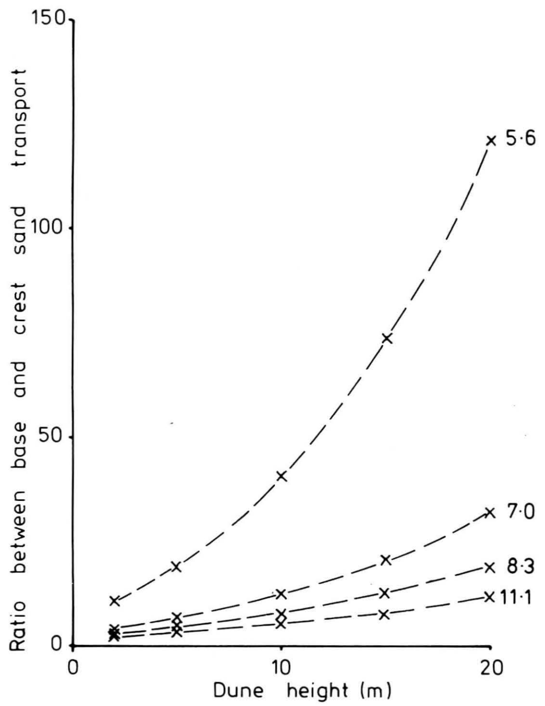

Fig. 7. Variation of ratio between base and crest sand transport rates for transverse dunes of different heights and winds of different velocities.

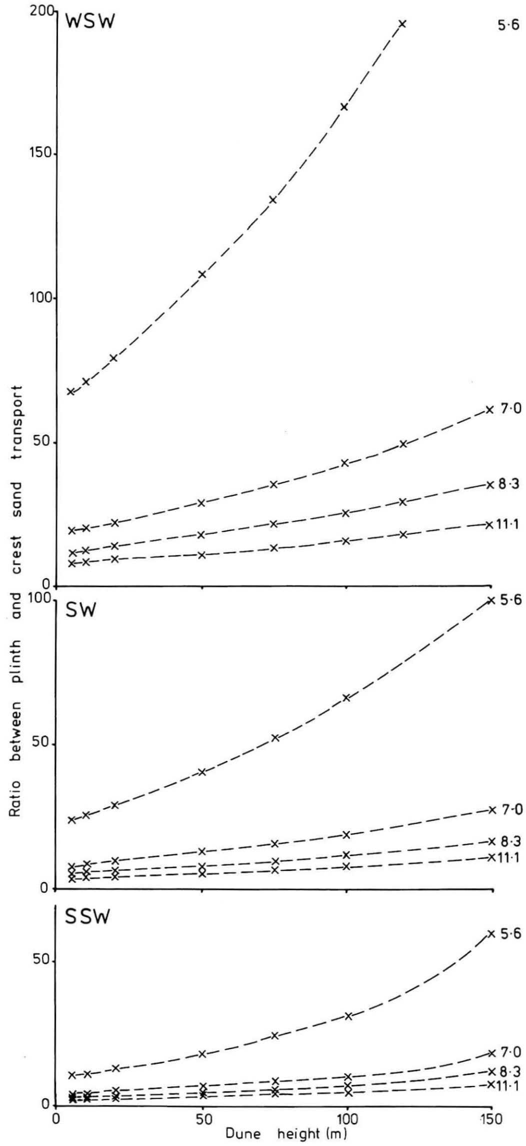

Fig. 8. Variation of ratio between plinth and crest sand transport rates for linear dunes of different heights and winds from different directions and velocities.

