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# AEOLIAN PROCESSES ACROSS TRANSVERSE DUNES. I: MODELLING THE AIR FLOW

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## ABSTRACT

This paper discusses a two-dimensional second-order closure model simulating air flow and turbulence across transverse dunes. Input parameters are upwind wind speed, topography of the dune ridge and surface roughness distribution over the ridge. The most important output is the distribution of the friction velocity over the surface. This model is dynamically linked to a model that calculates sand transport rates and the resulting changes in elevation. The sand transport model is discussed in a separate paper.

The simulated wind speeds resemble patterns observed during field experiments. Despite the increased wind speed over the crest, the friction velocity at the crest of a bare dune is reduced compared to the upstream value, because of the effect of stream line curvature on turbulence. These curvature effects explain why desert dunes can grow in height. In order to obtain realistic predictions of friction velocity it was essential to include equations for the turbulent variables in the model. In these equations streamline curvature is an important parameter.

The main flaw of the model is that it cannot deal with flow separation and the resulting recirculation vortex. As a result, the increase of the wind speed and friction velocity after a steep dune or a slipface will be too close to the dune foot. In the sand transport model this was overcome by defining a separation zone. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS air flow; wind; modelling; turbulence; curvature; dunes; wind erosion; aeolian processes

## INTRODUCTION

When studying wind erosion, or more generally the processes involved in aeolian detachment, transport and deposition of sediments, the turbulent characteristics of the air flow are important, since these determine the erosivity of the wind. The erodibility of the surface, on the other hand, is determined by factors such as grain size distribution and moisture content of the sediment, the presence of crusts etc. (e.g. Nickling, 1984; Nickling and Davidson-Arnott, 1990; Sherman and Hotta, 1990; Arens, 1994, 1996). The erosivity of the wind can be reduced by vegetation or vegetation residues on the surface (Raupach, 1992; Hagen and Armbrust, 1994; Hesp, 1983; Wasson and Nanninga, 1986; Buckley, 1987; Hagen, 1996).

Bagnold (1941) used the saltation process to derive a semi-empirical relation to model the transport capacity of the flow. Most sand transport equations published since (e.g. Kawamura, 1964; Lettau and Lettau, 1977; White, 1979; Sherman *et al.*, 1998) are modifications of Bagnold's original formula. Erosivity is expressed in terms of friction velocity $U_*$, whereas erodibility is expressed by a threshold friction velocity $U_{*t}$. Aeolian transport can occur if the friction velocity exceeds $U_{*t}$. So, from the aerodynamical point of view, friction velocity is the most important input parameter for modelling aeolian transport rates.

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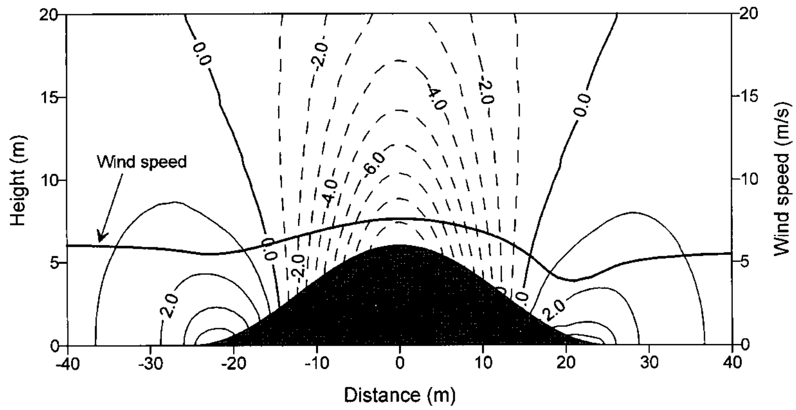


Figure 1. Wind speed at 2m height (thick line) and the kinematic pressure perturbation ($m^2 s^{-2}$) distribution over a 6m high sine-shaped dune. Negative values are indicated by broken lines

Over flat, uniform terrain under neutral atmospheric stability conditions, friction velocity can be obtained from the well known logarithmic wind profile. The constraint of neutral atmospheric stability does not limit the applicability of the logarithmic wind profile for calculating friction velocity and the resulting transport rates, since over most surfaces sediment transport starts at mean wind velocities over 6m $s^{-1}$ (at 2m height) and most transport takes place at considerably higher wind speeds. At these wind speeds the atmosphere can usually be considered to be near-neutral. The constraints of uniform and flat terrain do limit the applicability of the logarithmic wind profile over many surfaces.

When wind passes a roughness transition, an internal boundary layer develops, which grows slowly with the fetch over the new terrain (e.g. Elliott, 1958; Monteith, 1973; Stull, 1998). Above this internal boundary layer the flow is unaffected by the change in surface roughness. The growth rate of the internal boundary layer depends mainly on the roughness of the new terrain. For bare sand, a rough estimate of the thickness of the internal boundary layer would be 10 per cent of the fetch over the new terrain. However, only the lowest 10–15 per cent of the internal boundary layer has a logarithmic wind profile (Monteith, 1973). In the remainder, friction velocity gradually changes with height. Consequently, if one wishes to derive friction velocity from wind speed measurements up to 2m height one needs a uniform upwind fetch of approximately 200m

The effect of topography is more difficult to understand. A transverse dune or hill acts as an obstacle in the flow. In front of the dune and over the lower part of the slope the flow has to be deflected upward. The force needed for this deflection is provided by an excess pressure in front of the dune (Figure 1). Over the upper part of the slope and over the dune top the upward velocity will decrease due to a negative pressure perturbation. If the curvature of the surface is too strong, the negative pressure perturbation might not be large enough to keep the flow attached to the surface and flow separation will occur. Nevertheless it is hard to predict under which conditions flow separation will occur (Finnigan, 1988). At the leeward dune foot (or at the reattachment point), the wind, which is now moving down, has to be deflected to the horizontal again. Therefore a positive perturbation pressure will develop at the leeward dune foot (Figure 1). In general, concave slopes generate positive pressure perturbations and convex slopes generate negative pressure perturbations.

Pressure perturbations affect the horizontal component of the wind speed. Where pressure increases in the streamwise direction the wind speed decreases and where the pressure decreases the wind speed increases. So, in front of the dune wind speed decreases, and it increases on the windward slope. Over the crest wind speeds are relatively high. Downwind of the crest wind speed decreases again.

