In : Lee, Jeffrey A. and Zobeck, Ted M., 2002, Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA Publication 02-2 p.29

Wind tunnel and field investigation of flow dynamics within and around a valley

Brian Garvey, Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK, email: b.garvey@sheffield.ac.uk

Giles F.S. Wiggs, Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK, email: g.wiggs@sheffield.ac.uk

Ian P. Castro, School of Engineering Sciences, University of Southampton, Highfield, Southampton, S017 1BJ, UK, email: i.castro@soton.ac.uk

Joanna E. Bullard, Department of Geography, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK, email:j.e.bullard@lboro.ac.uk

Introduction

The influence of valley topography on boundary layer winds has been investigated in relation to wind velocity and turbulence (Sierputowski *et al*., 1995) and the dispersal of pollutants (Beniston, *et al*., 1989; Kalthoff *et al*., 2000). These studies, however, find their focus on valleys in hilly or mountainous terrain. Research has not adequately examined the effect of isolated valleys in flat, plateau terrain on boundary layer winds and no investigations to link consequent changes in wind patterns to sediment transport have been undertaken.

In the drylands of the world, where wind is a major transporting mechanism of sediment and organic matter, the interaction of ephemeral rivers and airflow has implications for the accumulation, transport and deposition of airborne material. This paper presents the first attempt to quantify the impact of incised valley topography on wind direction, velocity and turbulence using measurements from both field and wind-tunnel investigations.

Methodology and Procedures

Data are presented from wind tunnel measurements, using hot-wire anemometry and particle image velocimetry (PIV), made across an idealised 1:1000 scale model of a typical 200 m wide and 20 m deep incised valley with wind flowing normal to the long axis of the valley. Data are normalised to the free stream velocity in the wind tunnel (*Ur*).

The extent of flow modification caused by the valley and shown in the wind tunnel measurements is compared to field data collected from a tributary of the Gaub River in central Namibia, southern Africa. A site with a valley long axis of 300m in length, incising flat, homogenous terrain, was chosen for the experiments. Within this section the valley width, or short axis, varies between 150 m and 175 m at the valley edges. The depth of the valley is 20-22 m with and the slopes have gradients of 20-25^0.

Six stations, each with vertical arrays of rotating cup anemometers and a potentiometer windvane measured mean velocity and direction across the valley under a range of wind directions and thermal conditions. The portable stations were always aligned in a transect parallel to the dominant wind and measurements, made at a range of spatial scales in the vicinity of the valley, were compared to those made at the reference station.

In the co-ordinate system used for the data below, *x* refers to the horizontal distance and *z* to the vertical height above the ground surface. The leading edge of the valley encountered by the oncoming wind is always referred to as $x = 0$ for the field data and $x/L = 0$ (where L = length of short axis of the valley) for the wind tunnel data. Measurements upwind of this position are given a negative value. In all proceeding figures wind is from left to right.

Values of mean velocity calculated at a given height (u_z) were normalised with measurements at the corresponding height at the reference station (U_z). The changes in velocity across the transects are displayed below in the form of the fractional speed-up ratio (δs) which presents wind acceleration as a fraction and is an effective way of showing changes in velocity across a topography (Jackson and Hunt, 1975; Lancaster, 1985; Mulligan, 1988; Wiggs *et al*., 1996):

$$\delta s = \left(u_z - U_z\right) / U_z$$

The changes in wind direction as wind passes the valley are presented by showing the deviation of direction at each point of measurement from the mean direction recorded at the reference station:

Deviation = direction measured at point 'x' - direction at reference

Experimental observations

Field data

Figure 1 shows the fractional speed up measured at z = 0.4 m and z = 2.8 m above the surface for a westerly wind of 263^0 blowing normal to the valley axis.

