Desert Sand Dune Dynamics: Review and Prospect

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Considerable progress has been made over the past fifteen years in the study of patterns of sand transport and wind flow over individual desert sand dunes. Much of this progress stems from work carried out in the Namib Desert. This paper reviews the recent research on sand dune dynamics, emphasizing the advances made through careful monitoring of the dynamics of individual dunes, and the links with mathematical modelling of flow over obstructions in the atmospheric boundary-layer. It also considers the problems of recognizing equilibrium dune forms in the field, and of lag times in the response of dunes to a change of regime.

INTRODUCTION

Over the past fifteen years our understanding of desert dune dynamics has advanced considerably. There has been an exponential increase in the volume of literature on dune geomorphology which has included reports from conferences in Canada (Brookfield and Ahlbrandt, 1983; Nickling, 1986) and Denmark (Barndorff-Nielsen, Møller, Rømer Rasmussen and Willetts, 1985), a journal supplement devoted to dune studies (Jennings and Hagedorn, 1983) and numerous individual papers in various journals. Much of this upturn of interest has included contributions from researchers who have spent time at the Namib Research Institute studying Namib dunes.

The revival has been given its impetus by a number of developments. In North America there has been a move to find terrestrial analogues for aeolian bedforms on other planets (e.g., Greeley and Iversen, 1985). The provision of satellite and space shuttle images has facilitated more detailed surveys of remote and rather inhospitable parts of the arid lands (El-Baz, 1984; McKee, 1979). Microprocessor technology, particularly as used in date loggers, has improved sufficiently to provide monitoring equipment that can be relied upon in harsh environments. And the management of desert encroachment, often perceived as a problem of sand dune advance, has given added drive to sand dune studies (Cooke, Brunsden, Doornkamp and Jones, 1982; Harmse, 1982; Watson, 1985).

Aeolian geomorphology, like geomorphology as a whole, can be approached at several scales of space and time (Schumm and Lichty, 1965), and, following Warren and Knott (1983), it is possible to recognize three levels in the study of dunes. At the smallest spatial scale it is the entrainment and mobility of individual particles. At the largest scale the study is of entire sand seas. However, the recent past has seen a shift in the focus of attention to the intermediate scale of individual sand dunes. It has become clear that dune morphology cannot be viewed simplistically as a response to regional wind patterns. Neither, of course, can dune development be completely divorced from individual sand grain behaviour, but bridging the gap between these levels of study remains a major task for aeolian geomorphology. Most of the recent progress has been made, as Warren and Knott (1983) predicted, at the 'graded' scale of the single dune. This paper reviews that progress, and offers some pointers to future research requirements.

SINGLE DUNE STUDIES

No consideration of aeolian processes can avoid reference to Bagnold's (1941) pioneering study. Bagnold, an engineer, provided an excellent empirically based study of the conditions involved in the entrainment of individual sand grains, much of which remains substantially unmodified by subsequent research. But his theories about dune development, despite being based on many years of desert experience, were mainly deductive, and largely untested. An example of this approach was his roll-vortex theory of linear dune origin which he introduced highly speculatively (Bagnold, 1953), but which has subsequently been widely quoted. Similarly, Wilson's (1972) belief in the creation of regularly repeated aeolian bedforms in sand seas created by meteorologically induced secondary flows was derived from Allen's (1968) models of small-scale subaqueous bedforms and from observation of dune form rather than from a study of processes on desert dunes.

Gradually, though, it became clear that these simple deductive theories were far from adequate. Thus Howard, Morton, Gad-el-Hak and Pierce (1978) and Knott (1979) worked on barchans in California and Algeria respectively; linear dunes were studied by Tsoar (1978) in Israel and by Lancaster (1985) and Livingstone (1985) in Namibia; a dune network has been studied by Warren and Kay (1987) in Oman; Havholm and Kocurek (1988) worked on a draa in California; and Lancaster, Greeley and Christensen (1987) are studying star dunes in Mexico.

