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Threshold wind velocities for sand movement in the Mescalero Sands of southeastern New Mexico

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ABSTRACT

Saltation activity and threshold velocities were measured at two Chihuahuan Desert sites located in the Mescalero Sands to the east of Carlsbad, New Mexico. Sand movement was detected with piezoelectric saltation sensors, and these data were used to calculate saltation activity and threshold wind speeds for the two sites. Significant blowing events were observed on nine days of this 112-day study, and it was only during these active periods that threshold values could be calculated. During periods of sand transport, threshold values were calculated every 5 min. Average threshold values typically exceeded 10.5 m/s at both sites; these are about twice those measured previously at a less vegetated dune site in West Texas. Less saltation activity occurred at the Gnome site compared with the Near Field site, especially during April; and while this can be partially attributed to differences in wind speed, additional studies are needed to evaluate other important factors such as the influence of undulating terrain and complex vegetation. Nevertheless, the results demonstrate the feasibility of long-term unattended monitoring of wind erosion activity in remote locations and that reliable and consistent estimates of threshold velocity can be obtained in complex desert environments using the time-fraction-equivalence principle.

1. Introduction

East of the Pecos River in New Mexico, lies a vast sand sheet called the "Mescalero Sands", a name first introduced by Darton and Reeside (1926) of the United States Geological Survey. These undulating hills of fine sand extend eastward from the Pecos River to the Mescalero Escarpment, which forms the western edge of the Llano Estacado (Bretz and Horberg, 1949; Hall and Goble, 2008). Over most of its range, the Mescalero Sands have been partially stabilized by a complex mixture of vegetation, including shinnery oak (*Quercus havardii*), yucca (*Yucca campestris*), sand sagebrush (*Artemisia filifolia*), mesquite (*Prosopis glandulosa*), and various grasses (Hall, 2002). Due to the unreliable nature of rainfall in this area, which on average amounts to just over 300 mm per year, the vegetative cover is rarely continuous; typically, there are open patches of bare sand between individual plant clusters, providing opportunity for wind-induced sand movement.

The wind regime of the Mescalero Sands is characterized by strong winds during the late winter and spring months of March, April and May (NOAA, 2008); during which time the prevailing erosive winds are out of the southwest (Chepil et al., 1964; Muhs and Holliday, 2001). Average wind speeds during the spring hover around or just below 5 m s^{-1} in the Pecos Valley, which is approximately 20% lower than the windier high plains of the Llano Estacado to the east (NOAA, 2008). Nevertheless, during the spring, sustained wind speeds that often amount to two or three times the modest average wind speed may persist for periods of more than a few hours, and it is during these periods that strong wind gusts detach and transport the Mescalero Sands.

The portion of the Mescalero sand sheet east of Carlsbad is of special interest due to the fact that the area has a history of underground nuclear tests and is presently used for underground storage of low-level nuclear wastes. The Project Gnome site, located in southeastern New Mexico, was contaminated with artificial radionuclides in 1961 when the underground test of a 3-kiloton ^{239}Pu device caused venting of radioactive materials to the surface (Gard, 1968). That was the first detonation conducted for the Plowshare Program whose main objective was to develop nuclear explosives for peaceful applications. Remediation activities have since been conducted at the Gnome site, and even though the contamination is below risk-based action or clean-up levels, ^{137}Cs and plutonium have been detected in some samples of surface soils (DOE/NV, 2005; NNSA/NV, 2002). These contaminated soils are a practical concern because they are a potential source of

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contamination for environmental samples being collected to monitor potential releases of radionuclides from the Waste Isolation Pilot Plant (WIPP), a deep underground repository for low-level nuclear wastes, located ~14 km northeast of the Gnome site.

As a result of this concern, a field study was conducted at the Gnome site to investigate aeolian activity that could produce contaminants that could be transported to the WIPP site. Atmospheric transport is the main pathway of concern in this regard, and obtaining information on the dynamics of wind erosion and associated resuspension is considered a key first step needed to evaluate the potential mobilization of Gnome-derived radionuclides (Arimoto et al., 2005). This was a comparative field study designed in part to determine the potential for soil erosion at the Gnome site and at a reference site called Near Field, which was located within the WIPP land-withdrawal area (Arimoto et al., 2002,2005, Kirchner et al., 2002).

