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AIR FLOW OVER FOREDUNES AND IMPLICATIONS FOR SAND TRANSPORT

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ABSTRACT

More than 4000 hourly wind profiles measured on three topographically different foredunes are analysed and discussed. Wind flow over the foredunes is studied by means of the relative wind speed: the ratio between wind speed at a certain location and the reference wind speed at the same height. Relative wind speeds appear to be independent of general wind speed but dependent on wind direction. For perpendicular onshore winds the flow over the foredune is accelerated due to topographic changes and decelerated due to changes in surface roughness. Accelerations dominate over decelerations on the seaward slope. The pattern of acceleration and deceleration in relation to wind direction is more or less comparable for different foredunes, but the magnitudes differ. An increase in foredune height from 6 to 10 m leads to an increase in speed-up near the top of the seaward slope from 110 to 150 per cent during onshore wind, but further increase of foredune height from 10 to 23 m appears to have little effect, due to increased roughness and deflection of flow.

Topography also influences the direction of the flow. Between beach and top, the flow deflects in the direction of the normal during onshore winds. During offshore winds the flow is deflected to the parallel. Near the dunefoot, deflection is always in the direction of the parallel, and increases with steeper topography. The maximum deflection near the dunefoot was 90°, over a 23 m high dune, observed during offshore winds.

Patterns of erosion and sedimentation resulting from winds from different directions can be explained by the observed accelerations and decelerations. Owing to speed-up on the seaward front of the foredune, sand transport capacity of the wind increases, which results in erosion if vegetation is absent. During strong onshore wind, sand is lifted near the dunefoot and moves over the foredune in suspension. During weaker winds, vertical wind velocities do not exceed fall velocities of the sand grains, and most of the sand is deposited near the dunefoot.

KEY WORDS air flow; relative wind speed; scaling; speed-up; roughness change; coastal foredunes; stability effects; aeolian processes; sand transport

INTRODUCTION

Dune formation in The Netherlands is a topic of particular interest, since coastal dunes are of vital importance with respect to sea defence. In order to be able to predict the effects of a rising sea level, processes that play a role in dune formation should be understood. The importance of aeolian processes for the coastal sediment budget is widely recognized. However, on the quantification of aeolian processes acting in the foredunes, little is known. Arens and Wiersma (1994) showed that the extent of aeolian processes differs

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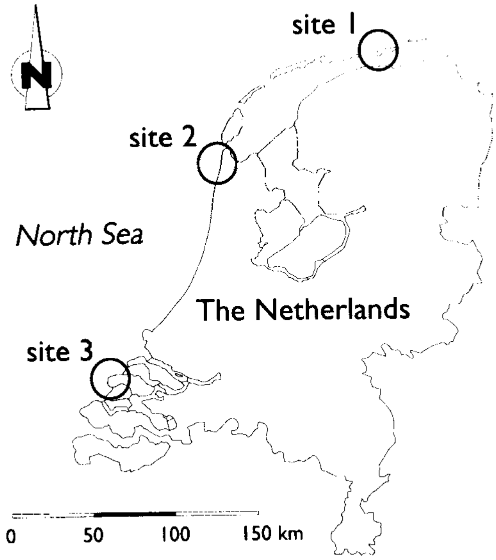

Figure 1. Location of sites

along the Dutch coast, depending on coastal dynamics, local characteristics (aspect, topography, vegetation density) and management. An increased knowledge of aeolian processes is also necessary for the 'natural management' of foredunes, which is presently a topic of interest in The Netherlands. In order to gain insight into the aeolian transport process, field measurements were carried out at different locations along the coast. Questions to be answered involved amounts of sand transported, relationships between the aeolian transport process and meteorological conditions, and environmental characteristics. In studies of aeolian transport, predictions often are made using theoretical transport equations (e.g. Svasek and Terwindt, 1974; Berg, 1983; Horikawa *et al.*, 1986; Sarre, 1988; Chapman, 1990) in which wind speeds or friction velocities have to be entered, mostly derived from measurements on the beach. However, several studies (Mulligan, 1988; Mikkelsen, 1989; Rasmussen, 1989) have proven that the use of beach-derived friction velocities can result in erroneous estimates of the sand transport onto the dunes. Wind speeds on the slope and top of foredunes differ considerably from those on the beach. For this reason it was felt necessary to make a careful analysis of the changes in the air flow which passes the foredunes. Because of the large influence of topography on the changes in air flow, measurements on three locations, differing in topography, were performed.

In this paper more than 4000 hourly wind profiles measured on three different sites are analysed and discussed. Reference is made to both field and simulation studies (either using wind tunnel models or numerical computer models).

STUDY AREAS

The study sites are situated in The Netherlands. The 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 alternating with cold periods often with moderate winds from easterly directions.

Three topographically different sites, located in the three main geomorphologic coastal regions (Wadden islands, Mainland coast and Zeeland estuaries), were studied. Locations of the sites are shown in Figure 1. The sites were selected according to several criteria, of which foredune height and geographical orientation were of major importance. Due to high recreational pressure along the Dutch coast, many sites with a

Table I. Environmental characteristics of the study sites

	Site 1 Schiermonnikoog	Site 2 Groote Keeten	Site 3 Nieuw-Haamstede
Aspect (degree)	314	286	298
Height above sea level (m)	6	10	23
Beach width (m)	600	80	150
Mean beach slope	1:500	1:40	1:75
Tidal difference (m)	2	1·5	2·5
Mean slope foredunes	1:12	1:4	1:5
Mean grain size (μm)	172	259	184
Vegetation (%)			
dunefoot	10	0	0
slope	50	10	>50
top	95	70	95
Management	presently none	planting of marram grass in blowouts	sand fence
Net sand budget ($m^3\ m^{-1}\ yr^{-1}$)	5	15	5
Variation			
perpendicular	small	small	large
parallel	small	large	moderate

scientific potential are not suitable for field measurements. Important environmental characteristics of all sites are presented in Table I. Figure 2 gives an impression of the sites.

Site 1: Schiermonnikoog

Site 1, on the Wadden island of Schiermonnikoog, is characterized by a very wide beach and a low, vegetated foredune which was established between 1972 and 1988 following the erection of sand fences. 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 orientation is such that they are parallel to the frequently blowing south-westerly winds. Tidal difference is 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.

Site 2: Groote Keeten

Site 2 is situated on the Mainland coast, approximately 10 km south of Den Helder. Due to a large (aeolian) supply of sand, the height of the foredunes increased from 4·0 to 10·5 m between 1968 and 1991; in some years the increase was more than 0·5 m. The seaward slope is steep and not vegetated. The beach is narrow and tidal difference is 1·5 m. Groynes are present on the beach, 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. Small blowouts are present locally.

Site 3: Nieuw-Haamstede

Site 3 is located on the former island of Schouwen. The height of the foredunes is more than 20 m above the beach surface, which is a common height for large parts of the Mainland coast and the Zeeland estuaries. The top of the foredune has been stable since 1965 and probably earlier The foredunes are irregular and densely vegetated. The beach is very narrow during high tide and wide during low tide. About 100 m to the south and to the north, pile rows are present. In front of the foredunes a series of low ridges have been established since 1980, using sand fences. The most seaward ridge is still covered with sand fences and marram grass.

