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Grain-size distribution of surface sediments of climbing and falling dunes in the Zedang valley of the Yarlung Zangbo River, southern Tibetan plateau

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Climbing and falling dunes are widespread in the wide valleys of the middle reaches of the Yarlung Zangbo River. Along a sampling transect running from northeast to southwest through 10 climbing dunes and two falling dunes in the Langsailing area, the surface sediments were sampled to analyse the grain-size characteristics, to clarify the transport pattern of particles with different grain sizes, and to discuss the effects of terrain factors including dune slope, mountain slope, elevation and transport distance to sand transport. Sand dunes on both sides of the ridge are mainly transverse dunes. Fine and medium sands were the main particles, with few very fine and coarse particles in the surface sediments. Particles $>4.00\Phi$ were blown upslope by suspension, particles $1.00-4.00\Phi$ were mainly transported upslope by saltation with opposite change tendency, and particles $<1.00\Phi$ mainly moved by creep were found almost exclusively at the bottom of the slopes. As terrain factors, elevation and transport distance were more important factors influencing the distribution of grain size and particle fraction on dunes. Local winds observation might be helpful for the transport mechanism study of particles on climbing and falling dunes, while the wind data from nearby weather station was hardly helpful.

Keywords. Climbing and falling dunes; grain-size distribution; sand transport pattern; wide river valleys; terrain factors.

1. Introduction

Grain-size distribution sensitively reflects the transport capacity of wind, it contains signals of past environmental and climate changes, reveals the development of palaeosoil, and implies sources and sinks of dust (Bagnold 1937; Tsoar 1986; Smith *et al.* 1991; Lancaster 1995; Zheng *et al.* 2009; Bao *et al.* 2010; Zhang *et al.* 2011). Therefore, it has been well studied both for individual sand dunes

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and for large sand seas (Watson 1986; Van Der Wal 1998; Livingstone *et al.* 1999; Wang *et al.* 2003; Pan *et al.* 2014). The grain size is especially effective and easy for the study of dunes developed on slopes since aeolian activity on slopes is more complex and difficult than that on a horizontal surface (Iversen and Rasmussen 1999; Barrineau and Ellis 2013).

Dunes were developed on slopes including climbing and falling ones, their forming is affected by slope gradient greatly (Tsoar *et al.* 1996; White and Tsoar 1998; Al-Enezi *et al.* 2008), and vividly named 'topographically controlled' sand dunes by Lancaster and Tchakerian (1996). The topographically controlled sand dunes are also influenced by the supply and characteristics of the sand source (Lancaster and Tchakerian 1996), and the wind speed and direction regimes (White and Tsoar 1998) beside the slope gradient. There are typical types of aeolian landforms developed in the river valleys of deserts all over the world, and have abundant sand source and sparse vegetation (Lewis 1936; Wasson 1984; Loope *et al.* 1995; Bullard and Nash 1998). Studies on topographically controlled dunes on Mars were fruitful that provided references for further studies of climbing and falling dunes on the Earth. Making use of photo-geologic, morphometric and thermo-physical techniques and high-resolution images, researchers have reached some valuable results on the sources of sand and the transport routes of climbing and falling dunes, the importance of influence factors, the geological history of the dunes, and the flow dynamics accounting for the distribution of aeolian sediment (Tanaka *et al.* 2003; Hayward *et al.* 2007; Zimbelman and Williams 2007; Chojnacki *et al.* 2010).

The climbing and falling dunes distributed in the wide valleys of China's Yarlung Zangbo River were characterised by a limited sand source, complex topography and greater vegetation cover. In such aeolian environments, locally originated sands are entrained and transported by near-surface winds controlled by the westerly jet circulation during the winter and mountain–valley winds during other seasons, formed extensively but discretely distributed climbing dunes on mountain slopes (Li *et al.* 1999). Some falling dunes are developed on steep slopes when climbing sand fell back or climbed over the mountaintop and falling at the opposite mountain side (Tsoar 1983). These mountain dunes destroyed the vegetation, which was very difficult to recover due to the harsh weather and poor soil conditions on rocky mountains even though the sands might be removed by winds again. Thus, the development and movement of climbing and falling dunes provides materials for weathering and erosion, accelerates desertification, increases the sediment transported by rivers and significantly impacts the local ecological environment, given that most climbing and falling dunes distributed on mountains beside wide valley of rivers.

To date, studies on topographically controlled dunes in the high elevation regions of China are lacking at present. The previous studies clarified the types of topographically controlled dunes and analysed their formation processes mainly by wind tunnel experiments, and discussed the distribution of grain size on climbing dunes (Li *et al.* 1997, 1999; Liu *et al.* 1999; Zhou *et al.* 2012). The importance of wind and slope gradient is still unclear in the field. This study chose a location in the wide valley that the topographically controlled sand dunes are dominated by climbing dunes, grain-size distribution study aims to (i) clarify the general characteristics of the grain-size distribution for climbing and falling dunes on a rocky mountain slopes; (ii) to analyse the reflection of grain size to particles transport pattern by winds; and (iii) to discuss the importance of terrain factors (dune slope, mountain slope, elevation and transport distance) to sand transport.

2. Study area and methods

2.1 *Study area*

The Langsailing study area is a representative area of the wide valley of the Yarlung Zangbo River, it lies at Zedang County of southern Tibetan Plateau and belongs to the middle reaches of the river (figure 1). Aeolian landforms are extensively distributed in the floodplain, on alluvial fans and on the mountain slopes. Many islands and sandbars are developed among the branches of the stream. Sand dunes are clustered in the valleys and on the mountain slopes mainly including barchans, compound barchans, dune chains, shrub dunes. These aeolian landforms occupied a total area of about 1929.95 km^2 in the wide valleys of the upper and the middle reaches of the Yarlung Zangbo River (Li *et al.* 1997). These dunes with complex patterns developed on the mountain slopes,

