Environmental Fluid Mechanics (2006) 6: 359–384
DOI 10.1007/s10652-005-6021-8

Modeling Flow Patterns in a Small Vegetated Area in the Northern Chihuahuan Desert using QUIC (Quick Urban & Industrial Complex)*

GEORGE E. BOWKER[a,*], DALE A. GILLETTE[b], GILLES BERGAMETTI[c] and BÉATRICE MARTICORENA[c]
[a] *National Exposure Research Laboratory, Atmospheric Modeling Division, U.S. Environmental Protection Agency, MD-81, Research Triangle Park, NC 27711, USA*
[b] *Air Resources Laboratory, Air-Surface Processes Modeling Branch, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, MD-81, Research Triangle Park, NC 27711, USA*
[c] *Laboratoire Interuniversitaire des Systèmes Atmosphériques, UMR CNRS 7583, Universités Paris 7-Paris 12, Créteil, France*

Received 24 August 2005; accepted in revised form 20 December 2005

Abstract. Sandstorms are frequent in the northern Chihuahuan Desert in New Mexico, an area characterized by open areas lacking vegetation, individual mesquite bushes, and mesquite coppice dunes. Field measurements of sand fluxes and wind velocities over a two year period provided a description of the area – suggesting that the "streets", the flat, elongated, non-vegetated areas aligned with the dominant wind directions are the principal sources of wind-dispersed soil and dust. However, since soil erosion and dust movement depend on the pattern, strength, and gradients in the wind field, modeling soil erosion and dust movement requires a continuous wind velocity field. Consequently, air flow patterns at this site were simulated using a semi-empirical mass-consistent diagnostic wind field model: QUIC version 3.5 (Quick Urban & Industrial Complex). Two hundred and fifty-one simulations were run encompassing several dust storms occurring in April 2003. Wind velocity vectors were compared between the model and field data at three heights for six locations and were found to correlate well for a majority of the situations suggesting that the flow patterns are consistent throughout the domain. In particular, good agreement was found for wind speeds at 0.75 m, the height for which the model was tuned. However, it overestimated velocities at 1.5 m (10%) and 3.15 m (13%).

---

*The research presented here was performed under the Memorandum of Understanding between the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) and under agreement number DW13921548. This work constitutes a contribution to the NOAA Air Quality Program. Although it has been reviewed by EPA and NOAA and approved for publication, it does not necessarily reflect their policies or views. U.S. Government right to retain a non-exclusive royalty-free license in and to any copyright is acknowledged.

*Corresponding author, E-mail: bowker.george@epa.gov

Generally, the model successfully identified locations of the highest wind velocities and wind stresses, predominately found in “streets” aligned with the driving wind, and locations of wake flow downwind of mesquite bushes where there was separation flow or otherwise shelter from the wind.

Key words: Chihuahuan Desert, desert vegetation, mesquite, sand transport, wind modeling, wind steering

1. Introduction

The production, transport, and deposition patterns of dust and soil in arid and semiarid regions influence processes from the local distributions of flora to the biogeochemistry of the soil [1]. Within the arid ecosystem found at the Jornada Experimental Range (JER) in the northern Chihuahuan Desert in the southern region of New Mexico, the landscape is a mix of mesquite bushes (*Prosopis glandulosa*) and coppice dunes interspersed among elongated vegetation-free sandy-soil patches, or “streets” oriented along the dominant wind direction [2]. This is a dramatic change from the flat semiarid grassland present 150 years ago. The form of the landscape, the nature of the soil, and heterogeneous distribution of plants appears to be affected by wind processes [2]. Dust and sandstorms are common in this region, and carry substantial amounts of soil, eroding the soil in some locations and depositing it on the down-wind edges of the coppice dunes and in other locations.

To clarify causes for accelerated sand movement in mesquite dominated ecosystems, field measurements of wind velocity profiles and net sand flux were made around the dunes and on the flat, elongated, bare soil during the spring of 2003 at a site called “Oriented” in the northern part of the Chihuahuan Desert (Figure 1, top) [3]. These measurements were motivated by findings of Gillette and Pitchford [4] at this site showing that the open “streets” are the most important areas for active sand movement.

The field study showed that the site was heterogeneous with respect to wind velocity patterns, and that these patterns varied with wind direction. Linking wind velocity patterns with the dust collected during the windstorm requires a complete velocity field for each time. The distribution of mesquite plants and coppice dunes and velocity measurement locations (masts and towers) are shown in the top of Figure 1. The focus of this paper is to develop a computer simulation capable of producing a complete velocity field for the “Oriented” test site.

QUIC (Quick Urban & Industrial Complex, version 3.5) is a fast-processing mass-consistent, semi-empirical wind field model being developed by Los Alamos National Laboratory and the University of Utah [5–7]. QUIC does not attempt to solve the Navier–Stokes equations. It applies an input vertical boundary layer to empirical formulations of the flow around blocks or

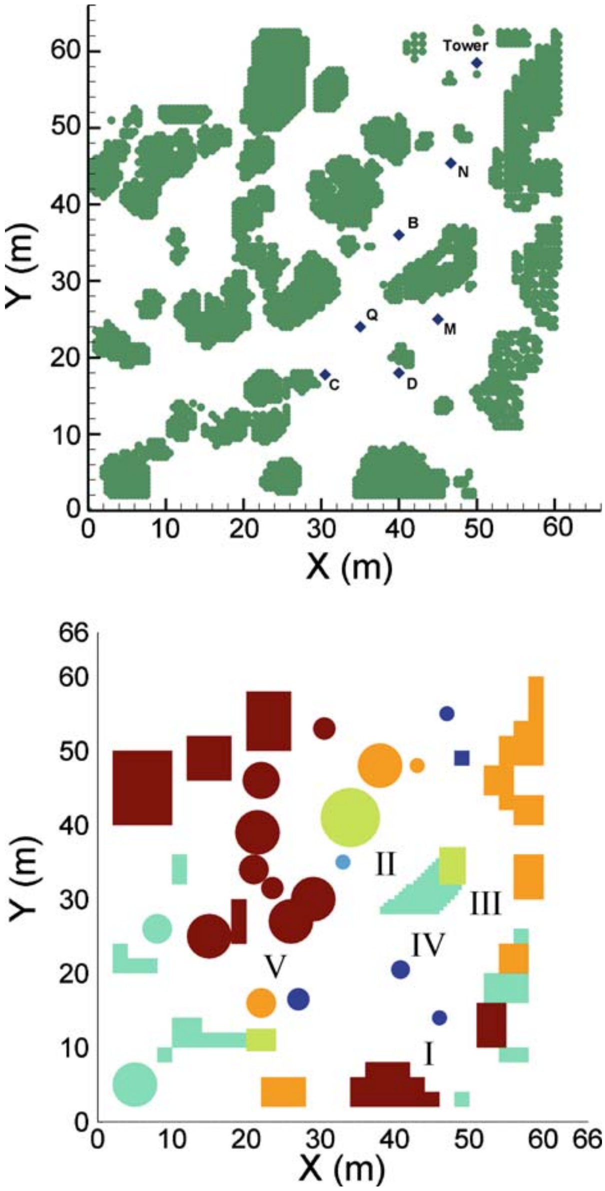

Figure 1. Overhead representations of the "Oriented" study domain in the field (top) and in QUIC (bottom). For the top figure, the location and extent of mesquite bushes and coppice dunes are shown with green circles. Mast positions and the 15 m tower are denoted by blue diamonds labeled with a capital letter (B, C, D, M, N, Q, and Tower). For the bottom figure, the location and extent of mesquite bushes and coppice dunes are shown as rectangular or cylindrical objects. The color of the object is related to the height (red 2 m; orange 1.5 m; yellow/green 1.25 m, light blue/green 1 m, medium blue 0.75 m, dark blue 0.5 m). Sub-regions are noted by roman numerals in the bottom figure.

cylinders. Then, the model forces mass-conservation throughout the volume of the domain. Primarily, QUIC is used to model wind flow and dispersion patterns in complex urban areas defined by regions of tall buildings and street canyons situated on flat terrain. The terrain at the "Oriented" site, while at a different size scale, appears to be of similar complexity and form – large blocks of mesquite bushes and dunes separated by open patches of flat sandy soil.

Like computational fluid dynamics models, QUIC produces ensemble averaged solutions at uniform locations throughout a gridded domain containing the geometry of interest. QUIC has seen broad application, primarily in modeling wind flow and dispersion patterns in built-up urban areas [8]. Its fast (seconds to minutes) processing and detailed solutions make it ideal for examining multiple scenarios such as how flow patterns change within a domain for small changes in wind direction. Evaluating whether the model successfully simulates flow patterns in the domain requires substantial direct comparisons between wind velocity measurements at the locations measured in the field.

Wind properties were measured at nine locations (one 15 m meteorological tower and eight 3 m masts), dispersed throughout the "Oriented" study site (a roughly 60 m by 60 m region). The 15 m meteorological wind tower placed at the site measured large-scale wind properties using five cup anemometers, two temperature sensors, and two wind vanes. The eight 3 m masts, called B, C, D, M, N, O, P, and Q, collected additional wind data at locations considered to be typical of different flow regions within the terrain. Figure 1 (top) shows the locations of the six masts used for comparisons in this study. Each mast measured wind speeds at three heights and wind direction at one height.

