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Changes in the Saltation Flux Following a Step-Change in Macro-Roughness

J.A. Gillies*, V. Etyemezian, G. Nikolich, W.G. Nickling, J.F. Kok

Under sediment supply limited saltation conditions a step change in macro-roughness alters the saltation reducing the horizontal flux by an amount that scales with the roughness density. The mean diameter of the saltating particles decreases in the horizontal and vertical dimensions with increasing distance. The e-folding height as a function of particle diameter increases with increasing distance, suggesting the particles are increasing their speed, which is likely due to the removal of slower particles as they travel through the roughness.

For Peer Review

1 **Changes in the Saltation Flux Following a Step-Change in Macro-Roughness**

2 J.A. Gillies, V. Etyemezian, G. Nikolich, W.G. Nickling, J.F. Kok

3 **ABSTRACT**

4 The effect of a step change in macro-roughness on the saltation process under sediment supply
5 limited conditions was examined in the atmospheric boundary layer. For an array of roughness
6 elements of roughness density $\lambda=0.045$ (λ =total element frontal area/total surface area of the
7 array) the horizontal saltation flux was reduced by 90% ($\pm 7\%$) at a distance of ≈ 150 roughness
8 element heights into the array. This matches the value predicted using an empirical design
9 model and provides confidence that it can be effectively used to engineer roughness arrays to
10 meet sand flux reduction targets. Measurements of the saltation flux characteristics in the
11 vertical dimension, including: saltation layer decay (e-folding) height and particle size, revealed
12 that with increasing distance into the array, the rate of mass flux change with increasing height
13 decreased notably, and (geometric) mean particle diameter decreased. The distribution of the
14 saltation mass flux in the vertical remains exponential in form with increasing distance into the
15 roughness array, and the e-folding height increases as well increasing at a greater rate as
16 particle diameter diminishes. The increase in e-folding height suggests the height of saltating
17 particles is increasing along with their mean speed. This apparent increase in mean speed is
18 likely due to the preferential removal, or sequestration, of the slower moving particles, across
19 the size spectrum, as they travel through the roughness array.

20 **Keywords:** saltation flux, macro-roughness, e-folding height, mean particle size changes

21 **Introduction**

22 Wind blowing over a surface with loose sand that exceeds a critical shear stress on the surface
23 will entrain these particles and move them downwind as bed-load in three recognized modes of
24 transport: creep, reptation, and saltation. The characterization of the saltation flux, in which
25 particles move in a series of repeated ejections and travel in ballistic trajectories followed by

impact on the surface has garnered considerable research effort in the earth sciences. The saltation process plays critical roles in aeolian bedform development across multiple scales (e.g., Anderson, 1987; Claudin and Andreotti, 2006; Dúran et al., 2011; Gillies et al., 2012; Parteli et al., 2014; Schmerler et al., 2016) and is a dominant mechanism driving the emission of dust-sized particles, which represent the suspended load in aeolian transport (e.g., Shao et al., 1993; Shao, 2001; Kok et al., 2012).

It is now generally acknowledged that the horizontal mass flux of wind-driven sand decreases exponentially with elevation above the surface (e.g., Bagnold, 1941; Chepil, 1945; Williams, 1964; Sørensen, 1985; Namikas, 2003; Farrell and Sherman, 2006, 2013; Martin and Kok, 2017a) and the general form of the relationship is:

$$Q(z) = Q_0 \exp(-z/z_q) \quad (1)$$

where $Q(z)$ is the stream-wise mass flux at elevation z above the bed, Q_0 is the scaling parameter for the profile and z_q the characteristic saltation layer decay height (i.e., the e-folding height). The magnitude of z_q depends on the typical hop height z_{hop} of saltating particles (Bagnold, 1941; Owen, 1964; Ungar and Haff, 1987; Namikas, 2003). That is (Martin and Kok, 2017a),

$$z_q = C_Q z_{hop} \quad (2)$$

where C_Q is a dimensionless constant of order 1. For ballistic trajectories, the hop height z_{hop} depends on the vertical speed, v_{zo} (m s^{-1}) with which saltating particles leave the surface upon rebound or ejection:

$$z_{hop} = v_{zo}^2 / 2g \quad (3)$$

where g is the acceleration due to gravity ($\text{m}^2 \text{s}^{-1}$). Since v_{zo} is closely linked to the mean particle speed (Owen, 1964; Kok, 2010), Eqs. (1) – (3) imply that the e-folding height z_q is a

sensitive function of the mean particle speed. In other words, a measured increase (decrease) in z_q denotes an increase (decrease) in mean particle speed.

Observations of the change in mean grain size as a function of height show complex patterns including a decrease in mean grain size with height (Williams, 1964; Li et al., 2008) while other available data reveal instances of an increase in mean grain size with height (Williams, 1964; Xing, 2007; Speirs et al., 2008; Gillies et al., 2013). Additionally, it has often been observed that at some distance above the surface the grain size trend can reverse (Williams, 1964; Xing et al., 2007; Farrell et al., 2012; Zhang et al., 2017), which may be indicative of a change in transport system dynamics (Andreotti et al., 2004). The available data on particle size relationships in the vertical and horizontal dimensions do not present a simple or consistent picture of grain motions and trajectories leading to a unified model for a bed of mixed particle sizes.