 

Jackson and Hunt (1975) modelled these effects for very gently sloping hills: $H/L < 0{\cdot}05$, where $H$ is hill height and $L$ is usually defined as the horizontal distance between the crest and half-height. The restriction of $H/L < 0{\cdot}05$ means that the slopes cannot be steeper than 3°. So, the requirements for the Jackson and Hunt (1975) model are not met in the case of flow over dunes. Moreover, for irregularly shaped dunes it becomes very difficult to define the horizontal length scale (Arens, 1994; Arens *et al.*, 1995).

Effects of streamline curvature on turbulence are much harder to understand (these are discussed in a later section). However, for flow over dunes or hills steeper than 3–5° these effects cannot be neglected. Turbulence is important since turbulent transport of momentum directly affects the mean flow. Other turbulent parameters affect the momentum flux and therefore they have an indirect influence on the mean flow field. Moreover, friction velocity is a turbulent parameter, since it is defined as the square root of the kinematic momentum flux. Only under favourable conditions (homogeneous, flat surface and neutral stability) can the friction velocity be derived from the logarithmic wind profile.

Our aim was to develop a flow model that provides adequate information on the friction velocity over bare or vegetated foredunes. This model operates in conjunction with an aeolian sand transport model (Van Dijk *et al.*, 1999). The flow model calculates flow characteristics, i.e. friction velocity, as it is influenced by topography and surface roughness. The sediment transport model uses the friction velocity, sediment characteristics, topography and vegetation properties to calculate erosion, deposition and topographical changes (Van Dijk *et al.*, 1999). These models were designed to study foredune development and the dynamics involved, but they should also be applicable to transverse desert dunes. Moreover, the models can provide valuable information about the dynamics of wind erosion processes over sloping or hilly terrain.

## DESCRIPTION OF THE FLOW MODEL

The flow model is designed to simulate air flow across linear ridges. For the time being the model is only applied to flows perpendicular to the ridge or foredune. Since the model is applied to perpendicular flow over long ridges, gradients perpendicular to the flow are negligible. Therefore a two-dimensional model space is used with the horizontal coordinate in the wind direction and a vertical coordinate. In the future we intend to investigate also the applicability of the model to oblique flows.

The flow model is a two-dimensional second-order closure model based on fluid dynamaics. It uses forward integration along streamlines. The model runs on a PC. This section starts with a global description of the model and the effects of streamline curvature, followed by an outline of the differential equations involved. A more detailed description of the model theory is given by Van Boxel and Arens (1997).

### *Global description*

The theory for modelling turbulent flow in the atmospheric boundary layer over flat terrain is rather well developed (e.g. Deardorff, 1973; Donaldson, 1973; Stull, 1988). Some models also account for roughness transitions (e.g. Rao *et al.*, 1974; Kroon, 1985). For very gently sloping hills ($H/L < 0{\cdot}05$) the Jackson and Hunt (1975) model can be used. For steeper hills the effect of streamline curvature on the turbulence cannot be neglected. Finnigan (1988) and Zeman and Jensen (1987) discuss the theory needed to model these effects. Originally we tried using the model developed by Zeman and Jensen (1987) as was done by Zeman and Jensen (1988) and Mikkelsen (1989). However, we found that their implementation of the model was not flexible enough to be applied to many different situations. Therefore we developed a new model on the basis of the theory presented by Zeman and Jensen (1987).

In the model, the pressure perturbation ($P$) is calculated as a function of topography and wind speed. The mean wind speed ($U$) is obtained by forward integration along a streamline oriented grid using a deterministic equation. This equation contains second moments (i.e. $\overline{uu}$ and $\overline{uw}$ which are strongly affected by the streamline curvature, induced by the dune. Therefore deterministic equations are included for turbulent parameters such as variance of wind speed in the wind direction $\overline{uu}$, perpendicular to the wind direction ($\overline{vv}$) and in the vertical direction ($\overline{ww}$), vertical flux of momentum ($\overline{uw}$) and dissipation (ε). These second-order equations contain third moments. The model does not include sound physical equations for the third moments, but parameterizations. Since the parameterization is done at the second-order level, it is called a second-order closure model (Stull, 1988).

The upwind profiles of $U$, $\overline{uu}$, $\overline{vv}$, $\overline{ww}$, $\overline{uw}$ and ε are obtained by running the model over a long stretch of uniform terrain, after starting from arbitrary profiles. The upper boundary of the model is taken at approximately 3 km height, which is well above the planetary boundary layer. Here the wind is assumed constant and the turbulent fluctuations are assumed to be negligible, so $\overline{uu}=\overline{vv}=\overline{ww}=\overline{uw}=\varepsilon=0$. At the lower boundary (height equal to topography plus local roughness length) wind speed is assumed zero, momentum flux is assumed to be invariant with height and the variances are assumed to be proportional to the momentum flux. Based upon Wilson and Shaw (1977), Taylor and Teunissen (1983) and Zeman and Jensen (1987) we choose $\overline{uu}/\overline{uw}=-4{\cdot}4$, $\overline{vv}/\overline{uw}=-2{\cdot}5$ and $\overline{ww}/\overline{uw}=-1{\cdot}6$.

At any point the differential equations are used to calculate rate of change of the dynamic variables $\mathrm{d}XX/\mathrm{d}x$ (where $XX$ can be $U$, $\overline{uu}$, $\overline{vv}$, $\overline{ww}$, $\overline{uw}$ or ε). The profiles of the dynamic variables in the next point are calculated from this rate of change and the distance step d$x$. Step size is adjusted so that none of the variables will change more than 2 per cent during one step. After the new wind speed is calculated, the height of each streamline is determined using the assumption of incompressibility and the continuity equation.

Because of the forward integration scheme, the model cannot handle recirculation vortices. If one wants to handle flow separation and recirculation in a physically correct way, much more complicated models are needed (Jensen, 1988). In our model recirculation is avoided by prescribing that friction velocity and wind velocity at any height cannot be less than 25 per cent of its upwind value. This is generally low enough to have a friction velocity below the critical friction velocity needed for sediment transport, so that the transport capacity reduces to zero, but it is high enough to let the model run smoothly over common dune topographies. We realize, however, that this is not a sound physical approach. One of the drawbacks of this approach is that the point where the flow starts to accelerate again (reattachment point) is too close to the leeward foot of the dune. However, this error has only minor effects on practical applications. In the case of bare dunes a slipface usually develops, which prevents removal of sediment from the back of the dune. In the case of vegetated dunes the sediment transport at the back of the dune is limited by the presence of vegetation.