The common theme in all these studies has been an interest in the interplay between dune form and wind flow. The new working hypothesis assumes that there is an equilibrium response of dune form to a given wind regime, and that through a feedback mechanism between form and process an equilibrium dune morphology is achieved. The dune thus changes in such a way as to create a wind flow pattern which is conducive to its self-perpetuation.

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Studies have therefore been undertaken to monitor these two elements – sand surface change and wind flow – in the field. In the Namib a range of techniques has been used to measure sand mobility. Besler (1975, 1980) has been monitoring the advance of the tips of small, simple linear dunes throughout the northern part of the Namib sand sea since 1969, although her study sites are not typical of the massive linear dunes that cover much of the sand sea. Between 1979 and 1984 three concurrent studies monitored different linear dunes by measuring surface change against steel posts. As part of the Kuiseb River Project, Ward (1984) measured the northward advance of the tips of linear dunes into the bed of the Kuiseb River, and reported an advance of between 0 and 1,85 m yr^{-1}. Lancaster also undertook a one-year post-measuring project at three sites on complex linear dunes, taking measurements once a month (Lancaster, 1985, 1987). Two grids of posts established by Livingstone in 1980 at a site on a linear dune 8 km southeast of Gobabeb were measured every week for four years (Livingstone, 1989). Livingstone (1985) also monitored sand movement using sand traps and fluorescent dye. Wind speeds have been measured using anemometers by Lancaster (1985) and Livingstone (1985, 1986), and flow patterns visualized using smoke flares (Livingstone, 1985). Monitoring programmes of this sort have provided a range of information about single dune dynamics.

LINEAR DUNES

The move away from a belief in meteorologically induced secondary flow patterns controlling dune forms to a consideration of feedback mechanisms between dune form and wind flow is well illustrated from two studies of linear dunes, one of which is from the Namib.

A linear dune can be defined as a dune in which net sand transport is parallel to the dune crest, and in which the long axis dimension greatly exceeds the cross-dune width (Livingstone, 1989). The Namib provides some of the largest examples of active linear dunes in the world (Lancaster, 1983). Often the dunes display marked parallelism and continuity of form, and the area around Gobabeb is therefore an excellent field area for their study. Many theories have been offered to explain linear dune origin, but no monitoring programmes had previously been undertaken (for a review of linear dune morphologies, sizes and theories of origin see Lancaster, 1982).

Elsewhere, though, Tsoar worked on a single linear dune in the Negev Desert. The dune had a maximum height of 12 to 14 metres and extended for 1,5 km. Tsoar was able to show that the intrusion of the dune itself into the atmospheric boundary-layer created a lee-side eddy pattern conducive to its own self perpetuation (Tsoar, 1978, 1983). He argued that any wind crossing the dune crest obliquely would be subject to a separation of flow from the dune surface, and would be diverted along the lee slope of the dune. The separation of flow would also lead to a reversal of flow at the surface on the lee side (Fig. 1). Sand could thus be prevented from leaving the downwind edge of the dune, and net sand transport would be parallel to the dune crest. Lee side eddies and the diversion of flow, Tsoar argued, could account for the maintenance of linear dune form.