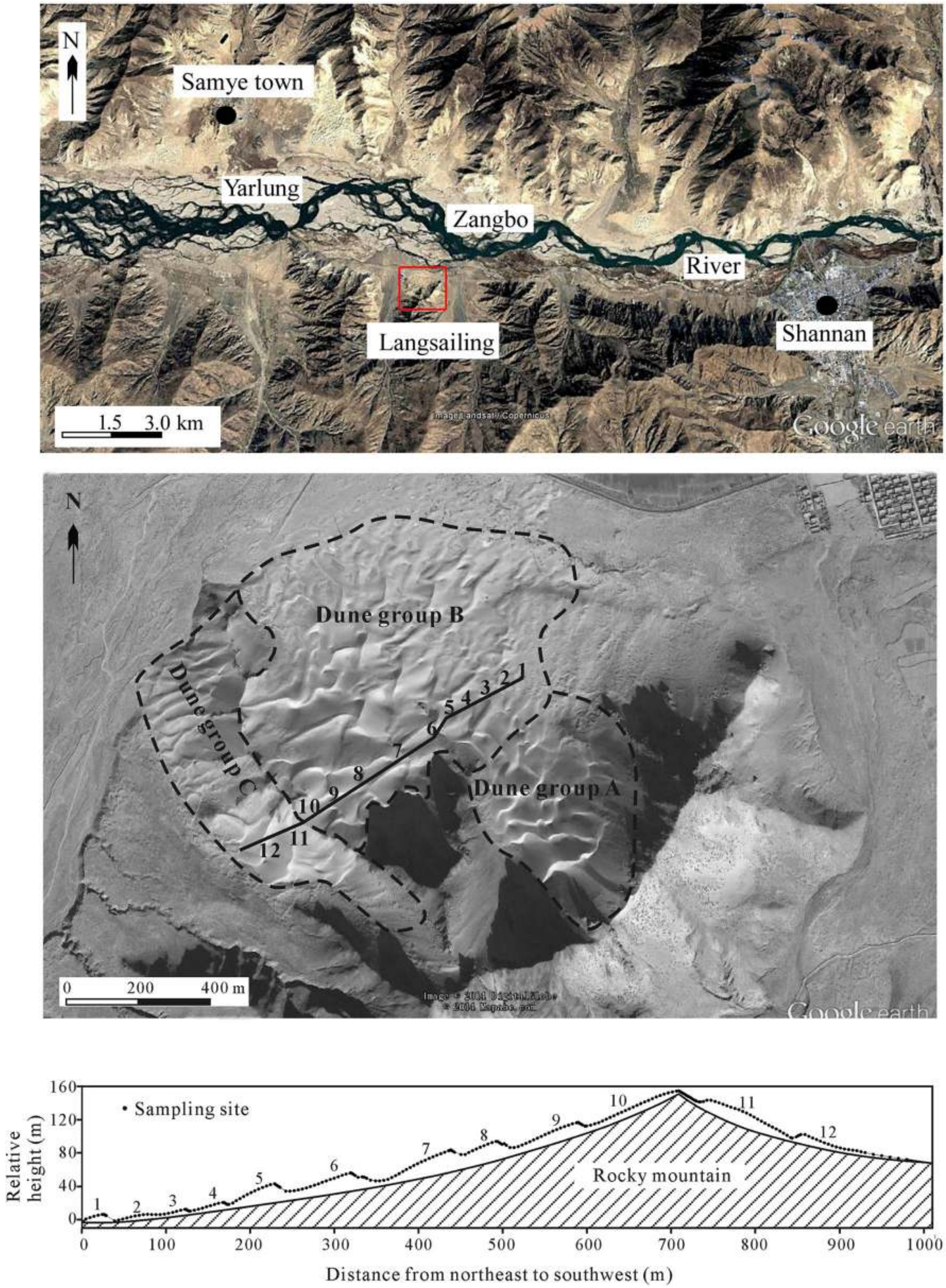

Figure 1. Climbing dunes in the study area and illustration of the slope profile within the sampling transect. Note that the vertical scale is not sufficiently large to show some variations in the elevation of the sampling points; some sample locations on the leeward slope of one dune were lower in elevation than locations on the windward slope of the next dune.

embedded in grasslands or forests, forming a unique natural landscape in the valleys of the Yarlung Zangbo River.

The climbing and falling sand dunes in this study are located on two opposite sides of a sloping ridge on the right bank of the Yarlung Zangbo River

(29°14′N, 91°35′E) with elevation ranging from 3600 to 3750 m above sea level (figure 1). The prevailing wind is from the west, but the mountainous topography exerts significant influence on regional wind patterns, and winds tend to blow upslope in the daytime and down the slope at night due to the heat difference between the air and the mountains (i.e., terrain effects). Protruding mountain ridges also alter the near-surface wind directions. Thus, the wind direction and the consequent travel direction of sand dunes are quite complicated. Climbing dunes often form on windward slopes, and falling dunes develop on leeward slopes (Goossens and Offer 1997; Chojnacki *et al.* 2010). In the study area, the dunes in group B should be climbing dunes based on their relationship with the winds, the field investigation of the dune topography and the relative position with the sand source. The dunes in group A are falling dunes based on their relationship with the winds, shapes of dunes and underlying steep mountain slope (figure 1). The dunes in group C are also probably falling dunes (reasons will be explained in section 4.1). All sections were covered by sand, and with no bare mountain ground could be reached. Samples were collected along a transect line from climbing dunes on the northeast slope to falling dunes on the southwest slope of the mountain ridge, which covered dunes in groups B and C. Sampling dunes were mostly transverse dunes with heights ranging from 2 m to more than 15 m. Figure 1 shows the vertical profile along the sampling transect, and the slope of mountain is estimated under each dune. On the northeast slope of the mountain, the area under dune 1 is almost flat, the slope is roughly constant from dunes 2 to 5 (6.8°), increased thereafter to the mountain ridge (18.7°) except on dune 7. Mountain slope underlying dune 7 was more gentle than its adjacent dunes, but similar to the area of dunes 2–5. Dune 10 crossed the mountain ridge, and the part on the northeast slope (dune 10-NE) was lying on steeper mountain slope than the part on a southwest slope (dune 10-SW). For the sampling area on the southwest slope, the mountain slope was steepest underlying dune 11, and the gentlest close to the ridge (table 1).

2.2 *Measurements and sampling*

Based on the travel direction of the dunes, we selected a sampling transect through dune groups B and C that ran from the foot of the northeast slope of the Langsailing ridge to the crest of the ridge, and then down the slope on the opposite (southwest) side of the ridge. The sampling line included one branch (dune 1) and nine transverse dunes on the northeast side, where the sampling line is approximately parallel to the travel direction of the dunes; it also included two transverse dunes on the southwest side, where the sampling line is at a slight angle to the travel direction of the dunes (figure 1). Sampling sites, including inter-dunes, were sand covered areas.

Surface sediment samples (0–5 cm) were collected along the sampling transect at intervals of 2–10 m. Samples covered the windward slope, dune crest, lee slope and inter-dune ground for each dune. The intervals were determined based on the length of the dune's slope. Each dune comprised 6–24 sampling sites on the windward slope, 1 site at the crest, 2–13 sites on the lee slope and 1 site at the inter-dune ground between each pair of dunes.

