13.4 DYNAMIC AIRFLOW CHANNELLING EFFECTS IN BENT VALLEYS

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1. INTRODUCTION

Previous investigations of dynamic channelling of airflow in mountain valleys have been limited to straight valleys, where a constant along-valley component of the synoptic pressure gradient can be assumed. In nature, however, valleys are often curved or bent, and therefore composed of segments having different orientations. In these valleys, the along-valley component of the synoptic-scale pressure gradient differs from one segment of the valley to another. This paper presents a simple conceptual model of the changes in wind speed and direction that will occur along the axis of a bent valley due to pressure driven channelling when adjacent valley segments have different orientation, but constant width and depth. Special emphasis is given to horizontal flow convergence or divergence and compensatory lifting or subsidence within (and above) the valley. The effects of the magnitude of the angle between valley segments on the expected flow patterns in the valley are analysed. Examples are discussed for Southern Hemisphere situations.

2. CHANNELLING IN STRAIGHT VALLEYS

The term channelling describes dynamic processes that cause winds approaching a valley from any direction to be forced to flow along the valley's axis. This means that the variety of wind directions above ridge height is reduced to only two possible wind directions within the valley. Observed wind direction frequency distributions measured during channelling events in valleys therefore show a typical bimodal structure independent of the time of the day. Previous observational and modelling studies (Fiedler, 1983; Wippermann, 1984, Vogel et al. 1986) show that channelling of air in long, broad and well defined valleys is directed from high to low pressure (Figure 1). Whiteman and Doran (1993) have called this process pressure driven channelling. This form of channelling is quite different from pure deflection of synoptic scale winds into an along-valley direction, which is called forced channelling and appears to be the dominating channelling mechanism in short and narrow valleys (Weber and Kaufmann, 1998).

The wind speed in a valley caused by pressure driven channelling can be assumed to be proportional to the along-valley component of the synoptic scale pressure gradient, so that the strongest and weakest winds are expected for geostrophic winds perpendicular and parallel to the valley, respectively. In previous channelling studies it was shown to be useful to define wind direction at ridge level as the wind direction of the geostrophic (or gradient) wind (WD_G) at that level. For certain directions of the geostrophic wind at ridge height the channelled flow in the valley is opposite to the along-valley wind component of the geostrophic wind at ridge height. This is called a counter-current (Figure 1).

3. CHANNELLING IN BENT VALLEYS

For spatially invariant horizontal pressure gradients, the wind speed and direction in an idealised, long and straight valley with homogeneous aerodynamic surface roughness is constant along the valley axis. In curved or bent valleys, the along-valley component of the synoptic-scale pressure gradient differs from one segment of the valley to another. Figure 2 shows an example of such a bent valley with an angle of α=120° between the two valley segments, and the flow field in

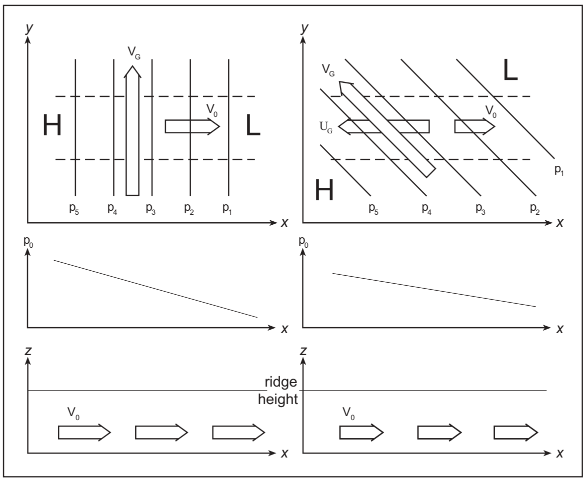

Figure 1. Schematic representation of pressure driven channelling in an idealised, long, straight east-west oriented valley in the Southern Hemisphere for southerly (left) and south-easterly (right) geostrophic wind directions. Top panel: Plan view of the pressure distribution and the wind field above and within the valley. Dashed lines indicate the lateral boundaries of the valley. Isolines represent the pressure field at ridge level, $\mathbf{V_G}$ is the geostrophic wind vector, U_G is the along-valley component of $\mathbf{V_G}$, and $\mathbf{V_0}$ is the near-surface wind vector within the valley. Middle panel: Distribution of the surface pressure p_0 along the valley axis. Bottom panel: Vertical cross section showing winds along the valley axis.