Effects on erosion—deposition patterns on dunes

From the above, it will be evident that rates of potential sand transport are much greater in crestal areas of dunes, compared to basal or plinth areas. Confirmation of the much greater activity of sand movement in the crestal areas of linear dunes comes from measurements of erosion or deposition on fixed

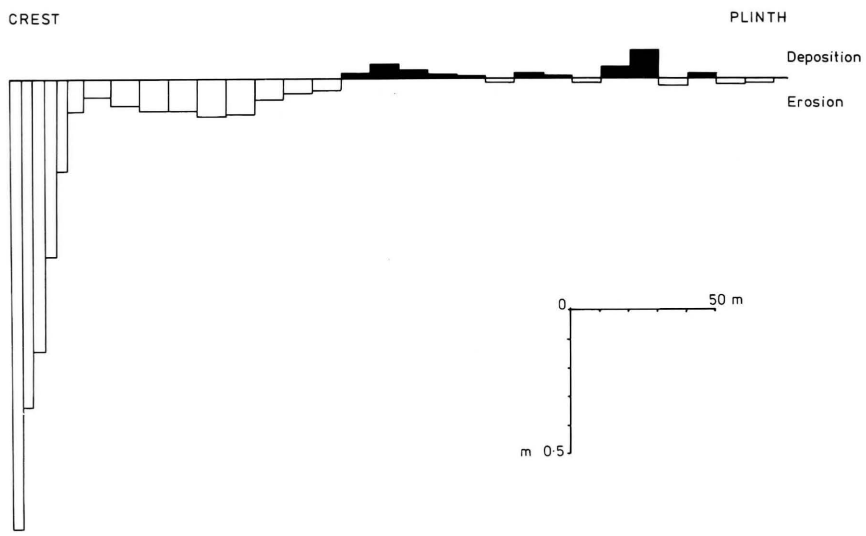

Fig. 9. Cumulative erosion and deposition on windward flank of linear dune at Narabeb, September 1981–October 1982.

steel poles at 10 or 5 m intervals along a transect across a 93 m high linear dune at Narabeb. The general pattern is illustrated in Fig. 9, which shows the net erosion or deposition for each part of the windward slope of this dune in the 12-month period October 1981–September 1982. On the plinth, net sand movements are on a small scale, with slight net deposition occurring, probably as a result of accretion with the change in surface roughness from interdune to dune (Bagnold, 1941). From a point approximately half-way up the windward slope of the dune, there is a rapid increase in net erosion, which reaches a peak, at 1·566 m, near the crest.

The implications of velocity speed-up for dune morphology

The foregoing discussion of velocity speed-up on the windward flanks of transverse and linear dunes suggests that its principal effect is to increase considerably the rate of potential sand transport in the crestal areas of these dunes. This effect is most marked for large dunes and when the wind is blowing with a moderate velocity at a large angle relative to the alignment of the dune crest.

There is clearly a complex relationship between dune morphology, velocity speed-up, sediment transport rates and patterns of erosion and deposition, which give rise to a dynamic-equilibrium morphology for dunes. These relationships can best be explored by means of the sediment-continuity equation (Middleton & Southard, 1978; Fredsoe, 1982; Rubin & Hunter, 1982). Thus

$$\frac{\partial h}{\partial t} = \frac{-\partial q}{\partial x}$$

in which h = surface elevation, q = local volumetric sediment transport rate in the direction x and t = time. By integration, q (local) $= k \cdot h$ where k is a constant. Additionally, the migration rate of the dune (Q_B) can be given, following Bagnold (1941), as

$$Q_B = \frac{q\,(\text{crest})}{H}$$

where H is the height of the dune. Combining the two equations (Fredsoe, 1982)

$$\frac{h}{H} = \frac{q\,(\text{local})}{q\,(\text{crest})}.$$

Consequently, for a dune of a given height (H), the sand transport rates for any wind velocity can be found by applying the appropriate speed-up factor for the crest [q (crest)] or for any height on the dune (h) [q (local)]. It is thus possible to calculate the shape of transverse-dune ridges which would develop in winds of different velocities. Examples of these are given in Fig. 10 and suggest that at low wind velocities dunes tend to develop rather steeper profiles than at high wind velocities. Thus transverse-dune ridges appear to become broader and more rounded as wind velocity increases, in a similar manner to sub-aqueous dunes (Yalin, 1972; Fredsoe, 1982), which tend to flatten out as flow velocity increases. The shape of transverse-dune ridges, and also their crest-to-crest spacing for a given height, is thus governed by the velocity of the winds in an area. Thus, such dunes tend to be shorter, steeper and more closely spaced in areas of low average wind velocity and longer, spaced further apart, and more rounded in cross-section in areas of high wind velocity.

