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Transport rates and volume changes in a coastal foredune on a Dutch Wadden island

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Abstract. Sediment dynamics on a coastal foredune on the Dutch Wadden island of Schiermonnikoog were studied from November 1990 to May 1991 to get an insight into rates and frequencies of aeolian processes. Digital Terrain Models were constructed to describe volume changes and zonation of deposition. Recording of heights were related to important events. Three periods are distinguished: (1) a period with storm surges resulting in dune erosion, (2) a winter period with mainly offshore winds; (3) a period with several days with strong onshore winds, resulting in dune building. In these periods detailed meteorological measurements and observations of aeolian sediment transport rates were performed. This paper presents comparisons between volumetric changes as derived from DTM calculations and calculated aeolian transport based on meteorological observations and current transport equations. The main conclusion is that only during a part of the year the observed changes in volume correspond reasonably well to the predicted transport, using standard transport equations and meteorological measurements.

Keywords: Aeolian process; Digital Terrain Model; Sand transport; Sediment budget.

Abbreviations: DTM = Digital Terrain Model; NAP = Dutch ordnance level.

Introduction

Most studies on coastal dune development either focus on the measuring of transport processes at a short time scale (days) (e.g. Sarre 1989a; Bauer et al. 1990; Dingler et al. 1992; Nordstrom & Jackson 1992; Nordstrom et al. 1996) or the measuring of elevation changes at a longer time scale (months to years) (e.g. Sarre 1989b; Davidson-Arnott & Law 1990). Thus far, few studies (e.g. Wal & McManus 1993; Anthonsen et al. 1996) directly correlated aeolian transport with dune building. Mostly, changes in elevation are related to a calculated (potential) transport, using transport equations and wind data. However, in coastal environments, the calculation of transport from wind data usually results in amounts that far exceed the observed transport, because of the involvement of a number of factors which limit aeolian transport, such as rainfall, effective beach width and moisture effects (Nickling & Davidson-Arnott 1990; Sherman & Hotta 1990; Arens 1996).

The problem of linking transport processes with dune building (sediment budgets) can be seen as a scale problem. Transport processes operate at a micro-scale, while the resulting dune building operates at a meso-scale (Sherman 1995). Integration of micro-scale processes over time results in changes in meso-scale structures. In this paper the meso-scale changes in topography are compared with an integration of micro-scale meteorological measurements and sand transport observations. By using Digital Terrain Models, volume changes are calculated for three periods, which roughly correspond to autumn, winter and spring. By means of measurements and observations, transport calculations over series of events are performed and compared to the total volume changes over the three periods.

Methods

The study area is situated on Schiermonnikoog, one of the Wadden islands in the north of The Netherlands (Fig. 1). The site comprises a wide (> 500 m) beach and a northwesterly exposed, low (< 6 m +NAP), gently sloping and well-vegetated foredune (Arens 1994; Arens et al. 1995). Four Digital Terrain Models were constructed after important geomorphic events. In an area of 50 m × 250 m, heights were recorded at obvious changes in slope and transformed into an equidistant grid with pixels 5 m × 5 m. Meteorological variables were measured using electronic equipment (Arens 1994, 1996; Arens et al. 1995). Transport rates were measured using saltation sand traps (Arens & van der Lee 1995) and saltiphones (Spaan & van den Abeele 1991; Arens 1996). The saltiphone is an acoustic sensor, which counts the number of impacts. The number of impacts are used as a relative measure of sand transport, as it is not possible yet to relate grain counts by the saltiphone directly to mass transport. The advantage of a saltiphone is that (despite of some instrumental problems) continuous data

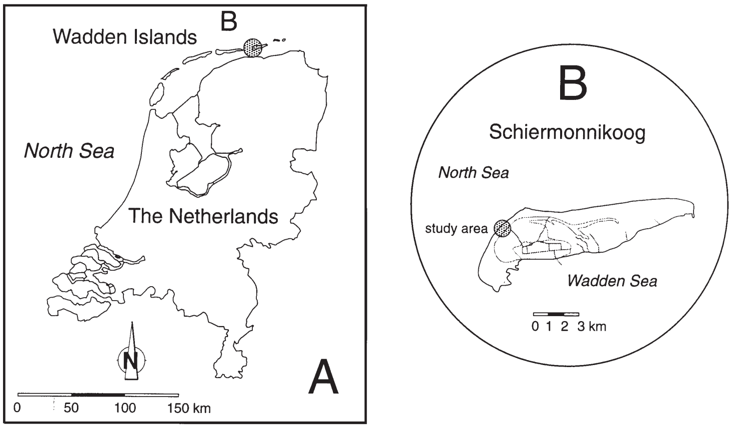

Fig. 1. Location of study area.

