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Wind Velocity and Algal Crusts in Dune Blowouts

J.L.A. Pluis & J.H. van Boxel

Summary

In two saucer-shaped blowouts wind velocity was measured at 0.18 m height and compared to the wind velocity data from the nearest standard meteorological station at Valkenburg about 3.5 km to the northeast. In blowout 1 relative velocities are highest when the wind blows from directions between E and SSE. In blowout 2 winds blowing from directions between S and WSW are relatively stronger. In general the wind speed increases as its moves along the surface inside the blowout, because the aerodynamic roughness of the blowout surface is less than that of the surrounding area. Less important are the influence of the configuration of the terrain surrounding the blowout and the influence of the slopes within the blowout.

The frequency distribution of the general wind at Valkenburg is analysed and combined with the horizontal wind velocity pattern within blowouts. A simulation model, producing the spatial distribution of the wind power shows that the prevalence of algal crusts at the SW side of blowouts agrees well with the location which reaches the lowest wind power values. In other parts of the blowouts algal crusts are damaged by moving sand at times of high wind velocity.

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1 Introduction

In some terrains of the coastal dune area of Meijendel near The Hague, The Netherlands, measures for the fixation of moving sand have been suspended since 1979. Overall the area of moving sand has increased since then, but in some areas deflation has spontaneously stopped (Jungerius & Van der Meulen 1989). Van den Ancker et al. (1985) have suggested that an important stabilization mechanism is the colonization of the sand by algae. Blowouts are the most important deflation features in the coastal dunes of the Netherlands. These depressions, formed by deflation, are usually saucer-shaped. The general orientation of large blowouts suggests that they are elongated by SW winds.

The natural stabilization of blowouts has been studied by Pluis & de Winder (1990). It was shown that cyanobacteria are commonly the initial colonizers, being succeeded by green algae. The deflation rate is decreased by the formation of algal crusts (photo 1). Algal crusts are found mainly at the SW side of blowouts (fig. 1). Where this is the case, the blowout will no longer grow in its customary manner which is towards the SW (Jungerius et al. 1992).

Various mechanisms could explain the pattern of algal distribution in blowouts. In order to investigate if this pattern is related to wind velocity distribution because at high wind speeds the algal

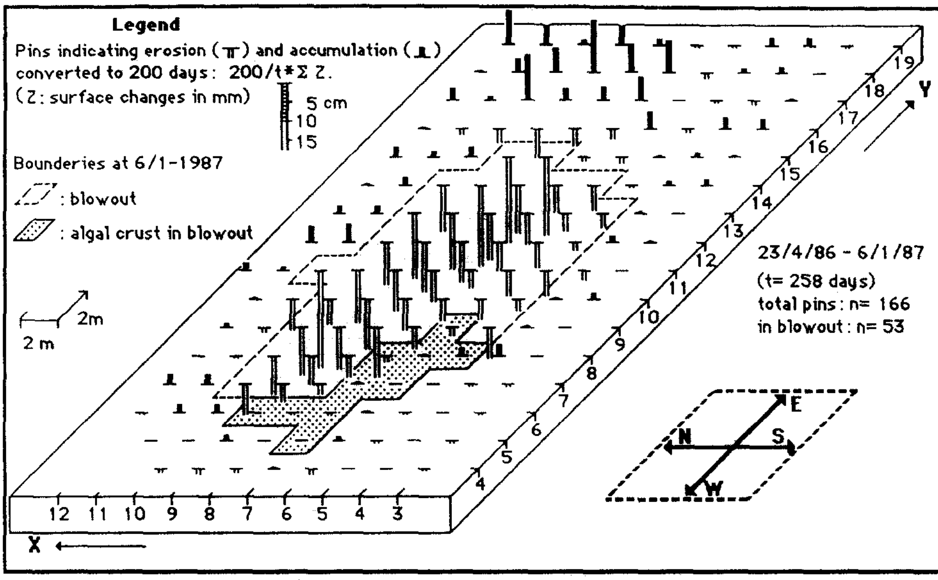

Fig. 1: *The spatial distribution of algal crusts at blowout 2 during the period 23/4-86 and 6/1-87. The algal coverage is based on analysis of biomass content and species composition at the erosion pin sites. The erosion pins illustrate the net change in surface level for the whole period (derived from Pluis & de Winder 1989).*

crust is damaged by moving sand, wind velocity was measured in two blowouts. The composition and location of algal crusts in blowout 2 have been described by Pluis & de Winder (1989). A similar algal crust distribution pattern was found for blowout 1. Firstly, the change of wind speed along transects within the blowouts will be evaluated. Secondly, the sensitivity of the blowouts to the general wind will be compared. Finally these results will be combined with the frequency of occurrence of the general wind to analyse the significance of the wind power distribution for algal crusts.

