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CHANGES IN GRAIN SIZE OF SAND IN TRANSPORT OVER A FOREDUNE

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ABSTRACT

Suspended sand is sampled at several heights and positions on a beach and foredune, providing detailed insight into the vertical and horizontal variation in sand content in the air during landward transport. Grain-size analysis is used to study the changes in grain-size distribution during landward transport. Mean grain size and sorting decrease during transport. Changes in textural parameters follow a gradual and regular path when the sediment is transported into the foredune. Sediment trapped on the seaward slope at a height of 30–50 cm above the surface closely resembles the sediment trapped landward, which implies that changes in the direction of transport are related to vertical changes within the sediment transport profiles. The movement of sand over the vegetated foredunes is induced by turbulent forces created by the air flowing across the vegetation and the foredune, leading to a change from saltation on the beach to modified saltation and suspension on the foredune. Small grains are lifted higher and fall more slowly than coarse grains and therefore are transported further landward, resulting in a gradual decrease in grain size of the landward-deposited sediment. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: sand transport; coastal foredunes; grain-size distribution; transport mechanism; suspension; vertical sediment concentration

INTRODUCTION

Extensive literature exists on grain-size distributions in dune environments. An overview is given by Pye and Tsoar (1990). Much attention is paid to the differences between beach and dune sediments and grain-size patterns in desert dune environments. Folk and Ward (1957), Mason and Folk (1958) and Vincent (1986) conclude that aeolian sediments can be distinguished, at least locally, from beach sediments on the basis of mean, sorting and skewness. In contrast, Bigarella *et al.* (1969) states that where beach sands are fine grained, aeolian transport is not selective and there are no significant differences in the mean size, sorting and skewness between the beach and adjacent dune sands. However, where beach sands are coarse and poorly sorted, adjacent dune sands are usually finer and better sorted. Depuydt (1972) comes to a similar conclusion for the beach and dune sand along the French and Belgian North Sea coast: distinction between beach and dune sands is difficult, because the beach sediments are very well sorted and the transport distance from beach to foredunes is short.

Most of the literature describes the analysis of grain-size distributions of surface samples, but some of the recent literature deals with grain size of sediment in transport (e.g. Chen *et al.*, 1995; Chen and Fryrear, 1996; Martz and Li, 1997; Van der Wal, 2000). Grain-size parameters give some indication of environmental conditions and transport dynamics (Depuydt, 1972). According to Christiansen and Hartmann (1988), the environmental discrimination of sediments depends to a high degree on the sampling method. When surface sediments are sampled (for example the first centimetre of the surface layer), the samples contain a mixture of grain populations derived from several wind conditions, as was already recognized by Doeglas (1952).

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Folk (1971) proposed a quantum model of aeolian deposition: wind deposits consist of a series of quantum bursts or swarms of well-sorted sand grains. Each quantum is carried by a separate gust and deposited as a thin layer of grains. The characteristics of the grains depend on the direction and strength of the gust. The resulting deposit is a mixture of quanta, which is reflected in the polymodal or skewed nature of the frequency curves (Folk, 1971). For these reasons, samples from beach and foredune are difficult to compare with respect to transport dynamics. Better results will be obtained if only the active layer is sampled (Otto, 1938; Hartmann and Christiansen, 1988). However, in the dune environment, sampling of the active layer is difficult to achieve when the surface is vegetated. In this case, trapping of the sediment when it is transported potentially renders good results.

On 16 April 1991 during a period of strong onshore winds, 95 samples were trapped along nine vertical transport profiles from the sediment moving over the beach and foredune on Schiermonnikoog, one of the Dutch Wadden islands. Analysis of the trapped sediment offers the possibility to test the current theories on changes in grain-size distribution during transport and to elucidate the mechanisms for aeolian transport. This paper discusses the results of the grain-size analysis of the trapped samples.

STUDY AREA

The study area is located in the northwestern part of the Wadden island of Schiermonnikoog, in the north of The Netherlands (Figure 1). A profile was studied, perpendicular to the coastline, including beach and foredunes. The beach here is wide (600 m) and very gently sloping (approximately 1 : 500), and flooded by seawater only during storms. It is partly covered with shell fragments. The height of the foredunes is almost 6 m above Dutch Ordnance Datum (NAP, approximately mean sea level). Development of the foredunes was initiated in 1972 by erection of sand fences, and stimulated until 1988. Since 1988 management efforts have been limited to stabilizing blowouts by planting marram grass. The dunefoot is poorly vegetated, mainly with sand couch (*Elymus farctus*) and marram grass (*Ammophyla arenaria*). The top of the foredune is densely