The investigation centered on measurements of saltation activity at the two sites and the relationship between wind strength and wind erosion; the main point of interest being the threshold wind velocity of the sands in this complex, partially vegetated environment. Details of the experimental approach will be described later in more detail, but briefly the objective was to measure saltation activity and thereby determine threshold wind velocities in the field, that is, the wind velocities at which aeolian sediment transport was initiated. These threshold velocities were calculated from measurements of saltation activity and the mean and standard deviation of wind speed (Stout, 2004).

1.1. Past work

The experimental system used for this study was successfully employed in prior field studies, but those tests were conducted at sites with much less complex relief and especially less vegetation than is typical of the Mescalero Sands of the northern Chihuahuan Desert. For example, previous studies were conducted on eroding cropland on the Llano Estacado (Stout and Zobeck, 1997) and on a section of flat bare sands in the Lea-Yoakum dune fields of northwestern Texas (Stout, 2004,2007). Interest in determining how the system functioned in more complex terrain was another major motivation for the present study.

There have been numerous past attempts to study wind erosion processes in the relatively complex environment of the northern Chihuahuan Desert. Much of this work has focused on the Jornada Experimental Range north of Las Cruces, New Mexico, where studies have been ongoing for more than 100 years, beginning with the pioneering work of Wooton (1908). Today, the Jornada Searchable Bibliography, maintained by the USDA-Agricultural Research Service and New Mexico State University, contains over 2000 publications that document the extensive research history of the Jornada Range. The Mescalero Sands, on the other hand, have garnered much less attention. There have been a number of studies of the vegetation and wildlife of the Mescalero Sands region (Henderson, 2006; Peterson and Boyd, 1998) and there have been a number of excellent studies of the geomorphology, stratigraphy, and age of dunes and other sedimentary deposits of the region (Bretz and Horberg, 1949; Hall and Goble, 2006; Holliday, 2001; Price, 1987); however, we are not aware of any past attempts to measure active wind erosion processes in the Mescalero Sands region using sampling systems capable of detecting sand transport while measuring relevant meteorological factors.

2. Methods

Two essentially identical sampling systems were deployed; one at Near Field (32.37788°N, 103.79873°W) and the other at the Gnome site (32.26580°N, 103.86768°W) (Appendix 1 electronic version only). Each sampling system was designed to operate unattended for extended periods, powered by 12 Volt batteries that were charged daily by solar power. At the core of each sampling system was a data-logger mounted on a 2-m tall meteorological tower equipped with sensors for measuring wind speed, relative humidity, precipitation, solar radiation, and air temperature. Meteorological variables were sampled at 1 Hz and averaged over 5-minute intervals.

Sampling of saltation activity made use of a device known as a Sensit saltation sensor – a commercially available piezoelectric transducer used to detect the movement of wind-blown particles (Stockton and Gillette, 1990). Each sampling system had one Sensit mounted several meters to the west of the meteorological tower (Appendix 2 electronic version only). Care was taken to place each Sensit in an open patch of less vegetated sand; thereby ensuring that the measured threshold represented the lowest wind speed required to set sand in motion. During periods of active saltation, the piezoelectric transducer produced a signal that was used simply as an on-or-off indicator of saltation activity. That is, when the impact of one or more saltating grains was detected during a given second then that second was registered as one "saltation second". At the end of each 5-minute period, saltation seconds were summed and divided by 300 s to form a dimensionless parameter called "saltation activity".

The underlying assumption for the present study is that saltation activity, here referred to as the dimensionless fraction of time that active saltation was observed, is equal to the fraction of time that winds exceed the threshold for sand movement (Stout and Zobeck, 1996). This time-fraction-equivalence principle allows one to calculate the threshold wind velocity (u_t) for each 5-minute sampling interval using the following equation (Stout, 2004):

$$u_t = \overline{u} - \sigma\Phi^{-1}(\gamma)$$

where $\bar{u}$ is the arithmetic mean wind speed, σ is the standard deviation of wind speed, Φ^{-1} is the inverse of the normal distribution function, and γ is saltation activity, defined as the fraction of time during each 5-minute period that the Sensit detected impinging particles. Calculations of threshold were made whenever the total number of saltation seconds during each 5-minute period was greater than 5 s because prior studies have shown that values of threshold are less reliable when values of saltation activity are close to zero (Stout, 2007).

