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Patterns of sand transport on vegetated foredunes

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Abstract

The aeolian development of coastal foredunes is studied at two sites along the Dutch coast. Amounts of sand transport are measured in cross-sections over the foredunes, and changes in surface height are monitored. Sand transport decreases rapidly landward of the vegetation boundary. Near the dunefoot, changes in surface roughness and topography generate turbulence and upward flow, causing a small part of the sand to be transported in suspension. Patterns of transport are found to be closely related to air flow, which in turn is related to topography and vegetation density. With steeper topography, the amounts of sand transported landward from the dunefoot increase, if vegetation density is low. During oblique onshore winds, most of the sand accumulates at the dune front. During perpendicular onshore winds, a large proportion of the sand is deposited landward of the slope. When deflection of flow occurs, landward transport of sand is interrupted.

1. Introduction

Many studies have been conducted on transport rates in the beach environment, but relatively little is known of gradients in transport rates between beach and vegetated foredunes. Most studies indicate an exponential decrease in transport rates when the sand moves from an unvegetated beach into vegetated foredunes. However, little attention has been paid to the transport rate patterns and their relationship to local topography. According to Willetts (1989) these patterns are directly influenced by the dune shape. The spatial differences of transport rates on a dune result in changes in surface elevation. As a result, the dune either changes in shape, or in position.

Hesp (1983) found a dominant influence of vegetation on foredune formation in Australia. He concluded that density of the vegetation is more important than vegetation type; an increasing density produces an increase in roughness and, consequently, a decrease in wind speed near the surface. Below a critical level of vegetation density, the roughness elements act independently of each other within the flow, and the contribution of the culms to the total drag becomes small (Hesp, 1989). Saltation continues up to a certain distance within the vegetation, depending on vegetation density and wind speed (Hesp, 1983); when vegetation density is high, the foredune traps most of the incoming sand. This causes the dune to grow vertically in place, rather than through slipface deposition and migration (Goldsmith et al., 1990). Hesp (1989) discerns a positive feedback between vegetation and deposition: where sand deposition is greatest, plant growth is encouraged, resulting in an increased aerodynamic roughness and higher deposition.

Sarre (1989) and Carter et al. (1990) describe the development of coastal foredunes as a natural cycle of erosion by marine action and deposition by aeolian processes. Sarre concludes on the basis of 18

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months of field measurements in the foredunes of Braunton Burrows (Great Britain), that the pattern of erosion and accretion is strongly controlled by the vegetation cover and wind speed. Transport rates decrease exponentially with increasing distance from the dunefoot; negligible amounts of sand are transported inland beyond the dune ridge. The exponential decrease in relation to increasing vegetation density is supported by measurements of Wasson and Nanninga (1986) and Buckley (1987) and expressed in the relationships they propose between transport and vegetation density. Sarre (1989) found dune height to exert some influence on the deposition pattern: on higher dunes sand can move further inland, but also deposition at the dunefoot increases because of a stronger deceleration of the air flow. During the winter, sedimentation occurs over the complete foredune, whereas during summer, the sand mainly accumulates near the dunefoot. Sarre (1989) explains this by lower wind speeds in summer, but it might also be related to higher vegetation densities in summer.

This paper is part of a study on the aeolian development of coastal foredunes (Arens, 1994). It focuses on the sand transport rate patterns, observed at two different sites, during several events. Special attention is paid to the interaction of the aeolian transport processes with both topography and vegetation. Patterns of erosion and deposition are examined, together with their relation to wind flow characteristics.

2. Study areas

The study sites are situated in the Netherlands. Climate in the Netherlands is temperate humid, with strong seasonal contrasts. The stormy season, with strong winds from SW, W or NW usually extends from October to February, mostly alternated by cold periods often with moderate winds from easterly directions. Two topographically different sites were studied. The location of the sites is shown in Fig. 1, together with some profile data and estimated vegetation densities.

2.1. Site 1: Schiermonnikoog

Site 1 (illustrated by Fig. 2), on the Wadden island of Schiermonnikoog, is characterized by a very wide beach and a low foredune which was established between 1972 and 1988 following the erection of sand fences. The dunefoot is poorly vegetated (10%), mainly with sand couch (*Elymus farctus*) and marram grass (*Ammophila arenaria*). The top of the foredune is densely vegetated with