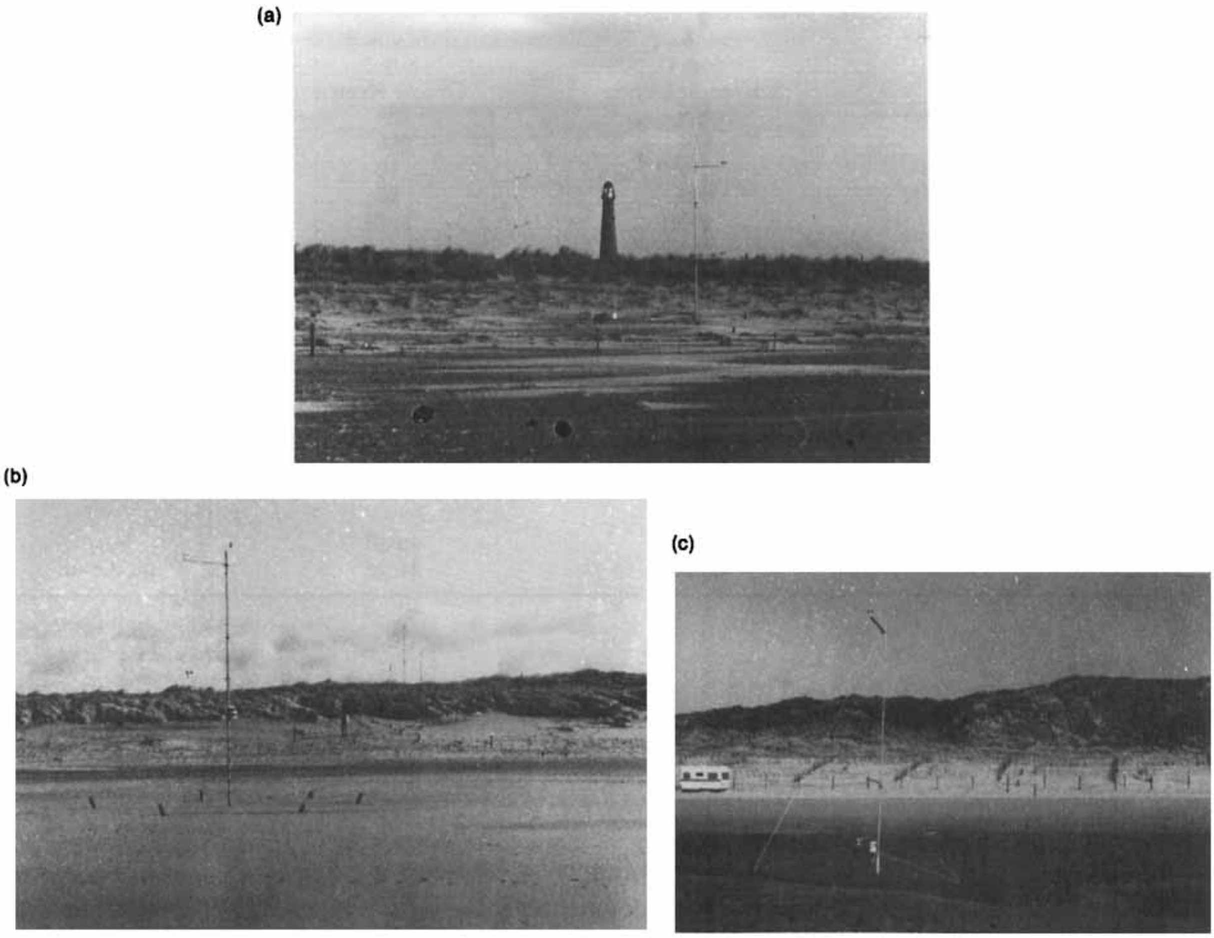

Figure 2. Photographs of the sites studied. (a) Site 1, Schiermonnikoog; (b) Site 2, Groote Keeten (Noord-Holland); (c) Site 3, Nieuw-Haamstede (Schouwen)

METHODS AND DATA MANAGEMENT

In The Netherlands, major aeolian events with respect to dune formation and sand transport take place during storms in the winter and spring season. Summer storms do occur occasionally, but their frequency is low (e.g. Wieringa and Rijkoort, 1981). Field measurements extended from October 1990 to May 1991 on site 1, and took place in February 1992 on site 2 and May 1992 on site 3. During the measurements on site 1, aeolian processes were studied extensively; measurements on the other sites were mainly to study differences in transport mechanisms due to topographical differences.

Field measurements were carried out using automatic meteorological equipment. Measurements of wind speed and wind direction, humidity, temperature, rainfall and radiation were performed along a line perpendicular to the foredunes. At certain places on the foredune (beach, dunefoot, slope, top, lee) masts were erected with cup-anemometers at several heights. The position of the instruments is illustrated in Figure 3.

Data acquisition and selection

Wind speeds were recorded over 5 s intervals, and averaged. For each 10 min and 1 h period, averages, maxima, minima and standard deviation were stored. In 10 min averages, variations of wind speeds due

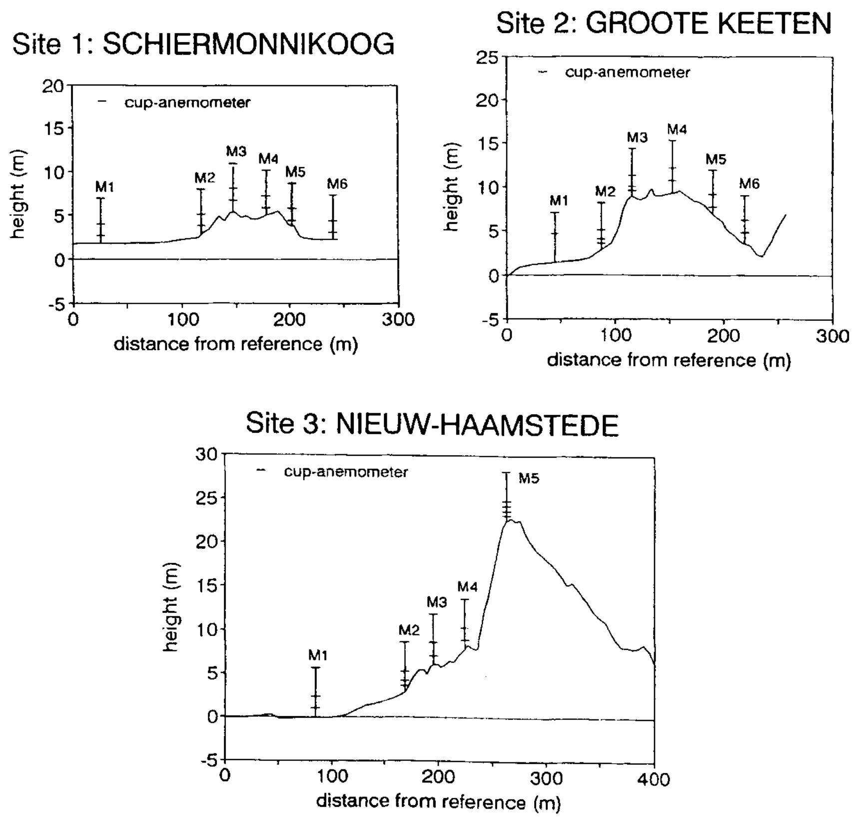

Figure 3. Arrangement of meteorological equipment

to turbulence are still present. To study equilibrium wind profiles, wind speeds should be averaged over a period of 30–60 min (Stull, 1988). For this reason only hourly averages are discussed here.

