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Simultaneous observations of the critical aeolian threshold of two surfaces

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Abstract

Threshold is an important parameter in wind erosion research and in the field of aeolian research in general. A new technique was recently developed that provides a means of determining threshold with a sampling system that continuously collects wind data along with critical information regarding saltation activity. By employing two identical sampling systems, it was possible to monitor the threshold of a highly mobile sand surface while simultaneously monitoring the threshold of a less mobile playa surface. Results indicate that threshold could be measured at both locations with enough precision to establish clear differences between the surfaces. The sandy surface at the Morgenstern Dunes site was considerably more active than the Yellow Lake playa site over the 113-day sampling period because of its consistently lower threshold. The Morgenstern site tended to maintain a fairly constant threshold of around 5.4 to 5.5 m/s whereas the threshold of the Yellow Lake playa surface varied from a low of 6.4 m/s to values greater than 13.3 m/s. Limitations of this method lie in the fact that threshold can be determined only when winds are blowing sufficiently strongly to cause sediment transport.
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Keywords: Threshold; Saltation; Blown sand; Wind erosion; Aeolian research; Dune; Playa

1. Introduction

Under naturally turbulent wind conditions, gusts may intermittently exceed threshold, producing bursts of sediment entrainment and transport leading to dust emissions, topsoil loss, and a host of other environmental problems. Recently, a new technique was developed that provides a practical method for establishing the critical threshold of an erodible surface under natural wind conditions. Threshold is calculated from measurements of saltation activity and the mean and standard deviation of wind speed (Stout, 2004).

This technique provides a means of determining threshold using data supplied by a sampling system that continuously collects wind and saltation data while left unattended in the field for extended periods. By employing multiple sampling systems, it is possible to use this technique to monitor the threshold of multiple surfaces, simultaneously.

Here, this technique was employed to monitor threshold at two sites with fundamentally different surfaces — the flat clay surface of a saline playa lakebed and the highly mobile surface of an unvegetated sand sheet — both located on the Southern High Plains of West Texas.

2. Physical setting

At the southern end of the Great Plains of North America, lies an elevated plain of approximately 73,400 km^2 called by various names including Llano Estacado, Staked Plains, South Plains, or Southern High Plains. This immense plain is bounded by caprock

escarpments 50 to 200 m high (Reeves and Reeves, 1996). The western and northern escarpments separate the plateau from the Pecos and Canadian River valleys, respectively. Spring sapping and headward erosion by tributaries of the Red, Brazos, and Colorado Rivers have carved away at the eastern escarpment, which separates the Southern High Plains from the Rolling Plains of Texas and Oklahoma (Holliday, 1995).

Among the more interesting geomorphic features within this region are the dune fields that stretch across the plains in long finger-like projections and the irregularly shaped saline playas that are found scattered across the more stable regions between the dune fields. Both of these features are of aeolian origin: playas are deflationary features whereas the dune fields developed as a result of aeolian transport and deposition of sands from their source regions along the valley of the Pecos River located to the west and southwest of the Southern High Plains. With respect to this project, these features are of special interest because they provide excellent sites in which to study basic aeolian processes.

A map marking the locations of the two sampling sites is presented in Fig. 1. The sites are spaced 55 km

Table 1
Altitude and location of the two sampling sites

Site	Altitude (m)	Latitude	Longitude
Yellow Lake	1045	33° 48′ 54″	102° 27′ 24″
Morgenstern Dunes	1080	33° 19′ 17″	102° 29′ 27″

apart and are roughly aligned in a north–south direction centered on the West Texas town of Levelland. The exact location and altitude of each sampling site is summarized in Table 1.

Aerial photographs of the sites are presented in Fig. 2 and ground-level photographs of the sampling sites with the sampling systems in place are shown in Fig. 3. The two sites chosen for this study are similar in that they both naturally lack vegetation and tend to be prone to frequent aeolian activity. However, the texture, composition and structure of the two surfaces are fundamentally different.

The Morgenstern Dunes form the eastern tip of a much larger 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 (Muhs and Holliday, 2001). The
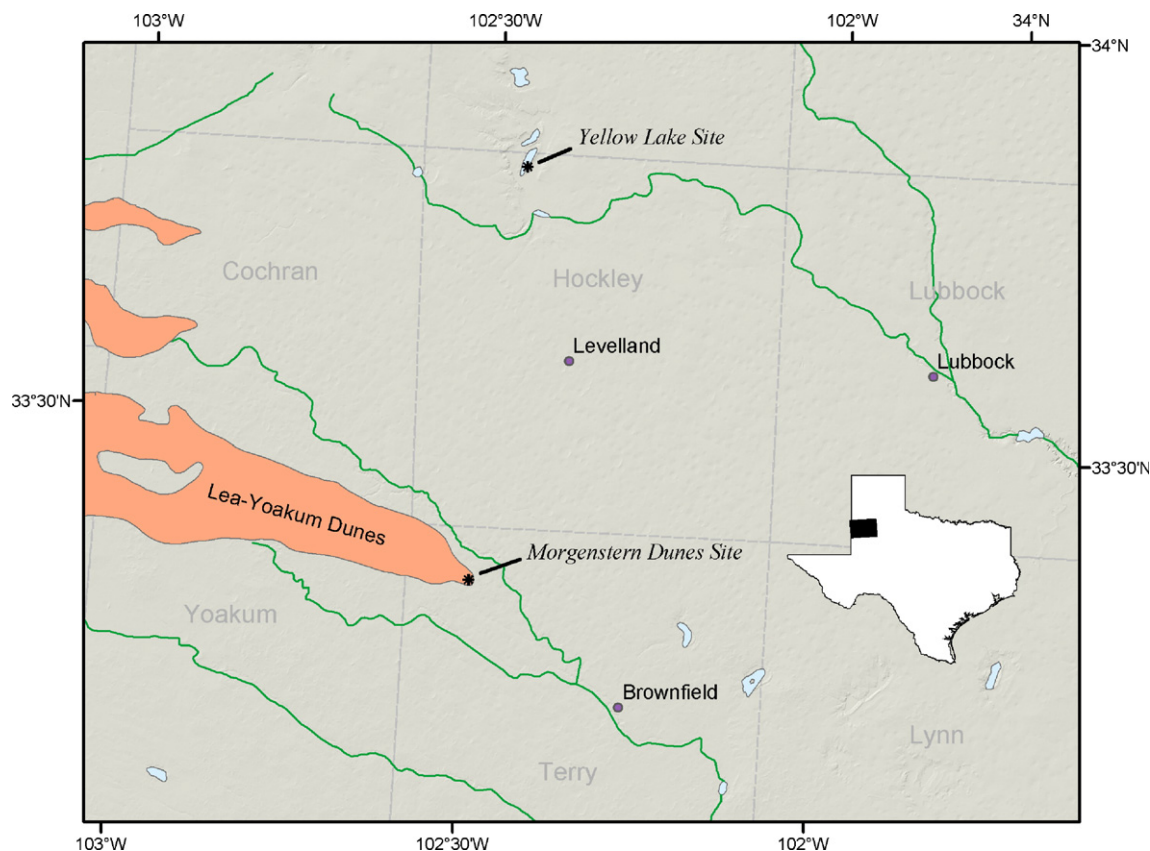