2 Materials and methods

The study area is located in Meijendel near The Hague, The Netherlands. The area consists of many secondary dune forms including parabolic dunes and more or less transverse inner dune ridges. Average height of the dunes is 10–20 m. Plant communities of the xerosere type prevail. Open short vegetation (Rubus, mosses and lichens) and dwarfshrubs (Salix and Hippophaë) are most common.

The field data have been collected in the two blowouts during the year 1989 (from 26/1 to 4/7 and from 13/7 to 21/11, respectively). After removal of hours with variable wind direction or low wind speeds about 1000 hours of mea-

Photo 1: *Shallow saucer-shaped blowout viewed toward the east. The blowout is stabilized by algal crusts at its southwestern side (dark zone in the deflation area).*

surements were left for each blowout. For each wind direction some 40 to 200 hours of measurement were available for analysis except for wind direction ENE in blowout 2. Blowout 1 is situated at 22.5 m height above sealevel 2750 m from the sea and blowout 2 at 12.5 m height 1300 m from the sea. Readings were obtained at 3 locations in blowout 1 and 5 locations in blowout 2 (fig. 2). Mean wind velocities were measured every five minutes using rotating cup-anemometers. The starting speed of the anemometers averaged 0.17 m/s. The centre of the cups (diameter 5.4 cm) was installed 18 cm above the surface. In both blowouts three anemometers were located along the east-west axis of the blowout. In blowout 2 two more anemometers were situated at both sites of the centre anemometer on a perpendicular transect (fig. 2). The wind data from the three or five anemometers were collected synchronously by a datalogger.

It was noted by Borowka (1980) that by measuring the wind velocity at just one height near the surface the wind velocity might be influenced by the sand flux. Transported sand exerts a drag on the cup anemometers, resulting in an increase in the measured wind velocity. However this effect is not important in these blowouts, because here the sand flux generally is very small and several orders of magnitude less than on a beach. Anemometers accelerate

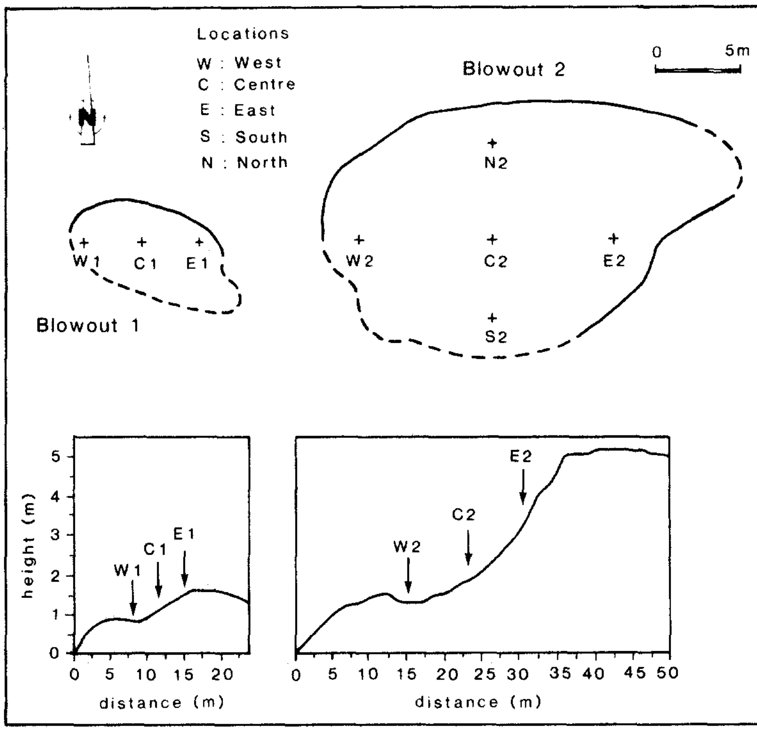

Fig. 2: *Location of the anemometers in the blowouts 1 (left) and 2 (right) and longitudinal cross section of the blowouts. The continuous line in the upper figures represents a steep cliff which separates the inner blowout slope from the surrounding area.*

faster than they decelerate. Therefore in a turbulent boundary layer the average wind speed is overestimated (Mac Cready 1966, Hyson 1972, Wieringa 1980). Kaganov & Yaglom (1976) theoretically calculated that this overestimation equals about 8–10%. No correction has been applied here since the overspeeding applies to all anemometers.

The nearest weather station at Valkenburg (K.N.M.I.), about 3.5 km to the northeast, was used as a reference point. This station gives mean hourly wind data measured at ten metres above ground level. In order to study the modification of the general wind speed pattern in the blowouts the mean wind velocity values of the blowouts have been adjusted to this hourly interval.

