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Dune sand transport as influenced by wind directions, speed and frequencies in the Ordos Plateau, China

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Abstract

The Ordos Plateau in China is a region with extensive wind erosion, severe desertification and various aeolian sand hazards. In order to determine aeolian sand transport in this region, the relationship between the sand transport rate and wind speed at 10 min frequencies was established by field observation in both the Qubqi Sand Desert and the Mu Us Sandy Land. Threshold wind speeds (2 m above the ground) for mobile, semi-fixed and fixed dune surfaces were estimated by field observations. The sand transport rate increased with the increase of the bare land ratio and near-bed wind speed. High-resolution meteorological 10 min average wind velocity data at 10 m above the ground were converted into velocity values at a height of 2 m to calculate sand transport potential based on three specific parameters decisive for sand transport: wind speed, duration and direction. The quantity of aeolian sand transported was calculated for various wind speed levels and directions, and the overall characteristics of sand transport on different dune surface types were determined by vector operation techniques. Sand transporting winds took place mainly in springtime. The prevailing wind directions were W, WNW and NW, with a frequency of more than 60% in total, and sand transport in these directions made up more than 70% of the total transport, corresponding to a general southeastward encroachment of aeolian sand in the study area. The relationship between wind frequency and speed can be expressed by a power function. High magnitude strong winds had a low frequency, but they played a dominant role in aeolian sand transport.

Keywords: Ordos Plateau; Sand transporting winds; Sand transport rate; Land surface types

1. Introduction

The Ordos Plateau in China is a region with extensive wind erosion, severe desertification and various types of aeolian sand hazards (Zhu et al., 1980; Yang et al., 1991; Liu, 1999). Understanding

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and quantification of the temporal and spatial variability in sediment transport are essential not only for prediction of the rates of dune growth and migration, but also for evaluation and control of aeolian sand hazards (Nickling et al., 2002).

Aeolian sand transport is a process affected by many different variables such as grain size distribution, wind regime, vegetation, and surface moisture (Skidmore, 1965; Skidmore and Tatarko, 1990; Neuman and Scott, 1998; Iversen and Rasmussen, 1999). Numerous authors worked on these problems and important progress has been made in understanding aeolian sediment transport (Owen, 1964; Lancaster, 1985; Anderson, 1986; Anderson and Hallet, 1986; Wasson and Nanninga, 1986; Anderson and Haff, 1988; Buckley, 1987; Gillette et al., 2001; Zou et al., 2001). Problems remain in applying the results to the calculation of sand transport under field conditions, due to the complexity of natural factors and insufficient data (Anderson and Willetts, 1991). Meteorological wind velocities averaged over periods of hours may not be useful to estimate the potential of sand movement in certain regions (Barth, 2001), and the wind data collected at a high position, such as 10 m above the ground at weather stations, should be converted into realistic near-bed wind velocity (Anderson and Willetts, 1991). A better understanding of the wind erosion process requires detailed field measurements of particle transport in relation to near-bed wind flow (Butterfield, 1991; Sterk et al., 1998).

In this study, relationships between the sand transport rate and 10-min average wind speed at 2 m above the ground were established through field observations in the Ordos Plateau, China. High-resolution data of 10-min average sand transporting wind velocity from local weather stations throughout a typical year were converted into the velocity at a height of 2 m for the calculation of aeolian sand transport. The objective of this study is to determine dune sand transport potential and sand movement as influenced by the wind direction, wind speed and frequency in the Ordos Plateau.