Wind direction, dry and wet bulb temperature (at 1 and 5·5 m height) and radiation were recorded instantaneously every 5 s. Also for these parameters, for every 10 min and 1 h interval, averages, standard deviations, maxima and minima were calculated and stored. Precipitation was measured using a 0·2 mm tipping bucket. Total amounts were sampled over 10 min and 1 h intervals.

Site 1: Schiermonnikoog. After removal of obvious measurement errors and of wind speeds below 1 m s^{-1} (measured on the beach at 0·8 m height), 4369 hourly arrays were left. Friction velocity and roughness length were calculated by means of linear regression between the wind speeds measured at three heights (0·78, 2·21 and 5·18 m above surface) on the beach and the logarithm of the height. Assuming a logarithmic wind profile:

$$U_z = \frac{U*}{\kappa} \ln \frac{z}{z_0} \tag{1}$$

where U_z is wind speed at height z and κ is von Karman's constant (0·41), and using wind speed as the dependent and the logarithm of the height as the independent variable, friction velocity $U*$ and roughness length z_0 can be calculated from the regression parameters a (slope) and b (offset) by:

$$U* = a\kappa \tag{2}$$

and

$$z_0 = e^{-\kappa b/U*} \tag{3}$$

Table II. Number of used data points (hourly averages) per cup-anemometer. (Cam[i–j] is cup-anemometer j in mast i, 1 is at the top)

Cam [i–j]	Site 1	Site 2	Site 3	Cam [i–j]	Site 1	Site 2	Site 3	Cam [i–j]	Site 1	Site 2	Site 3
1–1	3923	392	9	3–1	2942	391	229	5–1	3429	391	227
1–2	3923	392	9	3–2	2010	391	229	5–2	3353	391	231
1–3	3923	392	9	3–3	2883	391	229	5–3	3033	391	231
2–1	3096	392	233	3–4	–	355	–	5–4	–	–	231
2–2	1862	392	233	4–1	3765	391	211	5–5	–	–	231
2–3	2976	392	233	4–2	3738	391	211	6–1	2084	391	–
2–4	–	392	233	4–3	3508	391	211	6–2	2055	391	–
								6–3	1533	391	–

Wind profiles on the beach for which linear regression resulted in $R^2 < 0{\cdot}96$ were deleted (365 hourly arrays). These profiles were either wrong by errors in measurement, or not in equilibrium with the surface (often during offshore winds). The value of 0·96 is based on the analysis of stability effects and will be explained below.

Owing to instrumental problems with some of the cup-anemometers, wind speeds above $7\,\mathrm{m\,s^{-1}}$ were not reliable from October 1990 until February 1991 for masts 2, 3 and 6. In the same period, rotation of the masts during very strong winds resulted in erroneous measurements of wind direction. After correction, 3923 arrays of hourly measurements were left for analysis.

Site 2: Groote Keeten. All hourly arrays for which measurements on the beach were available (392) were used. Owing to the risk of damage during high water, wind speeds were recorded only at two heights (2·94 and 5·33 m). Selection of wind profiles on the basis of the coefficient of explanation (R^2) was not possible.

Site 3: Nieuw-Haamstede. For site 3, wind profiles on the beach were measured only occasionally. Permanent measurements on the beach were not possible, because during high tide almost the whole beach was flooded. Occasionally a mast was erected on the beach for short term measurements. Consequently, only a few wind profiles are available, with a limited variety in wind direction. At wind speeds below $3\,\mathrm{m\,s^{-1}}$ (measured in the top of mast 2), relationships between wind profiles measured over the foredunes were not clear. For this reason, arrays for which the wind speed at the top of mast 2 was below $3\,\mathrm{m\,s^{-1}}$, were deleted (120 hourly arrays). The number of data points available after selection is shown in Table II.

Reference wind speeds

To study the changes in the wind profile during passage over the foredunes, wind profiles measured over the foredunes were compared to a reference wind profile. Ideally this is a wind profile measured on a flat and homogeneous beach at a certain distance upwind of the foredunes, such that the disturbing influence of the foredunes is absent. If a logarithmic wind profile is assumed and friction velocity and roughness length are known, a reference velocity U_{REFz} can be calculated for every height z by:

$$U_{\mathrm{REFz}} = \frac{U*}{\kappa} \ln \frac{z}{z_0} \tag{4}$$

The procedure for obtaining $U*$ and z_0 differs for the three locations and is explained below.

For site 1, the distance between mast 1 and the dunefoot is 90 m. In this case, measurements in mast 1 are suitable as reference wind speeds. $U*$ and z_0 are derived from linear regression (Equations 1–3).

For site 2, wind speeds at mast 1 with onshore wind are possibly influenced by the foredunes, owing to the narrowness of the beach and the height of the foredunes. However, these measurements are most suitable for reference wind speeds. $U*$ and z_0 are derived from linear regression through two points.

For site 3, measurements in mast 2 were used as a reference. Because the wind profile in mast 2 is certainly influenced by the presence of the foredunes, a hypothetical profile REF′ was calculated, using the wind speed measured in the top of mast 2 (5·80 m above the surface) and the roughness length determined on the beach (10^{-3} m). From analysis of beach measurements and the results of sites 1 and 2, it was concluded that in the case of onshore winds the wind speed in mast 2 equals between 88 and 92 per cent of the wind speed on the beach. During offshore winds the disturbance of the wind profile in mast 2 is much larger (lee effects), and in that case comparing wind profiles to profile REF′ gives only relative information. $U*$ and z_0 are calculated by:

$$U* = \frac{(1/0{\cdot}90)U_{\mathrm{CAM2-1}}\kappa}{\ln\dfrac{z_{\mathrm{CAM2-1}}}{z_0}} \tag{5}$$

and

$$z_0 = 10^{-3}\mathrm{m} \tag{6}$$

where $U_{\mathrm{CAM2-1}}$ is the wind velocity measured by cup-anemometer 1 in mast 2 at a height $z_{\mathrm{CAM2-1}}$ above the surface.