3 Acceleration of the wind within the blowout

The magnitude of acceleration or deceleration of the wind within the blowouts has been calculated for wind blowing parallel (at an angle of less then 15°) to the transects along which the anemome-

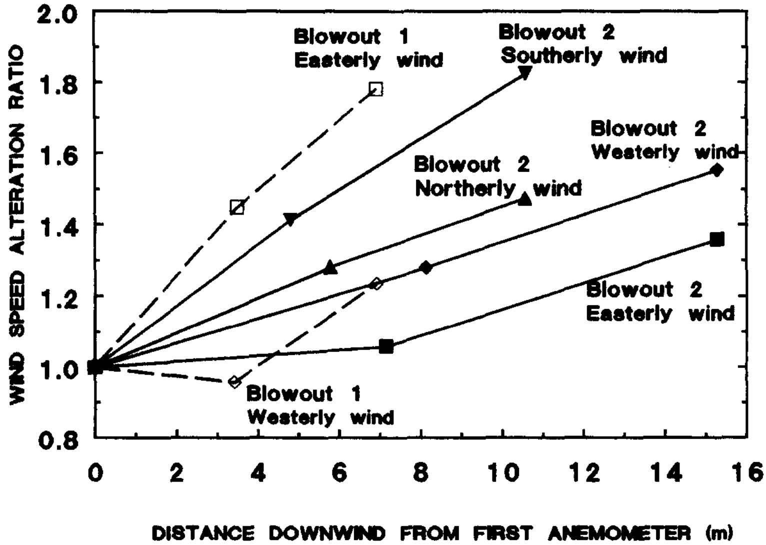

Fig. 3: *Average wind alteration ratio's for wind blowing parallel to the transect, calculated relative to the most upwind anemometer.*

ters were located. Wind speed alteration ratio's indicate the degree to which wind velocity was either reduced or increased at the sample points relative to the most upwind anemometer. The wind speed alteration ratio's for both blowouts are shown in fig. 3.

In general the wind speed increases as it moves along the surface inside the blowout. In blowout 1 the highest alteration ratio's are measured at location W1 during easterly winds with an increase of 78% over a distance of 7 m. In blowout 2 the highest ratio's were found at location N2 during southerly wind with an increase of 83% over 10.6 m.

The acceleration of the wind within the blowouts can be explained by (a combination of):

a) the slopes of the terrain in which the blowouts are located

b) the slopes within the blowouts

c) the change in surface roughness.

Ad a) Wind velocity in the blowout might be related to the geomorphology of the terrain in which the blowouts were formed. It is noted that the acceleration rate remains roughly the same when wind moves along the surface inside the blowout. Therefore the acceleration of the wind might be related to the configuration of the upwind terrain on which the wind is blowing before it enters the blowout. Both blowouts are located on a slope of about 10% near to the top of a dune. Lancaster (1985), Tsoar (1985) and Livingstone (1986) showed for desert sand dunes that as the flow approaches the upstream foot of a hill, the velocity is reduced compared to the flow over flat ground. Wind speed increases rapidly as the flow moves toward the hill top and maximum velocity is reached at the top. This flow acceleration also applies to the windward slope of coastal dunes (Mulligan 1988, Hesp 1989, Rasmussen 1989). At the lee side of hills the wind speed usually decreases from the top to the bottom of the hill (Tsoar 1985, Livingstone 1986). In the blowout an increase of the wind speed is observed even if the blowout is on the lee side. Therefore the topography is not considered to be the most important factor in explaining the acceleration of the wind within the blowout.

Ad b) The influence of the slope of the dune surrounding the blowout on the wind velocity might also apply to the wind on the inner blowout flanks. For wind blowing upslope from the centre to the edge of the blowout convergence of streamlines may have caused wind acceleration. However, it appears that in blowout 2 acceleration occurred during eastern and northern wind. This is surprising in view of the assumption that, if wind is blowing down the inner slope, vertical divergence of streamlines is expected to occur, which would lead to decelerating winds. Moreover it is noted that in this blowout the acceleration has a fairly constant rate for westerly winds blowing along the transect W2-C2-E2 and for southerly winds blowing along the transect S2-C2-N2. The increase of the slope along the first part of the transect compared to the second part does not influence the acceleration rate. Apparently, acceleration and deceleration of wind within the blowout tend not to be primary determined by the slope angle of the blowout itself. The modification of the general wind speed pattern in the blowout will be discussed in section 4.

Ad c) Wind speed will increase when entering the blowout because of the low degree of roughness of the bare sand compared to the vegetated area surrounding the blowout. Hesp (1989) and Rasmussen (1989) state that the equilibrium between the applied force from above and the retarding drag of the ground is reached "rapidly" for local changes in roughness, but their observations provide no quantitative information. Observations by Hallsworth et al. (1982) indicate that, at a decrease in average size of the surface irregularities of 35 cm, the wind velocity at 1 metre height adjusts within a downwind distance of 5 m.

