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Process-Scaling Issues For Aeolian Transport Modelling in Field and Wind Tunnel Experiments: Roughness Length and Mass Flux Distributions

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ABSTRACT

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This paper examines the scaling impact of wind tunnels on modelling the wind velocity and mass flux profiles for wind blown sand transport. Firstly, a modified Charnock relationship, which describes the relationship between the shear velocity (u_*) and surface roughness (z_0) parameters is used to examine the characteristics of the aeolian transport system for both environments. Both parameters are estimated from the wind velocity profile. Secondly, the influences on the decay rate (or slope) of sand transport away from the surface in the two environments are analyzed. This is done by examining the vertical distribution of mass flux during saltation. This research analyzes results from published experiments in wind tunnel and field environments. A total of 213 wind velocity profiles and 121 mass flux profiles were gathered and analyzed. Results show that surface response to flow differs significantly between wind tunnels and natural beaches. The apparent roughness measured in the field is 6-7 times greater than the roughness measured in the laboratory. The relative proportion of mass flux moving in the near-bed region is much greater for wind tunnel experiments. The findings from this research suggest that multi-scale approaches are paramount to obtaining better transport models.

ADDITIONAL INDEX WORDS: Saltation, velocity profile, exponential function.

INTRODUCTION

At present, modeling of aeolian sediment processes across natural beaches remains rudimentary because of the difficulties in developing deterministic physically-based theories and in measuring the appropriate variables in the field. Transport models developed on the basis of laboratory or field experiments have a number of inherent problems and these have been well documented over the past 40 years (WILLIAMS, 1964; SARRE 1988, SHERMAN *et al*., 1998). Similarly the problems inherent in trying to simulate natural conditions in a wind-tunnel setting have been widely documented by engineers and geomorphologists alike (WHITE and MOULA 1981, GERETY 1985, SPIES *et al*., 1995). In order to ascertain the applicability and/or reliability of any model it is important to assess the model's physical basis and its treatment of the various components of the transport system, and also the assumptions associated with its development.

It is well established in aeolian studies that saltating sand causes windspeed near the bed to decrease and the velocity profile to steepen (i.e. du/dz increase, where u is the time averaged velocity at elevation z above the bed). This modification of the velocity profile is believed to be a fundamental response of a self regulating saltation process in both air and water. Without such physical controls, a saltation layer could grow uninhibited (at an exponential rate) to any height above the surface. Since the concept of a saltation layer was first introduced into transport models by BAGNOLD (1941) and OWEN (1964) workers have attempted to accommodate this important feedback into improved models.

The Saltation "Layer"

OWEN (1964) hypothesized that the saltation layer and roughness parameter are intrinsically related whereby "the saltation layer behaves, so far as the flow outside it is concerned, as an aerodynamic roughness whose height is proportional to the thickness of the layer (p.266)". Owen described the increase in roughness associated with the development of a saltation layer, or "effective" roughness (z_o^1), as a function of the imposed shear velocity, u_*, which was much larger than the roughness of stationary beds; z_0=D/30:

$$z_0{}^1 = C\frac{u_*{}^2}{2g} \tag{01}$$

where C was an empirical constant considered to approximate 0.02 for wind tunnel experiments. He derived this CHARNOCK (1955)-type relationship by assuming the saltation-induced roughness to be proportional to the mean saltation-layer height, which was assumed to be of the order $u_*^2/2g$. He proposed an alternative logarithmic law to describe the mean velocity distribution in a turbulent boundary layer:

$$\frac{u_z}{u_*} = \frac{1}{0.4}\ln\left(\frac{2gz}{u_*{}^2}\right) + D^1 \tag{02}$$

