

The Role of Field Experiments in Studies of Dune Dynamics and Morphology

Nicholas Lancaster

Desert Research Institute, University and Community College System of Nevada,
P.O. Box 60220, Reno, NV 89506, U.S.A.

Abstract : Field measurement of aeolian process-form interactions in the desert have provided in recent years many new informations on the characteristics of the dune-building winds and their patterns of interaction with the dune forms. It is now confirmed that flow acceleration along the dune slope leads to increased sediment flux towards the crest as well as net erosion. Dune shape and the wind direction in relation to the dune determine the pattern of lee side airflow and sand flow pattern there. Information on these and many other relationships have helped to understand how the different dune types interact with the wind regimes and evolve over space and time.

Key words : Dune dynamics, field studies, airflow, dune shape, sediment flux.

In order to understand large, complex, and slowly changing geomorphic systems, it is necessary to study a smaller and simpler analog using carefully designed and conducted experiments. Experiments in geomorphology involve the study, under closely monitored or controlled conditions, of specific variables and/or processes as they operate in a physical representation or model of a selected geomorphic feature (Mosley and Zimpfer, 1978). There are three broad classes of physical models: segments of unscaled reality or geographically restricted localities that are examined in great detail, scale models, and analog models (Chorley, 1967). The study of segments of unscaled reality via field experiments is a widely used approach in other branches of geomorphology and has a long history of providing valuable understanding of fundamental processes (Schumm *et al.*, 1987). The same is true for aeolian geomorphology, starting with the work of R.A. Bagnold (Bagnold, 1941). In this paper, I will give examples of the use of field experiments in aeolian process studies, with an emphasis

on the advances that have been made recently in studies of dune dynamics using this approach.

Aeolian process experiments can be conveniently divided into wind tunnel studies (generally conducted in a laboratory wind tunnel) and field studies that use a variety of instrumentation to measure airflow and sediment transport. Laboratory wind tunnel studies have provided fundamental understanding of the physics of sand movement and the relations between surface characteristics (particle size, slope, roughness, moisture content, crusting and cohesion), wind shear velocity, and flux rates, beginning with the seminal work of Bagnold (1941) and continued by numerous investigators (for a recent review of the state of this field see Anderson *et al.*, 1991). Field studies (especially in coastal environments) have provided confirmation of these fundamentals. Scaling of dunes to the restricted boundary layer height obtained in most wind tunnels has meant that wind tunnel studies of dunes are rare (Tsoar, 1983a; Tsoar *et al.*, 1985; Weng *et al.*, 1991), so that field studies have made a major contribution to

understanding of dune dynamics. Bridging the gap between these two groups of studies are those that use field-portable wind tunnels (e.g. Gillette, 1978; Hardisty and Whitehouse, 1988; Nickling and Gillies, 1989). In addition to studies of dune dynamics, field investigations have proved valuable in understanding dune initiation processes (Kocurek *et al.*, 1992), relation between wind, sediment flux, and surface roughness characteristics (Blumberg and Greeley, 1993; Lancaster *et al.*, 1991), and between sediment flux and vegetation cover (Musick and Gillette, 1990; Stockton and Gillette, 1990; Wasson and Nanninga, 1986).

At all times, there should be synergistic relationship between theoretical and modelling studies, laboratory, and field experiments. Hypotheses generated as a result of field experiments can be used to develop general models of landform response. Theoretical studies and development of analog and mathematical models can indicate the critical variables to be assessed in experiments, while the experiments provide the quantification of parameters.

Approaches and Techniques for Field Studies of Dune Dynamics

The initiation, development, and morphology of all dunes are determined by changes in sediment transport rates in time and space that give rise to erosion or deposition. Patterns of local erosion and deposition on dunes can be viewed in terms of concepts of sediment continuity. The kinematics of sediment transport require that the mass or volume of sediment is conserved (Middleton and Southard, 1984). For each area of the dune surface, a decrease in local sand transport rates with distance means that the influx of sediment to the area will exceed the outflux, leading to sediment storage and, therefore, an increase in the local bed elevation by deposition of

sediment. Conversely, increased sediment transport rates with distance result in sediment outflux exceeding influx, leading to removal of material and lowering of the local bed elevation by erosion of sediment. These relations can be expressed in terms of the sediment continuity equation :

$$dh/dt = -dq_s/dx \quad \dots\dots\dots(1)$$

where,

h is the local bed elevation,
 q_s is the local volumetric sediment transport rate in the direction x , and
 t is time.

Spatial changes in sand transport rates are therefore a fundamental control of dune morphology. In area where wind directions vary seasonally, the spatial pattern of erosion and deposition also changes with each wind season as the dune adjusts towards a new equilibrium with the winds of the time. In turn, the developing bedforms influence local transport rates through form-flow interactions and secondary flow circulation, leading to a dynamic equilibrium between dune morphology and local airflow.

Understanding of dune dynamics using this paradigm requires knowledge of both airflow characteristics and sediment transport rates on and around dunes. Traditionally, airflow over dunes is characterized in terms of speed and direction using cup anemometers and wind vanes. The anemometers may be set at a single height, or deployed at multiple positions to measure boundary layer wind profiles, from which the wind shear velocity (u^*) and aerodynamic roughness (z_0) can be derived using the Prandtl-von Karman wind profile equation. Sediment flux rates can then be estimated from these data using relations established in laboratory wind tunnel studies. There are, however, fundamental problems

in assessing wind profile parameters on sloping dune surfaces (Frank and Kocurek, 1996; Lancaster *et al.*, 1996; Mulligan, 1988). In addition, as will be shown below, anemometers may not be capable of measuring that part of the boundary layer that is significant for sediment transport. To overcome these difficulties, some investigators have begun to use hot-wire anemometry for field studies.

The pattern of erosion and deposition on a dune provides information on how it behaves under different wind conditions so that the processes that maintain its form can be inferred. Erosion and deposition can be measured by repeated surveys using a theodolite or electronic distance measurement techniques (Tsoar, 1983b; Warren, 1988) or by reference to erosion pins at different locations on the dunes (Lancaster, 1989a; Livingstone, 1989; Livingstone and Thomas, 1993).

Sediment transport patterns can be inferred from wind directions measured by wind vanes, assessed using sand dyed with various tracers (Tsoar and Yaalon, 1993), or by detailed mapping of wind ripple patterns (Havholm and Kocurek, 1988). Detailed measurements of actual sand flux are rare in studies of desert dunes (e.g. Wiggs, 1993), but can provide a unique data set (Lancaster *et al.*, 1996). Flow over dunes is three-dimensional, and some investigators have used a variety of flow visualization techniques to demonstrate patterns of flow separation and diversion. These include flags and smoke candles (Lancaster, 1989a; Livingstone, 1986; Tsoar, 1983b) and balloons (Tseo, 1990; Warren and Knott, 1983).