The height of the internal boundary layer (the layer which is affected by the change in surface roughness) can be determined as a function of the fetch, being the distance downwind from a change in surface roughness (Elliott 1958, Rao et al. 1974, Panofsky et al. 1982, Kroon 1985):

$$h/z_{o2} = a(x/z_{o2})^{0.8} \qquad (1)$$

where a = 0.75–0.03 $\ln(z_{o2}/z_{o1})$, h = depth of the internal boundary layer, z_{o1} and z_{o2} are the aerodynamic roughness lengths respectively upwind and downwind of the border, x = the distance downwind from the change in surface features (fetch).

The actual aerodynamic roughness length has not been measured in our situation, so we have to use estimated values. The roughness length for the area surrounding the blowout (z_{o1}) was considered to be 4 mm (Bressolier & Thomas 1977, Stull 1988, Jacobs & van Boxel 1988) and that for bare sand (z_{o2}): 0.1 mm (Vugts & Cannemeijer 1981, Stull 1988). If the height of the internal boundary layer must equal the height at which the cup-anemometers measure the wind speed (18 cm) fetch needed appears to be about 1.4 m. However one has to bear in mind that only the lowest part of the internal boundary layer has adjusted to the new surface and has a normal (logarithmic) wind profile. The height of the adapted layer is estimated to 15% of the affected layer (Monteith 1973). Therefore a fetch of approximately 15 m is required in order to create an adapted layer of 18 cm height. Elliott (1958) showed that in his case the wind speed at 20 cm height increases up to at least 50 m after the step in surface roughness (fig. 4, p. 1052). Since the change in surface roughness at blowouts (from 4 mm to 0.1 mm) is of the same order of magnitude as in Elliot's research (from 20 mm to 0.2 mm), it follows that the decrease in surface roughness strongly affects the change of the wind speed near the surface, even at 18 cm height.

From this analysis we conclude that the change in surface roughness is the main cause of the acceleration of the wind within the blowouts.

4 The modification of the general wind speed pattern within the blowout

In order to assess the sensitivity of the two blowouts to the general wind characteristics, the wind velocities in the blowouts were compared with the data from Valkenburg. Paired average wind velocity values of Valkenburg and the sample locations in the blowouts were used to calculate regression equations for both eight and twelve wind sectors. It appeared that the use of twelve sectors gave more reliable results than the use of eight sectors. Only the ENE sector gave insignificant results due to the low quantity of data.

Most regression equations gave a good fit using a simple linear equation $y = ax$ in which y indicates the wind velocity in the blowout at a height of 18 cm, x the wind velocity measured in Valkenburg at a height of 10 metres and a is the regression coefficient. Most correlation coefficients were within the range of 0.7 to 0.9. All directions reveal a certain degree of scatter caused by: the choice of the classes used for Valkenburg (0.5 m/s for wind speed and 10° for direction), the variability of the wind directions within the wind sectors, differences in atmospheric stability, and inaccuracies in cup-anemometer heights.

The mean response of each individual location to the general wind is expressed graphically in fig. 4. In blowout 1 the highest regression coefficients are found during E and ESE winds. For blowout 2 the highest relative wind velocities were recorded for SSW and WSW winds. The sensitivity of the eight locations in the two blowouts to the general wind clearly varies between the blowouts as well as within the blowouts. The differences between the blowouts are primarily related to the distance from the sea and the height of the local terrain, relative to the surroundings. It is likely that the comparatively high position of blowout 1 in the surrounding terrain is the reason why the highest velocity is attained for this blowout. The sensitivity of blowout 2 for wind from directions between W and S might be explained by its relatively short distance to the coast.

The way in which the locations in the blowout respond to wind from different directions is more irregular for blowout 2 than for blowout 1. At blowout 2 relatively high wind velocities are encoun-

