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Diurnal patterns of blowing sand†

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ABSTRACT: The diurnal pattern of blowing sand results from a complex process that involves an interaction between solar heating, thermal instability, atmospheric turbulence, wind strength, and surface threshold conditions. During the day, solar heating produces thermal instability, which enhances the convective mixing of high momentum winds from the upper levels of the atmosphere to the surface layer. The sun also dries the sand surface so that the critical threshold is as low as possible. Thus, in the afternoon, the combination of strong turbulent winds and a low surface threshold increases the likelihood that winds may intermittently exceed the critical threshold of the surface to produce bursts of blowing sand. Here an attempt has been made to explore this dynamic aeolian process using a new method for monitoring the diurnal pattern of blowing sand. This technique involves detecting blowing sand with a piezoelectric saltation sensor to determine the relative proportion of time that blowing sand is detected for a given 'time of day'. Measurements taken over a seven-month period on the high plains of the Llano Estacado of West Texas and eastern New Mexico suggest that sand movement tends to occur more frequently during daylight hours with a peak in aeolian activity occurring in the afternoon between 14:00 and 15:00 Local Standard Time (LST). Published in 2010 by John Wiley & Sons, Ltd.

KEYWORDS: blowing sand; diurnal; saltation; aeolian; threshold

Introduction

It has been recognized for some time that dust storms tend to occur more frequently during the day and less frequently at night. Early accounts of exploration and settlement in arid regions often contain vivid descriptions of dust storms that occur preferentially during daylight hours. For example, the Scottish explorer, James Bruce, while searching for the source of the Nile in North Africa, describes 'moving pillars of sand' that tend to form 'immediately after sun-rise' and he describes a 'Simoom' forming at eleven in the 'forenoon' and ceasing at 'twenty minutes to five' (Bruce, 1790). Jehudi Ashmun (1826), an early settler of Liberia, provides an account of a Harmattan dust event that 'commenced about nine o'clock in the morning,' peaked in intensity between noon and two in the afternoon, and gradually diminished in strength and 'subsided entirely, after prevailing six hours.' In a report on the Kharga Oasis, published at the end of the nineteenth century, John Ball, of the Geological Survey of Egypt, wrote that violent sandstorm winds of the Libyan Desert were 'never experienced both at night and in the daytime: in the case of the strong gales lasting several days, the wind always abated at sunset, beginning again about 9 a.m. on the following morning' (Ball, 1900; p116).

Scientific investigations of blowing dust have confirmed that there is a strong tendency for dust storms to occur preferentially during the day. Sreenivasaiah and Sur (1937; p209) of the Indian Meteorological Office found that 'The hourly frequencies of occurrence of duststorms show that no duststorms ordinarily occur between 6 and 8 A.M. The frequency increases thereafter with advance of the day and reaches a maximum between 16 and 18 hours, suggesting that insolation plays an important part in duststorm phenomena.' Similarly, Orgill and Sehmel (1976) analyzed hourly visibility observations recorded at US weather stations to compute the number of hours of blowing dust associated with a given hour of the day. Their analysis showed that higher frequencies of airborne dust occur 'in the afternoon period between 1200 and 2000 LST [Local Standard Time], or during the period of maximum thermal instability.' A similar approach was taken in West Africa where researchers found that the 'diurnal cycle shows a reduction of visibility during the daytime hours in areas where dust is generated, a consequence of the elimination of the nocturnal inversion' (N'Tchayi Mbourou *et al.*, 1997). More recently, Chaboureau *et al.* (2007) analyzed satellite observations and found that dust coverage over the Sahara follows a well-defined diurnal cycle, typically peaking at 15:00 UTC (Coordinated Universal Time).