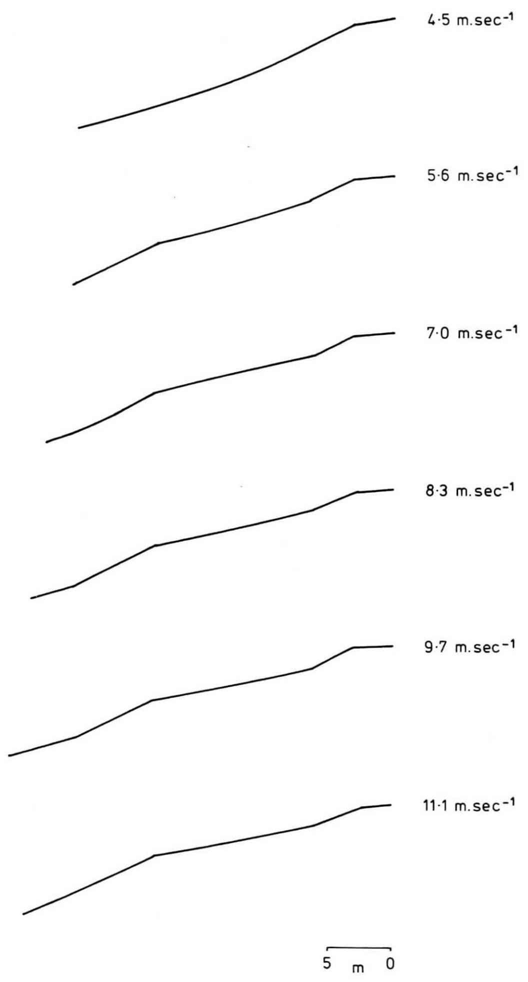

Fig. 10. Simulated profiles for a 7 m high transverse dune ridge subjected to winds of varying velocities at the upwind base.

Sediment size may also be important, through its influence on threshold velocity and sand transport rates. Thus, fine-grained sands may have a similar effect on dune morphology as low wind velocities and produce steep, closely spaced dunes. Coarse sands, or poorly-sorted sands with a prominent coarse tail, may have an effect on dune morphology similar to that of a high velocity wind regime, by raising the threshold velocity for sand movement and changing the effective wind regime, leading to the development of broad, low dunes, as have commonly been noted in association with coarse, poorly-sorted sands (e.g. Warren, 1972; Tsoar, 1978; Lancaster, 1982, 1983). The broad cross-section of such dunes will give rise to a large crest-to-crest spacing. These observations help to explain the correlations between the size of the coarsest 5th or 20th percentile of the sands of transverse dunes and their spacing noted by Wilson (1972) and Lancaster (1982, 1983).

The factors which may influence the morphology of dunes of linear form, with varying directions of flow which are often oblique to the dune, are more complex. Theoretical rates of erosion or deposition on the dune monitored at Narabeb were examined using the sediment continuity equation and data for velocity speed-up. They show that, unlike on transverse dunes, rates of erosion tend to increase with height on the dune. Three zones of different rates of erosion can be identified on the windward flanks of the dune. Their relative magnitude is similar for both SW and SSW winds of varying velocity, although the absolute magnitude increases rapidly with velocity. On the plinth, erosion rates are very low, but rise rapidly up the dune as velocity speed-up occurs. The mid-slopes are characterized by moderate rates of erosion, approximately 2 times those on the upper plinth and half those at the dune crest for SSW winds; but with SW winds an area of deposition occurs in the upper parts of this zone. The upper windward slopes of the dune are characterized by a high rate of surface lowering. Comparison of the calculated and observed rates of erosion for this dune (Fig. 11) show a general degree of correlation, except that the observed deposition on the plinth is not predicted by the sediment continuity equation.