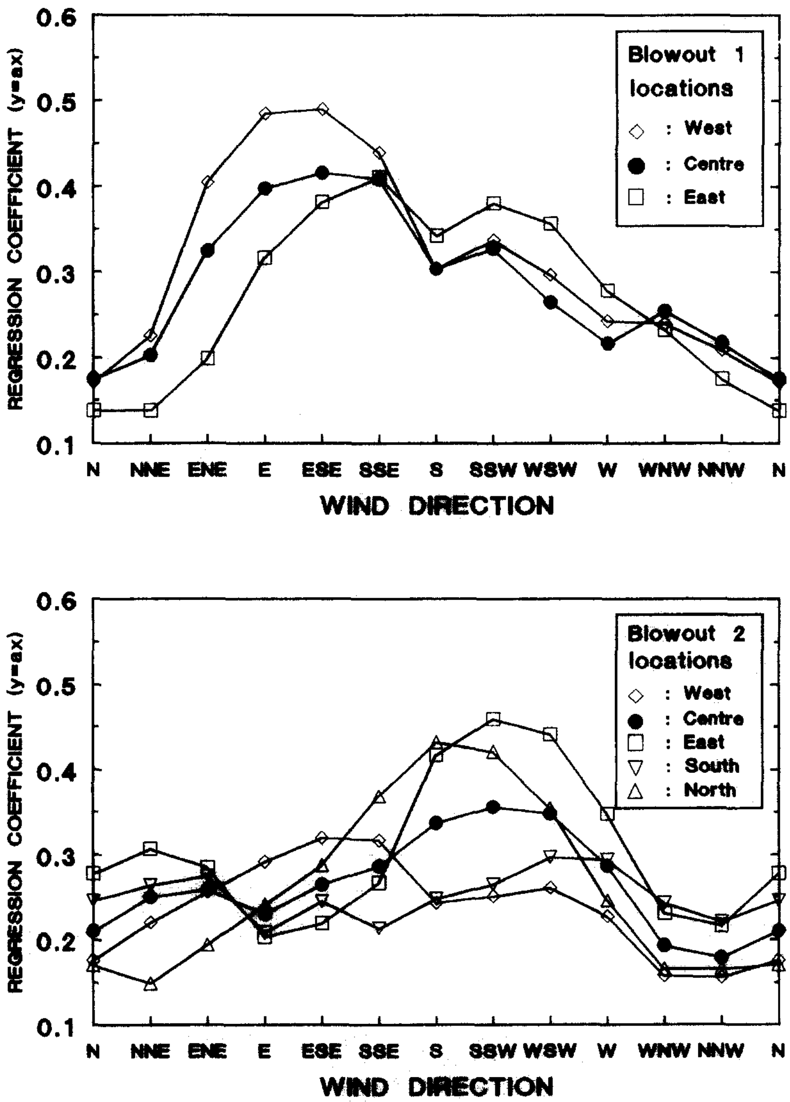

Fig. 4: *The regression coefficients of the equations expressing the relationship between the general wind velocity in Valkenburg and the wind velocity in the blowouts 1 and 2 on three and five locations, respectively.*

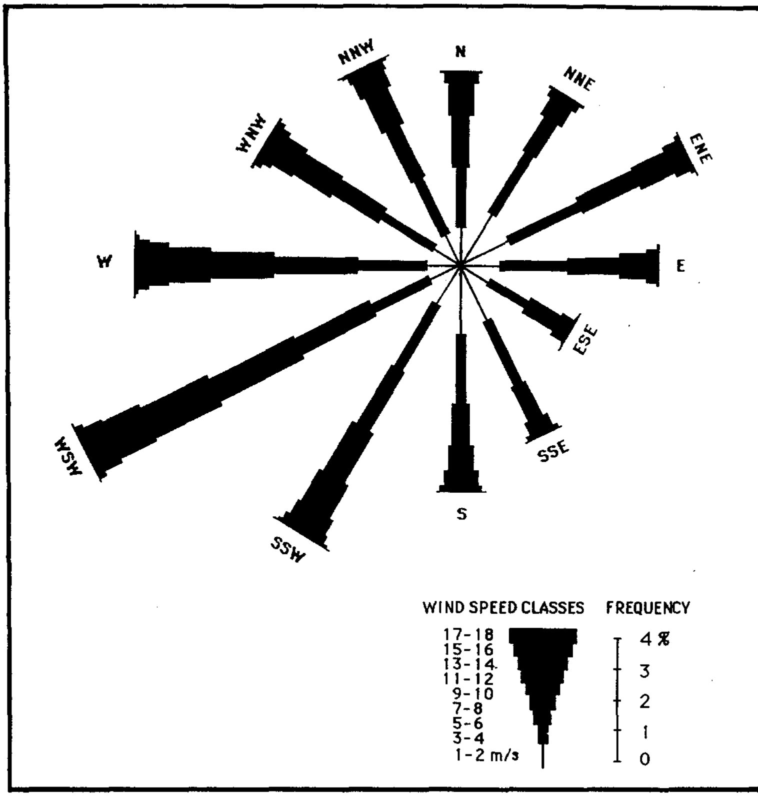

Fig. 5: *Wind frequency distribution in Valkenburg during the period 1961-1980 for nine wind velocity classes and twelve wind direction classes.*

tered for many wind directions at location E2. Greatest wind velocity differences are found at location N2, established by comparatively low velocities during NNE winds and high velocities during S winds. On the other hand, location S2 responds almost equally to all wind directions. Only for W and SW winds, the relative velocity is slightly higher.

At certain wind directions, some surface areas in the blowout may become under the lee of steep inner flanks. For instance, location N2 in blowout 2 is sheltered from wind directions between WNW and NNE as it is located up the steep inner blowout slope facing south. Location E2, located up the inner slope facing west, is sheltered for E and ESE winds. It is comparatively less sheltered from N and NNE winds. Apparently these winds are able to enter the blowout here due to the absence of steep inner slopes at this side.