For each time period at each mast location, a friction velocity (u_*, m s^{-1}), roughness length (z_0,m) and aerodynamic displacement height (d, m) were found by fitting the velocity measurements as a function of height using the standard logarithmic velocity profile equation:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right), \tag{1}$$

where κ is Von Karman's constant (nominally taken to be 0.4) and z is the reference height for the wind speed. The resulting parameters varied between locations and changed with time (which corresponded to changes in wind direction). The friction velocity is related to the shear stress (τ):

$$u_* = \sqrt{\frac{\tau}{\rho}}, \tag{2}$$

where ρ is the density of the air (1.2 kg m^{-3}).

The results of the field study suggest that the wind interacts with the landscape, and that the resulting wind flow patterns are indeed helping to further shape the landscape [3]. For example, the field measurements showed wind direction "steering" of 1.47 m high winds by the mesquite bushes and coppice dunes by up to 20 degrees. Furthermore, within the streets, regions of accelerated flow were seen – reinforcing the idea that these areas are the source of the wind-dispersed sediments. With respect to airflow patterns, the area can be characterized by three distinct flow regimes:

(1) Street flow: For times and areas where strong sand movement is taking place, these areas are found to have aerodynamic displacement heights (d) of zero and aerodynamic roughness heights (z_0) less than 0.06 m.

(2) Interference (interactive) flow: Areas of mesquite streets downwind of mesquite bushes or coppice dunes for distances between 10 and 20 heights of the dune or bush have $d = 0$ and $z_0 > 0.06$ m. That is, aerodynamic roughness is larger for this range of distances downwind of mesquite than for distances larger than 20 times mesquite height.

(3) Wake flow: In zones that are immediately downwind of mesquite bushes or coppice dunes (upwind roughness) to a distance of roughly 10 times the height of the mesquite plant or coppice dune, there is either a separation flow, or a zone of non-zero d. The wind velocity is smaller than in streets, with large deviations (up to complete reversal) in wind direction compared with that of the tower. Consequently, in these wake zones, sand fluxes were much smaller than in the other two categories.

While the field measurements indicate that the area is highly heterogeneous with respect to wind zones, the complete velocity field is needed to characterize the flow patterns for the entire area and to have the density of simulation points necessary to model wind erosion. The flow around sand dunes and the effects of plants on air flow patterns have been modeled, for example, by Musick and Gillette [9], Raupach *et al.* [10], Wyatt and Nickling [11], Lancaster and Baas [12], Grant and Nickling [13], Gillies *et al.* [14], Frank and Kocurek [15], Lancaster *et al.* [16], Nickling and McKenna Neuman [17], Walker and Nickling [18] and Parsons *et al.* [19]. While showing that form, orientation, and size can dramatically influence resulting air flow patterns, this study examines flow within a field of mesquite coppice dunes, with an emphasis on interdune regions.

For neutral atmospheric boundary layers over relatively uniform surfaces, friction velocity, or the shear stress at the surface (u_*), and the corresponding aerodynamic roughness length (z_0) can be used to characterize the shape of the velocity gradient [20]. Differences in the terrain between locations (e.g. mesquite coppice dunes compared with flat sand) affects the velocity profile of the atmospheric boundary layer and, thus, u_*

and z_0. At the "Oriented" site, u_* and z_0 were calculated from wind profile measurements at the 15 m meteorological tower and were found to be approximately 1.00 m s^{-1} and 0.066 m, respectively. These values represent the integrated area response of the velocity gradient to perturbations from upwind dunes, bushes, and open "streets". For a different site, called the "Scrape" site, located near the "Oriented" site, the velocity gradient was much steeper, characterized by a u_* and z_0 of 0.25 m s^{-1} and 0.00035 m [21]. The "Scrape" site has a similar surface texture with nearly identical soil composition to the "Oriented" site, but devoid of vegetation and large coppice dunes. The values for the "Scrape" site are in agreement with wind tunnel measurements of u_* and z_0 over loose sand [22].

The roughness length describing the velocity gradient at "Oriented" varied with height and location, and was influenced by the extent and proximity of upwind roughness. For example, within the streets, within the first few centimeters of the ground, the apparent roughness is caused by pebbles and small bits of debris. The roughness length necessary to match the velocity gradient at these heights is on the order of millimeters. However, slightly higher above the ground for those same locations, mesquite bushes upwind (tens of meters away) influence the flow, and a "best-guess" roughness length is on the order of a few centimeters. Even higher, above the mesquite bushes and coppice dunes, presumably well above the influence of any particular obstacle, the roughness length is on the order of 0.1 m, on the order of a tenth of the average roughness element height [3].

The fact that the threshold friction velocity was four times larger at "Oriented" than at "Scrape" site, which had similar soil but no vegetation or dunes, was interpreted as being caused by partitioning of momentum. That is, the momentum needed to move the soil at the "Oriented" site was apportioned as follows: 15/16 $(1-\{0.25\,\mathrm{m\,s^{-1}}/1.00\,\mathrm{m\,s^{-1}}\}^2)$ of the momentum was transferred to the bushes and dunes while 1/16 $(0.25\,\mathrm{m\,s^{-1}}/1.00\,\mathrm{m\,s^{-1}})^2$ of the momentum was transferred to the soil and available to initiate soil movement. In effect, we assume that the roughness length measured near the surface of the soil (in a shallow wind profile) is the same as the roughness length measured for an identical soil lacking the vegetation and coppice dunes in a deeper wind profile.

If momentum is being transferred to mesquite bushes and dunes prior to reaching the ground, the resulting wind velocity gradients at the "Oriented" site will not be simple log-linear profiles. It is possible that the velocity gradient at each location could be described as a composite of several "internal" boundary layers, with each segment characterized by a constant (but different) "apparent" u_* and z_0. Thus, the apparent friction velocity and z_0 may vary as a function of height within a heterogeneous domain. One purpose of this investigation is to find the differing sets of friction velocity and aerodynamic roughness length necessary for the QUIC model to match wind speed data taken at different locations and heights in the "Oriented" site. That is, we assume that there are different boundary layers depending mainly on height. Then we fit roughness lengths to adequately reproduce the observed wind speed at each observation height and finally evaluate how well a single roughness length can characterize the entire domain for a single height.

With respect to modeling sand movement, matching velocities using a single roughness length would be best done for a height just above the saltating sand layer, where all vertical transfer of momentum goes to sand movement [23]. Since this height is variable but always lower than 0.75 m [21], we have focused on matching velocities at the 0.75 m height (the lowest height of available wind velocity measurements at the field site).

The goals of this study are fourfold: (1) we will evaluate whether the QUIC model is able to adequately simulate wind velocity fields for the "Oriented" site. Once confirmed that the model adequately describes the air flow patterns throughout the domain, the goals will be to identify: (2) locations of wake zones behind mesquite bushes and coppice dunes, where wind speeds and directions are substantially different than ambient and are primary locations of sand/dust deposition rather than entrainment; (3) locations of the fastest flow, surface shear stresses (and friction velocity u_*, $\mathrm{m\,s^{-1}}$), and the corresponding shapes of the velocity profiles; and (4) how momentum partitioning, roughness length, and apparent friction velocity vary with height.

2. Materials and Methods

QUIC simulations were run for 10 min wind velocity averages (from the onsite meteorological tower) for a 66 m by 66 m by 5 m high section of the "Oriented" study area (Figure 1, top, described by Gillette *et al.* [3]). The areas occupied by mesquite bushes and coppice dunes are shown with green circles. Open areas, or those areas lacking green circle symbols, are open, relatively flat, and free of vegetation. Locations of wind velocity measurements are marked with blue diamonds and are labeled with capital letters (B, C, D, M, N, Q, and Tower) (Figure 1, top). During the spring dust storms, the wind ranges primarily from the South to the West [3].

Within the QUIC model, the domain was constructed of cubical grid cells (0.25 m on a side), with velocities output at the center of each cube (0.125 m being the center of the first grid cell). The wind directions used in this study are referenced to the arbitrary grid system established at the "Oriented" site in 1999 which is 10 degrees less than the "true" directions reported by Gillette *et al.* [3]. QUIC calculates wind field patterns using mass-consistency (continuity) imposed on empirically-based solutions for the flow patterns around isolated rectangular or cylindrical obstacles. It requires a vertical input profile of wind speed. The “Oriented” study area includes multiple mesquite coppice dune obstacles varying in height up to about 2 m and close enough together to have interacting wake zones. In QUIC, these dunes were modeled using assemblies of solid rectangles and cylinders, each varying in size, height, and location. The heights and locations of dunes/mesquite bushes were derived from field observations and photographs made by Gillette *et al.* [3] and Gillette and Pitchford [4]. The geometry model within QUIC was created through an iterative process where the geometry was compared with the gridded field observations of mesquite bushes and dune locations having a resolution of 0.5 m (Figure 1). Care was taken to match the plan form area, or “footprints”, of the dunes and bushes. The plan form area of the dunes and bushes was 26.7% in the field [3], while the coverage in QUIC was 26.9%. Based on preliminary runs of the model, predicted wind velocities were nearly uniform above the 2 m high obstacles permitting a relatively shallow model domain height (5 m).