### *Effects of streamline curvature*

The effect of streamline curvature on turbulence and thereby on mean flow and friction velocity is very important. Streamline curvature ($R$) is defined as positive on concave slopes (near the dune foot) and negative on convex surfaces (near the dune top).

At the dune foot curvature ($R$) is positive. In the momentum flux equation (9) the term $-(2\overline{uu}-\overline{ww})U/R$ causes a decrease in $\overline{uw}$. But since $\overline{uw}$ is negative this means that in absolute sense momentum flux and also friction velocity ($U_*\sqrt{(-\overline{uw})}$) increase. Turbulent kinetic energy ($qq\equiv\overline{uu}+\overline{vv}+\overline{ww}$ increases ($2\overline{uw}\ U/R-4\overline{uw}\ U/R$, with $\overline{uw}$ always negative), mainly due to an extra production of vertical variance ($\overline{ww}$). These effects can be compared to the effects of an unstable boundary layer stratification, which also produces more vertical fluctuations and an increase in the absolute value of the momentum flux.

Near the top, where the slope is convex and curvature is negative, the effects are reversed. Turbulent kinetic energy and the absolute value of the momentum flux are reduced. The friction velocity decreases, despite the higher wind velocities. In fact one of the reasons for the acceleration of the wind is the reduced friction. This situation could be compared to stable stratification, where the fluxes are very small, and the gradients can become very steep.

*Calculating pressure perturbation*

The kinematic pressure perturbation due to the presence of an obstacle (dune) in the flow is calculated from (Zeman and Jensen, 1987):

$$P(x,z) = -U_0^2 \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{\eta'(s)\,(x-s)}{(x-s)^2 + z^2}\,\mathrm{d}s \qquad [\mathrm{m^2 s^{-2}}]\ (1)$$

where $x$ and $z$ are the horizontal and vertical coordinate, $s$ is the integration variable, which varies along the horizontal coordinate, $U_0$ is a reference velocity for which we choose the geostropic wind speed. Zeman and Jensen (1987) are not clear about their shape function $\eta'(s)$, but from the Fortran code of their model we concluded that it was equal to the tangent of the slope divided by the height of the dune. This shape function has three flaws. Firstly, it becomes large for very small dunes. Secondly, it goes to infinity for very steep slopes. Thirdly, it is not dimensionless, so the dimensions of Equation 1 will not be correct. We therefore choose:

$$\eta'(s) \;=\; \mathrm{Par}\,\sin(\alpha) \qquad (2)$$

where $\alpha$ is the slope and *Par* is a dimensionless proportionality constant. By fitting the calculated friction velocity to data published by Zeman and Jensen (1987) for the top of Askervein hill in Scotland we found a good fit when $Par = 0{\cdot}20$.

*Equation for the mean wind speed*

In many prognostic meteorological models, wind speed is calculated from of the Navier–Stokes equation which in a Lagrangian notation will read:

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fV - \frac{\partial \overline{uw}}{\partial z} \qquad [\mathrm{ms^{-2}}]\ (3)$$

where $\rho$ is the density, $\partial p/\partial x$ the large-scale pressure gradient ($\mathrm{Pa\,m^{-1}}$), $f$ the Coriolis parameter, $V$ the lateral component of the wind speed, and $\partial\overline{uw}/\partial z$ the vertical gradient of the momentum flux. Note that we use the total derivative $\mathrm{d}U/\mathrm{d}t$ instead of the partial derivative $\partial U/\partial t$. Due to this Lagrangian notation the equation contains no advection terms, in contrast to the more conventional Eulerian notation. When $\mathrm{d}U/\mathrm{d}t$ is replaced by $U\,\partial U/\partial x$, $(1/\rho)\partial\rho/\partial x$ by $fV_g$ ($V_g$ = lateral component of the geostrophic wind speed), we introduce the effects of the kinematic pressure perturbation ($P$) and terms resulting from the non-orthogonal coordinate system; we get (Zeman and Jensen, 1987):

$$U\frac{\partial U}{\partial x} = -\frac{\partial P}{\partial x} + (V - V_g)f - \frac{\partial \overline{uw}}{\partial z} - \frac{\partial \overline{uu}}{\partial z} - \frac{W}{U}\frac{\partial \overline{uu}}{\partial z} \qquad [ms^{-2}]\ (4)$$

where $W$ is the vertical velocity and $\overline{uu}$ is the variance of the longitudinal wind velocity. $W/U$ equals the tangent of the streamline slope.

 

*Second-order equations*

The variances of longitudinal ($\overline{uu}$), lateral ($\overline{vv}$) and vertical ($\overline{ww}$) wind speed are calculated from:

$$U\frac{\partial\,\overline{uu}}{\partial x} = -2\,\overline{uw}\,\frac{\partial U}{\partial z} - 2\overline{uu}\,\frac{\partial U}{\partial x} + 2\overline{uw}\,\frac{U}{R} - \frac{C}{T}\left(\overline{uu} - \frac{qq}{3}\right) - RD_{uu} - \frac{\partial\overline{uuw}}{\partial z} - \frac{2}{3}\varepsilon \tag{5}$$

$$U\frac{\partial\,\overline{vv}}{\partial x} = \quad prod\,\overline{vv} \quad - \frac{C}{T}\left(\overline{vv} - \frac{qq}{3}\right) - RD_{vv} - \frac{\partial\overline{vvw}}{\partial z} - \frac{2}{3}\varepsilon \tag{6}$$

$$U\frac{\partial\,\overline{ww}}{\partial x} = \quad +2\,\overline{ww}\,\frac{\partial U}{\partial x} - 4\overline{uw}\,\frac{U}{R} - \frac{C}{T}\left(\overline{ww} - \frac{qq}{3}\right) - RD_{ww} - \frac{\partial\overline{www}}{\partial z} - \frac{2}{3}\varepsilon \tag{7}$$

**I II III IV V VI VII**

where $R$ is the streamline curvature, $C$ is a proportionality constant (Zeman and Jensen (1987) proposed $C = 3{\cdot}25$), $T$ is the dissipation time scale ($T \equiv \mathrm{qq}/\epsilon$), $qq$ the turbulent kinetic energy ($qq \equiv \overline{uu} + \overline{vv} + \overline{ww}$), $RD$ is rapid distorion, and $\epsilon$ the dissipation rate.