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the valley resulting from pressure driven channelling for different geostrophic wind directions. The along-valley pressure gradient is constant only for geostrophic wind directions parallel to a line bisecting the valley bend, resulting in a constant along-valley wind within the valley (Figures 2a and 2e). For geostrophic winds from directions between the bisection angle and the bisection angle ± $\alpha/2$, the along-valley pressure gradient is of the same sign but of different magnitude in both parts of the valley (Figures 2b, 2d, 2f and 2h). This should result in a convergence or divergence in the along-valley wind at the valley bend and therefore lead to mass compensating vertical air motions. For the remaining geostrophic wind directions the along-valley pressure gradient changes its sign at the bend, which should also result in directional convergence or divergence in the along-valley wind at the bend and associated mass compensating vertical air motions.

Special cases occur when the direction of the geostrophic wind is perpendicular to the bisection angle of the valley bend (Figures 2c and 2g). In these cases, the along-valley pressure gradient is of a different sign, but of the same magnitude in both parts of the valley, so that convergence or divergence is purely directional. For the other cases, the magnitude of the along-valley wind component is of different sign and different magnitude, which means that convergence or divergence is also caused by different along-valley wind speeds in both segments of the valley. The effect of pressure driven channelling on the wind direction in valleys as a function of the geostrophic wind direction is shown in Figure 3 for a straight valley and bent valleys with α=120° and α=60°. The occurrence of convergence or divergence of the along-valley wind component as a function of geostrophic wind direction is illustrated in Figure 4. It is obvious that, independent of the magnitude of α, both examples of bent valleys show the same principal flow features. However, with decreasing angle α, the size of the sectors in which directional convergence or divergence occurs increases, while the sectors where convergence or divergence is caused purely due to change of speed in the along-valley wind component decrease in size.

4. MAGNITUDE OF WIND SPEED, HORIZONTAL FLOW CONVERGENCE AND VERTICAL MOTION

To illustrate the relative magnitude of wind speed expected in the two adjacent valley segments, the along-valley pressure gradient force normalised with the synoptic scale pressure gradient force is depicted in Figure 5 for valleys with α=150°, α=120° and α=60°.