Contributions of Field Studies

The contribution of field experiments to understand dune dynamics can be discussed

in terms of: (i) airflow over dunes, (ii) erosion and deposition patterns, and (iii) sediment flux variations. Recent studies (in the past 15 years) have given rise to a new understanding of dune dynamics and the fundamental processes that determine dune morphology. In turn, this has led to new models for the formation of major dune types (especially linear and star dunes).

Airflow over dunes

Measurements of wind speeds over crescentic, linear and star dunes by many workers show that wind speeds at dune crests are typically 1.1 to 2.0 times those measured immediately upwind of the dune (Burkinshaw *et al.*, 1993; Howard *et al.*, 1978; Lancaster, 1985; Lancaster *et al.*, 1996; Livingstone, 1986; Mulligan, 1988; Tsoar, 1985; Wiggs, 1993). This occurs because, as dunes grow, they project into the atmospheric boundary layer so that air flow is compressed and streamlines converge toward the crest, giving rise to a corresponding increase in wind speed and shear stress on the stoss, or windward slope. The magnitude of the velocity increase is represented by the speed-up ratio (Δ_s) or amplification factor (A_z):

$$A_z = U_2/U_1 \quad \dots\dots(2)$$

where,

U_2 is the velocity at the dune crest and
 U_1 is the velocity at the upwind base of the dune.

The amplification factor varies with dune height and aspect ratio, which is the steepness of the dune, h/L (Lancaster, 1985; Tsoar, 1985; Fig. 1).

Measurements of winds on linear and star dunes show that amplification factors also vary directly with the angle of attack of the wind, or the wind direction relative to the

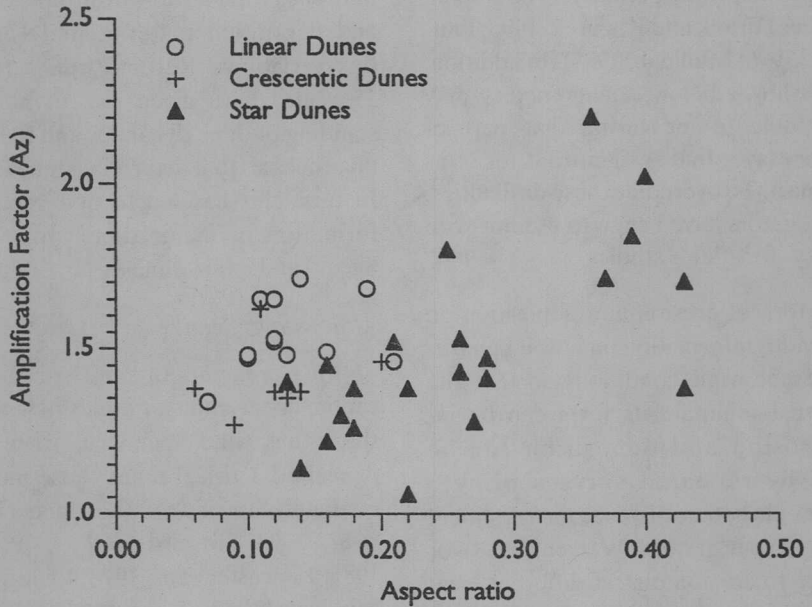


Fig. 1. Relation between amplification factor and dune aspect ratio. Data from Namib linear dunes (A) and Gran Desierto star dunes (B).

dune. This is because the effective aspect ratio increases as the wind blows more nearly perpendicular to the dune crest (Tsoar, 1989). Thus, the effective aspect ratio becomes h/L_a where,

$$L_a = L/\sin \alpha \quad \dots\dots(3)$$

where,

- L_a is the dune length measured parallel to the wind direction,
- L is the dune length, and
- α is the angle of attack.

Wind velocity profiles have been measured on the stoss slopes of dunes by many workers (Burkinshaw *et al.*, 1993; Frank and Kocurek, 1996; Howard *et al.*, 1978; Lancaster *et al.*, 1994; Mulligan, 1988; Weng *et al.*, 1991; Wiggs, 1993). These studies show that profiles are approximately log-linear near the base of the slope, but become progressively less so up slope (Fig. 2), as a result of the effects of

flow acceleration and streamline convergence. Frank and Kocurek (1996) and Lancaster *et al.* (1994) recognize a decrease in wind shear stress up the dune slope, even though wind speed and measured sediment transport increase up the dune. This phenomenon results from the progressive development of an internal boundary layer equivalent to the inner layer of Jackson and Hunt (1975) on the dune slope. The inner layer, with a maximum thickness of 0.5 - 1.0 m, is characterized by increasing shear velocity toward the crest, but has not been recognized because conventional wind profiles derived from anemometry on dunes do not measure the part of the boundary layer that is significant for sediment transport. In the lee of the crest, field studies show that wind velocity decreases rapidly as a result of flow expansion between the crest and brink and flow separation on the avalanche face. Sweet and Kocurek (1990)

suggest that there are three types of flow in the lee of dunes: (i) separated, (ii) attached, and (iii) attached and deflected that are controlled by the dune shape (aspect ratio), the incidence angle between the wind and the crest line (the angle of attack) and the stability of the atmosphere (Fig. 3).

Flow separation occurs mainly where the dune aspect ratio is high and flow is transverse to the crest. The existence of eddies and

and atmospheric stability. Detailed studies of lee side airflow (Frank, in press) show that the reverse flow eddy extends about four dune heights downwind of the dune brink, with a range in the point of reattachment from 1.6 to 5.4 dune heights. Beyond the point of reattachment, the wind velocity profiles can be divided into four regions (Fig. 4): (1) the interior is a low shear region above the dune where the effects of the dune are minimal; (2) a transition zone with high shear,