Term I is a normal production term which is found in any second-order closure model. Term II is an extra production resulting from horizontal gradients due to roughness transitions and topography. Term III models effects of streamline curvature. Term IV represents the redistribution of turbulent kinetic energy between the three directions due to turbulent pressure fluctuations. Term V is redistribution as a result of rapid distortion (deformation of turbulent eddies in a sheered flow). Term VI is a third-order term representing the divergence of the vertical transport. Term VII is dissipation.

Streamline curvature is calculated from (Zeman and Jensen, 1987):

$$R = \left[1 + \left(\frac{\partial z_s}{\partial x}\right)^2\right]^{3/2} \quad \left[\frac{\partial^2 z_s}{\partial x^2}\right]^{-1} \qquad [m] \tag{8}$$

where $z_s$ is the height of the streamline relative to a fixed reference height. Here the radius of curvature is defined as positive if the local centre of curvature lies above the streamline and negative if it lies below the streamline. This is opposite to Zeman and Jensen (1987), but confirms with Finnigan (1988). Over gradual slopes curvature is at first approximation equal to the reciprocal of the second derivative of streamline height.

The vertical flux of horizontal momentum is calculated from:

$$U\frac{\partial\,\overline{uw}}{\partial x} = -\overline{ww}\,\frac{\partial U}{\partial z} \quad - (2\,\overline{uu} - \overline{ww})\,\frac{U}{R} - \frac{C}{T}\,\overline{uw} - RD_{uw} - \frac{\partial\overline{uww}}{\partial z} \tag{9}$$

**I III IV V VI**

The numbering of the terms is the same as in the equations for the variances.

*Modelling rapid distortion*

Rapid distortion is the fast redistribution of turbulent kinetic energy, produced in one direction, over the other directions as a result of the deformation of turbulent eddies in a sheered flow. For the general form of the rapid distortion equations, Zeman and Jensen (1987) refer to Zeman and Tennekes (1975).

 

The rapid distortion term in the variance equations is parameterized as:

$$RD_{uu} = -\left(\frac{2}{3}\alpha_1 + 2\alpha_2\right)\overline{uw}\frac{\partial U}{\partial z} - \frac{4}{3}\alpha_1(\overline{uu} - \overline{vv})\frac{\partial U}{\partial x} - \frac{2}{5}qq\frac{\partial U}{\partial x} + \frac{16}{3}\alpha_2\overline{uw}\frac{U}{R} \quad (10)$$

$$RD_{vv} = +\frac{4}{3}\alpha_1\overline{uw}\frac{\partial U}{\partial z} - \frac{4}{3}\alpha_1(\overline{ww} - \overline{uu})\frac{\partial U}{\partial x} + \frac{4}{3}\alpha_2\overline{uw}\frac{U}{R} \quad (11)$$

$$RD_{ww} = -\left(\frac{2}{3}\alpha_1 - 2\alpha_2\right)\overline{uw}\frac{\partial U}{\partial z} - \frac{4}{3}\alpha_1(\overline{vv} - \overline{ww})\frac{\partial U}{\partial x} + \frac{2}{5}qq\frac{\partial U}{\partial x} - \frac{20}{3}\alpha_2\overline{uw}\frac{U}{R} \quad (12)$$

where $\alpha_1$ and $\alpha_2$ are model parameters calculated from $\alpha_1 = \alpha_0 + \Delta\alpha$ and $\alpha_2 = \alpha_0 - \Delta\alpha$. Zeman and Jensen (1987) proposed $\alpha_0 = 0{\cdot}300$ and $\Delta\alpha = 0{\cdot}075$ resulting in $\alpha_1 = 0{\cdot}375$ and $\alpha_2 = 0{\cdot}225$. In these equations the last terms refers to the effect of rapid distortion on the turbulent kinetic energy produced by curvature terms, whereas the other term reflects the effect of rapid distortion on the turbulence created by the normal production terms.

For the rapid distortion term in the momentum flux equation, Zeman and Jensen (1987) proposed:

$$RD_{uw} = -\frac{1}{5}qq\frac{\partial U}{\partial z} - (\alpha_1 - \alpha_2)b_{11}\frac{\partial U}{\partial z} - (\alpha_1 + \alpha_2)b_{33}\frac{\partial U}{\partial z} - \alpha_2(2\overline{uu} - \overline{ww})\frac{U}{R} \quad (13)$$

where $b_{11} = \overline{uu} - qq/3$ and $b_{33} = \overline{ww} - qq/3$.

In the momentum flux equation we used a simpler parameterization (proposed by Wilson and Shaw, 1977) for rapid distortion created by the normal production terms (not the curvature terms) resulting in:

$$RD_{uw} = -C_R qq\frac{\partial U}{\partial Z} - \alpha_2(2\overline{uu} - \overline{ww})\frac{U}{R} \quad (14)$$

During the initialization phase, when the model is run over homogeneous terrain, the dimensionless proportionality constant $C_R$ is adjusted in such a way that close to the surface the model produces a momentum flux which is invariant with height and a logarithmic wind profile. In all cases the model produced a value slightly above 0·14.

By comparing Equations 13 and 14 one would expect that:

$$C_R = \frac{1}{5} + (\alpha_1 - \alpha_2)\frac{b_{11}}{qq} + (\alpha_1 + \alpha_2)\frac{B_{33}}{qq} \quad (15)$$

If we take $\alpha_1 = 0{\cdot}375$ and $\alpha_2 = 0{\cdot}225$ as proposed by Zeman and Jensen (1987) and assume $\overline{uu}/\overline{uw} = 4{\cdot}4$, $\overline{ww}/\overline{uw} = 1{\cdot}6$ and $qq/\overline{uw} = 8{\cdot}5$ (the lower boundary condition), Equation 15 yields $C_R = 0{\cdot}141$. This is very close to the value determined by the model. However, for any other value of $\Delta\alpha$ the model will calculate values different from those predicted by Equation 15.

