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Time-averaged numerical modelling of airflow over an idealised transverse dune

Parsons, D.R. Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK (d.parsons@sheffield.ac.uk)

Wiggs, G.F.S. Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK (g.wiggs@sheffield.ac.uk)

Walker, I.J. Department of Geography, University of Victoria, Victoria, British Columbia, V8W3P5, Canada (ijwalker@uvic.ca)

Garvey, B.G. Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK (ggp99bgg@sheffield.ac.uk)

Ferguson, R.I. Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK (r.ferguson@sheffield.ac.uk)

Introduction

There has been much recent interest in the complex interactions evident between sand dune morphology, windflow and sediment transport (McKenna-Neumann et al, 1997, 2000; Wiggs, 2001; Walker and Nickling, 2002). Research concerning secondary flow regimes governing dune/flow interactions and the existence of a dynamic equilibrium between dune morphology and windflow patterns has dominated recent dune literature (see reviews by Nickling and McKenna-Neumann, 1999; and Wiggs, 2001). The research focus on the dynamics of dune windward slopes (e.g. Lancaster et al, 1996; Frank and Kocurek, 1996a; Wiggs et al, 1996; McKenna-Neumann et al, 2000) has been complemented by similar field and wind tunnel studies investigating flow patterns and sediment dynamics in the turbulent lee-side eddies downwind of transverse dune crests (Frank and Kocurek, 1996b; Walker and Nickling, 2002). The acceleration of windspeed and surface shear stress to a maximum on the stoss slopes of sand dunes followed by a lee-side re-circulating eddy and region of flow recovery are now well documented. Progress is still hampered, however, by the small number of field sites investigated and by the limited dune geometries that have been experimented upon in wind tunnel studies. Additionally, due to design limitations, regions of highly turbulent or reverse flows have not been quantified in wind tunnel experiments, resulting in deficient understanding of the flow structure over dune forms.

Whilst physical experimentation has provided us with a substantial insight into a number of flow-form interactions (flow acceleration, crestal separation, re-circulation, re-attachment etc.), questions remain as to the sensitivity, structure, and dynamic function of these interactions with changing dune geometry. An adaptable and rapid method by which our understanding of flow patterns could be further improved involves the mathematical modelling of the flow field over different dune geometries. Previous attempts to model the turbulent boundary layer over isolated dunes (e.g. Howard et al, 1977; Wippermann and Gross, 1986; Stam, 1997) have been hampered by the lack of detailed empirical data against which the models could be validated. Furthermore, the models used to calculate the flow structure over dune forms often have severe limitations. For example, Stam (1997) applied an analytical flow model based on a boundary-layer model (e.g. Jackson and Hunt, 1975), which is unable to solve the reverse flow in lee-side eddies often present over dune forms. This limits the calculation of flow structures to low angle dunes where lee-side eddies are not present. With the recent proliferation of field and wind tunnel data concerning dune processes it is now appropriate to apply new refinements in numerical calculations of flow fields around bedforms to questions of dune flow dynamics.

Numerical flow models (Computational Fluid Dynamics, CFD) have been widely applied in engineering disciplines for many years. In the last few years, there has been a proliferation of the use of CFD in the fields of geomorphology and hydrology (see Bates and Lane, 2000). These models enable an improved simulation of important processes providing prediction fields that allow considerable insight into the spatial distribution of these processes. CFD modelling has offered a new methodology that is complementary to traditional field and laboratory approaches. Indeed, the models can provide details of the flow field that are often difficult to measure and offer controlled conditions in which certain aspects of the experimental set up can be varied rapidly.

This paper represents the first stage in applying a numerical code to flow field patterns around dunes and validates a new numerical model against wind tunnel derived experimental data (from Walker and Nickling, in press). It provides details of model background set-up and application. Once validation is complete, the model may be used to examine the variation in the flow field around both isolated and closely-spaced dunes of differing geometries. This latter procedure will be the subject of an accompanying paper.