on (relative) sand transport are available, so that transports under many different circumstances can be compared. Data used here were recorded on the beach (station 1, Fig. 2c): wind speed at 0.78, 2.21 and 5.18 m height, wind direction at 5.5 m height; saltiphone at 0.11 m height. Relative humidity (using dry and wet bulb temperatures) was measured at 1.15 m. A temperature gradient was derived by comparing dry bulb temperatures recorded at 1.15 and 5.5 m. Rainfall was measured on the foredune (station 2), using a tipping bucket rain gauge. Instruments were read every 5 sec; data were averaged over 10 min. and 1 h. Here, 1-h means and totals (rainfall) are used. Wind frequencies were calculated for sectors of 30°.

Calculation of friction velocity

Standard transport equations use the friction velocity for calculation of potential transport. By assuming a logarithmic wind profile in the inner boundary layer,

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

with $\kappa = 0.41$ (von Karman's constant) and U_z = wind speed at height z, the friction velocity U_* and the roughness length z_0 can be calculated, using the wind speeds recorded at different heights. The wind speeds were corrected for stability effects due to thermal stratification. The influence of stability effects can be calculated using Eqs. 2 and 3 for the wind and the temperature profile (e.g. Rasmussen 1989; van Boxel 1986; van Boxel et al. 1989)

$$U_z = \frac{U_*}{\kappa}\left[\ln \frac{z}{z_0} \pm \Psi_{m_z}\right] \tag{2}$$

with Ψ a dimensionless stability parameter, depending on height and the Obukhov length L (Obukhov 1946);

$$\Theta_z = \frac{\Theta_*}{\kappa}\left(\ln \frac{z}{z_0} \pm \Psi_{h_z}\right) + \Theta_0 \tag{3}$$

with Θ_z the potential temperature at height z (°C); Θ_0 the potential temperature at height $z = z_0$; Θ_* the characteristic potential temperature scale. The Obukhov length L is calculated using Eq. 4.

$$L = \pm \frac{T}{\kappa g} \frac{U_*^2}{\Theta_*} \tag{4}$$

with T absolute temperature in K.

For unstable conditions ($L < 0$) Ψ can be calculated as follows (Paulson 1970; Wieringa 1980):

$$\Psi_{m_z} = 2\ln\left(\frac{1+x_z}{2}\right) + \ln\left(\frac{1+x_z^2}{2}\right) \pm 2\arctan(x_z) + \frac{\pi}{2} \tag{5}$$

$$\Psi_{h_z} = 2\ln\left(\frac{1+y_z^2}{2}\right) \tag{6}$$

$$\text{with } x_z = \left(1 - 22\frac{z}{L}\right)^{0.25} \tag{7}$$

$$\text{and } y_z = \left(1 \pm 13\frac{z}{L}\right)^{0.25} \tag{8}$$

For stable conditions ($L > 0$) Ψ_m can be calculated by (Webb 1970; Wieringa 1980):

$$\Psi_{m_z} = \pm 6.9\frac{z}{L} \tag{9}$$

$$\Psi_{h_z} = \pm 9.2\frac{z}{L} \tag{10}$$

The stability parameters are solved using an iterative procedure. For a first estimation of L the values of U_* and z_0 are used, derived by linear regression. The value of Θ_* is derived by assuming a linear temperature profile, and fitting a line through the temperatures recorded at 1.15 and 5.5 m above the surface. The value of L is used for calculation of the stability correction parameters. The procedure is repeated, usually for six iterations. A detailed description of the calculation procedure is available upon request from the author.

Calculation of potential transport

Potential transport is defined as the maximum transport, assuming that all winds above the threshold can transport sand, thus disregarding all factors which negatively influence sand transport. Usually these conditions are only met in desert environments with enough sand supply, and in wind tunnels. Potential transport according to White (1979) is calculated by:

$$q = C_W \frac{\rho}{g}(U_*)^3\left(1 \pm \frac{U_{*t}}{U_*}\right)\left(1+\frac{U_{*t}}{U_*}\right)^2 \qquad (11a)$$

which is an adapted version of Kawamura's equation (Kawamura 1951):

$$q = C_K \frac{\rho}{g}(U_* \pm U_{*t})(U_* + U_{*t})^2 \qquad (11b)$$

with q in kg·m^{-1}·s^{-1} and

$U_{*t} = 0.22$	(m/s)	critical friction velocity
$C_W = 2.61$	(-)	White's constant
$C_K = 2.78$	(-)	Kawamura's constant
$\rho = 1.22$	(kg/m)	density of air
$g = 9.81$	(m/s^2)	gravitational constant

Note that in most of the literature White's equation is cited wrongly, based on a printing error in the original publication (White pers. comm.; Blumberg & Greely 1993).

