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Change in the aerodynamic roughness height by saltating grains: Experimental assessment, test of theory, and operational parameterization

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Abstract. Data from an experiment at Owens Lake provided an opportunity to verify the validity of Raupach's formula that predicts the apparent roughness height at equilibrium with saltation during wind erosion episodes. In addition to that verification, a simplification of Raupach's formula is presented which allows the computation of the wind friction velocity affected by saltating sand grains without the need to measure the threshold wind friction velocity and to do iterative calculations. This method estimates the increase of the wind friction velocity Δu_* , above the nonsaltating wind friction velocity caused by the saltating grains: $\Delta u_* = 0.3 [U - U_t]^2$ where U and U_t are the wind speed and the threshold wind speed, respectively, at 10 m.

1. Introduction

When particles in a broad size-range are transported by the wind, they have ballistic trajectories, including saltation, in which the particles proceed mainly in a series of leaps. During saltation the soil grains interact with the air and transfer a part of the wind momentum to the ground. This phenomenon leads to an apparent increase of aerodynamic roughness height of the surface z_0 (the Owen effect). Owen's [1964] theory describes the modification of the wind velocity profile as a positive feedback to soil wind erosion by increasing the wind shear stress. Since increase in potential wind erosion is indirectly expressed as an increase of $z_{0\text{salt}}$, it is very important to account for it realistically. Recently, Raupach [1991] incorporated the theory of Owen [1964] to provide an expression to compute the aerodynamic roughness height of smooth or rough surfaces when a saltation layer is developed. Although some observational studies have presented data consistent with the Raupach formula, up to now there has not been a rigorous test of it. Wind tunnel studies were criticized by Raupach [1991] as having insufficient heights to develop equilibrium saltation layers and thus cannot be used to test the Raupach formula. Outdoor measurements by Rasmussen and Mikkelsen [1991] described the aerodynamic roughness height of beach surfaces during wind erosion but, unfortunately, without measurements of z_0 for the initial noneroding surfaces. Outdoor studies of wind erosion at Owen Lake [Gillette *et al.*, 1996] have shown statistically significant increases of aerodynamic roughness height caused by airborne sand but have provided too few data to test the Raupach formula. A later study done on another part of Owen Lake [Gillette *et al.*, 1997] presented data taken from three towers for more than a year. Because the data were from three simultaneously operating towers, each on an erodible

surface having a different surface roughness, and were of sufficient volume so that conditions near neutral stratification and constant wind direction could be maintained, the study could be used to test the Raupach formula.

The Raupach formula is not very easy to use because it requires knowledge of the threshold wind friction velocity and involves iterative computation. Thus a second purpose of this paper was to simplify the application of the Raupach formula. This simplification follows from and is an extension of the approach used by Marticorena *et al.* [1997a]. Part of their wind erosion model concerned the increase of the aerodynamic roughness height after the threshold of wind erosion had been exceeded. Specifically, these authors used a third-degree polynomial to fit friction velocities computed from Raupach's formula for wind speeds at 10 m above the surface and a range of aerodynamic roughness heights. For our calculation, we use a relationship between aerodynamic roughness height and threshold friction velocity. This approach is further developed by changing the form of the fitted polynomial and specifying values for constants of a polynomial approximation to the Raupach formula. Finally, we propose a formulation to compute the friction velocity during saltation that needs only the wind velocity and the initial roughness height of the surface as input parameters. The limitations of its use are discussed.

2. Raupach Formula

As mentioned above, Raupach [1991] incorporated the theory of Owen [1964] to provide an expression for the aerodynamic roughness height when saltation occurred on smooth or rough surfaces, $z_{0\text{salt}}$. The expression for $z_{0\text{salt}}$ is equal to aerodynamic roughness height for wind speed below the threshold of particle movement, i.e., for nonsaltating conditions, z_{0NS} , and is roughly equal to Owen's aerodynamic roughness height for saltation on smooth surfaces. The main advantage of Raupach's formula is that it extends Owens approach provides values for the aerodynamic roughness height for rough sur-

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faces that have particles moving in saltation and rationally approaches the limit of small u_* . The Raupach formula provides $z_{0\text{salt}}$ for a wider range of potentially eroding surfaces than Owen's theory does.