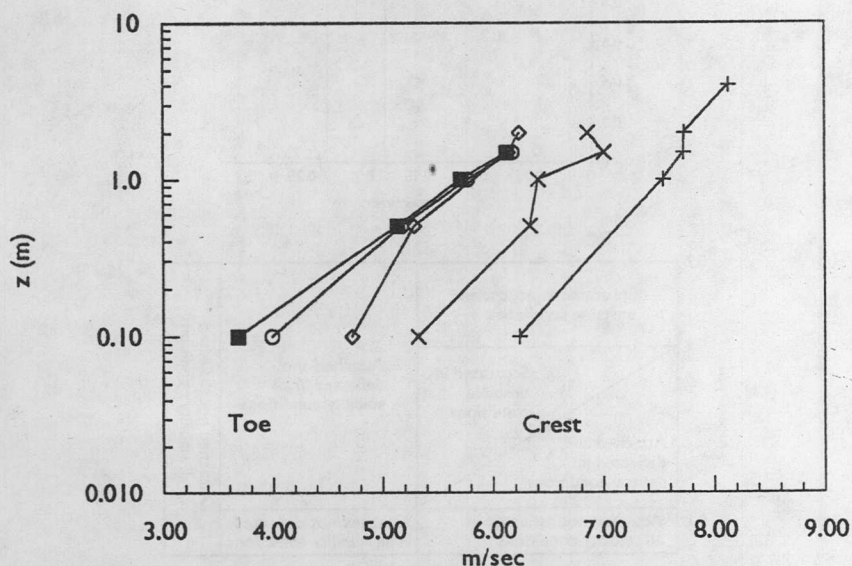


Fig. 2. Wind velocity profiles on the stoss slope of a barchan dune.

reversed flow directions is controversial, due in part to the considerable problems of visualizing such flows. Reverse flow in the lee of crescentic dunes was discounted by Cooper (1958) and Sharp (1966), but field observations (Hoyt, 1965; Warren and Knott, 1983; Frank, in press; Sweet and Kocurek, 1990) support its existence. The width of the separation zone for dunes that are truly transverse to the flow is controlled by the wind speed at the crest, dune aspect ratio,

because the upper part of this zone exhibits decelerating flow while the lower part consists of the upper wake with accelerating flow; (3) the lower wake with low shear and low wind speeds; and (4) the internal boundary layer, which is characterized by relatively high shear. Downwind from the dune, the wake is progressively accelerated as momentum is transmitted downward from the airflow above the dune. This results in increased shear in the lower part of the wake so that by about

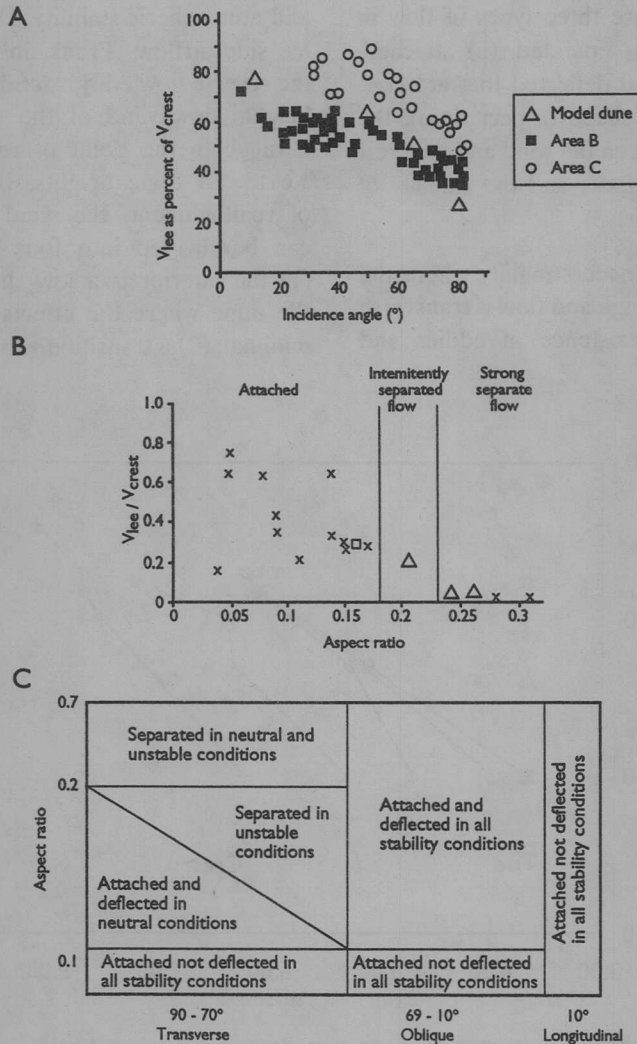


Fig. 3. Flow on the lee side of dunes (modified from Sweet and Kocurek, 1990). A: reduction of wind velocity on the lee slope as a function of the angle of attack of the incident wind; B: reduction of wind velocity on the lee slope as a function of the dune aspect ratio; and C: a generalized model of lee slope airflow.

eight dune heights from the brink, the lower wake and transition zone have merged into a single zone in which the profile is log-linear.

Winds that approach the dune crest at an oblique angle are diverted to flow parallel

or sub-parallel to the lee face. The degree of wind deflection is inversely proportional to the incidence angle between the crest line and the primary wind :

$$U_l = U_c (K \ln (\cos \alpha + A)) \dots\dots\dots(4)$$

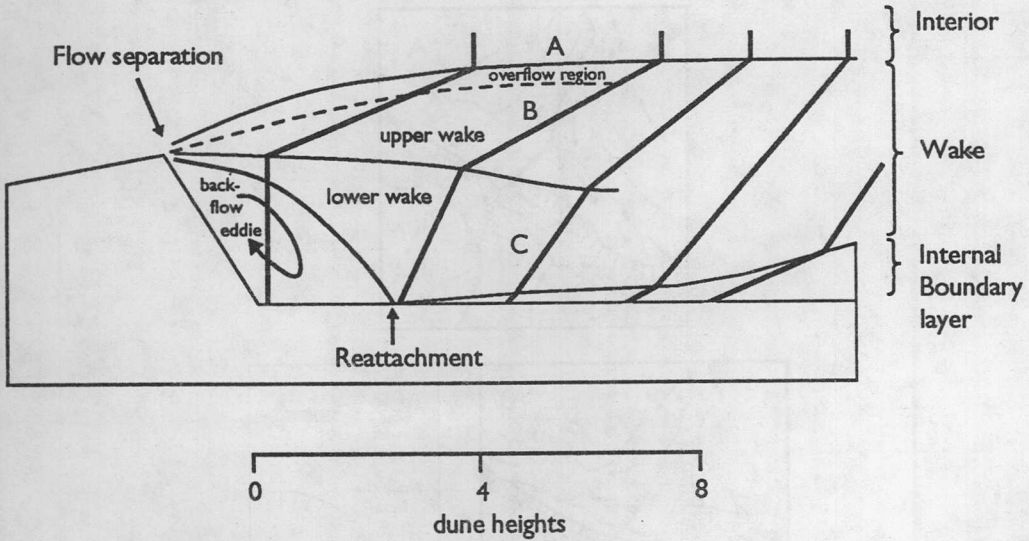


Fig. 4. Model for airflow on the lee side of flow-transverse dunes (after Frank, 1994)

where,

U_l is the wind speed at the base of the lee slope,

U_c is the wind speed at the dune crest,

α is the incidence angle,

A is the maximum value of U_l/U_c and

K is an empirical constant that is 0.83 for Algodones Dunes (Sweet and Kocurek, 1990).