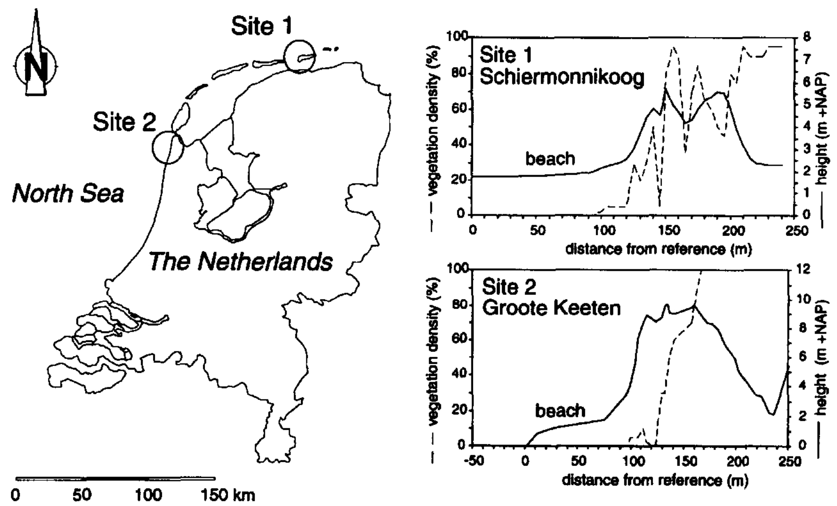

Fig. 1. Location of study areas, with indication of foredune profile and estimated vegetation densities.

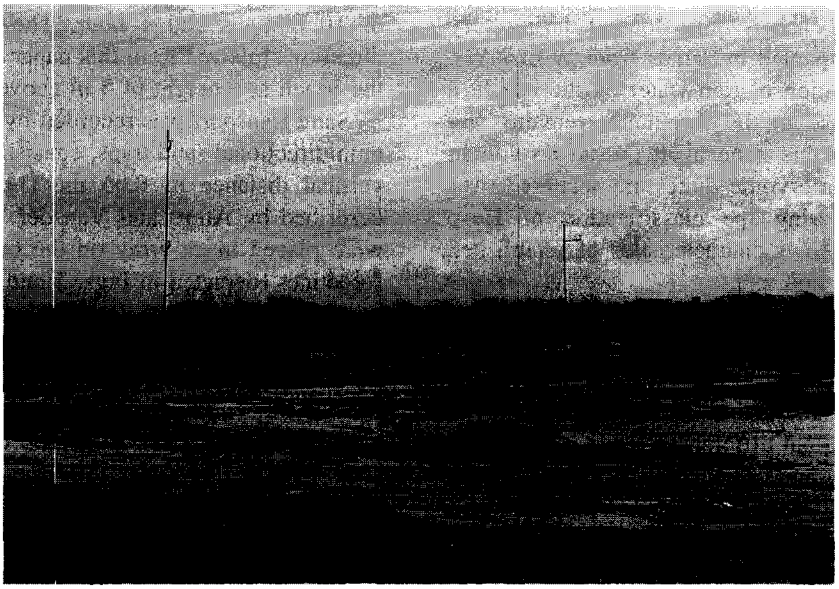

Fig. 2. Site 1, Schiermonnikoog, with installed sandtraps. View from the beach.

marram grass (95%). Since 1988 management has been limited to the planting of marram grass in blowouts (outside the measurement area). The foredunes are nearly two-dimensional, i.e. variation along-shore is small. The stoss slope is gradual (5–10°), without scarps. On top of the slope, a 10% increase of flow velocity was observed at a height of 2 m above the surface (Arens et al., 1995). Orientation is such that the frequent south-westerly winds blow parallel to the foredunes. The tidal range is

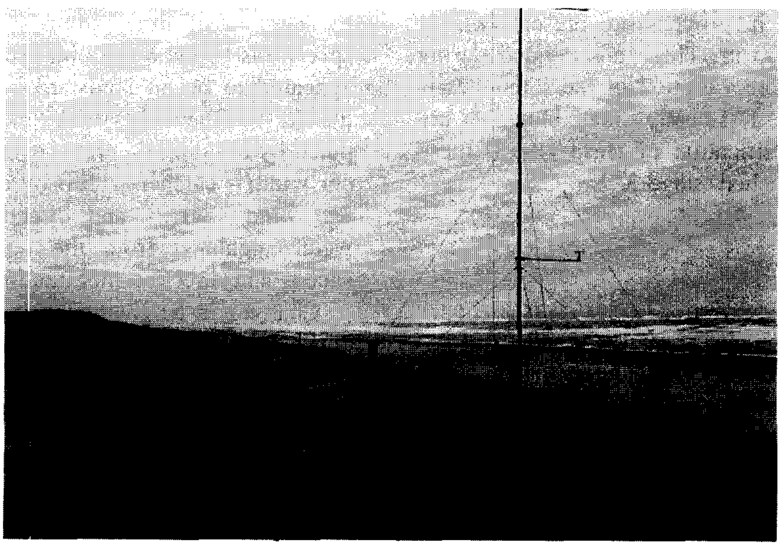

Fig. 3. Site 2, Groote Keeten. View from the foredune.

about 2 m. The beach is only flooded during very high tides (accompanied by winds from W or NW). Because of stagnation of rain water on the beach, a narrow zone, close to the foredunes, remains wet during winter. In this zone algal crusts develop in spring. Isolated embryonic dunes are scattered over the beach. Following the classification of Hesp (1988), the site shows characteristics of established foredunes stage 1 and 2.

