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A METHOD FOR ESTABLISHING THE CRITICAL THRESHOLD FOR AEOLIAN TRANSPORT IN THE FIELD

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ABSTRACT

A basic feature of any wind-eroding surface is its threshold – the wind speed at which sediment transport is initiated. A new method was developed and tested that allows for the rapid determination of threshold under natural wind conditions in the field. A mathematical expression that relates saltation activity and relative wind strength was reformulated so that threshold may be calculated from measurements of saltation activity and the mean and standard deviation of wind speed. To test the new method and determine its usefulness, a field experiment was performed within a region of low-relief dunes on the Southern High Plains of West Texas. The experimental system consisted of a 2-m meteorological tower and a piezoelectric saltation sensor. It was found that during periods of active aeolian activity, threshold values could be calculated every 5 minutes. This new method allows for routine monitoring of surface threshold conditions in the field. Example threshold calculations are presented and they demonstrate that the method works well. Published in 2004 by John Wiley & Sons, Ltd.

KEY WORDS: threshold; saltation; wind erosion; aeolian research; dunes

INTRODUCTION

Wind blowing across a sandy surface exerts fluid forces upon that surface. As wind speed increases, a point is reached at which sufficient forces are produced to cause the individual grains that compose the surface to move. This critical point is called the threshold for aeolian transport. The precise measurement of threshold is of fundamental importance in aeolian research.

In the past, wind tunnel tests have been used to establish the threshold condition for aeolian transport (Bagnold, 1941; Kawamura, 1951; Zingg, 1953; Nickling, 1988; Iversen and Rasmussen, 1994). Typically, a surface is transplanted from the field into the test section of a wind tunnel, wind speed is adjusted, and the critical wind speed at which sediment movement is initiated is noted. Wind tunnels provide a controlled environment that allows a careful and systematic study of the threshold condition. The determination of threshold under natural field conditions is more complicated.

In the naturally turbulent atmosphere, rapid and chaotic wind fluctuations limit our ability to conduct controlled experiments. Yet we need to venture to the field to study the threshold condition if we wish to obtain a true picture of the wind erosion process under realistic wind and surface conditions. It is difficult to properly simulate the full spectrum of fluid motions within a laboratory wind tunnel (Snyder, 1981). Turbulence characteristics within the atmospheric boundary layer are established as winds blow across vast stretches of the Earth's surface, and it is hard to reproduce these same characteristics within the limited fetch of a wind tunnel test section. Furthermore, the transplanted soil surface in most wind tunnel experiments may not properly represent the actual soil conditions within the field. Certainly, these problems could be overcome but perhaps it is more practical to improve the method of direct determination in the field.

Here we describe a simple method for calculating threshold from measurements of saltation activity, wind speed, and the standard deviation of wind speed. First an equation is derived from basic principles then field measurements of wind speed and saltation activity are used to calculate threshold.

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THEORY

Saltation activity, γ, is defined as the fraction of time within a given period that saltating particles are detected at a point (Stout and Zobeck, 1997). For example, $\gamma = 0{\cdot}25$ indicates that saltation was detected for one-quarter of the measurement period. The value of γ always falls between 0 and 1, where $\gamma = 1$ corresponds to the condition of continuous saltation activity and $\gamma = 0$ corresponds to the inactive condition.

The level of saltation activity is governed primarily by whether wind speed fluctuations, characterized by the standard deviation σ, can span the gap between the mean wind speed $\bar{u}$ and the threshold wind speed u_t, expressed by $\bar{u} - u_t$. A dimensionless parameter that expresses this relative wind strength may be written as

$$S \equiv \frac{\bar{u} - u_t}{\sigma} \tag{1}$$

To demonstrate the relationship between the relative wind strength, S, and saltation activity, γ, two possible situations are sketched in Figures 1 and 2.

Figure 1 illustrates the condition of negative relative wind strength, $S < 0$. If S is negative then the mean wind speed is less than threshold. In this case, occasional gusts may exceed threshold and produce blowing soil. As $S \to -\infty$, saltation activity tends toward zero or $\gamma \to 0$.

Figure 2 illustrates the condition of positive relative wind strength, $S > 0$ (the mean wind speed is greater than threshold). Under this condition, saltation will occasionally cease when wind speed dips beneath threshold. If $S \gg 1$ then wind fluctuations σ are small compared to the velocity difference $\bar{u} - u_t$ and consequently there is a low probability that winds will dip beneath threshold. As $S \to \infty$, soil transport tends toward continuous saltation activity or $\gamma \to 1$.

In turbulent flows, wind speed fluctuations can be described by a probability density distribution $p(u)$ (Batchelor, 1953). The probability that wind speed will exceed threshold may be expressed as

$$P(u > u_t) = 1 - \int_{-\infty}^{\frac{u_t - \bar{u}}{\sigma}} p(w)\,dw \tag{2}$$