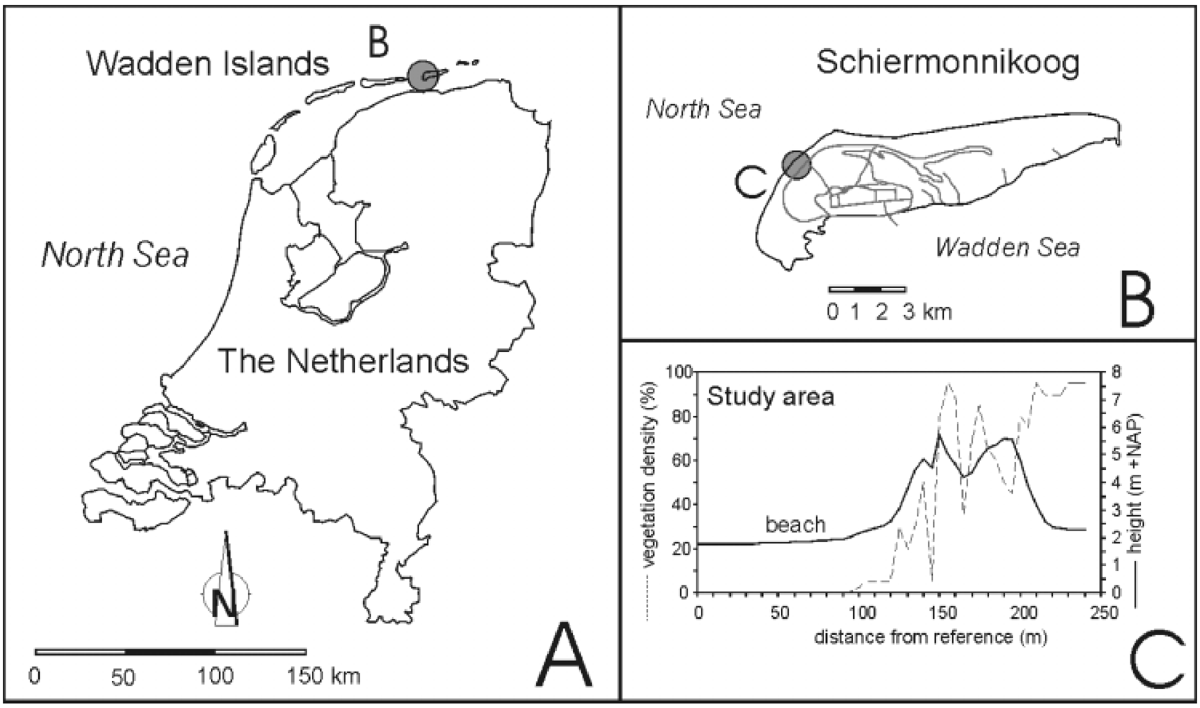

Figure 1. Location of the study area and characteristics of the studied cross-section, with profile height and vegetation density

vegetated with marram grass, with a vegetation cover of 30 to 60 per cent (see Figure 1). In recent years a sand bar has formed about 2 km in front of the beach, resulting in a seaward migration of the surf zone. Probably because of this, wave energy on the beach is low, even during gales.

METHODS

Measurement of meteorological parameters

On the beach and dune, masts were erected to measure wind speed (at 0·75, 2·00 and 5·00 m above the surface) and direction (at 6·00 m above the surface). Air temperature and humidity were measured on the beach at 1·15 and 5·50 m above the surface. On the foredune, rainfall and solar radiation were recorded. All meteorological variables were sampled every 5 s, and averaged over 10 min except for rainfall, which was totalled every 10 min. Occasionally moisture content of the surface layer was determined by sampling the top 2 mm.

Figure 2. Saltation sand trap. The number of trays can be adapted, according to the height of the sand cloud

Measurement of sand transport

Saltating and suspended sand was collected, using omnidirectional sand traps (Figure 2), divided into 0·05 m high compartments. Efficiency of the sand traps is about 15 per cent, determined in the wind tunnel, but depends on wind speed and sediment characteristics. In this study no corrections for efficiency are applied. Sand traps and calibration are described by Arens and Van der Lee (1995). It is assumed that the efficiency for all size classes is equal. Because of obstacle effects small grains might be taken in the air that flows around the trays. We expect that this effect becomes more important for higher wind speeds. If this is true, the result would be a decrease of mean grain size with height. Sand traps were placed in an array at eleven positions along the transect (Figure 3). Heights of the sand traps differed from 0·30 m on the beach, to more than 1 m on the foredune. On the beach it appeared that more than 99·5 per cent of the transported sand was trapped at a height below 0·30 m. On the foredunes most of the sand traps (maximum height 1·50 m) did not reach the top of the sand cloud, as it appeared from observations that even at heights above 1·50 m sand was passing. Exposure time of the traps depended on transport rates and ranged from 52 min at the beach, to more than 9 h on the foredune, in order to trap enough sand to be analysed.

Analysis of grain-size distribution

At all positions the transported sediment was sampled (Figure 3). Samples trapped at locations 10 and 11 were too small to be analysed (see Table I). In total 95 samples were collected, of which the grain-size distributions were determined. The number of samples per sediment transport profile is given in Table I. For the grain-size analysis, large samples (larger than 100 g) were split to about 80–100 g; some smaller samples were combined (Table I). The size of the sample slightly influences the sieving results. Splitting up of a sample into subsamples with different sizes, revealed that because of shielding effects, the results for small samples tend to be slightly finer than results for large samples. Comparison of a range of split samples from 100 to 5 g proved that the smaller subsamples showed a decrease in grain size of about $0{\cdot}03\varphi$ (see Table II).