2.2. Site 2: Groote Keeten

Site 2 (Fig. 3) differs in some respects from Site 1. The most important differences are in topography, vegetation density and coastal aspect. Orientation of the foredune is SSW–NNE. The site is situated in a very narrow dunefield (less than 400 m wide) on the Mainland coast, approximately 10 km south of Den Helder. Due to a large supply of sand, the height of the foredunes increased from +4.0 m to +10.5 m NAP between 1968 and 1991; in some years the increase was more than 0.5 m (Fig. 2 in Arens and Wiersma, 1994). The seaward slope is steep (20°, scarped in winter) and barely vegetated, mainly with sand couch. Vegetation density increases towards the top; dense marram grass vegetation is alternated by bare patches. Influence on the air flow is strong, with a maximum increase in flow velocity of 50%, at a height of 0.5 m above the surface (Arens et al., 1995). The beach is narrow and tidal difference is 1.5 m. On the beach, groynes are present, with a spacing of about 200 m. These are flooded during high tide. Along-shore variation of the foredunes is larger than for Site 1. Locally small blowouts are present. In the classification of Hesp (1988) these foredunes are established, stage 3.

3. Methods

Detailed measurements of meteorological and geomorphological variables were undertaken. The measuring periods extended from October 1990 to May 1991 on Site 1 and to February 1992 on Site 2. Meteorological variables measured were wind speed and direction, temperature (dry and wet bulb), rainfall and radiation. All meteorological variables were measured over 5 seconds and averaged over periods of 10 minutes and 1 hour. The wind speeds and directions referred to in this paper were measured on the beach at a height of 5 m above the surface

Sand transport was recorded by means of vertical omnidirectional sand traps, consisting of trays with a vertical distance of 0.05 m. This type of trap is described by Arens and Van der Lee (1995). Traps were placed in an array on the beach and over the foredunes (depicted in Figs. 2 and 3). On the beach, traps of 6 trays high (0.30 m) were deployed, to arrest the saltating sand (usually moving below 0.25 m). On the foredunes, the height of the traps depended on wind speed. During strong winds, sand was transported over a height of several meters above the surface. Therefore trap height ranged between 0.50 and 1.50 m. The sand content of all trays was weighed and totalled. Depending on wind strength and direction, traps were deployed for periods of time from 5 minutes to more than a day. Because of the sharp decrease of sand transport from beach to foredune, exposure on the beach was usually less than 1 hour, on the foredunes more than 3 hours. When the storage capacity of the lowest tray of the trap was exceeded, the amount of sand trapped was estimated from the amounts trapped in the upper trays, using the linear relationship between log(weight) and height. This method is described in more detail in Arens (1994, Chapter 4). Occasionally exposure time of traps placed on the foredune was more than a day. Exposure time was corrected for the amount of time within this period, that wind speed was below 8 m/s (at lower wind speeds there appeared to be no landward sand transport beyond the crest). Then, the sand flux per hour was computed by dividing the trapped weight (amount per 10 cm width = catcher width) by exposure time. Average wind velocity and direction during exposure were calculated from the hourly averaged wind speeds and direction measured on the beach.

Changes in height in the front zone of the foredunes were monitored by regular measurement of erosion pins. During sand transport events, changes were recorded daily. The number of pins used differed for the two locations: 13 arrays of 6 pins each for Schiermonnikoog, 12 arrays of 3 pins each for Groote Keeten.

For Schiermonnikoog three slightly different profiles were recorded: one profile for the meteorological masts, the second profile for the array of sand traps and the third profile for erosion pins.

4. Results

4.1. Evidence from Site 1, Schiermonnikoog

Between November 1990 and March 1991 hardly any transport of sand into the foredunes was observed. Even during gales, the transport of sand by wind was negligible. Occasionally during strong westerly winds, sand moved over the foredunes and partly covered the vegetation in the front zone. This occurred mostly in combination with rainfall. Under these conditions, the sand is deposited in a sheet over the wet marram grass, and after some days, gradually sinks down into the vegetation. Most of the deposition of sand from the beach in the foredunes occurred during strong northerly winds in April and May 1991. At first, much sand was deposited near the dunefoot. With increasing wind speed, this sand was eroded and deposited on the foredunes. When transport of sand from the beach ceased, also the lower part of the slope suffered from erosion. The largest amount of sand was deposited in a zone of increasing vegetation density. A triangular shaped dune was formed, with a gentle stoss slope and a typical steep slip face (Fig. 4), which exactly conforms to the description of Hesp (1983). At the end of the measuring period, the foredunes had gained about 3 m^3 m^{-1}, most of which was deposited in only a few days.