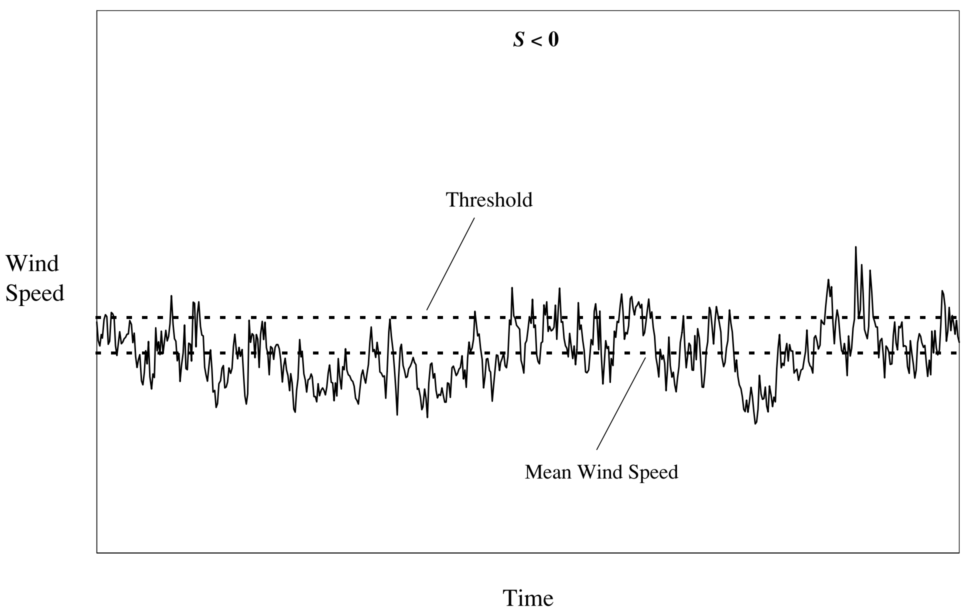

Figure 1. Illustration showing the condition of negative relative wind strength, $S < 0$, where mean wind speed is less than threshold wind speed. In this case wind speed is most often below threshold and saltation activity occurrs intermittently when occasional gusts exceed threshold

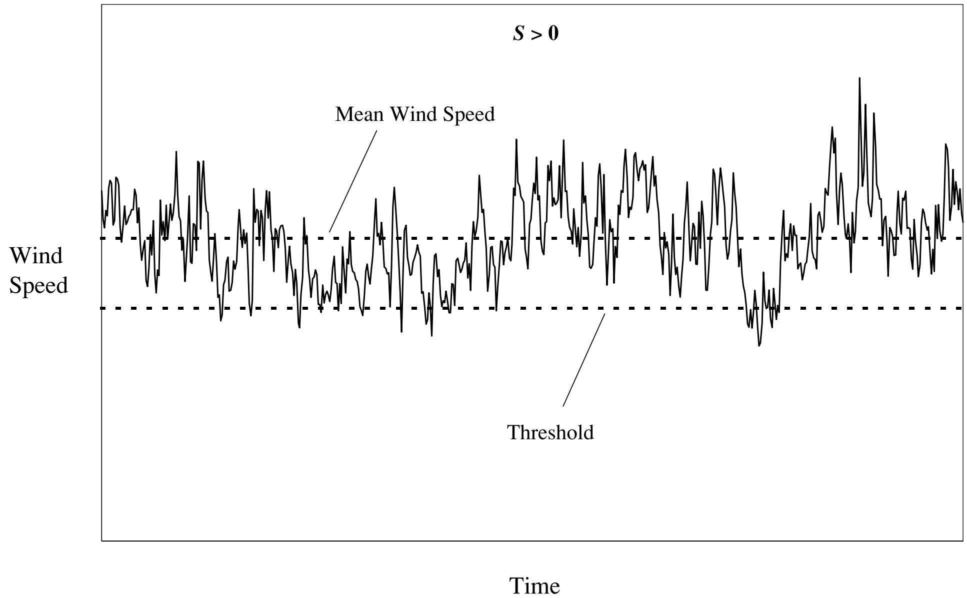

Figure 2. Illustration showing a positive relative wind strength condition, $S > 0$, where mean wind speed is greater than threshold wind speed. In this case wind speed is most often above threshold and saltation ceases only when occasional lulls cause wind speed to dip below threshold

where $w = \dfrac{u - \bar{u}}{\sigma}$. Let Φ denote a distribution function defined as

$$\Phi\left(\frac{u_t - \bar{u}}{\sigma}\right) \equiv \int_{-\infty}^{\frac{u_t - \bar{u}}{\sigma}} p(w)dw \tag{3}$$

Note that the argument within the brackets is equal to $-S$, so the probability that the wind speed will exceed threshold may be rewritten in terms of the relative wind strength S as

$$P(u > u_t) = 1 - \Phi(-S) \tag{4}$$

The distribution function Φ satisfies the property

$$\Phi(-S) = 1 - \Phi(S) \tag{5}$$

Combining Equations 4 and 5 yields

$$P(u > u_t) = \Phi(S) \tag{6}$$

The fraction of time that saltation occurs should be equal to the fraction of time that wind exceeds threshold. Thus

$$\gamma = P(u > u_t) \tag{7}$$

and it follows from Equations 6 and 7 that

$$\gamma = \Phi(S) \tag{8}$$

Equation 8 states that saltation activity, γ, follows a curve defined by a distribution function of relative wind strength, $\Phi(S)$.

So far we have not defined the form of the distribution function $\Phi(S)$. From Equation 6, we know that the form of the wind speed distribution governs the form of $\Phi(S)$. It is generally agreed that under ideal conditions of homogeneous and stationary turbulence the distribution of wind fluctuations conforms closely to the normal or Gaussian distribution (Simmons and Salter, 1934; Sutton, 1949; Lumley and Panofsky, 1964; Kuo and Corrsin, 1971). Although a truly homogeneous and stationary turbulent field rarely exists in the atmosphere, the assumption of stationarity is sometimes acceptable in selected short periods of time and the assumption of homogeneity is well approximated at heights sufficiently far from the bounding surface (Batchelor, 1953; Maitani, 1979; Sorbjan, 1989). Thus, it is possible for the wind speed distribution to be adequately described by the normal distribution despite the fact that the conditions of homogeneous and stationary turbulence are not rigorously satisfied. It follows from Equation 6 that the distribution function, $\Phi(S)$, is adequately described by a normal distribution function and, therefore, saltation activity as defined by Equation 8 follows a normal distribution function of S, as shown in Figure 3.

Taking the inverse of the distribution function, $\Phi(S)$, Equation 8 becomes:

$$S = \frac{\bar{u} - u_t}{\sigma} = \Phi^{-1}(\gamma) \tag{9}$$

Rearranging, one can solve for threshold velocity as:

$$u_t = \bar{u} - \sigma\Phi^{-1}(\gamma) \tag{10}$$

Thus, the threshold of a surface can be calculated using Equation 10 from field measurements of saltation activity, mean wind speed, and the standard deviation of wind speed.