Although we had planned to deploy the system in March to take full advantage of the strong spring winds, we were not able to secure permission to use the sites until April. Both sampling systems were deployed on 7 April and began collecting data at midnight (8 April) and we were able to obtain a continuous record until the termination of the field study on 29 July 2005. Other than routine exchanges of data storage modules, the sampling systems were left unattended during the course of the experiment.

3. Results and discussion

This study provided continuous records of saltation activity and local meteorological conditions at both sampling sites over a four-month period extending from 8 April to 29 July 2005. Full records of saltation activity are plotted as time series in Fig. 1. Note that blowing events appear as sudden bursts of saltation activity that extend outward with varying magnitude. Periods of aeolian activity are highly intermittent, characterized by long periods of inactivity punctuated by relatively short bursts of blowing sand. These bursts of saltation activity occur during those exceptional periods when

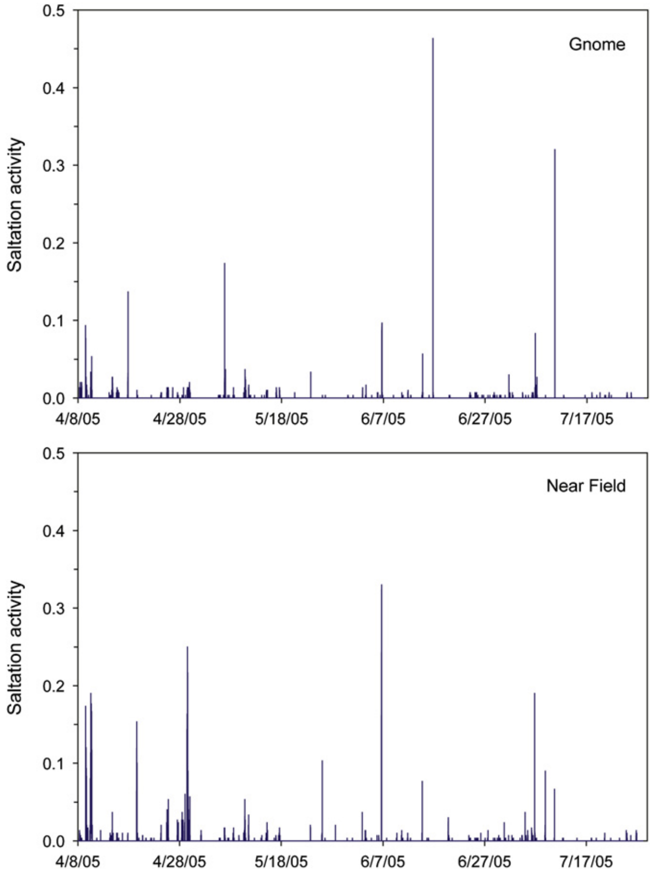

Fig. 1. Time-series plots of saltation activity measured simultaneously at both sites.

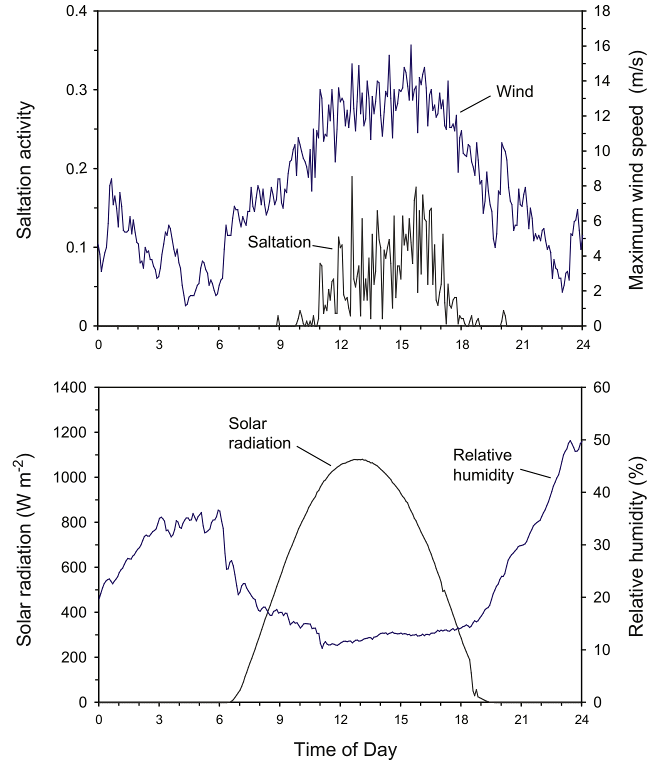

Fig. 3. Plot of measured 5-minute saltation activity, maximum wind speed, relative humidity and solar radiation for the blowing event that occurred at the Near Field site on 10 April 2005.

both atmospheric and surface conditions are favorable for sand transport.