where the quantity D^1, which was established empirically at 9.7, is equivalent to setting the proportionality constant (C) between roughness height during saltation (z_o^1,) and $u_*^2/2g$ at 0.02. This expression gives results in good agreement with wind tunnel experiments by RASMUSSEN and MIKKELSEN (1991), where C approximates 0.022. Subsequently, SHERMAN (1992) noticed that there appeared to be systematic differences between laboratory and field-based estimates of the C proportionality constant (see Table 1). This is a good indicator that there may exist fundamental differences, probably related to the scaling constraints of laboratory conditions, between the surface/airflow interactions in wind tunnels and natural environments. These differences are explored in the first part of this paper using a modified Charnock relationship as a basis for comparison. This was derived by changing the parameterizations of the shear velocity and roughness length similar to that described in SHERMAN (1992). SHERMAN (1992) modified Charnock's relationship to reflect sediment conditions and suggested that a modified Charnock relationship was more physically correct:

$$z_0{}' - \frac{2D_{50}}{30} = C(u_* - u_{*t})^2 \tag{03}$$

where D_{50} is mean grain diameter, assumed to be the primary control on roughness without saltation. For this relationship, C was estimated to be 0.0252 based on an evaluation of mostly published laboratory studies. The variation of u_*^2 explains over 70% of the statistical variation in z_o. SHERMAN (1992) found that the that the low probability estimate for this relationship ($p<0.001$) "suggests that it is not fortuitous, and an equilibrium adjustment between the wind field and sediments is obtained (p.425)". BAUER *et al*., (2004) compared models used to predict the variation in surface rougness length as a function of shear velocity during aeolian transport and found that Sherman's modified relationship provided more accurate results than those predicted by BAGNOLD (1941), OWEN (1964) or CHARNOCK (1955).

In a review of the performance of the commonly cited transport models, SHERMAN *et al*., (1998) noted that attempts to model the development of coastal dunes using process-based models of sand transport cannot produce results of a quality greater than that produced by the individual model components. To address this challenge researchers have dismantled the saltation process into several component processes such as entrainment, particle trajectory, wind field modification, and grain-bed collision. These component processes are, to a large degree, well understood with the exception of grain-bed collision which have remained resistant to theoretical treatment (NAMIKAS, 2003). This process, for which stochastic 'splash' functions have been developed, exerts a major influence on modeled saltation path heights and lengths by assigning particle launch velocities and angles. The influence of trajectories is in turn reflected in the simulated distribution of mass flux with elevation above the bed, and with distance from a fixed point. Thus implies that a thorough understanding of the distribution of mass flux may be key to further refining the numerical models of saltation (NAMIKAS, 2003). Reported values of flux in wind tunnel studies suggest that the proportion of sediment moving in the near-bed region ranges from 80-90% below 2cm (BUTTERFIELD, 1993; RASMUSSEN and MIKKELSEN, 1998); 75% below 1.3cm (GILLETTE and Walker, 1973) and 50% below 1cm (CHIU, 1972; ZINGG, 1953) or 1.5cm (GERETY, 1984). Again systematic differences between these values and equivalent field derived proportions of transport fluxes suggest fundamental differences occur between the two environments. The differences in reported distributions of mass flux in wind tunnels and field experiments is the focus of the second part of this paper.

METHODS

A large part of the data for this study was obtained from published papers and reports. Data that met one of the following two criteria were gathered: (i) wind velocity profiles that allowed estimates of shear velocity and surface roughness to be calculated and applied to the Modified Charnock relationship and, (ii) mass flux profiles that quantified the vertical distribution of saltating particles during transport using stacks or arrays of sediment traps.

Wind Velocity Profiles

A data set comprising 213 wind velocity profiles was assembled with 134 velocity profiles from laboratory studies (BAGNOLD, 1936; BELLY, 1961; CHEPIL, 1945; GERETY, 1984; HORIKAWA *et al*., 1984; HORIKAWA and SHEN, 1960; KADIB, 1965; LI and MARTZ, 1995; SPIES *et al*., 1995; WALKER, 1981; WILLETTS, 1983; ZINGG, 1953; BUTTERFIELD, 1993) and three published field data sets (BAGNOLD, 1936; RASMUSSEN *et al*., 1985; SVASEK and TERWINDT, 1974) and three field experiments (AMELAND, HOLLAND 1996; CASTROVILLE, CALIFORNIA 1993; INCH, IRELAND 1994). All wind profile data, with the exception of those gathered experimentally, were obtained from electronic digitizing of graphs from the published reports.