*Parameterizing third-order terms (closure)*

The third-order terms (terms VI in Equations 5 to 9) are transport terms. Just as $\overline{uw}$ is the vertical transport ($w$) of horizontal momentum ($u$), we could interpret $\overline{uuw}$ as the vertical transport ($w$) of longitudinal variance ($\overline{uu}$). Deriving explicit equations for these terms would yield more and more complicated equations of which the terms are more difficult to interpret. Furthermore these equations will contain fourth-order terms. Equations for fourth-order terms will contain fifth-order terms etc. This is called the closure problem (Stull, 1988). At some point the set of equations has to be closed by making assumptions for the higher-order terms. Here it is assumed that the transport of $\overline{uu}$, $\overline{vv}$, $\overline{ww}$ or $\overline{uw}$ is proportional to the gradient of the quantities multiplied by a turbulent exchange coefficient:

$$\overline{uuw} = -K\,\frac{\partial\,\overline{uu}}{\partial z}, \quad \overline{vvw} = -K\,\frac{\partial\,\overline{vv}}{\partial z}, \quad \overline{www} = -K\,\frac{\partial\,\overline{ww}}{\partial z}, \quad \overline{uww} = -K\,\frac{\partial\,\overline{uw}}{\partial z} \tag{16}$$

The turbulent exchange coefficient is parameterized as: $K = 0{\cdot}075\ \overline{ww}\ qq/\epsilon$.

*Dissipation*

Some second-order closure models will not contain an explicit equation for the dissipation, but will parameterize it as a function of other turbulent parameters, such as the turbulent kinetic energy (Stull, 1988). Zeman and Jensen (1987), however, proposed:

$$U\frac{\partial \epsilon}{\partial x} = -3{\cdot}8\,(\epsilon - \beta\Pi)\,\frac{\epsilon}{qq} - \frac{\partial}{\partial z}\left(K_\epsilon \frac{\partial \epsilon}{\partial z}\right) \tag{17}$$

Here $\Pi$ is the total production of turbulent kinetic energy, $\beta$ is a dimensionless model parameter (Zeman and Jensen propose $\beta = 0{\cdot}75$) and $K_\epsilon$ is the turbulent exchange coefficient for dissipation (Zeman and Jensen propose $K_\epsilon = 0{\cdot}68K$). The first term on the right-hand side is a production term for dissipation, which depends on the balance between dissipation and production of turbulent kinetic energy, and the second term is a transport term.

## RESULTS FOR THREE TOPOGRAPHIES

This section discusses the results of the flow model for three different topographies. The first example is the flow over a sine-shaped dune ridge. The second and third examples show the flow over dunes that evolved after running the combined flow and sediment transport model (Van Dijk *et al.*, 1999) over this sine-shaped ridge with and without sediment input. Both dunes develop on a fixed surface, meaning no erosion occurs below the level of 0·0m. In all cases the dunes are bare and the roughness length is assumed to be 1mm (this value is considered representative for a bare surface with saltating sand grains).

*Sine-shaped dune*

The sine-shaped dune ridge is 6m high and has a total width of 50m. The maximum slope is 21·6°. Figure 2 shows the wind speeds modelled for a height of 0·5, 2·0 and 10m. The wind speed at a height of 10m is very slightly reduced in front of the dune, increased by 10 per cent at the top and again slightly reduced at the leeward foot. At 0·5m height the reduction of wind speed in front of the dune is 25 per cent and at the top the increase is 54 per cent. The reduction of wind speed on the lee slope is much higher than in front of the dune, but there are no signs of flow separation. Relative speed-ups or reductions do not change if the model is run at different wind velocities. This scaling of the flow field was also observed during extensive field measurements (Arens *et al.*, 1995). Figure 3 shows that modelled wind profiles at the dune foot and over the top deviate from the logarithmic profile. These wind profiles are very similar to profiles observed over low hills (Raupach and Finnigan, 1997).

 

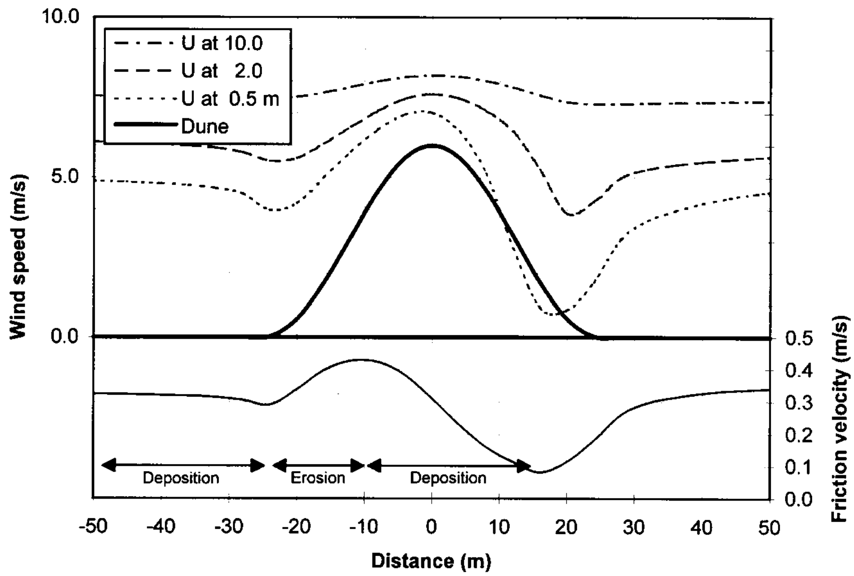


Figure 2. Simulated wind speeds at 0·5, 2 and 10m height and friction velocity at the surface over a 6m high sine-shaped dune. The arrows indicate depositional or erosional areas, based on the simulated friction velocity (ignoring the effect of slope on the threshold friction velocity)