Fig. 1. Map showing the location of the two sampling sites and their relation to other geomorphic features on the Southern High Plains.
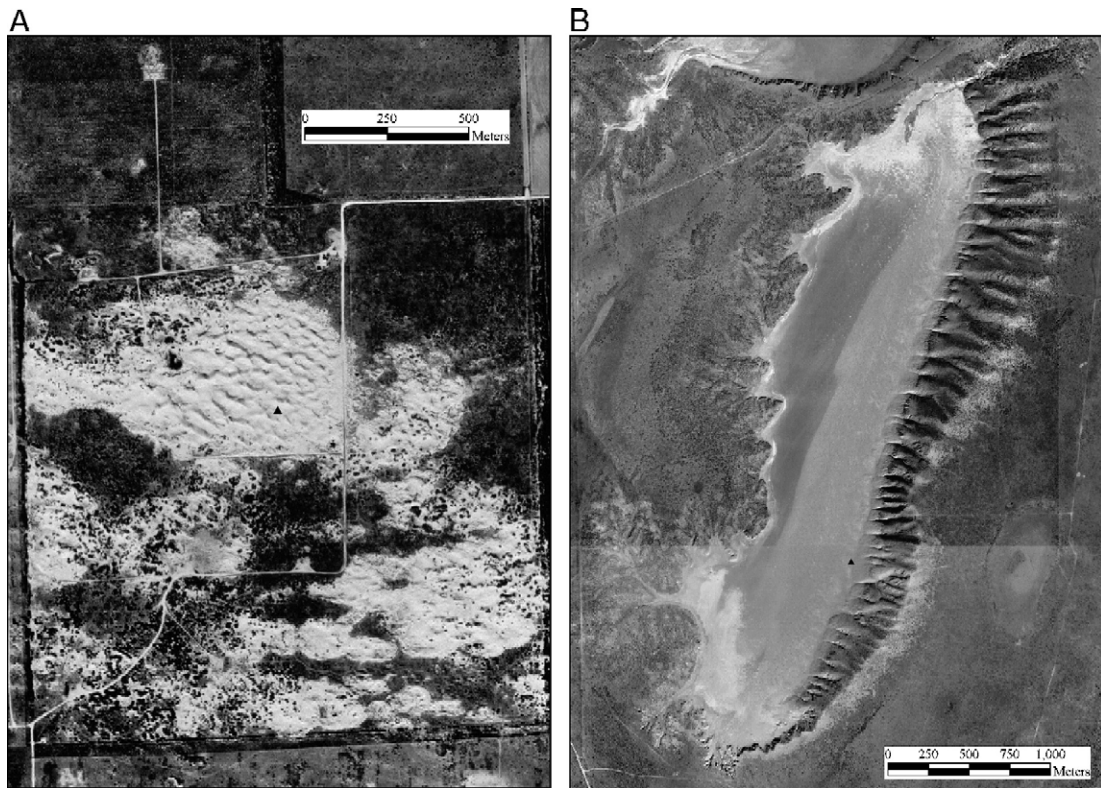
Fig. 2. Aerial photographs of the Morgenstern Dunes and Yellow Lake. Locations of sampling sites are marked with black triangles.

Lea-Yoakum Dunes contain both well-formed dunes of fine quartz sand and low-relief aeolian sand sheets stabilized by scrubby vegetation. The Morgenstern section of the Lee-Yoakum Dunes tends to be less vegetated and more active than the rest of the dune field.

Yellow Lake is one of two large saline playas within the Yellow House Basin, a closed basin located on the Yellow House Ranch of Lamb and Hockley counties of West Texas (Stout, 2003). The flat clay surface of the playa can shift rapidly from a highly erodible state to a condition of complete stability. At times, the surface may be dry and hard enough to walk on without leaving tracks as shown in Fig. 4. During wet periods, surface waters form a broad shallow pool that often occupies a limited fraction of the playa surface. Even those areas free of standing water may remain moist and muddy for many weeks following rain since the clay surface dries slowly (Fig. 4). The playa surface is most erodible following extended dry periods but even when the surface is dry, the amount of loose erodible material can be highly variable. As shown in Fig. 5, the surface can at times be firm with deep desiccation cracks that tend to trap potentially erodible grains. At other times, weathering may soften the crust causing it to breakdown and form sand-sized clay aggregates. Transport of these

aggregates can further abrade the crust, forming additional aggregates that often move across the playa surface as miniature dunes, as shown in Fig. 6. As more and more clay aggregates blanket the surface, the erodibility of the playa increases such that the playa surface begins to respond more like a simple sand surface.

3. Methods

Identical sampling systems were installed at each site, each capable of measuring a continuous meteorological record as well as collecting information regarding aeolian activity (Fig. 3). Measured meteorological variables include wind velocity, relative humidity, air temperature and precipitation. Wind velocity was measured with a fast-responding propeller-type anemometer mounted at a height of 2 m. 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 summarized every 5 min.