For conditions of no erosion we may express the change of wind speed with height [Kaimal and Finnigan, 1994] as

$$U(z) = \frac{u_*}{k} \ln \left(\frac{z}{z_{0NS}} \right) \quad (1)$$

where $U(z)$ is wind speed at height z , u_* is friction velocity, k is von Karman's constant (0.4), and z_{0NS} is aerodynamic roughness height for nonsaltating conditions.

For conditions when wind erosion is occurring, the aerodynamic roughness height during saltation $z_{0\text{salt}}$ is given by the Raupach formula as

$$z_{0\text{salt}} = \left[A \frac{u_*^2}{2g} \right]^{1-R} z_{0NS}^R \quad (2)$$

where A is a constant of the order of 1, and $R = u_{*t}/u_*$ where u_{*t} is the threshold friction velocity for wind erosion, and g is the acceleration of gravity. Thus three quantities are required for the evaluation of the Raupach formula: u_{*t} , u_* , and z_{0NS} .

3. Experimental Data

The data obtained by Gillette *et al.* [1997] consisted of friction velocities versus wind speed at 1 m height obtained on an erodible part of Owens (dry) Lake near the town of Keeler, California. The experimental surface was loose and sandy. The experimental sites and both upwind and downwind areas were flat and unvegetated for several kilometers. Three meteorological towers were spaced at distances of more than 1 km from each other. Although the surfaces at the tower sites were flat, differences in thickness of loose, sandy material overlying hard crusts and transport/drift of loose material resulted in different aerodynamic roughness heights from one tower to another and, at different times, at the same tower. The changes of aerodynamic roughness height caused by differing surface roughnesses for wind direction differences were minimized by restricting the data to the wind direction $326^\circ \pm 15^\circ$ (10 episodes) or $146 \pm 15^\circ$ (1 episode). Wind speed was measured at 1, 2, and 4 m for 20-min periods. Air temperatures were measured at 1 and 4 m. Richardson number Ri for the 20-min means were estimated using the wind and temperature data. More details on the experiment, including the size distribution of the lake-floor sediment, are given by Gillette *et al.* [1997].

To minimize stratification effects (as illustrated by Frank and Kocurek [1994], we chose wind speed for close-to-neutral conditions ($-0.03 < Ri < 0.03$). For negative Ri we estimate that the largest increase of friction velocity above that for neutral conditions using the corrections used by Gillette *et al.* [1997] would be about 10%. For stable conditions the friction velocity would be reduced by as much as 17%. The overall mean 80% confidence interval for the three sites is 13.5%.

The threshold friction velocities for wind erosion were evaluated by Gillette *et al.* [1997] as the lowest observed friction velocity at which particle movements (as detected by Sensit instrument response) were measured. Measured threshold friction velocities in 1993 for the three observational sites have a range from 39 to 48 cm s^{-1} . Since this range is quite limited, we used a constant value of 42 cm s^{-1} for the overall threshold friction velocities.

Apparent aerodynamic roughness height z_0 was computed for the data for each 20 min in (1) with z_0 substituted for z_{0NS} . Aerodynamic roughness heights z_{0NS} for noneroding conditions were averages of the z_0 values for nonsaltating conditions. To be sure we excluded cases where saltation occurred, we selected an upper limit for u_* equal to 38 cm s^{-1} which was below the lowest threshold velocity. We set the lower limit for u_* to be 20 cm s^{-1} because low gradients for low wind speeds led to unacceptable errors in friction velocity estimations. For the three sites, arithmetic mean aerodynamic roughness heights were calculated to be 0.01 (± 0.009), 0.01 (± 0.009), and 0.025 (± 0.01) cm for sites 5010, 5011, and 5012, respectively. These roughness heights were in relative qualitative agreement with observations of the surface.

4. Testing the Raupach Formula

The above values for u_* , z_{0NS} , and u_{*t} were used to calculate $z_{0\text{salt}}$ in (2) to compare with the z_0 values calculated from the experiment for $u_* > u_{*t}$. Figure 1 shows a comparison of the measured z_0 and the computed $z_{0\text{salt}}$ values when the A parameter of (2) is set to 0.38, which was the best fit to the data. Since Raupach had originally predicted the value of A to be 0.2 to 0.3, we claim consistency with the Raupach formula. The slope of the regression is close to 1 (0.97), suggesting good agreement between measured and computed aerodynamic roughness heights for a range of z_0 between 0.01 and 0.3 cm. The dispersion is relatively low and r^2 is 0.824 for 278 pairs of data. Although the standard deviations for the z_{0NS} measured at sites 5010 and 5011 are of the same order as the mean value (that is, the z_{0NS} have wide confidence intervals), the Owen effect (increase of aerodynamic roughness height with saltation) is seen in the order-of-magnitude change from dust-free conditions ($z_{0\text{salt}} \approx 0.25\text{--}0.3$ cm for the site where z_{0NS} is 0.025 and $z_{0\text{salt}} = 0.1\text{--}0.15$ cm for the two sites for which the z_{0NS} is 0.01 cm).