The observed diurnal cycle of blowing sand and dust results from a process involving the interaction between solar insolation, thermal instability, atmospheric turbulence, and the movement of sand grains by wind. During the day, solar insolation is strong and thermal instability is at a maximum. Thermal instability enhances convective mixing within the atmosphere producing a downward transport of high momentum winds from the upper levels of the atmosphere to the surface layer, thereby enhancing surface winds (Sreenivasaiah and Sur, 1937; Takemi *et al.*, 2005). This momentum transfer occurs as swirling vortices or eddies swept along by the main flow. The larger eddies intermittently produce significant gusts that may exceed the critical threshold of the surface to produce bursts of blowing sand. As saltating sand grains move across the surface under the influence of gravity, they repeatedly strike the soil surface and bring about the release of fine particulate matter. Once airborne, dust particles tend to become suspended and may be transported over great distances.

In the present study, attempts have been made to explore this dynamic aeolian process from a slightly different perspective. Instead of using blowing dust as an indicator of aeolian activity, direct detection of blowing sand was used to compute diurnal patterns. Blowing sand was detected using a fast responding 'saltation sensor' that utilizes a piezoelectric transducer to detect the movement of saltating grains. Such instruments, if used properly, can provide valuable information regarding the temporal variability of blowing sand.

Methods

If a saltation sensor is sampled every second, then it is possible to obtain information regarding sand movement each second. That is to say that for every one-second period during an experiment it is possible to determine if sand movement occurred and if sand movement did occur then we have a record of the exact time when it occurred. Thus, a continuous record of aeolian activity can provide two key pieces of information – the fraction of time that sand was actively blowing and the temporal distribution of the active periods.

Here a piezoelectric saltation sensor (Sensit) was used to detect sand movement. The Sensit is designed to produce a pulse signal each time the transducer is impacted by a saltating grain. It was possible to obtain a continuous record of aeolian activity by sampling the output from the Sensit every second. During periods of active sand movement, the piezoelectric transducer produced a signal that was used simply as an on- or off-indicator of aeolian sediment transport. Each pulse signal generated by each particle impact was detected and if one or more impacts were detected during a given second then that second was registered as one 'saltation second.' At the end of each five-minute period, saltation seconds were summed to obtain the total number of seconds that blowing sand was detected, the counter was then reset to zero, and the process repeated during the next five-minute period (Stout, 2007).

Measured meteorological variables include wind speed and direction, relative humidity, air temperature, and precipitation. Wind velocity was measured with a fast-responding propeller-type anemometer mounted at a height of 2 m (Figure 1). All other meteorological sensors were mounted at a height of 1 m above the surface. These include 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 averaged every five minutes.

The sampling site chosen for this study was a level surface of loose sand located at the eastern edge of the Lea-Yoakum dunes – an extensive sand sheet that stretches across the Llano Estacado from the Pecos River Valley through Lea County, New Mexico and into Yoakum, Cochran, and Terry counties of west Texas (Holliday, 2001). The sampling system was installed near the center of what may be described as a large, nearly circular blowout of around 300 m in diameter. The surface within this blowout consists of highly mobile sands with little protective vegetation, which contrasts sharply with the surrounding, mostly vegetated, Lea-Yoakum dune sheet (Stout, 2007).

A sample of sand was obtained from the site and sieved to obtain the particle size distribution. The analysis revealed that these sands are properly classified as 'fine sand' with a median grain diameter of 180 μm. Less than 10% of the grains were found to be smaller than 110 μm and only 8% had diameters greater than 250 μm.

Sampling began in the fall of 2002 and extended through the winter and into the spring of 2003. The full record extends from 25 September 2002 to 1 May 2003, a period of roughly seven-months. On the high plains of the Llano Estacado this period is typically windy and relatively dry compared to the rest of the year. Due to the highly mobile nature of the sand surface, the site was visited frequently to ensure that the Sensit was not covered by drift sand and to adjust the height of the Sensit so that the piezoelectric sensor remained within a target range of between 0 and 5 cm above the surface.

