SIMULATION MODEL OF ISOLATED DUNE SCULPTURE BY WIND

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Summary

A simulation model has been developed for eolian erosion and deposition on isolated three-dimensional sand bodies. The boundary-layer turbulent flow model developed by Taylor, Walmsley and others is used to predict near-surface winds. Sand transport is estimated using the approach of Howard, et al. (1978) with corrections for effect of slope on transport rate and deflection of transport direction by topographic gradients. Erosion and deposition are proportional to the divergence of transport rate if the flow is saturated. The simulation proceeds with alternating episodes of wind field calculation and erosion and deposition. Preliminary simulations starting from a symmetrical, "cosine-squared" hill shape develop a barchanoid shape, although problems of numerical stability remain to be addressed.

1. Introduction

Sedimentary bedforms result from interactions of fluid flow, sediment transport and the bedform topography; as a result of these interactions plane beds are generally unstable if the transport rate is close to saturation, resulting in the creation of ripples, dunes or other bedforms. The modelling of these interactions has been limited both because of imperfect understanding of the transport mechanisms and because of the difficulty in predicting the characteristics of the fluid flow for a given bedform shape, particularly in the generality of three dimensions.

One of the simplest bedforms is the eolian barchan dune (Fig. 1), which forms as an isolated feature on a desert floor under nearly unidirectional winds. Barchans can migrate long distances downwind while maintaining nearly constant (equilibrium) form and size. The sand transport over one such dune was modelled by Howard et al. (1978); they demonstrated that the spatial pattern of changes in trasport rate in response to variations of wind shear over the dune causes corresponding patterns of erosion and deposition that maintain the equilibrium form during migration. This modelling utilized field measurement of the wind directions and speeds over the dune, as well as laboratory measurements over a scale-model dune. Their conclusions were therefore limited to the specific dune geometry and wind directions for which the meteorological data had been collected.

The prediction of sand movement over a dune requires an accurate wind flow model in combination with a physically realistic model for the transport of sand by wind. Recent inprovements in modelling of turbulent boundary layer flow have made possible the rapid caclulation of the wind field over smooth, isolated, gently-sloping landforms protruding above a generally level surface (Walmsley, et al., 1982). The barchan dune is such a feature, with the exception of the downwind-facing slip face (Fig. 1). Walmsley and Howard (in press) have explored the suitability of the numerical flow model to modelling flow over barchan dunes, with the conclusion that the model gives reliable results over the upwind (stoss) slopes of the dune, where the spatial pattern of erosion and deposition determine overall dune geometry.

2. The Turbulent Flow Model

The calculations of normalized wind speed and wind direction changes over a topographic obstacle utilize a model developed by Walmsley *et al.* (1982) and based upon Mason and Sykes' (1979) three-dimensional extension of Jackson and Hunt's (1975) approximate theory of flow over a low hill. The model is computationally efficient because it provides an analytical rather than iterative solution for terrain-induced flow perturbations. The main limitations of the theory and the model are that the terrain must be of low slope (<0.2) and consist of an isolated feature on an otherwise flat plain. The version used in the present calculations assumes areally uniform roughness, but a version permitting roughness variations has been developed.

The model divides the flow into an outer, inviscid region and an inner layer within which turbulent shear stresses are represented by a mixing-length closure. Pressure gradients determined from the outer-layer solution drive the flow perturbations in the inner layer. A logarithmic profile is assumed to characterize the undisturbed upstream flow. The basic inputs to the model are the topography, an assumed roughness, and the assumed flow direction. To assure reliable wind values over the obstacle, the lateral dimensions of the obstacle should be less than about 1/4th of the total calculation domain.

The predictions of the flow model were compared with field and laboratory measurements of near-surface wind speed and flow direction made by Howard *et al.* (1978). Figure 1a shows the topography of the target barchan (located in the Salton Sea, California, dune field) field. Figure 1b shows the speedup values measured at a relative height of 0.8 meters above the dune. The speedup values are the observed wind speed divided by the indisturbed wind speed at the same relative height above the desert floor. The deflection of the surface wind direction from the direction of the oncoming wind (in degrees, with counterclocwise deflection positive) is shown in Figure 1c.