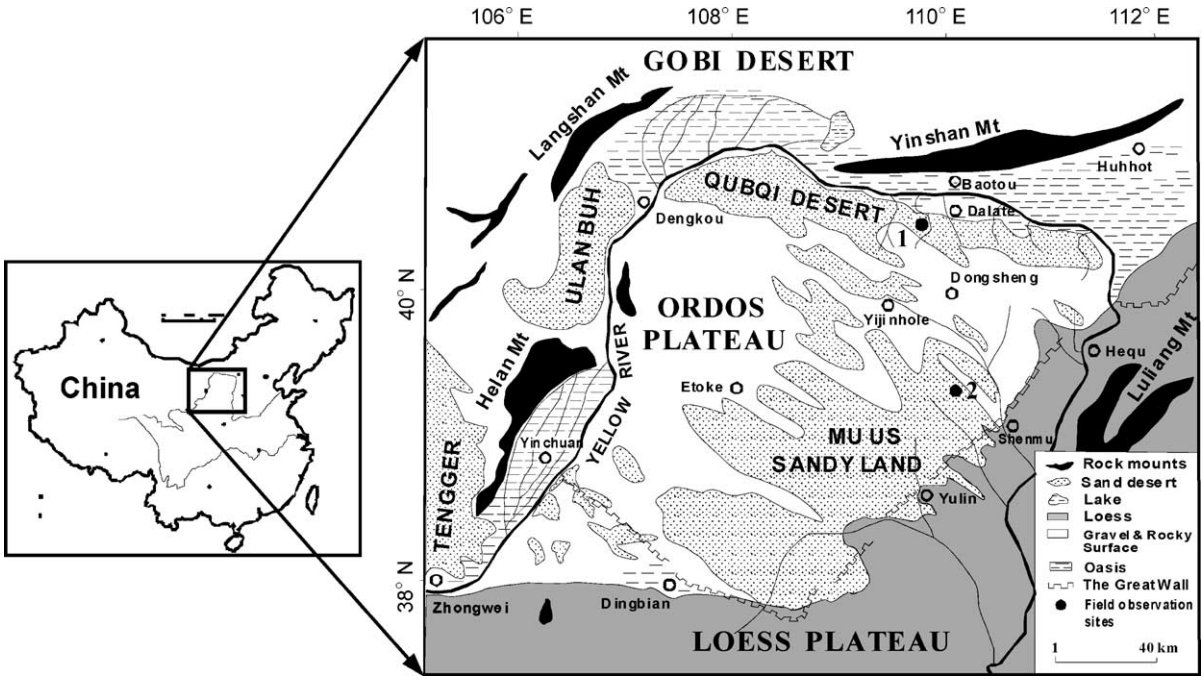

Fig. 1. Locality map of the Ordos Plateau. Two field observation sites are: (1) Singing Sand Bend in Inner Mongolia, and (2) Big Willow Terrace in Shaanxi Province.

2. The study area

The Ordos Plateau is a geographical unit demarcated by the Yellow River's elbow section in the north and the ancient Great Wall in the south (37°35′24″–40°51′40″ N, 106°42′40″–111°27′20″ E). It covers an area of 86,752 km^2, with elevations varying between 1000 and 1500 m above sea level. The Ordos Plateau is located in the sand desert belt between the Gobi Desert to the north and the Loess Plateau to the south (Fig. 1).

Annual average precipitation in this region ranges from 450 mm in the southeast to 150 mm in the northwest (Liu, 1999). Aeolian sand activity is strong and frequent. On a 30-year average, the annual wind speed is between 1.8 and 4.0 m s^{-1}; strong wind (≥17 m s^{-1}) occurs 10 to 35 days/year; and dust storm activity occurs 5 to 39 days/year with a general increase from southeast to northwest (Central Meteorological Bureau of China, 1979). Aeolian sand transport occurs mainly in the spring season. The main land cover type is sandy grassland, in which *Artemisia ordosica* is a dominant species. Other land cover types include steppe, meadow and shrubs (Wu and Ci, 2002). More than 20 tributaries of the Yellow River originate from the Ordos Plateau. There are salt and saline lakes in the middle and western areas.

Two of the twelve major sand deserts in China are located in this region. The Qubqi Sand Desert covers an area of 16,800 km^2 in the north, stretching from the west to the east along the southern bank of the Yellow River (Fig. 2a). The Mu Us Sandy Land covers an area of 32,100 km^2 in the southeast, with distinct encroachment onto the hilly Loess Plateau region in the forms of patchy sand sheets, and protruding tongue-shape sand belts (Fig. 2b). The middle and west are aeolian denuded high flats with outcrops of Cretaceous and Jurassic sandstone, occupying an area of 25,200 km^2. Due to frequent aeolian sand activities, the Ordos Plateau has become a region with the most severe wind erosion, land desertification and aeolian sand hazards

Fig. 2. Aeolain landforms in the Ordos Plateau. (a) Sand sheet, barchan dunes and compound megadunes in the Qubqi Sand Desert. (b) Satellite image of the main body of Mu Us Sandy Land, the arrow indicates a sand sheet encroachment onto the Loess Plateau. (c) Severe wind erosion on the ground under an artificial poplar shelterbelt to the west of Yijinhole Banner. (d) Road from Yulin Conuty to Uxin Banner blocked by sand dune.

in China (Wu and Ling, 1965; Yang et al., 1991; Zhu et al., 1980). Wind erosion occurs throughout the whole area (Fig. 2c). Shifting dunes repeatedly blocked the country roads between some major cities (Fig. 2d). Sand transporting winds blow a large quantity of dune sand into the main stream and the tributaries of the Yellow River. The relatively coarse dune sand blown into the river is mostly re-deposited on the river bed in the lower reaches, and is now a great concern of the "suspended river" problem of the lower Yellow River (Yang et al., 1988).

3. Materials and methods

Of the two field observation sites, one is located at the Booming Sand Bend, Dalate Banner, in the middle of the Qubqi Sand Desert in the north; the other one is located at the Big Willow Terrace, Shenmu County, representing the Mu Us Sandy Land in the southeast (Fig. 1). These sites were selected due to availability of various kinds of dune types and accessibility. The mobility of dune surface was classified into shifting, semi-fixed and fixed sandy lands according mainly to vegetation conditions. There is much literature regarding dune activity and dunefield activity, which encompasses ideas of how fixed, vegetated, partially vegetated, and dormant dunes can be defined (Thomas, 1992; Lancaster, 1994; Wiggs et al., 1995; Bullard et al., 1996). In this study, shifting, semi-fixed, and fixed sandy lands were classified based on vegetation cover ratios of <5%, 5–50%, and >50%, respectively (Zhu et al., 1980; Wu and Ci, 2002). Due to lower precipitation, the dune surface in the Qubqi Sand Desert is generally shifting and semi-fixed (Fig. 3a,b). The sand transport rate was measured on these two land surface types. In the Mu Us Sandy Land, more than half of the sandy land is fixed or semi-fixed under higher rainfall conditions. The sand transport rate was measured on