Results

For each five-minute sampling interval, the total number of saltation seconds was divided by 300 seconds to form a dimensionless variable called 'saltation activity,' a value that varies from a minimum of zero to a maximum of one. The full record of saltation activity measured at the site is plotted as a time series in Figure 2. These data provide a continuous record of aeolian activity at the sampling site from 25 September 2002 to 1 May 2003. Note that 'blowing events' appear as bursts of saltation activity with peaks that extend outward with varying magnitude. Variations in saltation activity reflect

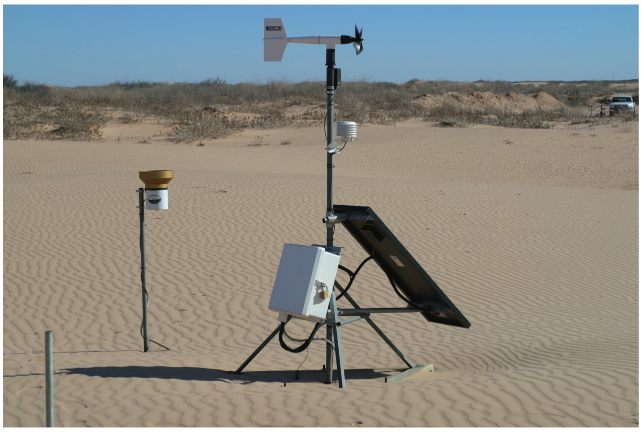

Figure 1. Photograph of the sampling system. This figure is available in colour online at www.interscience.wiley.com/journal.espl

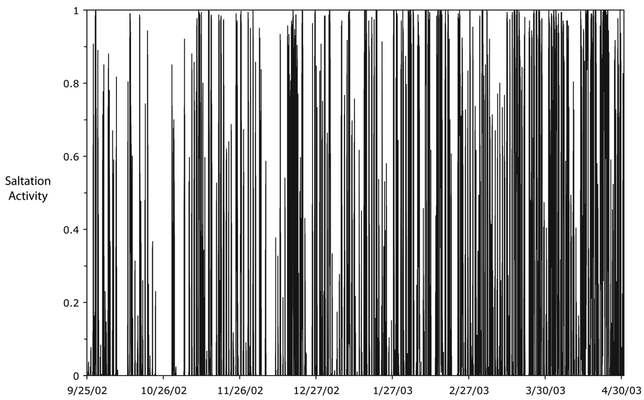

Figure 2. Time-series plot of five-minute saltation activity measured at the site from 25 September 2002 to 1 May 2003.

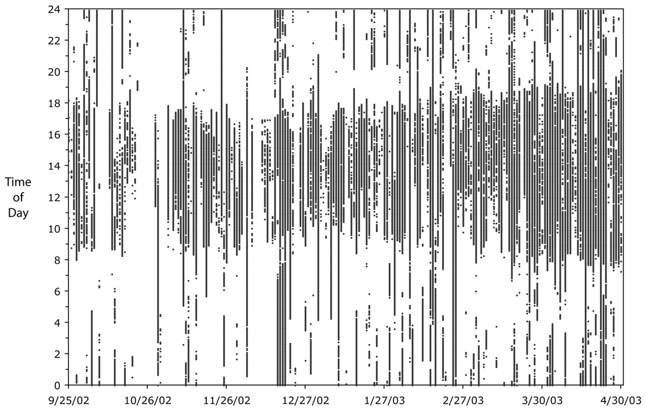

Figure 3. Diurnal activity plot with time of day on the vertical axis and calendar day on the horizontal axis. Each point represents a five-minute period with more than one saltation second.

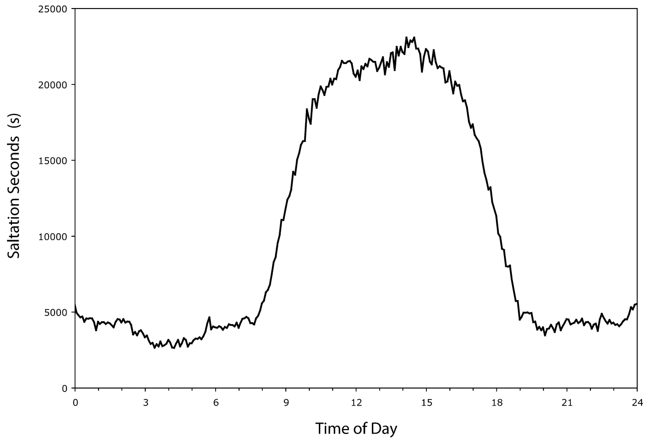

Figure 4. Diurnal distribution of the total number of saltation seconds measured over a seven-month sampling period from 25 September 2002 to 1 May 2003. Values represent the total number of saltation seconds for a given five-minute interval that defines the 'time of day'.