It is important to consider that these results apply to the two study sites, being representative of shallow saucer shaped blowouts. The influence of

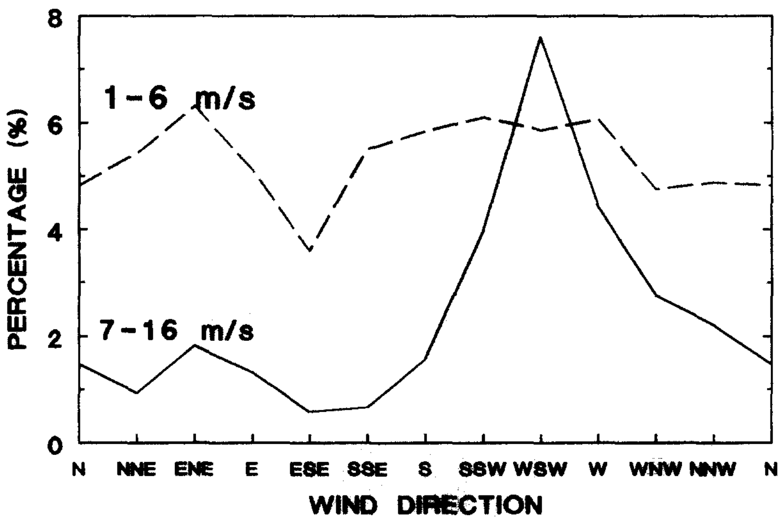

Fig. 6: *Directional distribution of sand moving winds (continuous line) and inactive winds (dashed line) at Valkenburg.*

the internal blowout morphology on the wind velocity is likly to be more important in trough blowouts which have high steep flanks (Carter et al. 1990), inducing strong turbulence flow (Hails & Bennett 1980). Wind velocity in trough blowouts is clearly stronger if it is blowing along the centreline axis (Carter et al. 1990).

5 Distribution of wind speed and direction at Valkenburg

The wind climate is based on hourly values of mean wind velocity and direction measured at Valkenburg. The data consist of twelve wind directional sectors and ten wind velocity classes (width 2 m/s) over a period of 20 years (1961–1980). The distribution of wind speed and direction at Valkenburg is shown in fig. 5. The wind climate is characterized by the more frequent SSW, WSW and W winds of which the frequency of occurrence exceeds the average 8.3% of the time. The highest velocity wind is the WSW wind, but the frequency differences seem too small to distinguish a clear prevailing wind direction.

According to observations by Jungerius et al. (1981) the sand can only be moved by a wind velocity exceeding 6.25 m/s. Therefore division is made between inactive winds (1–6 m/s) and sand moving winds (7–16 m/s) (fig. 6). In general the effective winds (sand moving winds) occur at about one third of the time. The inactive winds are almost evenly distributed over all directions, but there is a strong prevalence of the high speed winds for SSW, WSW and W directions.