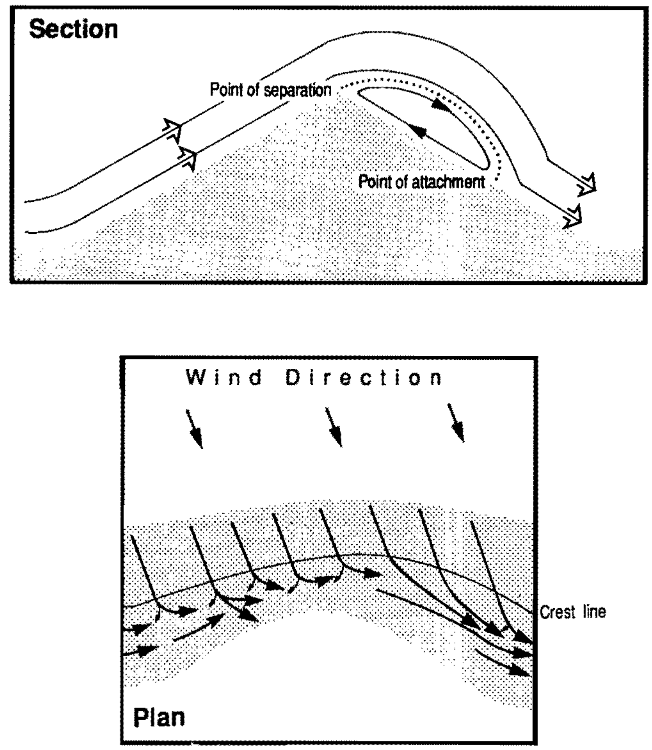

Fig. 1

Tsoar's (1978, 1983) model of wind flow over a linear dune. Oblique incident winds are deflected at the crest so that net sand movement on the lee slope is along the dune parallel to the crest.

For this mechanism to operate, two conditions must be fulfilled. First, there must be a sufficiently sharp dune crest that flow separation occurs, and second, there must be a seasonally or diurnally bi-directional wind regime. Unlike some other theories of linear dune genesis such as the roll-vortex theory, the formative winds in Tsoar's model do not blow parallel to the dune crest, but blow obliquely from either side of the crest. The side of the dune which is the lee flank in one season, is the windward (stoss) slope in another season. The longitudinal extension of the dune is then along some vector resultant of the annual wind regime.

Tsoar's model is innovative in that, although secondary air flow patterns are invoked, they are seen as created by the dune itself. The dunes are formed in bi-directional wind regimes; every wind direction is deflected on a lee flank; and the relative speed and eddy size of the deflected wind depends on the angle of incidence of the wind to the crest. Tsoar (1983) also explained the characteristic meandering pattern of a seif dune crest in terms of zones of erosion and deposition on the lee flank.

Working on a linear dune in the Namib sand sea, Livingstone has also been concerned with wind flow patterns created by the dune's intrusion into the boundary-layer, but his concern has been more with patterns of wind speed change than with eddies (Livingstone 1986, 1988). While a lee side eddy covered the entire lee slope of Tsoar's dune, Livingstone, using