Table 1. *The terrain of dunes on the sampling transect.*

Dune no.	1	2	3	4	5	6	7	8	9	10	11	12
Dune height (m)	5.4	5.2	7.0	5.8	9.3	24.5	22.4	37.5	30.8	41.3	46.2	27.7
Northeast slope length (m)	28.0	28.0	33.0	30.0	37.0	56.0	75.0	95.0	94.0	117.0	15.0	18.0
Southwest slope length (m)	25.5	5.0	20.0	10.0	12.0	21.5	37.5	16.0	16.0	30.0	105.0	120.0
Mountain slope (°)	−0.6	6.6	7.8	6.5	6.4	16.5	7.6	20.3	18.4	19.5, −6.8*	−23.0	−10.3

1. The height of dunes is calculated based on the elevation of dune top and the lower elevation of two slope toes.
2. The mountain slope is the average slope gradient of the underlying mountain under each dune. It was estimated based on the elevation, latitude and longitude recordings of sampling sites at inter dunes. They were recorded as positive gradients when increased at the northeast–southwest direction, otherwise recorded as negative gradients.
*These values are the mountain slopes of northeast side (19.5°) and the southwest side (6.8°), respectively, as dune 10 distributed at both sides of the mountain ridge.

The number of sampling sites is proportional to the size of the dune. The distance of a sampling site to its adjacent sampling site was measured using a measuring rope, and the slope gradient was measured with a clinometer. The combination of distance and slope will allow the determination of the change in elevation between the consecutive sampling sites. We estimated the average mountain slope gradient under each dune according to height changes of interdunes, latitude and longitude, while the dune slope gradient was measured at each sampling sites. Both mountain slope gradient and dune slope gradient were expressed as the ratio of elevation and distance changes. Based on these measurements, figure 1 shows the topographic profile along the sampling line. We collected a total of 235 samples, of which 171 samples were from the northeast side of the ridge and 64 samples were from the southwest side. Measurements and sampling were carried out in August 2010. The average wind speed data at Gongga airport (29°15′N, 90°58′E) from 2008 to 2012 were extracted from the China Meteorological Forcing Dataset (Institute of Tibetan Plateau Research 2016). The data were hourly average value, recording every two hours from 0:00 to 21:00 at 10 m height. Unfortunately, wind directions were not available.

2.3 *Grain-size measurements and analysis*

The grain-size distribution of the sand samples was determined using Mastersizer 2000 (Malvern Instruments, Malvern, UK) at the Key Laboratory of Environmental Change and Natural Disaster of Beijing Normal University in November 2010. The grain-size parameters (grain size, standard deviation, skewness and kurtosis) were calculated using the formulas of Folk and Ward (1957). We expressed the grain size with Φ value ($\Phi = -\log_2 d$), which is calculated from particle diameter (d, mm).

3. Results

3.1 *Grain-size distribution of the surface sediments on the dunes*

Supplementary table S1 summarised the grain-size characteristics. The average grain size was $2.11 \pm 0.12\Phi$, well sorted ($0.46 \pm 0.06\Phi$), symmetrically (0.01) and mesokurtically (0.95) distributed as a whole. Dunes were mainly grouped depending on the slope gradients of the underlying mountain, as it is a very important terrain factor affecting the particle transport on climbing dunes (Tsoar *et al.* 1996; White and Tsoar 1998; Iversen and Rasmussen 1999). From dunes 1 to 5 (56 samples), the grain size averaged $2.02 \pm 0.14\Phi$, moderately well sorted ($0.51 \pm 0.07\Phi$). The average grain size of dunes became significantly coarser with increasing height of mountain at a rate of 0.12Φ per 10 m ($R^2 = 0.96$, $p < 0.05$), and it also got significantly coarser with increasing sampling distance along the sampling line at a rate of 0.10Φ per 100 m ($R^2 = 0.88$, $p < 0.05$) (figure 2). The grain size of dunes 6 to 10-NE (119 samples) averaged $2.13 \pm 0.10\Phi$, well sorted ($0.45 \pm 0.03\Phi$). The average grain size of these five dunes did not change significantly both with increasing of height and sampling distance at 95% confidence level. On the southwest slope of the ridge, the grain size of dune 11 (25 samples) was $2.21 \pm 0.08\Phi$, which was 0.04Φ finer than that of dune 10-SW (14 samples) on the southwest slope, and both of them were much finer than that of dune 12 (24 samples, $2.03 \pm 0.07\Phi$). All dunes on the southwest slope were well sorted; however, dune 10-SW ($0.38 \pm 0.02\Phi$) had better sorting than dunes 11 ($0.42 \pm 0.03\Phi$) and 12 ($0.43 \pm 0.03\Phi$). Sorting varied the most widely on the climbing dunes at the bottom of the northeast side of the ridge. The variation decreased and the average sorting of each dune improved 0.08Φ per 100 m ($p < 0.05$), increasing the elevation on both sides of the ridge. Dune 11, at the top of the southwest slope and just below the ridge, showed the minimum variation in sorting the increasing height. Both skewness and kurtosis showed obvious variation from dune 1 to dune 5, but was stable in all other areas of the climbing and falling dunes (figure 2).

Particles transported upslope by wind influenced by not only mountain slope gradient but also elevation. For adjacent dunes, the grain size turned fine significantly when the slope gradient increased ($p < 0.05$). This was observed at both sides of the mountain such as dunes 5 and 6, and dunes 11 and 12. Dunes 5 and 11 with smaller slope were 0.23 and 0.18Φ finer than dunes 6 and 12, respectively. At the terrain undulation area (dunes 5–8), the grain size of dune 6 was finer than that of dune 5, contributed greatly by the increase in the slope underlying it. The steep terrain underlying dune 6 both sheltered dune 7 from strong wind from the valley and limited the grain size of particles that can winnow across it, resulting in the greater