The potential transport per hour is calculated as

$$q_i = 3600q \qquad (11c)$$

Application of a wind frequency distribution yields the total transport Q_j per windsector j in m^3/m by summation of all calculated hourly transport rates q_i

$$Q_j = \frac{1}{1600}\sum_{i=1}^{n_j} q_i \qquad (12)$$

with n_j the total number of hours for wind sector j and assuming a bulk density of sand of 1600 kg/m^3. Total input into the foredunes then can be calculated by summation of the contribution of all sectors. Therefore, the total transport per sector should be multiplied by the cosine of the transport direction (parallel winds: input zero).

$$Q = \sum_{j=1}^{12} Q_j \cos\left[dd_j\right] \qquad (13)$$

with $\cos[dd_j]$ is the cosine of the average wind direction relative to the normal for sector j, assuming a wind frequency distribution based on 12 sectors of 30° each.

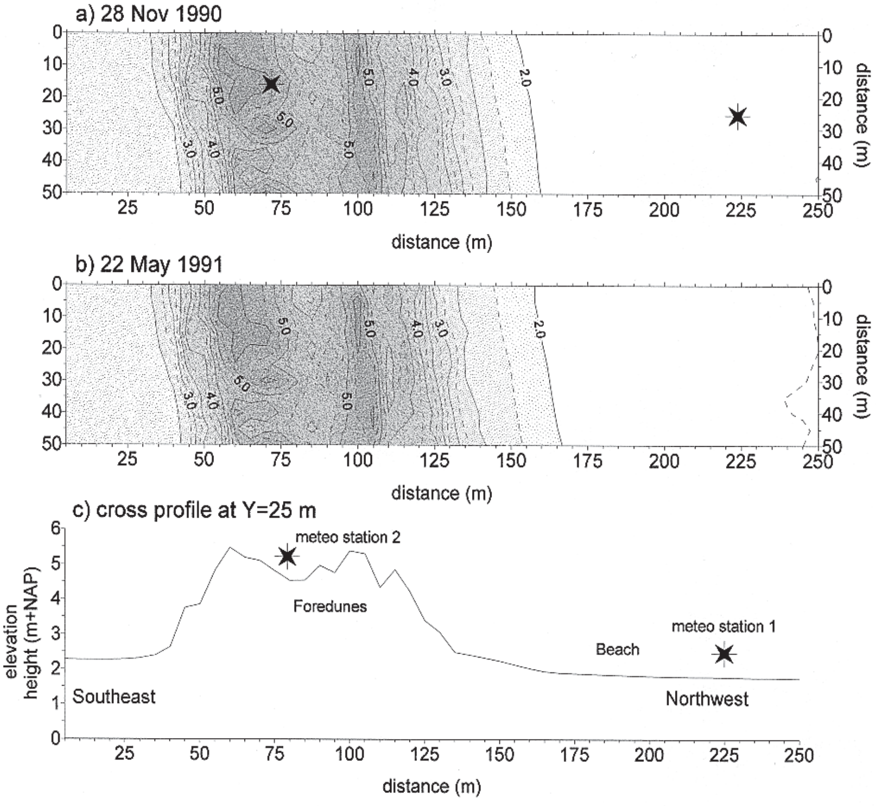

Fig. 2. Isolines, showing lines of equal height (m NAP);
a. Situation 28-11-1990.
b. Situation 22-5-1991.
c. Cross profile.

Results

Due to seasonal variations in weather conditions, several time periods can be distinguished. Usually the storm season, with strong winds from southwest to northwest, extends from November to January/February. In the winter season, stormy periods often alternate with cold periods, characterised by temperatures below zero and easterly winds. From March to May weather conditions can be variable: calm conditions and high temperatures are alternated with conditions with strong northerly winds and periods of rainfall.

Changes in topography; comparison of DTMs

Fig. 2 shows the isolines for the study area at the beginning and the end of the measuring period, Fig. 3 shows the changes in height after the periods described below.