These data were then subjected to three "quality" control tests for the purposes of our Charnock relationship analysis. These criteria include:

1. Was fully developed saltation occurring? Transport is predicted when the measured shear velocity exceeds the threshold shear velocity (u_{*t}) for any particular sediment size. The threshold shear velocity was calculated using Bagnold's threshold expression and then directly compared with the shear velocity value for the same profile. Profiles where $u_*<u_*t$ were eliminated from the analysis.
2. Was the sedimentologically-based roughness, $2D_{50}/30$, less than the velocity profile derived roughness? For the purposes of this study, it is assumed that if active sand transport is occurring, the aerodynamic roughness length (z_{os}) should exceed the static, grain-induced roughness of a stationary bed ($2D_{50}/30$). Any profiles that didn't meet this requirement ($z_{os} < 2D_{50}/30$) were eliminated.
3. Was the r^2 value of the best fit regression line of a velocity profile equal to or exceed a value of 0.99. This is to minimize errors, introduced through line fitting, in our estimates of u_* and z_o - especially the latter. Errors may derive from many different sources, e.g. digitizing of the published velocity plots, instrument reading errors, design set up of experiment. A true representative velocity gradient is vital for these studies as both the shear velocity (u_*) and roughness length (z_o) are estimated from this relationship. The r^2 value gives an indication of the correspondence of individual profiles with the law of the wall and thus a good indicator of how accurate our estimates of shear velocity (u_*) and roughness length (z_o) are.

Mass Flux Profiles

In order to examine the behavior of the saltating particles during laboratory and field experiments, a data set incorporating 16 different experiments was gathered using either digitizing tools or curve fitting techniques. These sources included data from published wind tunnel experiments (KAWAMURA, 1951; WILLIAMS, 1964; GERETY and SLINGERLAND, 1983; MIKKELSEN, 1989; SORENSEN, 1992; RASMUSSEN and MIKKELSEN, 1998; ZOU *et al*., 2001; Dong *et al*., 2003; NI *et al*., 2002) and field investigations (RASMUSSEN *et al*., 1985; MIKKELSEN, 1989; GREELEY *et al*., 1996; NAMIKAS, 1999). This data set was supplemented with mass flux profiles measured during two separate field investigations: GUADALUPE, CALIFORNIA (1995) and AMELAND, HOLLAND (1996). A total of 121 mass flux profiles were gathered.

A number of steps were taken to assemble a set of mass flux profiles that was deemed suitable for analytical purposes. These included choosing an appropriate height to best represent the trap (geometric mean *vs*. logarithmic height *vs*. top or bottom trap heights); converting to a standardized unit of flux ($g/cm^2/s$); and normalising the flux data by total flux to allow comparison.

In this case the sediment flux recorded in each individual trap after each test run (q_z) was divided by the total mass flux of sediment ($SUM(q_z)$). This allowed the relative mass flux (RMF) with elevation above the surface for each test run to be calculated ($q_z/SUM(q_z)$). Final versions of the adjusted, normalized values for the data were plotted.

RESULTS AND DISCUSSION

Velocity Profiles and Charnock Relationships

The data gathered here were plotted following the implementation of the three quality control methods. This resulted in a loss of 52 laboratory profiles and 12 field profiles. The modified Charnock relationship (Equation 3) is plotted in Figure 1 for the sets of laboratory and field data. The axes were logged because the data span several orders of magnitude for both parameters. From this analysis a number of observations can be made:

1. The two data sets are statistically distinct. A difference of means test (t-test) indicates that there is less than a 1%

Table 1. *Published values of Charnock Constant (C): where $z_o' = C u_*^2/2g$*

C	Investigator	Environment
0.028	Mikkelsen (1989)	Wind tunnel
0.02	Owen (1964)	Wind tunnel
0.022	Rasmussen & Mikkelsen (1991)	Wind tunnel
0.0252	Sherman (1992)	Wind tunnel, Beach
0.1	McEwan (1991)	Numerical Model
0.14	Rasmussen *et al*., (1985)	Beach
0.18	Rasmussen *et al*., (1985)	Beach

probability ($P < 0.01$) that the Charnock constants are derived from the same population.