changes in wind and surface conditions. During most blowing events, dry and windy conditions led to saltation activity values approaching unity indicating nearly continuous sand transport over a given five-minute period. During other periods, light wind or moist conditions prevailed resulting in little or no saltation activity. Overall, there were only 22 days of the full 218-day sampling period without measurable saltation activity.

Another way of viewing the measured saltation activity time series is shown in Figure 3. Here the vertical axis represents the time of day, the horizontal axis is calendar day, and the plotted points represent five-minute periods with more than one saltation second. This type of 'saltation activity diagram' provides an interesting graphical depiction of aeolian activity at the sampling site and it provides insight into the dynamic nature of the process. For example, the fact that points are found at any time of the day confirm that blowing events can and do occur at any time, including late at night and early in the morning. The results also show a conspicuous dark band or streak running through the center of the plot indicating a zone of enhanced saltation activity associated with daylight hours, roughly between 09:00 and 18:00 Local Standard Time (LST). This band of enhanced saltation activity appears to gradually expand as one moves from the relatively short days of winter to the longer daylight hours of spring.

Diurnal patterns of blowing sand

To quantitatively establish diurnal patterns, the total number of saltation seconds was summed for a given 'time of day' for all days within the seven-month sampling period. For example, if we choose the five-minute period from 13:35 to 13:40 LST as the 'time of day' then we simply sum all saltation seconds that were recorded during this five-minute period for every day of the seven-month sampling period. The same process is repeated for all other five-minute periods and the results of this analysis are shown in Figure 4, where values of the total number of saltation seconds are plotted as a function of time of day.

Overall, relatively high levels of saltation activity were recorded during daylight hours and relatively low values were recorded at night and early morning. The lowest values of saltation activity are associated with the early morning period between 03:00 and 05:30 LST, with a minimum occurring at 04:15 LST. As the sun begins to rise, there is a rapid rise in saltation activity, especially from 08:00 to 10:00 LST, which corresponds to the initial phases of solar heating of the surface. Relatively high levels of saltation activity are maintained from around 11:00 to around 17:00 LST with peak values occurring in the afternoon at 14:10 and 14:30 LST followed by a decline in saltation activity as solar input to the system fades with the declining sun angle. The most rapid decline in saltation activity occurs from around 16:30 to 19:00 LST, eventually reaching a low point in the evening at 20:05 LST.

A close inspection of the overall shape of the curve (Figure 4) reveals that it is roughly bell-shaped and nearly symmetric, with the exception of a curious dip near its peak from 12:00 to 14:00 LST. Overall, the curve is somewhat flatter (less peaked) than a standard 'bell curve' and unlike a normal distribution, there is no period with zero saltation seconds, indicating that blowing events can occur at any time including at night and in the early morning. The nighttime passage of synoptic-scale cold fronts, the collapse of thunderstorms and associated outflows, are a few examples where exceptionally high winds can occur after sunset (Warn, 1952; Wigner, 1984).

Climatic factors

Diurnal patterns of blowing sand are influenced by diurnal variations of key meteorological factors. As discussed earlier, the climatic factors measured during this study include wind speed, solar radiation, and relative humidity. All climatic variables were sampled at 1-Hz and at the end of each five-minute period, values were averaged to form a five-minute average value of wind speed, solar radiation, and relative humidity. At the end of the seven-month sampling period, all of the five-minute values were averaged for a given time of day in much the same way that saltation seconds were summed. That is to say that all values associated with a specific time of day were averaged over the seven-month sampling period.