5. Influence of Saltation on Wind Velocity Profile

Because of the variation of the saltation roughness height with the wind friction velocity, one should expect an influence of the sand movement on the wind velocity profile. Below the threshold, in neutral conditions, the wind velocity vertical profile is logarithmic (equation (1)), and thus for a given initial roughness height, the wind friction velocity is proportional to the wind velocity at a given height:

$$u_{*NS} = KU(z) \quad (3)$$

with

$$K = k/\ln(z/z_{0NS})$$

This wind friction velocity (u_{*NS}) is referred as "nonsaltating," denoting that it is determined by the nonerodible roughness elements present on the surface. When the erosion threshold is reached, the roughness height of the surface varies as a function of the wind friction velocity; the relation between u_* and $U(z)$ becomes more complex. Equation (3) can be rewritten for saltation wind friction velocity $u_{*\text{salt}}$ (the friction velocity corresponding to the wind profile above the saltation layer, including the influence of the increase of the overall roughness height caused by the saltation layer):

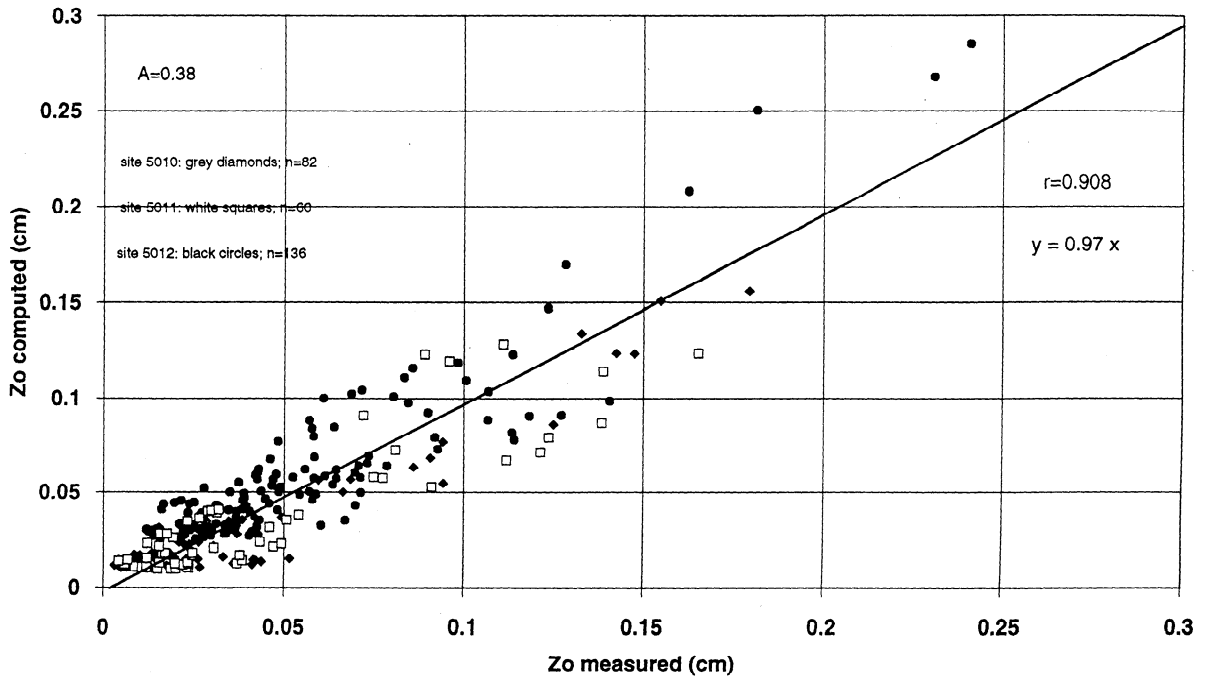


Figure 1. Saltation roughness heights $z_{0,\text{salt}}$ computed using Raupach's formula (Equation (2)) versus the apparent roughness height z_0 measured for wind friction velocity at three sites at Owens Lake (California).

$$u_{*,\text{salt}} = kU(z)[\ln(z) - \ln(z_{0,\text{salt}})]^{-1} \quad (4)$$

$$u_{*,\text{salt}} = a_0 + a_1U + a_2U^2 + a_3U^3 \quad (5)$$

Equations (3) and (4) indicate that one would expect a wind velocity (vertical) profile above the erosion threshold that is different from the one below.