2. Values of r^2 obtained for these data sets are both significant at 99.9% confidence level as well as the differences in the slopes of the least squares line.
3. The basic Charnock relationship is not entirely applicable to a saltating sand system. The modified Charnock relationship is more physically representative of a saltating system (i.e. it incorporates a threshold term and better illustrates the dependence of z_0 on varying values of u_*).
4. The statistical explanation of enhanced roughness decreases substantially for the field data (r^2 drops from 76% to 56%). Although the predictive power of the field relationship is reduced the parameterization contains more physical information.
5. For the modified Charnock relationship, the response of the two systems is similar only for very low excess shear velocities (u_*-u_{*t}).

RAUPACH (1991) investigated the applicability of the Charnock relationship to the saltation process on natural beaches and found the Charnock constant was strongly dependent on the shear velocity. Raupach derived an analytical expression based on a modified form of the Charnock equation that treats the saltation layer as a dynamic system. This modified Charnock equation predicts that the saltation related roughness (z_{os}) is a weighed mean of the undisturbed roughness length (z_o) and a length ($Au_*^2/2g$) proportional to the characteristic height of the saltation layer:

$$C = \frac{z_{os}}{u_*^2/2g} = A^{\sqrt{1-r}} \left(\frac{z_{os}}{u_*^2/2g} \right)^{\sqrt{r}} \tag{04}$$

where $A = 0.22$, $r = u_{*t}^2/u_*^2$, for $u_* > u_{*t}$, and $r = 1$, for $u_* < u_{*t.}$

The modified Raupach (1991) relationship predicts results similar to those found in the first part of this study in the sense that roughness lengths measured in wind tunnels are under-predicted. The variability in *C* is clearly illustrated in Figure 2 which also reaffirms the scaling difference between the two environments. The Raupach relationship also gives a clear indication of the variation in the predicted value of the Charnock constant. These relationships indicate that further investigation of the *C* value is necessary before the Charnock relationship can be fully used (see Butterfield, 1993) e.g. can the scatter be explained by some grain size-sorting parameterization or wind unsteadiness?

Mass Flux Profiles

Recent approaches to incorporate the distribution of the saltation trajectory population into numerical models have re-iterated the need to accurately model the vertical and horizontal distribution of mass fluxes. Reliable prediction of mass flux is necessary for verification of computer models and the calibration of theoretically derived flux equations.

In general it is accepted that the amount of sediment in saltation rapidly decays away from the surface. The most commonly cited relationship for mass flux takes the exponential form:

$$qz = ae^{bz} \tag{05}$$

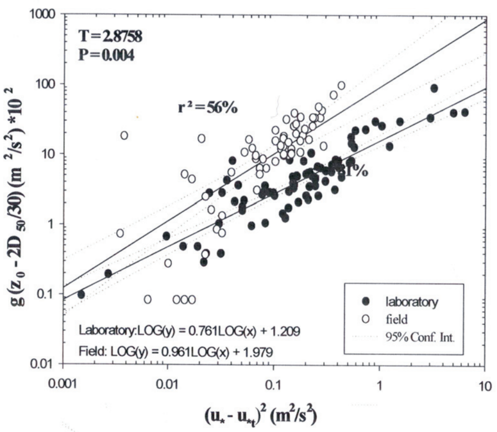

Figure 1. Modified Charnock relationship for laboratory and field data. Data has been 'quality-controlled' using described criteria.

where q is the measured flux at height z above the bed, and *a* and *b* are regression coefficients. Different forms of exponential expressions have been presented e.g. WILLIAMS, 1964; GREELEY *et al*., 1996; DONG *et al*., 2003; NAMIKAS, 2003; NI *et al*., 2002. Other functions have also been proposed including a modified power function (ZINGG, 1953) and logarithmic function (RASMUSSEN and MIKKELSEN, 1998). Vertical and longitudinal distributions are closely related to the modes of sand transport. Thus, it would be expected that saltation studies should use similar functions to fit to the observed transport. The range of relationships for observed fluxes suggests there may be experimentally derived controls on sand transport.