It is important to note that function $\Phi^{-1}(\gamma)$ is undefined and threshold is indeterminate when there is no saltation activity ($\gamma = 0$) or when there is continuous saltation activity ($\gamma = 1$). Thus, threshold can be calculated only when the condition $0 < \gamma < 1$ is satisfied. The upper limitation, $\gamma = 1$, is usually not a major problem since for every period with continuous saltation activity there are often neighbouring periods where γ is less than unity. However, there can be extensive periods when winds are too weak or the soil surface is too moist and the lack of saltation activity prevents the determination of threshold using this method. As a result, this method

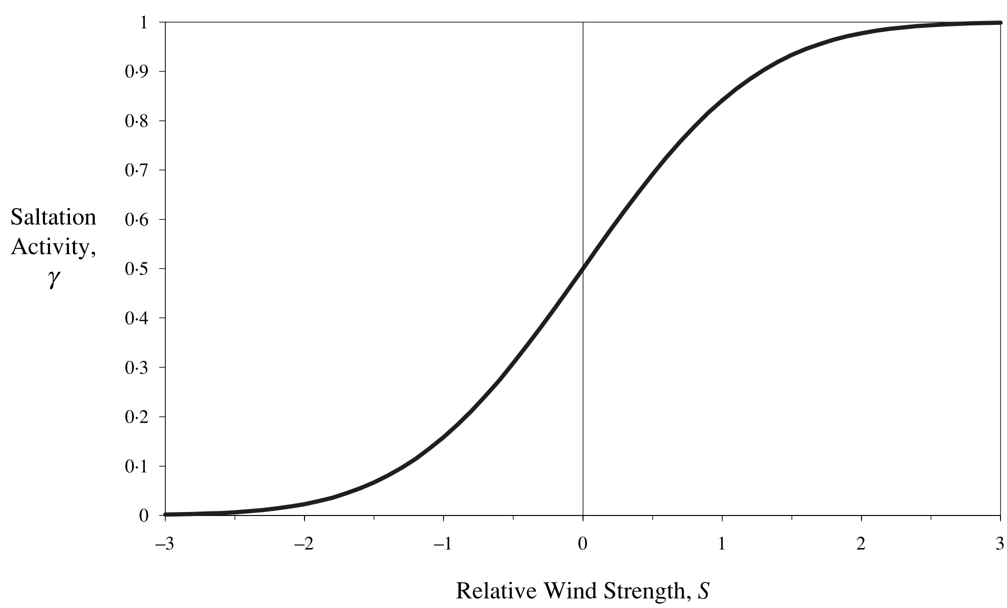

Figure 3. Plot of the relationship between saltation activity, γ, and relative wind strength, S, as defined by Equation 8

rarely provides continuous measurements of threshold. Instead we obtain glimpses of threshold during windows of opportunity when surface conditions and meteorological conditions are favourable for sediment transport.

FIELD STUDY

Saltation activity, wind speed, and the standard deviation of wind speed were measured at a site located within a dune field 65 km to the southwest of Lubbock, Texas, as shown in Figure 4. The site, locally referred to as the Morgenstern Dunes, contains partially vegetated low-relief dunes composed of fine quartz sand. The Morgenstern Dunes form the eastern tip of a much larger, mostly vegetated dune field, called the Lea-Yoakum Dunes, which extends from the Pecos River Valley through Lea County New Mexico and into Yoakum, Cochran, and Terry counties of West Texas (Figure 4) (Muhs and Holliday, 2001).

The sampling system consisted of a 2-m tall meteorological tower and a piezoelectric saltation sensor installed on the flat crest of one of the shallow dunes within the dune field, as shown in Figure 5. Measured climate variables include wind velocity, relative humidity, air temperature and precipitation. Wind velocity was measured with a lightweight, fast-responding propeller-type anemometer mounted at a height of 2 m. Other meteorological sensors included a tipping-bucket rain gauge with a resolution of 0·1 mm per tip, a thermistor temperature sensor and a capacitance-type relative humidity sensor. All variables were sampled at a frequency of 1 Hz and summarized every 5 min.

A piezoelectric saltation sensor, placed 10 m to the west of the meteorological tower, monitored saltation activity. Due to shifting sands the height of the sensor tended to vary with time from its nominal height of 5 cm.