Recent research has documented the change in the mass flux of particles in saltation as the saltation cloud moves from relatively flat, unobstructed flow conditions to one in which the flow encounters and is perturbed by the presence of large roughness elements (e.g., Gillies et al., 2006, 2007, 2014, 2015; Gillies and Lancaster, 2013). Measurements of the saltation flux exterior and interior to a change of roughness show clearly that the mass flux decreases exponentially with increasing distance into the roughness, reaching a new equilibrium flux at >100 roughness element heights (Gillies et al., 2015). The rate of change of the mass flux with distance and the resultant roughness adjusted saltation flux scale with the roughness density (λ) (Gillies et al., 2015):

$$\lambda = n b h/S \quad (4)$$

where n is the number of roughness elements occupying the area S (m^2), b is element breadth (m), and h is element height (m). Both Gillies and Lancaster (2013) and Gillies et al. (2015)

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3 73 report this scaling relationship based on spatially-distributed measurements of saltation mass
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5 74 flux at only one height above the surface, which allowed for a comparison of the spatial
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7 75 characteristics of the mass flux in response to its interaction with large roughness elements.
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10 76 Although this recent research has established that the change in saltation mass flux at a specific
11
12 77 height scales as a function of λ as it responds to the presence of macro-roughness, it has not
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14 78 examined how the scaling changes over the vertical dimension. It has also not been
15
16 79 determined if the observed change in mass flux is accompanied by a change in the mean grain
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18 80 diameter.
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21 81 Understanding how large roughness elements affect sand transport is important as there are
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23 82 many natural surfaces where sand transport occurs among large roughness elements including
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25 83 vegetation or sediment mounds covered in vegetation, for example nebkhas (Wolfe and
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27 84 Nickling, 1994; Al-Awadhi, 2014; Gillies et al., 2014), or varying amounts of solid roughness
28
29 85 elements composed of rocks (Gillies et al., 2010, 2013; Lancaster et al., 2010). Arrays of large
30
31 86 roughness elements that have been manufactured have been tested to evaluate their
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33 87 effectiveness to serve as a method to reduce sand transport and the associated dust emissions,
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35 88 for example, at the Keeler Dunes, Keeler, CA (Gillies et al., 2015). Increased understanding of
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37 89 how roughness modulates saltation, which in turn affects the dust emission process, may result
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39 90 in improved saltation and dust flux models that account for roughness effects and also ways to
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41 91 better use roughness to reduce dust emissions, improve air quality, and meet air quality
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43 92 standards.
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47 93 In this work, we present results from a field study where changes in vertical profiles of sand flux
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49 94 and size, before and after encountering regularly spaced roughness elements, were measured
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51 95 to quantify the effect of the step change in roughness. By carrying out this study in a field
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53 96 setting there were no constraints on the saltation system, the boundary layer flow, or the size of
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55 97 the roughness elements that were used, as would be the case for wind tunnel based
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3 98 experiments (White and Mounla, 1991; Sherman and Farrell, 2008). The supply of sediment,
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5 99 however, was not unlimited upwind of the array of roughness, nor were the elements resting on
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7 100 a deformable bed of sand.
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10 101 **Materials and Methods**

11
12 102 A new set of time-integrated, particle size distribution- and height-resolved mass saltation flux
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14 103 profiles were collected as saltating particles travelled through an array of macro-roughness
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16 104 elements in the atmospheric inertial sublayer in 2015 and 2016. This was carried out as part of
17
18 105 an experiment to evaluate methods to reduce sand transport and dust emissions at Owens
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20 106 Lake, CA, which is a source of dust known to contribute to local and regional air quality
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22 107 degradation (Ono et al., 2011). Measurement of the vertical saltation flux profiles were made
23
24 108 upwind of, and at defined distances through, a large array of large roughness elements to
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26 109 investigate how the mass flux is affected in the vertical and along-wind directions by a step-
27
28 110 change in roughness.
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31 111 **The Roughness Elements and the Roughness Array**

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34 112 The roughness elements used in this experiment were commercially manufactured, rectangular
35
36 113 plastic bins (model SNT300) with the dimensions of an individual element being: 0.725 m
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38 114 (length) $\times$ 0.38 m (height) $\times$ 0.45 m (width). The roughness elements were placed and
39
40 115 organized into a staggered array pattern of fixed dimensions on an area of crusted playa
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42 116 surface at Owens Lake, CA, where sand transport was also known to occur (Fig. 1). The open
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44 117 fetch upwind of the northerly and southerly edges of the array well-exceeded 500 m. The
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46 118 roughness array was composed of 1620 elements with the length dimension of the elements set
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48 119 perpendicular to the predominantly bi-modal wind directions of 147° and 327° , determined from
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51 120 a 21 year record from a nearby 10 m high meteorological tower operated by the Great Basin
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53 121 Unified Air Pollution Control District (Bishop, CA). The center-to-center spacing between
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55 122 elements was 2.48 m as was the row-to-row distance (Figs. 1 and 2). The elements were
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123 weighted down by adding sediment to prevent them from being shifted by strong winds. The
124 length and width of the array was 100 m, creating an area of 1 hectare with $\lambda=0.045$. The
125 normalized (total) sand flux (NSF_T , the ratio of sand flux measured internal to the array to that
126 measured upwind and external to the array) was expected to be 0.10 for sediment in transport
127 deep into the roughness array (i.e., horizontal distance >100 element heights) based on Gillies
128 et al.'s (2015) Eq. 4.