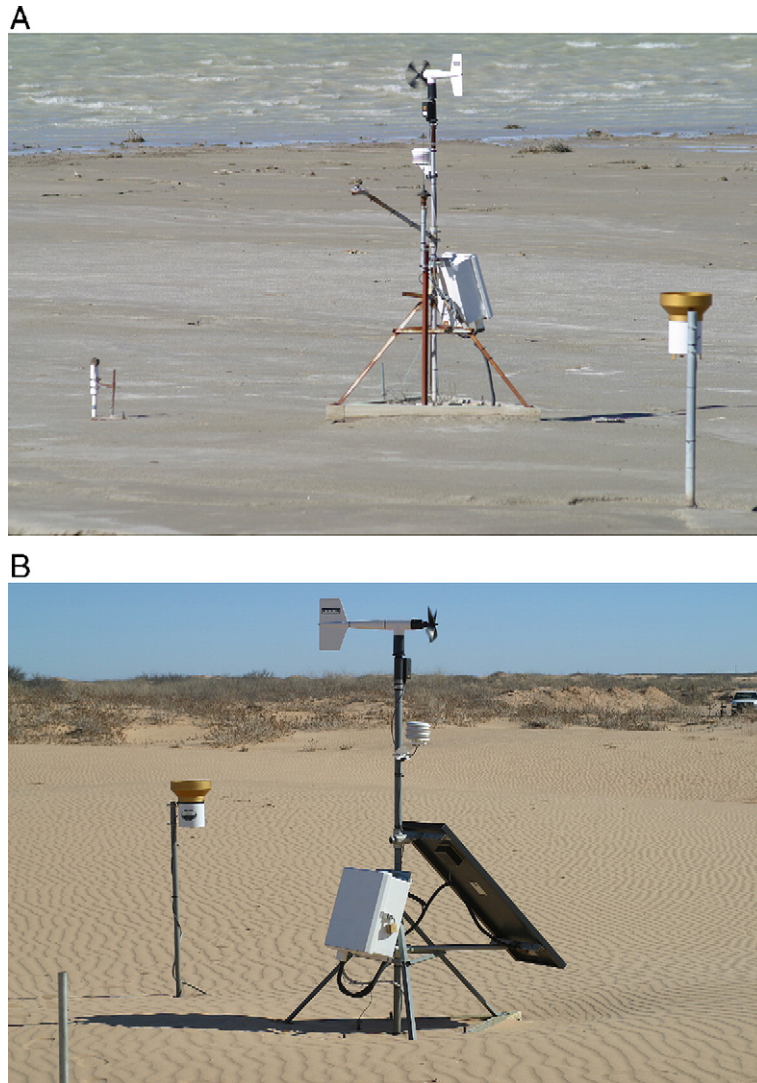A key component of each sampling system was a piezoelectric saltation sensor, a device that produces an

Fig. 3. Photos showing the sampling systems installed at Yellow Lake (top) and the Morgenstern Dunes (bottom).

electrical pulse signal when it is impacted by saltating grains. A single saltation sensor was located 10 m to the west of each meteorological tower at each site. The center of the piezoelectric sensing element was mounted at a height of 5 cm above the surface. Both saltation sensors were custom made by the manufacturer so that they had the same sensitivity.

During periods of active saltation, the piezoelectric transducer produced a signal that was used as an indicator of aeolian sediment transport. Each pulse signal generated by each saltating particle 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". At the end of each 5-minute period, saltation seconds were summed and

the total was output as one of the variables stored on the data logger.

The total number of saltation seconds recorded during each five-minute period was divided by 300 s to form a dimensionless parameter called saltation activity. Saltation activity, denoted γ, can vary from 0 to 1 and simply expresses the fraction of time that aeolian activity was detected at the sampling point. Saltation activity is governed primarily by the frequency at which wind fluctuations exceed threshold. As shown by Stout and Zobeck (1997), this relationship is expressed mathematically by an equation of the form:

$$\gamma = \Phi\left(\frac{\bar{u}-u_t}{\sigma}\right), \tag{1}$$

Fig. 4. The erodibility of the clay playa surface at Yellow Lake is intimately linked to rainfall. A sudden precipitation event can transform a dry and highly erodible surface to a stable muddy surface in a manner of seconds. Unlike the dune sands at the Morgenstern site that tend to dry rapidly, the moist surface conditions at Yellow Lake can persist for many weeks after rainfall.

where threshold wind speed is denoted by u_t and the mean and standard deviation of wind speed are denoted by $\bar{u}$ and σ, respectively. The symbol Φ denotes a distribution function, the form of which follows the form of wind speed distribution. When considering short periods of less than 1 h, turbulent winds follow closely a normal distribution function, as was demonstrated by Stout and Zobeck (1997).

By taking the inverse of the normal distribution function, denoted by Φ^{-1}, Eq. (1) may be reformulated so

that threshold may be calculated from field measurements of saltation activity and wind statistics (Stout, 2004):