The locations, heights, and dimensions of the obstacles chosen to represent the study area in QUIC are shown in Figure 1. Since QUIC was originally designed to model air flow and dispersion around rectangular flat-topped buildings on flat terrain, the rounded dunes, “porous” mesquite bushes, and slightly “bumpy” “streets” can only be approximately rendered in the model – leading to some inaccuracies in the results. For example, plants, with their open form, ability to change shape or reconfigure during times of high flow, and leaf fluttering which extracts momentum from the passing air generally have different (and sometimes larger) drag coefficients than similar solid objects [13, 14, 24, 25].

Several options within QUIC were chosen to attempt to accurately depict the flow patterns above and between the dunes. The “no-slip” condition was not applied to the top of the rectangular dunes (instead of applying recirculation, or a logarithmic profile), thereby, minimizing the impedance of the flow. This condition was chosen because the tops of the dunes are rounded and covered in “porous” mesquite bushes and therefore do not influence the flow as much as the solid objects with rectangular edges depicted in the QUIC model. Within QUIC the most up-to-date empirical algorithms for modeling the street canyon vortex (PKK option) and the upwind cavity (MVP option) were chosen. With appropriate geometry and domain specified within the model, QUIC requires an input vertical boundary layer – in this case, the boundary layer passing into the domain, to predict the air flow patterns. We chose a simple logarithmic incoming boundary layer, specified by a single reference wind velocity (U_{ref}) at a reference height (z_{ref}) and a roughness length (z_0), empirically chosen to be characteristic of the domain and the upwind roughness. That is, referring to Equation (1), where $U(z)$ is U_{ref} and z is z_{ref}. The displacement height is taken to be zero for these simulations. Specification of the reference parameters allows the model to calculate a u_*, and to create an initial vertical boundary layer to apply throughout the domain. The reference velocities (one for each simulation), U_{ref} were taken at the topmost measurement point of the meteorological tower (z_{ref} of 14.9 m) – because the value is, presumably, the least affected by the lower level flow disturbances resulting from wind interactions with the mesquite coppice dunes. The final parameter required to define the incoming boundary layer was a roughness length.

Based on preliminary simulations using four different initial boundary layer roughness heights (0.001, 0.015, 0.02, and 0.04 m) of seven times (7 h 40 min, 10 h 30 min, 11 h 10 min, 11 h 50 min, 13 h 40 min, 17 h 00 min, 17 h 50 min from 4/15/2003) representing distinct wind directions (175, 203, 214, 223, 234, 243, 251 degrees in the QUIC coordinate system) (for 6 different comparison locations, e.g. masts B, C, D, M, N, and Q), we found an individual "optimal" input boundary layer z_0 needed to match the field wind speed at each location for each comparison height (0.75, 1.5, and 3.15 m). The reference wind speeds used to drive the QUIC simulations were from the top (14.9 m) of the meteorological tower: 12.1, 13.8, 15.4, 19.2, 15.3, 15.1, and 13.6 m s^{-1}, respectively. For each location and height, the "optimal" z_0 value was found by fitting a least squares log-linear regression line to the velocities predicted by QUIC as a function of applied boundary layer z_0 (0.001, 0.015, 0.02, and 0.04 m), and determining the z_0 needed to exactly match the velocity measured in the field (Figure 2). The "optimal" z_0 is not constant, but varies with height, increasing from about 0.01 m (at a height of 0.625 m) to about 0.1 m (at a height of 3.125 m) (Figure 3). Ultimately, for these simulations, where we are most interested in the air flow patterns below the tops of the dunes, we decided to attempt to match the field measurements at 0.75 m. The average of the medians of the "optimal" z_0 values from the 0.625 m and 0.875 m QUIC heights, the two heights closest to 0.75 m, was 0.017 m.

Using this average "optimal" z_0, the model was run independently for 251 different combinations of wind speed and wind direction based on 10-min time average measurements at 14.9 m on the meteorological tower. These times were chosen because they represented times when all 9 measurement towers were active in the field site – each providing wind velocity measurements at three heights. Due to positioning of the anemometers in the field, this paper focuses on comparisons for 6 of the masts (B, C, D, M, N, and Q) at three heights (0.75, 1.5, and 3.15 m). Mast P was excluded from this comparison, because its location on top of the "test dune" placed its respective anemometers at substantially different heights than the other masts. Mast O was excluded because it was too close to the "test dune", and experienced strong gradients and wake flow for nearly all wind velocity combinations.

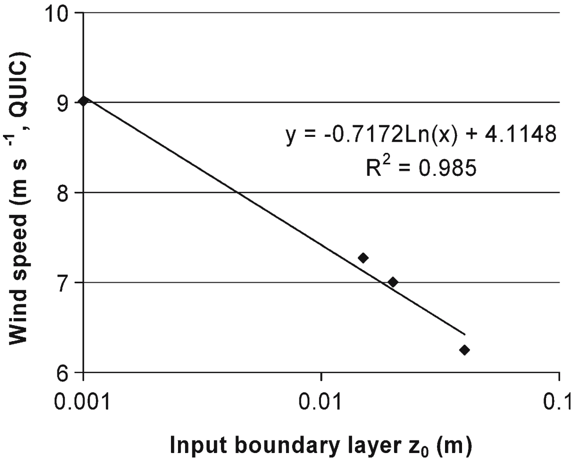

Figure 2. An example least squares regression plot for mast M (0.75 m) at 17 h 50 min on 4/15/2003 showing how the wind speed predicted by QUIC (0.625 m height) varies with input boundary layer z_0. For this particular time, location, and height, a wind speed of 8 m s^{-1} was measured in the field. Consequently, an input boundary layer z_0, or "optimal z_0" of about 0.004 m is needed by QUIC to match the field measurement.

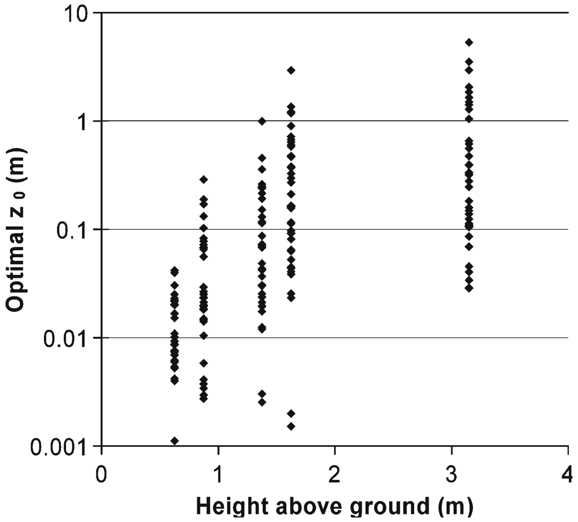

Figure 3. The roughness length (z_0, m) of the needed incoming logarithmic boundary layer as a function of height above the ground (z, m) needed to exactly match the field velocity measurements at a particular mast location (six total) and height (three) for one of seven different wind directions. Unrealistically small optimal roughness heights (< 0.001 m), representing 25 of the total 210 calculations were omitted from the plot. These points probably coincide with times and locations when the model predicted slow (wake) flow, but high velocity flow (channeling down streets) was measured in the field.

3. Results

3.1. ESTIMATION OF THE "OPTIMAL" ROUGHNESS LENGTH

Determining an appropriate roughness length, z_0, proved challenging as no single value seemed to be characteristic of the entire domain, independent of height. For example, our initial attempt at simulating the wind fields within the domain used a z_0 of approximately 0.066 m derived from the field measurements from the 5 anemometers located on the 15 m tower (located approximately at equal logarithmic intervals from 1.3 to 15 m heights). We found, that, while the simulations produced reasonable wind speed matches at higher levels (1.5 m and higher), QUIC substantially underestimated wind speeds at the lower level (0.75 m) suggesting that a smaller z_0 was necessary. When z_0 was estimated from the 15 m tower field data using just the top 3 anemometers on the tower, it increased from 0.066 to 0.115 m. Only the velocities at the highest levels within the domain were adequately simulated with a z_0 of this magnitude. In contrast, field measurements of the velocity gradient (below 3 m) from masts yielded aerodynamic roughness lengths as small as a few millimeters when the mast was experiencing fast channeling "street" flow [3]. When the masts were experiencing interference or wake flows due to proximity of large upwind roughness elements like mesquite bushes, the velocity profiles yielded larger roughness lengths (e.g. 0.06 m) and sometimes non-zero d values. Because the aerodynamic parameters z_0, d, and u_* from the masts were calculated from field measurements at just three heights, the numbers contain around 15% uncertainty based on the regression correlation of the fitting [3]. To simulate velocities at 0.75 m in QUIC, often an input z_0 of approximately 0.01 m was needed.

As a result of these field measurements and preliminary QUIC simulations, we conclude that the boundary layer in the field was not completely "log-linear", and could not be adequately characterized at all heights by a single friction velocity and aerodynamic roughness length. However, for a particular height, our ability to predict velocities with a specific z_0 suggests that the velocity gradient in the field was nearly logarithmic at any particular height. Thus, at each height, we can find a logarithmic velocity profile characterized by an apparent u_* and z_0 to fit the velocities.