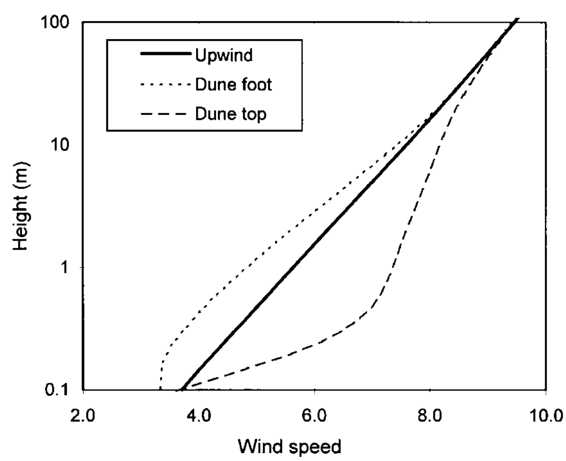


Figure 3. Simulated vertical wind profile upwind (solid line), at the dune foot (dotted line) and over the dune top (dashed line) for a 6m high sine-shaped dune

The reduction of friction velocity in front of the dune is less than the deceleration of the wind at 0·5m height (Figure 2), because the reduction in wind speed is largely compensated by the increased turbulence due to the curvature effects. Similar results were found by Wiggs *et al.* (1996) from wind tunnel experiments.

On the windward slope, where the wind speed accelerates strongly, the friction velocity increases. The maximum friction velocity is found approximately half-way up the slope. Beyond that point friction velocity decreases, despite the still-increasing wind velocity, because convex curvature has effects similar to those of a stable stratification. After the top, friction velocity still decreases slowly to a minimum at

 

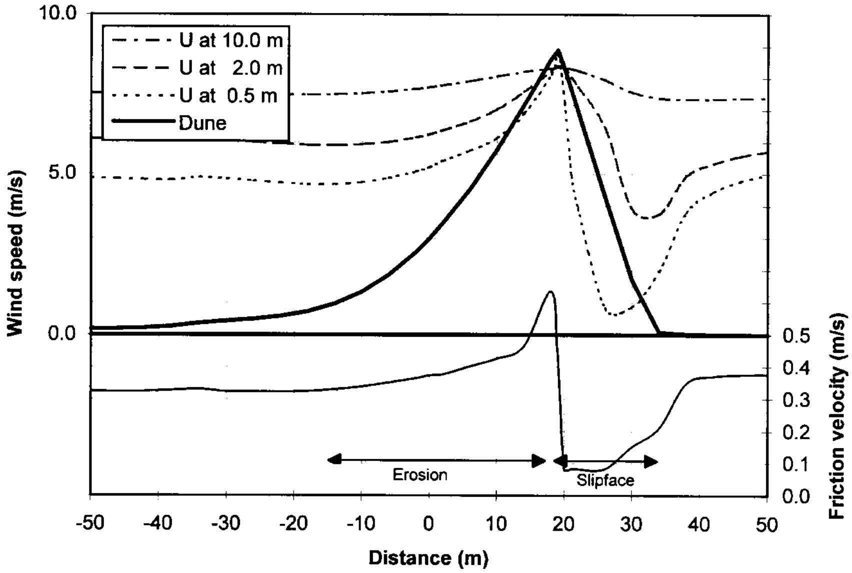


Figure 4. Modelled wind speeds at 0·5, 2 and 10m height and friction velocity over a dune that evolved after simulating 100 days with sediment input (friction velocity was 1·5 times the threshold over flat terrain)

the leeward dune foot. Here concave curvature causes an increase in turbulence intensity and turbulent exchange, resulting in an increased friction velocity to a level which is slightly higher than that in front of the dune. The increased turbulent exchange also causes the wind speed close to the surface to increase to a value that slightly exceeds the wind in front of the dune, but further downstream wind speeds and friction velocity return to their original values.

If there is an input of sediment at the upwind boundary the slight decrease of friction velocity causes deposition in front of the dune. The lower half of the windward slope erodes and deposition occurs on the upper half of the slope and the dune top. This means that initially the slope steepens and the height of the dune increases.

*Dune with sediment input*

This dune shape is created by letting the combined flow and sediment transport model run over the sine-shaped dune for 100 days with an upwind friction velocity which was 1·5 times the critical velocity ($U_{*t} = 0{\cdot}22\,\mathrm{m\,s^{-1}}$). The flow was saturated with sand at the upwind boundary. In most climates it would take several years before one would have 100 days with a wind speed that is strong enough to induce sand transport. The dune has adjusted to the flow. There has been a small deposit in front of the dune (see Figure 4). The dune has grown in height and the crest has moved downwind. The windward slope angle is determined by the upstream friction velocity that is used in the simulation. A slipface developed downwind of the crest. The volume of the dune increased because most of the sand input at the upwind boundary is trapped in the slipface.

Because the dune shape has adjusted to the flow, the wind speed reduction in front of the dune is only 5 per cent (Figure 4). The speed-up of the wind speed at 10m height is slightly stronger than in the case of the sine-shaped dune, probably because of the increased height of the dune. Close to the surface the speed-up is much stronger than in the case of the sine-shaped dune. Over the slipface there is a very strong reduction in wind speed. In reality we would probably have a recirculation vortex here. Beyond

 

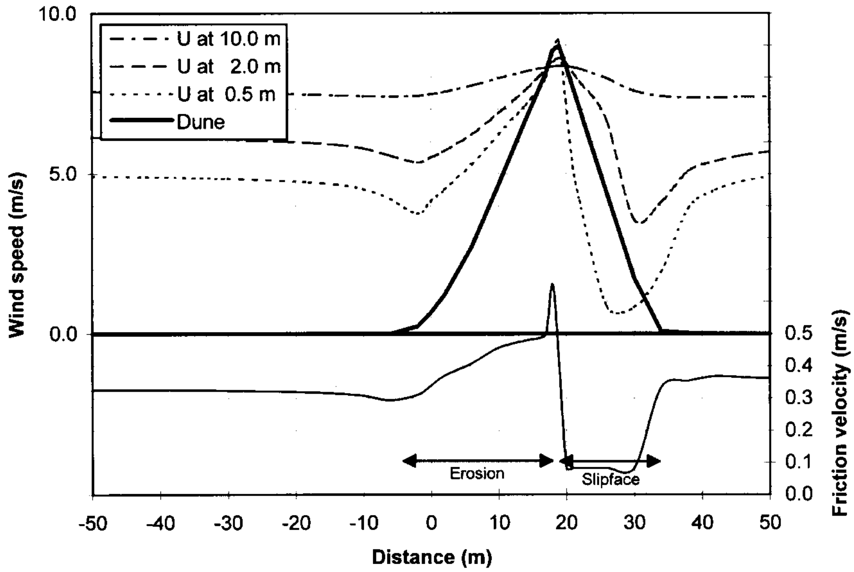


Figure 5. Simulated wind speeds 0·5, 2 and 10m height and friction velocity over a dune that evolved after simulating 100 days without sediment input at the upwind boundary (same friction velocity was used as in Figure 4)

the foot of the slipface the wind speed increases again. Probably this increase is too sharp and too soon, because the model does not allow for flow separation.