Sampled sand was washed with demineralized water, but not decalcified to prevent break down of possibly transported aggregates. After drying at 70 °C, samples were sieved for 10 min each, using a mechanical shaker. A nest of sieves was chosen that consists of mesh sizes assigned to 1·875, 2·125, 2·500, 3·000, 3·500, 3·875 and $4{\cdot}125\varphi$ mid-class values. Arbitrary mid-class values of $4{\cdot}125\varphi$ for the finest sand fraction and $1{\cdot}875\varphi$ for the coarsest fraction were designated. Both fractions were less than 1 per cent of the total weight of the sample. Sediment grain-size parameters were computed according to Folk and Ward (1957) by means of the computer program GAPP (Fay, 1989) to determine the population distribution characteristics sensitive to aeolian sediment transport. Comparison of mathematical and graphical parameters of our samples indicates a deviation in absolute values (of skewness and kurtosis). However, differences between samples are the same for both methods, but the transition between different depositional environments is much clearer and more

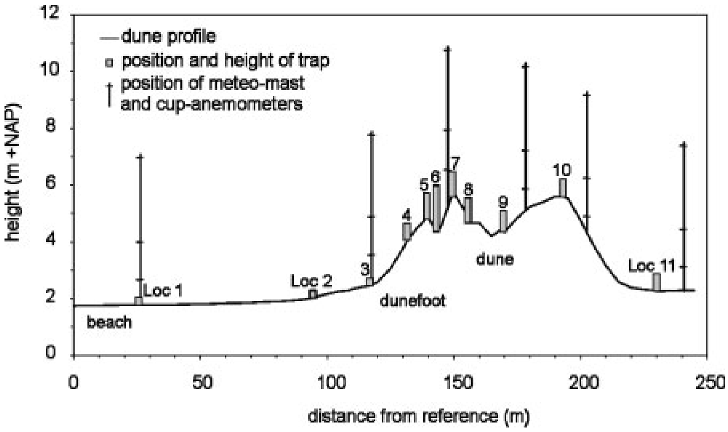

Figure 3. Position of the sand trap locations (trap locations are numbered and height of the traps is indicated by the length of the bars)

Table I. Number of samples, sample height and total weight per profile

Location	Total sampled weight (g)	Height of sand cloud sampled (cm)	No. of trays per sample	No. of samples
1	660·2	0–25	1	5
2	847·6	0–25	1	5
3	618·0	0–25	1	5
4	1383·8	0–50	1	10
5	1241·9	0–45	1	8*
		45–75	3	2
6	1939·1	0–150	1	30
7	208·4	0–45	1	9
		45–75	3	2
8	242·6	0–75	1	15
9	45·3	0–50	2	4*
10	3·3	0–50	2	5
11	0·9	0–30	3	2†
		30–50	4	1†

* one sample missing.
† sample not analysed.

Table II. Effects of sample size on grain size parameters according to Folk and Ward (1957)

Fraction	Weight	Arithmetic Mean	Sorting	Skewness	Kurtosis (−3)
1	172·83	2·58	0·26	0·03	0·90
1/2	84·54	2·59	0·26	0·03	0·88
1/4	46·60	2·57	0·26	0·04	0·95
1/8	22·85	2·60	0·26	0·03	0·83
1/16	11·29	2·60	0·26	0·02	0·83
1/32	5·40	2·61	0·26	0·00	0·80

gradual for graphical parameters. For this reason, in this paper only the grain-size parameters according to Folk and Ward (1957) are considered. Grain-size distributions of total samples are computed by numerically mixing all samples of each vertical profile: all weights of each size class are totalled, and the grain-size parameters are determined for the total sample.

Grain-size parameters were then correlated with process parameters, transport rates, heights of traps above surface and terrain features to elucidate the mechanism for sediment transport from the beach to the foredunes for the studied event.

RESULTS

Wind speed during the measuring period averaged 15·2 m s^{-1} (measured at a height of 5 m), with a maximum 10 min wind speed of 17·8 m s^{-1} and a minimum of 11·6 m s^{-1} and a maximum (5 s) gust of 24 m s^{-1}. Wind direction ranged from 335 to 345° (NNW), which deviates 20 to 30° from perpendicularly onshore. With onshore winds airflow is accelerated on the windward slope to about 110 per cent of the wind speed on the beach (Arens *et al.*, 1995). Further landward, flow is decelerated to 40–60 per cent due to lee effects and increased surface roughness. Presence of the foredunes results in both accelerations and decelerations of flow, and in vertical air movements. The vegetation on the foredunes causes a deceleration of the flow due to increased aerodynamic roughness and turbulence intensity.

A number of light showers, occasionally with hail, occurred sporadically during the day. Air temperature varied from 5 to 7 °C, relative humidity was 70 per cent, and solar radiation ranged from 600 W m^{-2} to less than 200 W m^{-2} during showers. During sand transport on the beach, moisture content of the top 2 mm was determined at 18 per cent.

Results of transport measurements

Transport of sand from the beach to the dunefoot was high in the morning but decreased in the afternoon when seawater covered the beach during high tide. Transport from the dunefoot landward continued. Although the top of the foredune is densely vegetated (Figure 1), sand is transported over the vegetation. There is no interaction of the sand cloud with the surface, i.e. no grains are being taken up. Figure 4 shows the sediment curves for some profiles. Clearly the amount of sand decreases with increasing height above the surface and the sand cloud expands during transport over the foredune. On the beach the total amount of sand transported is constant, whereas it decreases near the dunefoot, and decreases very rapidly after the first crest. Transport of sand on the beach is approximately a thousand times the amount transported over the top of the foredunes (Arens, 1996). Because of the density of the vegetation cover, all sand that moves over the dune must be derived from the beach.

Results of grain-size analysis

Figure 5A–D presents the calculated mean, sorting, skewness and kurtosis respectively (according to Folk and Ward, 1957) in relation to transport (trapping) height.