Effects of stability

The reference wind profiles were not corrected for stability effects due to thermal stratification. The influence of stability effects can be calculated using Equation 7 (e.g. Rasmussen, 1989; van Boxel *et al.*, 1989):

$$U_z = \frac{U*}{\kappa}\left(\ln\frac{z}{z_0} - \Psi_{\mathrm{m}}\right) \tag{7}$$

where Ψ_{m} is a dimensionless stability parameter, depending on height and the Obukhov length L (Obukhov, 1946). For unstable conditions ($L < 0$), Ψ_{m} can be calculated by (Paulson, 1970; Wieringa, 1980):

$$\Psi_{\mathrm{m}} = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\arctan(x) + \frac{\pi}{2} \tag{8}$$

with

$$x = \left(1 - \frac{22z}{L}\right)^{1/4} \tag{9}$$

For stable conditions ($L > 0$), Ψ_{m} can be calculated by (Webb, 1970; Wieringa, 1980):

$$\Psi_{\mathrm{m}} = -6{\cdot}9\left(\frac{z}{L}\right) \tag{10}$$

During stable and unstable conditions, calculation of the friction velocity and roughness length by means of linear regression leads to unrealistic values. The roughness length $z_{0\mathrm{LR}}$ determined by linear regression shows a diurnal variation, which is related to the temperature gradient on the beach ($T_{\mathrm{bottom}} - T_{\mathrm{top}}$, Figure 4). Linearity of the profile is not indicative of stability (van Kaam-Peters, 1992). Even if profiles are selected for which R^2 is larger than 0·9999, the diurnal variation in $z_{0\mathrm{LR}}$ is present. Using Equation 4, it can be calculated that for hypothetical profiles, with data points at 0·8, 2·0 and 5·0 m height, under very unstable conditions (Obukhov length $L = -5$ m) R^2 is larger than 0·995, whereas under very stable conditions ($L = 2$ m) R^2 is larger than 0·96 (for an example, see Figure 5). For this reason it is believed that when $R^2 < 0{\cdot}96$, this is not the result of stability effects. Probably these profiles are either erroneous or not in equilibrium with the surface.

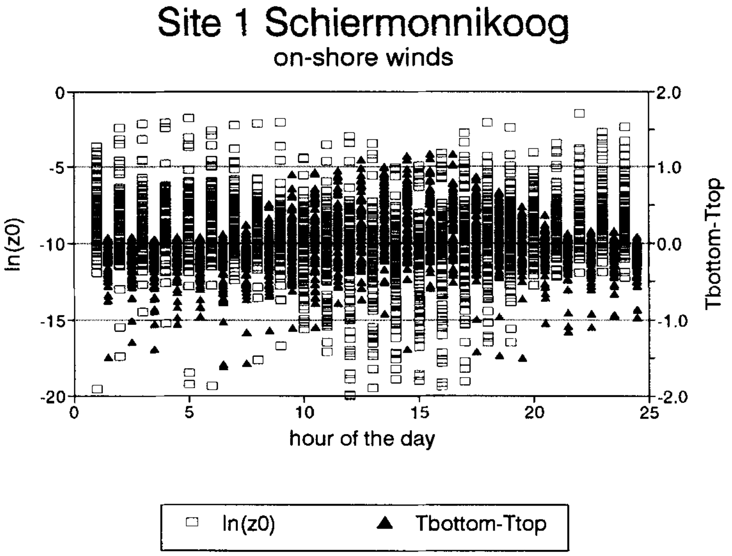

Figure 4. Diurnal variation in z_{0LR} and temperature gradient

Calculation of relative wind speeds

Relative wind speeds provide insight into changes in the air flow while passing the foredunes. Relative wind speed is defined as the ratio between a wind speed measured at a certain height at some location and the reference wind speed at the same height:

$$U_{RELz} = \frac{U_z}{U_{REFz}} \tag{11}$$

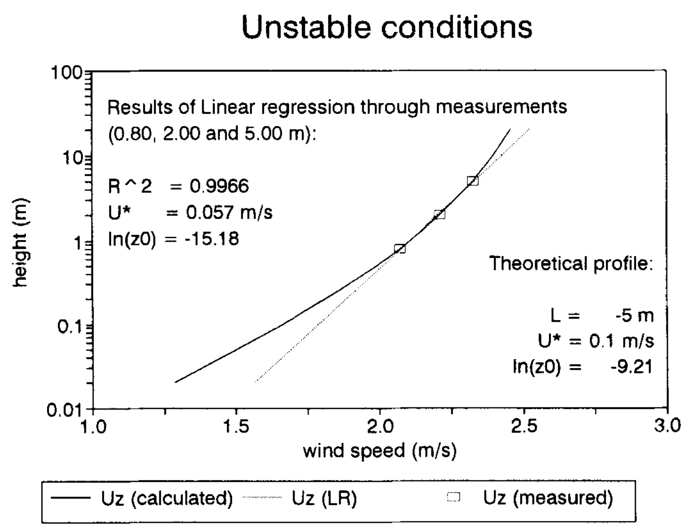

Figure 5. Stability effects on a wind profile and calculation of roughness length z_0 and friction velocity $U*$, when using linear regression.

Relative wind speeds greater than 1 indicate acceleration, and those less than 1 deceleration. Relative wind speeds change with wind direction. For reasons of presentation, relative wind speeds were averaged over ranges in wind direction of 10°.

Although neglect of stability effects leads to unrealistic values of $U*$ and z_0 when the thermal stratification deviates from neutral, the errors in the calculated relative velocities are less than 2 per cent for the range of heights which is used (van Kaam-Peters, 1992). For larger or smaller heights the deviation will increase, which is illustrated by Figure 5. For example, if a reference wind speed is computed at 0·15 m, the deviation is more than 4 per cent. Since these deviations are small, between 0·50 and 6·0 m, the time-consuming correction for stability effects was not executed.

RESULTS

When the air passes the foredunes, the wind profile, which was in equilibrium with the beach surface, will be disturbed. Disturbances are caused by both topographical and roughness changes. The change in topography is expected to cause accelerations on the seaward slope and top and decelerations near the dunefoot and on the lee slope. The landward increase in roughness is expected to cause decelerations. The combined effects of changes in topography and roughness are evaluated below using relative wind speeds, i.e. the ratio between a wind speed measured at a certain height at some location and the reference wind speed at the same height.

Relative wind speeds

Figure 6 shows relative wind speeds for mast 4, site 1, to illustrate the clear relationship between relative wind speed and wind direction. More than 3500 data points per cup-anemometer are presented. Relative wind speed appears to be independent of wind speed itself. Scaling of the wind speed with the reference velocity was very effective. Wind speed at any location is directly proportional to the reference wind speed, implying that the processes leading to acceleration or deceleration do not change fundamentally with wind speed. For site 1, masts 3 and 4, a very weak (but statistically significant) relationship was found between relative wind speed and reference wind speed. This is believed to be a result of a decrease in roughness length when strong winds cause the marram grass to bend.

Figure 7 presents mean relative wind speeds versus wind direction for all masts. For the three sites, the wind direction is oriented in such a way that 0° is perpendicular onshore. For all profiles the variation (standard deviation) increases from top to bottom. For sites 1 and 2 masts were positioned almost identically (Figure 3).

The curves for site 1 are smooth and standard deviations are low, even for offshore winds. For sites 2 and 3 the data points available are not equally spread over all wind directions; for site 2 most points are available in the range between 135 and 285° while for site 3 most points are available in ranges 355 to 65° and 185 to 255°.

The blocking effect of the foredunes causes a deceleration of the wind speed in mast 2 to *c*. 90 per cent of its original value (Figure 7). This deceleration is slightly higher when the wind direction is perpendicular to the foredunes. For parallel winds the relative wind speed increases from top to bottom for both sites 1 and 2.

