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Factors Affecting the Stochastics of Near-Surface Wind Speeds in Wind Storms

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Summary:

Wind erosion event intensities vary from occasional saltation to massive storms resulting in significant soil loss and fugitive dust. We examined soil loss data from 172 wind erosion events at Big Spring, Texas, USA to determine the range and distribution of event-wise soil loss. We also collected 1 s wind speed profiles in six fields with differing soil surface conditions and vegetative residues. We found that soil loss from wind erosion events was log-normally distributed and that the most intense 10% of wind erosion events accounted for 50% of the total soil loss. We also found that 2-m mean wind speeds < 12 – 14 m s^{-1} resulted in normally distributed near-surface wind speeds that were always less than the 2-m mean. Mean 2-m wind speeds greater than 12 – 14 m s^{-1} resulted in non-normally distributed near-surface wind speeds and the 95th percentile wind speed was greater than the 2-m mean.

Resume:

Les intensités d'événement d'érosion de vent changent du saltation occasionnel à massif donne l' assaut à ayant pour résultat la perte significative de sol et la poussière de fugitif. Nous avons examiné des données de perte de sol de 172 événements d'érosion de vent au Big Spring, Texas, USA pour déterminer la gamme et la distribution de la perte événement-sage de sol. Nous avons également rassemblé des profils de 1 de s vitesse de vent dans six domaines avec des états extérieurs différents de sol et des résidus végétatifs. Nous avons constaté que la perte de sol des événements d'érosion de vent était notation-normal distribuée et que le 10% le plus intense d'événements d'érosion de vent a représenté 50% de toute la perte de sol. Nous avons également constaté que des vitesses de vent moyennes de 2-m <12 - 14 m s^{-1} ont eu comme conséquence les vitesses de vent proches de la surface normalement distribuées qui étaient toujours moins que le moyen de 2-m. Vitesses de vent du moyen 2-m 12 plus grands que - 14 m s-1 ont eu comme conséquence des vitesses de vent proches de la surface non-normally distribuées et la quatre-vingt-quinzième vitesse de vent de percentile était plus grande que le moyen de 2-m.

Introduction

Wind erosion is a soil degrading process that results from the interaction of wind with unprotected soil surfaces. Wind erosion events vary from a few minor episodes of saltation following turbulent gusts to catastrophic storms that reduce visibility to scales of meters and result in fugitive dust clouds transported thousands of kilometers. Over the last half century, predictive wind erosion models have been developed and have advanced from relatively simple empirical equations such as the Wind Erosion Equation (Woodruff and Siddoway, 1965) to more recent mechanistic models such as the Wind Erosion Prediction System (Hagen, 2004). Wind speed (u) data is an input parameter common to all wind erosion models. Earlier models predicted wind erosion over monthly or annual time periods and used monthly mean u data as input since that was all that was available for many locations. More recent models have the ability to predict erosion activity at shorter time steps and can use 1 minute mean u data that are currently available for many locations. Where 1 minute means are not available, weather generators have been used to stochastically generate 1 minute u from hourly or daily means. These weather generators typically use a 2 parameter gamma function, 2 parameter Weibull function, or, preferably, an existing database to randomly assign varying instantaneous values based on the reported mean (van Donk et al., 2005).

Although the wind impacting the surface is the actual motive force initiating wind erosion, u is almost exclusively measured at 2-m above the surface. The minimum u necessary to cause particle movement is termed the threshold velocity (v_t). Research performed in wind tunnels has shown that v_t may be as low as 0.2 m s^{-1}. As wind moves over the earth's surface, friction with the surface results in a logarithmic decrease in u as the surface is approached and u at any height (z) above the surface, u_z, is described by Prandtl's equation:

$$u_z = \mathrm{k}\, u^* \ln(z/z_o) \qquad \text{(Eq. 1)}$$

where k is von Karman's constant (~0.4), u^* is the friction velocity, and z_o is the aerodynamic roughness height at which u approaches 0. Thus, recorded 2-m u greatly in excess of 0.2 m s^{-1} may not result in particle movement. The models have evolved to fit available data, in this case 2-m mean u ($\bar{u}_{2m}$), and various models define v_t as $\bar{u}_{2m}$ of 5 to 7 m s^{-1}.