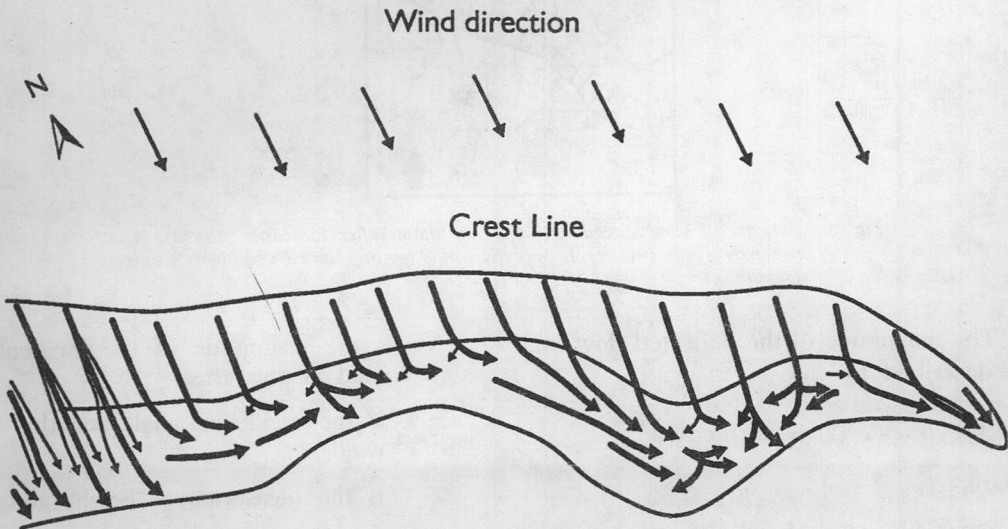


Fig. 5. Patterns of lee side air flow on a linear dune (after Tsoar, 1978).

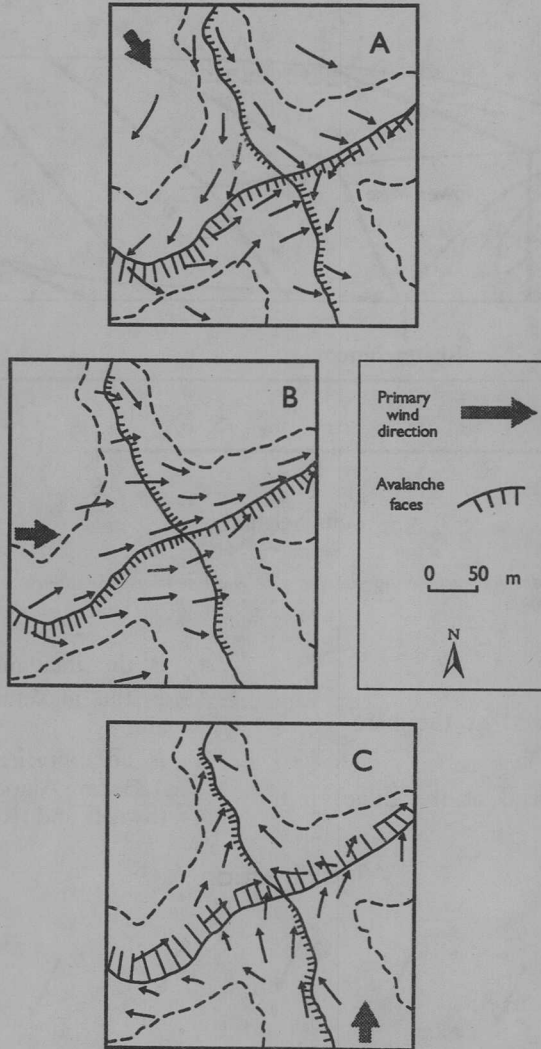


Fig. 6. Patterns of wind directions on a star dune (after Lancaster, 1989a). A: northerly winds (winter), B: westerly winds (spring), and C: southerly winds (summer).

The magnitude of the deflected flow can be described by :

$$C_p(z) = V_w(z + dz) \cos \alpha$$

where,

$C_p(z)$ is the magnitude of the wind vector parallel to the crest,

V_w is the magnitude of the incident wind at the crest,

α is the incidence angle for the wind,

z is the measurement height and

dz is the change in elevation as a result of flow separation.

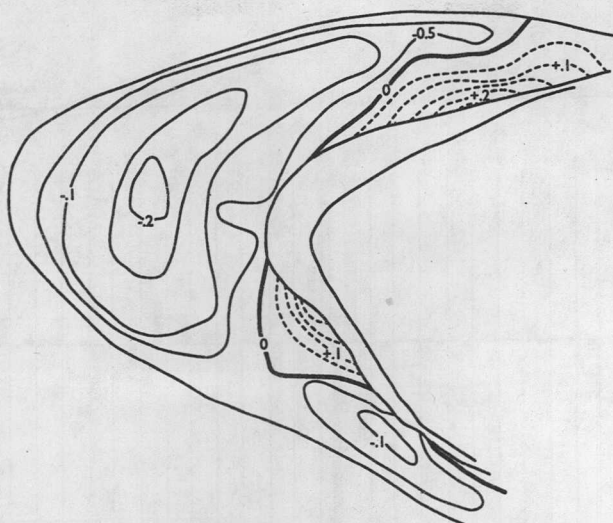


Fig. 7. Changes in surface elevation (in metres) on a barchan dune (after Howard *et al.*, 1978).

When the angle between the dune and the wind is less than 40° the velocity of the deflected wind is greater than that at the crest and sand is transported along the dune (Tsoar, 1983a). When winds are at an angle of more than 40° to the crest line the velocity of the deflected wind will be reduced, giving rise to lee side deposition.

Airflow in the lee of linear and star dunes is complex, especially where the crest line is sinuous. The same primary flow may be simultaneously separated or deflected at different points along the dune. The detailed measurements of winds and sand movements on a 6 to 13 m high sinuous simple linear dune (Tsoar, 1978; 1983b) show that a separation zone exists in the lee of the crest even when winds blow obliquely to the dune, which has a high aspect ratio resulting from its triangular profile (Fig. 5). At the point of attachment of the separated flow, wind velocities increase again, and may reach values 1.05 - 1.20 times of those measured at the crest.