Mean. For most transport profiles the mean either decreases or does not show any relation to height. Only on the beach (location 1), the mean grain size increases (decreasing φ) with height. For location 3 (dunefoot) the decrease with height is pronounced, about 0·2 φ. For location 8 (top, lee of second crest) mean grain size seems to be constant with height. From beach to foredune the mean grain size decreases gradually from 2·55 to 2·80φ (171–144 µm). Since the trend with height is opposite to what we expect if results are influenced by trap efficiency, we conclude here that trap efficiency is not of importance in the interpretation of our results.

Sorting (standard deviation). On the beach, dunefoot and seaward slope, sorting decreases (standard deviation increases) about 0·1φ units with height. For the landward profiles the change with height is less pronounced. Sorting of samples on the foredune (locations 7 to 9) is poorer than on the beach and seaward slope. The poorest sorting is found in the upper parts of the slope profiles.

Skewness. The relationship between transport height and skewness is more complicated. In the upper part of the profiles skewness decreases with height. On the beach (location 1) the relationship is almost identical to the relation between mean and height; for the other locations the relationship is inversed. For location 8 skewness is more or less constant with height.

Kurtosis. Kurtosis on the beach is constant with height. For profiles near dunefoot and slope kurtosis decreases rapidly with height. On the foredune (location 7 to 9) kurtosis is reduced to 0·7, without any

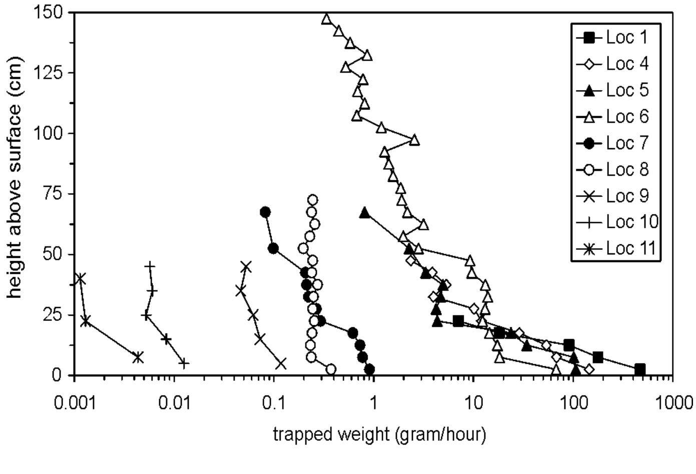

Figure 4. Sediment curves of some of the profiles sampled on 16 April 1991

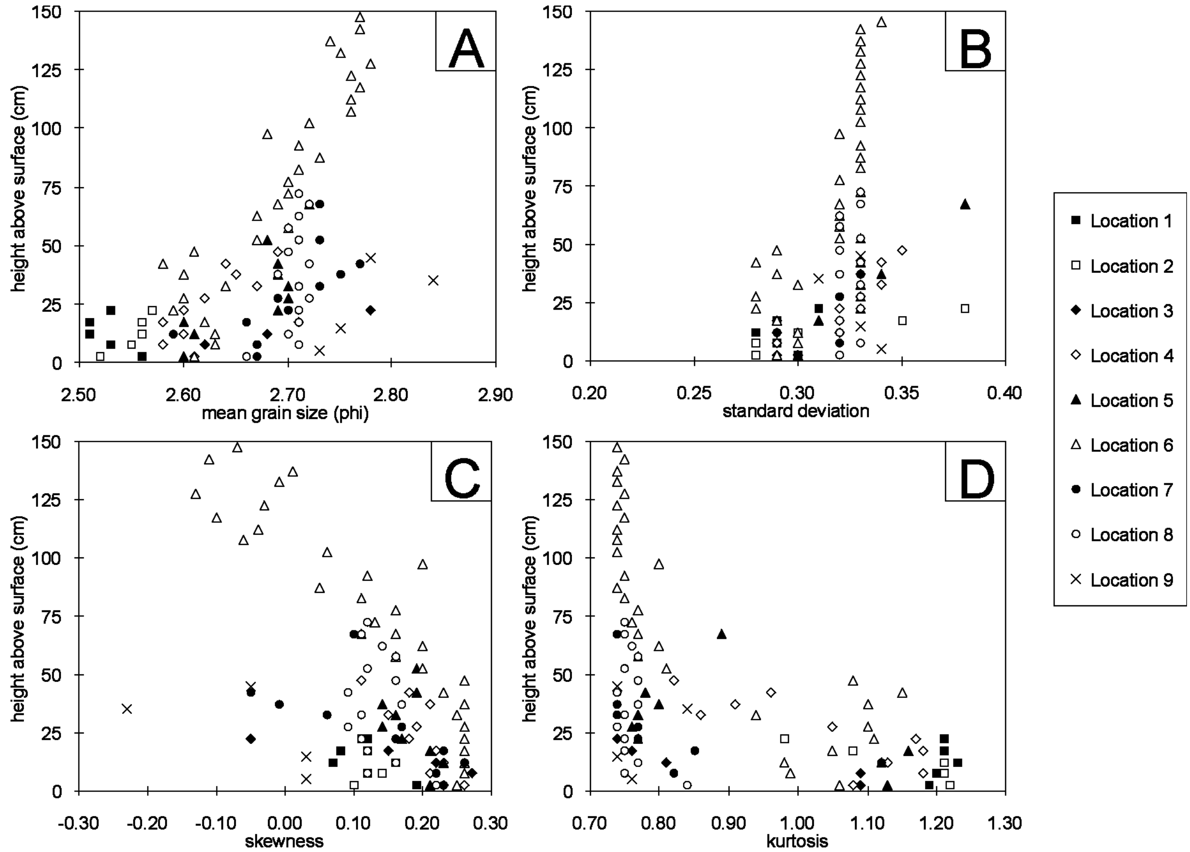

Figure 5. Mean, standard deviation, skewness and kurtosis (according to Folk and Ward, 1957) for all samples, plotted versus height

relationship to height. The difference between dune and beach samples is most pronounced with respect to kurtosis.