On top of the seaward slope (mast 3, sites 1 and 2; mast 5, site 3) the wind speed increases during onshore winds. At all levels the relative wind speed exceeds 1, except for the lowest cup-anemometer in site 1 (Figure 7). For site 1, speed-up is maximal between 1 and 2 m above the surface. For site 2 the maximum is closer to the surface, at approximately 0·80 m. This is probably due to the smaller roughness of the seaward slope at site 2, since this slope is scarcely vegetated. For site 1, relative wind speeds decrease to less than 1 when the wind direction changes from perpendicular to parallel. For site 2 the pattern is comparable, but for parallel winds the flow at mast 2 is not decelerated. For perpendicular wind, accelerating effects due to topography are stronger than decelerating effects due to an increased roughness. For parallel winds, the fetch over the foredune is so long that the wind profile is more or less in equilibrium with the foredune surface. In the latter case, differences in wind speed between masts will be due to differences in surface roughness.

Relative wind speeds decrease from top to bottom. As the roughness of the scarcely vegetated foredune of site 2 is smaller than the roughness of the more densely vegetated foredune of site 1, parallel winds are less decelerated in site 2 than in site 1 (Figure 7). Speed-up near the top of the upwind slope (mast 5) on site 3 is

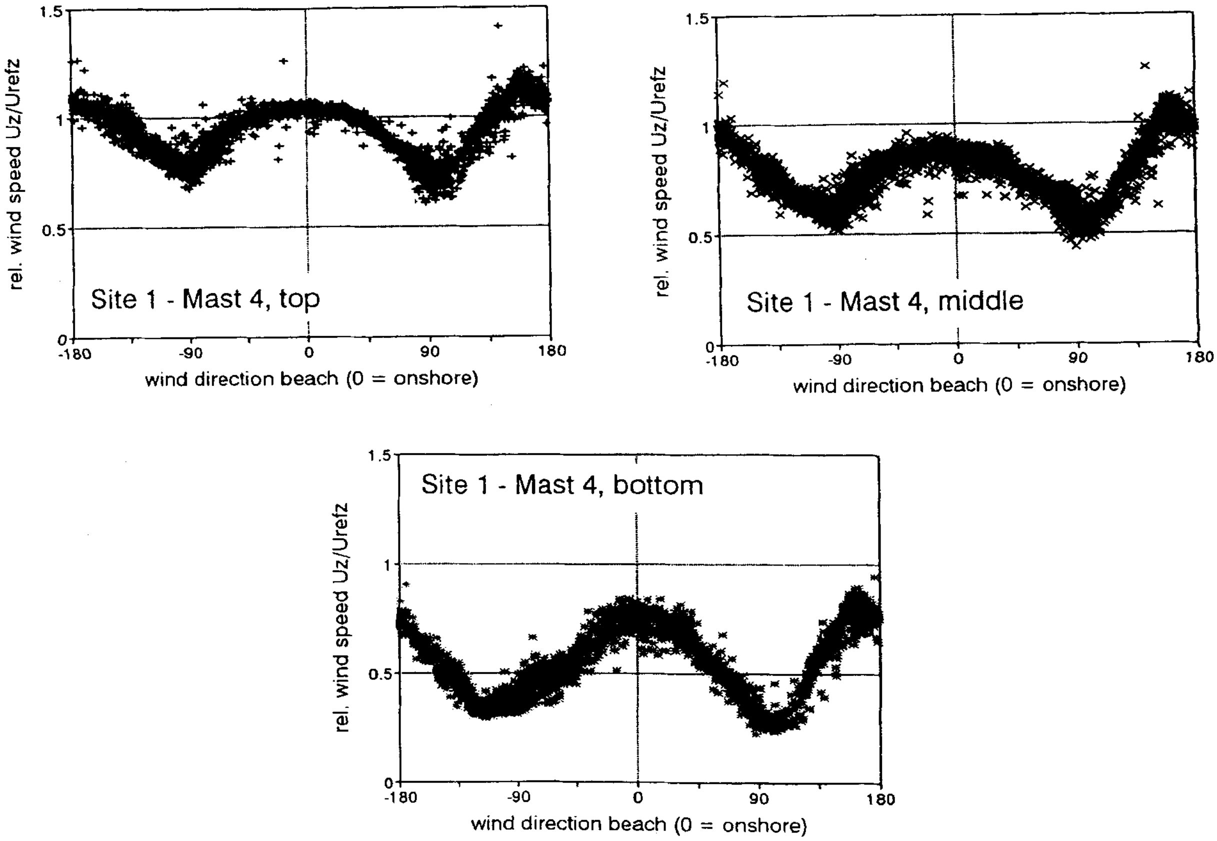

Figure 6. Relative wind speeds for mast 4, site 1

less than expected with regard to steepness and height of the foredune, which is almost double the height of site 2. The magnitude of speed-up is of the same order. Probably this is related to the upwind roughness (presence of fences and dense vegetation), but another possibility is that the height of the foredune in combination with the convex coastline forces the flow to deflect, leading to three-dimensional flow. Relationships between wind direction and relative wind speeds are symmetrical, especially at the top of the masts.

The differences between relative wind speeds in mast 3 for sites 1 and 3 indicate that relative wind speeds are influenced by both the upwind and downwind topography. While the variation with wind direction is very pronounced on site 1, it is almost absent on site 3 (Figure 7). This must be related to the presence of the high dune in the lee of mast 3 on site 3, since the upwind topography and roughness for both sites are almost identical. Possibly the effect is caused by the deflection of the flow to the parallel in front of the high dune.

The position of mast 4 on site 3 is not comparable to any of the other masts. Wind speed is decelerated and deceleration increases from top to bottom (Figure 7). Possibly this is the result of an upstream vortex, but no wind direction measurements at this position were available to verify this hypothesis. Also, for this mast, the absence of variation with wind direction is remarkable. This is probably the result of the reference wind speed (top of mast 2). A deceleration in the top of mast 2 of 90 per cent is assumed, irrespective of wind direction. However, relative wind speeds for mast 2 at sites 1 and 2 indicate a stronger deceleration during offshore winds. For site 3, this deceleration will be even stronger due to the height of the foredune. Therefore, lower relative wind speeds in masts 2, 3 and 4 (than shown in Figure 7) are expected during offshore winds.

For sites 1 and 2, the wind speed in mast 4 is accelerated at the top of the mast and decelerated near the surface (Figure 7). The speed-up in the top is caused by the topography, while the deceleration near the