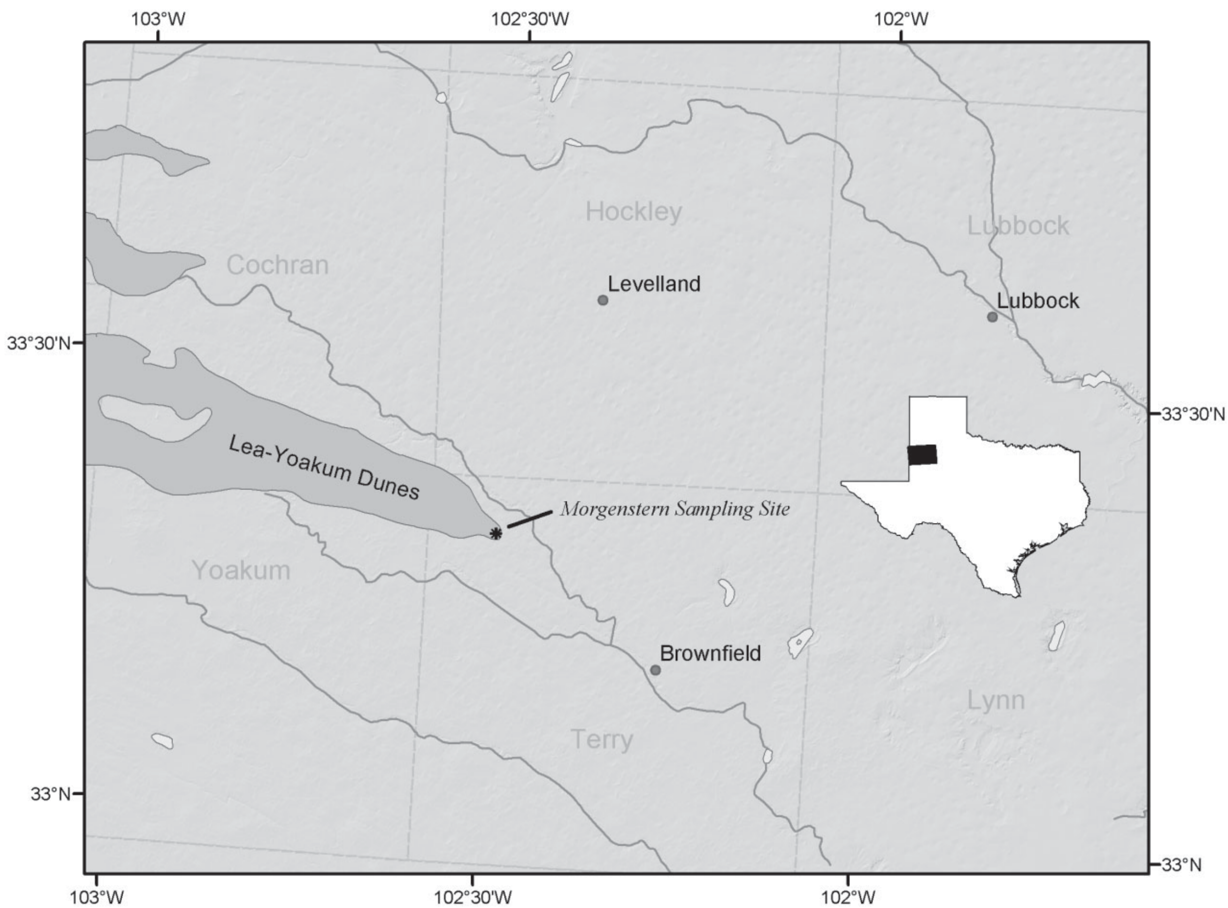

Figure 4. Map showing the location of the dunes and the sampling site

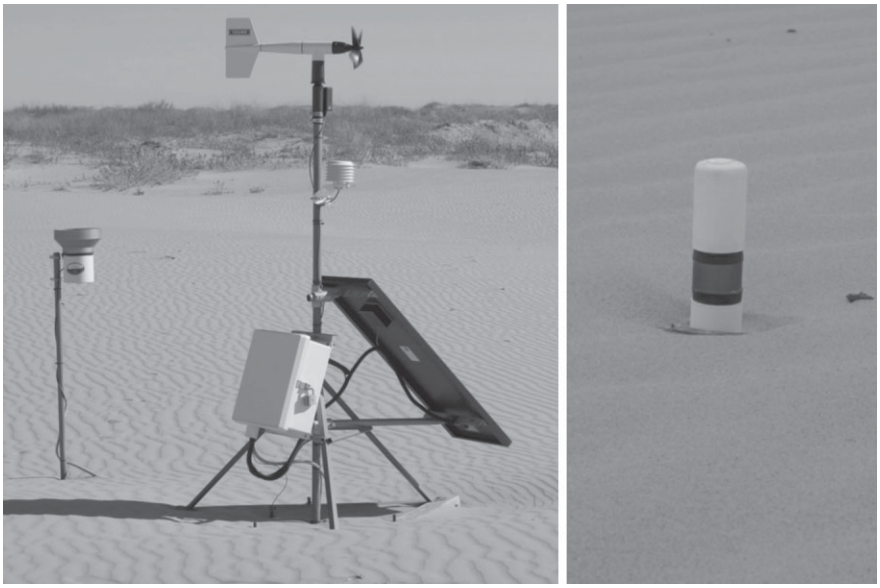

Figure 5. Sampling system consisting of a 2-m meteorological tower and a piezoelectric saltation sensor

During weekly visits, the height of the sensor was recorded and if necessary readjusted to a height of 5 cm. During periods of active saltation, the piezoelectric transducer produced a signal that was used simply as an on-or-off indicator of saltation activity. Each pulse signal generated by each saltating grain that impacted the sensor was detected and if one or more impacts were detected during a given second then that second was registered as one 'saltation second' or one second of saltation activity. At the end of each 5-min period, the total number of saltation seconds are summed and output to final storage.

Saltation activity is expressed as a dimensionless ratio of the total number of saltation seconds divided by the total number of seconds within the period of measurement. Thus, 5-min saltation activity is simply the total number of saltation seconds recorded during a 5-min period divided by 300 s. Using these same data one can also calculate hourly, daily, monthly, seasonal or yearly saltation activity. In each case, saltation activity expresses the fraction of time that aeolian activity was detected.

Although the saltation sensor was designed to primarily respond to the impact of saltating grains (Stockton and Gillette, 1990), it can occasionally provide false indications of blowing sand for various reasons. Precipitation can cause false readings when raindrops or hailstones impact the sensor directly or when rain splashes a mixture of water and sand onto the sensor. Less frequently, false indications occur when animals or insects contact the sensor. In an attempt to limit errors due to false readings, threshold values were not calculated during rain events. Other false readings were detected by sorting the data set by maximum wind gust and a judgement was made as to whether saltation activity was possible given the maximum-recorded wind speed. Saltation seconds were manually set to zero if the maximum wind gust remained well below threshold. For example, if the maximum wind speed was only 2 m s^{-1} and threshold is normally around 5 to 6 m s^{-1} then one can be fairly certain that wind forces were not sufficient to detach sand grains and that any indications of saltation activity under such low wind conditions are highly suspect. Unfortunately, it was not always possible to distinguish between false readings and real blowing events when maximum wind speed was near threshold and, therefore, the final dataset may still contain a few false indications of blowing sand.