Figure 2a shows the model predictions for speedup and Figure 2b shows the calculated wind deflection for an assumed roughness of 1 mm. The correspondence to the field measurements is obviously strong, with a 0.90 correlation coefficient for speed and a 0.84 correlation for deflection, with mean errors of -0.086 for speedup and 0.17 degrees for deflection. The major discrepancies are a calculated speedup in the immediate vicinity of the central crestline which is considerably higher than observed and a slightly higher range of surface deflection than observed. The discrepancies, particularly at the crestline, may result either from inability of the model to account for the flow separation downwind from the crestline or from errors in the measurement of the target dune geometery (speedup values are very sensitive to slight changes in dune geometry).

3. The Simulation Model

The favorable correspondence between predictions of the flow model and measurements over a barchan has encouraged the authors to use the model as a component of the simulation model. Modelling of sand transport in simulations to date uses the

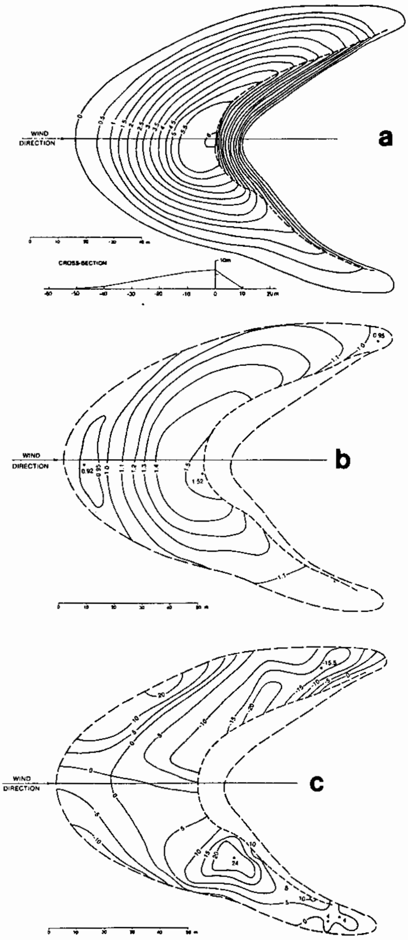

Figure 1. Topography (a), observed wind speedup values (b), and wind deflection (c) for a barchan dune in the Salton Sea dune field in California. Contour interval for topography 0.5 m, for speedup 0.1, and for wind deflection 5°.

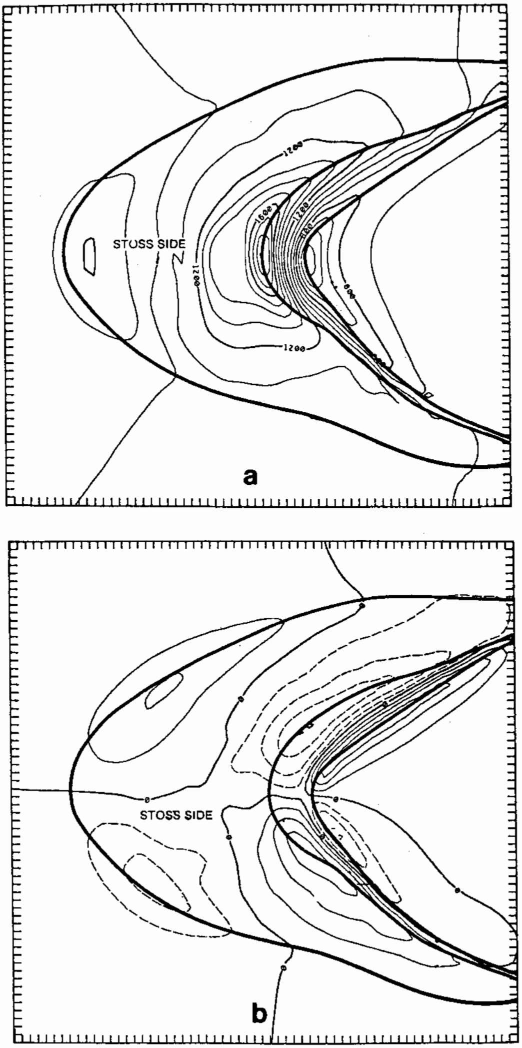

Figure 2. Calculated wind speedup values (a) and wind deflection (b) for dune shown in Figure 1, using the Walmsley _et al._ (1982) flow model. Contour interval for speedup is 0.1 with a 1000x scaling factor, and for deflection is 10 degrees.