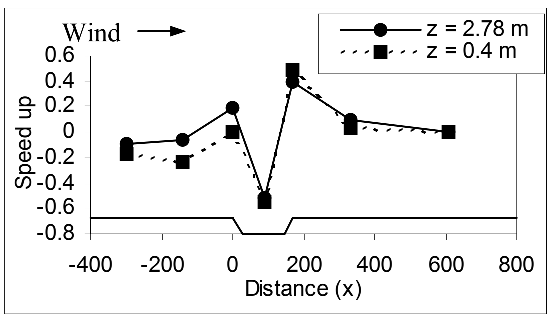

Figure 1 Fractional speed-up across the valley measured at z = 2.78 and z = 0.4.

There is an acceleration in wind velocity towards the upwind edge of the valley with $\delta s = 0.3$ at z = 2.78 m and 0.2 at z = 0.4 m. This acceleration occurs from x = -150 m. There is then a dramatic reduction in wind velocity into the centre of the valley where $\delta s = -0.44$. Following this is an acceleration up the downwind valley side and velocity reaches a maximum at the downwind edge of the valley, where δs is 0.81 at 0.4 m in height and 0.53 at 2.78 m in height. Velocity reduces in the wake of the downwind edge and begins to resemble upwind values beyond x = 300 m.

Visualisation of the flow using smoke canisters confirmed that flow separates off the leading edge and a recirculation zone extends for at least 50 m into the valley with flow reversing up the upwind slope. Smoke experiments also indicated a smaller recirculating zone in the wake of the downwind edge. They also indicted that the incident angle of the approaching wind to the axis of the valley may limit the extent of the separation zone.

Figure 2 compares the deviation of wind within the valley channel for a perpendicular wind and a wind blowing at an acute angle to the long axis of the valley. The maximum deflection of a 93° wind is only some 25°, occurring at the downwind edge (x=200 m). This is contrasted with a deflection of

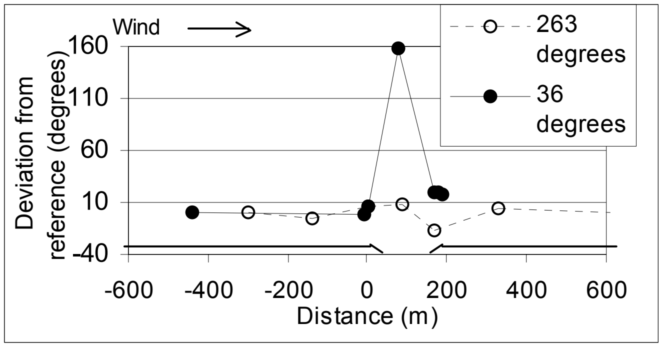

Figure 2 Deviation of wind from the reference station across the valley

160° in the centre of the valley (x = 100 m) when wind approaches the valley at 36°. It appears that the role of the valley in deflecting wind along its geometry is more pronounced when the angle of wind approach is less than 45°.

Wind tunnel data

Results from the wind tunnel hot-wire anemometry experiments show a considerable increase in both velocity and turbulence (Figure 3) from *x/L*=-1 to the leading edge of the valley (*x/L*=0). There is a slight increase in turbulence towards the leading edge, followed by a tremendous increase over the valley as the shear layer is encountered. At the downwind edge (*x/L*=1) the flow has passed the shear layer and, although turbulence is depressed, values remain significantly greater than those upwind of the valley.

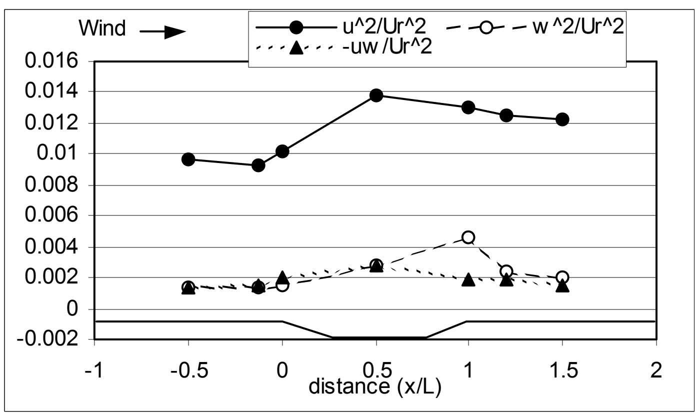

Figure 3 Horizontal profiles of streamwise (*u^2*), vertical (*w^2*) turbulence and Reynolds shear stresses (-*uw*) measured at z/H= 0.2.