To determine the "best fit" z_0 for each height, we ran simulations of seven different wind directions for four different input boundary layer roughness lengths. It appeared that the flow patterns were consistent, with velocities at a particular height varying systematically with roughness length. For a constant wind direction, location (masts B, C, D, M, N, or Q) and height (0.75, 1.5, or 3.15 m), we found an approximately log-linear relationship between the predicted velocity and z_0 (Figure 2). Each location and height had a unique linear relationship. From each equation, we extrapolated the "optimal" roughness lengths needed by the simulation to exactly match the "Oriented" field measurements at each location and height for the seven wind directions (Figure 3). However, since the grid resolution of the QUIC model is 0.25 m, with increments starting at 0.125 m in z, it was not possible to extract values at the exact field measurement heights and locations. Thus, we opted to compare with grid cells found just above and below and in the lateral grid cells surrounding the field locations. Typically, velocities were underestimated for the grid cells at 0.625 m and overestimated for grid cells at 0.875 m when compared with the field measurements at 0.75 m. Similarly, in comparing with the field data at 1.5 m, results from 1.375 and 1.625 m were taken.

As mentioned above, the "optimal" z_0 was found to increase with height. Since dust and sand movement depend on the flow patterns within the mesquite dunes, we chose a roughness length that optimized the wind speed match at 0.75 m, the lowest height for which field velocity data are available. Thus, for the 251 simulations, an average "optimal" z_0 of 0.017 m was chosen based on the average of the median "optimal" z_0 values for the 0.625 and 0.875 m layers from the preliminary QUIC runs using four different input roughness lengths for seven different wind directions (Figure 3).

3.2. COMPARISONS OF QUIC WIND SPEEDS WITH MEASURED WIND SPEEDS

The reference velocities (wind speed and wind direction, measured at the highest location at the on-site meteorological tower) used for the 251 QUIC simulations are shown in Figure 4. The times for these velocities encompass 5 primary dust storms which occurred during April 2003. Wind speeds in the field at 0.75 m, varied from just over 2 m s^{-1} to well over 10 m s^{-1}

The patterns of flow were dependent on boundary layer input wind direction and speed. For a specific case, the patterns were highly heterogeneous within the domain, with notable areas of low, "wake flow". Channeling of flow was apparent, with airflow aligned with specific "streets" that are aligned with the overall flow direction. Figure 5 shows example flow patterns for four common wind directions (260, 240, 220, and 200 degrees). For all four simulations, the reference wind velocity at 14.9 m (the top of the tower) was 12.5 m s^{-1} and the incoming boundary layer roughness length was 0.017 m. For times when the wind was largely southerly (around 200 degrees), intense channeling was present along the largely North/South street (sub-region II, Figure 1) to the west of the "test" dune, the highly resolved structure with approximate coordinates of X = 40, Y = 30. As the wind shifts westerly, channeling of flow up this street stops, becoming largely wake flow. Instead, the flow appears to channel along the East/West street (sub-region IV, Figure 1) passing along the southern edge of the "test" dune.

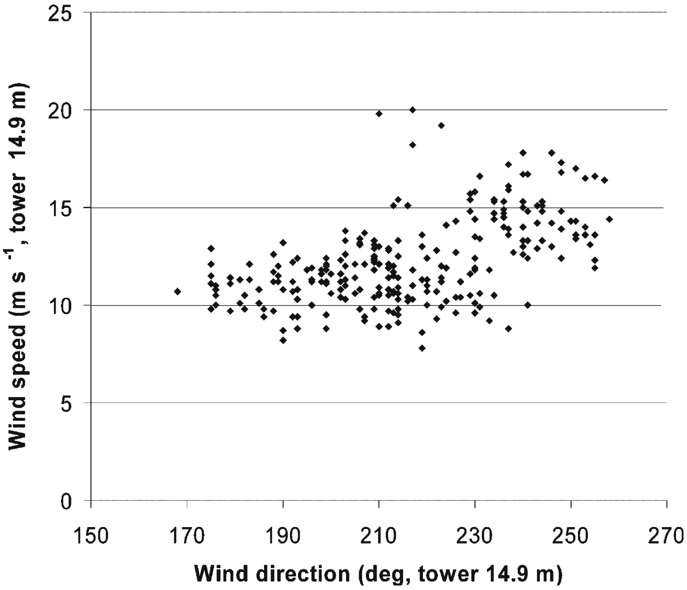

Figure 4. Wind speed as a function of wind direction measured at 14.9 m from the onsite meteorological tower. These 251, 10-min averages were used as the reference velocities driving the input boundary layer for the QUIC simulations. The highest sand and dust fluxes were measured along with the highest wind speeds at about 220 degrees on April 15, 2003 [3].

As notable as the regions of channeling, are the regions of wake flow (sub-region I, Figure 1). Open areas that experience high flow for some wind directions experience low flow in others (sub-regions III and V, Figure 1). Since it appears that open regions where the flow is high are source locations for airborne sediments, not all open regions are acting as sources for a particular wind direction.

The general patterns of flow depicted in Figure 5, were indicative of flow patterns for various wind directions throughout the 251 simulations. The goal of these simulations, and the resulting velocity comparisons with the field data, is to show that the patterns predicted by the QUIC model are representative of the patterns found in the field.

For nearly all times and locations for all 251 simulations, the wind speeds were similar between those measured in the field and those predicted in QUIC. The wind speed comparisons are excellent, with many points appearing to be well matched. At the lowest heights in the field (0.75 m), the wind speeds predicted by QUIC at 0.625 m are, on average, slight underestimates (−10%, 11% standard deviation) while those at 0.875 m (1%, 12% standard deviation) are slight overestimates compared with the measured wind speeds (Figure 6). However, particularly for the

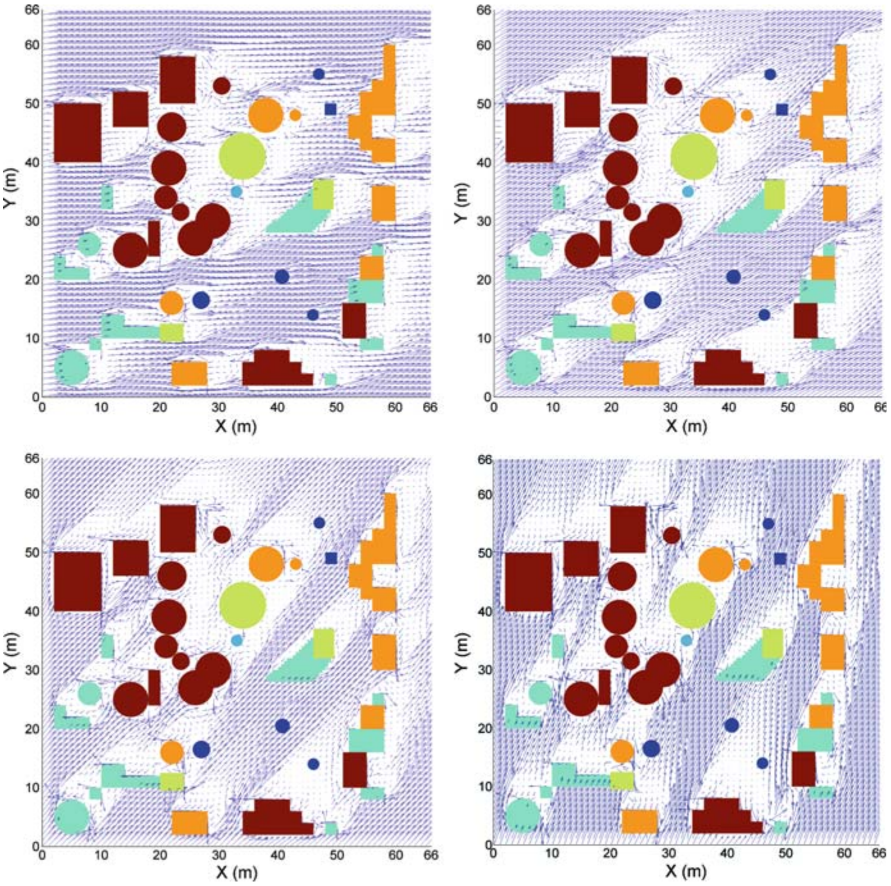

Figure 5. Horizontal wind vectors at 0.625 m in the "Oriented" domain for four common wind directions (260 (top left), 240 (top right), 220 (bottom left), and 200 (bottom right) degrees) as simulated by the QUIC model. For all four simulations, the reference wind velocity at 14.9 m (the top of the tower) was 12.5 m s^{-1} and the incoming boundary layer roughness length was 0.017 m.

comparisons with the 0.75 m height, the wind speed averages from QUIC were forced to be lower by a large number of points, when QUIC substantially underestimated the wind speed (Figure 6). Generally, these times and locations appeared to coincide with regions of wake flow in the QUIC simulation. However, it is possible that some of the differences in wind speed between the QUIC predictions and the field measurements are traceable to the discrete representation of velocity within QUIC. Each point represents an overall velocity for that grid cell. In areas where strong gradients are present (such as along the ground or on the side of a "bush"), the resulting value may be an over or underestimate.