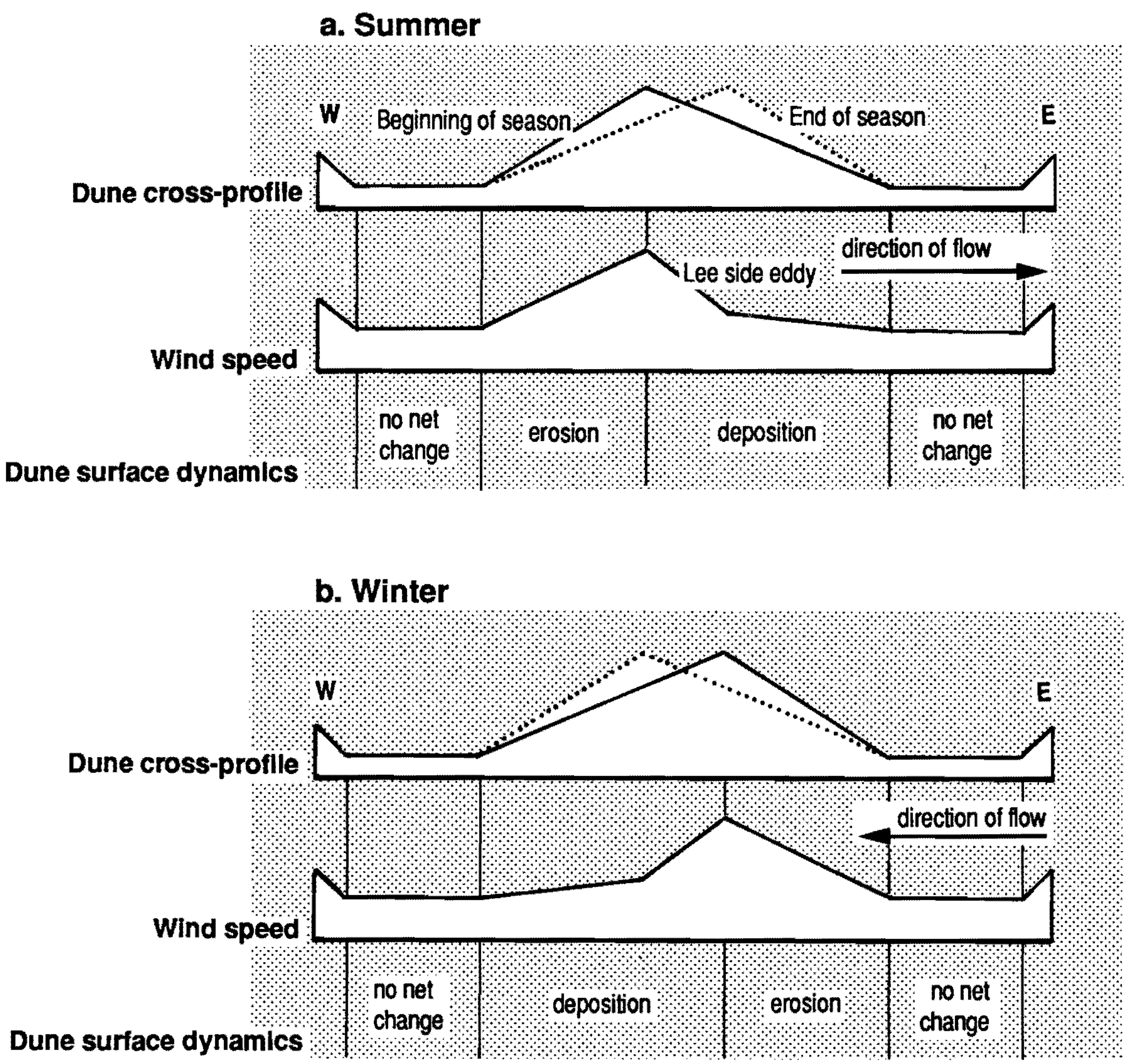

Fig. 2

Livingstone's (1986, 1988) model of linear dune dynamics in a seasonally bi-directional wind regime such as that in the Namib sand sea. In summer, when winds are from the west, sand is eroded from the west slope of the dune and deposited on the east slope. In the easterly winds of winter this pattern of erosion and deposition is reversed.

smoke flares, found that similarly sized eddies covered only part of the lee slope of his study dune which was 50 m high. Winds recovered their incident direction on the lower part of the lee slope where a series of secondary dunes was formed (Livingstone, 1987). Sand was not therefore prevented from leaving the dune in the way Tsoar had suggested.

Livingstone argued instead, following Bagnold (1941), that an increase in wind speed would induce a proportional increase in the capacity of the wind to carry sand, and the sand surface would therefore be eroded (Fig. 2). Decreasing wind speeds would cause a decreasing capacity to carry sand, and sand would be deposited. Thus an increase of wind speeds towards the crest on the windward slope led to erosion, and decreasing speeds on the lee slope led to deposition. In the seasonally bi-directional regime of the Namib Desert, where summer winds from the southwest and northwest and winter winds are from the east, the patterns of erosion and deposition were seasonally reversed, so that the west slope was eroded in summer, but sand was deposited here in winter (Livingstone, 1986, 1988).

The Tsoar and Livingstone models are not mutually exclusive. The range of linear dune types could indicate an equifinal form, or the two mechanisms – one of flow separation and diversion, the other of erosion and deposition patterns related to wind speed change – could be complementary and operate in tandem.