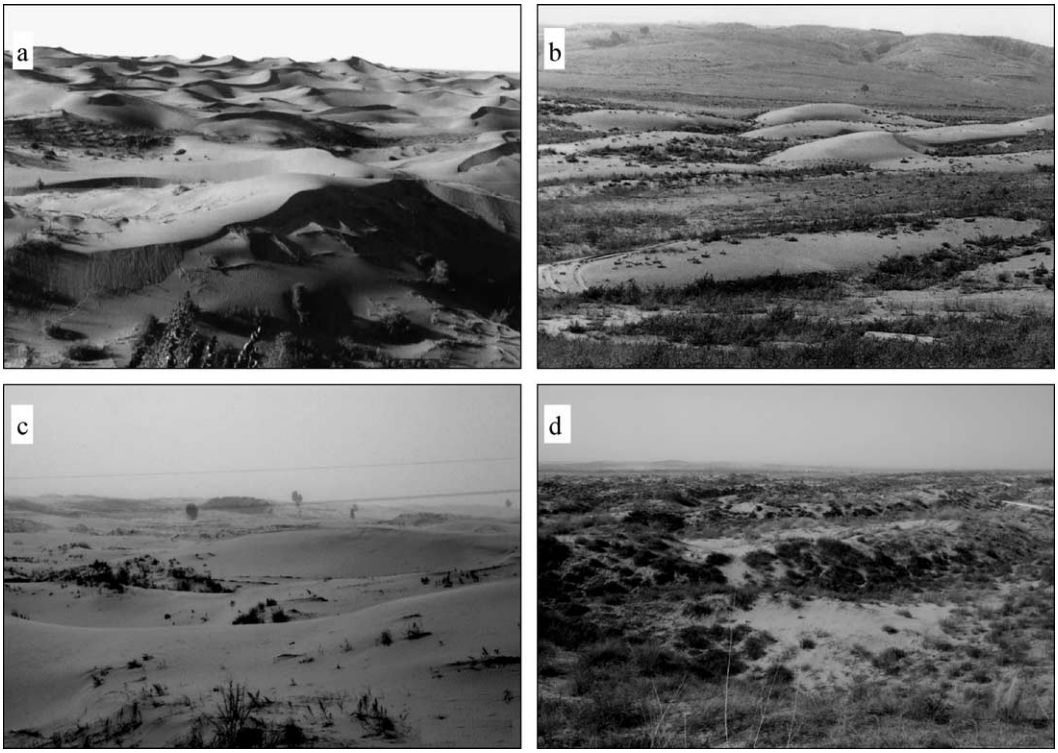

Fig. 3. Sand dunes in the observation sites. (a) Shifting dunes and (b) fixed, semi-fixed sand flats and barchan dunes in the Qubqi Sand Desert; (c) shifting dunes and (d) fixed and semi-fixed sandy land with patchy blowouts in the Mu Us Sandy Land.

shifting, semi-fixed and fixed dune surfaces (Fig. 3c,d). The sedimentology and mineralogy of dune sand in the Qubqi Sand Desert and the Mu Us Sandy Land have been discussed by Peterov (1959), Zhu et al. (1980) and Wu (1987). It was concluded that the dune sand on the Ordos Plateau was derived from local fluvial and lacustrine sediments.

At the both sites, we conducted fieldwork for 40 days to observe 10 min wind speed and synchronous sand transport rate data. Threshold wind speed was estimated with an instantaneous spinning-cup anemometer and through direct observations of sand movement on dune surfaces. On the anemometer, wind velocity at 0.5 and 2 m heights above the ground was measured using an electrical generator driven by the spinning cups. All the anemometers were calibrated in a wind tunnel using standard pitot tubes before measurement in the field. Synchronous with the wind speed measurement, the amount of sand transport in every 2-cm segment up to 40-cm height was measured by two segmented sand traps stacked together (Yang et al., 1991; Liu, 1999). We conducted these measurements about 25 times for each sand dune type in each region, trying to obtain data for a wide range of wind speed. The sand trapped during every 10 min was put in plastic bags and weighed with a 1/100 g portable manual scale to determine sand transport rates (three replicates). Wind tunnel experiments indicated that the efficiency of the sand trap was 70–90% at wind velocities from 6 to 18 m s^{-1}, and the trapping efficiency increased with the increase of wind speed (Liu et al., 2003). An average efficiency of 80% was used for calibrating the field-measured sand transport data. Because Chinese aeolian researchers mostly measured wind speed at 2 m high in the field (e.g., Wu and Ling, 1965; Wu, 1987), the relationship between the calibrated wind speeds at 2 m high and the sand transport rate was examined to permit comparisons with previous observation results.

There are eight county-level meteorological stations in the Ordos Plateau and more than 10 other stations in the vicinity of the border. Ten-minute average wind data have been collected continuously at the stations since 1959. The Dalate station (40°17′N, 110°11′E; 1011.0 m asl) is located near the Qubqi Sand Desert and the Yijinhole station (39°34′N, 109°44′E; 1329.3 m asl) is located in the north of the Mu Us Sandy Land (Fig. 1). The wind conditions at these two stations fluctuated from year to year. We used the wind data in 1983 to represent long-term characteristics, because in that year the average wind speed, strong wind days and precipitation were close to the annual mean of the past three decades.

4. Results and discussion

4.1. Relationship between sand transport rates and wind speed by field observation

Sand transport rate determined by sand traps was expressed as the amount of sand transported by wind through unit width in unit time (Bagnold, 1941). Relationships between the field-measured sand transport rates and wind speeds at 2 m above the ground were established by regression analysis (Figs. 4 and 5). The coefficient R^2 varied from 0.95 to 0.98. The sand transport rate on the shifting dune surface was higher by approximately an order of magnitude than the semi-fixed dune surface, and sand transport rate on the semi-fixed dune surface, in turn, was higher by an order of magnitude than the fixed dune surface (Figs. 4 and 5).