RESULTS AND DISCUSSION

The full record of saltation activity measured from 24 September to 3 December 2002 is plotted as a time series in Figure 6. These data provide a continuous record of aeolian activity at the sampling site during this 71-day period. Note that 'blowing events' appear as intermittent bursts of saltation activity that extend outward with

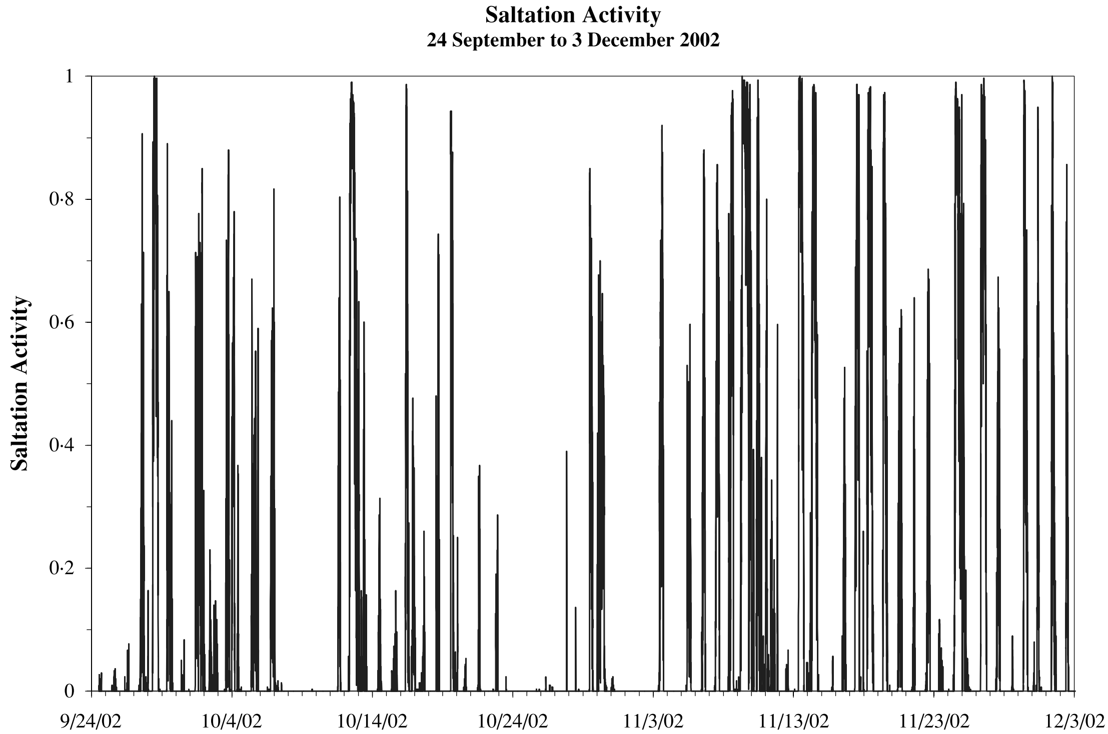

Figure 6. Saltation activity measured at the Morgenstern Dunes site from 24 September to 3 December 2002

varying intensity. Variations in saltation activity reflect changes in environmental conditions. During a few blowing events, dry and windy conditions led to saltation activity values approaching unity indicating nearly continuous sediment transport over a 5-min period. During other periods, light wind or moist conditions prevailed resulting in little or no saltation activity.

Measurements of saltation activity along with measurements of the mean and standard deviation of wind speed provide the raw data necessary to calculate threshold using Equation 10. Theoretically, values of threshold can be calculated for any period in which saltation activity is between zero and one ($0 < \gamma < 1$); however, it was found that values of saltation activity very close to zero or close to unity occasionally yield unrealistic values. Calculating threshold under slightly more restrictive conditions of $0{\cdot}02 < \gamma < 0{\cdot}98$ eliminated many of these troublesome outliers.

What follows are selected daily plots of calculated threshold values plotted along with measured values of maximum 5-min wind speed (Figures 7–9). Each plot shows a single 24-hour period. Days with strong and sustained winds were preferentially selected and plotted here since they provide sufficient saltation activity to allow threshold calculations for multiple hours within the day. During a typical day, wind speed tends to increase during morning and at some point, winds exceed threshold and sufficient saltation occurs to allow the calculation of threshold. Threshold values were calculated every 5 min whenever saltation activity was within the range $0{\cdot}02 < \gamma < 0{\cdot}98$. Because of the typical diurnal cycle of wind speed, most threshold values were obtained during daylight hours when winds were sufficiently strong to produce saltation activity.

The first set of four plots (Figure 7) shows threshold values calculated for 27 September, 29 September, 1 October and 11 October 2002. Overall, computed values of threshold appear to be independent of the magnitude of the ambient wind speed. For example, on 27 September, maximum wind speed increased from 5 m s^{-1} at around 10:00 to values greater than 10 m s^{-1} at around 15:00 yet threshold values consistently hovered around the average value of 5·89 m s^{-1} throughout the day. Similarly, on 29 September, wind speed decreased in intensity from 09:00 to 16:00 yet threshold remained stable during this same period. These examples suggest that calculated threshold values are not significantly influenced by wind speed. This result is consistent with the