Plots of u_* versus $U(z)$ are convenient tools to detect and to illustrate the influence of saltation because the experimental determination is more precise for friction velocities than for aerodynamic roughness heights. Figures 2a–2c show the measured wind friction velocities versus the measured wind velocities at 1-m height for each site. We plotted lines in the figures corresponding to velocities that could be obtained from a logarithmic profile with no saltation (equation (3)) using the measured $z_{0,\text{NS}}$. We also plotted the curve corresponding to (4).

All three sites for $u_* > u_{*t}$ show an increase of the wind friction velocity with saltation compared to the u_* computed with the log profile with no saltation. This increase of u_* due to saltation is significant because it is greater than 15% when the wind erosion threshold is exceeded by 25%. If we wish to find a value of $u_{*,\text{salt}}$ from knowledge of wind speed at a given height, (2) (Raupach's formula) and (4) give $u_{*,\text{salt}}$ on both sides of the equation. To avoid use of an iterative approach for finding $u_{*,\text{salt}}$, we need a way to easily compute the increase, Δu_* , of the wind friction velocity induced by saltation compared with that with no saltation.

6. Quantification of Wind Friction Velocity Increase Due to Saltation

6.1. Analytical Expression of Δu_*

Martcorena *et al.* [1997b] have used third-degree polynomials to fit the wind friction velocities computed from Raupach's formula (equation (2)) above the erosion threshold for wind speed at 10 m above the surface [$U(10)$] and a range of initial roughness heights

where a_0 , a_1 , a_2 , and a_3 are constants for a given initial roughness height.

By comparison with experimental data, Gillette *et al.* [1997] found that this expression can be further simplified because the zeroth- and third-order terms do not play a significant role in the results. Above the erosion threshold the saltation wind friction velocity can be written in the form

$$u_{*,\text{salt}} = b_1U + b_2U^2 \quad (6)$$

where b_1 and b_2 are constants.

This expression includes a term proportional to U , which is similar in form to the log-profile wind friction velocity of (1). Thus it seems that the saltation wind friction velocity can be decomposed into two terms, one representing $u_{*,\text{NS}}$, the non-saltating wind friction velocity, and the other representing the additional effect produced by the saltating particles:

$$u_{*,\text{salt}} = u_{*,\text{NS}} + \Delta u_* \quad (7)$$

Assuming that $b_1 = K$, it follows that the increase of wind friction velocity Δu_* must be proportional to U^2 . To ensure that Δu_* is equal to 0 at the erosion threshold, this term must be proportional to $(U - U_t)$ to some positive power, U_t being the wind velocity at the erosion threshold. So finally, we looked for an expression of Δu_* as a function of $(U - U_t)^2$.

In the previous section, we showed that the wind friction velocities computed with Raupach's formula for the saltation roughness height reproduce the experimental $u_{*,\text{salt}}$ versus U relation quite well. Considering Raupach's formula to be valid over a wide range of roughness height, we can compute the $u_{*,\text{salt}}$ for various initial roughness heights and use these values as a reference data set for fitting of Δu_* .