4.2. Direction, magnitude and frequency of sand transporting winds

Sand transporting winds cause actual entrainment of the sand particles, and no sand is transported by weaker winds (Anderson and Willetts, 1991). In the study area, the threshold wind speed (2 m above the ground) on the shifting dune surface was 5–6 m s^{-1}, and that on semi-fixed and fixed dune surfaces was 6–8 m s^{-1}, because the measurement data show that almost no sand was transported if wind speed was lower. Some highly effective high-speed gusts might be smoothed into lower mean values even in the 10-min average wind velocity data (Barth, 2001). However, such wind data recorded by most weather stations may be the most detailed and sufficient to increase the resolution of regional large-scale and long-term characteristics. The 10-min average wind speed for the Dalate station was estimated from the

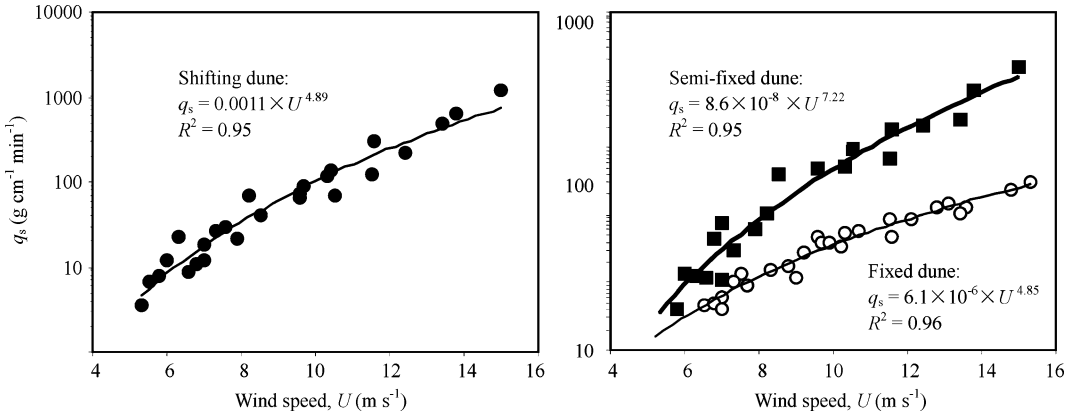

Fig. 4. Relationship between the sand transport rate and wind speed at 2 m high above the ground in the Mu Us Sand Land. ● Shifting dune, ■ semi-fixed dune, ○ fixed dune.

recording charts in the representative year, by manual counting method for every 10-min interval. The relationship between the wind speed and the 10-min average wind speed at the Dalate station at 2 m above the ground in the field can be expressed as:

$$U_2 = 0.86 \times U_{10} - 0.70 \qquad R^2 = 0.95 \qquad (1)$$

where, U_2 is wind speed at 2.0 m high in the field and U_{10} is 10-m-high wind speed at the weather station (Fig. 6). We converted U_{10} into U_2 using Eq. (1) and eliminated winds lower than threshold. Then monthly sand transporting wind data in Dalate were compiled to estimate seasonal sand transport with different wind speed and direction (Table 1). A similar data compilation was performed for Yijinhole (Table 2), although it remains to be confirmed whether Eq. (1) for Dalate is also applicable to Yijinhole. For convenience, the wind speed levels in the tables were expressed as whole numbers after rounding estimation.

The total duration of sand transporting winds made up 8.4% of the whole year time in Yijinhole and 6.6% in Dalate in 1983. The highest 10-min average wind speed at 10 m was 20 m s^{-1} in both the stations. Strong winds (≥17 m s^{-1}) occurred only for 260 min (0.59% of a year) in Yijinhole and 70 min (0.2%) in Dalate, meaning that dust storms due to strong winds were rare. The relationship between frequency (f; %) and wind speed (U; m

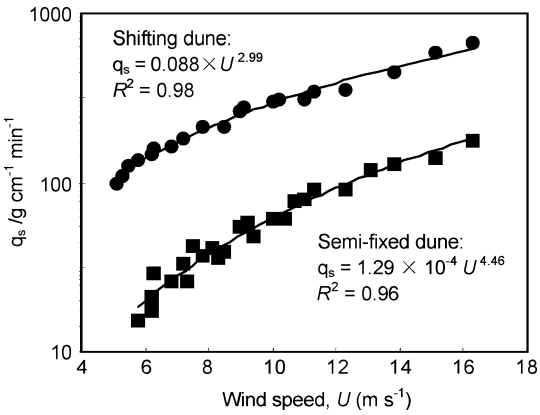

Fig. 5. Relationship between the sand transport rate and wind speed at 2 m high above the ground in the Qubuqi Sand Desert. ● Shifting dune, ■ semi-fixed dune.

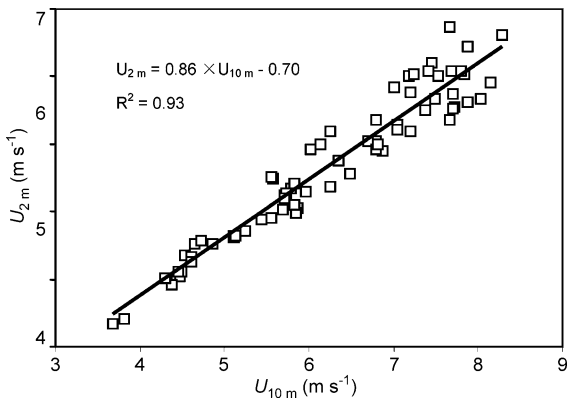

Fig. 6. Correlation between wind speed at 2.0 m in the field and wind speed at 10 m height at the Dalate station.