Bi-variate analysis of grain-size parameters

Irrespective of transport height the relationship between the different grain-size parameters can be studied. Figure 6A–C displays the bivariate plots, with mean grain size plotted versus sorting, skewness and kurtosis respectively. Relationships are clear: there appears to be very little scatter. The transition from beach to dune samples is very gradual. From beach to dunefoot a decreasing mean grain size is accompanied by a decrease in sorting, an increase in skewness and a slight decrease in kurtosis. From the dunefoot landward mean grain size decreases further, accompanied by a decrease in sorting, skewness and kurtosis.

Vertical distribution of grain-size parameters

Many of the samples trapped close to the surface show different trends compared to samples trapped more than 20 cm above the surface. On the basis of the relationships between grain-size parameters and height as presented in Figure 5 and discussed above, most profiles can be separated into lower and upper transport layers (compare Chen and Fryrear, 1996). The relationships between grain-size parameters and height differ for the two transport layers, especially with respect to the mean grain size and the kurtosis: trends for upper and for lower layers are completely different. Complex profiles are locations 4 (division at 25 cm), 5 (20 cm), 6 (50 cm) and 7 (20 cm). Probably only the lower part of profile 8 is sampled. In the upper transport layers most changes with height are more pronounced than in the lower layer. Samples of lower (L) and of upper (U) transport layers are each numerically mixed, by totalling weights of each size class for all samples. For these

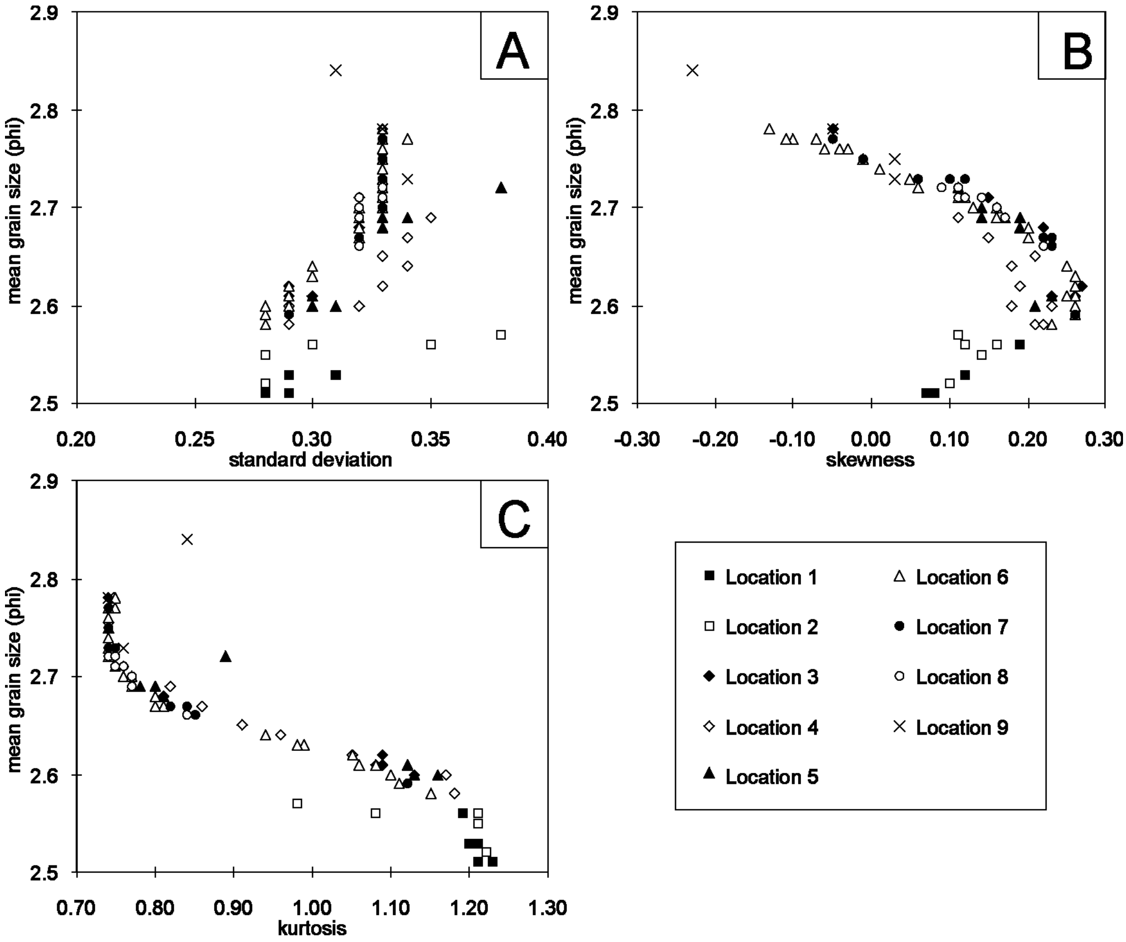

Figure 6. Bivariate plots of standard deviation, skewness and kurtosis for all samples

mixed samples again grain-size parameters according to Folk and Ward (1957) are calculated and presented in Figure 7.