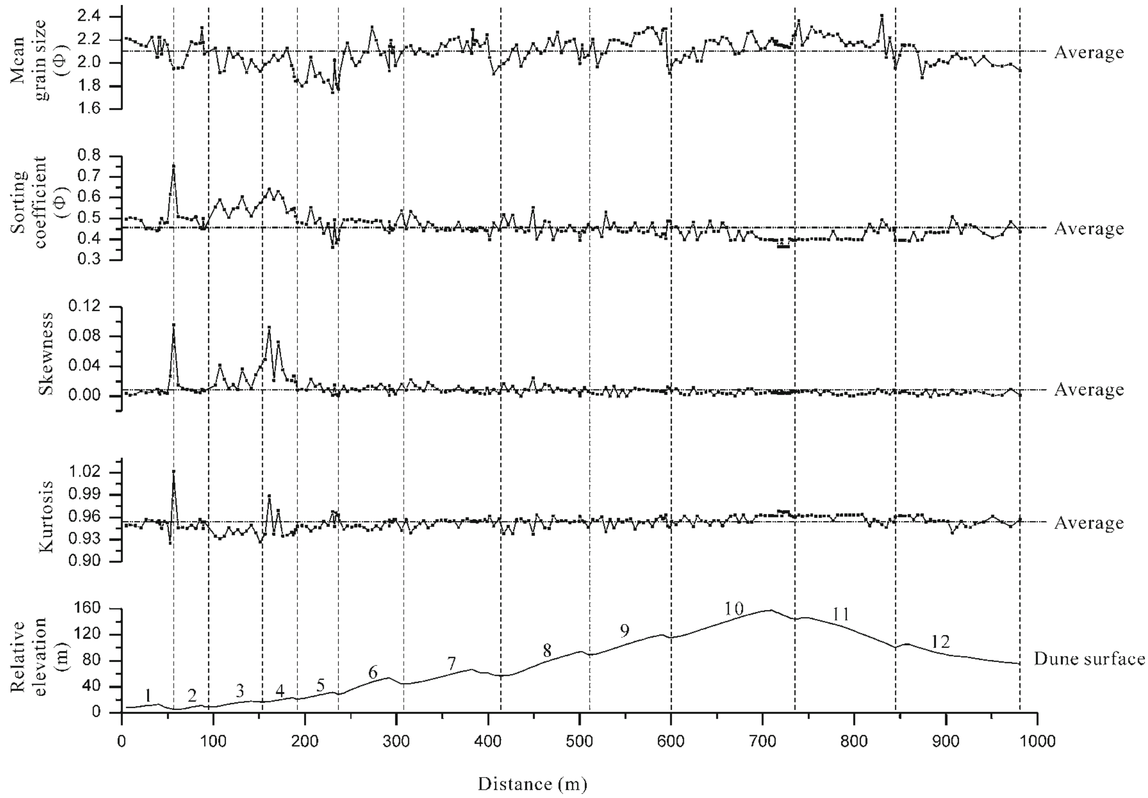

Figure 2. Variations of grain-size parameters along the sampling transect.

grain-size value of dune 7 compared to dune 6 (figure 3d). The continuous decrease of grain size from dunes 2 to 5 showed the importance of elevation since they are developed on a mountain slope with almost the same gradient. The effect of elevation also revealed by dune groups 3 and 7, and dune groups 8, 9 and 10-NE (figure 3a–c). Moreover, for adjacent dunes with similar mountain slope, the variation of grain size among dunes close to the mountaintop was smaller than among those at its bottom (figure 3a and c). The average grain size of dunes 2, 4 and 5 decreased with the increase of elevation at a rate of 0.15Φ per 10 m ($R^2 = 0.98$, $p < 0.05$), while there was no significant change on the average grain size from dune 8 to dune 10-NE.

Besides the mountain terrain (slope gradient and elevation), dune terrain also affects the grain-size distribution. For individual dunes, the grain size of the surface sediments showed similar patterns on the northeast and southwest slopes of the ridge: the surface particles became gradually finer from the toe to the crest of the dune on the windward slope and then became coarser downward from the crest on the lee slope in undulation (figure 3). This is similar to the results of White and Tsoar (1998).

3.2 *Particle size fractions distribution in the surface sediments of the dunes*

Using the USDA (1951) grading standard, we classified particles in the surface sediments of the climbing and falling dunes into silt and clay (>4.00Φ), very fine sand (3.00–4.00Φ), fine sand (2.00–3.00Φ), medium sand (1.00–2.00Φ) and coarse sand (<1.00Φ). The grain-size analysis showed that fine and medium sands were the dominant particles in all dunes; the contents of very fine sands and coarse sands were less than 6% and 3%, respectively, and the silt and clay were missing in the surface sediments of all dunes except in three samples from dune 1 with the content <2.6%.

Along the sampling line, coarse sands were most abundant in the surface sediments of dunes 1–5 (averaged 1.8%), while there were almost no coarse sands for the upper mountain dunes (dunes 8–12), and only averaged 0.3% for the rest dunes. The contents of medium and fine sands averaged 43.6% and 53.6%, respectively, in the surface sediments of all dunes. As the dominant particles, the medium and fine sands showed opposite change trends along the sampling line. On the northeast slope, the content of medium sands increased from dunes 1 to 5, while it decreased from dune 6 up to the top of