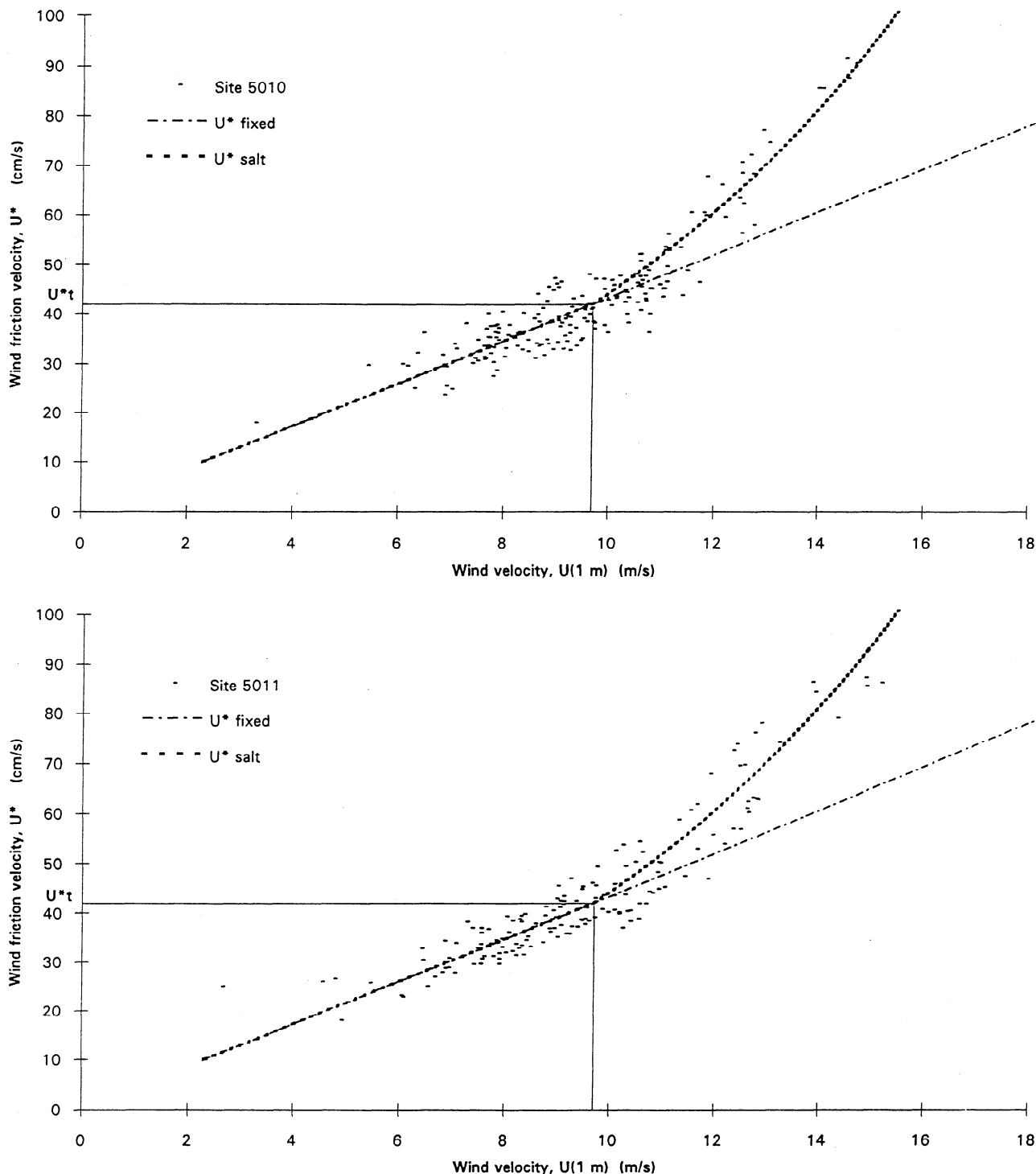


Figure 2. Wind friction velocity u_* versus wind velocity at 1 m $U(1\text{ m})$ for three different sites of Owens Lake: (a) site 5010, (b) 5011, (c) 5012). The dotted line is the saltation wind friction velocity computed using Raupach's formula for $z_{0\text{salt}}$ with the measured u_* , and z_{0NS} ; the dashed line is the wind friction velocity computed from equation (3) for nonsalting conditions. The threshold friction velocity u_{*t} is indicated by the solid horizontal line.

6.2. Parameterization of u_{*t} and U_t

To use Raupach's formula for various initial z_{0NS} values, we must allow for the change in u_{*t} resulting from changes in aerodynamic roughness height. Indeed, Marticorena and Bergametti [1995] showed that the threshold wind friction velocity is strongly dependent on the roughness height. These authors

derived a drag partition scheme from an approach developed by Arya [1975]. This scheme describes the partition of the wind energy between the erodible surface and the nonerodible elements. Marticorena and Bergametti's partition scheme expresses the ratio of wind friction velocity u_{*s} for a smooth erodible surface to the total wind friction velocity u_* , or the