The diurnal pattern of blowing sand appears to follow a pattern that is roughly similar to the diurnal pattern of wind speed (Figure 5a). Generally, we find relatively strong winds during the day and lighter winds at night. The morning increase in wind speed, beginning around 07:00 LST, is associated with the rising sun and the resulting rise in incoming solar radiation (Figure 5b). As discussed earlier, solar radiation produces thermal instability and enhances the mixing of high momentum winds from the upper levels of the atmosphere to the surface layer.

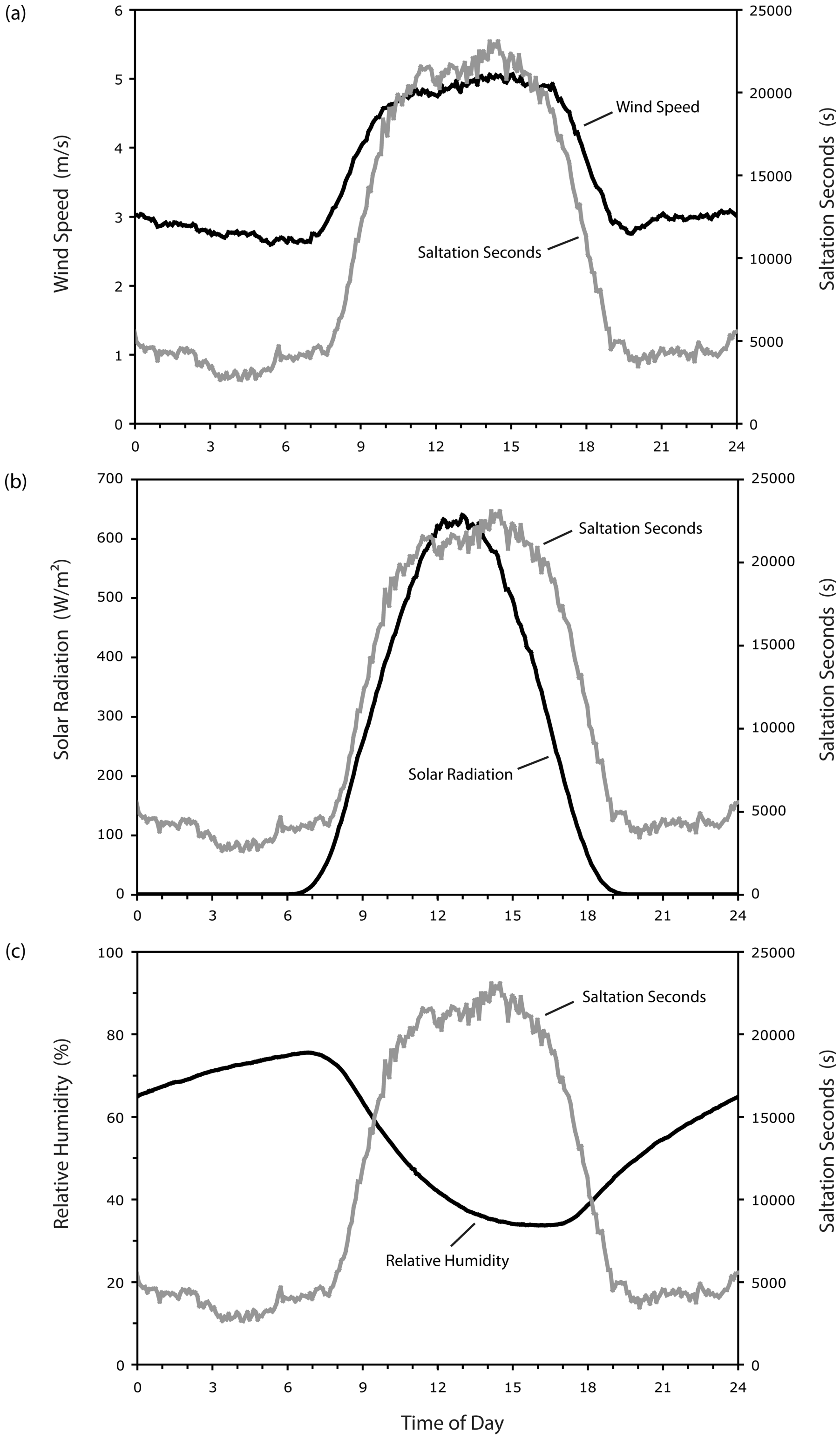

Figure 5. Comparison of the diurnal distribution of blowing sand with the diurnal distribution of key meteorological factors such as (a) wind speed, (b) solar radiation, and (c) relative humidity.