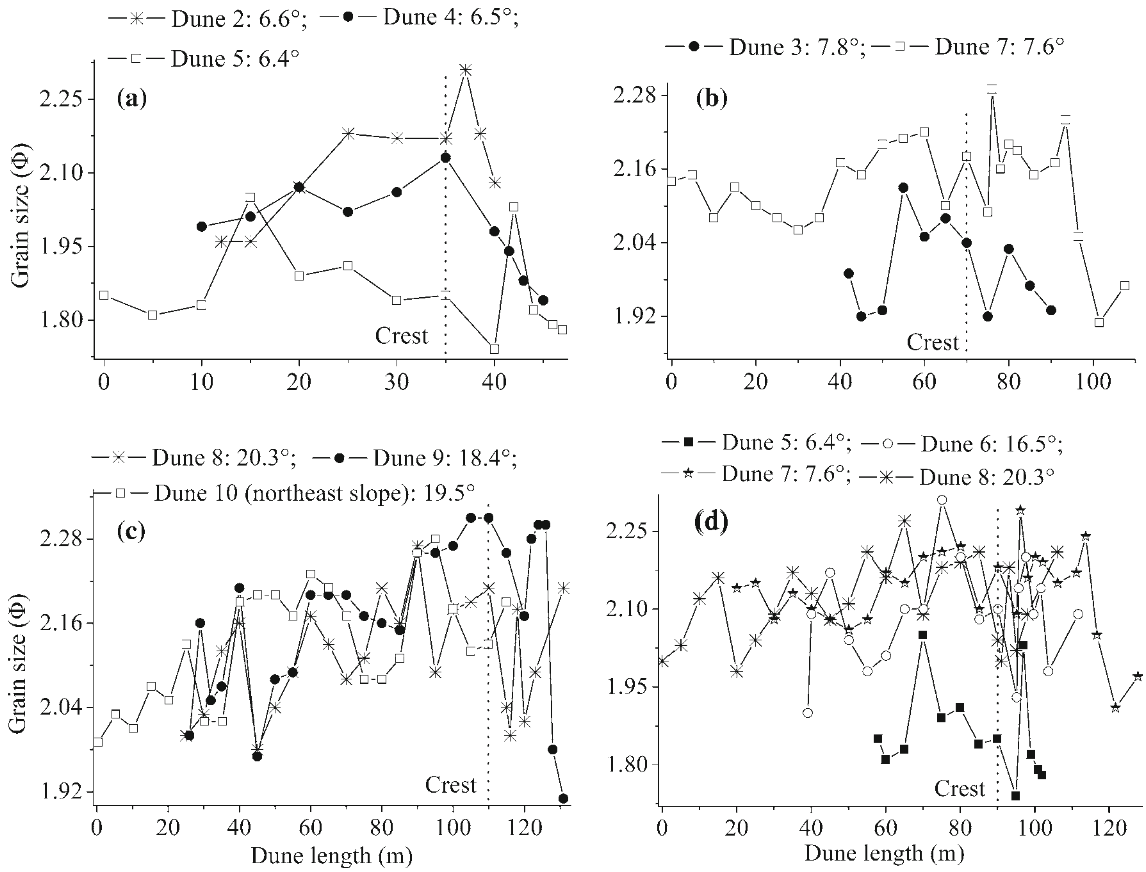

Figure 3. The influence of mountain slope and elevation on the grain-size distribution of climbing dunes. The length of dunes are different, dunes in the same group are aligned at dune crest position. The sampling is from the northeast slope to the southwest slope of dunes.

the mountain. The average content of it deceased 7.0% for dunes 6 to 10-NE from 48.6% for dunes 1–5. The content of fine sands decreased moving upward to dune 5, increased from dune 6 up to the top of the mountain. The average content of it increased 9.4% for dunes 6 to 10-NE from 46.6% for dunes 1–5. On the southwest slope, the content of medium sands in the surface sediments was much higher at the lower part of the slope (dune 12) than that at the upper part of the slope (dune 11). In contrast, the content of fine sands was much higher for dune 11 than for dune 12 (figure 4 and table 2). Overall, the content of fine sands increased upslope while medium sand decreased upslope at both mountain slopes. The content of fine sand increased 2.6%, while medium sand decreased 2.1%. Distributions of particle size on individual climbing and falling dune were similar for all dunes. Fine particles increased from the windward slope's toe to the crest of the dune and then decreased down the lee slope, whereas coarse particles decreased from the windward slope toe to the crest of the dune and then increased down the lee slope (table 2). However, the magnitude of these changes depends on the mountain elevation of the dunes. That is the content of fine sands increased for dunes located at higher mountain elevation, while medium sand decreased. This implied that the mountain slope gradient, elevation and transport distance might all affect the fractions of grain size.

The above analysis implied that both grain-size distribution and particle fractions were affected by dune slope gradient, mountain slope gradient, elevation and transport distance. The importance of these factors is very helpful for the understanding of particle transport. It was analysed with the principal component analysis in IBM SPSS statistics 19. Results showed that for all dunes, there were two principal components contributed to the variations of grain size and particle fraction. Principal component 1, explained 59.24% of the total variation, was highly correlated with factors including elevation, transport distance and mountain slope gradient, while principal component 2, explained additional 27.85% of the total variation, was highly correlated with dune

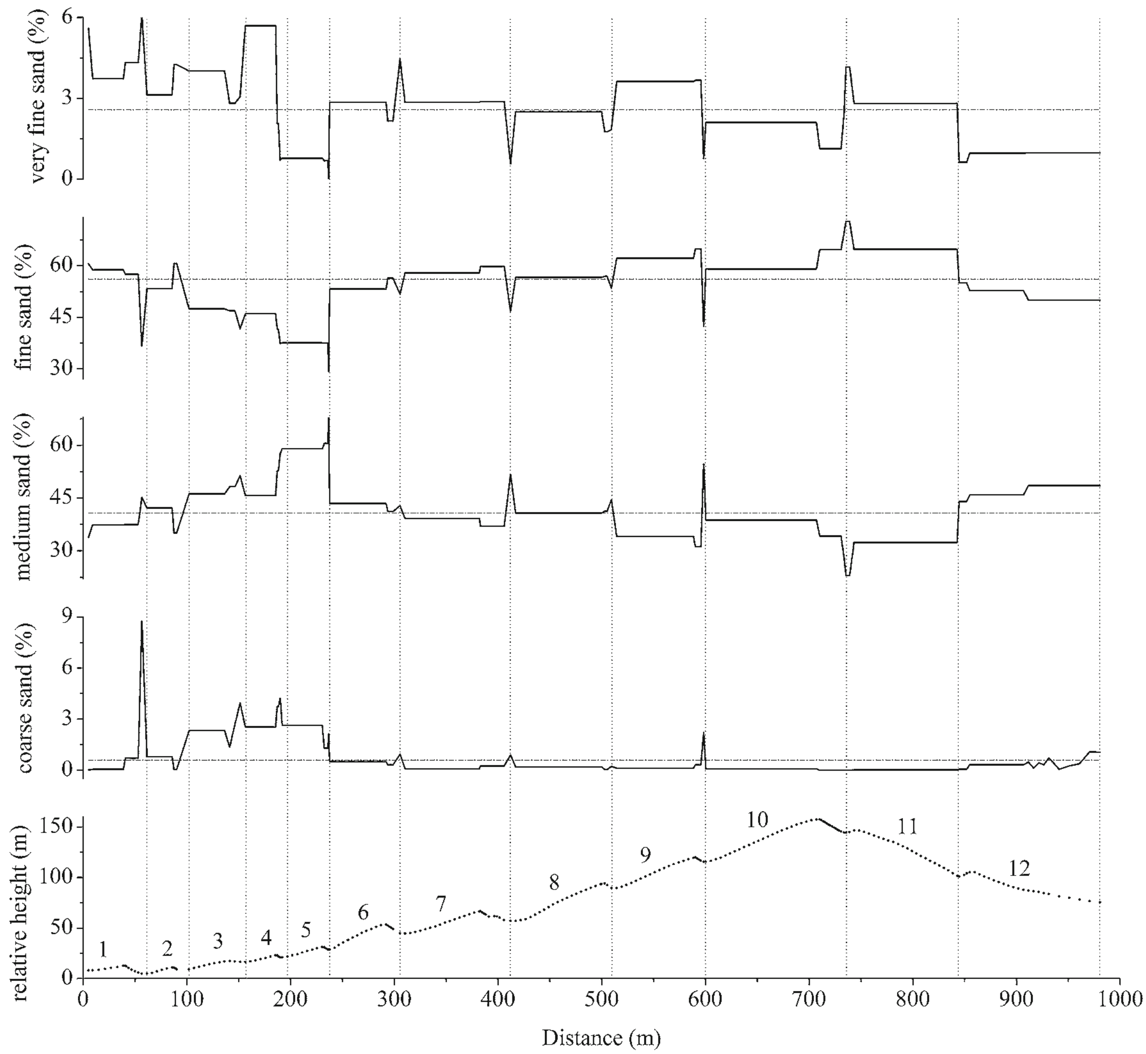

Figure 4. Variation of the grain-size fractions of the surface particles of the climbing dunes along the sampling transect. Values in this figure represent average for each dune.