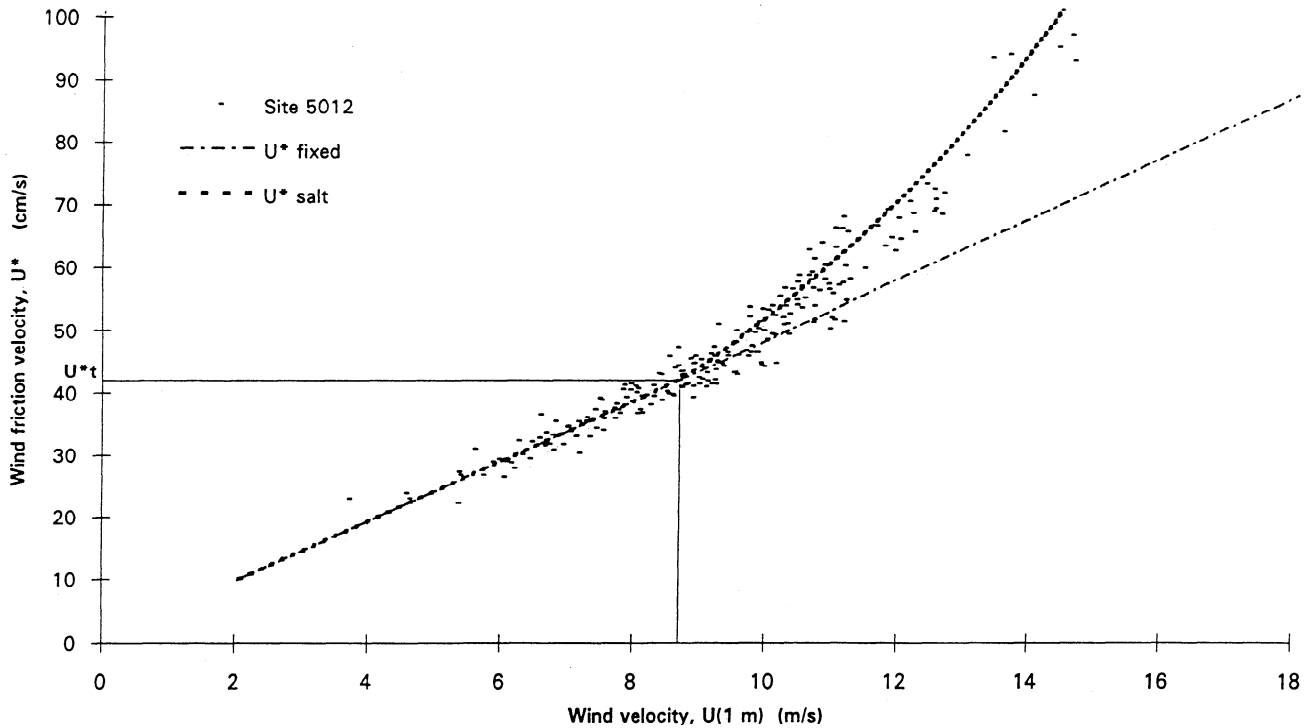


Figure 2. (continued)

so-called “efficient fraction,” f_{eff} . The purpose of this scheme is to express the drag partition as a function of the roughness height of the smooth erodible surface z_{0s} and of the roughness height induced by the nonerodible elements z_0 :

$$f_{eff} = \frac{u_{*s}}{u_*} = 1 - \frac{\ln \frac{z_0}{z_{0s}}}{\ln \left[0.35 \left[\frac{10}{z_{0s}} \right]^{0.8} \right]} \quad (8)$$

The threshold wind friction velocity u_{*t} is then expressed by

$$u_{*t} = u_{*ts} / f_{eff} \quad (9)$$

where u_{*ts} is the threshold wind friction velocity for a smooth surface.

On the basis of experimental data, *Martcorena et al.* [1997b] showed that this parameterization reproduces the measured threshold well when using a constant value for z_0 and u_{*ts} . The value of z_0 corresponds to the roughness height measured on the smoothest surface and is roughly 0.0005 cm. The value of u_{*ts} corresponds to the wind friction velocity of particles having diameters between 60 and 120 μm and is 21.7 cm s^{-1} .

Table 1. Measured Nonsalting Roughness Heights and Threshold Wind Friction Velocities for Three Sites at Owen Lake and Corresponding Threshold Wind Friction Velocity Computed Using Equation (9)

Site	z_{0NS} , cm	u_{*t} (cm s ⁻¹) Measured	u_{*t} (cm s ⁻¹) Computed
5010	0.0098	42	38.27
5011	0.0097	42	38.17
5012	0.025	42–47	50.37

For the three sites described above, the difference between the measured and the predicted value for the threshold wind friction velocities is about 10% (see Table 1). Since the uncertainty of the measured threshold is also about 10%, we are satisfied with the agreement.