4.2. Measured fluxes

Fig. 5 displays the fluxes measured during a selection of 25 days. During offshore winds (Fig. 5a), transport starts at the seaward slope, within the vegetation. Transport on the slope is very small, but increases rapidly within some tens of metres. At a short distance from the dunefoot transport reaches equilibrium (no further increase); only a limited fetch is needed. With prolonged winds some erosion near the dunefoot may occur, but changes in height are slight.

During parallel winds (Fig. 5b) transport is mainly limited to the beach, but some transport on the foredune slope occurs during strong winds. Very high transport rates may be reached, but the impact on foredune development is small. Only at some locations which are scarcely vegetated, some land-

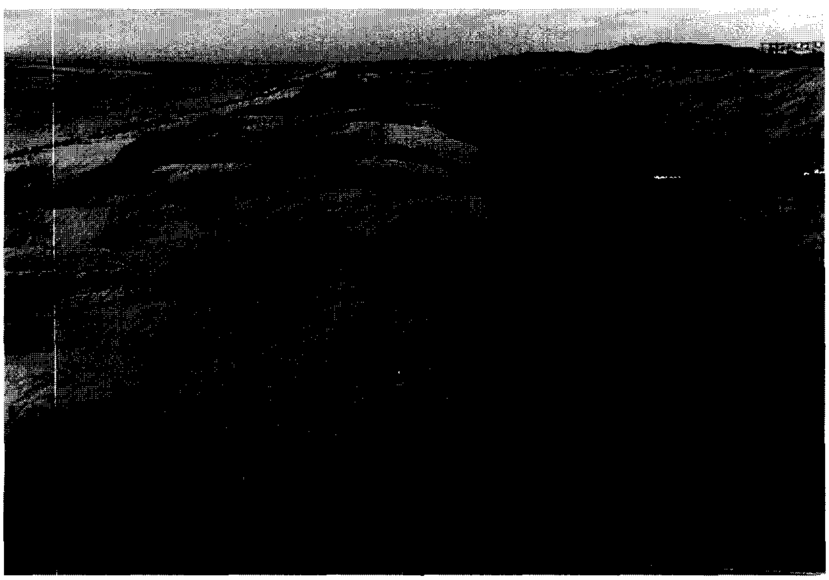

Fig. 4. Newly formed dunes on Schiermonnikoog after some days with strong onshore (northerly) winds.