Results: the numerical model

In order to ascertain the capabilities of the model it was initially used to predict the measured flow velocities for the wind tunnel experiment of Walker and Nickling (in press). The model validation was based on 415 predicted points within the model domain, which coincided with the locations of measurements taken in the wind tunnel.

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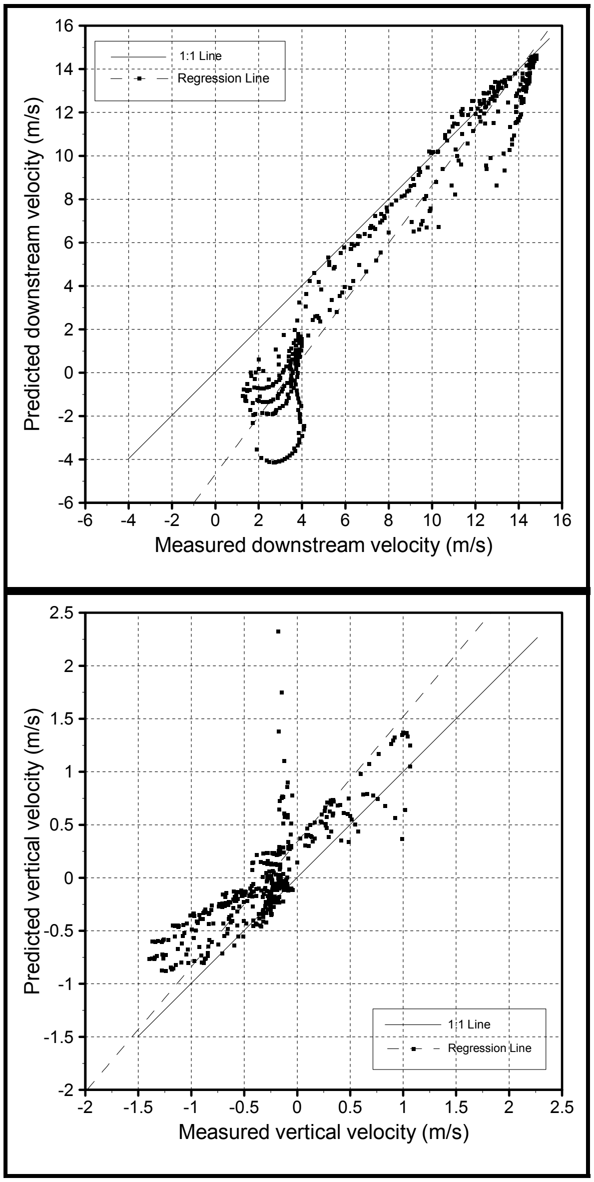

Figure 1: Predicted against observed values of (a) streamwise and (b) vertical velocity

For the downstream velocity component the agreement is generally very good with a high correlation coefficient and the 1:1 line in close agreement for the higher velocity values (figure 1a). However, there is a significant zone of disagreement for the lower velocities, where the predicted velocities are negative whilst the measured are positive. These points are from the lee separation zone, where, due to design limitations, the probe was unable to resolve the highly turbulent and negative velocities apparent, which were correctly predicted by the model (figure 2). Although slightly weaker, the agreement between measured and predicted values of vertical velocity (figure 1b) is still high with most points clustered close to the origin. Nevertheless, there is considerable disagreement in three distinct areas: (1) a vertical line of points where the model predicts very high positive values in comparison with the slightly negative measured values; (2) a group of points in the bottom left of the graph where the measured values are higher than the predicted; (3) a small group of points that extends towards the top right between the line of best fit and the 1:1 line. The first group of points is explained by the high positive vertical velocities predicted by the model flowing up the lee of the dune in the separation zone that are not correctly measured by the probe. The second area is explained by the separation re-attachment, where the model predicts lower velocities overall, perhaps due to energy dissipation through high turbulence intensities that would again compromise the measurement probes performance. Finally, the third area of disagreement is due to the model slightly over predicting the stoss side vertical velocity components .