At the erosion threshold the wind profile is described by (3), so that U_t can be computed from u_{*t} using the nonsalting roughness height in (1). On the basis of this parameterization we defined 10 m height U_t for roughness height ranging from 0.0005 to 0.1 cm and wind friction velocity u_{*t} shown in Table 2.

6.3. Parameterization of Δu_*

For each initial roughness height, we have computed the wind friction velocities using Raupach’s formula for the salta-

Table 2. Aerodynamic Roughness Height, Threshold Friction Velocity, and Threshold Wind Velocity at 10 m

z_0 , cm	u_{*t} , cm s ⁻¹	U_t , m s ⁻¹
0.0005	21.70	7.87
0.00075	23.06	8.13
0.001	24.1	8.34
0.0025	28.34	9.14
0.005	32.63	9.96
0.0075	35.81	10.56
0.0085	36.92	10.78
0.01	38.47	11.07
0.02	46.84	12.67
0.03	53.68	13.97
0.04	59.87	15.16
0.05	65.77	16.28
0.06	71.52	17.38
0.07	77.22	18.47
0.08	82.96	19.56
0.09	88.78	20.68
0.1	94.72	21.81

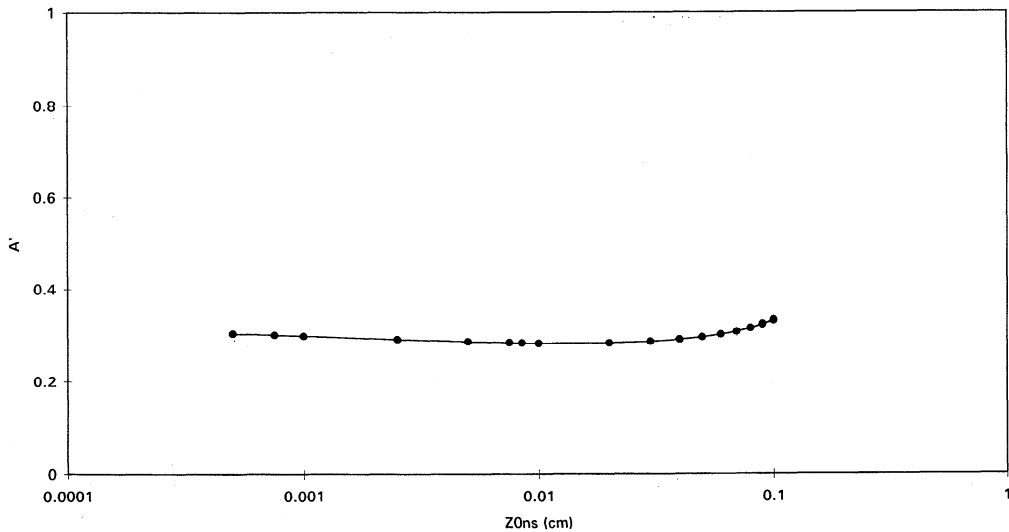


Figure 3. Plot of the coefficient A' (equation (11)) versus z_{0NS} for a data set based on saltation wind friction velocities computed by using Raupach's formula for z_{0salt} and using a parameterization of u_{*t} as a function of z_{0NS} .

tion roughness height and the corresponding wind velocity at 10 m height. This data set corresponds to saltation wind friction velocities up to $u_{*salt} = u_{*t} + 115 \text{ cm s}^{-1}$ by steps of 0.25 cm s^{-1} .

From these wind velocities and the initial roughness heights, we computed the wind friction velocity corresponding to a nonsaltating situation, assuming a logarithmic wind profile. On the basis of this data set of u_{*salt} , $U(10 \text{ m})$, and u_{*NS} we have computed Δu_* .

$$\Delta u_* = u_{*salt} - u_{*NS} \quad (10)$$

Then we fitted Δu_* as a function of $(U - U_t)^2$:

$$\Delta u_* = A'(U - U_t)^2 \quad (11)$$

Coefficients A' obtained from this fitting are plotted versus the initial roughness height in Figure 3. We see that A' decreases slowly from $z_{0NS} = 0.005$ to 0.02 cm and then in-

creases more rapidly from $z_{0NS} = 0.02$ to 0.1 cm . The values range from 0.282 to 0.333 which represents a maximal difference of 15% . Consequently, this coefficient can be considered constant over the whole range of z_0 and equal to 0.3 without large error.