The mass flux profiles can be analyzed (and compared) by assessing (1) the decay rate of sediment load away from the surface, (2) the environmental controls affecting the amount of sediment in transport, and (3) the fitted functions derived to parameterize the measured mass flux. The regression coefficients derived from the regression analysis of the commonly cited exponential functions represent a scaling factor for "a", and the rate of decay (or slope) of the flux for "b". Intuitively one would expect that the only difference between measured flux profiles for a range of different wind speeds should be a scaling factor if surface properties are consistent. This is best illustrated by normalizing the flux profiles taken at different wind speeds. Figure 3 is a plot of the published data reported by of GREELEY *et al*., (1996) for a field study and WILLIAMS (1964) for a wind tunnel experiment. The same profiles were normalized by the total flux rate and re-plotted in Figure 3. The profiles for each study converge to similar slopes. This occurs as the influence of the "a" coefficient is removed from the exponential function.

From these analyses a number of points are apparent. Firstly, the results confirm that more sand is transported at any given height as wind speed increases. However, the same proportion of sediment moves at any given elevation with a range of windspeeds. This infers that more grains follow the same set of trajectories and the saltation layer becomes denser.

Secondly, although the profiles converge to similar slopes some scatter is evident. This should be expected for field-based studies where spatial and temporal controls on measured fluxes are important. Further, there is no control on surface properties and the development of features such as lag deposits will influence mass flux. Still, the results confirm findings of previous studies that found slopes of the mass flux profiles do not vary with wind speed to a significant degree. This suggests that the vertical distribution of flux is independent of wind speed, or any dependence is so weak as to be obscured by natural variability and/or measurement error (NAMIKAS, 2003).

Numerous workers have carried out extensive wind tunnel experiments (e.g. DONG *et al*., 2003; NI *et al*., 2002; and SHAO and RAUPACH, 1992) to examine surface controls on flux distribution. The influence of grain size and fetch were perceived as having a strong influences on the slope of the

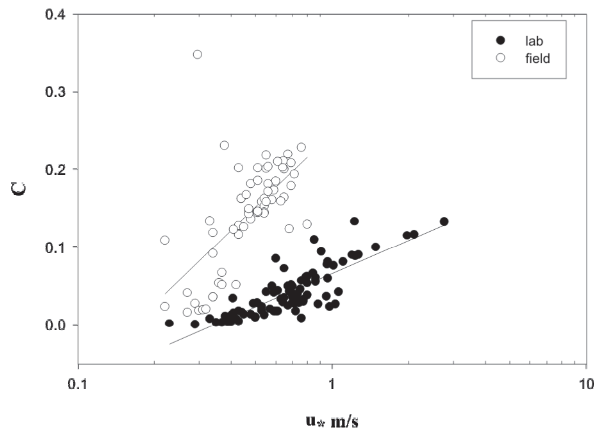

Figure 2. Comparison between the values of C for laboratory and field data using the Raupach derived Charnock relationship.

profiles. The influence of grain size is illustrated in Figure 4 which shows normalized plots from DONG *et al.*, (2003). These authors examined the decay rate of saltating sediment above the surface using a series of test runs with varying grain size and wind speeds. Three sets of test runs are shown. Each set comprises mass flux measurements during four different wind speeds (16, 18, 20, 22m/s). The three sets varied in sediment sizes from 0.8-1.0mm, 0.4-0.5mm and 0.1-0.15mm. The profiles are normalized as before to account for scaling differences between windspeeds.