The friction posed by the surface roughness creates shear stresses within the moving airmass, resulting in turbulent eddies that dissipate energy. At larger values of u, the eddies increase in size and become more efficient dissipaters (Clifford and French, 1993). This turbulence causes variations from the mean wind speed at all heights near the surface. Thus mean wind speeds less than v_t may be composed of short duration gusts during the averaging period in excess of v_t. The gusts are the result of the detachment and ejection of laminar air flow near the surface and a subsequent sweep phase of wind across the surface that may trigger additional bursts. At wind speeds approaching v_t , these intermittent gusts result in spatial and temporal patterns of particle movement, primarily saltation. Although time averaged rates of saltation have been widely used and correlate well with $\bar{u}_{2m}$, extremely high saltation rates subsequent to turbulent gusts may dominate the process (Hardisty, 1993). Recently, Stout (2004) has proposed the use of $\bar{u}_{2m}$ resulting in saltation > 50% of the time to define v_t.

During a recent validation exercise of several wind erosion models using event-wise field measured soil loss and the event 10 minute $\bar{u}_{2m}$, it was found that a model containing a stochastic generator tended to underestimate large magnitude storms and overestimate smaller events when using a constant stochastic perturbation factor (Van Pelt et al., 2004). Because of this observation, we initiated this study to investigate the statistical distributions of soil loss from wind erosion events at a single location and to investigate instantaneous near-surface u ($u_{0.01}$) stochastics for a broad range of $\bar{u}_{2m}$ over several agricultural fields.

Methods and Materials

The measured soil loss from 172 wind erosion events (Fryrear et al., 1998) were sorted from least to greatest and cumulative soil loss was calculated. Saltation impact records collected from piezo-electric impact sensors during the 1993, 1994, and 1995 wind erosion seasons were summed over 1 hour periods and plotted against the corresponding 1 hour $\bar{u}_{2m}$.

In the 2001 5 month wind erosion season, anemometer masts consisting of cup anemometers at 0.5, 1.0, and 2.0-m and a fast response hot wire anemometer at 0.01-m above the surface were installed on 6 agricultural field surfaces representative of field conditions during the fallow period. These surfaces were: 1.) a bare flat crusted surface; 2.) a bare surface with eroded beds spaced 1-m apart; 3.) freshly raised beds spaced 1-m apart; 4.) freshly raised beds spaced 0.75-m apart; 5.) eroded beds on 1-m spacing with sorghum residue mowed to a 0.15 m height; and 6.) a flat surface with initially standing and progressively flattened small grain residue. Measured u data were collected from all anemometers at a frequency of 1 Hz for all time periods that the 5 min $\bar{u}_{2m}$ exceeded 3.5 m s^{-1}. We calculated $\bar{u}_{2m}$ at 1 min intervals and all $u_{0.01}$ were sorted from least to greatest for each 1 min averaging period. The resulting data sets were analyzed for distribution properties using the FREQ procedure in SAS v. 8.2. Points of variation from behavior at lesser $\bar{u}_{2m}$ termed 'knot points' and were fit to the 95th percentile curves of $u_{0.01}$ using the REG procedure in SAS v. 8.2.

Results and Discussion

The cumulative probability of event-wise soil loss for 172 wind events at Big Spring, Texas is presented in figure 1. The strong log normal nature of the distribution is evident from the log scale spanning four orders of magnitude. The single largest wind storm accounted for 7% of the total soil loss and the 17 largest events (10%) accounted for half the total soil loss. The saltation impact sensor hourly sums for wind events during the 1993, 94, and 95 erosion seasons are presented in figure 2. Although saltation was observed to occur at all hourly $\bar{u}_{2m}$ greater than 2 m s^{-1}, it increased greatly for hourly $\bar{u}_{2m}$ greater than 6 m s^{-1}. This explains visual observations of intermittent saltation during wind events with smaller $\bar{u}_{2m}$ and more continuous saltation activity covering a larger area at greater $\bar{u}_{2m}$.