Table 1
Duration of sand transporting winds (10 m high, in minutes) in different directions, at varied speed levels, and distribution in different months in Dalate, 1983

Wind directions	U (m s^{-1})	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
N	6		70	110	90	60	30	20					
	7		20	140	40	20			20			10	
	8		10	70	10		30					20	
	9		10		10		20					20	
	10		10						10				
	11					10							
NNE	6						30	20	10				
	7				10		10		10				
NE	6					100	10		10				
	7					10	1						
ENE	6				100	300	50		70	30	120	20	
	7				40		20			10			
	8				10	100	20						
	9				10	100							
	10						10						
E	6	110	50	90	80	220	330	80	50	50	40	30	10
	7	30		40	40	120	200	40	10	30			
	8	20			20	30	70	10					
	9	30					30						
	10	10					10						
ESE	6	30						30		10			
	7	20						10					
	8							10					
SE	6						100	20					
	7						10	10					
SSE	6								10				
	7						10						
	10						10						
S	6				400	100	20	10	100				
	7				150	40	30	10	120	10			
	8				180	20	70	10					
	9						10		20				
	10						10	10					
	11					10							
SSW	6				110	20	50	10		10			
	7				90	20	40	20					
	8				100	40	20	30					
	9				10	10	10	10					
	10				100	40							
	11					30							
	12					10	20						
	14					10							
	15					20							
SW	6				90	130	20	30	30				
	7				60	40		110					
	8				40	60	10						
	9					60	10	20					
	10					20							
	11					20							

(continued on next page)

Table 1 (*continued*)

Wind directions	U (m s^{-1})	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SW	12					10							
	15					10							
WSW	6			10	160	60	20	10		10		140	10
	7		10	10	50							30	
	8				90	10		30				20	
	9					10		10				20	
	10				30	10						30	
	11				10							20	
	12											10	
	13											10	
	15											10	
W	6	80	220	170	1290	240	150	90	170	330	30	150	90
	7	50	180	70	610	100	40	150	90	210		160	20
	8	50	170	20	440	100	40	80	50	130		160	40
	9	40	60	20	450	20	20	70	10	100		190	40
	10	20	20	30	440	10		70	10	40		90	60
	11		10	10	90				20			130	60
	12				220							110	
	13											110	
	14				160							50	
	15				150							10	
	18				60								
WNW	6	140	60	180	180	540	330	160	30	20	70	290	
	7	20	120	140	140	300	200	120	30	10	50	170	
	8		140	20	110	140	40	50		10		190	
	9		40		130	120	10	20			10	70	
	10				120	50		10				70	
	11					10						10	
	12				30	10						30	
	14				20								
NW	6	450	330	500	410	430		150		60	120	200	140
	7	190	390	400	340	260		100	20	30	70	340	50
	8	150	440	200	290	80		20	20	20	40	370	
	9	50	190	220	180	50		10				90	
	10		220	110	220	10						60	
	11		100	80	20	10						10	
	12		10	30	40								
	13			20									
	14				10								
	15				10								
NNW	6	50	150	220	200	200	100	110	30	20	20	220	80
	7	100	210	120	200	90	130	30	20	40		250	50
	8	60	200	60	220	90	50	10				200	
	9	40	210	60	130	20	20			20		100	
	10	40	70		140	10						30	
	11		20			10	10					10	
	12			10	60							10	
	13							10					
	14				20								
	15				40								
	20				10								

Table 2
Duration of sand transporting winds in minutes at 10 m height in Yijinhole, 1983

Wind speed (m s^{-1})	Wind directions																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
7	590	150	70	140	50		20	500	980	1240	1030	1150	2030	3720	3920	2500	18090
8	290	40		80			10	130	580	960	760	410	1100	2240	2810	1310	10720
9	40	10		40				30	110	370	230	140	360	2110	2120	960	6520
10	30			10				10	60	240	80	40	180	1700	1500	510	4360
11	10									210	20		30	940	500	200	1910
12	10									140	20	20	40	430	330	100	1090
13										30	10		10	340	190	70	650
14										40	20			140	100	40	340
15										20				200	180	10	410
16	10									10					10		30
17															10		10
18	20														40	10	70
20														50	10		60
Total	1000	200	70	270	50	0	30	670	1730	3260	2170	1760	3750	11870	11720	5710	44260
%	2.26	0.45	0.16	0.61	0.11	0.00	0.07	1.51	3.91	7.37	4.90	3.98	8.47	26.82	26.48	12.90	100.00