approach of Howard et al. (1978) [referred to as H78]. The flow model is used to predict wind velocities at a given relative height above the dune (0.1 m is used in simulations reported here). Surface wind shear is estimated from the modified logarithmic profile of Bagnold (1941, p. 61) as reproduced in H78 (Eq. 4), with a threshold velocity and reference height using Equation 11 of H78. Threshold shear velocities are calculated using Equations 10 and 12 from H78 which apply a correction for topographic gradient. Transport rate is calculated using Bagnold's formula (1941, p. 66, also H78, Eq. 7) or an alternative relationship. The Lettau and Lettau formula (1978, p.111, also H78, Eq. 8) was used for the simulations reported here. Calculated transport rates were adjusted by an upwind averaging scheme using a geometric weighting function (H78, Eq. 20) to account for lag between change of velocity at the reference height and corresponding change in transport rate. An average lag of 2 m. was assummed for the present simulations. Due to the topographic slope of dunes, sand transport is deflected somewhat downgradient from the direction of the surface wind (Howard, 1977). The full correction to transport direction (H78, Eq. 15) is assumed in these simulations, although the actual transport direction lies somewhere between the surface wind and the value calculated from H78, Equation 15, which applies primarily to the creep component of the flow. The oncoming sandflow is assumed to be partially saturated, with 85% saturation used in the reported simulations.

Erosion and deposition rates are equal to the spatial divergence of the transport rate vector field divided by the bulk density of the sand. The simulation proceeds by calculation of the wind field at the reference height, followed by calculation of transport rate and direction as outlined above. The erosion and deposition rates calculated from the transport divergence are used to modify the topography using an assumed temporal interval (a temporal interval resulting in an average downwind migration of the dune of 0.4 m per iteration was used). The wind field is recalculated for the modified topography and the process is repeated for as many iterations as desired.

An arbitrary symmetrical, rounded pile of sand (a radially-symmetric "cosine-squared" geometry) with height of 4 m and diameter of about 70 m was used as the initial configuration for the simulations (Fig. 3a). A grid spacing of 2 m was used in the simulations, with a total calculation domain of 256m by 256m. Speedup values for the initial hill are shown in Figure 3b, and wind deflection in Figure 3c. The slope-corrected sand transport direction is shown in Figure 3d. An undisturbed wind speed of 15 m/s at a height of 1 m was assumed. The resulting transport rate in relative units is shown in Figure 3e. The normalized erosion and deposition rates that would be required to maintain the geometry of the hill during downwind translation (equilibrium erosion and depositon rates) are shown in Figure 3f, whereas the actual normalized erosion-deposition rates are shown in Figure 3g, and the difference between the equilibrium and calculated rates are shown in Figure 3h.

Note from Figure 3h that the simulated erosion rates will result in net lowering of the central portions of the hill, a lengthening of the dune by deposition along the leading edge, and

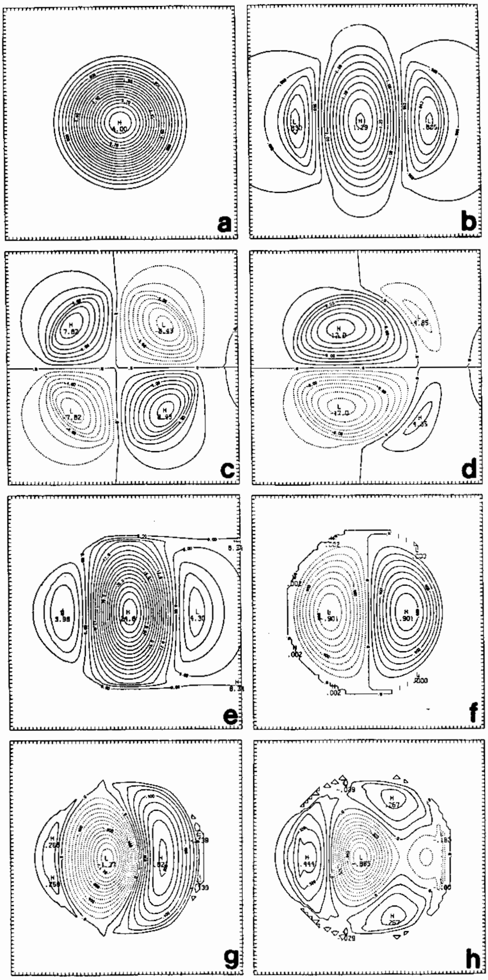

Figure 3. Cosine-squared model hill showing topography (a), wind speedup (b), wind deflection (c), sand transport deflection (d), sand transport rate (e), equilibrium normalized erosion rate (f), simulated normalized erosion rate (g), and (h), the difference between (f) and (g).