Period 1: 28 November 1990 - 14 December 1990

This period is mainly characterised by strong winds in combination with high rainfall. Very strong onshore winds did not result in landward transport of sand because of the wet conditions. The largest change in morphology was caused by wave erosion during one major storm (12 December). The occurrence of a high water level (3.40 m + NAP) resulted in a redistribution of sand within the dune system. The output of sand, transported beyond the study area, was limited (10 m^3 over the total area, 0.2 m^3/m). This sand mainly originates from the beach. In the area above 4.00 m + NAP no volume changes were observed. Erosion of the seaward slope of the foredune resulted in a decrease in height, locally of 0.5 m. Most of this sand was deposited on the upper part of the beach (between 2.25 and 2.75 m + NAP, increase in height up to 0.1 m). In this case, wave erosion caused a redistribution of sand within the system without scarp development.

Period 2: 14 December 1990 - 7 March 1991

The second period is characterised by stormy weather alternating with cold conditions. Most of the time the wind was parallel to the foredunes or offshore. Parallel winds have limited effects on topography, mainly concentrated in the zone between the dune foot and the upper part of the beach. With offshore winds, some erosion of sand near the dune foot may occur. For this site, the displaced sand is redeposited on a lower, moist part of the beach. Some events with onshore winds and sediment transport occurred, with deposition of sand at the front of the foredune (above 3.25 m + NAP). In total, the volume of the study area changed slightly (an increase of 4 m^3 or 0.08 m^3/m).

Period 3: 7 March 1991 - 22 May 1991

The third period is the main period of dune building. The main changes in topography occurred within a few days, with strong onshore winds, sometimes accompanied by showers. Onshore winds supplied sand from the beach. First, this sand was deposited near the dune foot. During stronger onshore winds (when transport on the beach ceases, due to flooding by sea water), most of this sand was eroded and transported up slope. In a period of only a few days, new dunes were constructed on the vegetated slope, with a characteristic gentle windward slope and steep slipface. The height of these dunes extended to 0.50 m above the former surface. The total sediment input in the system was 106 m^3, or 2.1 m^3/m. Sediment input from the beach declined in May because of the development of algae crusts on the beach. From that time, sediment transported inland was derived from aeolian erosion of the dune foot.

Comparison of volume changes and transport rates

The observed change in topography during period 3 is expressed as a change in volume (2.1 m^3/m). Total amounts of sediment transport for the third period (7 March-22 May) can be calculated, using the meteorological measurements for that period and the transport equations. By converting the calculated transport to volumes of sand (cumulative short term transport), the result can be compared to the change in sediment volume as observed in period 3 (long term transport).

Fig. 4a represents the wind frequency distribution of hourly wind speeds measured in the period 7 March to 22 May 1991. Onshore winds were dominant during this period, with the strongest winds from the north and southwest. Combination of the wind frequency distribution and Eq. 12 gives the potential sand transport (Fig. 4b), the transport which would occur when no limiting factors would influence sand transport. The total potential transport yields 34.6 m^3/m when totalled over all wind directions. The correction of friction velocities for stability effects has resulted in a 35 % higher prediction of sand transport. When the transport direction is taken into account, the potential transport Q_{pred1} amounts 16.6 m^3/m, of which 18.0 m^3/m is transported landward during onshore winds and 1.4 m^3/m is transported seaward during offshore winds. These amounts are much higher than the observed volume change of 2.1 m^3/m.

Arens (1994, 1996) showed that the transport observed in the field, here referred to as the actual transport, approaches potential transport only during specific conditions. Because of differences in moisture levels, rainfall and fetch, thresholds for sand transport change, and the amounts of sand actually transported are less