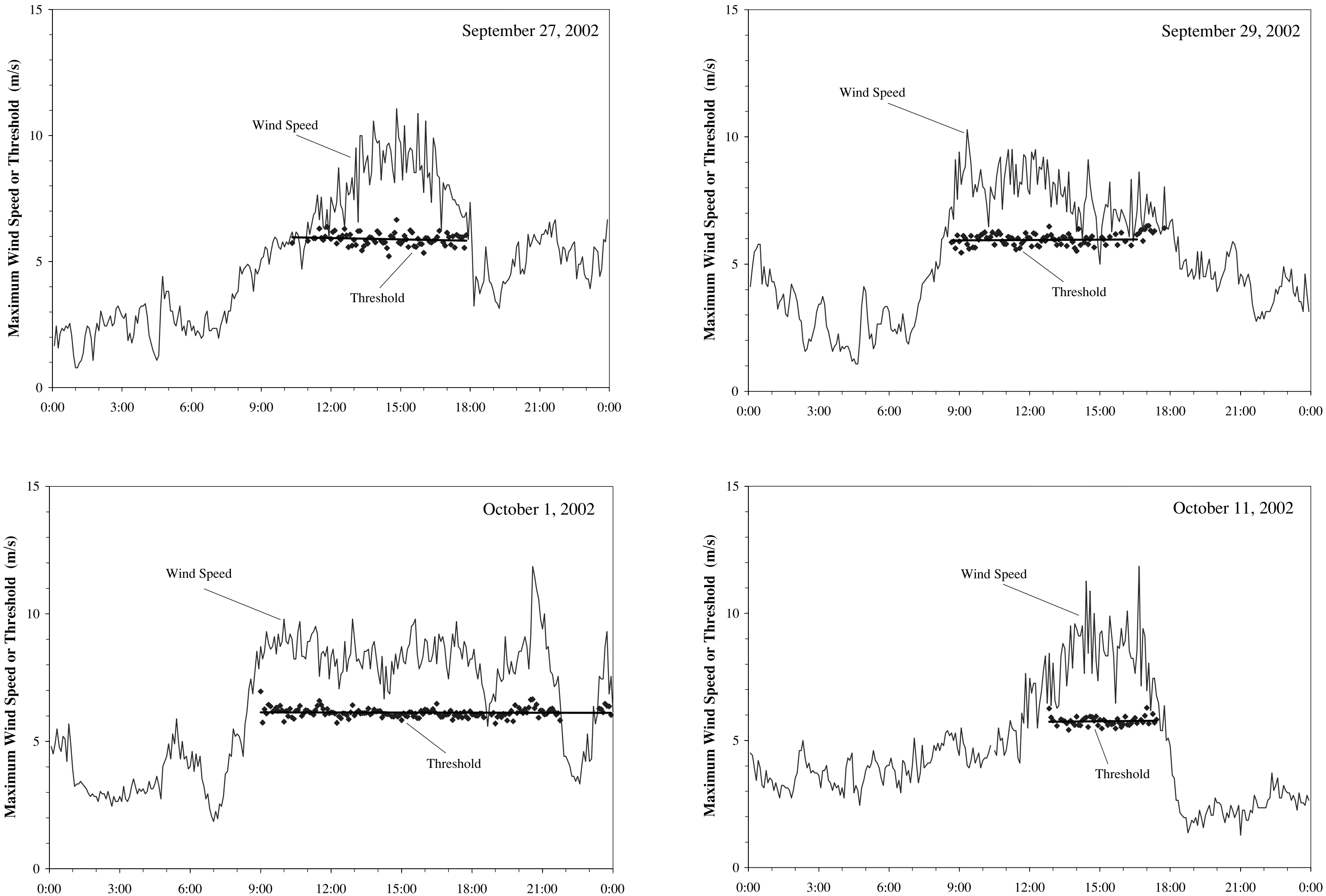

Figure 7. Calculated threshold values and measured maximum wind speed plotted together for 27 September, 29 September, 1 October, and 11 October 2002. Note that threshold values can be calculated only when maximum wind speed exceeds threshold. In these four examples, trend lines are essentially flat