$$u_t = \bar{u} - \sigma \Phi^{-1}(\gamma). \tag{2}$$

This equation is essentially a more elegant mathematical statement of the "time fraction equivalence" (TFE) method first proposed by Stout and Zobeck (1996) and later investigated by Schönfeldt (2003), Schönfeldt and Löwis (2003), Schönfeldt (2004), and Wiggs et al. (2004).
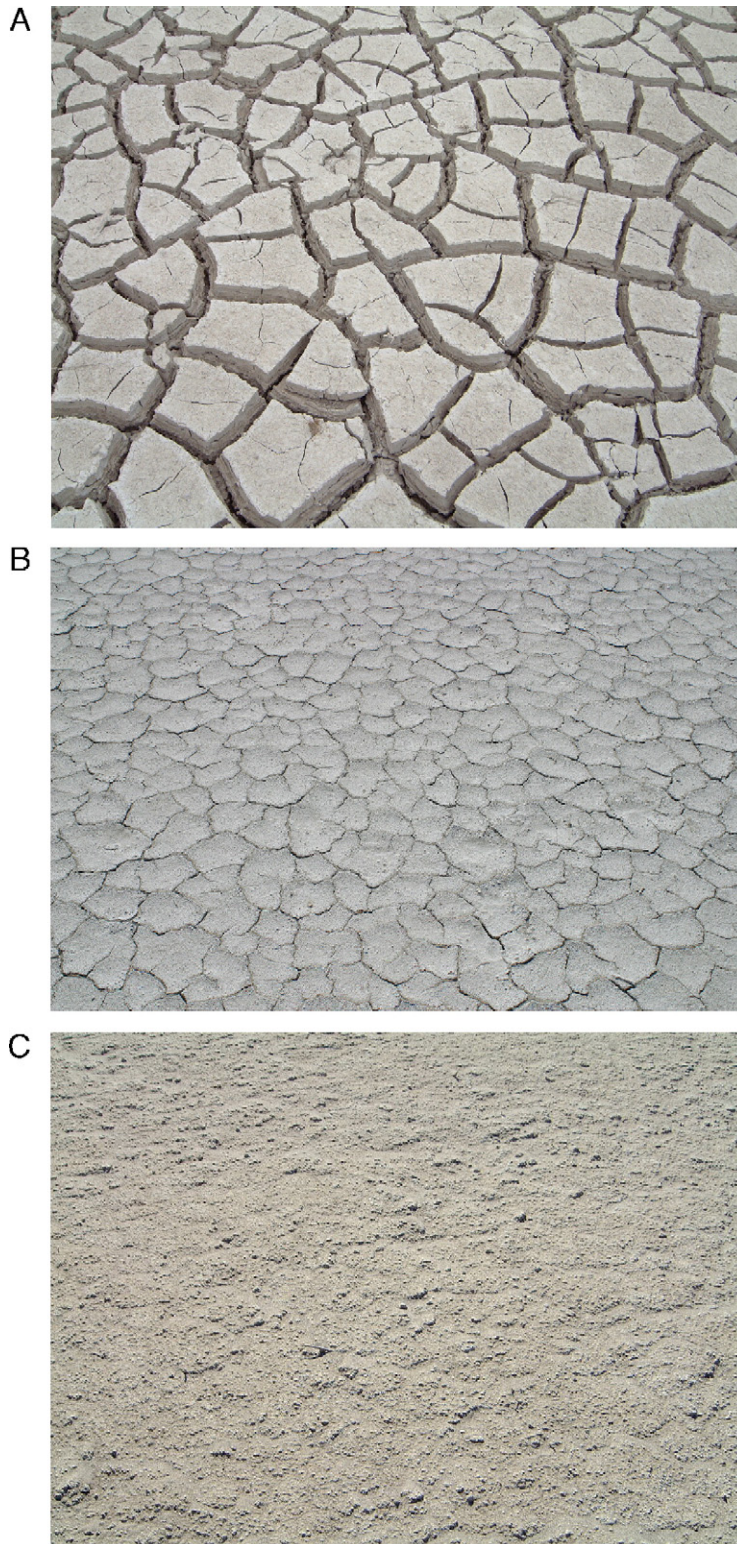
Fig. 5. The dry playa surface of Yellow Lake may at times be firm with large desiccation cracks that tend to trap saltating grains. Over time, the crust may degrade due to weathering. Sediments may eventually fill the cracks creating a smoother surface that is more favorable for aeolian transport. As more grains are transported across the playa surface, the crust may become highly abraded by saltating grains.
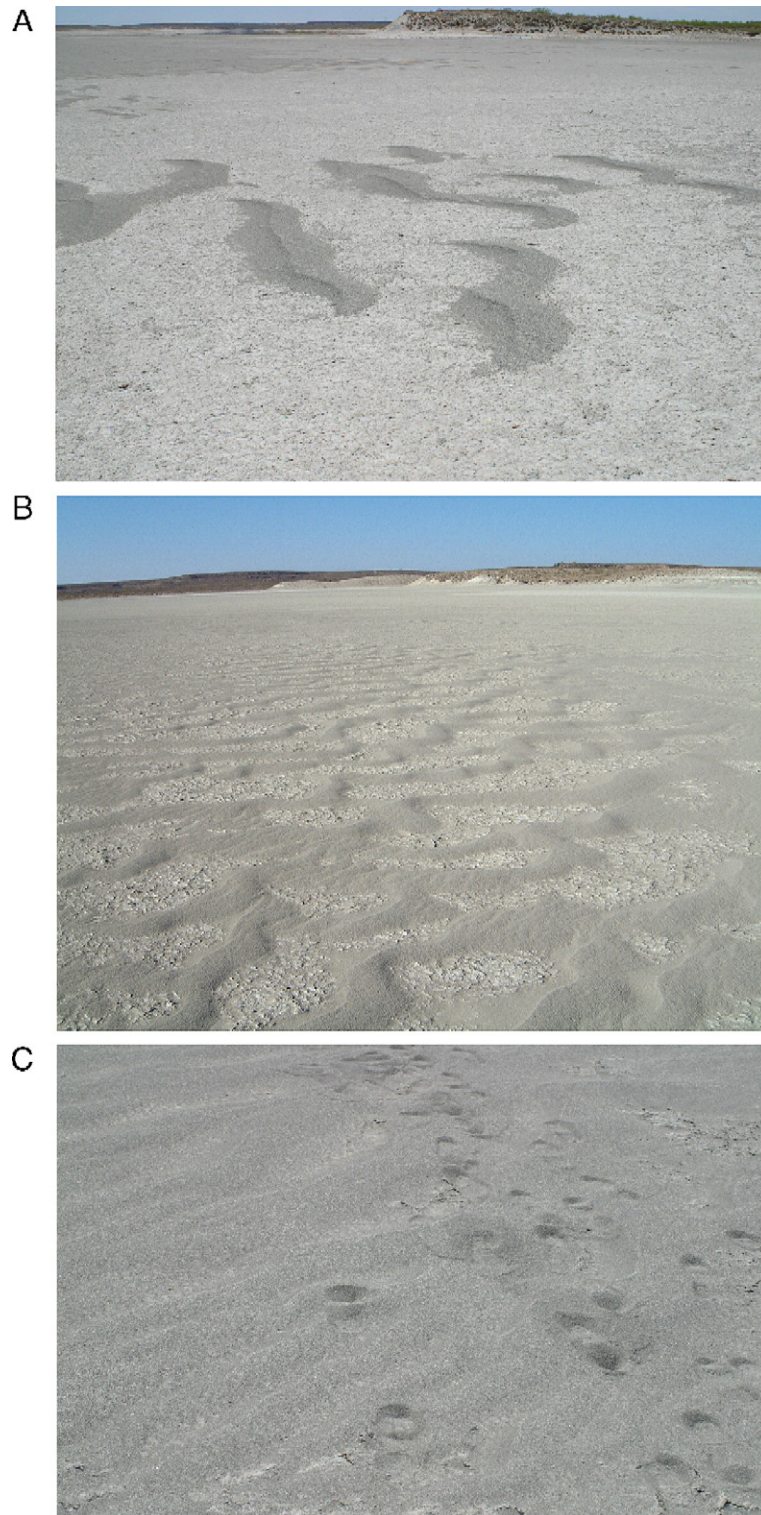
Fig. 6. Clay aggregates move across the playa surface forming miniature dunes that share many similar characteristics with larger dune forms. In some places, especially near the playa margins, clay aggregates accumulate sufficiently to form highly mobile surfaces that are composed entirely of sand-sized grains.