Although there are notable differences between the measured and modelled results, they are primarily due to the limitations with the measuring instrument rather that the numerical model. In regions were the instrument is known to perform well the match is very good. We therefore have confidence in the performance of the numerical model to use it for both the investigation of the flow structures over the dune, particularly in the lee, and for future experiments where different aspects of dune form can be investigated.

Results: the flow structure

Results indicate that the model predicts the flow patterns over the dune very accurately. Figure 2 illustrates the predicted stream wise and vertical velocity over the dune.

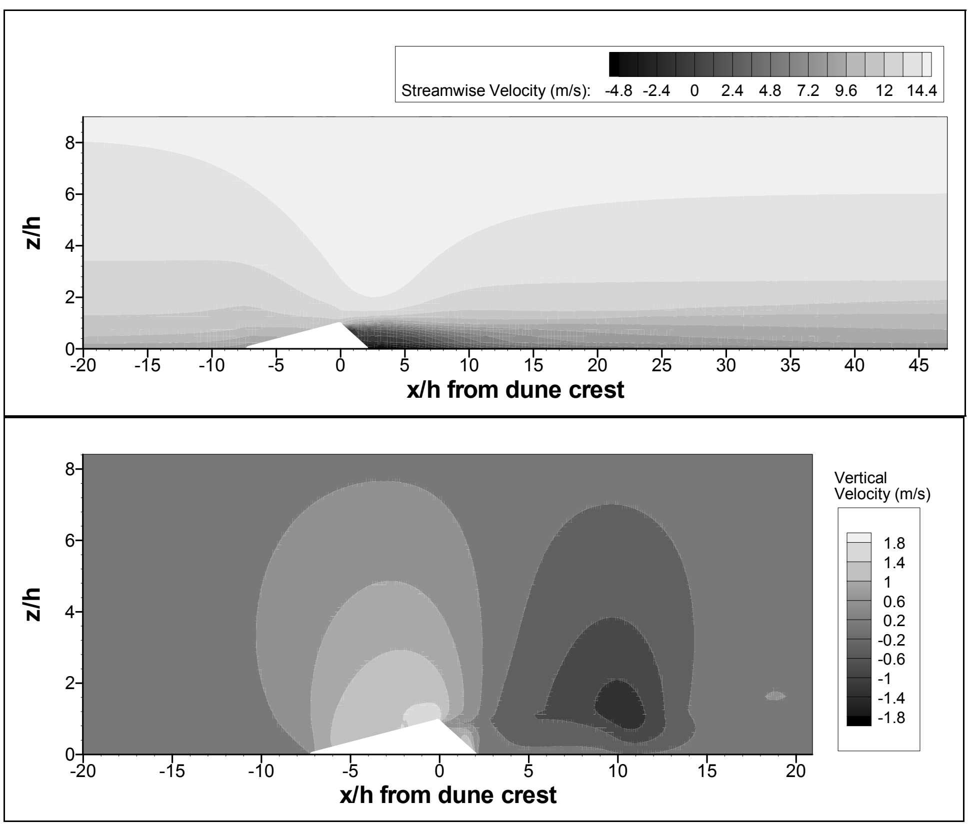

Figure 2: Streamwise and vertical velocity contour maps

The model produces regions of flow stagnation at the toe, acceleration up the stoss slope and a convincing region of flow separation in the lee of the dune. These results show broad similarity to a range of studies into flow dynamics over dunes, and permit a more in-depth analysis of the flow structures.

Conclusion

The numerical model presented in this study successfully predicts the flow structure over an idealized transverse dune and validates extremely well to experimental wind tunnel measurements. Moreover, the model seems to correctly simulate the flow in regions of high turbulence and flow reversal, where experimental limitations are unable to provide flow information. Thus, the model provides a complete picture of the flow structure, which is spatially much richer than results produced by current wind tunnel experiments and field studies. The ease of use and flexibility of the modelling allows testing of a variety of isolated and complex dune morphologies, which are subjects of forthcoming papers.

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