Besides the gradual transition from beach to dune profiles, the plots of Figure 7 show a clustering of profiles (layers). Beach samples (1 and 2L) are separated from a group consisting of dunefoot, slope and first crest (3L, 4L, 5L and 6L); all lower layers near the dunefoot and slope show comparable grain-size distributions. Intermediate are 4U and 7L. The last cluster contains 3U, 5U, 6U, 7U, 8L (probably here only the lower part of the profile is sampled) and 9; apparently the sediment in the upper layers of the slope profiles is comparable to that of the profiles on top of the foredune; horizontal changes (i.e. changes in transport direction) are related to vertical changes (i.e. changes in height). It seems that the change of grain-size distribution with increasing transport distance can be explained by the differences between transport layers.

To gain more insight into the mechanisms of change, weight percentages per profile for each grain-size class are presented in Figure 8. Classes coarser than 150 μm ($2{\cdot}75\varphi$) tend to decrease from beach to foredune, while classes finer than 150 μm increase. The gradient of change is related to the topography. From locations 1 to 2 (both beach) small changes are observed. From locations 3 to 6 (dunefoot–slope) there is a slight increase in both coarsest and finest classes. From locations 7 to 9 (crest) fine classes increase at the expense of the coarse classes. The increase of percentage $>$ 250 μm ($2{\cdot}0\varphi$) observed in location 9 is unexpected.

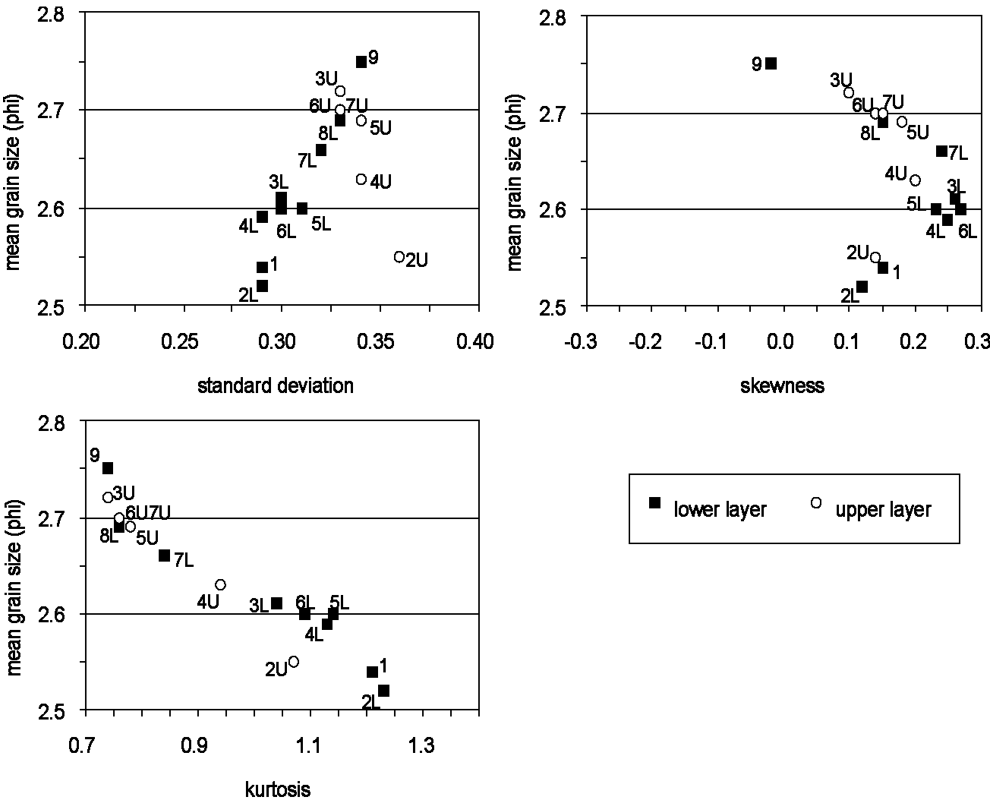

Figure 7. Bivariate plots of mixed samples for upper (U) and lower (L) layers

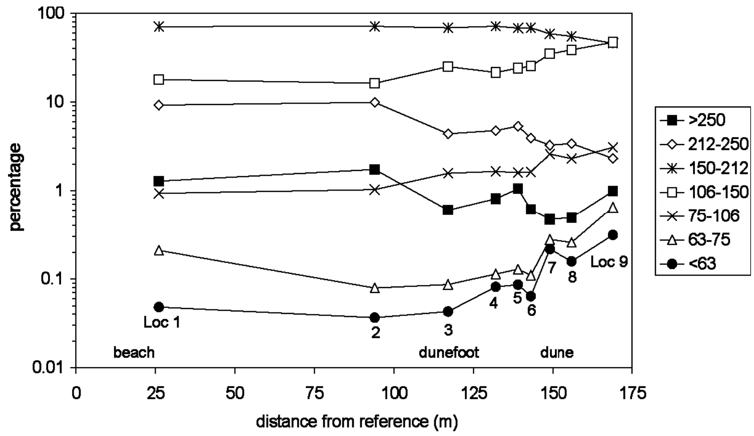

Figure 8. Change of frequency distributions of sampled profiles in relation to transport distance

DISCUSSION

An increase in grain size with height on a beach was reported by Draga (1983), Van Dijk (1990), Greeley *et al.* (1996) and Van der Wal (2000). Williams (1964) reported increasing grain size with height within certain ranges of height. A reversed relationship was observed by Sindowski (1956) on the beach of Nordeney, one of the German Wadden islands. Chepil and Milne (1939), Bagnold (1954) and Sharp (1964) observed that large grains saltate higher than small grains during sand storms of moderate intensity, which explains an increase in grain size with height.