The underlying principle of "time fraction equivalence" is that the fraction of time that aeolian transport occurs should be equivalent to the fraction of time that winds exceed threshold. The TFE method was originally proposed as an iterative process whereby a series of threshold values were selected until time fraction equivalence was achieved (Stout and Zobeck, 1996). This new formulation eliminates the need for manual iterations by providing a more direct calculation of aeolian threshold.

Theoretically, values of threshold can be calculated for any period in which saltation activity is greater than zero and less than one ($0 < \gamma < 1$); however, experience has shown 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 $0.02 < \gamma < 0.98$ eliminates many of these outliers.

4. Results

Measurements were obtained at both sites from 16 October 2002 through 5 February 2003. Complete re-cords of saltation activity measured at each site are plotted as time series in Fig. 7. These results show a clear difference in the level of saltation activity between the two sites. Some level of saltation activity was detected at the dune site for 107 days out of the full 113-day sampling period whereas sediment transport at Yellow Lake was detected for only 61 days during the same period.

A more precise way to quantify the overall difference in aeolian activity between sites is to sum the total number of saltation seconds recorded at each site during the 113-day sampling period. At the dune site, saltation was detected for 1,151,581 s out of a possible 9,763,200 s. The overall saltation activity is simply the ratio of these two values or 0.118, which is equivalent to saying that aeolian transport was detected at the Morgenstern Dunes site for 11.8% of the time during the 113-day sampling period. A much lower number of 254,938 saltation seconds was recorded during the same period at the playa site. The overall saltation activity was 0.026, which suggests that aeolian transport was detected at Yellow Lake for only 2.6% of the time from 16 October 2002
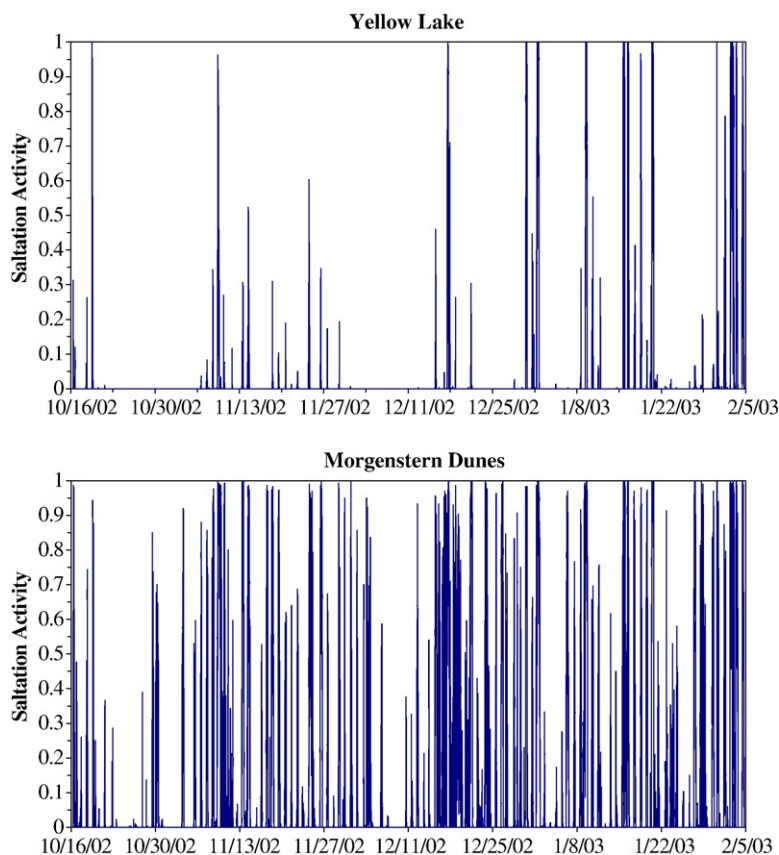

Fig. 7. Five-minute saltation activity records measured at the Morgenstern Dunes and Yellow Lake from 16 October 2002 through 5 February 2003. Five-minute saltation activity is a dimensionless variable that describes the fraction of time that aeolian transport was detected during a five-minute interval.

Table 2
Summary of key meteorological parameters and saltation activity from 10/16/02 through 2/5/03, a period of 113 days or 9,763,200 s

Site	Average 2-m wind speed (m/s)	Average relative humidity (%)	Rain (mm)	Saltation seconds (s)	Average saltation activity
Yellow Lake	3.24	61.5	85	254,938	0.026
Morgenstern Dunes	3.31	61.4	104	1,151,581	0.118

through 5 February 2003. Thus, saltation activity at the dune site was greater than that at the playa site by a factor of 4.5.

One naturally wonders why there is such a clear difference in saltation activity since it is unlikely that two sites, spaced only 55 km apart, experienced radically different wind conditions. In fact, as shown in Table 2, the average wind speed over the 113-day sampling period was 3.24 m/s at Yellow Lake and 3.31 m/s

at the Morgenstern Dunes, a difference of only 2%. Such a small difference is probably within the accuracy of the instruments and cannot account for such a large difference in saltation activity. Similarly, the average relative humidity was 61.5% at Yellow Lake and 61.4% at the Morgenstern Dunes, which suggests that the level of atmospheric moisture was not significantly different between sites. With regard to precipitation, the total rainfall at the dune site was 104 mm, a value that is significantly higher than the 85 mm of rain that fell at Yellow Lake. In addition, the Morgenstern Dunes received measurable rainfall on 21 days as opposed to only 18 days at Yellow Lake during the 113-day sampling period. Thus, rain fell more frequently and with higher volume at the dune site, yet saltation activity was still significantly higher at the dune site.