Maximum five-minute saltation activities were typically below 0.5 (maximum of 0.33 at Near Field and 0.46 at Gnome) indicating that sand transport was never observed during more than half of any five-minute sampling interval. This contrasts with data collected at the Morgenstern Dunes of West Texas where five-minute saltation activities often approached unity, indicating periods of continuous sand movement (Stout, 2004,2007). The most obvious difference between the sites is the much more abundant vegetation of the Mescalero Sands compared with the relatively bare sands of the Morgenstern Dunes.

A summary of these data by month reveals that saltation activity was highest at both sites during the month of April with 5331 saltation seconds recorded at Near Field and 952 saltation seconds at the Gnome site (Appendix 3 electronic version only). The high number of saltation seconds recorded in April reflects the fact that winds were strong, precipitation was low, and the air was drier than other months. In addition, cool temperatures limited the growth of the mostly dormant Chihuahuan Desert vegetation. Saltation activity reduced at both sites in May with only 569 saltation seconds recorded at Near Field and 680 saltation seconds recorded at the Gnome site. Wind speed declined and rainfall and humidity increased in May and warmer temperatures may have spurred growth of vegetation, providing additional shelter from the wind. In June and July, warm temperatures and adequate rainfall

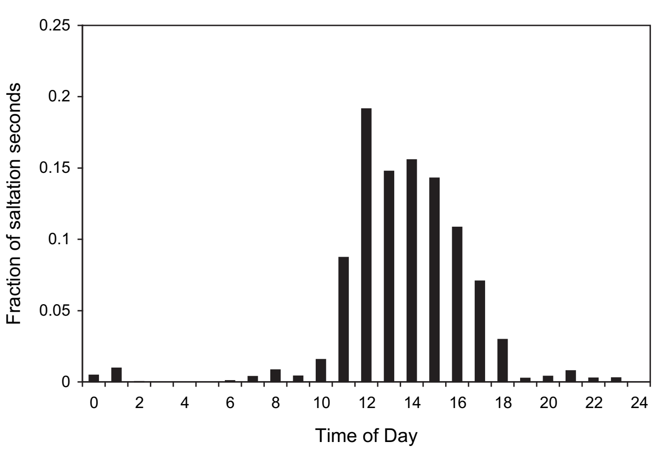

Fig. 2. Diurnal distribution of the fraction of saltation seconds measured during the month of April at the Near Field site.

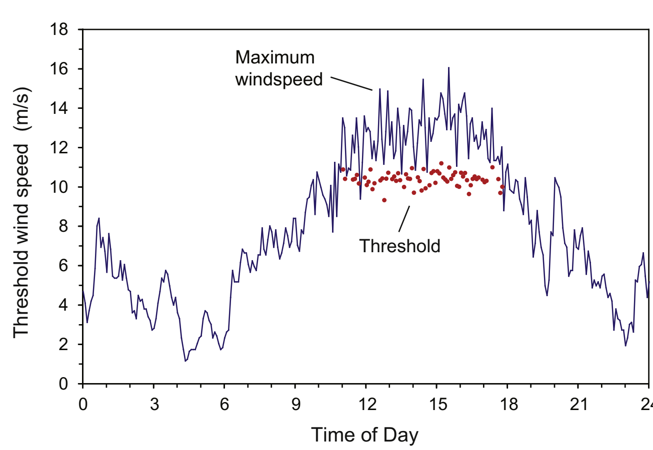

Fig. 4. Maximum wind speed and threshold values measured at the Near Field site on 10 April 2005.

Table 1
Daily summary of meteorological conditions, saltation seconds, and threshold velocities measured at the Near Field (NF) and Gnome (GN) sites for days with significant soil movement.