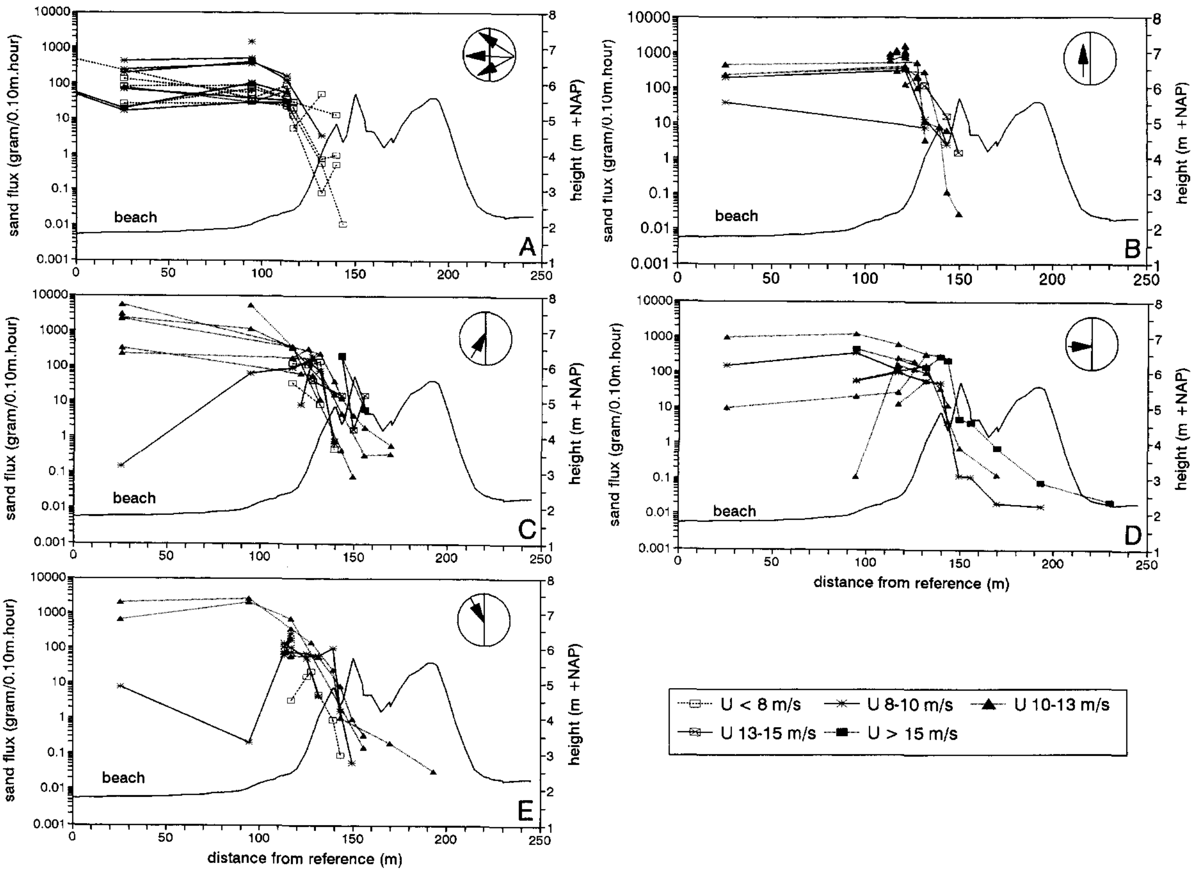

Fig. 5. Measured fluxes during parallel, onshore and offshore winds; Site 1, Schiermonnikoog. (a) offshore, 60–210°; (b) parallel, 210–240°; (c) oblique onshore; 240–285°; (d) perpendicular onshore, 285–345°; (e) oblique onshore, 345–030°.

ward transport may occur, but this is restricted to the very front zone. Occasionally, during strong parallel winds, the dunefoot is slightly eroded.

Oblique and perpendicular onshore winds are the most effective for foredune development. In both cases, the fluxes diminish exponentially when reaching the foredune, with increasing distance from the dunefoot. Most of the saltating sand is trapped in the vegetation. The gradient of change depends on wind speed: during low wind speeds the gradient is steeper than during high wind speeds (Fig. 5c, d and e). This is illustrated by Fig. 6, where fluxes are averaged for certain ranges of wind speed. When wind speed is lower than 10 m/s, most of the sand accumulates in front of the dunefoot, that is *before* reaching the vegetation boundary. When wind speed exceeds 10 m/s, the sand is able to pass the vegetation boundary. Then the decrease in flux between crest and lee of the dune is much more gentle than the decrease between dunefoot and crest. Perhaps these different trends are reflections of different transport mechanisms.

There are differences in transport patterns between perpendicular and oblique onshore winds. However, when fluxes are averaged, differences are small and within the range of standard deviations. Because of the small sample size and the importance of some exceptional days, it is not possible to statistically analyse the differences between perpendicular and oblique winds. Therefore, the different patterns are elucidated by two examples: one day (16 April 1991) with strong perpendicular onshore winds, which accounts for a large part of the total accumulation during the measuring period, and one day (1

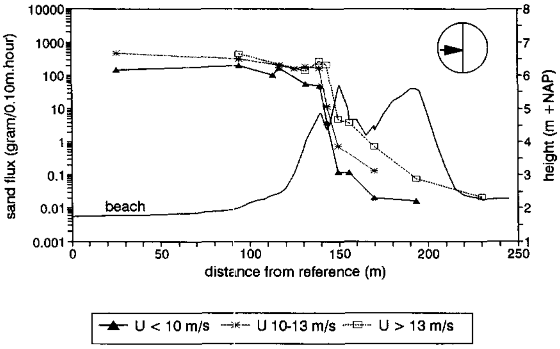

Fig. 6. Averaged fluxes during perpendicular onshore winds; Site 1, Schiermonnikoog.

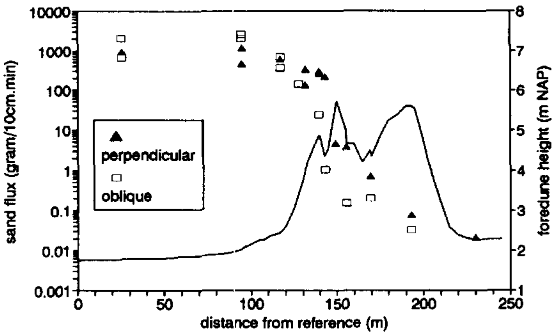

Fig. 7. Measured fluxes for 16 April (perpendicular winds, wind speed 12–15 m/s) and 1 May 1991 (oblique winds, wind speed 11 m/s).

May 1991) with oblique winds. Fig. 7 displays the measured fluxes. During oblique winds about 40% of the sand transferred from the beach passes the dunefoot, of which almost all is deposited on the slope. During perpendicular winds about 64% of the sand imported from the beach passes the dunefoot, of which only 40% is deposited on the slope. The rest is transported further landward. Relative changes are larger for oblique winds, which means that the decrease in flux with increasing distance from the beach is steeper.

It is evident from Fig. 7 that the input into the foredunes during perpendicular winds is much larger than during oblique winds. With oblique winds the sand mainly accumulates in the lower part of the profile. This is clearly reflected in the changes in height recorded between 16–17 April and 1–2 May (see below, Fig. 8).