slope gradient. For dune groups located at different mountain slope areas, only one principal component was extracted, which explained more than 54.59% of the variation. The principal component was closely correlated with elevation, transport distance and mountain slope gradient for dune groups located at the northeast slope, while it was positively correlated with elevation and negatively with transport distance (tables 3 and 4). Though the principal component 2 was not extracted for dune groups, their total initial eigenvalues (>0.98) were very close to a threshold value for decision (>1.00). Besides, this component explained more than 24.50% of the variation, and cumulatively explained >79.11% of the variation together with principal component 1. Thus, it could be treated as the secondary principal component approximately. This means that the dune slope gradient also played an important role in the variation of grain size and particle fraction for dune groups located at different mountain positions. As principal component 1 highly correlated with factors including elevation, transport distance and mountain slope gradient, it is useful to clear the importance of these factors. The analysis showed that the elevation is the most important factor, followed by transport distance, and mountain slope gradient is the least one as a whole. For dune groups 1–5 and 6 to 10-NE, the transport distance is more important than elevation. For dunes on the southwest slope, the transport distance affected positively for the variation, while elevation affected negatively (table 5).

Although all factors including dune slope gradient, mountain slope gradient, elevation and transport distance affected the grain-size distribution and particle fraction, it is difficult to express

Table 2. *Variation of the particle fraction of the surface particles of the climbing dunes.*

Sand fraction (%)	Dune position	1	2–4	5	6	7	8, 9	10	11	12
Very fine sand	Northeast slope toe	5.6	4.3	0.3	0.2	2.5	2.9	0.9	2.5	0.1
	Middle of northeast slope	3.7	4.2	1.7	3.2	3.0	3.1	2.4	5.8	0.9
	Crest	1.2	4.2	0.2	1.0	2.0	2.2	1.5	1.4	1.3
	Middle of southwest slope	4.1	3.3	1.0	2.6	2.5	2.8	1.2	2.4	0.9
	Foot of southwest slope	6.2	2.0	0.0	2.7	0.6	1.9	1.6	4.5	0.6
	Average	4.2	3.6	0.6	2.0	2.1	2.6	1.5	3.3	0.7
Fine sand	Northeast slope toe	59.5	47.0	37.8	40.9	59.0	55.4	48.1	69.9	45.4
	Middle of northeast slope	60.7	48.4	41.8	54.1	56.4	58.7	59.1	75.8	59.7
	Crest	53.0	52.7	31.1	49.9	57.7	60.0	63.5	63.4	63.6
	Middle of southwest slope	59.9	50.3	40.9	58.4	60.1	62.2	65.1	63.7	50.8
	Foot of southwest slope	40.9	45.6	29.9	49.6	44.4	52.7	64.1	59.2	45.9
	Average	54.8	48.8	36.3	50.6	55.5	57.8	60.0	66.4	53.1
Medium sand	Northeast slope toe	34.8	46.6	58.6	57.3	38.5	40.9	50.3	27.6	54.3
	Middle of northeast slope	35.6	45.1	53.8	42.3	40.5	38.0	38.4	18.4	39.4
	Crest	45.7	41.5	66.5	48.5	40.4	37.7	35.1	35.2	35.1
	Middle of southwest slope	36.0	45.0	57.0	39.0	37.4	35.0	33.8	33.8	48.0
	Foot of southwest slope	45.3	49.8	68.1	46.6	53.5	44.8	34.4	36.2	52.6
	Average	39.5	45.6	60.8	46.7	42.0	39.3	38.4	30.2	45.9
Coarse sand	Northeast slope toe	0.1	2.1	3.3	1.5	0.0	0.8	0.8	0.0	0.2
	Middle of northeast slope	0.0	2.0	2.6	0.4	0.1	0.2	0.1	0.0	0.0
	Crest	0.1	1.6	2.3	0.5	0.0	0.0	0.0	0.0	0.0
	Middle of southwest slope	0.1	1.5	1.0	0.0	0.0	0.0	0.0	0.0	0.4
	Foot of southwest slope	6.2	2.6	2.0	1.1	1.5	0.5	0.0	0.1	0.9
	Average	1.3	1.9	2.2	0.7	0.4	0.3	0.2	0.0	0.3

The silt and clay were missing in the surface sediments of all climbing dunes except three samples from dune 1 and dune 4 with the content less than 2.6%, so these values are not presented.

Table 3. *Results of the principal component analysis with IBM SPSS statistics 19.*

		Initial eigenvalues			Extraction sums of squared loadings		
Dunes	Component	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1–12	1	2.370	59.24	59.24	2.370	59.24	59.24
	2	1.114	27.85	87.10	1.114	27.85	87.10
	3	0.389	9.71	96.80			
	4	0.128	3.20	100.00			
1–5	1	2.508	62.70	62.70	2.508	62.70	62.70
	2	0.998	26.95	87.65			
	3	0.448	11.20	98.86			
	4	0.046	1.14	100.00			
6–10-NE	1	2.463	61.58	61.58	2.463	61.58	61.58
	2	0.980	24.50	86.07			
	3	0.547	13.66	99.74			
	4	0.011	0.26	100.00			
10-SW–12	1	2.183	54.59	54.59	2.183	54.59	54.59
	2	0.981	24.52	79.11			
	3	0.826	20.66	99.77			
	4	0.009	0.24	100.00			

The analysed factors were dune slope gradient, mountain slope gradient, elevation and transport distance.
10-NE and 10-SW represent the northeast and southwest parts of dune 10, respectively.

the distribution of particles on climbing and falling dunes with these factors well based on the linear-regression analysis (almost all explanation ranged from 22.6% to 47.4%). Besides these influencing factors, wind condition was the driving force for the movement of particles, and sand source on

Table 4. *The variance maximising the rotated matrix.*

	Component				
	Dunes 1–12		Dunes 1–5	Dunes 6–10	Dunes 10^*–12
Factors	1	2	1	1	1
DS	−0.152	0.954	0.290	0.299	0.528
MS	0.774	0.415	0.833	0.754	−0.196
El	0.947		0.901	0.949	−0.962
TD	0.921	−0.176	0.959	0.951	0.969

DS is the dune slope gradient, MS is the mountain slope gradient, El is the elevation and TD is the transport distance.