129 **Sand Flux and Wind Instrumentation**

130 The test area was instrumented to measure sand flux external and internal to the array. Table 1
131 defines the positions of the instruments relative to the roughness array. Sand flux was
132 measured using modified BSNE-style traps (Fryrear, 1986) as described by Gillies et al. (2012,
133 2013), which they used to measure sand flux in the McMurdo Dry Valleys in Antarctica. The
134 version used here did not make use of the automated opening and closing of the trap inlets.
135 Briefly, the traps have four wedge-shaped compartments that self-orient into the wind (Fig. 3).
136 Each trap had four catchers spaced logarithmically with heights between ≈ 0.17 m and ≈ 1.3 m.
137 The opening of each catcher is $0.02\text{ m} \times 0.05\text{ m}$. The total collection volume per receptacle is
138 approximately 0.0025 m^3 . The four catchers are connected through the tail fin assembly, which
139 keeps them all facing the same direction and aligned into the wind. By convention, the lowest
140 trap compartment is 1, the highest 4. Eight traps were used in this experiment. By convention,
141 the trap furthest to the north is designated as 1, the furthest south as 8. The traps interior to the
142 array were set ≈ 2.5 m from the centerline with the offset staggered to the west and then the east
143 for successive traps through the array. In addition, 30 Cox Sand Catchers, a single
144 measurement height trap (Gillies et al., 2015), were placed into the roughness array with their
145 annular opening at 15 cm above the surface. Eight were collocated with the BSNE traps and
146 the remaining were located at the same positions as the BSNE traps, with one along the center-

line, and the other two half way to the edge on either side of the center-line. This allowed for a more spatially diverse measurement of saltation flux through the roughness array. Wind speed at five heights above ground level (1.25 m, 2.20 m, 3.87 m, 6.82 m, and 10 m) and wind direction at 10 m were measured on four 10 m towers. Their positions exterior and interior to the array are provide in Table 1. To characterize the airflow among the roughness elements 20 anemometers and four wind vanes were placed external and internal to the array at a height of 0.25 m above ground level (AGL). This is 0.13 m below the top of the roughness elements. One anemometer and one wind vane were placed 3 m upwind of the center-line of the array also at 0.25 m AGL on the north end of the array. The other 19 anemometers and four wind vanes were placed inside the array from its northern boundary extending ≈ 50 m into the array. The positions of the anemometers and wind vanes relative to the roughness elements are shown in Fig. 2 and this pattern is repeated four times between the northern edge of the roughness array and halfway through (≈ 50 m).

Particle Size Distribution Measurements

Sediment samples retrieved from the trap compartments were returned to the lab for gravimetric and particle size analysis. The sediment samples were weighed on an electronic balance (Model MS1602S, Mettler-Toledo, Columbus OH) to a precision of 0.01 g. Following the weighing, sediment samples were submitted for particle size analysis to the DRI Soils Characterization Lab (Desert Research Institute, Reno NV USA) using a Malvern Mastersizer 3000 (Malvern Instruments Inc., Westborough MA). The particle size range covered was 0.75 μm to 1500 μm with 34 particle diameter bins reported.

Results

Wind Conditions

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3 170 Although saltation threshold was not monitored at the field site, as reported for a nearby sand-
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5 171 dominated surface (Gillies et al., 2015) transport conditions are likely to occur when wind speed
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7 172 measured at 4 m AGL exceeds 5 m s^{-1} . Wind roses for the met towers exterior to the edge of
8
9 173 the roughness array for winds $\geq 6 \text{ m s}^{-1}$ measured at 10 m shows the likely sand transport
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11 174 directions are dominated by winds from the south and south-south-east and the north-northwest
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13 175 (Fig. 4). For the case of wind approaching $\pm 10^\circ$ from perpendicular to the rows, the near
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15 176 surface spatially-averaged wind speed at the normalized distance $ND \approx 137$ ($ND = \text{horizontal}$
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17 177 distance/element height) was reduced by approximately 49% ($\pm 13\%$) compared to the
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19 178 measurement of wind at the same height upwind of the array (Fig. 5).
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23 179 Although a small percentage of wind speeds exceeded 6 m s^{-1} at 10 m with approach angles to
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25 180 the array between 45° and 90° from perpendicular to the front of the array during the different
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27 181 collection periods, their effect on the sand collected in the BSNE traps is likely not significant
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29 182 enough to alter the sand flux reduction pattern with increasing distance into the roughness that
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31 183 the array orientation was designed to characterize. The reasons are two-fold: 1) the above
32
33 184 threshold winds for this direction range for the east and west sides of the array is between 6%
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35 185 (east) and 12% (west) of the entire time winds were measured to be $\geq 6 \text{ m s}^{-1}$ at 10 m, and 2) as
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37 186 wind direction approach angle to the front of the array changes between 45° and 90° , λ changes
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39 187 from 0.052 to 0.033 due to the changing frontal area of the elements, which would reduce the
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41 188 sand flux by 92% (at 45°) to 81% (at 90°) according to Gillies et al. (2015, Eq. 4) for BSNEs
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43 189 along the center-line of the array.
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46