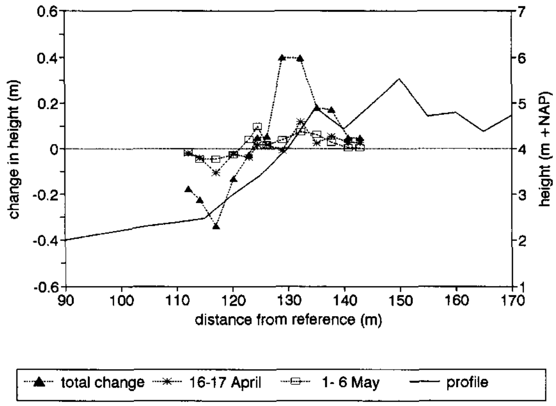

Fig. 8. Changes in height for two events in April and May 1991 (averaged per row) and total change during the period 23 Dec 1990 to 25 May 1991.

4.3. Changes in height

Fig. 8 shows the total changes in height during the period 23 December 1990 to 25 May 1991, as recorded with erosion pins. All changes are due to aeolian erosion or deposition, since there was hardly any marine erosion during this period. Although there is some scatter, the trends are consistent: erosion near the dunefoot, deposition at the top of the slope, mainly before the first crest. The zone of maximum deposition is where the maximum change in sand flux is measured.

4.4. Evidence from Site 2, Groote Keeten

Because of a steeper topography and lower roughness related to a scarce vegetation, the acceleration of the wind on the slope is more extreme in comparison to Site 1 (Arens et al., 1995). As a result, the amount of sand that can be transferred from the beach is larger. During onshore winds the acceleration on the seaward slope is large, causing the erosive capacity of the wind to increase. Because the front zone of the foredune is sparsely vegetated, this results in a redistribution of sand within the foredune. In contrast to Site 1, where most of the sand accumulated in a narrow ridge, sand is mainly deposited in sheets over the foredune, locally with a steep slip face. This is probably related to the irregular pattern of the vegetation (Hesp, 1983). Due to accelerations on the dune front and a low vegetation density, transport of sand on the foredune surface may occur, when the wind speed on the beach is below the critical threshold velocity. The steep transition from beach to foredune results in a large amount of deposition near the dunefoot during onshore winds with limited strength. In spring and summer the slope flattens. In the stormy season the slope is scarped again by marine erosion. This cyclic feature is common for coastal dunes (Sarre, 1989; Carter et al., 1990).

4.5. Measured fluxes

Fig. 9 illustrates the differences between fluxes during parallel and perpendicular onshore (Fig. 9a) and oblique onshore (Fig. 9b) winds. Differences are clearer than at Schiermonnikoog, which is probably the result of the steeper topography. The decrease in flux during strong oblique winds is less; a larger part of the sand reaches the top of the foredune. Between beach and dunefoot, the flux decreases slightly during oblique winds. Therefore, some accumulation of

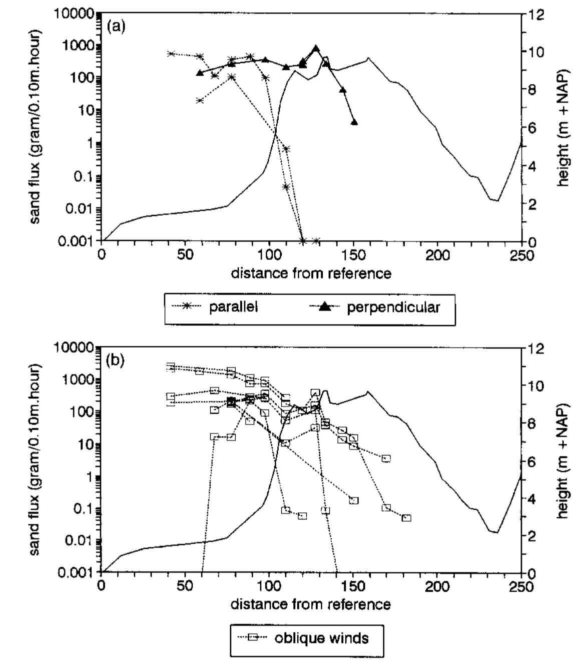

Fig. 9. Measured fluxes; Site 2, Groote Keeten. (a) parallel and onshore; (b) oblique-onshore.

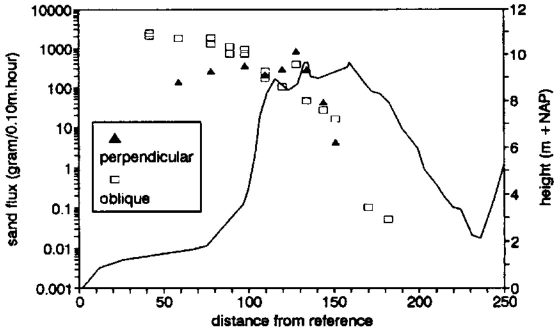

Fig. 10. Measured fluxes for 15 (perpendicular winds, wind speed 11 m/s) and 22 February 1992 (oblique winds, wind speed 13 m/s).

sand near the dunefoot will occur under most conditions. An increase in flux is observed at the top of the slope during strong winds. During perpendicular onshore winds, the fetch on the beach and therefore aeolian transport is limited. Because of an accelerating wind speed on the slope of the foredune, the erosivity of the wind increases. As the surface is scarcely vegetated, sand is taken up and transported further inland. In general, during strong perpendicular onshore winds, the top of the slope will erode, and sand is redistributed within the foredune. During strong oblique winds, there is a slight increase of the sand flux at the top of the slope. However, there is no evidence that this has resulted in erosion (see below).