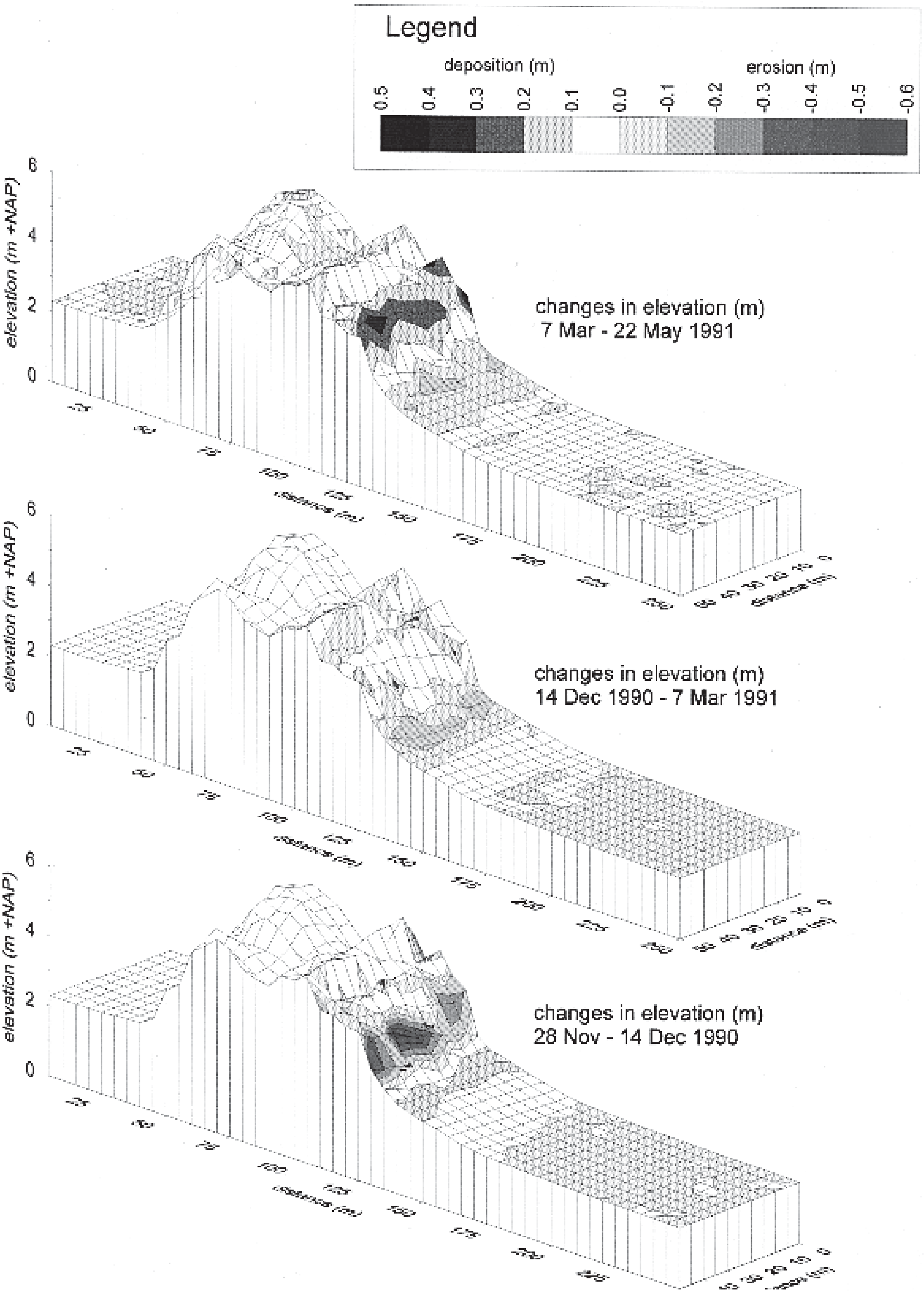

Fig. 3. Changes in height (in m) for three periods: 28 Nov - 14 Dec 1990; 14 Dec 1990 - 7 Mar 1991 and 7 Mar - 22 May 1991 (negative numbers indicate erosion, positive numbers indicate deposition).

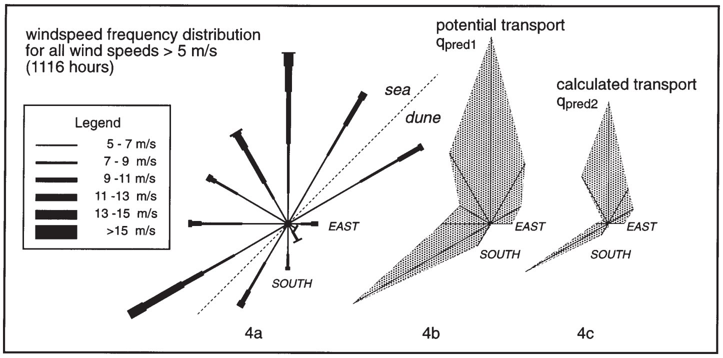

Fig. 4. Wind frequency distribution and potential and calculated sand roses for the study area. **a.** Wind rose for hourly averaged wind speeds (measured at the beach at 5.15 m above the surface), 7 March - 22 May 1991. Wind speeds < 5 m/s are neglected. Length of vectors indicate percentage of occurrence, thickness indicates wind speed. **b.** Sand rose for potential transport q_{pred1}, calculated with the wind frequency distribution of 4a and the transport equation of White (1979). Vectors indicate importance of sectors relative to total sand transport. (Vectors are connected for comparison only.) **c.** Sand rose for calculated transport q_{pred2}, using the wind frequency distribution of 4a and the transport equation of White (1979) adapted with the empirical relationships between transport and humidity, rainfall and wind direction according to Arens (1996).