the development of "wings" downwind from an on either side of the center of the dune. Figure 4a shows the hill form after 25 iterations, illustrating these tendencies and the initial stages of development of a barchanoid form. Speedup (Fig. 4b), wind direction (Fig. 4c), transport direction (Fig. 4d), equilibrium normalized erosion rate (Fig. 4e), and actual normalized erosion rate (Fig. 4f) are also shown. The simulation appears to be heading towards an equilibrium barchanoid form, since the correlation between the observed and equilibrium erosion-deposition rates increases during the simulation and the standard deviation of the differences between the two rates diminishes. Note that the sand form diminishes and height but increases in lateral dimensions during the simulation. Depending upon the input parameters, dune volume may either increase or decrease slightly.

Unfortunately, the model in simulations to date shows a tendency to develop instabilities which eventually result in a "rumpling" of the dune surface. The endpoints of four simulations for different assumed conditions are shown in Figure 5. The instabilities generally become manifest after 20 to 30 iterations. The dune shown in Figure 5d represents the strongest development of a barchan form in simulations to date.

The instabilities result from the strong sensitivity of transport rate (and hence erosion-deposition rate) to variations in wind velocity (a third-power relationship) coupled with a strong, and probably exaggerated sensitivity of the flow model to small-scale topographic perturbations (Walmsley et al., 1982). Since natural barchans of the model scale are stable, some

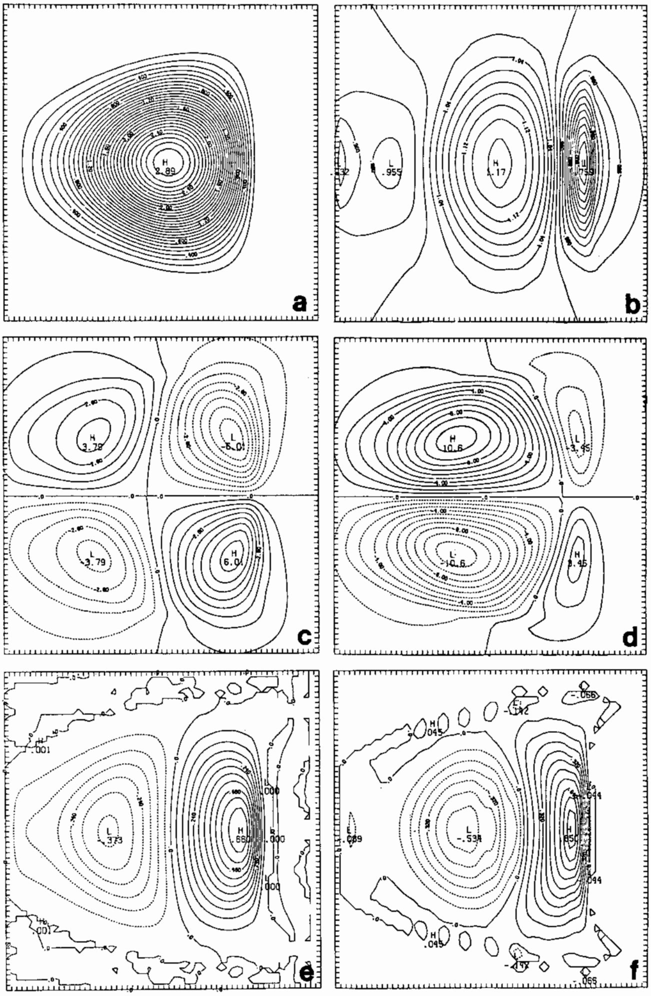

Figure 4. Cosine-squared hill after modification by simulation model, showing topography (a), wind speedup (b), wind deflection (c), sand transport deflection (d), equilibrium normalized erosion rate (f), and simulated normalized erosion rate (g).