Date	Wind speed ($m s^{-1}$)		Max gust ($m s^{-1}$)		Wind direction		Air temperature (C)		Relative humidity (%)		Saltation seconds (s)		Threshold ($m s^{-1}$)	
	NF	GN	NF	GN	NF	GN	NF	GN	NF	GN	NF	GN	NF	GN
4/9/05	3.5	3.2	15.9	14.7	227	214	20.4	20.9	21.7	18.5	969	240	10.5	10.9
4/10/05	4.8	4.2	16.1	14.5	253	249	15.1	15.6	23.1	20.5	1881	125	10.4	10.7
4/29/05	4.8	4.0	17.8	12.4	264	268	20.1	21.0	22.9	19.8	1439	104	10.1	10.0
5/10/05	4.0	3.5	13.3	14.0	136	126	24.1	24.7	45.6	41.4	162	126	10.7	10.8
6/2/05	2.6	2.7	21.6	18.3	156	148	26.1	26.6	48.7	46.5	31	5	10.4	10.6
6/6/05	3.5	3.6	18.5	14.7	137	123	24.4	24.9	65.6	63.8	217	134	11.5	10.6
6/14/05	2.9	2.8	16.9	14.9	96	99	25.5	26.7	62.4	57.8	49	78	11.9	10.9
7/6/05	4.2	3.7	17.2	18.1	135	117	29.1	29.3	34.5	33.6	146	79	10.8	10.4
7/10/05	3.0	2.6	14.2	17.5	102	108	26.1	26.6	52.7	54.2	22	109	11.3	10.0

promoted additional growth of grasses and sagebrush resulting in further reductions in saltation activity.

Saltation events were observed simultaneously at both sites; however, a close inspection reveals significant differences in levels of saltation activity recorded during specific blowing events (Fig. 1). For example, on 29 April a peak saltation activity of 0.25 was measured at the Near Field site whereas a much smaller peak of only 0.02 was measured at the Gnome site. There are other examples where the Gnome site recorded more saltation activity than the Near Field. For example, on 6 May a peak saltation activity of 0.17 was measured at the Gnome site whereas a peak of 0.02 was measured at the Near Field. One naturally wonders why there are such large discrepancies in saltation activity.

There were occasional differences in rainfall, humidity and wind speed between sites and it is possible that these climatic differences contributed to measured differences in saltation activity. One must also consider the possibility that differences in soil conditions at the two sites contributed to differences in saltation activity. However, according to the soil survey of Eddy County, soils at both sites were mapped as "Kermit-Berino fine sands" (Chugg et al., 1971) and field observations of the Mescalero sand sheet confirm that it is fairly uniform with regard to soil texture. A more plausible explanation for the large discrepancies in saltation activity may lie in the complex interaction between the wind and the non-uniform distribution of plants surrounding each sampling site. Wind direction is an important factor in this regard since it determines which plants are located upwind of the saltation sensor and it is primarily these upwind plants that determine the degree of sheltering of the sand surface. It follows that a shift in wind direction can completely change the exposure of the sand at each site.

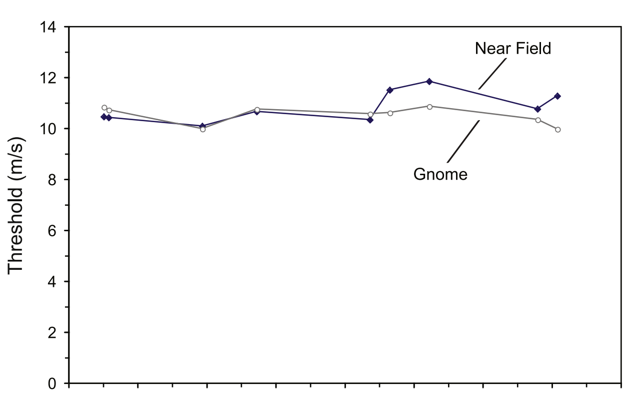

Fig. 5. Plot showing the temporal variation of threshold at both sites.

3.1. Diurnal patterns

Blowing events can occur at any time of the day when conditions are favorable; however, in a prior study, Stout (2010) observed that a diurnal pattern in wind strength caused saltation activity to occur most often during daylight hours. A similar pattern was observed in this study. A plot of the fraction of saltation seconds recorded at the Near Field site for each hour of the day during the most active month of April is shown in Fig. 2. Note that saltation activity is at a low point during the early morning hours and tends to be more significant during daylight hours starting around 10:00 AM, peaking at noon, remaining at high levels during the mid afternoon, and then steadily declining in the late afternoon.