Wind directions observed in this zone are parallel to the dune. The increased wind velocities and sand transport rates in the attachment zone are the result of the concentration of streamlines as the separated flow returns to the dune surface. The greatest increase in wind velocity parallel to the dune occurs when the wind crosses the crest at an angle of $30^\circ \pm 10^\circ$ to the dune. Beyond this zone of reattachment, wind velocities tend to decrease again and to resume their original direction. Similar patterns of winds occur on Namib linear dunes (Lancaster, 1989b; Livingstone, 1986).

Airflow on the star dune studied by Lancaster (1989a) is directed up the windward arm of the dune, but radially outward on the stoss slopes of both flow-transverse arms. There is a strong separation of flow at the crest of both east and west arms of the dune (Fig. 6). Beyond this zone, a well developed secondary circulation in the lee of these arms sweeps sand along the base of the avalanche

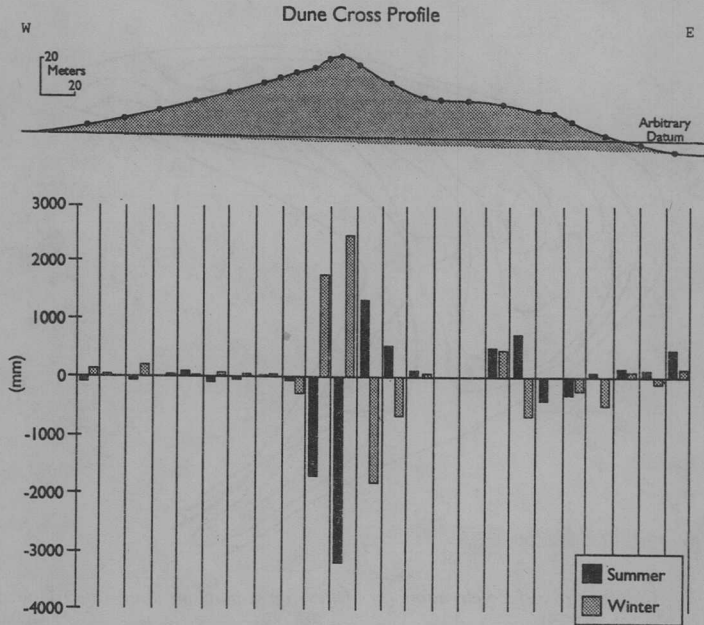


Fig. 8. Seasonal changes in pattern of erosion and deposition a Namib linear dune corresponding to changes between summer SSW to SW winds and winter easterly winds (after Livingstone, 1989).

face towards the flow-parallel arm. This circulation is a return flow, probably in the form of helical eddy, from the end of the dune arm towards the low pressure zone created by flow separation at the dune crest. The pattern is reversed as winds change direction seasonally.

Erosion and deposition patterns on dunes

Erosion and deposition patterns on crescentic dunes are characterized by erosion on the stoss slopes and deposition in the lee. Few direct measurements of erosion and deposition have however been made on crescentic dunes. Howard *et al.* (1978) measured changes in surface elevation on a barchan dune over a two week period (Fig. 7) and found an erosion maximum on the central part of the stoss slope and on the southern horn, with deposition on brink each side of the crestal area of the dune.

On the lee slope, field studies (McDonald and Anderson, 1995) show that the maximum deposition occurs 0.2 - 0.4 m from the top of the lee face, and declines exponentially with distance from this point. The decrease in deposition rate has a length scale of approximately 1 m, typically less than the length of the lee face, giving rise to oversteepening and subsequent failure and avalanching.

All linear dunes display a similar pattern of erosion and deposition which is characterized by low activity on the plinth and high rates of erosion and deposition on the upper flanks of the dune, with a peak at the dune crest and major slip face. Tsoar (1978; 1983b) found that the crest line of a simple linear dune migrated laterally over a distance of 5-7 m under the influence of summer NNE and winter SSW-SW winds so that the dune became more asymmetric as the wind season

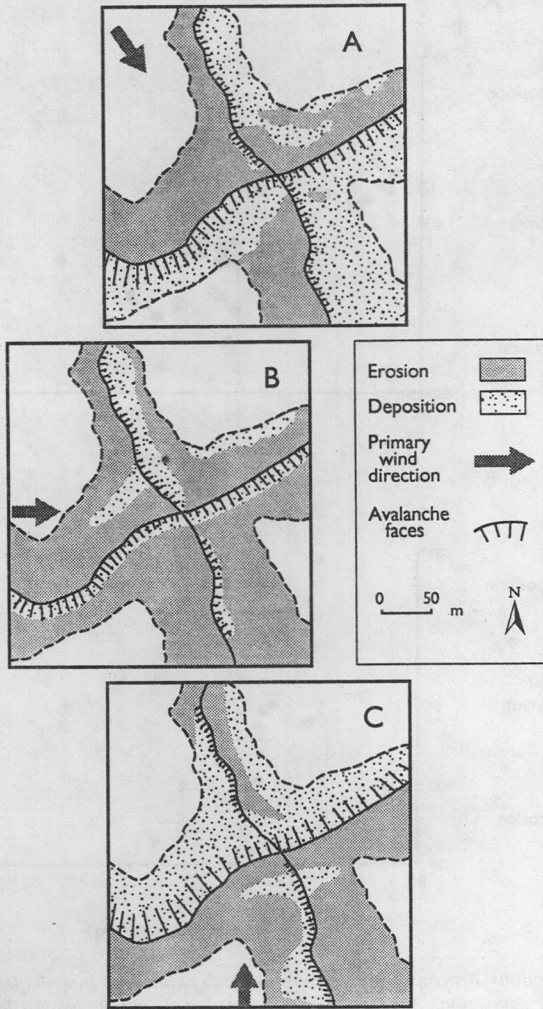


Fig. 9. Patterns of erosion and deposition on a Gran Desierto star dune (after Lancaster, 1989a). A: northerly winds (winter), B: westerly winds (spring), and C: southerly winds (summer).

progressed. Seasonal changes in wind directions give rise to spatial changes in the pattern of erosion or deposition on the dune, creating a sinuous pattern of narrower, lower saddles and higher, wider peaks. Studies by Livingstone (1986; 1989) and Lancaster (1989b) of large S - N trending complex linear dunes in the Namib Sand Sea show that the

magnitude of erosion and deposition varies significantly from place to place across linear dunes (Fig. 8). The crestal regions of the dunes are the most active as they are reworked by winds from different directions according to season and migrate over a lateral distance of as much as 14 m over a 12 month period but with little net change over a period of