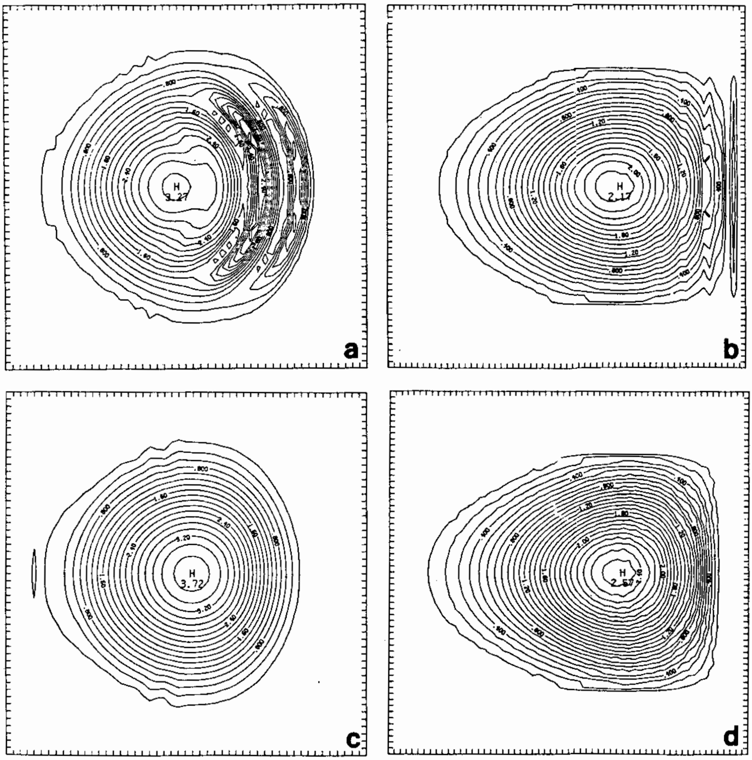

Figure 5. Endpoints of several simulations for different combinations of input parameters showing develoment of numerical instabilities.

corrective action to the model seems warranted. The simplest approach is to apply a low-pass filter to either the calculated speedup values or directly to the dune topography, or both. This can be done either either in Fourier space (used in the flow simulation calculations) or in real space using a moving filter. The latter approach has been used to date, but an ideal filtration which results in stability with minimal bias of results has not yet been achieved.

4. Conclusions

Despite the problem with numerical instabilities which remains to be resolved, the simulation model shows considerable promise for use in investigating the wind-transport interactions which control barchan size and shape. The model can be run with different combinations of input parameters and model assumptions to investigate the effects upon dune size, geometry and stability of such factors as wind speed, degree of saturation of the oncoming sand flow, wind direction variability, sand grain size, and different assumed relationships governing sand transport rate and direction. Unfortunately, computational costs of the model are fairly high due to both the lengthy calculations and large program size, which has limited the number of simulations conducted to date. However, we hope that facilities or funds will become available in the future to allow further investigation of this promising model.

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6. References

Bagnold, R. A. (1941): The Physics of Blown Sand and Desert Dunes. Methuen, London.

Howard, A. D. (1977): Effect of slope on the threshold of motion and its application to orientation of wind ripples. Bull. Geol. Society of America, 88, 853-856.

Howard, A. D., Morton, J. B., Gad-el-Hak, M., and Pierce, D. (1978): Sand transport model of barchan dune equilibrium. Sedimentology, 25, 307-338.

Jackson, P. S. and Hunt, J. C. R. (1975): Turbulent wind flow over a low hill. Quart. J. Roy. Meteorol. Soc., 101, 929-955.

Lettau, H. H. and Lettau, K. (1978): Experimental and micrometeorological field studies of dune migration. in Lettau, H. H. and Lettau, K., editors, Exploring the World's Driest Climate, Center for Climatic Research, University of Wisconsin, Madison, 110-147.

Mason, P. J. and Sykes, R. I. (1979): Flow over an isolated hill of moderate slope. Quart. J. Roy. Meterorol. Soc., 105, 383-395.

Walmsley, J. L., Salmon, J. r., and Taylor, P. A. (1982): On the application of a model of boundary-layer flow over low hills to real terrain. Boundary-layer Meteorol., 23, 17-46.

Walmsley, J. L, and Howard, A. D. (in press) Application of a boundary-layer model to flow over an eolian dune. J. Geophys. Research.