In front of the dune the friction velocity is almost constant. On the windward slope there is a slight increase in friction velocity suggesting light erosion. On the other hand, the slope also increases the threshold velocity. So, in order for the sand transport rate to remain constant over the windward slope the friction velocity has to increase. At the crest the convex curvature causes a very strong drop in friction velocity, despite the high wind velocities. This causes a rapid decrease in the sand transport rate and all the sediment is deposited on and just after the crest, feeding the slipface. Over the slipface the modelled friction velocity shows strong reactions to small irregularities in the surface. The modelled course of the friction velocity on the slipface does not look very realistic. In the sediment transport module (Van Dijk *et al.*, 1999) this problem is overcome by defining a separation zone behind the dune in which no erosion takes place.

*Dune without sediment input*

This dune shape is created by letting the combined flow and sediment transport model run over the sine-shaped dune for 100 days with an upwind friction velocity which was 1·5 times the critical velocity. In this case there is no sediment input at the upwind boundary. Therefore the windward slope is always eroding and deposition takes place at and just over the crest. The crest has moved downwind, but less than in the case with sediment input, because less sand was available to feed the slipface.

The reduction of the wind speed at 10m height (Figure 5) is comparable to the simulation over the sine-shaped dune and the acceleration compares to that over the dune with sediment input, which was approximately of the same height and also developed a pronounced crest and a slipface. At the dune foot the reduction of the wind speed at 0·5m height is stronger than in the other cases since the start of the slope is more sudden than in the other cases. The speed-up over the top is stronger because the slope is shorter and the crest is sharper. Over the slipface there is again a strong drop in wind speed suggesting flow separation. Since the model does not allow recirculation, the wind speed picks up again right at the foot of the slipface.

In this case we do see a reduction of the friction velocity in front of the dune. It seems that the dune shape adjusts in such a way that at the foot of the windward slope, where the erosion starts, the friction velocity is reduced to a value close to the threshold friction velocity. A higher friction velocity would cause strong erosion, which would rapidly steepen the slope. Most of the windward slope is almost linear, so the threshold velocity is constant over most of the slope. Friction velocity increases roughly as a root or a cube root, yielding a more or less linear increase in transport capacity. Therefore the erosion rate on the windward slope is constant and the shape of the slope is preserved. Most of the sediment is deposited, on and directly beyond, the crest. The pattern of friction velocity over the leeward slope looks unrealistic, because the model does not account for flow separation.

## DISCUSSION

The model shows that the wind profile over a dune does not obey the logarithmic law. This was also observed during field measurements (Mulligan, 1988; Arens *et al.*, 1995) and wind tunnel studies (Finnigan, 1988; Wiggs *et al.*, 1996). Because the wind profile is not logarithmic it cannot be used to derive friction velocity. Mulligan suggests that this can be overcome by measuring close to the surface, e.g. at 20 cm height. This is, however, questionable, since in order to measure a wind profile, measurements are needed at several heights. When measuring so close to the surface the uncertainty in the measuring height will cause large errors (e.g. where is the zero level, at the crest of the ripples or at the foot?).

In a modelling environment where we let new surfaces develop it is obvious that we cannot rely on measurements for providing the friction velocity; a model is needed.

Linearized models, like the Jackson and Hunt (1975) model, can only be used over very gently sloping surfaces. Jackson and Hunt (1975) state that $H/L$ should be less than 0·05, which implies that the slope should be less than 3°. Most natural dunes have slopes steeper than 3°. Also, natural dunes sometimes have irregular shapes, which makes if difficult to give a good estimate of the horizontal length scale $L$ (Arens, 1994). For dunes with slopes steeper than 3° ($H/L > 0{\cdot}05$) or irregularly shaped dunes there are no simple rules that can predict the speed-up over the crest. The friction velocity is even harder to predict since the logarithmic profile will not hold over these dunes.

Carruthers and Hunt (1990) show that mixing length models (first-order closure) are not suitable for modelling the shear stress profile over hills. Second-order closure models, however, can give a good approximation (Carruthers and Hunt, 1990). Also, Emeis *et al.* (1995) concluded that a satisfactory comparison between observations and numerical simulations could be obtained if rapid distortion and curvature effects are included in the simulation model. Stam (1997) argues that for low dunes the Jackson and Hunt (1975) theory implies that second-order terms are negligible. However, the reason that the Jackson and Hunt theory is limited to gently sloping dunes ($H/L < 0{\cdot}05$) is because for steeper dunes the second-order terms and curvature effects are no longer negligible.

Second-order closure models are a valuable tool in understanding the dynamics of dunes and sediment transport over hills. These models do not only model the mean flow field, but also the turbulent parameters. A correct modelling of the turbulence, including effects of curvature, is essential. First-order closure or analytic models will couple the friction velocity directly to the wind speed. These simplified models cannot explain why bare dunes grow in height, because this implies deposition at the crest where wind speed and therefore also the assumed friction velocity are high.

The second-order closure model presented here shows that over the sine-shaped dune the friction velocity does not have its highest value at the crest, but on the stoss slope. So, despite the fact that at some height the speed-up is maximal over the crest, the friction velocity is reduced due to curvature terms. As in a stably stratified atmosphere, turbulence over the convex crest is strongly reduced, causing a reduction of the turbulent exchange (e.g. the momentum flux). Therefore, very strong wind speed gradients can exist with very little friction. Wiggs *et al.* (1996) found similar results from field and wind tunnel measurements.

The fact that streamline curvature causes a reduction in the friction velocity at the dune crest and therefore of the sediment transport capacity of the air explains why dunes can grow in height, even in the absence of vegetation.