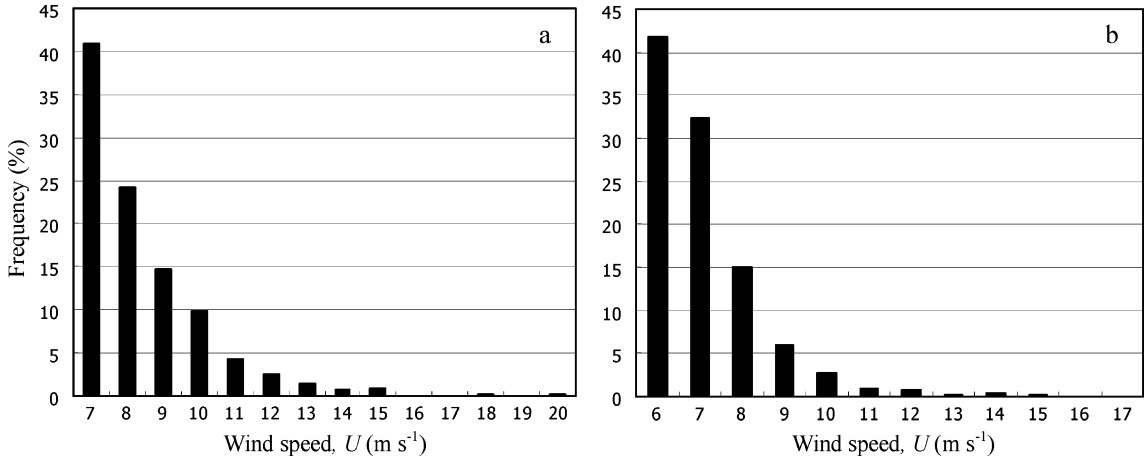

Fig. 7. Relationship between speed level and frequency of sand transporting winds. (a) Yijinhole, with threshold wind speed at 7 m s^{-1}, for its dominant fixed and semi-fixed sand surfaces. (b) Dalate, with threshold wind speed at 6 m s^{-1}, for its dominant shifting sand dunes.

s^{-1}) of the sand transporting winds in Yijinhole (Fig. 7a) can be expressed as:

$$f = 3.73 \times 10^8 U^{-7.79} \qquad R^2 = 0.82 \tag{2}$$

and that in Dalate (Fig. 7b) is:

$$f = 6.77 \times 10^6 U^{-6.66} \qquad R^2 = 0.81 \tag{3}$$

In the Mu Us Sandy Land, the two prevailing wind directions were WNW and NW, with frequency of 26.8% and 26.5%, respectively (Fig. 8a). In the Qubqi Desert, the prevailing sand transporting wind directions were W and NW, with frequency of 23.1% and 23.6%, respectively (Fig. 8b). The dominant wind from the northwest is common to most regions in northern China. The high-energy wind regime is controlled mainly by the strong monsoon system from Mongolia and Siberia. Local topography such as the Yellow River valley in the northern part of the Ordos Plateau may also play an important role in redistributing near surface wind field, and affecting the development and spatial distribution of the sand dune landforms in the Qubqi Sand Desert. Fig. 9 shows that springtime is the season with the highest frequency of sand transporting wind.

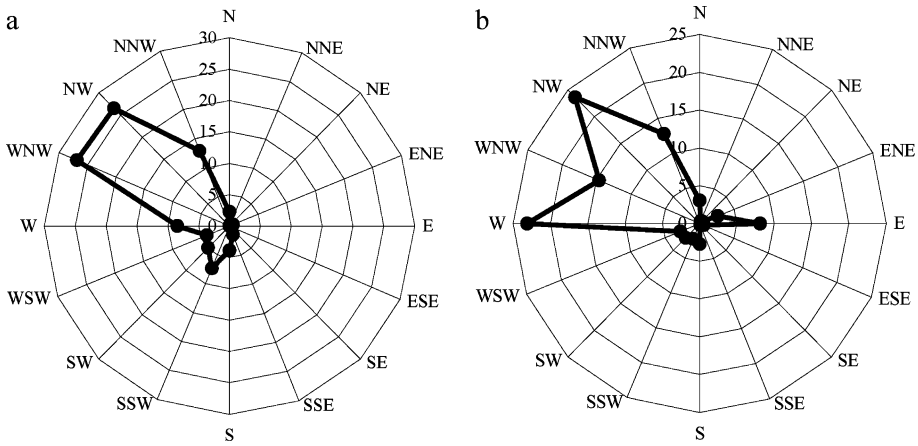

Fig. 8. Percentage frequencies of sand transporting winds in different directions. (a) Yijinhole, (b) Dalate.

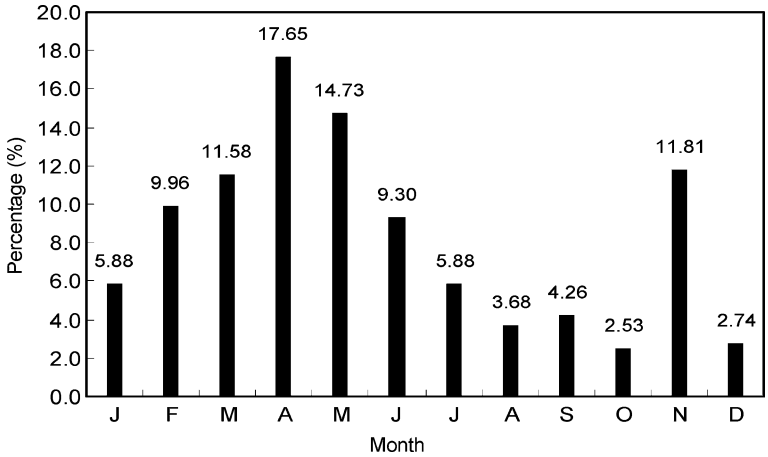

Fig. 9. Percentage frequencies of sand transporting winds in different months at Dalate.