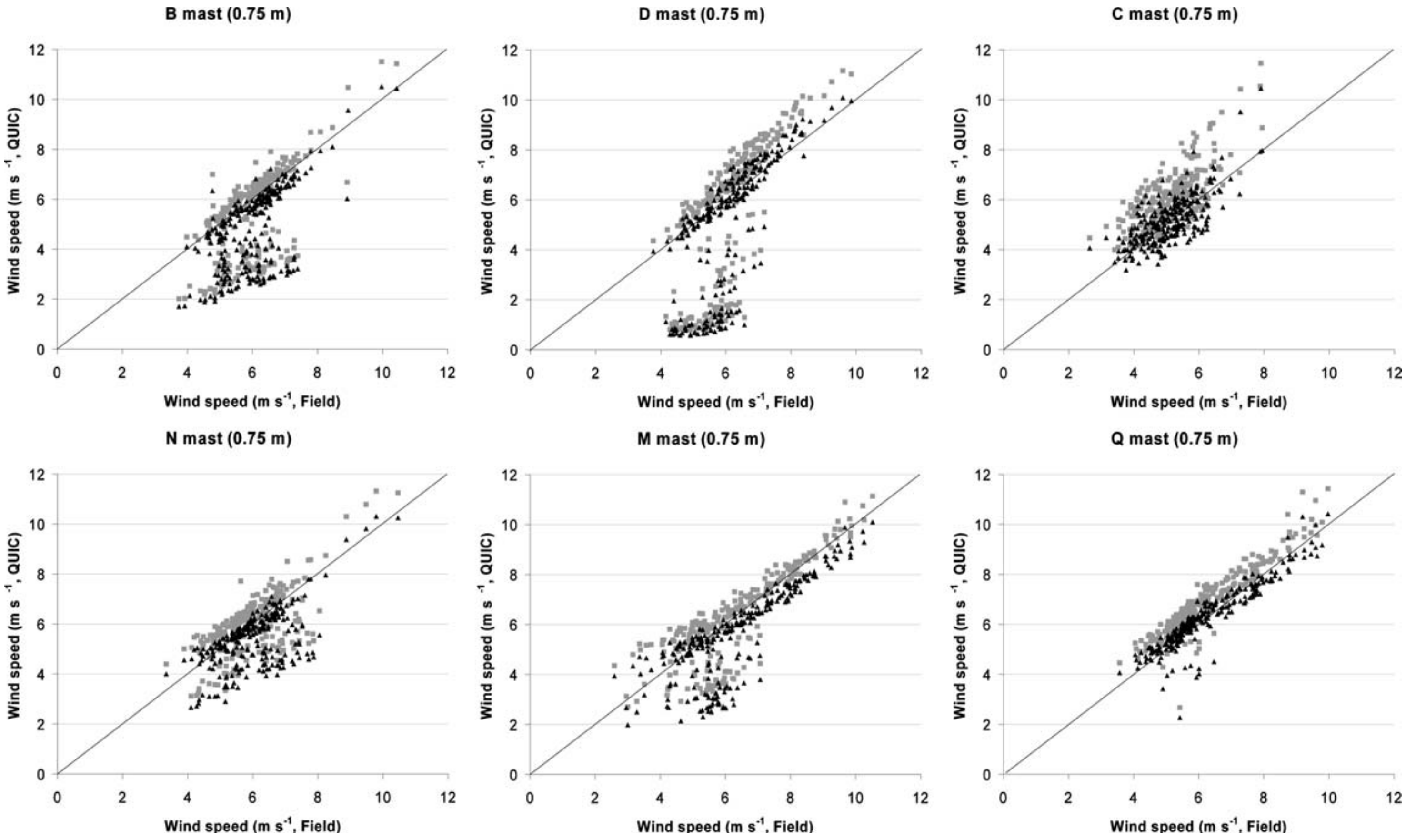

Figure 6. A comparison of wind speed between the field measurements (0.75 m) and those predicted by QUIC (0.625 m, black triangles; and 0.875 m, gray squares).

Generally, when the wind speed match was not as good (e.g. for the B and D masts, and to lesser degree M and N), it appeared that QUIC substantially underestimated the measured wind speed measured in the field (Figure 6). For these masts, it appeared that the quality of the prediction varied with wind direction (Figure 7), with the poorest matches consistently found together for specific wind directions. The difference in wind speeds appeared to be greatest for times when the mast was in a low velocity wake zone or otherwise in a strong lateral wind speed gradient. Similarly, the wind direction comparisons are more favorable for times when the wind speed match is good (Figure 8). The comparisons for the other heights (1.5 m and 3.15 m) showed that QUIC systematically overestimated the wind speeds. Comparing velocities for all six masts at the 1.5 m height, QUIC overestimated each wind velocity, on average, by 7% (standard deviation 12%) for the1.375 m height in QUIC, and 13% (standard deviation 12%) for the 1.625 m height in QUIC. At 3.15 m (3.125 m in QUIC), the model overestimated velocities by 13% on average (4% standard deviation). However, since both of these heights are above most of the mesquite dunes, wake interactions and the associated differences between the QUIC predictions and field measurements were minimized, and velocities for nearly all points and times were similar.

Fitting a logarithmic profile [estimating z_0 and apparent u_*, using Equation (1)] to the wind speeds at a particular location can help identify areas exhibiting "street flow" or "wake flow" based on the categories described by Gillette *et al.* [3]. However, with velocity comparisons at only three heights at each location, accurately calculating a displacement height, d, independent from the roughness length is challenging with only the correlation coefficient from the least squares regression model to asses whether one value of d is "better" than another [3]. In spite of the flow pattern predictions clearly showing regions of wake flow (Figure 5), d was assumed to be equal to zero for all simulations and locations. Data have shown [3] that for some of these areas, the roughness heights extrapolated from the field measurements are unreasonably large when the displacement height is not considered. Consequently, for QUIC, very large roughness heights probably are not valid and indicate areas where d is greater than zero.

Generally, the patterns were consistent, with increases in z_0 for the field correlated with increases in z_0 within QUIC confirming, in part, that QUIC is correctly identifying the overall flow patterns (street flow vs. wake zone) for the domain. Although, while excellent agreement was found for the qualitative location of zones of interference (e.g. where z_0 from QUIC was larger than about 0.04 m, Figures 9 and 10), absolute values of z_0 between the field measurements and QUIC were not in good agreement. In QUIC, z_0 appears to be roughly constant ($\sim$0.017 m – the value chosen as the input boundary layer used in the simulations) or significantly larger

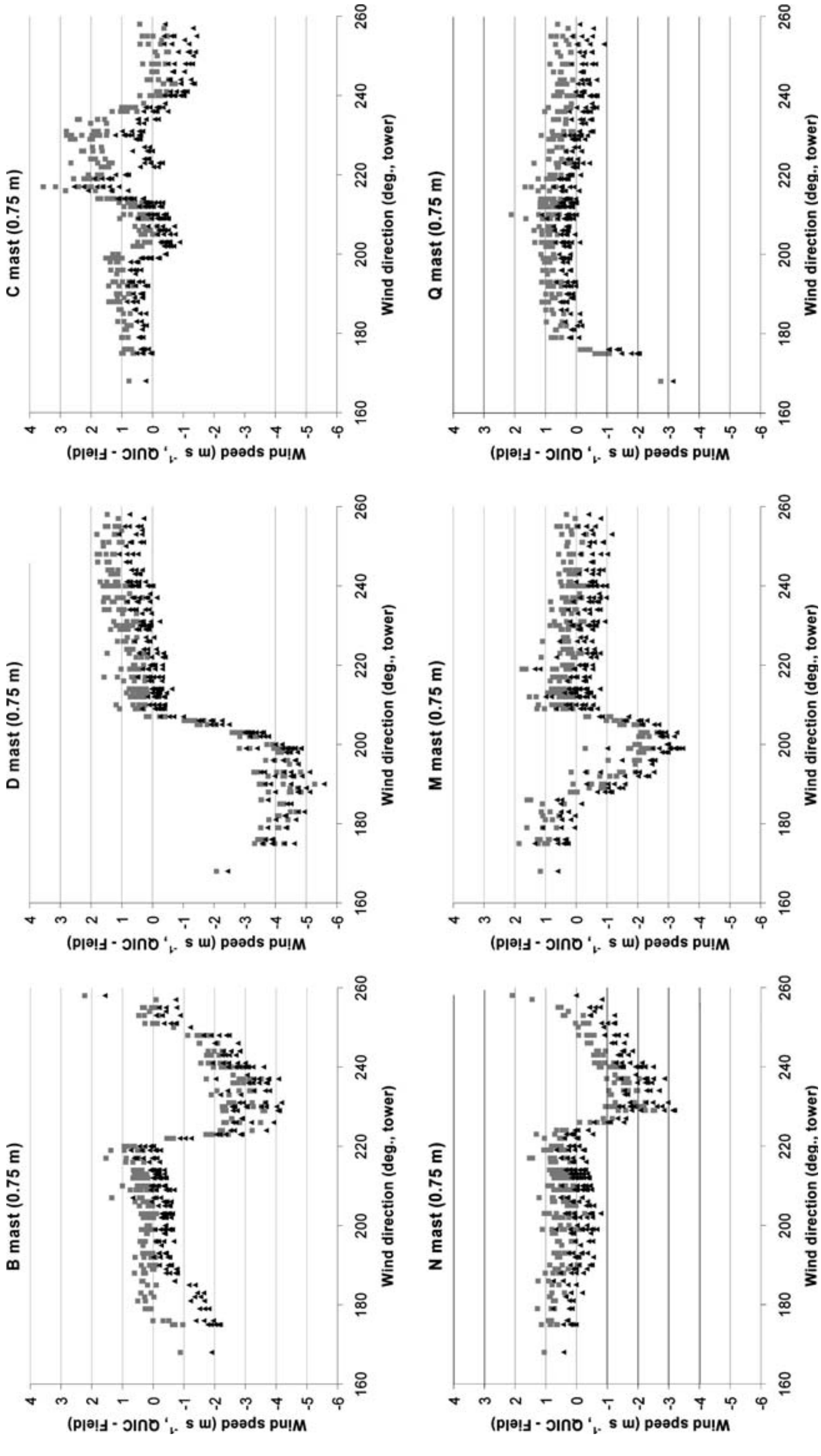

Figure 7. The difference in wind speed between the field measurements (0.75 m) and those predicted by QUIC (0.625 m, black triangles; and 0.875 m, gray squares) at each mast location as a function of wind direction measured at the tower.