Clearly, climatic factors cannot account for differences in the magnitude and frequency of aeolian activity between sites. It is more likely that fundamental differences in the inherent erodibility of the surfaces
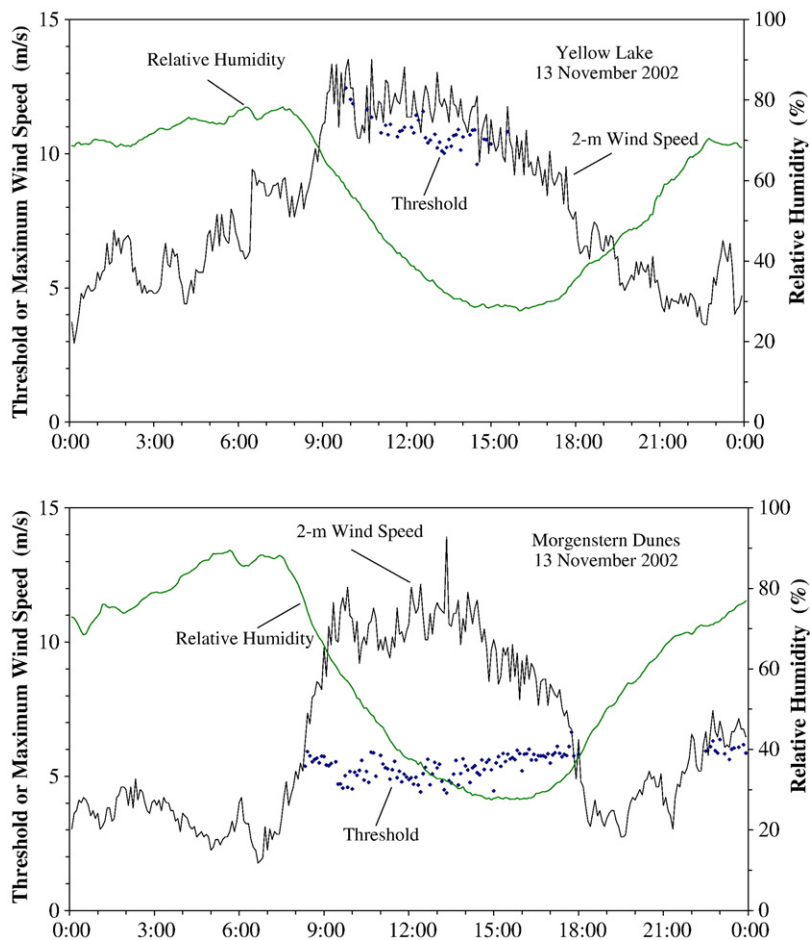

Fig. 8. Measurements of maximum wind speed, relative humidity and threshold obtained over a 24-hour period on 13 November 2002.

contributed to the difference in measured saltation activity. One measure of erodibility is threshold.

5. Daily examples

What follows are a series of examples in which threshold values were obtained at both sites during the same day. For each set, the upper plot shows measurements of relative humidity, maximum wind speed and calculated threshold values for Yellow Lake and the lower plot shows similar results for the same 24-hour period at the Morgenstern Dunes.

The choice of examples was limited to those days when saltation activity was detected at both sites since it is not possible to determine the threshold of a surface unless saltation activity is detected. This limited the comparison to windy days when both surfaces were dry enough to allow sediment transport. The less mobile playa surface was often the limiting factor since the slightest bit of rain could render it completely stable for weeks at a time. However, during periods of active

aeolian transport, values of threshold could be obtained at each site every 5 min.

The first example (Fig. 8) shows measurements obtained over a 24-hour period on 13 November 2002. At the dune site, wind speeds remained below threshold until around 0800 when winds suddenly strengthened and stayed above threshold for 10 h. Winds slackened at sunset then strengthened again near midnight. Although there is some scatter, calculated values of threshold at the dune site tend to hover around 5 to 6 m/s for most of the day with an average value of 5.4 m/s. During the same period, winds at the playa site show a more gradual increase in the morning with a sudden jump to a maximum around 0900. Although winds gusted to as high as 13.3 m/s at 0920 and then again at 0930, no sediment transport was detected suggesting that the playa surface threshold was higher than 13.3 m/s during this early morning period. It was not until 0950 that the threshold of the playa surface reduced to the point that saltation activity was detected and threshold values could be calculated using Eq. (2). The overall trend in the
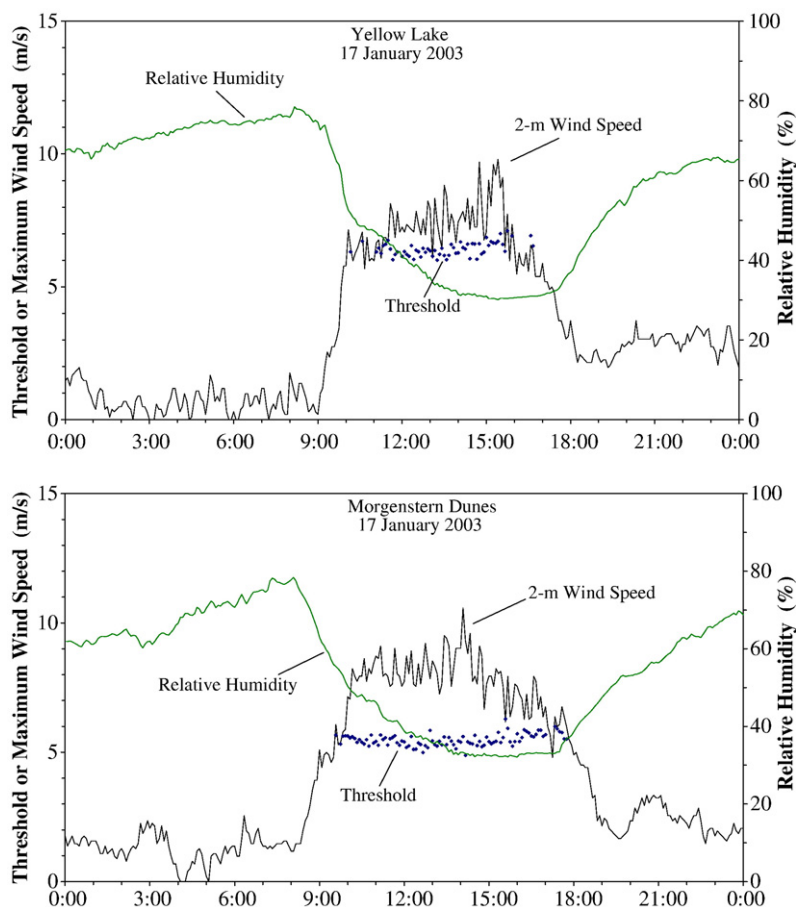

Fig. 9. Maximum wind speed, relative humidity and threshold measured on 17 January 2003.

morning shows threshold values decreasing at the playa site from 12.5 m/s at 0950 to around 11 m/s at 1130 with an overall average threshold of 10.8 m/s for the most active portion of the day. A less significant reduction of threshold was observed at the Morgenstern site where threshold values show only a slight dip from morning to noon followed by a slight rise from noon to 1800. One possible explanation for the late-morning reduction of threshold at the playa site is that the clay surface of the playa may have been initially moist due to early morning dew and the surface threshold may have declined as the sun rose and gradually dried the surface. Overall, the results show that on 13 November 2002 there was a clear separation between sites with threshold values at Yellow Lake around twice that of the Morgenstern Dunes.