The changes in flux during perpendicular and oblique onshore winds are illustrated by Fig. 10. In comparison to Site 1, the input into the foredune is much larger. In absolute terms, the amounts imported during oblique and perpendicular winds are comparable. However, in relative terms, the differences are more pronounced. During oblique winds about 45% of the sand imported from the beach passes the dunefoot, of which about 73% is deposited on the slope. During perpendicular winds transport increases from beach to foredune.

4.6. Changes in height

The differences in fluxes between oblique and perpendicular onshore winds are clearly illustrated by the resulting changes in height displayed in Fig. 11. Most of the changes in height resulted from the

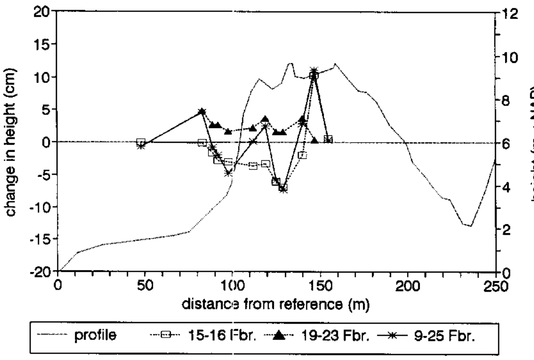

Fig. 11. Changes in height (averaged per row) for two events in February 1992 and change in height for the total period.

two days presented in Fig. 10. During perpendicular winds the front zone of the foredune is eroded (to more than 5 cm in one day). The sand accumulates further landward, where the vegetation density increases. During oblique winds, sand is imported from the beach, and accumulates in a wide range between dunefoot and top (accumulation between 2 and 5 cm).

5. Discussion

Sand on the beach is transported in saltation. In "pure" saltation (Jensen and Sørensen, 1983), the grain trajectories are determined by the average wind profile, whereas in "modified" saltation (Nalpanis, 1985), the trajectories are modified by the turbulent characteristics of the wind. However, most of the upward momentum of the grains is received from frequent impacts with the sand bed. Suspension is the movement of usually smaller grains, lifted from the surface by a vertical gust, and transported over longer distances, without any interaction with the sand bed. Anderson et al. (1991) presume a continuum of grain behaviour from pure saltation to prolonged suspension. When the sand moves to the foredune, changes in roughness and in topography generate turbulence, and therefore modify grain trajectories. Secondly, the presence of the dune forces the air flow to move upward. Near the topographic change, the average upward velocity of the wind may be larger than zero. During strong winds, vertical velocities exceed the settling velocities of sand grains. The lift-off of particles larger than 200 μm implies that the upward velocities are in the order of 1 m/s or larger. Small amounts of grains are taken up into the flow, and move with much larger grain trajectories. Without contact with the bed, they traverse a distance of some tens of metres beyond the dune crest. On top of the dune, the effects of the topographic change vanish, and grains gradually settle out at a certain distance, depending on wind speed. The strength of the upward flow increases for steeper slopes. For example, with reference to site 1, visual observations at nearby sites with a steep dune cliff of 1–2 m height, showed that with strong winds, a much denser sand cloud passed the dune crest than at the study site. Because of the movement in a jet-like flow, this special mode of suspension is termed jettation. This process, illustrated by Fig. 12, explains the movement of sand grains over steep slopes and densely vegetated surfaces. Observations of coarse suspended grains following the flow were also reported by De Ploey (1980) and Draga (1983). Jettation will only occur within a certain range of dune heights. Above a certain limit, deflection of the wind will prevent sand imported from the beach to reach the top of the foredune, in case of a vegetated slope. Possibly, this is the reason for a maximum height of vegetated foredunes. This is contrary to Ranwell (1972), Shepherd (1981, 1987) and Hesp and Thom (1990) who relate a maximum foredune

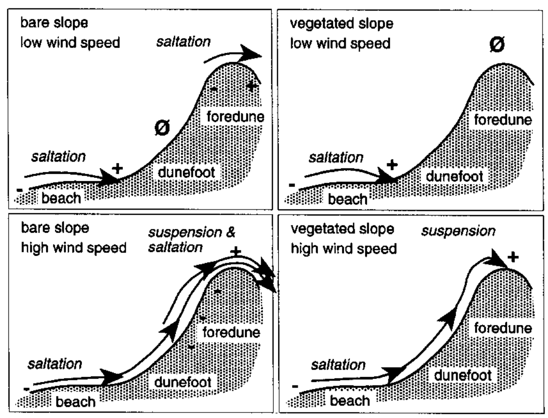

Fig. 12. Transport mechanisms for aeolian transport of sand over foredunes, for bare and vegetetated foredunes, with different combinations of wind speed (high–low). (+ indicates potential deposition, – indicates erosion; ∅ indicates no transport.)

height to an increased wind shear near the crest. Foredunes with a bare slope can reach heights of more than 100 m (examples are the Dune de Pilat in France and Rubjerg Knude in Denmark).