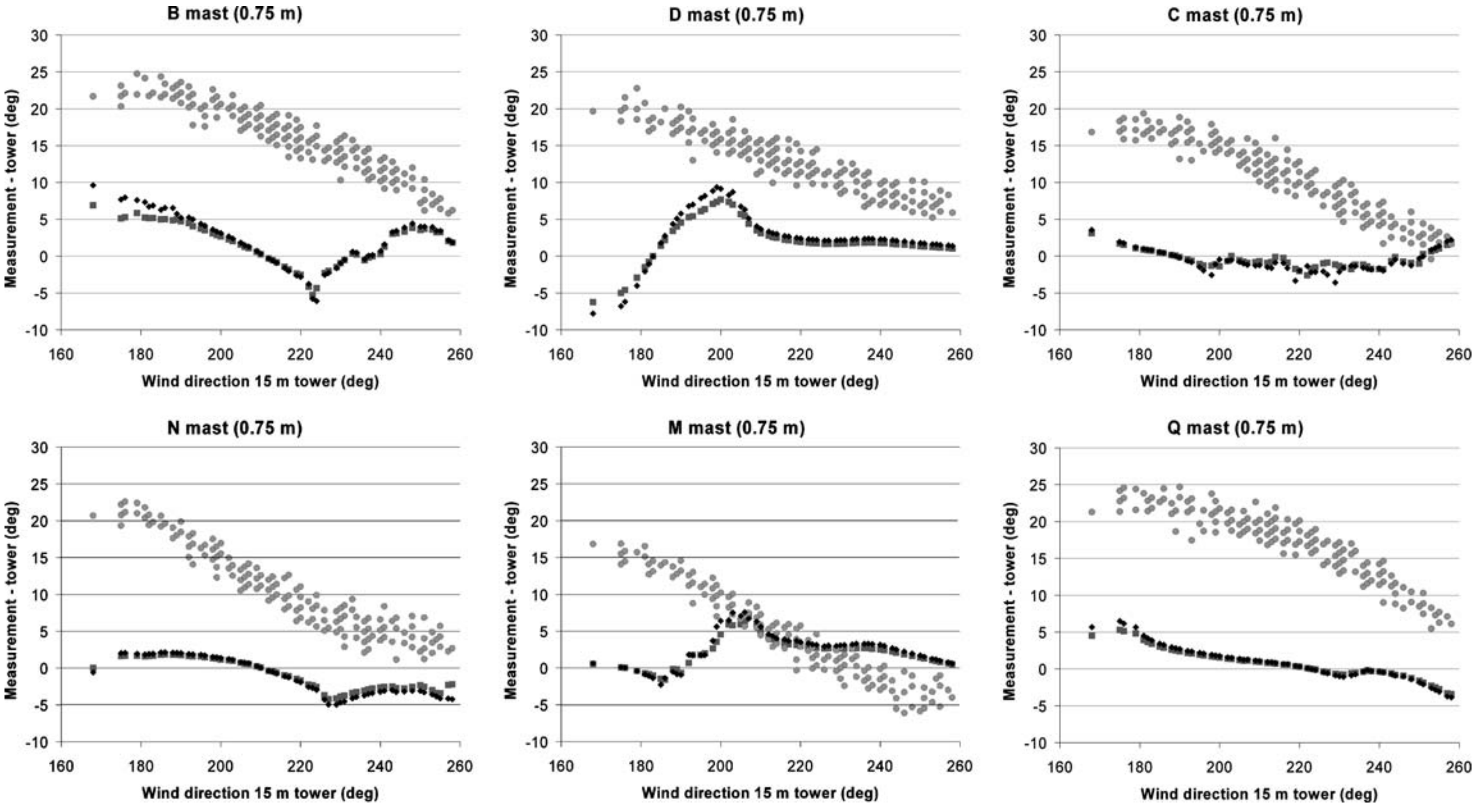

Figure 8. Differences between wind direction (degrees) measured at a mast and the 15 m meteorological tower for field measurements (measured at 1.5 m, gray circles) and QUIC model predictions (measured at 0.625 m, black diamonds and measured at 0.875 m, gray squares).

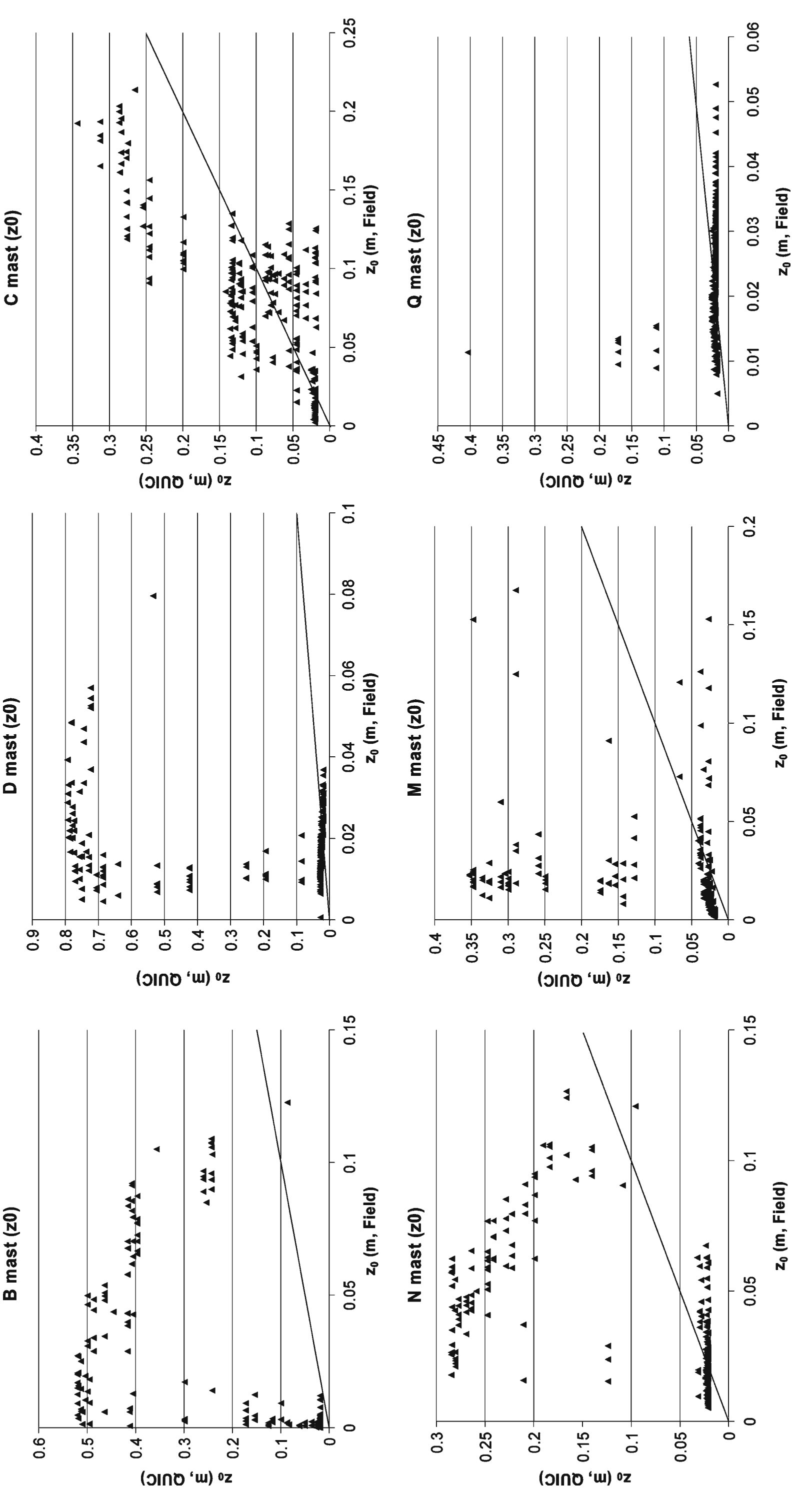

Figure 9. Comparisons at each mast location between roughness lengths (z_0) extrapolated from wind velocities at 3 heights (field measurements) and 5 heights (QUIC measurements) for each of the 251 10-min time and wind direction increments.