The next example (Fig. 9) shows measurements for the same two surfaces obtained around 2 months later on 17 January 2003. On this day similar diurnal wind patterns were observed at both sites with light winds in the early morning, strong gusty winds from around 0900 to 1800, and a considerable weakening of winds after

sunset. The average threshold at the Morgenstern site in January was 5.5 m/s, which is close to the average of 5.4 m/s measured in November. The average threshold at Yellow Lake was considerably lower with an average value of 6.4 m/s in January compared to a 12.5 m/s threshold measured in November.

The third and final example (Fig. 10) shows measurements obtained on 4 February 2003. The diurnal wind pattern was again similar to the other cases with winds shooting upward between 0900 and 1000, blowing hard for around 9 h until suddenly falling below threshold at around 1800. Again, one finds little change in the threshold at the Morgenstern site where the average threshold was 5.4 m/s, a value that is almost identical to the previous two cases. The threshold of the playa surface has increased to 8.1 m/s from a value of 6.4 m/s measured in January so that once again there is a significant separation between the Morgenstern and Yellow Lake sites.

Values of threshold measured at both sites are plotted together in Fig. 11. Here the horizontal scale is restricted
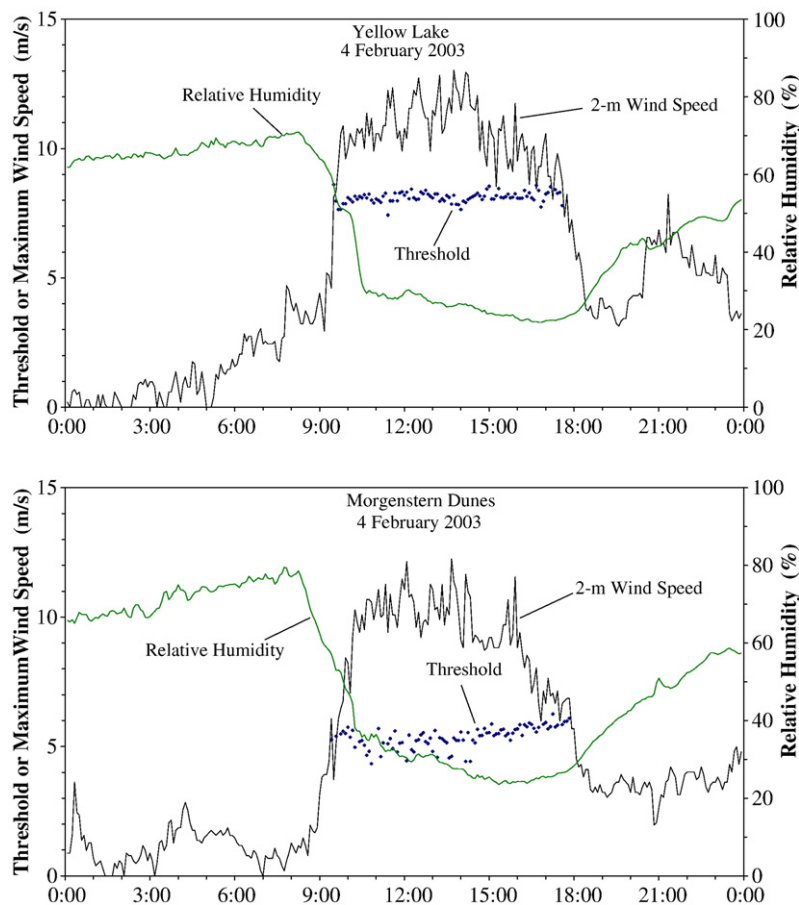