190 **Total and Vertically Distributed Mass Saltation Flux**

191 Four collections of the BSNE traps were made during the duration of the study: 2-10-2015, 29-
192 12-2015, 17-3-2016, and 16-5-2016, with each collection representing multiple transport events.
193 This results in mixing of different transport directions in this bi-modal sand transport wind
194 regime. The further downwind from the leading edge where the saltating particles enter the

array, the lesser this mixing effect occurs as it is expected that the flux will diminish with increasing distance into the roughness array as established by Gillies et al. (2015). The heights of the sample collection, mass of the trap compartment samples, and the corresponding normalized height (NH) and normalized mass (NM) samples are provided in Table 2. The height of collection is defined as the height above the surface of the geometric mean position of the rectangular trap opening (Ellis et al., 2009). NH is defined as: H_n/H_1 , where H_n is the distance above the ground to the position of the geometric mean of a rectangular opening in a trap compartment and H_1 is the distance above the ground to the position of the geometric mean of the rectangular opening of the lowest trap compartment. NM is defined as: $mass_n/mass_1$, where $mass_n$ is the mass in trap compartment n divided by the mass in the lowest trap compartment, i.e., $mass_1$ at H_1 .

For each collection period the total trap mass (i.e., the sum of the four compartments) divided by the total mass of a trap exterior to the array defines NSF_T , which is plotted as a function of ND for each collection period in Fig.6. These data show a rapid decrease in NSF_T with increasing distance into the array from either side. For all sample periods the plots show that sediment transport from south to north was dominant. Although as Fig. 6 shows there must have been some transport events from north to south as traps 1 and 2 show higher values than the interior traps.

The strongest signal of change in NSF_T as a function of ND is observed in the sequence of traps: 8, 7, 6, 5, 4, which represent the transport condition of sand entering the array on the southern edge and its subsequent movement towards the opposite edge. The relationship between NSF_T for the four collection periods and ND , and two trap types, is shown in Fig. 7, with the error bars representing the standard deviation of the mean. As observed in previous studies NSF_T decreases exponentially with increasing ND up to a point, after which it stabilizes

219 to a constant value (Gillies et al., 2015). For this array of roughness elements NSF_T stabilizes
 220 at $ND \approx 160 - 212$, with a mean value of $0.10 (\pm 0.07)$. This relationship can be expressed as:

$$221 \quad NSF_T = (1 - NSF_\infty) e^{(-a ND)} + NSF_\infty \quad (5)$$

222 where a is a dimensional constant and NSF_∞ the flux fully adjusted to the step change in
 223 roughness.

224 Equation 5 was not derived formally; rather, it represents a plausible general form to fit the data
 225 from a step increase (possibly also step decrease) in roughness. The parameter NSF_∞ is
 226 straightforward to understand and can be estimated easily either from direct measurement or
 227 based on Gillies et al.'s (2015) Eq. 4.

228 NM plotted as a function of NH represents the form of the normalized horizontal flux relationship
 229 (NF) based on the vertical variation of mass and defines the rate of change of the particle mass
 230 flux above the surface at a measurement position. This relationship for pairs of traps with the
 231 same ND from the edges of the roughness array and the mean values of NM representing the
 232 four collection periods are shown in Fig. 8. The error bars in each case represent the standard
 233 deviation of the mean NM . For each trap the vertical flux is well described by an exponential
 234 function. The two traps external to the array (i.e., T1 and T8) show a greater rate of change in
 235 NM with NH than do the trap pairs interior to the array (Fig. 8).

236 The z_q parameter in Eq. 1 is the characteristic saltation layer decay height. The change in this
 237 variable as a function of ND for the traps combinations: 1, 2, 3, 4, and 8, 7, 6, 5, which groups
 238 them based on having the same ND values for north to south and south to north transport
 239 directions is shown in Fig. 9.

240 Particle Size Distribution Changes in the Vertical Saltation Flux

241 The effect of the roughness on the particle size distribution characteristics of the saltation flux in
 242 the vertical dimension is revealed through the Malvern Mastersizer-generated data and the

calculation of grain size distribution characteristics using the Gradistat particle size analysis software (Blott and Pye, 2001; Kenneth Pye Associates Ltd., UK). Grain size statistics generated by Gradistat are all based on the method of moments and reported as geometric mean diameter (μm). The relationship between mean diameter and NH for the collection periods: 02-10-2015, 29-12-2015, and 17-03-2016 for the sequence of traps 8, 7, 6, 5 (i.e., south to north transport) is shown in Fig. 10. In these cases, the mean diameter decreased with increasing NH above the surface, and the relationship is well-described, most consistently, by a best-fit logarithmic relationship. Pooling the data by trap number for the three sampling intervals and normalizing the mean diameter by dividing each mean particle diameter by the mean diameter for the highest receptacle (i.e., $\text{mean diameter}_{Hn}/\text{mean diameter}_{H4}$) gave the result that for Trap 8, exterior to the roughness, between the lowest and highest collection heights the mean diameter differed by a factor of $3.0 (\pm 1.1)$. For the three interior traps (7, 6, and 5) the difference in mean diameter from lowest to highest is a consistent decrease by a factor of $2.0 (\pm 0.1)$. The mean diameter at similar collection heights also changes systematically with ND as shown in Fig. 11. The decrease in mean diameter as a function of collection height and ND is observed for collection heights 1 (≈ 0.2 m), 2 (≈ 0.5 m), and 3 (≈ 0.8 m), and is most consistently described by a logarithmic relationship. For collection height four (≈ 1.3 m), in two of the collection periods an increase in mean diameter was observed moving from outside the array to $ND=48.9$, thereafter little variation of mean diameter between $ND=48.9$ and $ND=159.9$ was observed at this height.