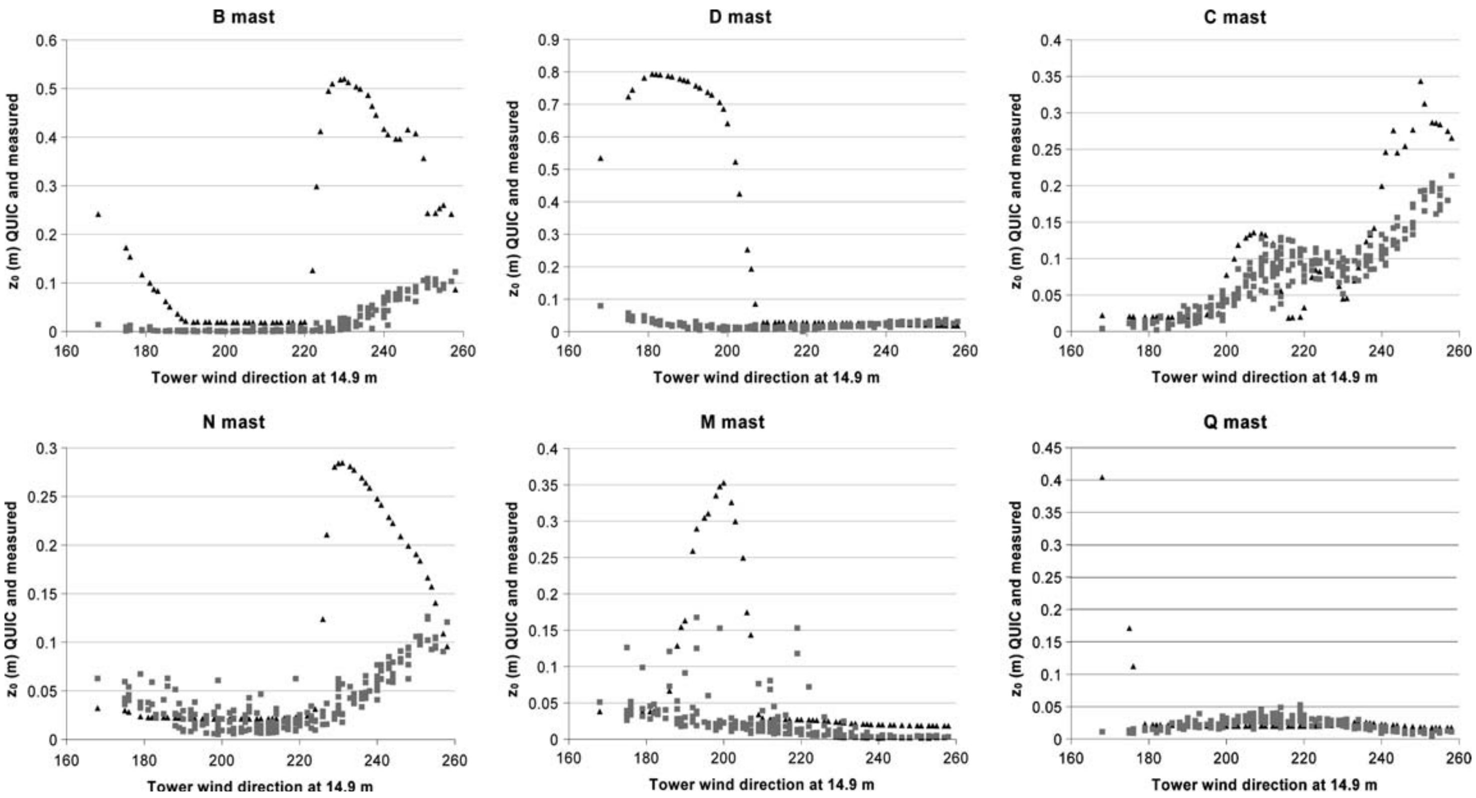

Figure 10. Field measurements (gray squares) and QUIC model predictions (black triangles) of the roughness length (z_0) extrapolated from velocity measurements at three and five different heights, respectively, as a function of the wind direction at the highest level (14.9 m) of the tower for six of the masts.

indicating that the location is in a wake zone from upwind bushes (or is within a zone of interference) (Figure 9). For regions of "street flow", where the roughness heights extrapolated from the field measurements are on the order of millimeters, QUIC was unable to produce smaller roughness heights than the initial z_0 used in the simulation (see masts N and Q, Figure 9). For both the QUIC and the field wind speed measurements, the z_0 extrapolations were functions of wind direction (Figure 10).

3.3. WIND DIRECTIONS

Generally, for the intermediate wind directions, QUIC does not predict quite as much "wind steering" as found in the field (Figure 8). The presence of flow along the axis of the "streets" for off street axis winds indicates that wind steering is present in the model results. For some masts and some wind directions, steering of 20 degrees (relative to the wind direction at the tower) is present in the field compared with steering of 10 degrees in QUIC (e.g. Mast B, 180 degrees, Figure 8).

4. Discussion and Conclusions

Understanding and being able to predict airflow patterns in detail within the desert environment could enable more-detailed modeling of entrainment and deposition of dust and sand from a region. For one such domain, called "Oriented" in the northern Chihuahuan Desert in the JER in southern New Mexico, substantial wind velocity measurements have been made in coordination with sand flux measurements [3]. These data present an opportunity to evaluate high-resolution gridded wind flow and dispersion models used to create complete wind velocity fields for a domain. If the models successfully generate adequate wind velocity fields, understanding and modeling the locations where dust and sand are entrained and deposited is possible. The diagnostic wind field and dispersion model, QUIC, version 3.5, was evaluated in this study.

These simulations represent our initial attempt to create detailed airflow patterns within the complex, heterogeneous, desert environment composed of morphologically complex mesquite bushes, coppice dunes, and other desert vegetation. It is intended to show that there is promise in this technique, and that a model such as QUIC could adequately reproduce the complex flow patterns present in this environment. Clearly, as part of a sensitivity study, refinement of the input geometry and further testing of meteorological parameters could be done to increase the accuracy of the simulation.

Based on the individual wind velocity comparisons for the six locations at three heights, the flow patterns are qualitatively consistent between

QUIC and field measurements. In particular, QUIC simulations agree very well with the field measurements for wind speeds at 0.75 m, the height for which the model was tuned. However, it overestimated velocities at 1.5 m (10%) and 3.15 m (13%). Based on field observations of z_0 values of less than 0.01 m for some locations within the "streets", we assume that velocities simulated at the lowest heights (0.125 m) are underestimates of actual velocities [3]. Roughness heights smaller than that used as the input boundary layer (0.017 m) to drive the model, appear to be unobtainable within QUIC. Consequently, for this environment, velocities from QUIC used for modeling dust and sand entrainment, movement, and deposition, should be taken at the 0.75 m height. For other situations, with smaller roughness elements, velocities at lower elevations could be used.

While quantitatively comparing well with wind velocity for the six comparison locations, the overall patterns of flow also seem to agree well with the field data. Areas of street flow and wake flow are consistent, with strong similarities in both the wind speed and direction for the six comparison locations. Generally, the model did an excellent job in identifying areas, the "streets", where flow was fast. For example, for southerly winds (180 degrees), strong flows are found in the street containing the C, Q, N and B masts (sub-region II) suggesting that large sand fluxes would be found in this area for winds from the south. There is an area of wake flow encroaching from the south toward the D, M, and Q masts (sub-regions I and IV) and behind the "test dune" [3]. This area would have low sand fluxes and would not be losing soil material for these wind directions. In contrast, for westerly winds (270 degrees), the street containing the B and N masts is almost entirely in wake flow, while the street containing masts Q, M, and D (sub-region IV) is experiencing high flow levels. For intermediate wind directions, the field data suggests that channeling of flow is present within the streets, when the local wind direction aligns with the axis of the streets.

Relative to the field study, the diminished wind steering and channeling in the model suggests that the input geometry may not be sufficiently refined (e.g. the size, extent, placement of the roughness elements meant to simulate plants and dunes may not be adequate for some wind directions). Alternatively, the initial empirically-based premise for the wind patterns (prior to the mass conservation requirement) may not adequately account for flow patterns initiated from "large-scale" geometry structures formed from a conglomeration of multiple obstacles.

For example, plant porosity influences the drag experienced by the plant, with plants having larger drag coefficients than comparable solid objects [13, 14, 25]. Plant optical porosities, or the percentage of unobstructed area looking through the bush to the total projected frontal area of the bush, for the "Oriented" site were given by Gillette *et al.* [3]. The mean optical porosity for smaller-than-3 m^2 frontal area bushes was 8.9% with 4.3% standard deviation. For mesquite coppice dunes mean optical porosity was 5.1% with 2.7% standard deviation. For the mesquite coppice dunes, approximately 75% of the volume of the dune is solid; the remainder is mesquite bush. However, during the spring months including March and April, when dust storms are most prevalent, the mesquite bushes have not leafed and the measured plant optical porosities, which were obtained in the summer, are lower than the spring values. Furthermore, the branches and stems of the mesquite are stiff, thereby minimizing the plant's ability to reconfigure to decrease drag with the wind [14, 24]. Since the dunes and bushes are modeled as solid objects within QUIC, the drag will be different, and the resulting wake flow patterns predicted by QUIC will also likely be different than actually present. For example, the "B mast" was predicted to be in very low speed wake flow for a range of westerly wind directions (e.g. around 240 degrees, Figure 7). The field measurements show that the wind speed remains fairly high for most of these directions, indicating that the model either did not adequately describe the channeling presumably occurring in the "street" or that it was overestimating the influence and extent of the wake zone.