than predicted. Based on 10 min. means of saltiphone recordings during period 3, Arens proposed empirical relationships, relating the changes in threshold velocity U_t to relative humidity, rainfall and wind direction:

$$U_t = U_{t\min}\left\{1+0.17(1+\cos[dd]) \pm \frac{2.11}{100} + \frac{2.11}{100 \pm \%RH}\right\} \quad (14)$$

for dry days and

$$U_t = U_{t\min}\left\{1+0.17(1+\cos[dd]) \pm \frac{2.11}{100} + \frac{2.11}{100 \pm \%RH} + 0.35\right\}$$

(15)

for wet days, with

$U_{t\min}$ = 5.45 m/s (at 5.15 m height)
dd = wind direction relative to the normal
$\% RH$ = percentage relative humidity of the air

Since these relationships were derived for wind speeds measured at 5 m height (CAM1-1), corrections are necessary:

$$U_{*t} = U_{t_{\text{cam1-1}}} \kappa \ln\left(\frac{z_{\text{cam1-1}}}{z_0}\right) \quad (16)$$

$$U_{*t\min} = 0.22 \text{ m/s} \quad (17)$$

Here a simplification is made, by neglecting stability effects. It is likely, that application of this method has resulted in slight deviations of the predicted critical friction velocities.

Although these equations present rather simple approximations of the complex physical relationships, they are useful for a (rough) quantitative estimation of the effects of rainfall, humidity and wind direction on sand transport. Taking the relationships into account (equations 14 and 15) and transforming wind speeds in friction velocities (16), an assumed actual transport Q_{pred2} is calculated, presented in Fig. 4c. Now, the total predicted transport equals 9.1 m^3/m (of which 10.1 m^3/m landward and 1.1 m^3/m seaward), which is still higher than the observed transport.

Comparison with transport measurements

The calculated transport rates presented above are theoretical transport rates, based on relationships between transport and meteorological conditions. As Arens (1996) showed, theoretical transport rates often deviate from actual or observed transport. The strongest deviations are observed when, despite high wind speeds, no transport occurs. Fig. 5 displays the total amounts per wind class (direction and speed). Rain in combination with wind speeds below 5 m/s are not considered. This figure illustrates that a large part of the high wind speeds are accompanied by rain. Because of the continuous registration of the saltiphone, hours without transport can be identified. Hours for which the saltiphone has recorded zero transport, can be neglected. Then, a new wind frequency distribution for hours with sand transport (434 hours) can be produced, which is visualised in Fig. 6a. Fig. 6b presents the calculated transport Q_{pred3}, using the same equations as above, in combination with the wind frequency distribution of Fig. 6a. Now, the 'predicted' transport amounts 4.3 m^3/m (5.3 m^3/m landward and 1.0 m^3/m seaward), which is still too high. In fact Q_{pred3} is not a proper prediction, because measurements of sand transport are used to identify hours without transport. Using current transport equations, it is apparently not possible to accurately predict under which conditions transport is zero.

To compare the predicted transport rates per sector

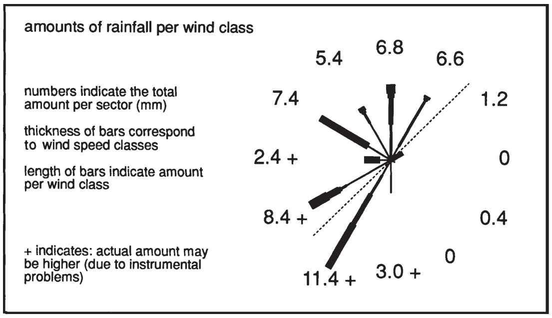

Fig. 5. Amounts of rainfall (mm) per wind frequency class. Period 7 March - 22 May 1991.

with the saltiphone observations, total recorded saltiphone impacts are calculated per sector. This gives a relative indication of transport. Results are shown in Fig. 6c. Differences show less important transport in sectors 11 and 12 and more important transport in sectors 1, 2 and 3. The observed differences for sectors 11 and 12 must be related to high water levels which caused beach flooding, and possibly also to rainfall events: with excessive rainfall sand transport will stop.