By partitioning the mass flux in each trap compartment by the mass fraction associated with the eight particle size bins for the sand-sized components of the material in each trap compartment (i.e., $750 \mu\text{m}$, $375 \mu\text{m}$, $225 \mu\text{m}$, $175 \mu\text{m}$, $137.5 \mu\text{m}$, $112.5 \mu\text{m}$, $87.5 \mu\text{m}$, and $68.7 \mu\text{m}$), z_q for each of these particle diameters can be estimated at the four measurement positions: $ND=0$, 16.3 , 48.9 , and 101.2 . The regression-derived value for z_q as a function of mean diameter for

the available data (from both transport directions), is shown in Fig. 12. As this Fig. shows, z_q increases for each particle diameter with increasing distance into the array, and as particle diameter decreases, z_q increases at a faster rate. The rate of change of z_q with increasing ND (i.e., m term in $z_q = m(ND) + b$, for each particle diameter in Fig. 11), as a function of particle diameter is shown in Fig. 13 and is well-defined by a power relationship.

Discussion

Effect of Roughness on the Mass Flux

As previously observed by Gillies et al. (2006, 2015), NSF_T scales as a function of λ . Gillies et al.'s (2015) Eq. 4 predicts that for $\lambda=0.045$, the equilibrium NSF_T for an array of large roughness elements should be 0.10. The mean NSF_T for the interior of the array for this experiment for $ND=159.9$ was $0.10 (\pm 0.07)$, which matches the model prediction very closely. The roughness adjusted NSF_T value was based on using measurements at multiple heights above the surface and as can be seen from Fig. 7, matches closely the saltation flux reduction pattern measured at the same height low to the ground and over a wider area.

The rate of change of NSF_T with increasing ND for that portion of the curve shown in Fig. 7 before the fully-adjusted flux is attained (i.e., $ND=0$ to $ND=101$) for this roughness array can be compared with other experiments that have measured the effect of roughness on NSF_T .

Defining this portion of the curve similarly to Gillies et al. (2006, 2015) and Lancaster and Gillies, 2013) as $NSF_T = a e^{(-B ND)}$, the value of B for this experiment for the BSNE trap data is -0.17 and -0.021 for the CSC trap data. Given the stochastic and variable nature of aeolian transport (e.g., Gares et al., 1996; Stout and Zobeck, 1997; Jackson et al., 2006) and the variability in wind direction, transport and surface conditions among the available studies, the values of B for this experiment fit closely with the predicted value of $B=-0.016$ based on the relationship presented by Gillies et al. (2015, their Fig. 11) that uses data from three

experiments. In general, the new Owens Lake NSF_T relationships fit quite well with previous measurements, which indicates that the established scaling relationship between sand flux and λ (Gillies et al., 2015, Eq. 4) is very robust at least for roughness that is relatively closely spaced and of all the same height. Chappell and Webb (2016) argue that λ is less successful in predicting shear stress partitioning and shelter effects for superposed roughness that covers a range of element heights and widths, which may also reduce the applicability of the Gillies et al., (2015) equation for estimating the effect of non-homogeneous roughness on sand transport. Their equation does, however, appear very useful for designing arrays of large roughness elements to control saltation flux and the associated dust emissions.

Effect of Roughness on the Particle Size Distribution of the Saltators

In general, for all trap samples the mean particle diameter decreases as a function of height above the surface (for $H > 0.17$ m), exterior and interior to the roughness. This matches the observations of Li et al. (2008) for wind tunnel tests using sand of mixed size and this pattern of decreasing grain diameter with height has also been observed by others in wind tunnel experiments (e.g., Williams, 1964) and in field measurements (Gillies et al., 2013), but as noted earlier this pattern is not universal (e.g., Williams, 1964; Xing, 2007; Speirs et al., 2008; Gillies et al., 2013). The reduction of mean particle diameter with passage of the saltators through the roughness array suggests that there is preferential removal of coarser grains through the height of the saltation layer. The removal is likely due to the preferential trapping of grains in zones of wind shear in the lee of the roughness elements that are below the threshold to keep particles in motion as well as long enough for particle inertia to be insufficient to carry them through to a zone of above threshold conditions. Deposits of sand were observed in the lee of roughness elements, most notably for the rows nearest the edges (i.e., rows 1 to 8 and 32 to 40).