WIND FLOW PATTERNS

What is apparent from studies by Tsoar, Livingstone and others is that a fuller understanding is required of how wind is affected by the intrusion of an obstruction such as a dune into the flow. Coincidentally, and fortuitously, as geomorphologists have become interested in wind flow over dunes, meteorologists, physicists and mathematicians have become concerned with the parallel problem of the intrusion of other topographic barriers, particularly isolated low hills into the atmospheric boundary-layer. This work, recently reviewed by Taylor, Mason and Bradley (1987), has involved mathematical modelling as well as empirical measurement both in the field and in the wind tunnel. Initially, solutions were derived for simple, two-dimensional hills in unseparated flow (Britter, Hunt and Richards, 1981; Jackson and Hunt, 1975; Taylor and Gent, 1974), but these have subsequently been extended to three-dimensional cases and to separated flow (Mason and Sykes, 1979; Walmsley, Salmon and Taylor, 1982).

These studies have provided a series of empirically or theoretically derived formulae, often based on the initial solution of Jackson and Hunt (1975). Lancaster (1985), Livingstone (1985) and Tsoar (1985) were each able to show the applicability of these formulae – especially as presented by Jackson (1977) – to the dune problem. All three were able to demonstrate a direct correspondence between their field measurements of wind speeds on the windward slopes of desert dunes and the speeds predicted by the Jackson formula.

The obvious next step is for the geomorphologists and the flow modellers to combine to develop models of dune dynamics. Already, Howard and Walmsley (1985) and Walmsley and Howard (1985) have attempted to model flow over the barchan studied by Howard *et al.* (1978), while Wippermann and Gross (1986) have been able to model the development of an initial cone of sand into an equilibrium barchan form.

There are two major stages to dune development modelling. The first is to model wind flow over the dune surface, and the second is to model the sand surface response to this pattern of wind flow. Watson (1987), in discussion of Lancaster (1985), has highlighted the problems of linking these two stages. Lancaster (1985), Livingstone (1986) and Tsoar (1985) have used measures of wind speed in their dune models, but Watson has rightly pointed out that the sand transport rate, and so the erosion and deposition rate, does not correspond directly to wind speed. It is the shear stress exerted by the wind at the sand surface which mobilizes sand particles. Watson has suggested, therefore, that models which relate sand transport to wind speed are inappropriate because surface shear stress is also related to the nature of the vertical velocity profile and to the surface roughness. Bagnold's assumption (1941: 61, equation 10a) was that under steady conditions over flat surfaces of uniform roughness, the wind velocity increased constantly with a logarithmic measure of height, and this assumption of a logarithmic velocity profile has been made by many subsequent studies of dune dynamics. But preliminary results from Lancaster's reply to Watson (Lancaster, 1987: fig. 3) and from Mulligan's (1988) work on transverse dunes indicate that this may have to be modified. Equally it is clear that roughness varies throughout the dune system in response both to changing surface materials and ripple topographies, and to a changing flux of saltating grains.

Watson's argument is that models using wind speed alone to indicate levels of sand mobility imply erosion at the dune crest, because wind speed increases from the foot to the top of the windward slope. If this were the case dunes would be progressively lowered, and there is no mechanism in these models, he suggests, for dune building. It is Watson's contention, therefore, that wind shear must reach a maximum somewhere on the windward slope, and he quotes experimental work by Lai and Wu (1978), who found that maximum shear stress occurred on the steepest windward slopes somewhere below the crest (see also Wilson, 1972: 199, fig. 7).