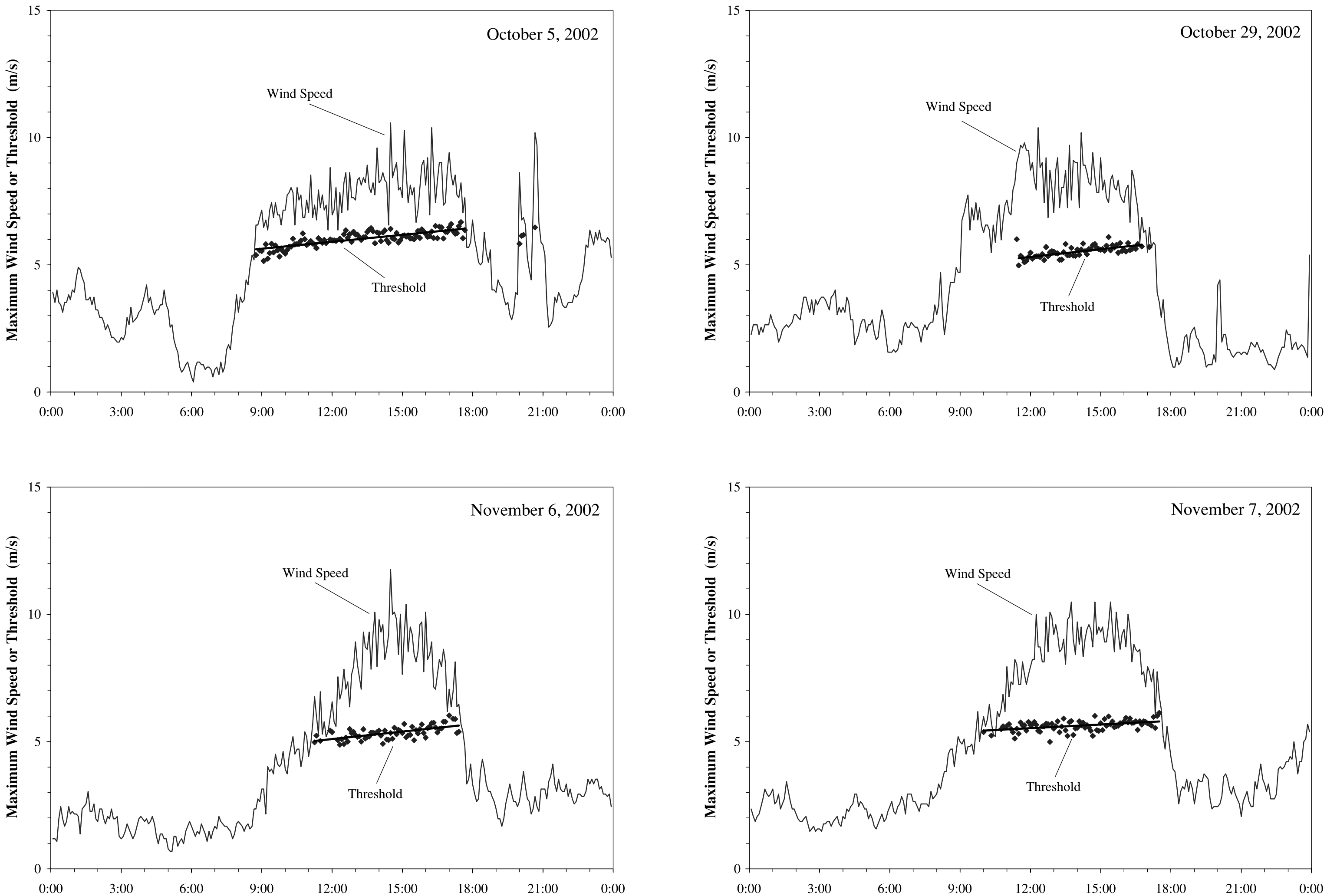

Figure 8. Calculated threshold values and measured maximum wind speed for 5 October, 29 October, 6 November, and 7 November 2002. In these examples, threshold tends to increase linearly during the measurement period

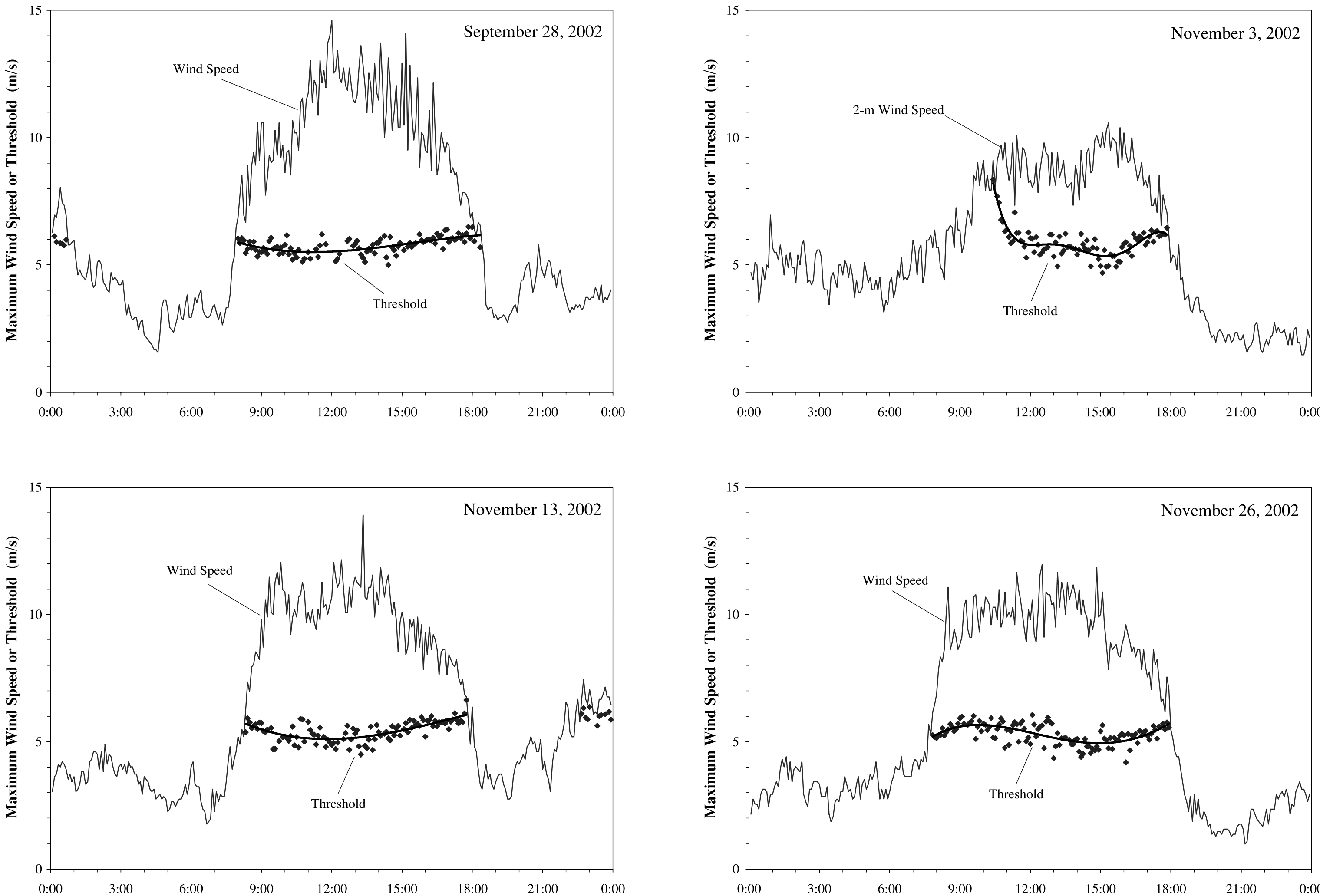

Figure 9. Calculated threshold values and measured maximum wind speed for 28 September, 3 November, 13 November, and 26 November 2002. Note that in these examples, threshold values exhibit more complex temporal patterns

Table I. Summary of average thresholds and slopes of trend lines for the four examples presented in Figure 7

Date (2002)	Period	Average threshold ($m\ s^{-1}$)	Slope ($m\ s^{-1}\ h^{-1}$)
27 September	10:20 to 17:50	5·89	−0·017
29 September	08:30 to 16:20	5·95	0·004
1 October	09:05 to 23:55	6·13	−0·001
11 October	12:55 to 17:25	5·76	0·006

fact that threshold velocity describes a surface erodibility condition and therefore should not be influenced by ambient wind speed.

Average threshold values and slopes of trend lines are summarized in Table I. All four examples presented in Figure 7 have trend lines that are essentially flat indicating that there was little or no change in threshold during the measurement period. As will be shown later, this is not always the case; however, these examples demonstrate that it is possible for a surface to maintain a steady threshold for many hours. A good example is that of 1 October, where it was possible to calculate threshold for a period of more than 13 hours. During this time, maximum wind speed fluctuated significantly and at one point dipped below threshold while threshold values consistently hovered around the mean value of $6{\cdot}13\ m\ s^{-1}$.