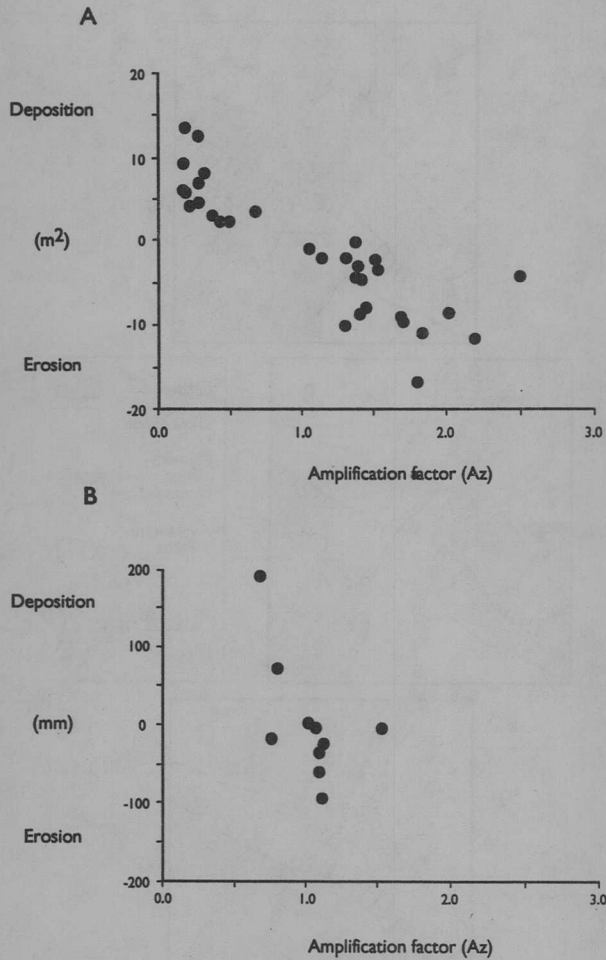


Fig. 10. Relations between wind velocity amplification and magnitude of erosion and deposition. A: Gran Desierto star dunes, and B: Namib linear dunes.

2 to 3 years (Livingstone, 1989). However, on a decadal time scale, significant changes in form do occur in the crestral areas of these dunes (Livingstone, 1993).

Recent field studies of vegetated linear dunes in the southwestern Kalahari show that most of the surface activity takes place in crestral areas and is limited by vegetation cover. The dunes show an overall threefold increase in dune activity following vegetation removal by fire, grazing pressure, or drought (Wiggs

et al., 1994). The net amount of surface change as a percentage of the dune cross-sectional area for devegetated dunes is comparable with Namibian linear dunes, indicating that they are episodically in an active state. In this area, the effects of vegetation are manifested mainly through the cover of plant litter on the dune surface, rather than by rooted vegetation cover (Wiggs *et al.*, 1995).

Observations of patterns of erosion and deposition on a 40 m high star dune in the

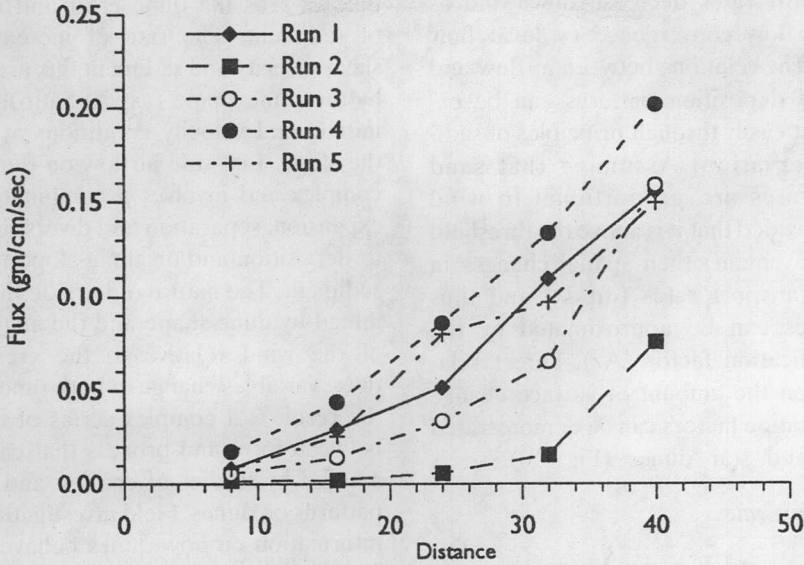


Fig. 11. Increase in measured sand flux on the stoss slope of a barchan dune.

Gran Desierto sand sea indicate that most of the changes in dune form are associated with the reworking of the crestal areas of the main NE - SW oriented arms of the dune as winds change direction seasonally (Lancaster, 1989a). Similar observations were made by Sharp (1966) on reversing dunes at Kelso, in the Mojave Desert. Approximately three times as much erosion and deposition takes place on the east-west arms which are approximately transverse to the major wind directions, compared with the north or south arms of the dune, which are parallel or oblique to these winds (Fig. 9). The plinths experience relatively little change in all seasons, whereas the crest lines of the east and west arms migrate over a distance of as much as 20 m. In the course of each major wind season, the profile shape of the main crest line changes so that it passes through a period when it is near-symmetrical in profile, but becomes progressively more asymmetric in the latter part of the season.

Erosion rates are highest at the crest of the dune soon after winds change direction,

but decline thereafter, as the point of maximum erosion moves upwind and the dune becomes more fully adjusted to the new conditions. The rate of advance of the crest line slows down as the wind season continues and the avalanche face height increases. The spatial patterns of erosion and deposition change seasonally, as the primary incident wind direction changes. In all seasons, most of the deposition occurs on the avalanche faces, but considerable lateral movements of sand also occur.

Relations between erosion and deposition patterns and winds

Field observations on all dune types show that there is a very close correspondence between patterns of erosion and deposition and wind velocity and direction. Erosional slopes are those which experience accelerating or divergent winds. Deposition takes place in two settings: rapid and large volume deposition on lee-side avalanche faces, where flow separation occurs; and slow deposition in areas where

sand transport rates decrease downwind as a result of flow convergence or local flow expansion. The relations between airflow and erosion and deposition patterns can be explained most easily through principles of sediment conservation. Assuming that sand transport rates are proportional to wind velocity (provided that it is above the threshold for sand movement) then spatial changes in sediment transport rates (dq/dx) and thus erosion rates can be approximated by the local amplification factor (A_z). Direct relations between the amount of surface change and amplification factors can be demonstrated for linear and star dunes (Fig. 10).