One of the goals of the experiment, and a product of the process of defining an appropriate input boundary layer, was to examine the overall shape of the boundary layer within the domain. Based on the QUIC simulations, the incoming boundary layer and the velocity gradients within the domain were not simple log-linear profiles, but appeared to be composed of multiple logarithmic layers, each of which could be characterized an individual z_0 and apparent u_*. For example, when the "optimal" 0.75 m input z_0 was used, QUIC consistently overestimated the wind speeds at the 1.5 m and 3.15 m heights. A larger input z_0 was needed to match velocities at these heights. This was supported by the field data, which suggest that z_0 increases with height, from values of millimeters in the "streets" to about 0.115 m at the highest levels of the 15 m meteorological tower [3]. The reason for the apparent variation of z_0 with height is the momentum loss associated with above-surface roughness elements like mesquite and the channeling of flow between these elements. The mesquite bushes and coppice dunes are extracting the majority of the momentum (probably on the order of 15/16ths of the total transferred to the bushes, dunes and ground) from the boundary layer. Thus, even though the near-surface threshold friction velocities are probably the same ($0.25\,\text{m}\,\text{s}^{-1}$) for the bare earth locations at both the "Oriented" and "Scrape" sites, the threshold friction velocity (as measured well above the roughness elements) is four times larger at the "Oriented" site because of the momentum absorption by the bushes. It is possible that an analysis of how the velocity gradients within the roughness elements are varying with location could help show how and where momentum is transferred to the mesquite bushes and dunes.

The agreement of QUIC and observed wind speeds is reasonable for nearly all locations characterized by small roughness heights (e.g. the "streets"). However, since the acclivity of the velocity gradient directly correlates with u_* and thus with dust and sand movement, it is important to accurately model the particular shape of the gradient and the velocities near the surface. Just above the ground surface in the "streets", the roughness heights were probably less than one centimeter while the corresponding threshold u_* was probably about $0.25\,\mathrm{m\,s^{-1}}$, a value consistent with that measured at the "Scrape" site. The small variations in z_0 (and u_* by extension) found in the field, but absent within QUIC could dramatically affect the movement patterns of sand and dust.

In addition to adding to the science of desertification and understanding of environmental degradation, this study contributes to the on-going development and evaluation of the QUIC model, demonstrating a broader use beyond its original targeted urban and industrial applications.

Acknowledgments

Mr. Ashok Patel carefully carried out model runs. We thank Bruno Pagnani, Steve Perry, and Dave Heist for insightful discussions. We also thank several EPA and NOAA reviewers, including Vlad Isakov and Ashok Patel.

References

1. Okin, G.S., Gillette, D.A. and Herrick, J.E.: 2006, Multiscale controls on and consequences of Aeolian processes in landscape change in arid and semiarid environments, *J. Arid Environ.* (in press).
2. Okin, G.S. and Gillette, D.A.: 2001, Distribution of vegetation in wind-dominated landscapes: Implications for wind erosion modeling and landscape processes, *J. Geophys. Res.* **106**, 9673–9683.
3. Gillette, D., Herrick, J. and Herbert, G.: 2006, Wind characteristics of mesquite streets in the Northern Chihuahuan Desert, New Mexico, USA, *Environ. Fluid Mech.* (in press).
4. Gillette, D. and Pitchford, A.: 2004, Sand flux in the northern Chihuahuan Desert, New Mexico, USA, and the influence of mesquite-dominated landscapes, *J. Geophys. Res.* **109**, 1–12, F04003, doi:10.1029/2003JF000031.
5. Pardyjak, E. and Brown, M.: 2001, Evaluation of a fast-response urban wind model – comparison to single-building wind-tunnel data, *Int. Soc. Environ. Hydraulics*, Tempe, AZ, Dec. 2001, LA-UR-01-4028, 6 pp.
6. Pardyjak, E. and Brown, M.: 2002, Fast response modeling of a two building urban street canyon, 4th AMS Symposium on the Urban Environment, Norfolk, VA, May 20–24, LA-UR-02-1217.

7. Williams, M., Brown, M., Boswell, D., Singh, B. and Pardyjak, E.: 2004, Testing of the QUIC-PLUME model with wind-tunnel measurements for a high-rise building, Fifth Symposium on the Urban Environment, Vancouver, B.C., Canada, LA-UR-04-4296, 10 pp.
8. Bowker, G.E., Perry, S.G. and Heist, D.K.: 2004, A Comparison of Airflow Patterns From the QUIC Model and an Atmospheric Wind Tunnel for a Two-Dimensional Building Array and a Multi-Block Region Near the World Trade Center Site. Fifth Symposium on the Urban Environment/13th Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association, Vancouver, B.C., Canada.
9. Musick, H.B. and Gillette, D.A.: 1990, Field evaluation of relationships between a vegetation structural parameter and sheltering against wind erosion, *Land Degrad. Rehabil.* **2**, 87–94.
10. Raupach, M.R., Gillette, D.A. and Leys, J.F.: 1993, The effect of roughness elements on wind erosion threshold, *J. Geophys. Res.* **98**, 3023–3029.
11. Wyatt, V. and Nickling, W.G.: 1997, Drag and shear stress partitioning in sparsely vegetated desert canopies, *Earth Surf. Processes Landforms* **21**, 607–620.
12. Lancaster, N. and Baas, A.: 1998, Influence of vegetation on sand transport by wind: Field studies at Owens Lake, California, *Earth Surf. Processes Landforms* **23**, 69–82.
13. Grant, P.F. and Nickling, W.G.: 1998, Direct field measurements of wind drag on vegetation for application to windbreak design and modeling, *Land Degrad. Dev.* **9**, 57–66.
14. Gillies, J.A., Nickling, W.G. and King, J.: 2002, Drag coefficient and plant form-response to wind speed in three plant species: Burning Bush (Euonymus alatus), Colorado Blue Spruce (Picea pungens glauca.), and Fountain Grass (Pennisetum setaceum), *J. Geophys. Res. Atmos.* **107**(D24), 10–1 – 10–15, 4760, doi:10.1029/2001JD001259.
15. Frank, A. and Kocurek, G.: 1996, Airflow up the stoss slope of sand dunes: Limitations of current understanding, *Geomorphology* **17**, 47–54.
16. Lancaster, N., Nickling, W.G., McKenna Neuman, C. and Wyatt, V.: 1996, Sediment flux and airflow on the stoss slope of a barchan dune, *Geomorphology* **17**, 55–62.
17. Nickling, W.G. and McKenna Neuman, C.: 1999, Recent investigations of airflow and sediment transport over desert dunes, In: A. Goudie, I. Livingstone and S. Stokes (eds.), *Aeolian Envrironments and Landforms*, Wiley and Sons, Chichester.
18. Walker, I.J. and Nickling, W.G.: 2002, Dynamics of secondary airflow and sediment transport over in the lee of transverse dunes, *Prog. Phys. Geogr.* **25**, 47–75.
19. Parsons, D.R., Wiggs, G.F.S., Walker, I.J., Garvey, B.G. and Ferguson, R.I.: 2002, Time-averaged numerical model ing of airflow over an idealized transverse dune, In: J.A. Lee and T.M. Zobeck (eds.), Fifth *International Conference on Aeolian Research/GCTE-SEN Joint Conference*, International Center for Arid and Semi-Arid Land Studies, Texas Tech University, Lubbock Texas, USA, Special Publication 02–2, pp. 261–267.
20. Priestly, C.H.B.: 1959, *Turbulent Transfer in the Lower Atmosphere*, University of Chicago Press, Chicago.
21. Gillette, D.A. and Chen, W.A.: 2001, Particle production and aeolian transport from a 'supply limited' source area in the Chihuahuan Desert, New Mexico, United States, *J. Geophys. Res.* **106**, 5267–5278.
22. Marticorena, B., Bergametti, G., Gillette, D.A. and Belnap, J.: 1997, Factors controlling threshold friction velocity in semiarid and arid areas of the United States, *J. Geophys. Res.* **102**, 23,277–23,287.

23. Owen, P.R.: 1964, Saltation of uniform grains in air, *J. Fluid Mech.* **20**, 225–242.
24. Vogel, S.: 1989, Drag and reconfiguration of broad leaves in high winds, *J. Exper. Bot.* **40**, 941–984.
25. Gillies, J.A., Lancaster, N., Nickling, W.G. and Crawley, D.: 2000, Field determination of drag forces and shear stress partitioning effects for a desert shrub (*Sarcobatus vermiculatus*, Greasewood), *J. Geophys. Res.* **105**(D20), 24, 871–24, 880.