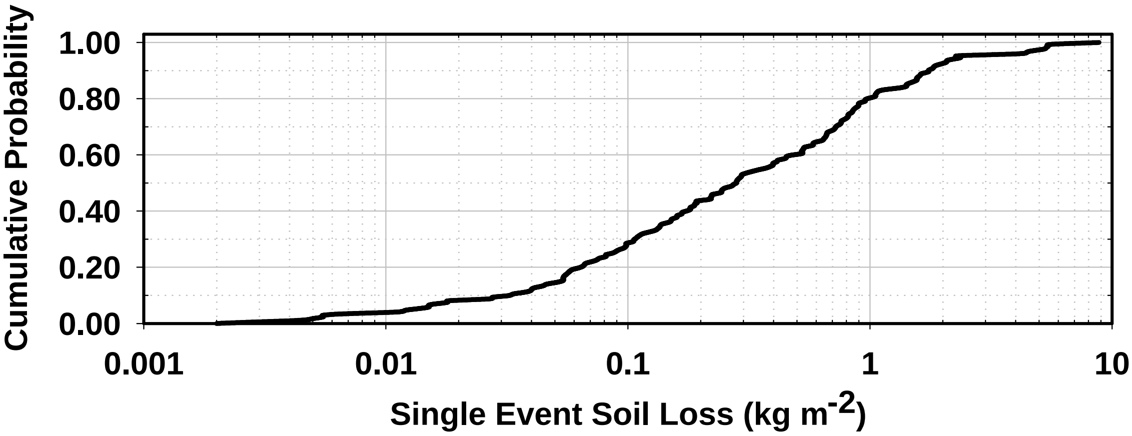

Fig. 1. Cumulative probability density function of measured event-wise soil loss for 172 wind events observed in Big Spring, Texas during 8 years from 1989 to 1997.

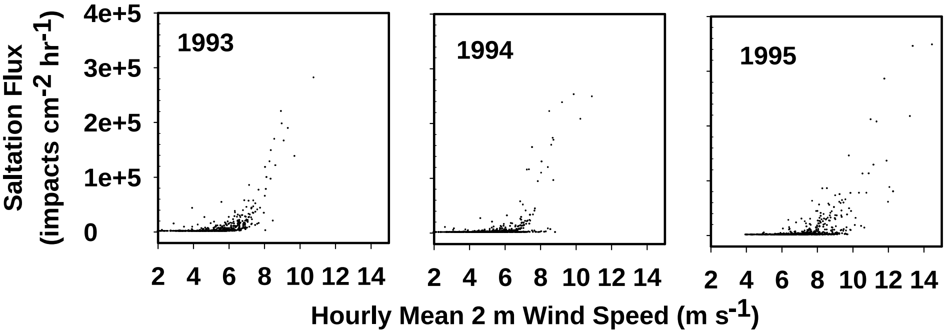

Fig. 2. Hourly summed saltation impacts as a function of hourly mean u at 2m.

The cumulative probability curves for $u_{0.01}$ at 4 different $\bar{u}_{2m}$ classes ($\bar{u}_{2m}$ +/- 0.5 m s^{-1}) are presented by surface type in figure 3. We originally expected the curves to be shaped like the curves for the 4, 8, and 12 m s^{-1} $\bar{u}_{2m}$ classes over the eroded 1 m ridges and the fresh 0.75 m ridges. We expected that the variability of $u_{0.01}$ would scale with the $\bar{u}_{2m}$ resulting in a more relaxed slope and predictably different Weibull coefficients for larger $\bar{u}_{2m}$ classes. Although the jagged nature of the line reveals that there are fewer observations in the 16 m s^{-1} $\bar{u}_{2m}$ class than the other three classes, the end sections of the curves are very different for the soil surfaces devoid of crop residue. There are both greater percentages of the time that $u_{0.01}$ is 0 at the lower end of the curves and much larger values of $u_{0.01}$ at the upper end of the curve. It is also obvious that the near maximum values of $u_{0.01}$ are greater than 16 m s^{-1}.

Plots of 95th percentile $u_{0.01}$ with respect to 1minute $\bar{u}_{2m}$ are presented in figure 4. Although for much of the range of $\bar{u}_{2m}$ the relationship is reasonably consistent among treatments and linearly related, there is a definite value of $\bar{u}_{2m}$ at which the slope of the line changes notably for all surfaces but the mowed sorghum residue. These ‘knot points’ indicate that the nature of turbulence at the surface changes rapidly at certain values of $\bar{u}_{2m}$ that are surface specific. In the case of the standing small grain residue, the ‘knot point’ represents a value of $\bar{u}_{2m}$ at which the 95th percentile $u_{0.01}$ reaches an asymptote beyond which it no longer increases. For the surfaces devoid of residue however, the ‘knot points’ represent values of $\bar{u}_{2m}$ for which the 95th percentile $u_{0.01}$ may actually exceed $\bar{u}_{2m}$. The ‘knot points’ fit for the different surfaces are presented in the lower right corners of figure 4. At and above these values of $\bar{u}_{2m}$, the burst and sweep mode of turbulence is occurring on time scales of at least once a minute. We believe this change in the nature and intensity of turbulence observed at $\bar{u}_{2m}$

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greater than the 'knot points' is the mechanism responsible for observations of extreme soil loss and dust generation during very high intensity wind events.