Thus the increase of wind friction velocity caused by saltation of soil particles can be simply described by (11) where A' is equal to 0.3 . To evaluate the error for estimated Δu_* , we compared the saltation wind friction velocity computed by using Raupach formula to the wind friction velocity computed from (7) and (11).

Figure 4 represents the mean relative error over the tested range of wind friction velocity, in terms of the 10-m wind velocity as a function of z_{0NS} . This mean error decreases as z_{0NS} increases. It is about 5% for the minimal value of $z_{0NS} = 0.0005 \text{ cm}$ and of 2% for $z_{0NS} = 0.01 \text{ cm}$. These values are of the same order of magnitude as the difference between the

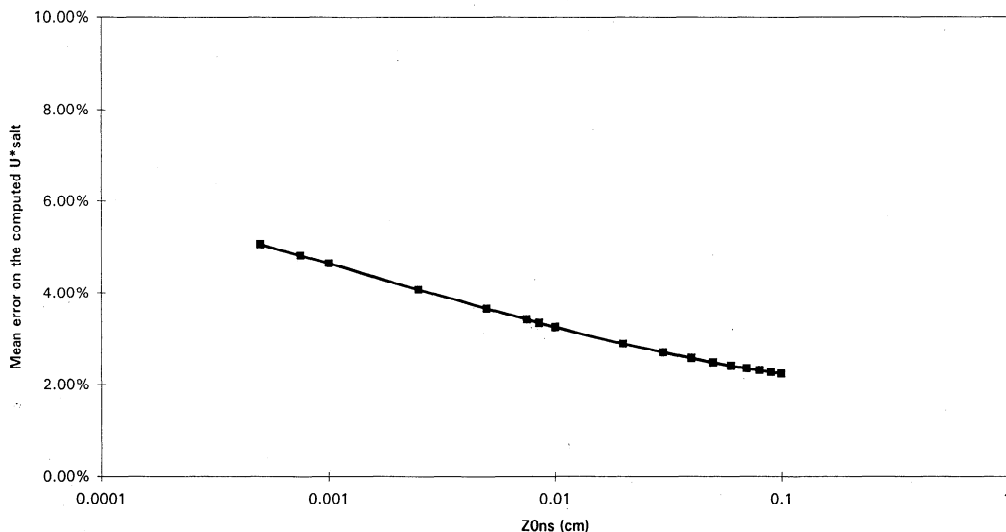


Figure 4. Plot of the mean errors of the computed saltation wind friction velocity using equation (12) where the "correct value" is the iterative computation using Raupach's formula.

experimental data and the wind friction velocity computed with the Raupach formula (Figure 2).

7. Conclusions

Data from an experiment at Owens Lake have provided an opportunity to test the validity of the formula proposed by Raupach [1991] to describe the change of the roughness height during saltation episodes. The agreement between measured and predicted values of the roughness height shows that the Raupach formula reproduces the increase of friction velocity due to saltating particles very well.

To use Raupach's [1991] formula to calculate $z_{0\text{salt}}$ from wind speed and nonsaltating aerodynamic roughness height, one must (1) obtain information on the threshold wind friction velocity and (2) do iterative calculations.

Our method for computing $u_{* \text{salt}}$ is based on wind velocity at 10 m and initial roughness height. This method consists of estimating the increase of the wind friction velocity Δu_* caused by the saltating grains above the wind friction velocity corresponding to nonsaltating conditions.

$$u_{* \text{salt}} = u_{* \text{NS}} + 0.3(U - U_t)^2 \quad (12)$$

with $U_t = u_{* \text{NS}} / (K f_{\text{eff}})$, K being expressed in (3) and f_{eff} in (8).

This expression gives results similar to the interactive computation using Raupach's formula of the saltation roughness height z_0 . Because it provides a direct relation between the saltation wind friction velocity and the parameters that can be easily measured (the wind velocity and initial roughness height in nonsaltating conditions), it is a convenient tool for modeling Owen's effect. In addition, this scheme and equations could be used to evaluate regional aeolian sediment transport potential, if estimates of z_0 can be obtained (e.g., through orbital radar data).

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