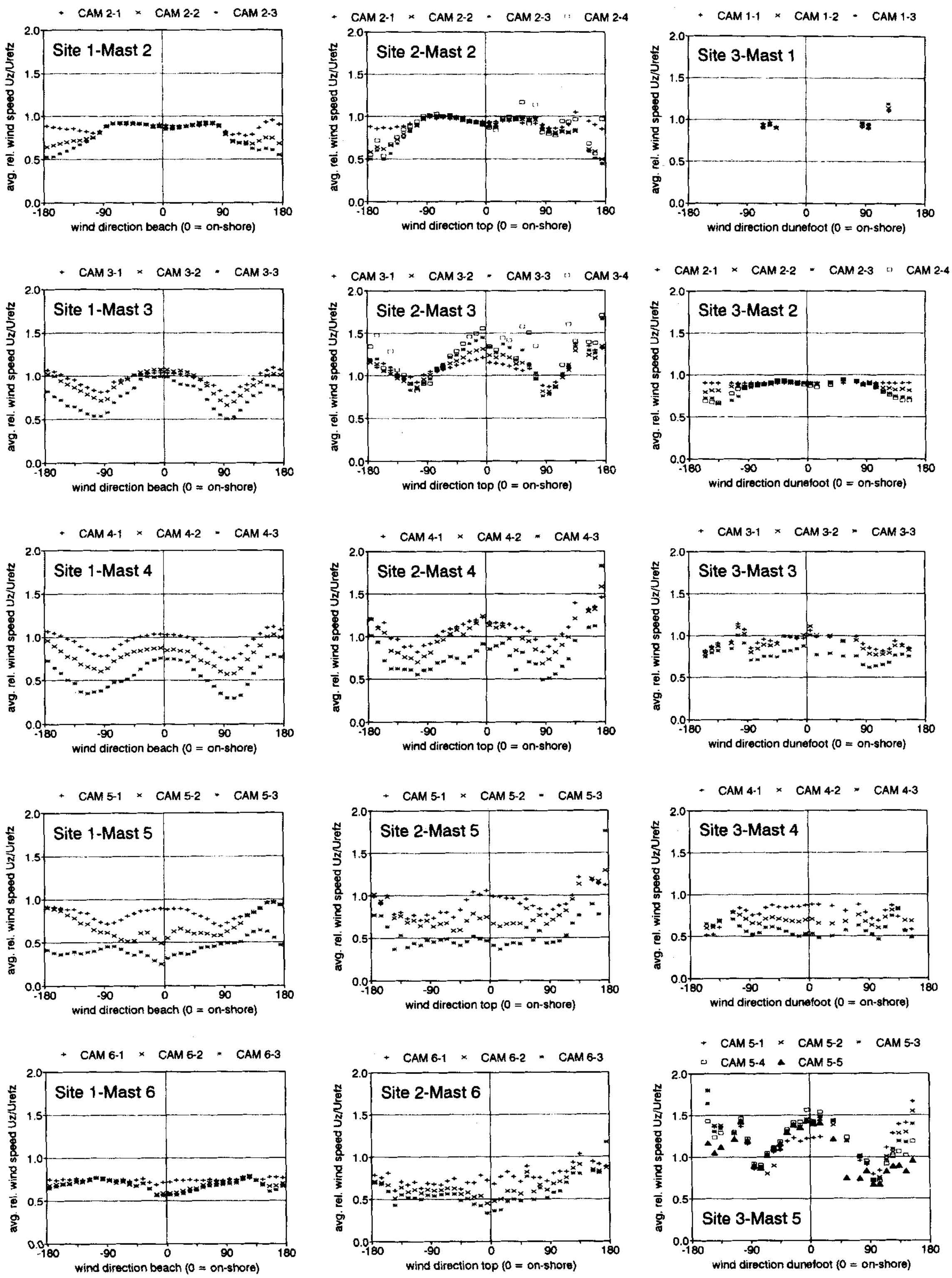

Figure 7. Relative wind speeds versus wind direction, for all masts at all sites

bottom is the result of increased roughness. For site 2 the pattern is more irregular than for site 1, probably because of the lower number of measurements. It is remarkable that for site 1 the wind directions at which the minimum relative wind speeds occur change from top to bottom. For site 2, minima occur at the same wind directions. The reason for this is not clear.

Mast 5 for both sites 1 and 2 is situated on the lee slope of the foredune. The relationship between wind direction and relative wind speed becomes more irregular due to an increasing irregularity of the topography, but this is mainly visible close to the surface. In the lower part of the profile wind speeds are decelerated to less than 50 per cent. There is a very distinct minimum in relative wind speed at $-5°$ (site 1) and 15° (site 2), which might be related to the occurrence of lee vortices.

Mast 6 for site 1 is situated in a dune valley. In the top of mast 6 relative wind speed is independent of wind direction. For parallel winds the wind profile is in equilibrium with the valley floor, and influence of the dune topography is limited. At all levels relative wind speed is approximately 0·75, decreasing for perpendicular winds in the lower part of the profile to about 0·6.

In summary, maximum relative wind speeds are observed during perpendicular winds, near the top of the seaward slope. The level of maximum speed-up depends on surface roughness; it occurs closer to the surface, when the slope is scarcely vegetated.

Relative wind profiles

Figure 8 displays the relative wind profiles for perpendicular and oblique (angle 60° to the normal) winds. The y-axis in Figure 8 represents the reference profile (straight line, relative wind speed = 1 at all heights, by definition).

For perpendicular onshore winds on site 2, the speed-up in mast 3 is much more pronounced than on site 1 and its maximum is closer to the surface (Figure 8a). The maximum may even occur closer to the surface than the lowest cup-anemometer (0·8 m). In mast 5 on site 3, which is situated in a similar position, the maximum occurs at *c.* 1 m above the surface and is of the same magnitude. For mast 4 on site 1, a speed-up is observed only at the top of the mast, while on site 2 a deceleration is observed only near the surface. For mast 5, profiles for sites 1 and 2 are comparable. The differences are in a small speed-up at the top of the mast on site 2 and a stronger deceleration on site 1. For mast 6 the deceleration is stronger on site 2, but here this mast is positioned on the lee slope.

When wind direction changes from perpendicular to oblique, accelerations gradually change into decelerations, but the shape of the relative wind profiles does not change appreciably (Figure 8b). For mast 2 on sites 1 and 3, differences between perpendicular oblique winds are small. On site 2 (low roughness) the relative wind profile deviates only slightly from the reference profile. At mast 3, flow is decelerated at all levels on sites 1 and 3. Only for site 2 is a small speed-up observed, but the maximum speed-up occurs at an elevation higher than for perpendicular winds. At mast 4 on site 1, flow is strongly decelerated near the surface. Also on site 2 flow is decelerated; only at the top of the mast is a small speed-up observed. At masts 5 and 6 on sites 1 and 2, flow is decelerated less than in the case of perpendicular winds, possibly related to the absence of lee vortices with oblique winds. In mast 5 on site 3, speed-up with oblique winds is small.

Speed-up factors

In order to estimate the potential sand transport, magnitude of the maximum wind speed-up and height at which it occurs are important. Of course, speed-up at heights which will never be reached by the sand grains are irrelevant for the prediction of sand transport. The maximum wind speed-up can be estimated by (Jackson and Hunt, 1975):

$$\Delta S_{\max} = 2\frac{h}{L} \qquad (12)$$

with $\Delta S_{\max}$ = maximum relative wind speed minus 1, h = height of the foredune and L = length scale of the dune.