Two points must be clarified. First, in order for a transverse dune to maintain its form as it progresses downwind, there must be some erosion at the crest, although there may be more erosion in the middle of the windward slope especially if the slope is markedly convex. Sand is deposited at a point immediately beyond the crest in the low pressure zone created by the separation of flow to form the new crest. Second, Watson's suggestion, based on the work of Lai and Wu, of a point of inflection on the windward slope, below which there is erosion and above which there is deposition, brings us no nearer an equilibrium form. His model implies a steepening of windward slopes which would involve no downwind progress of the dune. Fig. 3 is a schematic representation of the dynamics of a windward slope from which it is clear that erosion must occur on the entire windward slope for the dune to progress. Even with a more realistic convex profile *some* erosion is still necessary at the crest, although *maximum* erosion may be midway up the windward slope. Surface shear stress cannot reach a maximum somewhere on the windward slope below the crest as Lai and Wu (1978) and Watson (1987) suggest, although the rate of change of surface shear stress may not be maximum at the crest. Lancaster's (1987) riposte to Watson was to provide data which indicate that erosion does indeed occur at the crest of linear dunes, and this is supported by Livingstone's (1985, 1989) Namib data.

Ascertaining the actual relationship between shear stress and sand mobility, expressed as bulk transport (Q), lies in the realm of the smaller scale, steady state studies of grain mobility. Sarre (1987) has recently reviewed equations linking surface shear and grain mobility, highlighting some of the problems which exist. If surface roughness were constant, and the wind velocity profile remained logarithmic throughout the dune system, then shear stress would be directly proportional to velocity, and we could use wind velocity to indicate surface shear stress. As Lancaster (1987) points out, data such as his own (Lancaster, 1985), Livingstone's (1986) and Tsoar's (1985) provide a good 'first approximation' by using wind speed as a surrogate of surface shear stress. There can be no doubt, however, that 'data pertaining to the variations in shear stress and dQ/dx (spatial changes of bulk transport) under changing aeolian conditions would be of greater value than measurements of wind speed' (Watson, 1987: 515), for the closer we move to white-box models the better.

EQUILIBRIUM FORMS

The overriding assumption of all current, single dune studies is that, providing wind flow patterns are accurately modelled and the link between wind structure and sand movement correctly calculated, it will be possible to show that for a given incident wind there is an optimum dune form. Tsoar, for instance, defined this steady state as occurring when the dune's