Fig. 10. Maximum wind speed, relative humidity and threshold measured on 4 February 2003.
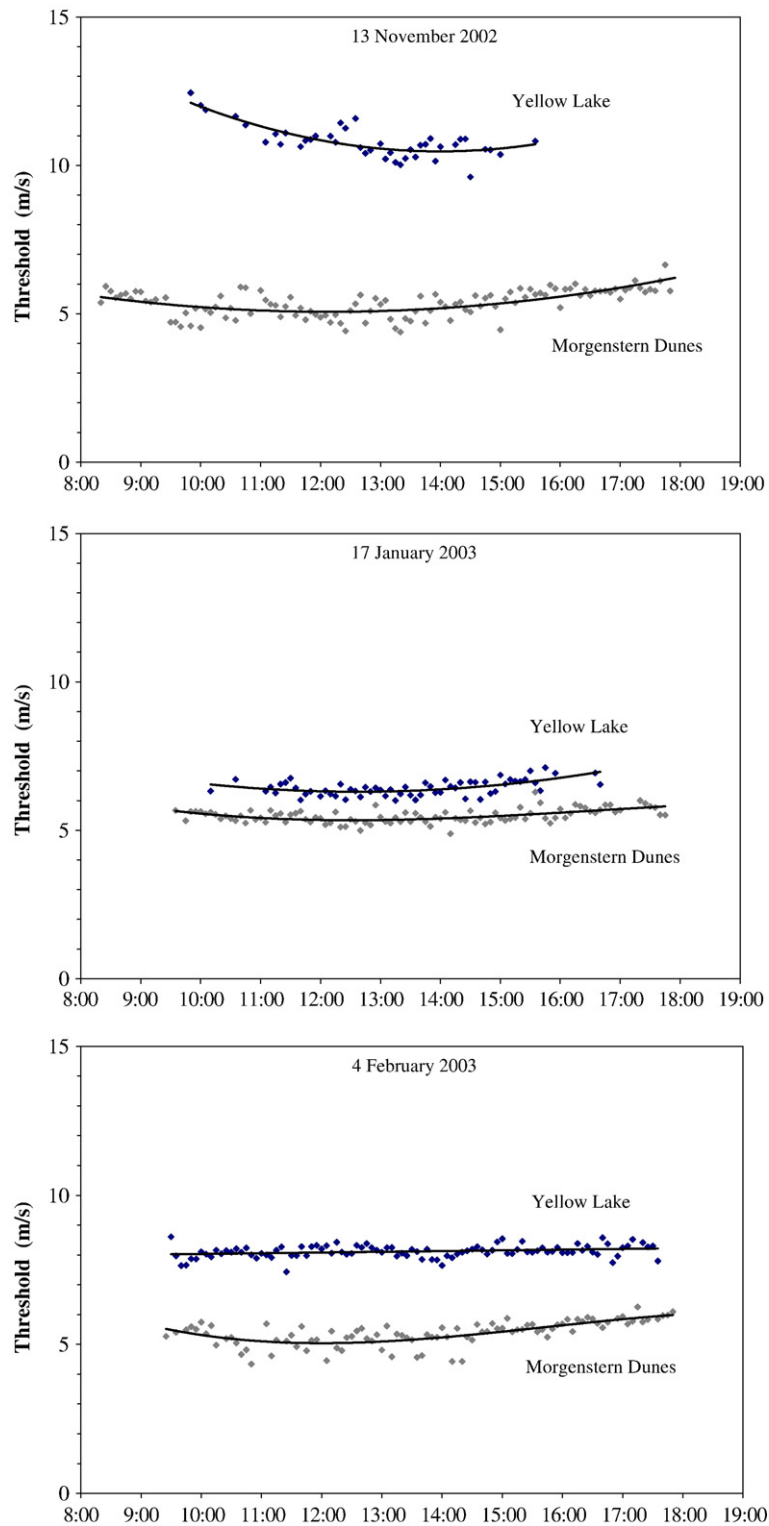
Fig. 11. Threshold values measured simultaneously at both sites on 13 November 2002, 17 January 2003 and 4 February 2003.

to an 11-hour period of maximum aeolian activity from 0800 to 1900 rather than the full 24-hour period shown previously. Plotted together, one can see more clearly that the threshold of the sand surface at the Morgenstern site remained fairly constant throughout the sampling period whereas the threshold of the playa surface tended to vary more appreciably. Overall, the results show that on 13 November 2002 there was a clear separation between sites with threshold values at Yellow Lake around twice that of the Morgenstern Dunes. This separation reduced considerably on 17 January 2003 where playa thresholds were only slightly higher than values measured at the dune site. By 4 February 2003, threshold values measured at the two sites were clearly separated once again, although the separation was less than that of 13 November 2002. A summary of the average threshold values measured on these dates is presented in Table 3.

Photographs taken during the sampling period offer some insight into the temporal variations of threshold at the two sites. Photographs of the sand surface at the Morgenstern site show a surface that changes very little. Rain would pass rapidly through the dune sands so that the sand surface dried quickly and the lack of clay prevented the formation of surface crusts. Thus, the dune threshold values tended to remain constant. The clay surface of Yellow Lake is another story. Photographs taken of the playa surface reveal that its surface conditions changed significantly during the sampling period.

In November of 2002, there was a shallow pool of standing water occupying a limited portion of the west side of Yellow Lake. On the east side, where the sampling system was located, moisture was just below the weakly crusted surface. Sediment could blow across the crusted surface but the supply of loose erodible material was somewhat limited. The supply-limited condition and the near-surface moisture most likely contributed to the relatively high threshold of the playa surface on 13 November 2002.

By the middle of January 2003, the pool of standing water had essentially evaporated; however, the playa surface remained moist in places. On the east side,

where the sampling system was located, photographs show a dry an abraded crust with indications of loose erodible material deflating from the playa surface and moving east past the sampling system and depositing on the fringing dunes. Because of the highly erodible condition of the playa surface and the abundance of loose erodible sediments at the sampling site, the measured threshold of the playa was considerably reduced in January compared to that in November.

No rain fell on the playa surface between 17 January and 4 February, so the increase in threshold from January to February cannot be attributed to rainfall. Photographs of the central playa region taken in February show a dry surface with numerous desiccation cracks that formed as the lakebed continued to dry. Strong winter winds blowing in January and into February removed most of the loose erodible material from the playa surface leaving behind a hardpan surface with little loose material. Along the eastern margins, where the sampling system was located, deflation of accumulated sediments continued, however, the lack of incoming grains from the central playa region gradually resulted in an increasingly supply-limited surface condition around the sampling system. Thus, a reduction of the supply of loose erodible material may be the key factor that led to an increase in threshold from January to February.

6. Conclusions

A new technique was recently developed that provides a simple and convenient method for establishing the threshold of an erodible surface under natural wind conditions using measurements of saltation activity and the mean and standard deviation of wind speed (Stout, 2004). This technique provides a means of determining threshold with a sampling system that continuously collects critical information while left unattended in the field for extended periods. By employing two sampling systems, it was possible to monitor the threshold of two fundamentally different surfaces — a sand surface and the clay surface of a saline playa lake.

Results reveal that a sand surface, such as that at Morgenstern Dunes, tends to maintain a somewhat consistent threshold of around 5.4 to 5.5 m/s while the threshold of a playa surface, such as that at Yellow Lake, can vary from as low as 6.4 m/s to values greater than 13.3 m/s.

On those days without sufficient saltation activity, the threshold of both surfaces may have been much higher than the examples presented here. Unfortunately,

Table 3
Summary of average threshold values measured simultaneously at both sites

Date	Morgenstern Dunes threshold (m/s)	Yellow Lake threshold (m/s)
11/13/02	5.4	10.8
1/17/03	5.5	6.4
2/4/03	5.4	8.1

due to the limitations of this method, threshold cannot be determined unless sediment transport is detected. As a result, there are often periods when winds remain below threshold and the lack of saltation activity prevents the determination of threshold. Nevertheless, when conditions are favorable, this method can provide valuable information regarding threshold that would be difficult to obtain in any other way.

Acknowledgments

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