It would seem at first sight that these dunes are not in equilibrium with the present environment, for they will in time be gradually lowered by erosion at the crest. However, erosion of the upper windward and crestal zones of these dunes affects sand deposited by easterly winds during winter months. Thus seasonal reversal of sand transport gives rise to alternate

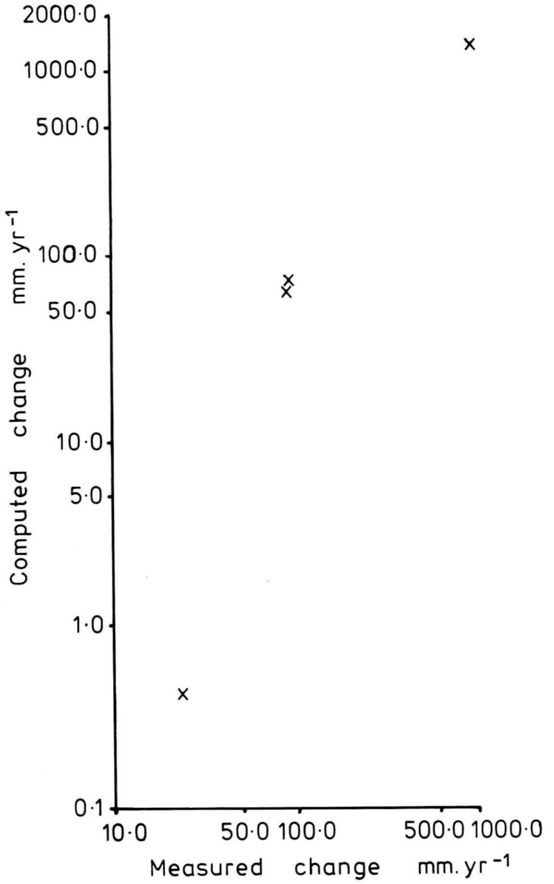

Fig. 11. Comparison between mean measured and calculated rates of erosion for windward slope of dune at Narabeb. Calculated rates derived using the sediment continuity equation (Middleton & Southard, 1978).

deposition and erosion at high rates, the long-term balance between which controls the size of the dune.

The converse of velocity speed-up, deceleration on lee slopes, may play an important role in the growth of large, complex dunes. On complex linear dunes in the Namib Sand Sea, dune-parallel leeside movement of sand in the manner described by Tsoar (1978) is limited to the uppermost parts of the dune only, and most movement of sand on the lee flanks is oblique to the dune. On the upper lee flanks, there are small oblique transverse ridges which are gradually moving into zones of progressively lower wind velocity, and sand is thus deposited in the manner of bedform climbing as described by Allen (1970) and observed on coastal dunes by Rubin & Hunter (1982). Except in periods of very strong winds, sand is not transported away from this zone in large quantities; it thus stays on the dune and adds to its bulk. It is in such zones on the lee flanks that active growth of these, and probably other, complex dunes occurs.

This discussion of the effects of velocity speed-up on dune morphology has been at a very tentative level. Its implications appear to be complex and require further modelling and field testing before hypotheses can be presented in a more precise form.

CONCLUSIONS

Measurement of wind velocities on the windward slopes of linear and transverse dunes has demonstrated that velocity speed-up results in considerable increases in potential sand-transport rates from the base to the crest of dunes. These differences, in conjunction with the nature, particularly the velocity distribution, of the wind regime, may ultimately control the size of desert sand dunes, subject to the availability of sand for dune building. The measurements provide a new insight into the controls of dune morphology and provide a useful starting point for more sophisticated modelling of dune behaviour and morphology.

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