Originally, Equation 12 was set up for symmetrical hills with slopes not steep enough to establish separation (Finnigan, 1988), and without roughness changes. L is usually defined as the distance between the crest

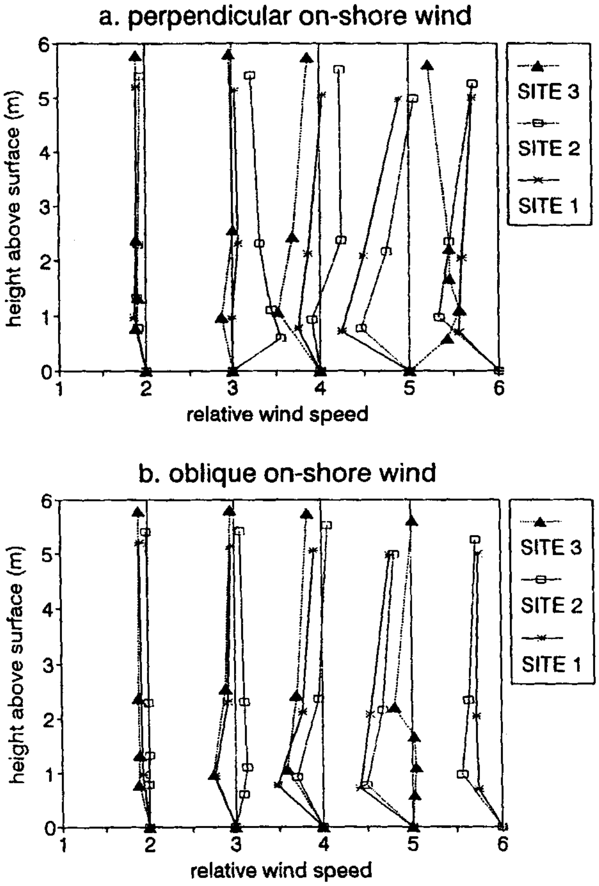

Figure 8. Relative wind profiles for (a) perpendicular and (b) oblique (60° to the normal) winds. The y-axis represents the reference profile (straight line, relative wind speed = 1 at all heights, by definition). For all subsequent masts relative wind speeds are increased by 1, so vertical grid lines represent relative wind speeds of 1 and minor ticks to the left and right represent relative wind speeds of 0·5 and 1·5, respectively

and half height (L_1), but could also be defined as the half distance between crest and dunefoot (L_2), which has considerable consequences for the predicted speed-up. In Table III, estimations of the maximum speed-up for all sites are given, using both definitions of L.

Equation 12 is valid only if the maximum height of the hill is much smaller than the length scale (i.e. $h/L < 0{\cdot}05$; Jackson and Hunt, 1975). A requirement for the length scale is $10^2\,\mathrm{m} < L < 10^4\,\mathrm{m}$. If the hill

Table III. Estimated (according to Jackson and Hunt, 1975) and observed maximum speed-up factors

	h	L_1	L_2	ΔS_{max1}	ΔS_{max2}	ΔS_{maxOBS}
Site 1	3.2	23.5	25.0	0.28	0.25	0.11
Site 2	7.8	32.0	30.0	0.49	0.52	0.55
Site 3	19.9	24.0	49.5	1.66	0.80	0.57

L_1, distance between crest and half-height (Jackson and Hunt, 1975)
L_2, half-distance between crest and dunefoot (half-upwind width)
$\Delta S_{max1,2}$, predicted maximum speed-up, using $L_{1,2}$
ΔS_{maxOBS}, observed maximum speed-up

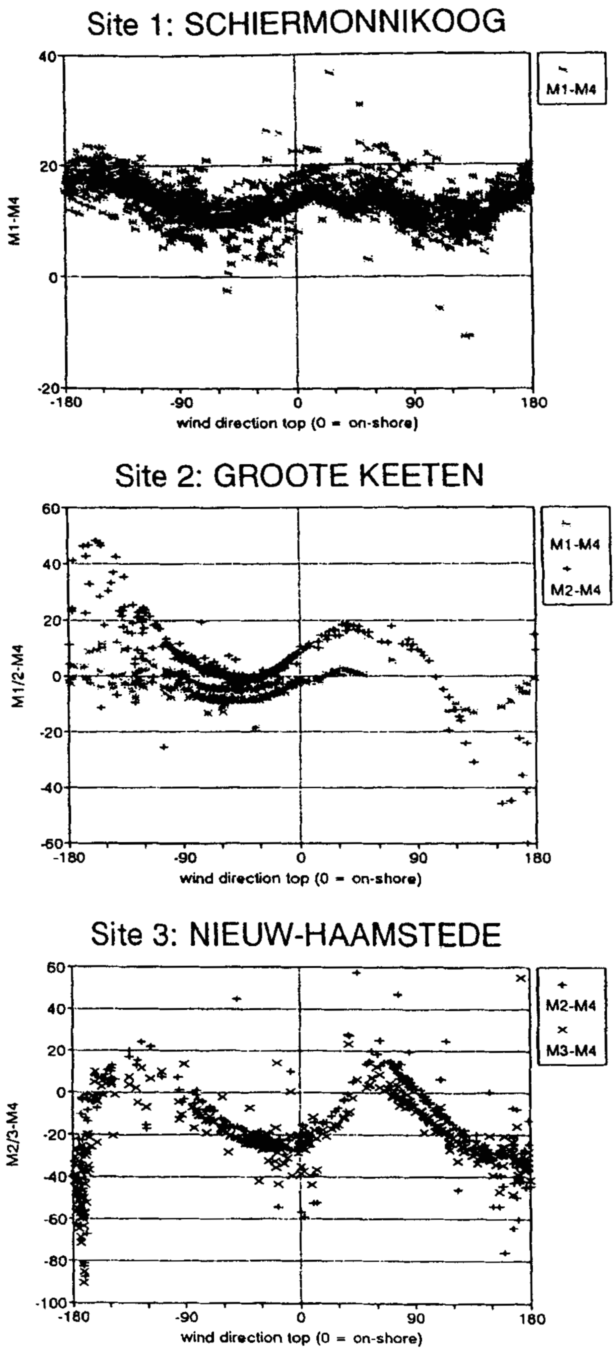

Figure 9. Differences in wind direction measured at several positions

is steep enough to establish steady separation, many of the basic tenets of Jackson and Hunt (1975) break down (Finnigan, 1988). All three sites do not satisfy these requirements. Despite this, Equation 12 gives some indication, especially for site 2 where the slope is barely vegetated. On sites 1 and 3, with distinct changes in roughness, the maximum speed-up is over-estimated by Jackson and Hunt (1975). The definition of L_2

(half-width of upwind slope) seems to give the best predictions, in the case of asymmetrical or irregularly sloped hills.

Wind direction

For all sites, wind direction was measured on top of the foredune and at one or two other places. Figure 9 shows the differences in wind direction measured on top of the foredune, at the dunefoot and on the beach. Because orientation of the vanes on top of the masts is difficult (differences of 10° due to improper orientation are possible), only patterns should be compared.

For sites 1 and 2 the differences between wind directions on top of the foredune (M4) and on the beach (M1) are similar. For onshore winds the flow is deflected into the direction of the normal. For offshore winds the flow is deflected to the parallel. For site 1 the difference between wind direction measured on top of the foredune and on the beach is 15° or less. For site 2 the difference is larger, but this is probably because of the short distance between measurements on foredune and beach on site 2. Possibly at mast 1 the flow is already deflected. Differences between wind direction on top of the foredune and near the dunefoot are larger for site 3 than for site 2. For site 2, deflection during onshore winds is about 20°, in the direction of the parallel, and for site 3 more than 30°. For offshore winds deflection is much larger on both sites 2 and 3. However, deflection never exceeds 90°, which implies that the wind direction in the lee of the foredune is never opposite to the general wind direction. This is confirmed by the orientation of wind ripples in the lee of the dunes, which was parallel to the orientation of the foredunes during perpendicular offshore wind.