A close inspection reveals that the initial rapid increase in saltation activity tends to lag the morning rise in wind speed by about 30 minutes to an hour (Figure 5a). This lag is most likely associated with the fact that wind speed must first rise to a point where fluctuations intermittently exceed the critical threshold of the surface before sand movement will occur. Due to this threshold effect, a time lag occurs between the initial increase of wind speed and the initiation of sand transport produced by winds of sufficient magnitude.

Another factor that may influence the time lag between the morning rise of saltation activity and the morning rise of wind speed may be surface moisture (Wiggs *et al.*, 2004). As shown previously, the critical threshold of a sand surface may be slightly higher in the early morning due to surface moisture or dew (Stout, 2007). Unfortunately, it was not possible to directly measure surface moisture during this study; however, measurements of relative humidity do hint at slightly higher levels of surface moisture in the morning (Figure 5c). Relative humidity is typically at a high from 06:00 to 07:30 LST, which would indicate the possibility of above average surface moisture in the uppermost layer of sand. As the sun rises, the sand surface is quickly dried, threshold is reduced, and this allows the sand to respond more directly to rising wind speeds.

In the late afternoon, saltation activity begins to decline before wind speed starts its downward path (Figure 5a). For example, wind speed remains fairly constant from 14:00 to 17:00 LST, whereas saltation activity peaks at 14:30 LST and generally declines thereafter. One naturally wonders why saltation activity would decline while wind speed remains strong. One possible explanation may lie in an observed reduction of turbulent wind fluctuations in the late afternoon. Turbulence intensity, which is defined as the ratio of the standard deviation of wind speed and mean wind speed, provides a measure of the intensity of gusts in the atmospheric surface layer. Although the mean wind speed remains fairly constant from 14:00 to 17:00 LST, turbulence intensity declines 14% during this same period. A reduction of turbulence intensity tends to reduce the probability that gusts will exceed threshold and thereby trigger bursts of blowing sand (Stout and Zobeck, 1997). Thus, a mid- to late-afternoon reduction of wind 'gustiness' can result in an associated reduction in saltation activity, despite the fact that mean wind speed remains strong.

Overall, the period of peak saltation activity, which occurs from around 14:00 to 16:00 LST, is associated with a period of favorable climatic conditions for sand transport. In this afternoon period, wind speed is at a maximum from around 14:00 to 16:30 LST, relative humidity is at a minimum from around 14:00 to 18:00 LST, and solar radiation has peaked from 12:00 to 14:00 LST. Thus, the diurnal peak in saltation activity occurs during the period of the day when the winds are typically at a maximum, humidity is at a minimum, and the sun has had ample opportunity to dry the sand surface, thereby ensuring the lowest possible threshold velocity.

Conclusions

This paper outlines a technique for monitoring the diurnal pattern of blowing sand. The key to this method is the use of the output from a piezoelectric saltation sensor as an on- or off-indicator of blowing sand, which allows the number of seconds with active sand movement within a given five-minute sampling interval to be counted. Next, the number of saltation seconds is summed for each specific time of day over a period of months to provide a relative measure of saltation activity associated with a given time of day. This technique effectively allows the diurnal pattern of blowing sand to be defined with great precision.

Direct measurements of blowing sand taken over a seven-month period on the Llano Estacado suggest that sand movement occurs more frequently during the day and less frequently at night. These results agree with the well-established finding that dust storms tend to occur more frequently during daylight hours when solar insolation is strong and thermal instability is at a maximum.

The diurnal pattern of blowing sand was found to peak in the afternoon between 14:00 and 15:00 LST. Overall, the diurnal peak resulted from a convergence of favorable climatic conditions including strong winds, low humidity, and a sun-dried sand surface with the lowest possible threshold velocity.

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