Discussion and Conclusions

For this particular site dune building was concentrated in a period of some weeks during spring. In spring conditions appeared to be most favourable for landward aeolian transport. In the storm and winter season, hardly any changes in topography due to aeolian events were observed, despite of periods with strong and very strong onshore winds. Changes during these periods were related to marine events. Studies reported by Wal & McManus (1993) also mention spring as the main period for dune building. Sarre (1989b) observed main dune growth in autumn, and related this to a larger trapping capacity of vegetation at the end of the growing season.

Prediction of transport for a certain period may be of the same order of magnitude as observed changes in volume. For longer periods it is very difficult to accurately predict when there is no transport. The use of volume changes as an indirect measure of sediment transport, as proposed by Davidson-Arnott & Law (1990), provides more realistic figures of sand transport then calculations with transport equations, if no leakage occurs (all sediments trapped in the foredune). However, as it provides an integration over time, it will not increase our insight of the conditions under which dune building occurs and of the frequency of those conditions.

For short periods of time, the different scales of sediment transport (micro-scale) and sediment budget (meso-scale) can be linked, if conditions during the studied period are favourable for sand transport, and the occurring transport can be described with existing deterministic models. For longer periods, conditions change, and many more factors become involved, which cause the existing models to fail. For example, for this study highest wind speeds (> 18 m/s) appeared to be relatively unimportant, because of their occurrence in combination with rainfall and flooding. A similar conclusion was made by Davidson-Arnott & Law (1996), who stated that beach (source) width is of more importance than wind energy. Apparently, the sediment budget of foredunes is strongly controlled by the supply of sediment.

Several important issues should be addressed to improve the existing deterministic models. The identification of conditions without aeolian transport (despite high wind speeds) might be the most important step. Therefore, aeolian transport during rainfall events and the effects of moisture (surface moisture, groundwater) need to be quantified. Secondly, the uncertainty in effective beach width, due to differences in water level

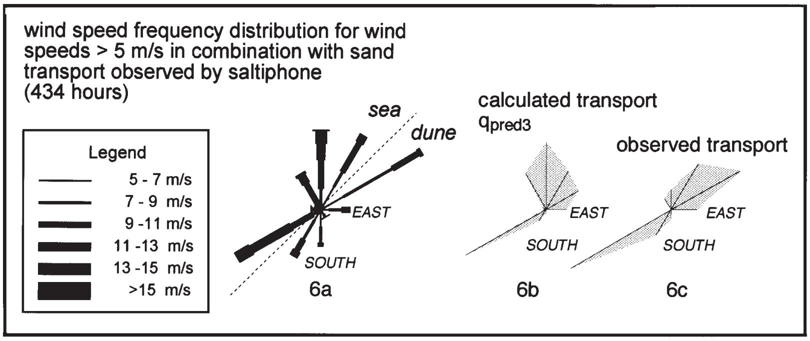

Fig. 6. Wind frequency distribution for sand transport events and calculated and observed sand roses for the study area. **a.** Wind rose for hourly averaged wind speeds during sand transport events. All events without sand transport (as observed with the salthiphone) are neglected. **b.** Sand rose for calculated transport q_{pred3}, as in Fig. 4c, but using the wind rose of Fig. 6a. **c.** Distribution of total number of impacts per sector, recorded by the salthiphone.

must be addressed, providing possibilities to predict beach flooding and thus changes in source width. Finally, the supply or subtraction of sand by wave action must be incorporated, because this determines the amount of sand that is actually available for aeolian transport.

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References

Anthonsen, K.L., Clemmensen, L.B. & Jensen, J.H. 1996. Evolution of a dune from crescentic to parabolic form in response to short-term climatic changes: Råberg Mile, Skagen Odde, Denmark. *Geomorphology* 17: 63-77.

Arens, S.M. 1994. *Aeolian processes in the Dutch foredunes.* Doctoral Thesis, University of Amsterdam.

Arens, S.M. 1996. Rates of aeolian transport on a beach in a temperate humid climate. *Geomorphology* 17: 3-18.

Arens, S.M. & van der Lee, G.E.M. 1995. Saltation sand traps for the measurement of aeolian transport into the foredunes. *Soil Technol.* 8: 61-74.

Arens, S.M., van Kaam-Peters, H.M.E. & van Boxel, J.H. 1995. Air flow over foredunes and implications for sand transport. *Earth Surface Process. Landforms* 20: 315-332.

Bauer, B.O., Sherman, D.J., Nordstrom, K.F. & Gares, P.A. 1990. Aeolian transport measurement and prediction across a beach and dune at Castrovill, California. In: Nordstrom, K.F., Psuty, N.P. & Carter, B. (eds.) *Coastal dunes; form and process*, pp. 39-55. John Wiley, Chichester.