The normalized profiles converge as the scaling influence of the "a" coefficient is removed. However this convergence only occurs for profiles measured with similar grain sizes. The three sets of profiles clearly have different slopes that are strongly dependent on grain size. Steeper slopes are measured with the coarser grain size ranges.

For field experiments the impact of grain size is less apparent. The variation in the field slopes can be attributed to any number of factors such as experimental error, spatial and temporal boundary-layer development, transport intermittancy or unsteadiness, or mixed grain populations. The difference in slope values seen in RASMUSSEN *et al.*, (1985) cannot be attributed to experimental procedure (as very similar traps were used) but probably stems from changes in surface properties as the results were from two different field sites with mean grain sizes of 0.26mm and 0.30mm.

The variation in flux profile slopes between different experiments may offer important insight into model performances. As previously stated many fitted functions for mass flux have been suggested. Recently, more efficient and less obstructive 'trapping' or 'counting' devices and mathematical models have shown that the near-bed flux distribution deviates from the standard exponential relationship. NAMIKAS (2003) reported that the exponential profile consistently under-represents the flux within the lowest 1cm by about 33% of the measured value. Interestingly this may offer a valid argument for RASMUSSEN and MIKKELSENS' (1998) logarithmic fit to wind tunnel flux data. These authors state that 90% of the flux moved below 20mm. This very large figure suggests that laboratory models models may not be comparable to field conditions where near-bed proportions of flux are much smaller.

MIKKELSEN (1989) found that similar type traps produced different mass flux profiles for laboratory and field experiments. He found that the laboratory profile had much more sediment moving nearer the bed. He suggests (p.22) that "a sand composition could explain the discrepancies, which may, however, also emanate from a real difference between flux profiles in nature and wind tunnel". It is reasonable to suggest, especially after examining the Charnock relationship, that wind tunnels constrain the ability of particles to attain maximum or "true" trajectory paths during equilibrium saltation. Figure 5 shows the regression-derived slope values for the RMF for the gathered mass flux experiments (open symbols indicate lab

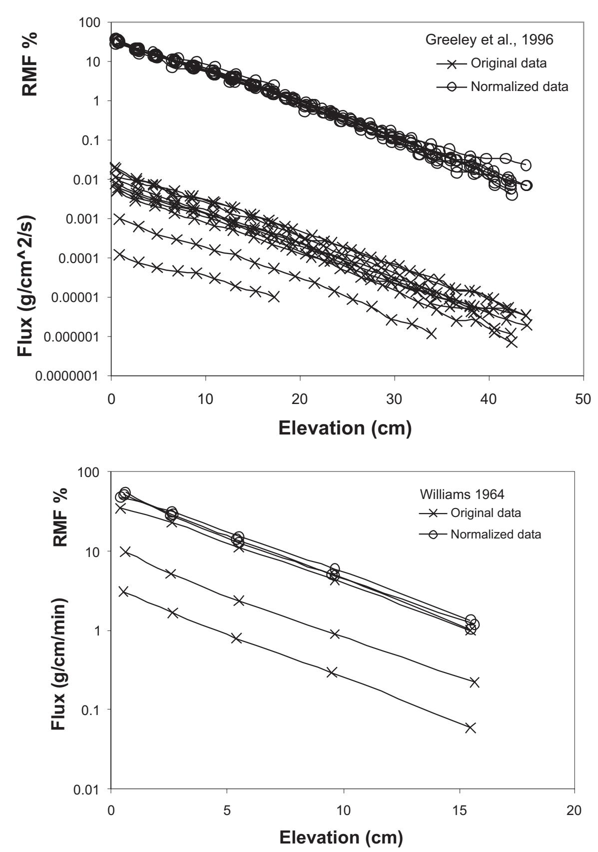

Figure 3. Published and normalised flux profiles of WILLIAMS (1964) and GREELEY *et al.*, (1996).