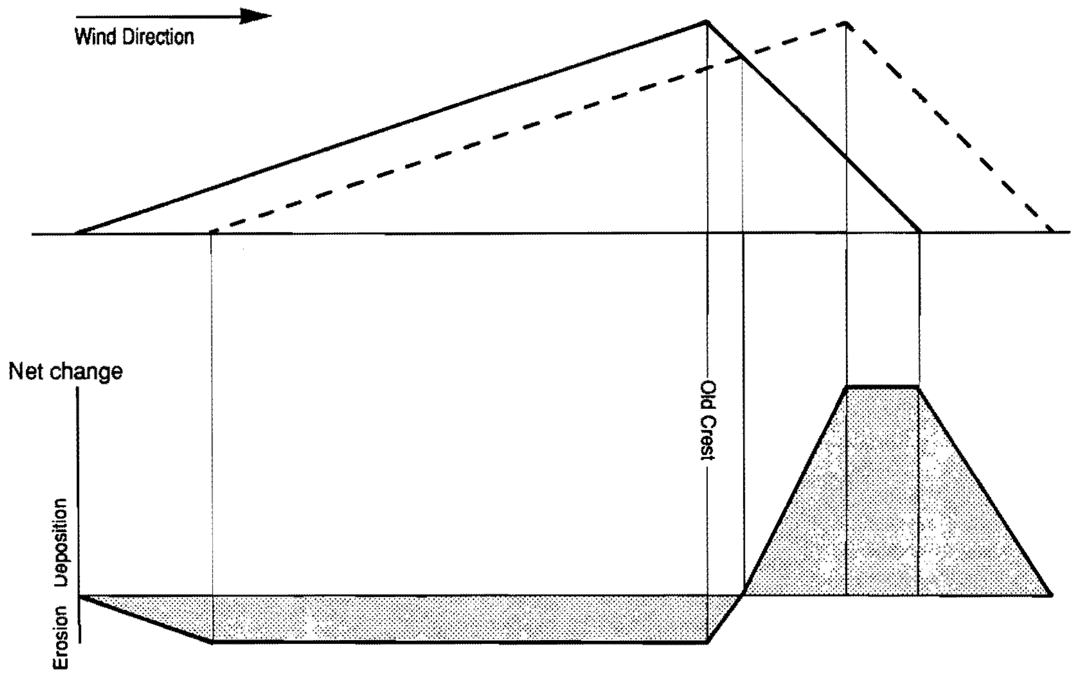

Fig. 3

Schematic representation of the patterns of surface change (erosion and deposition) on an advancing transverse dune. In order for the dune to maintain its form and advance downwind, erosion must occur on the entire windward slope.

'shape, size and profile do not change while the dune is advancing' (Tsoar, 1985: 51). Inherent in this assumption is the concept of a feedback mechanism between dune form and wind flow patterns, creating an equilibrium sand dune form.

This assumption is fraught with difficulties. Sand grain mobility is presumably a more or less immediate response to imposed surface shear stresses. The wind becomes instantaneously saturated with sand. At this smallest, steady scale it is possible to think in terms of dynamic equilibrium. But at the graded scale of individual sand dunes there is a lag time between process and response. If the wind changes direction there is a finite period before the dune is perfectly adjusted to the new wind, and this is acknowledged in theoretical modelling. Wippermann and Gross (1986), for instance, ran their model for 16 'days' before an equilibrium barchan form was achieved.

Warren and Kay (1987) have called the ability of sand dune patterns to 'hold', 'fix' or 'remember' the action of past winds the dune's 'memory' (see also Allen, 1974). All dunes lie between the qualitative extremes of high and low memory. Small dunes reorientate to new winds more quickly than large dunes, and therefore have shorter memories. Warren and Kay argued that the huge linear dunes, or mega-ridges, of the Wahiba Sands in Oman have mega-memories stretching back into the last glacial. It is more likely that their apparently long memories are a consequence of being fixed by vegetation than to long lag times. The case of the Namib dunes is less clear-cut. Besler (1980) has argued that the Namib dunes are also largely inactive today, and are remembering stronger winds of the last glacial. Another possibility is that because of their size they respond slowly and are still adjusting to a change of regime from the one which formed them. Most likely though, is that the Namib dunes are currently active and are more or less an equilibrium response to the present bimodal wind regime (Livingstone, 1989).

Nonetheless, the concept of lag times is crucial to the Tsoar and Livingstone models in which bi-directional wind regimes create linear dunes, and to Warren and Kay's model of dune network dynamics. For these models to operate the dunes must 'remember' the previous season's winds. If not, the dunes would form as a series of transverse dunes normal to the wind, and would reorientate every season. Even in a landform as apparently mobile as a sand dune, the response to a change of process is not instantaneous. Dunes are in quasi- rather than dynamic equilibrium.

Not only are there lag times in a dune's response, but we have as yet no universally accepted criteria for judging whether dunes have reached an equilibrium form. This is similar to the 'which discharge?' question in fluvial geomorphology when considering, for instance, the development of meanders (e.g., Knighton, 1984: 93–94). Clearly, determining whether a dune is in equilibrium with the present regime or merely 'remembering' some past regime is another nettle which must be grasped in future dune dynamic studies.

CONCLUSION

There remains considerable scope for small-scale studies to elucidate the relationship of sand budget to wind regime. The role of meteorologically induced secondary flows, which clearly do exist in desert areas, still needs to be examined. It would be dangerous, of course, to advocate that only small scale, inductive, empirically based studies of dune dynamics should be undertaken, while larger scale deductive models of dune field and erg development are forgotten. All knowledge cannot be derived by induction from particular case studies to universal hypotheses, and there must be some compromise between the multitude of particular cases which could be studied and developing some general rules governing the initiation and development of desert sand dunes. Nevertheless, much progress has been made in the last fifteen years or so by single dune studies, and there is still considerable scope for more to be gained in the future from studies of this nature.

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