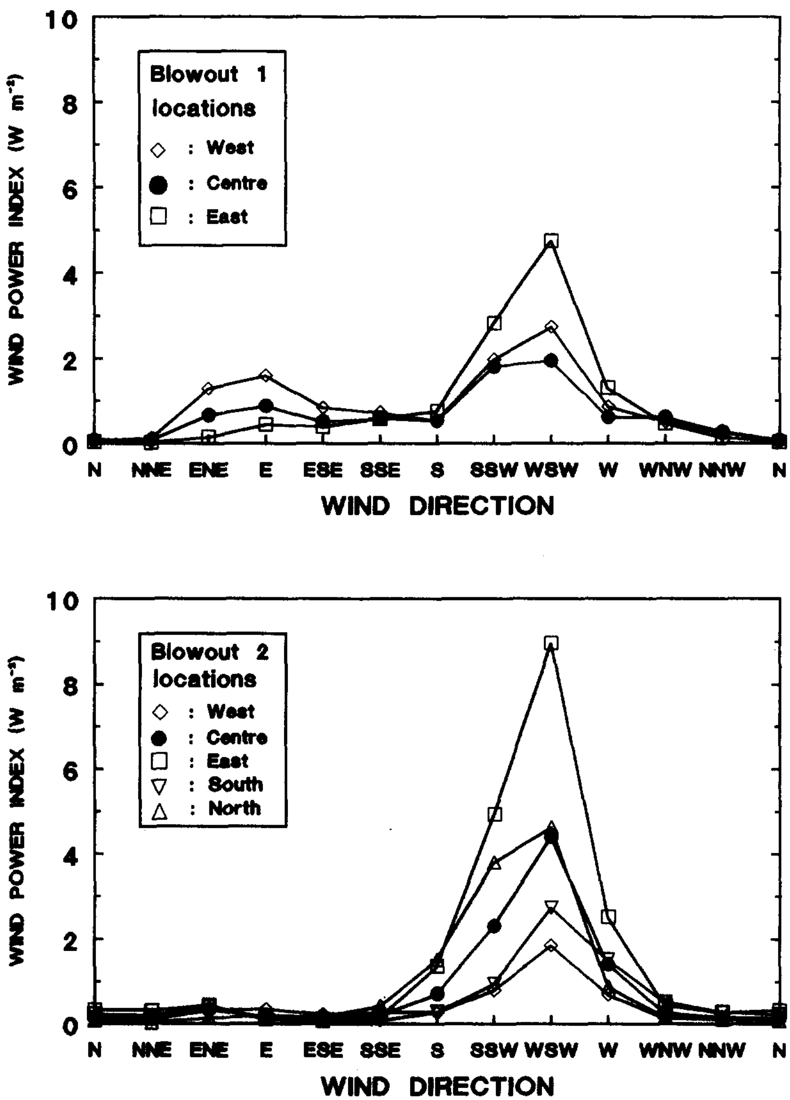

Fig. 7: *Wind power values which take into account the relationship between wind velocity in the blowouts and velocity at Valkenburg in combination with the wind frequency distribution.*

6 The significance of the wind power distribution for algal crust development in blowouts

The following computation takes into account the results of the wind velocity measurements in combination with the frequency of occurrence of the wind. The wind climate at each location within the blowout is simulated with the aid of long term (1961–1980) hourly wind velocity measurements at Valkenburg and the regression coefficients derived in section 4. From the simulated distribution of wind speeds and directions within the blowout the wind power is calculated for each location and each wind direction:

$$P_s = \rho \cdot \Sigma(a_s \cdot U)^3 \cdot F_{u,s} \tag{2}$$

where P_s = average wind power for each wind sector over a period of 20 years (W/m^2), ρ = the average density of the air (1.22 kg/m^3), a_s = regression coefficient for the relationship between wind velocity in the blowout and in Valkenburg, U = mean hourly wind velocity at standard 10 m height (m/s), $F_{u,s}$ = percentage of wind with strength U from section s, and s = wind direction class of 30° width. The cube of the wind velocity is used because the rate of sand transport is assumed to be proportional to the third power of the wind velocity (Bagnold 1941). The wind power calculated in this fashion is not an absolute value, but depends strongly on the height for which the regression coefficient a_s was derived. Therefore only wind power values which are calculated for the same heights can be compared.

The wind power distribution of the blowouts is characterized by high wind powers for SSW to W winds (fig. 7). It appears that the frequency distribution of the wind greatly influences the wind power values. Locations W1 and C1 in blowout 1 obtained the highest relative wind velocities for ENE to SSE directions but as high wind speeds from these directions have a low frequency the resulting wind power values are relatively low. Locations at the eastern side of both blowouts attained high velocity winds occurring at a high frequency.

Comparison of fig. 1 with fig. 7 shows that the lowest wind power values are obtained for the locations were algal crusts are most frequently found. The results demonstrate the importance of wind velocity distribution for the overall endurance of algae at a location in the blowout: at high speeds the algal crust is damaged by moving sand.

7 Conclusion

Pluis & de Winder (1989) noted that the spatial distribution of algae should be explained in terms of the balance between colonization and destruction. It was hypothesed that the overall greater endurance of algae at the SW part of the blowout compared to the rest of the blowout area is caused by an overall lower wind velocity there. The disappearance of algae from other locations was attributed to abrasion by saltating sand grains moved by the higher wind speeds prevailing there. A simulation model based on long term wind velocity measurements shows that the expected spatial wind velocity pattern indeed exists.

Acknowledgements

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References

BAGNOLD, R.A. (1941): The physics of blown sand and desert dunes. London. Methuen, 265 pp.

BOROWKA, R.K. (1980): Present day dune processes and dune morphology on the Léba Barrier, Polish coast of the Baltic. Geografiska Annaler **62A**, 75–82.

BRESSOLIER, C. & THOMAS, Y.F. (1977): Studies on wind and plant interactions on French Atlantic coastal dunes. Journal of Sedimentary Petrology **47**, 331–338.

CARTER, R.W.G., HESP, P.A. & NORDSTROM, K.F. (1990): Erosional landforms in coastal dunes. In: Nordstrom, K.F., Psuty, N.P. & Carter, R.W.G. (eds.), Coastal Dunes; Form and Process. 217–249.

ELLIOTT, W.P. (1958): The growth of the atmospheric internal boundary layer. Transactions American. Geophys. Union **39**, 1048–1054.