Effect of Roughness on the Mass Flux in the Vertical Dimension

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3 316 This new data set, for the first time, allowed for an examination of the effect of roughness on the
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5 317 mass flux based on integration in the vertical dimension using the multi-height BSNE traps. As
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7 318 Figs. 9, 10 and 11 show, the saltation flux is altered by its interaction with the roughness array in
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9 319 the horizontal and vertical dimensions. With increasing distance into the array the sand in
10
11 320 saltation shows an increase in z_q (Fig. 9), which can, in part, be explained by the diminishing
12
13 321 total mass flux. In addition, the mean particle diameter at all but the top measurement position
14
15 322 decreases with increasing distance into the array (Fig. 11). The particle size distribution data
16
17 323 offers some explanatory power for why these patterns occur.
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19
20 324 According to Martin and Kok (2017a), for saltating sand over an essentially roughness-element-
21
22 325 free and relatively flat surface with no sediment supply restrictions, mean particle speed and z_q
23
24 326 remain constant with changing surface shear stress (τ , N m^{-2}) above threshold. Martin and Kok
25
26 327 (2017a) note that z_q is not constant for all surfaces, but is likely controlled by the particle size
27
28 328 distribution of the source sand. In the case studied in our experiment, where the saltating sand
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30 329 encounters and interacts with the large scale roughness, there are profound changes in the
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32 330 mass flux as well as z_q as a function of particle diameter. As z_q increases with distance into the
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34 331 array it suggests that particle speeds are changing as the saltating particles move through the
35
36 332 array at least to $ND=101.2$. An increase in z_q represents an increase in the characteristic
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38 333 saltator hop height (Owen, 1964; Ungar and Haff, 1987; Namikas, 2003; Kok, 2010). Since hop
39
40 334 height is determined by the speed at which particles are launched from the surface (Eq. 3),
41
42 335 which in turn depends on the mean particle speed (Owen, 1964; Ungar and Haff, 1987; Kok,
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44 336 2010), our observation of increasing z_q into the roughness array implies that the mean particle
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46 337 speed also increases for all particle sizes and with increasing distance into the roughness.
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50 338 The observed effect of z_q increasing with increasing distance into the array and with decreasing
51
52 339 particle diameter in the presence of the roughness is different from that observed for saltation in
53
54 340 the absence of superposed roughness. Martin and Kok (2017b) report for unconstrained

saltation on sand sheets, z_q increases with particle diameter up to the modal diameter of the sand (that is of the source sand) and then decreases for particle diameters less than the modal diameter.

We suggest that the effects on z_q and mean diameter in the case of the superposed roughness are occurring due to the reduction in saltation flux caused by the presence of the roughness elements. Mechanisms that are driving the loss are the change in wind shear exerted on the saltation layer with increasing distance into the array due to shear stress partitioning as the wind adjusts to this step change in roughness (Raupach et al., 1993; Gillies et al., 2007), and the interaction of the saltation with the roughness elements (Gillies and Lancaster, 2013).

According to Gillies et al. (2007), the shear stress ratio (R , Raupach et al., 1993) for $\lambda=0.045$ at $ND > 127.5$, should be ≈ 0.62 , which would reduce the shear stress on the surface (τ_s , N m^{-2}) at that position by $\approx 38\%$. Applying the Shao (2005) scaling relationship between shear stress, expressed as the shear velocity u_* (m s^{-1} , where $\tau = \rho_a u_*^2$ [ρ_a is air density, kg m^{-3}]) and sand flux (q , $\text{kg m}^{-1} \text{s}^{-1}$):

$$q = C_{Shao} \frac{\rho_a u_*^3}{g} \left(1 - \left(\frac{u_{*t}}{u_*} \right)^2 \right) \quad (6)$$

where C_{Shao} is a coefficient and u_{*t} is the threshold shear velocity, the reduction in q at $ND=127.5$ should be $\approx 76\%$ compared to the flux external to the array. At $ND < 127.5$ the partitioning of shear stress between the roughness elements and the surface will be changing as a function of ND into the array at an approximately exponential rate to approximately $ND=73$ to 93 (Gillies et al., 2007). Gillies and Lancaster (2013) observed first that the reduction in saltation flux observed in an array of large roughness elements was greater than could be attributed to shear stress partitioning by itself and suggested the physical interaction of the saltating sand with the roughness and the environment around the elements accounted for the additional reduction in sand flux by the elements physically impeding the movement of the

particles. The shear stress partitioning, the physical dimensions of the roughness, and their distribution on the surface result in a reduction in mass flux through the roughness as defined by Fig. 7.

The loss of particles from the saltating population explains why the particles appear to increase their mean speed as indicated by the increase in z_q (Figs. 12 and 13). A plausible mechanism for this is that slower particles are being preferentially removed as they have a reduced probability of making it deeper into the roughness. Slower moving particles are less likely to have the momentum necessary to carry them through zones of lower shear stress created by the presence of the roughness. Hence as saltators of a given size range pass through the array, their mean speed increases as the distribution of speed is increasingly truncated at the lower end of the distribution, which is supported by the observed increase in z_q with increasing distance into the array (Fig. 9). The wind close to the surface decreases with increasing distance into the array (Fig. 5), so the particles cannot be gaining speed through interaction with higher speed winds.