4.3. Sand transport as influenced by wind direction, magnitude and frequency

The quantity of aeolian sand transport (Q_i; g cm^{-1}) can be expressed as:

$$Q_{\mathrm{i}} = \sum q_{\mathrm{si}} \times t_{\mathrm{i}} \tag{4}$$

where, q_{si} is the sand transport rate in g cm^{-1} min^{-1} and t_{i} is the duration of sand transporting wind in min. Using the relation formulae between the sand transport rate and wind speed on different dune surfaces (Figs. 4 and 5) and by converting the whole-year 10-min average sand transporting wind data at 10-m height into near-bed wind velocity at 2 m height, the annual potential of aeolian sand transport on dune surfaces can be calculated.

Wind velocity in Tables 1 and 2 were converted from that at 10 to 2 m high using Eq. (1), and Eq. (4) was employed to determine potential sand transport rates for different winds, months and surface conditions (Tables 3 and 4).

In the Mu Us Sandy Land, the total quantity of sand transport on shifting dunes was 39 and 217 times more than that on semi-fixed dunes and fixed dunes, respectively. Sand transported by winds from NNW and NW made up more than 70% of the total transport. In the Qubqi Sand Desert, the total quantity of sand transport on shifting dunes was 26 times more than that on semi-fixed dunes. Sand transported by W, WNW, and NW winds made up more than 70% of the total transport.

In the Qubqi sand desert, April was the month with the highest potential sand transport, accounting for 34.30% of total sand transport on shifting dunes and 46.14% on semi-fixed dunes (Table 4). The percentage of sand transport on shifting dunes in spring, summer, autumn and winter was 53.14%, 10.91%, 19.57%, and 16.38%, respectively, confirming that aeolian sand activities enhanced in spring.

Fig. 10 shows that about 67.6% of the annual total sand was transported by the high-frequency

Table 3
Quantity of sand transport in the Mu Us Sandy Land in different directions (kg cm^{-1} year^{-1})

Wind directions	Dune surface types		
	Shifting	Semi-fixed	Fixed
N	84.88	2.51	0.27
NNE	4.49	0.02	0.02
NE	1.69	0.01	0.01
ENE	5.09	0.05	0.03
E	0.66	0.00	0.00
ESE	0.27	0.00	0.00
SE	0.65	0.00	0.00
SSE	14.82	0.08	0.06
S	33.48	0.26	0.17
SSW	129.87	3.22	0.74
SW	52.44	0.82	0.29
WSW	35.76	0.32	0.18
W	76.18	0.90	0.42
WNW	1003.28	26.92	4.15
NW	707.92	19.37	3.32
NNW	207.33	4.39	1.12
Total	2358.80	58.86	10.79

Table 4
Quantity of sand transported in the Qubqi Desert in different directions and months (kg cm^{-1} $year^{-1}$)

Dune surfaces	Mon.	Wind directions																
		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Shifting dune	1				0.18	6.01	0.78							8.22	3.76	19.05	9.48	47.48
	2	3.02			0.24	1.39							0.64	19.38	10.62	65.70	31.67	132.66
	3	7.74				3.51	0.30					0.18	0.58	11.43	8.48	60.23	13.05	105.50
	4	2.90	0.39		1.87	2.73				6.67	14.54	3.82	9.68	231.58	32.12	60.48	61.49	428.27
	5	3.12		0.45	1.45	8.21				4.09	13.81	16.60	2.84	13.95	32.59	21.59	11.12	129.82
	6	3.00	0.57	0.51	3.22	15.06	0.43	0.76	0.94	4.83	6.14	2.39	0.42	7.88	11.83	0.73	0.80	59.51
	7	0.61	0.24			2.57	1.03			1.94	2.18	1.09	1.64	16.60	9.05	6.26	5.13	48.34
	8	1.27	0.51	0.18	1.88	1.97	0.36	0.45	0.43	4.78		3.94		9.29	1.12	1.34	0.91	28.43
	9				1.43	2.33				0.27	0.58	1.21	0.24	22.47	1.22	2.34	2.34	34.43
	10			0.06	2.61	1.33	0.30	0.06						0.97	3.14	4.88	0.24	13.59
	11	2.20			0.97	0.85							14.86	88.92	29.12	33.20	26.20	196.32
	12				0.55								0.30	16.62		4.08	2.81	24.36
	Year	23.86	1.71	1.20	14.40	45.96	3.20	1.27	1.37	22.58	37.25	29.23	31.20	447.31	143.05	279.88	165.24	1248.71
Semi-fixed dune	1				0.06	0.15	0.01							0.22	0.06	0.42	0.28	1.20
	2	0.08				0.02							0.01	0.50	0.27	2.12	0.95	3.95
	3	0.16				0.05							0.01	0.28	0.15	1.97	0.34	2.95
	4	0.06	0.01		0.05	0.05				0.15	0.45	0.08	0.27	13.13	1.25	2.16	3.31	20.97
	5	0.08		0.01	0.03	0.15				0.11	0.64	0.64	0.07	0.29	0.86	0.48	0.28	3.64
	6	0.07	0.01	0.01	0.01	0.32	0.01	0.01	0.03	0.13	0.21	0.04	0.01	0.15	0.23	0.08	0.22	1.54
	7	0.01				0.05	0.02			0.05	0.06	0.03	0.05	0.48	0.21	0.12	0.16	1.24
	8	0.04	0.01		0.03	0.03		0.01	0.01	0.10		0.09		0.26	0.02	0.03	0.02	0.65
	9				0.02	0.04				0.01	0.01	0.02		0.58	0.02	0.05	0.06	0.81
	10				0.04	0.02	0.01							0.01	0.06	0.10		0.24
	11	0.06			0.01	0.01							0.66	4.28	0.88	0.91	0.73	7.54
	12				0.01									0.59		0.07	0.05	0.72
	Year	0.56	0.03	0.02	0.26	0.89	0.05	0.02	0.04	0.55	1.37	0.90	1.08	20.77	4.01	8.51	6.40	45.46