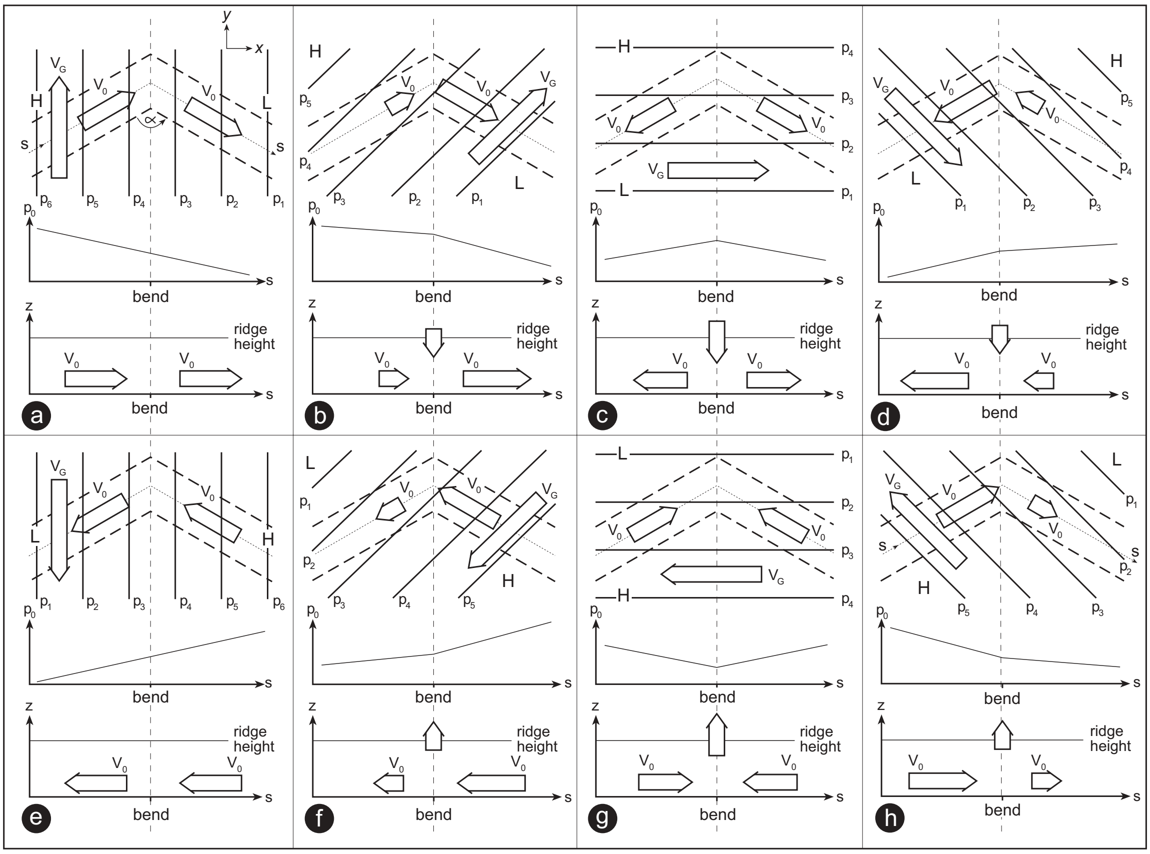

Figure 2. Same as Figure 1, but for a bent valley with α=120° and geostrophic wind directions from a) south, b) south-west, c) west, d) north-west, e) north, f) north-east, g) east, and h) south-east. *s* indicates the along-valley direction.

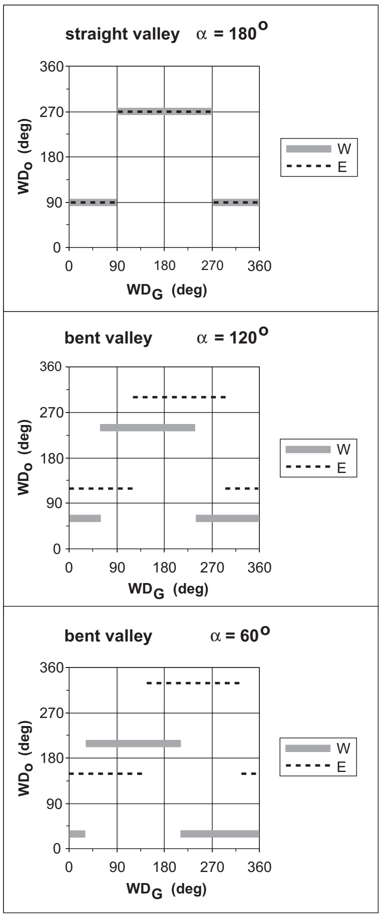

Figure 3. Relationship between the direction of the wind at ridge height (WD_G) and within the valley (WD_O) oriented as sketched in Figures 1 and 2, resulting from pressure driven channelling, for a straight valley (α=180°) and for bent valleys with α=120° and α=60°. W and E denote the western and eastern segments of the valley, respectively.

The magnitude of horizontal flow convergence and hence the magnitude of the mass compensating vertical motions in a bent valley can be described by the difference of the normalised pressure gradient force between the two parts of the valley, which is also shown in Figure 5. As discussed earlier, the strongest and weakest horizontal convergence or divergence and vertical motion in bent valleys are expected for geostrophic winds blowing perpendicular and parallel to the bisection angle, respectively. The magnitude of flow convergence or divergence, and hence compensating vertical air motion, increases with decreasing bend angle α.

So, for a bent valley located in an area of dominant west winds (such as the mid-latitudes) and an orientation as given in Figures 2 to 5, the area around the valley bend should frequently experience dynamically induced subsidence and hence more sunshine hours and stronger atmospheric stability compared to other parts of the valley (Figure 6). The same bent valley located in a climate dominated by

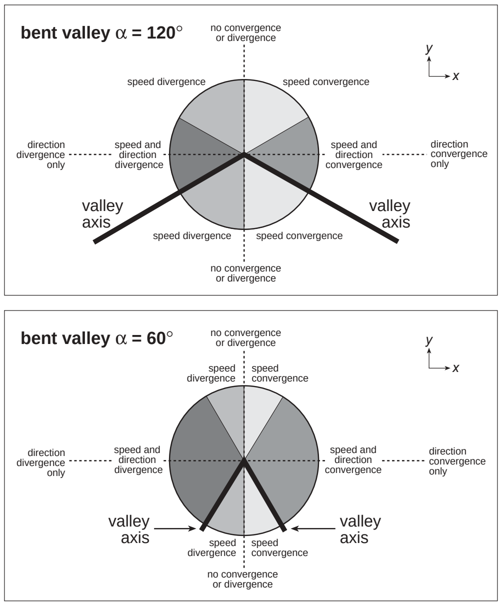

Figure 4. Occurrence of convergence and divergence in the along-valley wind in bent valleys with α=120° and α=60° as a function of the geostrophic wind direction.