The measurements of particle size resolved flux exterior to the roughness provide additional information on the scaling of sand flux with wind speed under these supply-limited conditions. Martin and Kok (2017a) demonstrated with saltation flux data that the saltation layer height does not change with u_* , implying that mean particle speed also remains constant with u_* . When the flux versus height relationships are binned by particle diameter, it is observed (Fig. 12 at $ND=0$) that z_q increases with decreasing particle diameter, implying that for this sand transport condition the smaller diameter particles are travelling at a faster speed than the larger diameter particles, suggesting in this case that particle launch velocity increased with decreasing particle diameter. A likely reason why z_q increases with particle diameter exterior to the array, as opposed to the observation of Martin and Kok (2017b) showing an increase in z_q up to the modal diameter, followed thereafter by a decrease, is due to the supply-limited sediment

conditions on the playa. Under supply limited conditions, particle speed is controlled by the restitution coefficient, determined by the soil surface condition, and the wind speed. Smaller diameter particles enter into the array with greater speed than larger ones so only the fastest particles in each particle size bin make it deep into the roughness array, and hence z_q increases for decreasing particle diameter.

Conclusions

The effect of a step change in macro-roughness on the saltation process was examined at the full scale in the atmospheric boundary layer. The saltation flux was profoundly altered in the horizontal and vertical dimensions as a result of its interactions with the roughness. The horizontal flux was reduced by 90% ($\pm 7\%$) at a distance of ≈ 150 roughness element heights into the array as predicted by the empirical model of Gillies et al. (2015), for an array of roughness with $\lambda = 0.045$. These results provide further corroboration of the robust nature of this simple model to estimate sand flux reduction for roughness elements of height dimension of ≈ 0.4 m that are evenly distributed across space, providing increased confidence that it can be effectively used to engineer roughness arrays to meet sand flux reduction targets.

Measurements of the saltation flux characteristics in the vertical dimension, including particle size characteristics, revealed that with increasing distance into the array mean particle diameter became smaller, reducing in size as a function of distance as well as a logarithmic function of height above the surface. The distribution of the saltation mass flux in the vertical as a function of increasing distance into the roughness array, trended towards a more uniform distribution, although it remained exponential in form. This is only possible if there is a diminishment of the particle flux, which was observed. This diminishment of flux appears to be associated with the loss of the slower speed particles so that with increasing distance into the roughness, the mean particle speed for a given particle diameter is shifted to a higher value, but remains less than the maximum speed of the initial distribution of speeds. It will require additional experimentation to

resolve the behaviour of the particle speed distribution as a function of particle diameter through measurement of actual particle speeds within superposed roughness for both supply and transport limited conditions. Further information on the particle speed distribution in the presence of the roughness would also be informative on how the roughness modulated saltation flux affects the dust emission process.

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Table 1. The positions of the instruments relative to the roughness array.

Instrument	Between Row #s (from north edge)	Horizontal Distance (from north edge), m	Normalized Distance* (<i>ND</i> , from upwind [north] edge defined as zero to southern edge defined as 260.0)
Trap 1	N/A (exterior)	-10.0	0
Trap 2	3-4	6.2	16.3
Trap 3	8-9	18.6	48.9
Trap 4	16-17	38.5	101.2
Trap 5	26-27	60.8	159.9
Trap 6	33-34	80.6	212.1
Trap 7	38-39	93.0	244.7
Trap 8	N/A (exterior)	110.0	261.0
Tower 1	N/A (exterior)	-10.0	0
Tower 2	16-17	38.4	101.2
Tower 3	25-26	60.8	159.9
Tower 4	N/A (exterior)	110.0	261.0

*ND=horizontal distance/element height

Table 2. The collected mass and its height of collection for the eight BSNE traps for the four collection periods.