If the dune grew in height without changing its shape, the radius of curvature would become bigger and bigger, and the curvature terms would become less important. On a very large dune or hill, turbulence would be generated by friction and destroyed by dissipation. During the Askervein hill experiment (Taylor and Teunissen, 1983, 1984) the speed-up over a 115m high and 900m wide hill ($H/L = 0{\cdot}51$) was 100 per cent at heights of 1 to 4m above the hill top (Zeman and Jensen, 1987). The friction velocity over the crest was about 1·4 times the upstream value (Zeman and Jensen, 1987). So, although over this large hill the friction velocity on the top is higher than the upstream reference, the increase is much less than would be expected from the increased wind speed.

The fact that the balance between friction-generated turbulence and the curvature terms is scale-dependent has serious implications if one wants to study the flow over hills using scale models in a wind tunnel. It is not only necessary to keep the shape (the same $H/L$), but one also needs to scale the roughness length (keep $H/z_0$ constant). Especially when studying the flow over bare dunes ($H/z_0$ typically 10000) it might be very difficult to meet this requirement.

Dunes will generally develop a slipface as they grow. In this case there is a sharp crest with a small convex curvature radius. Therefore we expect curvature terms to cause a strong reduction in momentum flux close to the surface, and therefore in friction velocity. On the other hand, one could argue that a sharp crest, from a more or less horizontal surface to a 32° slipface, is bound to cause flow separation (e.g. Finnigan, 1988), in which case streamline curvature is less.

If flow separation occurs, the model will not simulate the flow in the separation zone correctly, since it cannot handle the recirculation vortex. In the recirculation vortex, wind speed and friction velocity will, in almost all cases, be below the threshold velocity for sand transport. Consequently, any sand in transport will be deposited shortly after the separation point. On the slipface the main transport mechanisms is not aeolian, but avalanching. In the case of flow separation the model will also predict friction velocity well below the threshold. So, although the model cannot handle recirculation, the consequences for the sand transport at the crest are realistic. In reality the flow will usually reattach at some distance (several dune heights) downwind of the crest. A flaw of the model is that the reattachment point comes too soon, sometimes even on the slipface itself. Therefore, a separation zone is defined in the sediment transport module (Van Dijk *et al., 1999)*.

Finnigan (1988) and Jensen (1988) argue that flow separation will not just influence the flow in the separation zone, but will affect the flow over the entire hill, through the effect on the pressure distribution. Pearse *et al.* (1981) investigated the speed-up over triangular hills of different slopes and found that the highest increase was observed if the slope was gentle enough to just avoid flow separation. Also, this result suggests that the effect of flow separation extends to outside the separation zone.

Flow separation is rather poorly understood (Finnigan, 1988). In order to model it physically we need very complicated models (Jensen, 1988). From wind tunnel studies over triangular hills it seems that flow separation occurs whenever the slopes exceeds 15° (Finnigan, 1988; Merony *et al.*, 1978; Snyder and Britter, 1987; Arya and Shipman, 1981). On an escarpment with an upwind slope of 26° no flow separation was found (Emeis *et al.*, 1995). The change of the slope angle on a triangular hill with slopes of 15° is comparable to the change of slope at the crest of a dune with a slipface. So, at the top of the slipface, flow separation is to be expected.

Finnigan (1988) suggests that a rougher surface would more readily generate flow separation. Also, Merony (1990) states that flow separation is affected by changes in surface roughness. This might be important when studying the transport rates over thinly vegetated dunes.

On curved hills (roughly represented by a Gaussain or sinusoidal curve), the point of separation is harder to define (Finnigan, 1988). Also here the roughness seems to have an effect on the occurrence of flow separation. Finnigan (1988) summarizes various wind tunnel experiments. A very rough curved hill ($H/z_0 = 50$) with a 16° slope showed flow separation, whereas over a slightly smoother hill ($H/z_0 = 120$) of the same slope only intermittent flow separation was observed. So, the result of no flow separation over our sine-shaped dune (slope 21°, $H/z_0 = 6000$) might be realistic. Finnigan reports two experiments with comparable height-to-roughness ratios: one outdoor experiment over Cooper's Ridge (slope 8·5° and $H/z_0 = 3000$) and the other a wind tunnel experiment (slope 10° and $H/z_0 = 4000$). During both experiments no flow separation was observed.

More work has been done on flow separation in aquatic environments (e.g. Bennett and Best, 1995; Nelson and Smith, 1989; Zijlema *et al.*, 1995) but these results are not readily translated to the aeolian environment.

## CONCLUSIONS

First-order closure, or linearized, models are only applicable to very smooth hills ($H/L < 0.05$). Even though for steeper hills the speed-up predicted by the Jackson and Hunt (1975) theory might seem fairly good, the derived wind speeds cannot be used for obtaining friction velocities.

Second-order flow models may seem complicated, especially compared to first-order closure or analytical models, but they provide essential information on the structure of the turbulent boundary layer over dunes, the pattern of friction velocity and sand transport capacity of the flow and therefore on the dynamics of dunes.

Curvature of the streamlines generates extra turbulence on concave slopes (compare with an unstable boundary layer) and suppresses turbulence over convex slopes (comparable to stable stratification). Therefore friction velocity over the crest is much less than what would be derived from the assumption of a logarithmic wind profile.

Over low (1–10m high) dune ridges with a smooth curved topography, the wind speed will increase over the crest, but due to curvature effects the friction velocity will be less than the value upstream of the dune. When larger and larger dune ridges of the same shape are considered, the curvature effects become smaller and at some dune size the friction velocity may be the same or even higher than the upstream value.

If dunes grow higher they generally develop a slipface. Around the top of the slipface strong curvature effects will be present, regardless of the size of the dune. Because of the convex curvature of the surface, these will suppress turbulence and cause the friction velocity to be much less than what is to be expected from a logarithmic wind profile.

In order to obtain a good assessment of the friction velocity and the corresponding transport capacities on the crest of dune ridges with a slipface, it might be necessary to improve our knowledge of flow separation. The flow downwind of the slipface can only be modelled with acceptable accuracy if at least some pragmatic rules exist about the conditions under which flow separation occurs and the extent of the separation bubble.

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