Sediment flux rates

Recognizing the considerable problems associated with derivation of wind shear velocity and sediment transport rates from wind profiles on dune slopes, Lancaster *et al.* (1994) measured sediment flux rates on the stoss slope of a 5 m high barchan dune, directly using an array of sand traps. Their data indicate an increase in flux up the dune, with the maximum total and mean flux occurring at the brink line (Fig. 11). Similar observations were made by Wiggs (1993). The shape of the flux vs distance curve also varies with wind speed conditions. At low wind speeds, sediment flux tends to increase exponentially with distance up the dune whereas at higher wind speeds, the increase becomes approximately linear.

Conclusions

Recent field studies have provided a wealth of information on airflow, sand transport rate and erosion and deposition patterns on dunes. They show that all dunes are characterized by flow acceleration on windward (stoss) slopes. This results in an increase in sediment

flux towards the dune crest and net erosion of sediment. The rate of increase of wind shear velocity and sediment flux are controlled by the dune shape (aspect ratio) and by the initial wind velocity conditions at the toe of the slope. Lee side airflow on dunes is often complex and involves a combination of flow expansion, separation and diversion that leads to deposition and/or along-slope transport of sediment. The nature of lee side flow is determined by dune shape and the angle of attack of the wind relative to the crest line. As these variables change in both time and space, the result is a complex series of interactions between form and process that can be documented by studies of erosion and deposition patterns on dunes. Field investigations provide information on how dunes behave under different wind conditions and demonstrate the importance of interactions between the dune form and airflow so that dunes tend to evolve towards some form of dynamic equilibrium. Such observations provide the basis for new models that explain why dunes of different types occur in different wind regimes (e.g. Lancaster, 1989a; Livingstone, 1988; Tsoar, 1983b) and have ended years of speculation about how different dune types form.

As knowledge of the fundamentals of dune dynamics evolves, new concepts develop, which impact the next generation of field experiments. Currently, the importance of turbulence is being increasingly recognized (eg. Wiggs *et al.*, 1996), paralleling developments in fluvial bedform research (Bennett and Best, 1995). Many desert dunes are vegetated to some extent, and the role of vegetation in the dynamics of aeolian processes is increasingly recognized (Wolfe and Nickling, 1993) via its effect on transport thresholds (Raupach *et al.*, 1993) and sediment transport rates (Hagen and Armbrust, 1994). These new paradigms bring their own challenges in instrumentation and experimental design, but

are likely to lead to increasingly sophisticated models of dune dynamics in the future.

References

- Anderson, R.S., Sorensen, M. and Willetts, B.B. 1991. A review of recent progress in our understanding of aeolian sediment transport. *Acta Mechanica, Supplement 1*: 1-19.
- Bagnold, R.A. 1941. *The Physics of Blown Sand and Desert Dunes*. Chapman and Hall, London.
- Bennett, S.J. and Best, J.L. 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: implications for sediment transport and bedform stability. *Sedimentology* 42(3): 491-514.
- Blumberg, D.G. and Greeley, R. 1993. Field studies of aerodynamic roughness length. *Journal of Arid Environments* 25: 39-48.
- Burkknishaw, J.R., Illenberger, W.K. and Rust, I.C. 1993. Wind speed profiles over a reversing transverse dune. In *The Dynamics and Environmental Context of Aeolian Sedimentary Systems* (Ed. K. Pye), pp. 25-36. Geological Society, London.
- Chorley, R.J. 1967. Models in Geomorphology. In *Models in Geography* (Eds. R.J. Chorley and P. Haggett), pp. 59-96. Methuen, London.
- Cooper, W.S. 1958. Coastal sand dunes of Oregon and Washington. *Geological Society of America Memoir* 72: 167.
- Frank, A. 1996. Model of airflow patterns on the lee side of a eolian dunes. *Geomorphology* (in press).
- Frank, A. and Kocurek, G. 1996. Airflow up the stoss slope of sand dunes: limitations of current understanding. *Geomorphology* 17: 47-54.
- Gillette, D. 1978. Tests with a portable wind tunnel for determining wind erosion threshold velocities. *Atmospheric Environment* 12: 2309-2313.
- Hagen, L.J. and Armbrust, D.V. 1994. Plant canopy effects on wind erosion saltation. *Transactions of the ASAE* 37(2): 461-465.
- Hardisty, J. and Whitehouse, R.J.S. 1988. Evidence for a new sand transport process from experiments on Saharan dunes. *Nature* 332: 532-534.
- Havholm, K.G. and Kocurek, G. 1988. A preliminary study of the dynamics of a modern draa, Algodones, southeastern California, USA. *Sedimentology* 35: 649-669.
- Howard, A.D., Morton, J.B., Gad-el-Hak, M. and Pierce, D.B. 1978. Sand transport model of barchan dune equilibrium. *Sedimentology* 25: 307-338.
- Hoyt, J. 1965. Air and sand movements to the lee of dunes. *Sedimentology* 7: 137-143.
- Jackson, P.S. and Hunt, J.C.R. 1975. Turbulent wind flow over a low hill. *Quarterly Journal of the Royal Meteorological Society* 101: 929-955.
- Kocurek, G., Townsley, M., Yeh, E., Havholm, K. and Sweet, M.L. 1992. Dune and dunefield development on Padre Island, Texas, with implications for interdune deposition and water-table-controlled accumulation. *Journal of Sedimentary Petrology* 62: 622-635.
- Lancaster, N. 1985. Variations in wind velocity and sand transport rates on the windward flanks of desert sand dunes. *Sedimentology* 32: 581-593.
- Lancaster, N. 1989a. The dynamics of star dunes: an example from the Gran Desierto, Mexico. *Sedimentology* 36: 273-289.
- Lancaster, N., 1989b. *The Namib Sand Sea: Dune Forms, Processes and Sediments*. A.A. Balkema, Rotterdam.
- Lancaster, N., Nickling, W.G., McKenna Neuman, C.K. and Wyatt, V.E. 1994. Sediment flux and airflow on the stoss slope of a barchan dune. In *Response of Eolian Processes to Global Changes: Abstracts of a Workshop* (Ed. N. Lancaster), pp. 63-64. Desert Research Institute, Reno.
- Lancaster, N., Nickling, W.G., McKenna Neuman, C.K. and Wyatt, V.E. 1996. Sediment flux and airflow on the stoss slope of a barchan dune. *Geomorphology* 17:55-62.
- Lancaster, N., Rasmussen, K.R. and Greeley, R. 1991. Interactions between unvegetated desert surfaces and the atmospheric boundary layer: a preliminary assessment. *Acta Mechanica, Supplement 2*: 89-102.
- Livingstone, I. 1986. Geomorphological significance of wind flow patterns over a Namib linear dune. In *Aeolian Geomorphology* (Ed. W.G. Nickling), pp. 97-112. Allen and Unwin, Boston.
- Livingstone, I. 1988. New models for the formation of linear sand dunes. *Geography* 73: 105-115.
- Livingstone, I. 1989. Monitoring surface change on a Namib linear dune. *Earth Surface Processes and Landforms* 14: 317-332.
- Livingstone, I. 1993. A decade of surface change on a Namib linear dune. *Earth Surface Processes and Landforms* 18: 661-664.
- Livingstone, I. and Thomas, D.S.G. 1993. Modes of linear dune activity and their significance: an evaluation with reference to southern African examples. In *Dynamics and Environmental Context of Aeolian Sedimentary Systems* (Ed. K. Pye), pp. 91-102. Geological Society of London, Special Publication. London.
- McDonald, R.R. and Anderson R.S. 1995. Experimental verification of aeolian saltation and lee side deposition models. *Sedimentology* 42: 39-56.
- Middleton, G.V. and Southard, J.B. 1984. *Mechanics of Sediment Movement*. S.E.P.M., Tulsa, Oklahoma.
- Mosley, M.P. and Zimpfer, G.L. 1978. Hardware models in geomorphology. *Progress in Physical Geography* 2: 438-461.