Several observations on sparsely vegetated linear dunes (Folk, 1971; Lancaster, 1986), or on a bare coastal dune (Barndorff-Nielsen *et al.*, 1982) indicate an increase in grain size and improved sorting from base to crest. Lee slope deposits are generally finer than windward slope deposits (Cornish, 1897; Folk, 1971; Barndorff-Nielsen *et al.*, 1982). Lancaster (1981, 1982) observed at a regional scale that sands tend to become finer and better sorted in the direction of transport, which was confirmed by Hartmann and Christiansen (1988) on a longitudinal desert dune.

Reports of decreased sorting during transport are rarely found. Mainly on the basis of theoretical considerations McLaren and Bowles (1985) argue that decreasing sorting in the direction of transport is possible. It depends on the initial sorting of the source sediment. Doeglas (1952) explained a decrease in sorting during landward transport as the result of variations in wind speed, yielding deposits which are mixtures of coarse grains transported during high velocities, and small grains transported during low velocities. Localities at a long distance from the beach receive (fine) sediments only during very strong gusts, while localities close to the beach receive sediments from both strong and weak gusts. However, this means that close to the beach many different grain populations will be deposited, while on remote sites only fine grains will settle, implying that sorting should improve with transport distance. The decrease in sorting during landward transport in this study is explained as follows. The source sediment is very well sorted, with more than 70 per cent of the grains between 150 and 212 μm (2·75 and 2·25φ). A gradual shift from this class to the class 106–150 μm (3·25–2·75φ) means a decrease in steepness (kurtosis) and an increase in distribution width (standard deviation) and decrease in sorting.

With respect to the bivariate analyses, our results confirm those of Ahlbrandt (1975), who observed a negative correlation between mean grain size and skewness in the Killpecker dune field of Wyoming. Similar relationships were reported by Lancaster (1981) on linear dunes in Namibia, and by Pye (1982) in the coastal dunes of North Queensland.

Several explanations for the decrease in grain size from beach to dune crest are found in the literature. Changes in grain size and sorting can be explained in terms of the progressive loss of coarse grains in the direction of sand transport (Lancaster, 1986). The grain size and sorting patterns which may evolve in the direction of transport will depend, as originally suggested by Folk (1971), on the relative proportions of potential saltation, suspension and creep population in the source sediments (Lancaster, 1986). In a study to model the effects of transport in aquatic environments, McLaren and Bowles (1985) assumed that when sediment is being eroded, the probability of any grain going into transport increases with diminishing grain size. This causes the sediment in transport to be finer and more negatively skewed than its source. If the transfer function is assumed to increase monotonically with decreasing grain size, the sediment in transport is always finer and more negatively skewed than its source. In contrast, Martz and Li (1997) argue that larger particles can be more mobile than smaller particles if the wind speed is higher than the threshold for the larger particle. This could result in an increased grain size in the direction of transport.

Mixing of two grain populations in different ratios can produce these patterns in bivariate plots. An example is illustrated by Figure 9, showing the grain size parameters for mixtures of two populations, one with a mean size of 2·5φ the other with a mean size of 3·0φ, both with a sorting of 0·25φ.

Grain-size changes and transport mechanisms

The observed changes in grain size can be explained in terms of transport mechanisms. From beach to foredunes several transport modes can be distinguished, based on the trajectories of moving grains. Anderson *et al.* (1991) give an overview of transport mechanisms. On the beach, grains mainly move in saltation, reptation and creep. In saltation, grains jump to a certain height, depending on grain size and surface conditions. Smaller grains are influenced more strongly by air drag than larger grains (Anderson, 1988), which means that larger grains decelerate less than smaller grains, and therefore reach larger heights. This corresponds to an increasing grain size with height as we, and several other authors, observed at the beach.

Near the dunefoot, increased roughness due to vegetation and relief starts to influence the airflow by generating turbulence. Grain trajectories affected by turbulent motion move in modified saltation (Hunt and

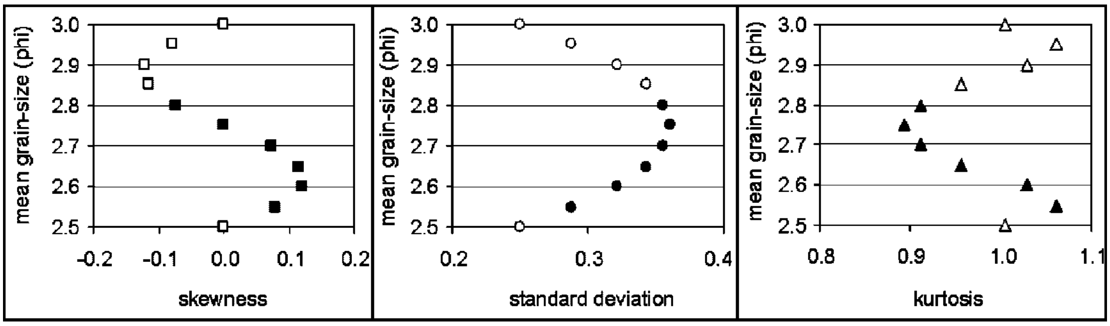

Figure 9. Mixing effects of two grain populations with average grain size of 2·5 and 3·0φ. The dots represent different mixtures in steps of 10 per cent (from 100 per cent 2·5 and 0 per cent 3·0φ to 0 per cent 2·5 and 100 per cent 3·0φ). The black dots are in the range of our samples