In all of these examples, there appears to be a small amount of scatter of calculated threshold values about the mean value. The source of this random scatter is not known precisely and in fact may be due to a number of factors. Rapid variations of surface conditions, especially surface moisture, could cause small variations in surface threshold. Variations of wind direction could cause the wind to blow more or less perpendicular to ripple patterns causing apparent variations in surface roughness. Random measurement errors of both wind speed and saltation activity may also contribute to apparent variations of threshold. In addition, minor deviations of the wind distribution from the assumed normal distribution could result in minor errors in the calculation of threshold (Schönfeldt, 2003). As discussed earlier, atmospheric turbulence is often adequately, but not always perfectly, described by the normal distribution. Deviations of the wind distribution from the normal distribution can result from adverse atmospheric conditions where the assumption of isotropic and homogeneous turbulence is not acceptable. A simple solution to this problem would be to test measured wind data for normality during each 5-min period. For example, one could compute kurtosis and skewness to see if they conform to values that are appropriate for the normal distribution and thereby avoid using the normal distribution during periods when a more complex distribution is required.

The next four examples, plotted in Figure 8, show a positive linear increase in threshold during the measurement period. As summarized in Table II, threshold was observed to increase at a rate as high as $0{\cdot}1\ m\ s^{-1}$ per hour on 29 October and 6 November. Similarly, threshold was found to increase at a rate of $0{\cdot}09\ m\ s^{-1}$ per hour on 5 October and a slightly lower rate of $0{\cdot}05\ m\ s^{-1}$ per hour on 7 November. The exact cause of the positive slope is not known; however, one may speculate that subsurface moisture plays a key role.

During periods of strong winds, sand grains are continuously removed from the surface while other grains are continuously deposited. The balance between the rate of removal and the rate of grain replacement determines whether a given point undergoes net deflation or net deposition. If the balance is such that a surface experiences significant net deflation then layers of underlying moist sand may be exposed. If the exposed surface dries quickly then threshold may not increase significantly; however, if the newly exposed surface dries slowly then the overall threshold of the surface may increase with time. Unfortunately, it was not possible to routinely monitor surface moisture during this experiment so the necessary surface moisture data are not available. However, large exposures of moist sand, such as that shown in Figure 10, were sometimes observed during occasional visits to the site, especially during extreme wind events.

Examples plotted previously in Figures 7 and 8 represent the simplest possible cases of either constant threshold or linear changes of threshold with time. The next four examples, plotted in Figure 9, illustrate more complex temporal patterns of threshold variation. For example, threshold values computed on 28 September appear to follow a smooth curve that dips downward from 08:00 to 11:00 and then bends slowly upward

Table II. Slopes of trend lines for the four examples presented in Figure 8

Date (2002)	Period	Slope (m s^{-1} h^{-1})
5 October	08:45 to 17:40	0·09
29 October	11:30 to 16:45	0·10
6 November	08:40 to 14:25	0·10
7 November	10:00 to 17:30	0·05

Figure 10. Photograph taken at the Morgenstern Dunes sampling site showing an exposed moist sand surface resulting from deflation of drier overlying sands. A moist surface, such as this one, will have a much higher threshold than a dry surface

until final threshold values at 18:00 are approximately 0·6 m s^{-1} higher than those measured at 11:00. Similarly, threshold values for 13 November also describe a smoothly curving temporal pattern with relatively low threshold values at midday and significantly higher values in the morning and evening. More pronounced temporal variations were observed on 3 November with relatively high threshold values of around 8·3 m s^{-1} at 10:30, dropping to as low as 5·5 m s^{-1} two hours later and occasionally reaching minimum values of less than 5 m s^{-1} at around 15:00. Threshold values then increased appreciably to as high as 6·5 m s^{-1} by 18:00. Threshold values computed for 26 November follow a more complex wave-like pattern where threshold values initially increased in the morning until 10:00, then declined from 10:00 to 15:00, and then increased from 15:00 to 18:00. These examples demonstrate that the threshold velocity of a dynamic surface can vary in complex ways and that this new method for calculating threshold can reveal these interesting temporal patterns.

In most cases, the cause of the observed decrease of threshold during the morning is likely related to changing surface conditions involving early morning moisture and the subsequent drying of the surface by sun and wind. In addition, the exposure of underlying moist sand by deflation may play an important role in the observed increase of threshold during the afternoon. Wind direction shifts may also contribute to the observed temporal patterns. Further research will be required to ascertain the relative importance of these various factors.

CONCLUSIONS

The goal of this paper was to present a new method that allows for the rapid determination of threshold under natural wind and field conditions and to present a few examples. The new method was derived by reformulating a mathematical expression that relates saltation activity and relative wind strength so that threshold can be calculated directly from measurements of saltation activity, mean wind speed, and the standard deviation of wind speed. During periods of active aeolian activity, the derived method can be used to routinely calculate threshold using data from an unattended and remotely located sampling system consisting of two essential parts – an anemometer and a piezoelectric saltation sensor.

Limitations of this method lie in the fact that threshold can be determined only when the surface is undergoing active saltation. As a result, there are often periods when winds are below threshold and the lack of saltation activity prevents the determination of threshold. Thus, this method cannot provide a continuous record of surface threshold. Nevertheless, when conditions are favourable, this method can provide valuable information regarding threshold that would be difficult to obtain in any other way.

Results from a field study conducted on a sandy surface in West Texas reveal that threshold can be established with enough precision to identify temporal patterns resulting from changing surface conditions. In some cases, threshold was found to remain constant for periods of many hours. In other cases, threshold was found to increase linearly with time at a steady rate as high as $0{\cdot}1\ \mathrm{m\ s^{-1}}$ per hour. In other cases, threshold was found to vary in strange and complex ways as shifting environmental conditions influenced surface threshold conditions. From data collected during this experiment it was not always possible to account for the observed temporal variations of surface threshold primarily due to the lack of information regarding surface moisture and various other environmental factors that influence surface threshold.

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