Blumberg, D.G. & Greeley, R. 1993. Field studies of aerodynamic roughness length. *J. Arid Environ.* 25: 39-48.

Davidson-Arnott, R.G.D. & Law, M.N. 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom, K.F., Psuty, N.P. & Carter, B. (eds.) *Coastal dunes; form and process*, pp. 177-200. John Wiley, Chichester.

Davidson-Arnott, R.G.D. & Law, M.N. 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. *J. Coast. Res.* 12: 654-663.

Dingler, J.R., Hsu, S.A. & Reiss, T.E. 1992. Theoretical and measured aeolian sand transport on a barrier island, Louisiana, USA. *Sedimentology* 39: 1031-1043.

Kawamura, R. 1951. *Study of sand movement by wind.* Reports of Physical Sciences Research Institute of Tokyo University 5 (3-4): 95-112 (in Japanese). Translated in 1964 as University of California Hydraulics Engineering Laboratory Report HEL2-8, Berkely, CA, pp. 1-38.

Nickling, W.G. & Davidson-Arnott, R.G.D. 1990. Aeolian sediment transport on beaches and coastal sand dunes. In: Davidson-Arnott, R.G.D. (ed.) *Proceedings Symposium Coastal Sand Dunes*, pp. 1-35. NRC, Ottawa.

Nordstrom, K.F. & Jackson, N.L. 1992. Effect of source width and tidal elevation changes on eolian transport on an estuarine beach. *Sedimentology* 40: 769-778.

Nordstrom, K.F., Bauer, B.O., Davidson-Arnott, R.G.D., Gares, P.A., Carter, R.W.G., Jackson, D.W.T. & Sherman, D.J. 1996. Offshore aeolian transport across a beach: Carrick Finn Strand, Ireland. *J. Coast. Res.* 12: 664-672.

Obukhov, A.M. 1946. Turbulence in an atmosphere with a non-uniform temperature. Tr. Akad. Nauk SSSR Inst. Teoret. Geofis. No 1 (translated in *Boundary Layer Meteorol.* 2: 7-29).

Paulson, C.A. 1970. The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J. Appl. Meteorol.* 9: 857-861.

Rasmussen, K.R. 1989. Some aspects of flow over coastal dunes. In: Gimingham, C.H., Ritchie, W., Willetts, B.B. & Willis, A.J. (eds.) *Coastal sand dunes. Proc. R. Soc. Edinb.* 96B: 129-147.

Sarre, R. 1989a. Aeolian sand drift from the intertidal zone on a temperate beach: potential and actual rates. *Earth Surface Process. Landforms* 14: 247-258.

Sarre, R. 1989b. The morphological significance of vegetation and relief on coastal foredune processes. *Z. Geomorph. N.F. Suppl.* 73: 17-31.

Sherman, D.J. 1995. Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geol.* 124: 339-349.

Sherman, D.J. & Hotta, S. 1990. Aeolian sediment transport: theory and measurement. In: Nordstrom, K.F., Psuty, N.P. & Carter, B. (eds.) *Coastal dunes; form and process*, pp. 17-37. John Wiley, Chichester.

Spaan, W.P. & van den Abeele, G.D. 1991. Wind borne particle measurements with acoustic sensors. *Soil Technol.* 4: 51-63.

van Boxel, J.H. 1986. *Heat balance investigations in tidal areas.* Doctoral Thesis, Free University, Amsterdam.

van Boxel, J.H., Vugts, H.F. & Cannemeyer, F. 1989. Effect of the water vapour gradient on the Obukhov length and the profile derived fluxes. *Z. Meteorol.* 39: 351-353.

Wal, A. & McManus, J. 1993. Wind regime and sand transport on a coastal beach-dune complex, Tentsmuir, eastern Scotland. In: Pye, K. (ed.) *The dynamics and environmental context of aeolian sedimentary systems. Geol. Soc. Spec. Publ.* 72: 159-171.

Webb, E.K. 1970. Profile relationships: the log-linear range and extension to strong stability. *Q. J. R. Meteorol. Soc.* 96: 67-90.

White, B.R. 1979. Soil transport by winds on Mars. *J. Geophys. Res.* 84 B8: 4643-4651.

Wieringa, J. 1980. A revaluation of the Kansas mast influence on measurements of stress and cup-anemometer overspeeding. *Bound. Layer. Meteorol.* 18: 411-430.

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