Table 5. *Importance order of factors highly correlated with principal component 1.*

Dunes	Factor	Rotated factor	Square rotated	% covariance	% importance	Order
1–12	MS	0.774	0.599	59.24	35.49	3
	El	0.947	0.897		53.13	1
	TD	0.921	0.848		50.25	2
1–5	MS	0.833	0.694	62.70	43.51	3
	El	0.901	0.812		50.90	2
	TD	0.959	0.920		57.66	1
6–10-NE	MS	0.754	0.569	61.58	35.01	3
	El	0.949	0.901		55.46	2
	TD	0.951	0.904		55.69	1
10-SW–12	El	−0.962	−0.925	54.59	−50.52	2
	TD	0.969	0.939		51.26	1

The importance of factor = square rotated × covariance (Gajbhiye *et al.* 2015).

the riverbed was limited, which also affected the particle transport greatly.

4. Discussion

4.1 *Properties of the dunes on the northeast and southwest slopes of the ridge*

The dune field on the southwest slope of the ridge is connected to the dune field on the northeast slope on the lee side of dune 10 (figure 1). It is possible that sands climbed over the mountain ridge, formed falling dunes on the southwest slope and were morphologically modified by local winds. It is also possible that dunes on the southwest slope climbed up from this side since they have a greater spatial relationship with the topography of the ridge and dune morphology of climbing dunes compared with falling ones (figure 1). However, evidences showed that the dunes on the southwest slope of the mountain were more likely falling dunes but not climbing dunes. Firstly, the grain size in the surface sediments varied almost continuously from dune 1 on the northeast slope to dune 12 on the southwest slope (table 2). Besides, dunes with similar elevation located at the opposite slope aspects had similar grain-size distribution, sorting and particle fraction. These characteristics suggested that sands of the dunes on the southwest slope very likely originated from the dune field on the northeast slope. Secondly, the main sand source was the moving sand from the riverbed, which is located at the north side of the mountain. It can hardly be the sand source for dunes at the southwest slope of the mountain ridge. Thirdly, there were multi-directional local winds, which played an important role in the morphological modification of dunes. The direction of the mountain–valley wind was modified by the mountain terrain, besides there was westerly jet circulation during the winter which affected both slopes of the mountain. The falling dunes would be affected greatly and changed their morphology. Fourthly, the elevation negatively affected the variations of grain size and particle fraction on the southwest slope, while it positively affected the variations on the northeast slope. This also implied the difference of sand-transport direction. Thus, sands climbed upon

Table 6. *The monthly wind speed condition at Gongga airport from 2008 to 2012.*

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average	1.10	1.44	1.82	1.53	1.36	1.30	1.24	0.98	1.03	1.15	1.08	1.13
Max	2.46	3.41	4.33	3.12	2.81	2.78	2.78	2.05	2.02	2.22	2.32	2.39
Min	0.23	0.44	0.35	0.32	0.29	0.40	0.26	0.25	0.34	0.33	0.32	0.38
The average frequency of wind ≥ 5 m s^{-1}	1	5	10	3	0	0	0	0	0	0	0	0

Wind data were interpolated with an interval of 0.1° for longitude and latitude, and the interpolation was on the basis of weather station recorded wind data.
The Gongga airport weather station was about 66 km away from the study site located in the wide valley, and the valley from the airport down the river to the study site was straight. Therefore, wind speed data from the Gongga airport could be used in this study.

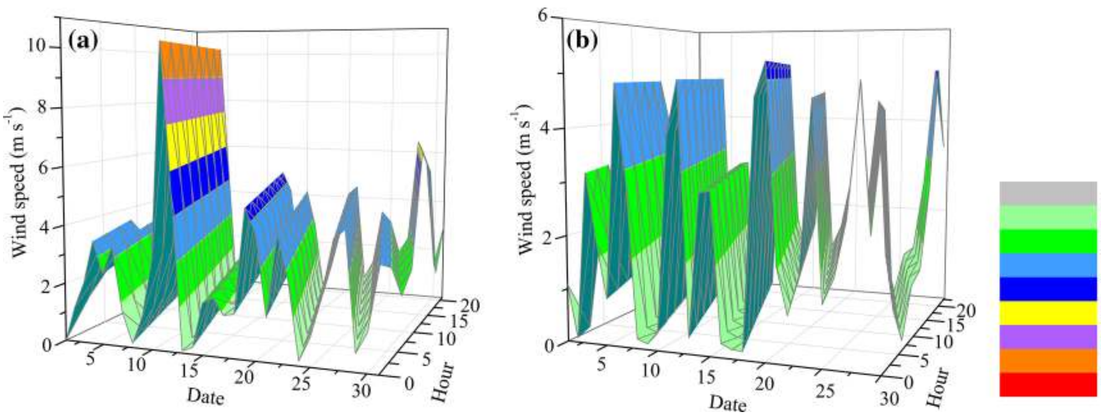

Figure 5. Hourly wind distribution at Gongga airport weather station, taking March (**a**) and April (**b**) of 2010 as an example (two months had stronger winds during 2008–2012).

from the northeast side of the mountain passed over the ridge, form falling dunes at the southwest slope, and changed their morphology under the control of local multidirectional winds and mountain terrain. Compared with falling dunes in group A, the falling dunes in group C were not as typical as group A, as the mountain slope gradient underlying group C was much gentle than that underlying group A (figure 1). Terrain factor controlled the morphology of dune group A, while winds affected the morphology of dune group C greatly.

Local wind condition should provide more reliable evidence than the characteristics of dune morphology and grain size for the judgment of dune types. Hourly average wind data ranged from 0.01 to 10.21 m s^{-1}, and averaged 1.30 m s^{-1} according to the wind speed data extracted from the China Meteorological forcing dataset. There were 120 values greater than 5.0 m s^{-1} from 2008 to 2012. Unfortunately, there were no obvious monthly changes for average wind, maximum and minimum wind speeds (table 6), or daily changes for hourly averaged wind speed (figure 5). Therefore, the wind speed data without direction information helped little for the particle transport analysis on climbing dunes.