HAILS, J.R. & BENNETT, J. (1980): Wind and sediment movement in coastal dune areas. Coastal Engineering, Proc. 17th Conf. Coast. Eng., ASCE, 1565–1575.

HALLSWORTH, E.G., BEATTIE, J.A. & DARLEY, W.E. (1982): Formation of soils in an aridic environment western New South Wales, Australia. In: D.. Yaalon (ed.), Aridic soils and geomorphic processes. CATENA SUPPLEMENT **1**, 83–102.

HESP, P.A. (1989): A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. Proceedings of the Royal Society of Edinburgh **96B**, 181–201.

HYSON, P. (1972): Cup anemometer response to fluctuating wind speeds. J. Appl. Meteorol. **11**, 843–848.

JACOBS, A.F.G. & VAN BOXEL, J.H. (1988): Computational parameter estimation for a maize crop. Boundary-Layer Meteorol. **42**, 265–279.

JUNGERIUS, P.D., VERHEGGEN, J.T. & WIGGERS, A.J. (1981): The development of blowouts in 'De Blink', a coastal dune area near Noordwijkerhout, The Netherlands. Earth Surface Porcesses and Landforms **6**, 375–396.

JUNGERIUS, P.D. & VAN DER MEULEN, F. (1989): The development of dune blowouts as measured with erosion pins and sequential air photos. CATENA **16**, 369–376.

JUNGERIUS, P.D., VAN DER MEULEN, F., LOEDEMAN, J.H. & STUIVER, J. (1992): A geometrical approach to monitoring blowout development from aerial photographs using a Geographical Information System (GIS). In: Carter, R.W.G., Curtis, T.G.F. & Sheehy-Skeffington, M.J. (eds.), Coastal dunes: Geomorphology, ecology and management. Balkema, Rotterdam/Brookfield, 129–138.

KAGANOV, E.I. & YAGLOM, A.M. (1976): Errors in windspeed measurements by rotation anemometers. Boundary Layer Met. **10**, 15–34.

KROON, L.J.M. (1985): Profile derived fluxes above inhomogeneous terrain: a numerical approach. Ph. D. thesis Agricultural University Wageningen, 159 pp.

LANCASTER, H. (1985): Variations in wind velocity and sand transport on the windward flanks of desert sand dunes. Sedimentology **32**, 581–593.

LIVINGSTONE, I. (1986): Geomorphological significance of wind flow patterns over a Namib linear dune. In: W.G. Nickling (ed.), Aeolian Geomorphology. 97–112.

MAC CREADY, P.B. (1966): Mean wind speed measurements in turbulence. J. Applied Meteor. **5**, 219–225.

MONTEITH, J.L. (1973): Principles of environmental physics. Edw. Arnold Ltd., London. 241 pp.

MULLIGAN, K.R. (1988): Velocity profiles measured on the windward slope of a transverse dune. Earth Surface Processes and Landforms **13**, 573–582.

PLUIS, J.L.A. & DE WINDER, B. (1989): Spatial patterns in algal colonization of dune blowouts. CATENA **16**, 499–506.

PLUIS, J.L.A. & DE WINDER, B. (1990): Natural stabilization. In: T.W.M. Bakker, P.D. Jungerius & J.A. Klijn (eds.), Dunes of the European coasts. CATENA SUPPLEMENT **18**, 195–208.

PANOFSKY, H.A., LARKO, D., LIPSCHUTZ, R., STONE, G., BRADLEY, E.F., BOWEN, A.J. & HOJSTRUP, J. (1982): Spectra of velocity components over complex terrain. Quart. J. Roy. Meteor. Soc. **108**, 809–830.

RASMUSSEN, K.R. (1989): Some apects of flow over coastal dunes. Proceedings of the Royal Society of Edinburgh **96b**, 129–147.

RAO, K.S., WIJNGAARD, J.C. & COTE, O.R. (1974): The structure of the two-dimensional internal boundary layer over a sudden change of surface roughness. J. Atmos. Sci. **31**, 738–746.

STULL, R.B. (1988): An introduction to boundary layer meteorology. Kluwer Academic Publishers, Dordrecht, 666 pp.

TSOAR, H. (1985): Profiles analysis of sand dunes and their steady state signification. Geografiska Annaler **67A**, 47–59.

VAN DEN ANCKER, J.A.M., JUNGERIUS, P.D. & MUR, L.R. (1985): The role of algae in the stabilisation of coastal dune blow-outs. Earth Surface Processes and Landforms **10**, 189–192.

VUGTS, H.F. & CANNEMEIJER, F. (1981): Measurements of drag coefficients and roughness length at a sea-beach interface. J. Appl. Meteor. **20**, 335–340.

WIERINGA, J. (1980): A revaluation of the Kansas mast influence on measurements of stress and cup anemometer overspeeding. Boundary Layer Meteorology **18**, 411–30.

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