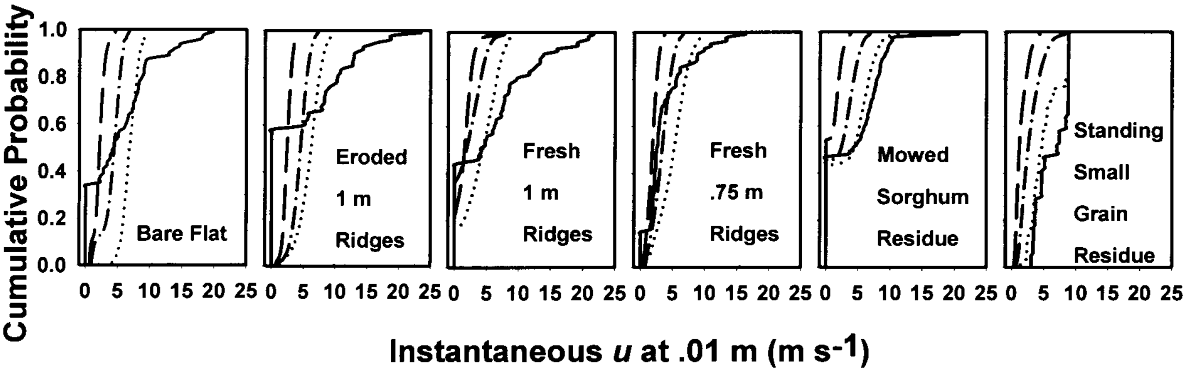

Fig. 3. Cumulative probability density functions of instantaneous *u* at the 0.01 m height for four classes of 2-m mean *u* ($\bar{u}$ +/- 0.5). The dashed line represents 4 m s^{-1}, the alternating dash and dot line 8 m s^{-1}, the dotted line 12 m s^{-1}, and the solid line 16 m s^{-1}.

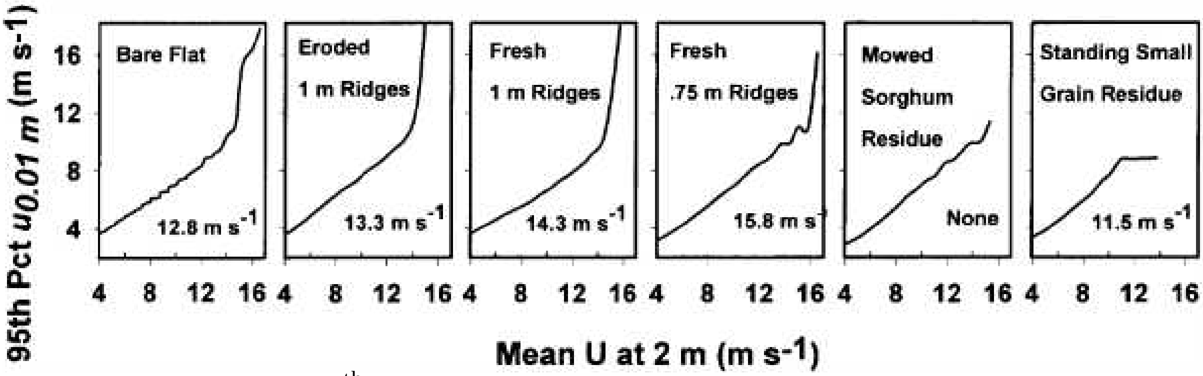

Fig. 4. Response of the 95th percentile instantaneous *u* at 0.01 m as a function of 2-m mean *u*.

Conclusions

It is clear from the log normal distribution of event-wise soil loss that a very few strong events are responsible for most of the soil loss due to wind erosion. This can be explained by an apparent secondary v_t of $\bar{u}_{2m}$, represented by 'knot points', above which $u_{0.01}$ increases markedly resulting in a great increase of energy available to move and entrain the soil. This may also explain why the Weibull function is not an accurate stochastic generator for $\bar{u}_{2m}$.

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