The sedimentation patterns on vegetated coastal foredunes are related to the patterns of transport rates. Steep gradients in transport rates result in thick deposits with a limited extent, while gentle gradients produce thin but widely extending deposits. Observations here for two sites with comparable vegetation but differences in topograpy and vegetation density, have indicated that this results in different morphology of deposits. Carter (1988) related differences in dune shapes, as observed by himself and Hesp (1983) to vegetation types (respectively *Spinifex* and *Ammophila*). However, it is more likely, that these are caused by locational differences like vegetation density.

The geographical orientation of the foredunes determines the effective wind climate, i.e. the distribution between onshore and offshore winds. Since only onshore winds are capable of moving sand into the foredunes, the coastal aspect is decisive for the conditions and frequency of dune formation. Secondly, this study has shown that oblique and perpendicular winds produce deposits in different parts of the foredune profile. Therefore, the geographical orientation of foredunes possibly has consequences for their morphology and sediment budget. For example, the highest foredunes in The Netherlands are situated on south-west facing coasts, where they experience the highest frequency of strong onshore winds.

6. Conclusions

Sand transport by wind on the beach is more than thousand times larger than the transport on the foredune. When the sand passes the partly vegetated dunefoot, most of the sand is deposited. This conforms with the observations of Hesp (1983, 1984, 1989), Gares (1987, 1990), Sarre (1989), Goldsmith et al. (1990), Carter and Wilson (1990), Davidson-Arnott and Law (1990) and Wal and McManus (1993). The landward decrease in flux is shown to depend on wind strength: low wind speeds result in a sharp decrease, high wind speeds in a more gentle decrease; during high wind speeds the sand is transported over a longer distance from the dunefoot than during low wind speeds. The landward decrease in transport is not linear. An initially strong decrease, between dune foot and crest is thought to be related to the saltation process. Between crest and back of the foredune, the content of suspended grains in the air decreases at a much slower rate, depending on the settling velocity of the grains.

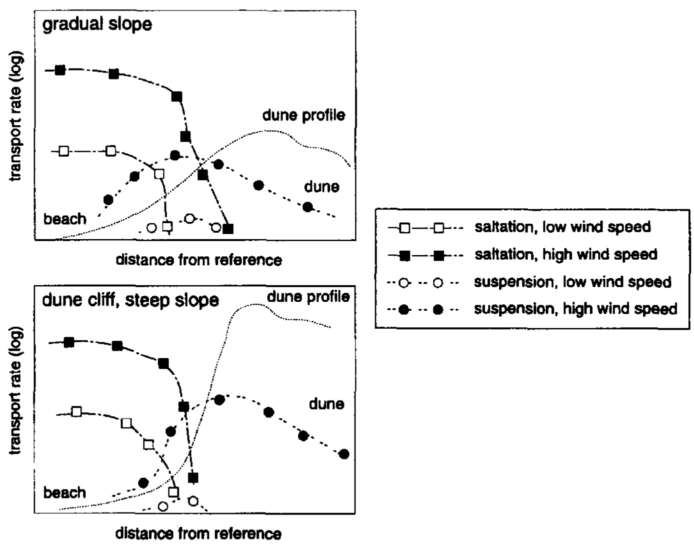

Fig. 13. Schematic model for the change in transport rates during landward transport.

The transport of fine and medium grained sand in suspension appears to be a common process, operating when wind speeds exceed a certain critical level. For Sites 1 and 2 the critical level ranged between 8 and 10 m/s, measured at the beach, at a height of 5 m above the surface. This mode of transport completes the general models of Hesp (1983) and Sarre (1989). The contribution of saltation and suspension is illustrated by Fig. 13. Saltating grains will only reach the foredune if the surface is scarcely vegetated. When the difference in height between beach and foredune becomes too large, the sand is not able to reach the foredune. Probably, the flow is deflected and the sand is not suspended, which could be the main reason for a maximum height of foredunes with a vegetated slope.

Due to differences in air flow, sedimentation patterns differ for oblique and for perpendicular onshore winds, as well as for sites with different topography. A steep topography in combination with a barely vegetated slope leads to large transport rates over the slope, and even an increase in transport upslope. When the wind blows oblique to the foredunes, the effective slope decreases and transport rates on the slope diminish; most of the sand is deposited in this part of the profile.

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