Results are in agreement with the observations of Mikkelsen (1989), who studied a foredune along the North Sea coast in Denmark, comparable to the topography of site 2. Svasek and Terwindt (1974) observed bending of streamlines in the direction of the normal near a 20 m high foredune front, using smoke candles.

DISCUSSION

Implications for estimation of sand transport

From the present study it has become clear that the use of linear regression to calculate friction velocities on the beach may result in large deviations, depending on stability, wind speed and measuring heights. Linearity of the profile, indicated by a high value of R^2 (>0·999), gives no guarantee for accurate predictions of $U*$ and z_0. For stable or unstable conditions it is preferable to calculate $U*$ using measurements close to the surface (e.g. 0·5 m) and a value of z_0 which is determined during neutral conditions (when z_0 is independent of wind speed).

The studies of Mulligan (1988), Mikkelsen (1989) and Rasmussen (1989) have shown that the prediction of potential aeolian sand transport into the foredunes, by application of a transport formula, will lead to errors if friction velocities are used which are derived from beach measurements. Changes in the wind profile over the foredunes are accompanied by changes in friction velocity. Foredunes of moderate height (10–20 m) experience wind speeds near the top that are 1·5 times larger than the wind speed on the beach (also depending on surface roughness). Application of beach-derived friction velocities then leads to an underestimation of potential transport of about 70 per cent.

Implications for geomorphic processes

The pattern of erosion and deposition on the foredunes can be understood by means of the relative wind profiles presented in Figure 8.

Site 1: Schiermonnikoog. Perpendicular winds of low speed ($<10\ m\ s^{-1}$) may be able to transport sand over the beach. Owing to a deceleration near the dunefoot, wind speed may decrease below the critical velocity, which will result in deposition. If sand feed from the beach is not limited, the zone near the dunefoot nearly always serves as an accumulation zone. During higher wind velocities, the sand is lifted in vertical air movements and transported over the foredunes, even if a dense vegetation cover is present ('jettation'; see Arens, 1994). Further inland, the flow is gradually decelerated and the sand settles.

In the case of oblique winds the acceleration at the foredune front is less than for perpendicular winds. Sand is deposited in the front zone of the foredunes. With increasing angle of attack, a higher wind speed is needed to move sand inland. For parallel winds, transport of sand is limited to the beach and dunefoot. Accumulation near the dunefoot is unlikely, since the direction of transport is parallel to the beach. Amounts of sand passing by can be enormous, but effect on topography is negligible.

Site 2: Groote Keeten. There are large differences in erosion and deposition between perpendicular and oblique winds. For perpendicular winds, deposition in the front zone (near mast 3) is unlikely. For low wind speeds, sand transported on the beach will be deposited near the dunefoot. Due to flow acceleration at the top of the slope, uptake of sand is possible, since this zone is barely vegetated. Sand removed from here is deposited landward. During higher wind speeds, sand is transported from the beach over the foredunes. The large speed-up near the top causes the wind to become unsaturated again and erode the front zone of the foredune. The general pattern for onshore winds is erosion of the barely vegetated front zone (mast 3) and deposition further landward (near mast 4).

For oblique winds, the speed-up near mast 3 is less than for perpendicular winds and there is no uptake of sand. Sand transported from the beach is deposited in the zone between masts 3 and 4, where the wind decelerates rapidly.

Site 3: Nieuw-Haamstede. The large difference in height between beach and dune top, in combination with the steep slope between masts 4 and 5, prevents any sand being transported over the foredune, despite the large speed-up near the top. Possibly this is also due to the fact that the flow in front of the high dune is deflected to the parallel. The eroding capacity of the wind near the top is large. However, slope and top are densely vegetated, and uptake of sand is zero. Most of the sand transported from the beach is deposited between the sand fences (masts 2 to 4). The large deceleration of wind near mast 4 (possibly caused by an upstream vortex) makes it very unlikely that sand will move further landward.

With respect to foredune management, two important conclusions can be derived from these case studies. Sand can be transported from beach to foredune even if a dense vegetation cover is present. This process only occurs on foredunes of a certain height (probably less than 20 m). However, due to a strong deceleration, most of the landward transported sand is deposited on the top or the leeward slope. This means that the foredune ridge acts like a sand trap; transport of sand landward from the foredunes is negligible.

CONCLUSIONS

Relative wind speeds provide an excellent tool for analysis of air flow over foredunes. Wind speed at any location can be expressed in terms of the reference wind speed. The proportion is independent of wind speed itself. For low wind speeds only, the relationship between local and upwind wind velocity is not clear, but for all sites studied this is in the range of wind velocities that are of no interest with respect to sand transport (less than 4 m s^{-1}, which is below the critical wind velocity).

Stability effects can be neglected in the study of relative wind speeds, when measurements on several locations on the foredune are within the same range of heights (for example 0·5 to 6·0 m). If that condition is satisfied, the assumption of a logarithmic wind profile on the beach during (un)stable conditions leads to very small errors in the calculated relative wind speeds (less than 2 per cent).

The influence of topography on wind speed is prominent. Maximum speed-up increases with height of the foredune. An increase in height from 6 to 10 m, in combination with a decrease in roughness, causes a rise in speed-up from 1·1 to 1·5. With respect to sand transport (cubic relationship with wind velocity) this may result in a three-fold increase of the sand-carrying capacity. A further increase in foredune height appears to have limited influence, probably because the increase in height (acceleration) is compensated by an increase in roughness (deceleration). Possibly there is also an effect of three-dimensional flow, caused by a convex coastline. Height of maximum speed-up increases and speed-up decreases with increasing roughness of the seaward slope; near the surface the change in roughness dominates over the change in topography. For a foredune more than 20 m high, it is believed that despite large accelerations near the top of the seaward slope, sand from the beach will not reach the top because the difference in height between beach and foredune is too large. Transport of sand will only occur if the seaward slope is scarcely vegetated.

The relationship between relative wind speed and wind direction is distinct. Deceleration near the dunefoot is largest with perpendicular onshore winds and decreases when the wind turns to the parallel. Maximum speed-up on the foredune occurs with perpendicular onshore winds, and is smaller with oblique winds and absent with parallel winds. In the case of parallel winds, relative wind speeds reflect the roughness of the foredune surface whereas the influence of topography is limited.

Speed-up factors predicted according to Jackson and Hunt's (1975) model deviate in some cases from the observed speed-up. For a barely vegetated foredune, where a change in roughness is not present, the predicted value approaches the observed value. This is surprising, as the basic requirements of Jackson and Hunt's model are not satisfied, especially because the foredune is much too steep. If a strong roughness change is present, the predicted speed-up deviates from the observed speed-up.

The topographic obstacle formed by the foredunes not only changes the velocity of the wind flow but also its direction. During onshore winds the flow is deflected to the parallel when it passes the dunefoot, then it turns back and deflects to the normal. The rate of deflection increases with foredune height.

The use of beach-derived friction velocities in aeolian sand transport equations may under-estimate the potential sand transport over foredunes. Application of linear regression to calculate friction velocity and roughness length leads to erroneous results in the case of stable or unstable conditions.

Patterns of erosion and deposition can be explained by the patterns of acceleration and deceleration of wind speed. Sand is transported in a jet-like flow from the beach over the foredune, even if the latter is densely vegetated. However, the amount of sand transported landward from the foredune is very small.

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