4.2 *Transport pattern of particles in different sizes on the dunes*

The variation of the grain-size fractions on the climbing dunes along the sampling transect suggests that fine sands were more easy to be transported up the mountain slope than larger particles, whereas the medium-grained sands moved upslope by winds decreased gradually with increasing mountain height, and the coarse sands could only stay at the bottom of the slope. The very fine sands have the high feasibility to be transported upslope by suspension, falling to the ground on the lee side of the ridge rather than settling to the ground at the windward side. After the formation of falling dunes, valley winds and westerly jets modified the dune shape. On dune 12 at the foot of the southwest slope, very fine sands could be easily blown upslope even under relatively weak valley winds, but would be unlikely to travel over the ridge when they reached the lee of dune 11. This would have

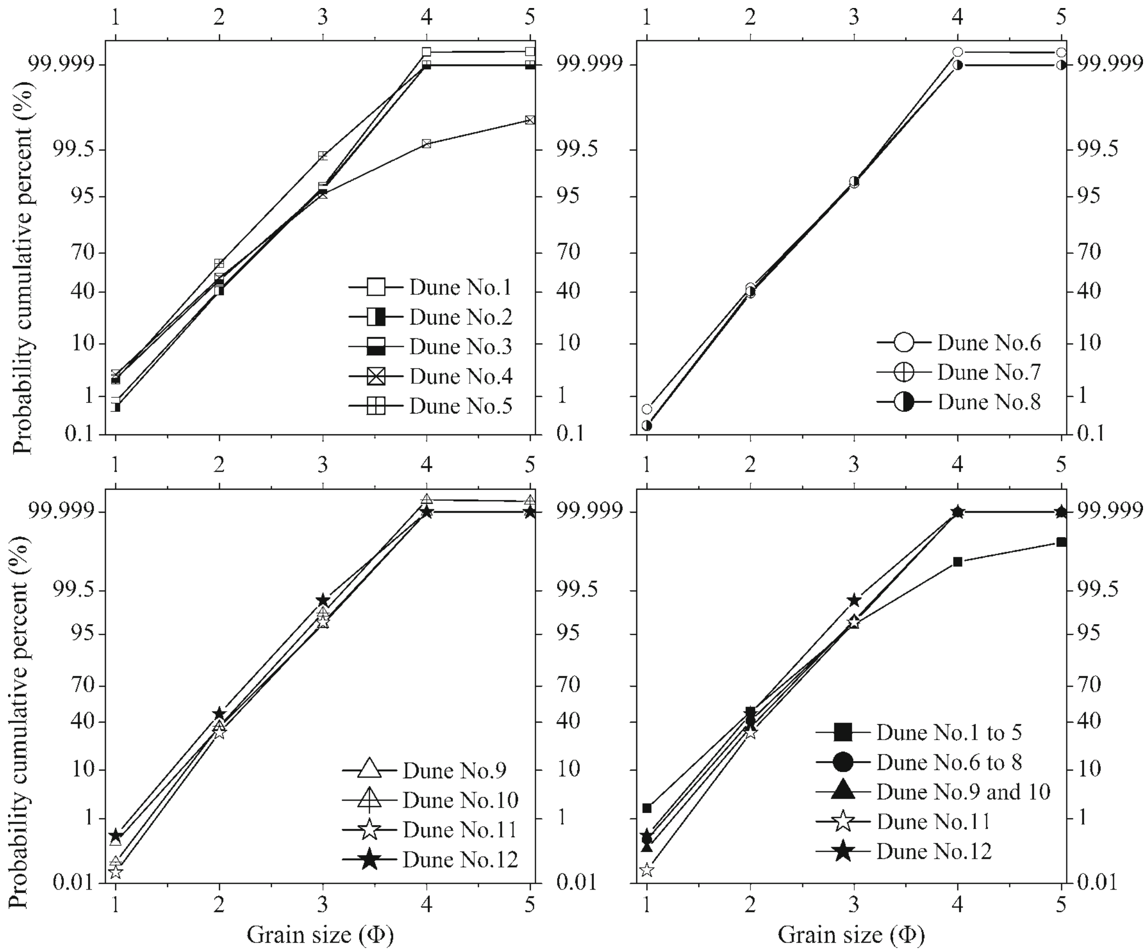

Figure 6. The grain-size cumulative probability curves for the climbing dunes.

promoted the enrichment of very fine sands in the lee of dune 11.

The grain-size cumulative probability curve is used to describe the transport patterns of particles since it is a useful tool in the study of particle transport and depositional environments (Pye 1987), and has been applied successfully in the studies of hydrodynamic or aeolian deposition (Pye 1987; Rajamanickam and Gujar 1997; Shao 2008; Luo *et al.* 2013). In the present study, the cumulative probability curves for sands on the climbing and falling dunes showed that particle saltation was the main transport way, accounting for more than 99.5% of the total particles in all dunes (figure 6). There were few particles coarser than 1.00Φ that were transported by creep, which means that the coarse sands are very difficult to be winnowed upslope. The transition point between saltation and suspension occurred at about 4.00Φ for most of the dunes. The grain-size probability curves for the particles transported by saltation are almost straight lines, and changed slightly with increasing relative elevation (figure 6). Dune 4 is an exception since the slope of its cumulative probability curve keeps changing throughout the range of particle sizes. Sorting of the particles between 1.00 and 2.00Φ (medium sands) during saltation improves with increasing height, whereas sorting of the particles between 2.00 and 3.00Φ (fine sands) varied slightly along the slope. Sorting of the particles between 3.00 and 4.00Φ (fine sands) on the upper part of the mountain slope was obviously better than that at the bottom of the slope. For particles between 4.00 and 5.00Φ, which would be transported by the suspension on the climbing and falling dunes, the slope of grain-size probability curves was near zero for most of the dunes, showing that the sorting of these suspension particles is poor. Sand finer than 4.00Φ that was transported by the suspension was found in this study, which is comparable to that found in the study by Zhou *et al.* (2012) at Mailing wide valley, located at the lower reaches of our study site. In the study by Zhou *et al.*, the creep sands were coarser than

2.00Φ, and grain size of saltation sands were from 2.00 to 4.00Φ, while, creep sands were coarser than 1.00Φ, and grain size of saltation sands were from 1.00 to 4.00Φ in this study.

5. Conclusions

This study analysed the grain-size distribution on climbing and falling dunes on two opposite slopes of a ridge in the Langsailing area, in the middle reaches the Yarlung Zangbo River of the southern Tibetan Plateau. Terrain factors, elevation and transport distance were the major factors affecting the distribution of grain size according to the principal component analysis as a whole. Besides, wind condition and sand source were important for the transport and distribution of particles. In order to clarify the transport pattern of particles under the conditions of complicated terrain, wind condition and limited sand resources, systematical observation of wind condition is very important, which should be included in future studies. Fine sands and medium sands were the dominant particles in the surface sediments of the climbing and falling dunes, accounting for more than 90% of the total. Silt and clay that cross over mountain ridge might have been transported upslope by suspension, fine and medium sands were winnowed high upslope by saltation with opposite change tendency, and coarse sands were mainly transported by creep were found almost exclusively in dunes at the bottom of the slope.

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