Experiments and solid symbols indicate field data). In most cases in was possible to also plot a mean grain size for the experiments. This analysis suggests that the mass flux profiles measured in wind tunnels are much steeper than those measured in field experiments for the range of grain sizes commonly reported in aeolian experiments (0.1-0.3mm). Moreso, the laboratory results appear to be influenced by wind tunnel height. The experiments of DONG *et al.*, (2003) and NI *et al.*, (2001) were carried out in a working section 1.2m high, whereas all other tunnels did not exceed a height of 0.5m. This may explain the slopes from these experiments that are closer to field slopes for similar grain sizes.

Quantitative analyses comparing mass flux experiments are difficult due to the large number of potential controls (e.g. surface properties, tunnel dimensions, trap attributes, boundary layer structure). However this analysis suggests that further investigations may provide useful information for refining current models and improving the predictive performance of the next series of aeolian transport models.

CONCLUSIONS

Wind tunnel experimentation is an important method in developing aeolian transport models. However, surface response to flow differs for wind tunnels and natural beaches. The apparent roughness measured in the field is 6-7 times greater than the roughness measured in the laboratory. The difference between the estimated roughness in the laboratory and field parameters increases with greater excess shear velocities.

Existing models of mass flux distributions suffer many limitations. These include: the use of fitted functions in which the significance of the key parameters have not been defined (which limits extension of these functions); the inherent difficulty in comparing different experiments due to the influence of surface properties on the distribution of mass flux; the validity of extrapolating flux measurements using

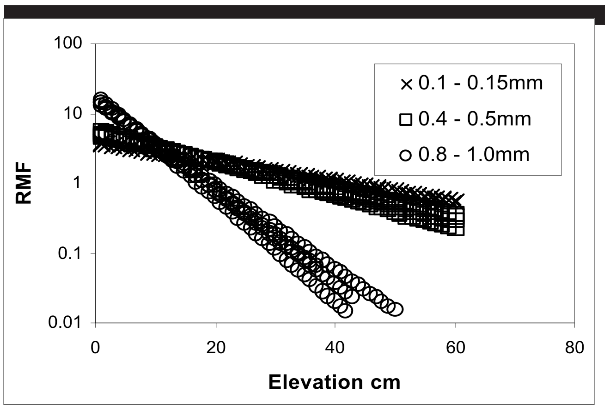

Figure 4. Normalized flux profiles of DONG *et al*., (2003).

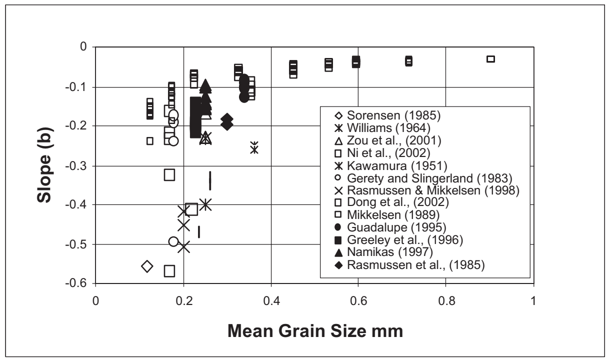

Figure 5. Mean grain size vs. Decay rate of mass flux.

datapoints well above the bed is uncertain because it assumes that there is no change in the flux gradient as one approaches the bed. Beyond these difficulties there appears to be a more fundamental problem regarding process-scale for experiments carried out in wind tunnel and field environments. Namely, the results of this study clearly indicate that scaling differences exist between the two environments. The underlying causes of these differences need to be identified and addressed, which stands as a key need in linking laboratory and field-based approaches to aeolian transport modelling.

The findings from this research suggest that fundamental corrections to existing models are required i.e. a re-assessment of the theoretical development and underpinnings of the models as well as a re-assessment of the associated empirical calibrations. More specifically, the response of surface particles to the flow in wind tunnel and field environments (a fundamental parameter in some classes of transport models) needs to be re-addressed. Universal transport functions must be specified to obtain commensurability between laboratory and field studies, or multi-scale approaches are necessary if an "unequivocally best" transport model is to be developed.

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