- Mulligan, K.R. 1988. Velocity profiles measured on the windward slope of a transverse dune. *Earth Surfaces Processes and Landforms* 13: 573-582.
- Musick, H.B. and Gillette, D.A. 1990. Field evaluation of relationships between a vegetation structural parameter and sheltering against wind erosion. *Land Degradation and Rehabilitation* 2: 87-94.
- Nickling, W.G. and Gillies, J.A. 1989. Emission of fine-grained particles from desert soils. In *Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport* (Eds. M. Leinen and M. Sarnthein), pp. 133-165. Kluwer Academic Publishers, Amsterdam.
- Raupach, M.R., Gillette, D.A. and Leys, J.F. 1993. The effect of roughness elements on wind erosion threshold. *Journal of Geophysical Research* 98: 3023-3029.
- Schumm, S.A., Mosley, M.P. and Waever, W.E. 1987. *Experimental Fluvial Geomorphology*. John Wiley & Sons, New York.
- Sharp, R.P. 1966. Kelso Dunes, Mohave Desert, California. *Geological Society of America Bulletin* 77: 1045-1074.
- Stockton, P.H. and Gillette, D.A. 1990. Field measurements of the sheltering effect of vegetation on erodible land surfaces. *Land Degradation and Rehabilitation* 2: 77-86.
- Sweet, M.L. and Kocurek, G. 1990. An empirical model of aeolian dune lee-face airflow. *Sedimentology* 37: 1023-1038.
- Tseo, G. 1990. Reconnaissance of the dynamic characteristics of an active Strzelecki Desert longitudinal dune, south central Australia. *Zeitschrift fur Geomorphologie* 34: 19-35.
- Tsoar, H. 1978. *The Dynamics of Longitudinal Dunes*. Final Technical Report, U.S. Army European Research Office, London.
- Tsoar, H. 1983a. Wind tunnel modelling of echo and climbing dunes. In *Eolian Sediments and Processes* (Eds. M.E. Brookfield and T.S. Ahlbrandt), pp. 247-259. Elsevier, Amsterdam.
- Tsoar, H. 1983b. Dynamic processes acting on a longitudinal (seif) dune. *Sedimentology* 30: 567-578.
- Tsoar, H. 1985. Profile analysis of sand dunes and their steady state signification. *Geografiska Annaler* 67A: 47-59.
- Tsoar, H. 1989. Linear dunes - forms and formation. *Progress in Physical Geography* 13(4): 507-528.
- Tsoar, H., Rasmussen, K.R., Sorensen, M. and Willetts, B.B. 1985. Laboratory studies of flow over dunes. In: *Proceedings of International Workshop on the Physics of Blown Sand* (Eds. O.E. Barndorff-Nielsen, J.T. Moller, K.R. Rasmussen and B.B. Willetts), pp. 327-350. University of Aarhus, Aarhus.
- Tsoar, H. and Yaalon, D.H. 1983. Deflection of sand movement on a sinuous longitudinal (seif) dune: use of fluorescent dye as tracer. *Sedimentary Geology* 36: 25-39.
- Warren, A. 1988. The dynamics of dune networks in the Wahiba Sands. *Journal of Oman Studies*, Special Report 3: 169-180.
- Warren, A. and Knott, P. 1983. Desert dunes: a short review of needs in desert dune research and a recent study of micro-meteorological dune initiation mechanisms. In *Eolian Sediments and Processes* (Eds. M.E. Brookfield and T.S. Ahlbrandt), pp. 343-352. Elsevier, Amsterdam.
- Wasson, R.J. and Nanninga, P.M. 1986. Estimating wind transport of sand on vegetated surfaces. *Earth Surface Processes and Landforms* 11: 505-514.
- Weng, W.S., Hunt, J.C.R., Carruthers, D.J., Warren, A., Wiggs, G.F.S., Livingstone, I. and Castro, I. 1991. Air flow and sand transport over sand dunes. *Acta Mechanica* Supplement 2: 1-22.
- Wiggs, G.F.S. 1993. Desert dune dynamics and the evaluation of shear velocity: an integrated approach. In *The Dynamics and Environmental Context of Aeolian Sedimentary Systems* (Ed. K. Pye), pp. 37-48. Geological Society, London.
- Wiggs, G.F.S., Livingstone, I., Thomas, D.S.G. and Bullard, J.E. 1994. Effect of vegetation removal on airflow patterns and dune dynamics in the southwestern Kalahari Desert. *Land Degradation and Rehabilitation* 5: 13-24.
- Wiggs, G.F.S., Livingstone, I. and Warren, A. 1996. The role of streamline curvature in sand dune dynamics. *Geomorphology* 17: 29-46.
- Wiggs, G.F.S., Thomas, D.S.G., Bullard, J.E. and Livingstone, I. 1995. Dune mobility and vegetation cover in the southwest Kalahari Desert. *Earth Surface Processes and Landforms* 20: 515-530.
- Wolfe, S.A. and Nickling, W.G. 1993. The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography* 17: 50-68.