Diurnal patterns of blowing sand are influenced by diurnal variations of key meteorological factors such as wind, humidity and solar radiation. Fig. 3 presents an example plot of measured saltation activity, maximum wind speed, relative humidity and solar radiation for the blowing event that occurred on 10 April 2005. Note that the lowest relative humidity values and the highest solar insolation values were observed at around the same time that wind speed and saltation activity reached maximum values. Thus, over short timescales, diurnal patterns in relative humidity and solar radiation may combine with wind speed to affect aeolian activity. Dry air and intense solar radiation tend to favor saltation activity by drying the uppermost soil surface and thereby reducing threshold velocity. The point to be emphasized here is that wind strength alone does not control saltation activity, but rather other factors, acting over timescales of hours to days, may also influence saltation activity.

3.2. Threshold velocities

Significant saltation events were observed at both sites on only nine days during the 112-day study, and it was only during these blowing events that saltation activity was large enough to reliably calculate threshold values. During the few hours of each day when sufficient saltation activity was observed, threshold values were calculated every five minutes. A good example is shown for the Near Field site on 10 April 2005 (Fig. 4). On this day, wind speeds remained below threshold until around noon when winds suddenly strengthened and remained above threshold for over 5 h. During this blowing event, maximum wind speeds were hovering just above threshold and occasionally dipped below threshold. During the core period, a total of 39 threshold values were calculated with an average of around 10.4 $m s^{-1}$ and a standard deviation of 0.4 $m s^{-1}$.

A daily summary of calculated threshold values along with a meteorological summary is provided in Table 1. Results suggest that threshold values were of similar magnitude at both sites with an average of around 10.8 $m s^{-1}$ at Near Field and 10.5 $m s^{-1}$ at the

Gnome site for all nine days. A comparison with results from prior studies suggests that threshold wind speeds for the Mescalero Sands sites were much higher than those observed at less-vegetated sites on the high plains of the Llano Estacado (Stout, 2004). Data collected at Morgenstern Dunes in West Texas showed that threshold was consistently 5.4–5.5 m s^{-1}, or approximately half of what was observed at the Near Field or the Gnome sites (Stout, 2007). We propose that the more abundant vegetation of the Mescalero Sands had the effect of increasing thresholds compared with the bare sands of the Morgenstern Dunes of West Texas.

Daily threshold values plotted as a function of time are presented in Fig. 5. These results show that the magnitude and temporal variation of Near Field and Gnome threshold values were nearly identical in April and May. Threshold values then diverged slightly after 2 June after which the Near Field thresholds tended to be slightly higher than those measured at the Gnome site. Comparisons of photographs taken before and at the conclusion of this experiment suggest that the amount of vegetative cover had increased more significantly at the Near Field site compared to the Gnome site, and this is consistent with the sudden divergence of threshold values.

4. Concluding remarks

It is obvious that the collection of more extensive meteorological data combined with more information on the parent soils and vegetation would be useful in evaluating sand transport from a phenomenological perspective. However, with respect to the primary goal of the study, the results demonstrate that the dispersal of contaminated soils from the Gnome site is likely to occur only when winds are greater than ~10 to 10.5 m s^{-1}. In addition, the results show that saltation activity is favored at certain times of the day, especially from noon to mid-afternoon. While only two sites were sampled for the study, and extrapolation to larger scales is not necessarily appropriate, these data suggest that the likelihood of aeolian activity at the Gnome site is no greater than from nearby areas.

A second objective was to test the functionality of the experimental system in a more complex natural environment. The results demonstrate that the system provides a simple and cost-effective approach for field investigations of soil erosion, especially for comparative studies. The reproducibility of the methods and internal consistency of the data can be seen in the small coefficient of variation for threshold values; these are the standard deviations of the threshold winds divided by the arithmetic means of the wind speeds. During the nine saltation events at the two sites, the highest relative standard deviation was only 7.7%, and all of the other values were less than 6%, which means that the threshold wind speeds varied by less than 10% during the individual saltation events. Thus, we conclude first that our approach for measuring saltation and threshold winds provides a practical means for studying aeolian activity in the field and second that the main challenges now lie in identifying the factors other than wind speed that affect aeolian activity and in developing ways to quantify the effects of those factors.

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Appendix. Supplementary data

Supplementary data associated with article can be found in online version at 10.1016/j.jaridenv.2010.05.011.

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