Vertical turbulence increases slightly to the leading edge, shows much greater values over the shear layer and, unlike the other profiles, greatest values at the downstream edge beyond which values decrease rapidly. The increased vertical component of the flow as flow is forced over the downwind edge indicates that separation is likely and is in agreement with observations from field smoke visualisation experiments.

Reynolds shear stress increases in intensity to the leading edge, shows greatest values over the centre of the valley and a decrease to the downwind edge, where intensities equate to those at the leading edge before decreasing at *x/L* = 1.5.

PIV experiments indicate that on passing the leading edge flow decelerates and separates just below the edge. The vertical and horizontal extent of the separation zone is shown by the streamlines in Figure 4 and flow reattaches by *x/L* = 0.7. Wind then begins to accelerate streamlines converge on encountering the downwind slope, consistent with the findings from the hot-wire and field data.

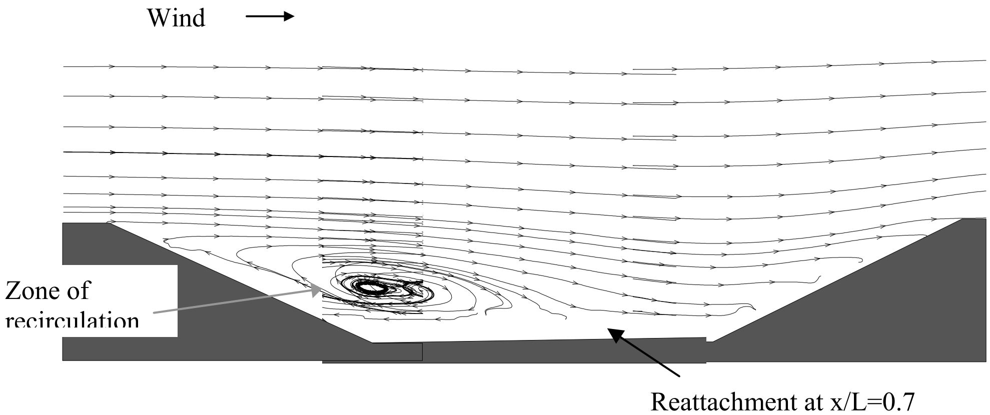

Figure 5 Streamlines for wind crossing valley channel.

Conclusion

Data presented here have shown the significant effect valley topographies have on wind velocity, turbulence and direction. An increase in velocity and turbulence to the leading edge of the valley is followed by rapid deceleration as flow separates off the leading edge and zone of recirculation extends to almost two thirds of the valley length. This recirculation zone is limited if flow approaches at an angle, whereby streamlines are funnelled along the long axis of the valley. High turbulent intensities are apparent above the shear layer of this zone.

Following reattachment, streamlines converge and velocity begins to accelerate up the downwind slope reaching a maximum at the downwind edge. There is evidence of flow separation at this edge as high turbulence and low velocities are recorded in its wake. Flow begins to recover between one and two valley lengths downwind of the valley.

These findings have important implications for predicting the distribution of wind borne material. Sediment erosion might be expected from x/L =-1 of the valley as windflow accelerates and shear stress increases towards the valley edge. Deposition of material in transport may result from flow separation and deceleration into the valley. Sediment eroded as flow accelerates up the downwind valley slope will potentially be deposited as the flow decelerates from a maximum velocity at the valley edge to x/L = 1.5 beyond which mean and turbulent velocities been to recover. The empirical evidence presented forms an important backdrop for the future prediction of wind patterns and transport of particulate organic and inorganic matter in relation to valley topographies.

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