normal winds (<17 m s^{-1}), and 32.4% by the low-frequency strong winds (≥17 m s^{-1}). We may reach a conclusion that high-frequency normal sand transporting winds play a dominant role in transporting highly erodible dune sand. However, despite the fact that the frequency of strong winds was generally lower than 0.6%, their more than 30% contribution to sand transport was quite significant. Fig. 10 also shows that the amount of sand transported by winds slower that 15 m s^{-1} does not change significantly with wind speed (ca. 5.5–8.6% for each wind speed class), but the percentage of sand transported by stronger winds changed greatly from one speed class to another. This might imply that high wind

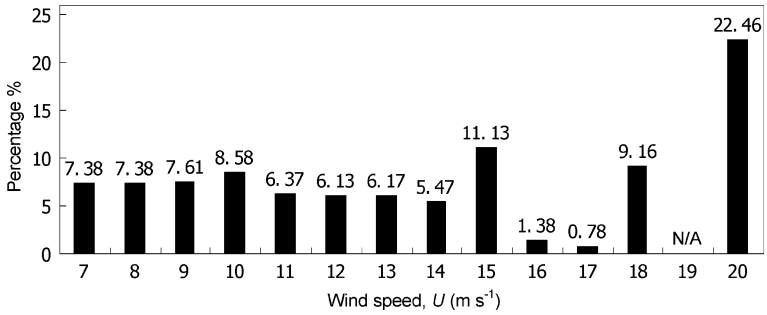

Fig. 10. Percentage of sand transport by sand transporting wind under different speed levels in the Mu Us Sandy Land.

Table 5
Total aeolian sand transport potential and overall transport direction determined by vector operation

Localities	Dune surface types	Sand transport potential (kg cm^{-1} $year^{-1}$)	Overall transport direction (azimuth angle)
Mu Us Desert	Shifting dune	2010.0	302.5°
	Semi-fixed dune	51.9	302.5°
	Fixed dune	7.9	303.6°
Qubqi Desert	Shifting dune	900.0	292.5°
	Semi-fixed dune	35.0	288.7°

velocities possess more irregularities in sand transport. The result supports Wolman and Miller (1960) view that extreme velocities associated with infrequent events are compensated for by their rarity, and the greatest bulk of sediment is transported by more moderate events. It is also consistent with Lancaster's (1985) conclusion that most sand transport is generated by winds of moderate velocity and frequency.

During certain strong dust storm events in China, such as the one that occurred on May 5, 1993, the amount of aeolian sand transport was enormous. In the Shapotou Station near Zhongwei County (Fig. 1), the highest 10-min average wind speed on May 5, 1993 was 25 m s^{-1}, and the highest instantaneous wind speed was 35 m s^{-1}. The quantity of sand transported during this single storm event was equivalent to 48.87% of the total annual quantity of sand transport in Yijinhole in 1983 (Liu, 1999). In addition, 96.58% of the total sand transported in this storm was accomplished by a 25 m s^{-1} wind event only in 10 min.

Aeolian sand transported in different directions possesses vector characters (Fryberger, 1979; Bullard, 1997). The composite vector of all directions yielded the annual sand transport potential and the overall transport direction (Table 5). The differences in sand transport potential indicate that dune surface properties and regional erosive wind regime significantly affect aeolian sand transport. The overall sand transport direction indicates the migration direction of saltating sand particles and movement of sand dunes. In the Qubqi Desert, the overall transport direction was approximately in line with the spatial distribution of the sand desert, and in the Mu Us Sandy Land, it was consistent with the sand encroachment phenomena in the north margin of the Loess Plateau.

5. Conclusions

In this study, relations between the sand transport rate and 10-min average wind speed 2 m above the ground were established through field observations in the Ordos Plateau, China. The threshold wind speed for sand transport at 2 m above the ground was 5–6 m s^{-1} on shifting dune surfaces and 6–8 m s^{-1} on semi-fixed and fixed dune surfaces. Three specific parameters, wind speed, duration and direction, were found to be decisive for aeolian sand transport. Sand transporting winds took place mainly in springtime. The prevailing sand transporting wind directions were W, WNW and NW, and sand transport in these directions made up more than 70% of the total transport. The composite direction of sand transport was from 288.7° to 303.6°, indicating the general migration direction of aeolian sand and sand dunes. High magnitude strong winds had a low frequency, but occasionally they could play a dominant role in aeolian sand transport.

In spring, blowing sand, strong-wind and dust-storm days make up around 40%, 50% and 60% of the annual total, respectively, due to insufficient rainfall and lower vegetation coverage. The average wind speed in spring is 40% more than that in the other seasons, and strong wind and dust storm activities in spring are two and four times more than those in other seasons, respectively.

This paper presented an attempt to use field observation data and meteorological data to determine dune sand transport potential and sand movement as influenced by the direction, speed and frequency of the sand transporting winds. Further work such as studies on dune surface properties, near-surface airflow patterns and their interactions would be necessary in understanding the process of dune sand transport and the migration of sand dunes.

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