Nalpanis, 1985; Nalpanis, 1985): the grain cloud expands. The presence of the dune also changes the flow. At abrupt topographic changes (cliffs) vertical movements are induced and the flow will separate at the top of the slope; the steeper the windward slope, the more significant these movements will be. This 'jet' flow will force sand grains of any size to move in suspension ('jettation'). Observations of coarse suspended grains following the flow were also reported by De Ploey (1980) and Draga (1983). The process is illustrated by Figure 10. At the windward slope, transport profiles will reflect different transport modes, as long as the saltating population is not blocked by vegetation. This explains the distinct breaks in the particle size relations at certain heights (Figures 5 and 7). A distinction in different layers was also found by Chen and Fryrear (1996) for wind-eroded material above a flat bare soil. They divided their transport profiles in a near-surface layer, reflecting the grains that move in saltation, and an upper layer, reflecting the finer material that moves in suspension. Chen and Fryrear argue that vertical sorting results in horizontal sorting and thus in spatial differentiation on redeposition.

Anderson (1988) proposes a model for lee slope deposition. On theoretical considerations, Anderson predicts a fining of sediment deposited on the lee slope of a dune. The model is experimentally verified by McDonald and Anderson (1995). Due to larger lift-off velocities of smaller grains at the brink of the dune, smaller grains move in larger trajectories and therefore deposit on a larger distance from the brink, resulting in a landward fining of the sediment. This effect outweighs the increased inertia of the larger grains, which are much less affected by air drag within the lee region (Anderson, 1988). Although the foredune system we studied lacks a pure slip face, the change in airflow behind the crest will be comparable to a lee slope in the strict sense. Steep changes in topography lead to separation of airflow; flow behind the crest will be strongly reduced, as was demonstrated by Arens *et al.* (1995). Anderson's assumption that all grains move in saltation is not valid here, since we observed that all grains passing the crest move in either modified saltation or short-term

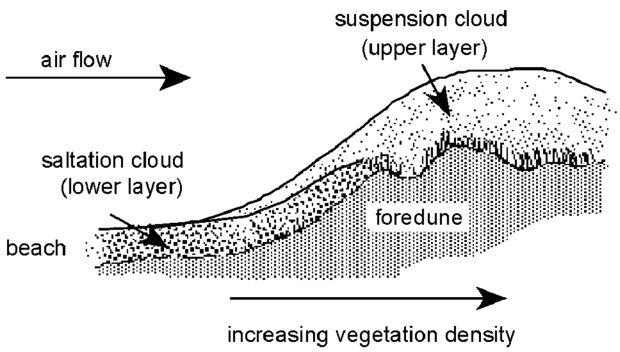

Figure 10. Transport mechanisms responsible for changing grain size during transport over a vegetated coastal foredune

suspension. However, because terminal falling velocities of grains are inversely proportional to their size, the effect is the same: smaller grains travel over a larger distance from the crest.

At the study site, grain lift-off and associated suspended transport appeared to occur when wind speed on the beach exceeded approximately 9 m s^{-1} (at 1 m above the surface). The stronger the gust, the larger the grains that will be suspended and the farther landward grains will be carried. Since moderate (average) gusts occur more often than very strong gusts, finer particles are more often in transport than coarse grains. As shown by Doeglas (1952) and Folk (1971), the foredune could be divided into zones receiving mixtures of different grain populations. Changes in grain-size distribution apparently can both be the result of preferential transport of fine grains (demixing from the source sediment point of view) and of mixing (deposit point of view) of (many) populations with different means.

CONCLUSIONS

Collection of sand in transport is difficult because of the disturbing effects of sand traps on the air flow. Our vertical traps, with a low efficiency, certainly will affect the grain size population of the sand that is trapped. However, since the observed trends are opposite to what is expected if they are mainly due to sand trap deficiency, we conclude that the efficiency of the traps does not affect the interpretation of the results.

Our results indicate that, even for a fine-grained, well sorted beach sediment, aeolian transport is selective. Transported beach and dune sediments, trapped during the same event, show differences in their grain-size distribution. Mean grain size decreases during landward transport by about $0{\cdot}25\varphi$. The decreased sorting of the transported sediments is believed to be the result of the narrow distribution and very well sorted source sediment.

Changes in grain distribution observed in the direction of transport are related to vertical changes within the sediment transport profiles. In the sediment profiles an upper and a lower transport layer are recognized, reflecting the operation of different transport mechanisms (Figure 10). In the lower layer the sand grains move in saltation. The importance of saltation declines during landward transport because of the increasing density of the vegetation, which causes most of the sand in transport to be deposited. In the upper layer, sand grains of any size are transported in either modified saltation or suspension without any interaction with the surface, driven by turbulent air movements, induced by changes in both roughness (vegetation) and topography. Landward of the foredune crest suspension transport becomes more important. The mechanism of deposition is comparable to the lee slope deposition model proposed by Anderson (1988) and McDonald and Anderson (1995).

The resemblance of sediment trapped at the windward side moving in the upper layer and the sediment trapped on the foredune, suggests that those grains which are ejected to greater heights by turbulent motions are finally deposited on and behind the foredune crest. Higher lift-off velocities and smaller fall velocities for small grains cause the fining of the sediment during landward transport.

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