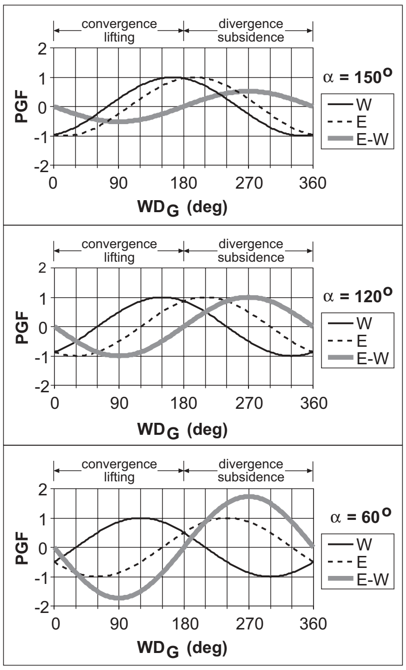

Figure 5. Normalised along-valley pressure gradient force (PGF) as a function of the geostrophic wind direction (WD_G) in the east (E) and west (W) segment of bent valleys with α=150° (top), α=120° (middle) and α=60° (bottom). Negative values indicate an along-valley PGF oriented in the minus *s*-direction. A magnitude of ±1 is equivalent to the strength of the synoptic scale PGF. The difference between the along-valley pressure gradient force in the two differently oriented valley segments (E-W) is also shown.

easterly synoptic scale winds is expected to frequently experience dynamically induced lifting, weaker atmospheric stability and increased convective cloud and precipitation occurrence in the area near the bend than in other parts of the valley.

5. DISCUSSION

The channelling processes were discussed for situations where differently oriented but straight adjacent valley segments form a bent valley, but the results can easily be adapted to smoothly curving valleys. The conceptual model can also be adapted to bent or curved valleys of any orientation and is not limited to the arbitrary examples shown in Figures 2 to 6. It can be expected that, in addition to the bend angle α, other parameters such as valley width and depth and atmospheric stability may have a strong influence on airflow channelling in non-straight valleys.

The dynamical effects associated with flow over the valley ridges might cause the pressure pattern at the valley floor to be different from the synoptic scale pressure gradient at ridge top (Ekman, 1998). Furthermore, dynamic pressure changes associated with the described flow acceleration (pressure decrease) and deceleration (pressure rise) will modify the pressure gradients within bent valleys.

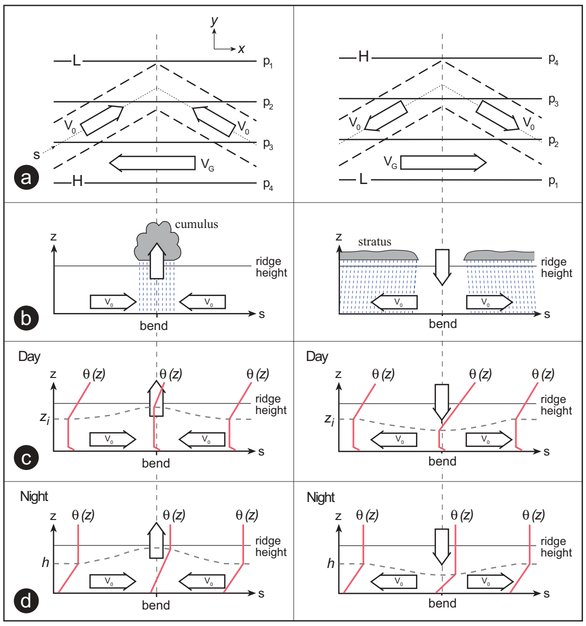

Figure 6. Idealised sketches of possible channelling effects in bent valleys under easterly (left) and westerly (right) flow conditions. a) plan view of airflow above and within the valley, b) effects on cloudiness and precipitation, c) effects on thermal stratification during day-time, and d) effects on thermal stratification during night-time. $\theta(z)$ denotes vertical profiles of potential temperature. z_i is the height of the mixed layer capping temperature inversion during day-time, and h is the height of the top of the nocturnal surface temperature inversion.

The conceptual model derived for flow patterns in curved or bent valleys has a wide range of applications in mountainous terrain including the dispersion of air pollutants, cloudiness, precipitation, bushfire propagation, wind energy potential and aviation. Numerical simulations of airflow over and in idealised bent valleys with varying parameters of valley width and depth, bend angle, upper level wind speed and direction and atmospheric stability appear suitable to test the hypothetical flow fields in a bent valley as outlined above. The horizontal convergence and divergence of airflow in bent valleys is of particular importance for the vertical transport of heat, moisture, momentum and air pollutants and could be further studied by the injection of an inert tracer at the valley floor or in an elevated layer above the valley. The conceptual model presented above is an attempt to promote observational and modelling studies to investigate these questions. A parameterisation of the orographic modification of vertical exchange as a function of valley width and depth, bend angle, upper level wind speed and direction and atmospheric stability for use in large scale models (which are not able to resolve these effects) would also be a desirable outcome of the future work.

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