			2/10/2015		29/12/2015		17/03/2016		16/05/2016			
	Height (m)	NH	mass (g)	NM	mass (g)	NM	mass (g)	NM	mass (g)	NM	Mean NM	Std. D. NM
T1H1 ¹	0.21	1	11.5	1	101.17	1.00	2.79	1	178.78	1.00	1	0.00
T1H2	0.50	2.38	13.43	1.17	30.03	0.30	0.82	0.29	46.47	0.26	0.50	0.44
T1H3	0.83	3.95	NS ²		15.70	0.16	0.46	0.16	16.93	0.09	0.14	0.04
T1H4	1.28	6.10	NS		7.72	0.08	0.04	0.01	3.93	0.02	0.04	0.03
T2H1	0.18	1	11.07	1	174.89	1.00	1.34	1.00	167.81	1.00	1	0.00
T2H2	0.48	2.62	8.95	0.81	56.17	0.32	0.70	0.52	51.03	0.30	0.49	0.23
T2H3	0.79	4.30	9.42	0.85	22.21	0.13	0.42	0.31	17.73	0.11	0.35	0.35
T2H4	1.26	6.90	9.6	0.87	7.61	0.04	0.13	0.10	4.06	0.02	0.26	0.41
T3H1	0.17	1	8.92	1	73.52	1.00	1.18	1.00	56.98	1.00	1	0.00
T3H2	0.48	2.79	8.34	0.93	25.18	0.34	0.36	0.31	20.28	0.36	0.48	0.30
T3H3	0.78	4.61	7.43	0.83	15.98	0.22	0.68	0.57	9.76	0.17	0.45	0.31
T3H4	1.26	7.39	NS		6.57	0.09	0.49	0.41	3.90	0.07	0.19	0.19
T4H1	0.17	1.00	7.86	1	35.95	1.00	2.05	1.00	5.10	1.00	1	0.00
T4H2	0.47	2.76	7.72	0.98	18.05	0.50	1.52	0.74	5.48	1.07	0.82	0.26
T4H3	0.77	4.55	NS		14.28	0.40	1.36	0.66	1.19	0.23	0.43	0.22
T4H4	1.26	7.41	NS		10.13	0.28	0.78	0.38	3.30	0.65	0.44	0.19
T5H1	0.18	1.00	21.49	1	69.52	1.00	2.35	1.00	67.44	1.00	1	0.00
T5H2	0.48	2.67	9.65	0.45	19.42	0.28	2.03	0.86	14.85	0.22	0.45	0.29
T5H3	0.78	4.34	8.43	0.39	13.44	0.19	0.97	0.41	6.82	0.10	0.27	0.15
T5H4	1.26	7.01	7.41	0.34	8.95	0.13	NS		2.42	0.04	0.17	0.16
T6H1	0.20	1.00	40.02	1	70.30	1.00	3.64	1.00	38.16	1.00	1	0.00
T6H2	0.54	2.70	19.37	0.48	29.98	0.43	3.15	0.87	15.05	0.39	0.54	0.22
T6H3	0.81	4.05	7.57	0.19	21.26	0.30	2.49	0.68	7.44	0.20	0.34	0.23
T6H4	1.29	6.43	9.97	0.25	9.34	0.13	1.34	0.37	2.64	0.07	0.20	0.13
T7H1	0.19	1.00	118.01	1	179.80	1.00	23.01	1.00	150.75	1.00	1	0.00
T7H2	0.49	2.58	31.4	0.27	68.81	0.38	9.13	0.40	42.41	0.28	0.33	0.07
T7H3	0.78	4.16	11.78	0.10	38.57	0.21	5.75	0.25	20.02	0.13	0.17	0.07
T7H4	1.27	6.73	8.76	0.07	11.60	0.06	2.41	0.10	4.27	0.03	0.07	0.03
T8H1	0.20	1.00	230.6	1	331.94	1.00	33.53	1.00	412.79	1.00	1	0.00
T8H2	0.46	2.32	44.86	0.19	72.88	0.22	6.69	0.20	44.07	0.11	0.18	0.05
T8H3	0.80	4.02	14.97	0.06	26.50	0.08	2.02	0.06	12.15	0.03	0.06	0.02
T8H4	1.28	6.44	7.82	0.03	7.76	0.02	1.41	0.04	3.35	0.01	0.03	0.01
¹ T1H1: trap 1, height 1												
² NS: no sample, trap compartment was empty of sand

Figure 1. The roughness array on Owens Lake, CA. The view into the frame is towards the south and the dimensions of the roughness array are $\approx 100 \text{ m} \times \approx 100 \text{ m}$.

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Figure 2. The spacing of the elements and the positions of the near surface anemometers and wind vane with respect to the roughness elements (gray rectangles). The pattern of near surface anemometers and wind vanes is repeated at four locations through to 50 m into the roughness array.

Figure 3. The modified BSNE style trap (left panel) and the Cox Sand Catcher (right panel) used to collect saltating particles.

Figure 4. Wind roses for the site based on 10 m AGL wind speed and direction measurements at the northern (T1) and southern (T2) edges of the roughness array.

Figure 5. The change in near-surface wind speed ratio, *WSR*, as a function of normalized distance, *ND*. The x-error bars represent the standard deviation of *ND* based on the *ND* for each individual instrument (Positions 1 through 4) in the clusters of instruments from $ND=5.2 (\pm 2.9)$ through to $ND=137 (\pm 0)$ (see Fig. 2). The y-error bars represent the standard deviation of the mean *WSR* based on the 5-minute mean *WSR* values.

Figure 6. Mean normalized total sand flux, NSF_T (normalized to trap 8) for the four collection periods. The lines serve only to emphasize the groupings of the data points by collection period

Figure 7. Mean normalized total sand flux, NSF_T , as a function of normalized distance, ND , for traps 4 ($ND=160$), 5 ($ND=101.2$), 6 ($ND=48.9$), 7 ($ND=16.3$), and 8 ($ND=0$) representing the dominant transport of sand from south to north during the observation period for the BSNE traps (black circles, top panel) and the CSC traps (open circles, bottom panel). Error bars represent the standard deviation of the mean value for the multiple measurement periods. NSF_∞ was set to the calculated NSF_T value (0.10) for fitting the relationship defined by Eq. (5).

Figure 8. The relationship between normalized mass, NM , and normalized height, NH , as a function of shared trap positions at $ND=0$ (Traps 1 and 8, top panel), $ND=16.3$ (Traps 2 and 7, middle panel), $ND=48.9$ (Traps 3 and 6), and $ND=101.2$ (Traps 4 and 5, bottom panel).

Figure 9. The mean e-folding height (i.e., z_q in Eq. 1) for the sequence of four traps for sand transport direction from north to the south and south to north at equivalent ND positions. Error bars represent the standard deviation of the mean.

Figure 10. The relationship between mean particle diameter and NH for three collection periods for the trap grouping 8, 7, 6, 5, representing the south to north sand transport direction.

Figure 11. Observed change in the mean particle diameter as a function of normalized distance (ND) for trap grouping: 8, 7, 6, 5, characterizing the south to north transport direction for three monitoring periods.

Figure 12. z_q as a function of ND and particle diameter.

Figure 13. The rate of change in z_q as a function of particle diameter as defined by the m term in the relationship $z_q = m ND + b$ for each particle size bin.