NOTES AND CORRESPONDENCE

Pressure-Driven Channeling Effects in Bent Valleys

M. KOSSMANN AND A. P. STURMAN

Department of Geography, University of Canterbury, Christchurch, New Zealand

14 March 2002 and 31 July 2002

ABSTRACT

Previous investigations of dynamic channeling 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, that is, composed of segments of 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 because of pressure-driven channeling when adjacent valley segments have a 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 processes are discussed for situations in which differently oriented but straight adjacent valley segments form a bent valley; however, the results can easily be adapted to smoothly curving valleys. The effects of the magnitude of the angle between segments (or, alternately, valley curvature) on the expected flow patterns in the valley are analyzed. 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, cloud formation and dissolution, precipitation, bushfire propagation, wind energy potential, and aviation.

1. Introduction

Wind fields over orographically complex terrain are characterized by thermally and dynamically induced processes. The occurrence and intensity of these processes depends on the weather situation and the shape of the orography. According to Geiger (1961), thermally induced processes can also be called active effects and dynamically induced processes can be called passive effects. This reflects the fact that thermally induced processes are usually best developed during calm and fair synoptic situations, during which differential heating and cooling of the air results in the development of diurnal wind systems of various scales such as slope, valley, or mountain winds (Whiteman 1990). On the other hand, dynamically induced processes such as gravity waves, flow splitting by mountains, or channeling in valleys are caused by orographic modification of synoptic scale winds. Usually, dynamically induced winds are best observed in the case of moderate to strong synoptic flow combined with weak heat exchange between the air and the underlying surface, because this suppresses the development of thermally induced winds. However, in many cases thermally and dynamically induced winds exist concurrently, making it difficult to interpret observed wind fields in orographically complex terrain (Kaufmann 1996). This study presents a conceptual model of dynamic effects on airflow channeling in bent or curved valleys, using Northern Hemisphere examples. Southern Hemisphere examples are given by Kossmann and Sturman (2002).

Corresponding author address: Andrew P. Sturman, Department of Geography, Corner of Arts and Forestry Roads, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.
E-mail: a.sturman@geog.canterbury.ac.nz

2. Channeling in straight valleys

The term channeling describes the 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, which, for example, has strong implications for the dispersion of air pollutants. Observed wind direction frequency distributions measured during channeling events in valleys therefore show a typical bimodal structure independent of the time of day (Wip-

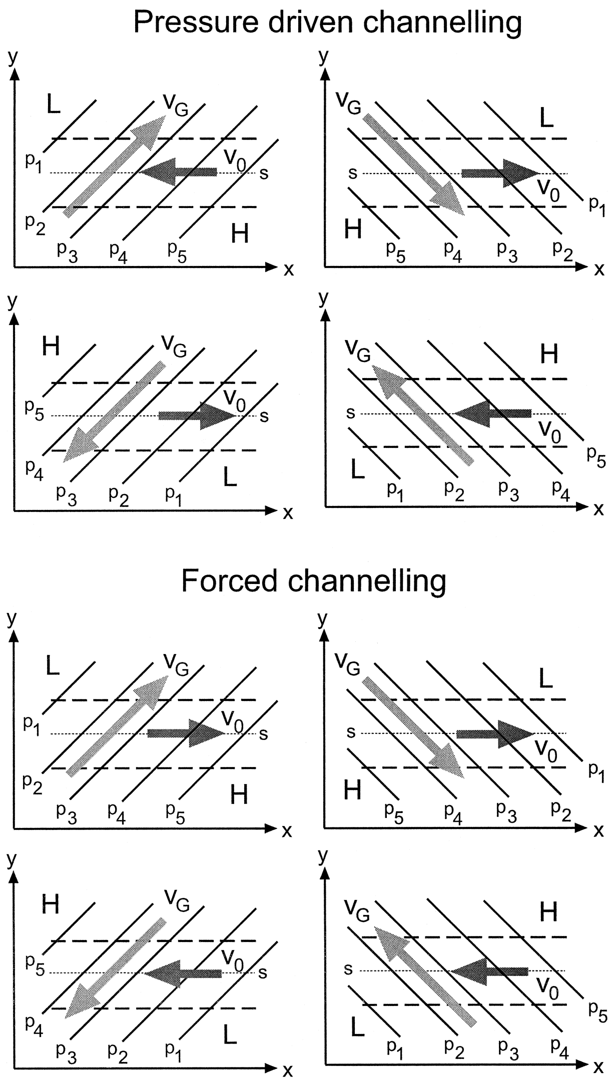

FIG. 1. Plan view of (top) pressure-driven channeling and (bottom) forced channeling in a long, straight (i.e., $\alpha = 180°$), east–west-oriented valley in the Northern Hemisphere for ridge-level geostrophic wind directions from southwest, northwest, northeast, and southeast: (dashed lines) valley sidewalls and (solid lines) isobars at ridge level with $p_{i+1} > p_i$; $\mathbf{V}_G$ is the geostrophic wind vector and $\mathbf{V}_0$ is the surface wind vector in the valley, and s indicates the along-valley direction.

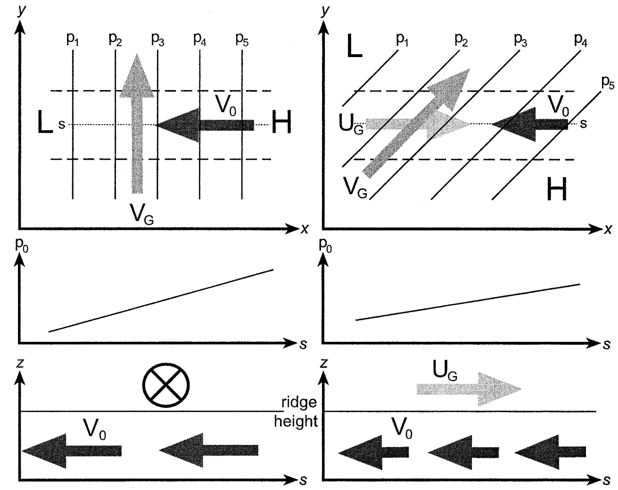

FIG. 2. Schematic representation of pressure-driven channeling in an idealized, long, straight (i.e., $\alpha = 180°$), east–west-oriented valley in the Northern Hemisphere for (left) southerly and (right) southwesterly geostrophic wind directions. (top) Plan view of the pressure distribution and wind field above and within the valley: (dashed lines) lateral boundaries of the valley and (isolines) pressure field at ridge height; $\mathbf{V}_G$ is the geostrophic wind vector, $\mathbf{U}_G$ is the along-valley component of $\mathbf{V}_G$, and $\mathbf{V}_0$ is the near-surface wind vector within the valley. (middle) Distribution of the surface pressure p_0 along the valley axis. (bottom) Vertical cross section showing winds along the valley axis: (cross inside the circle) flow into the page with the countercurrent indicated in the right-hand cross section; s indicates the along-valley direction.

permann and Groß 1981). Previous observational and modeling studies (Fiedler 1983; Wippermann 1984) show that channeling of air in long, broad, and well-defined valleys is directed from high to low pressure (Figs. 1 and 2). Whiteman and Doran (1993) have called this process pressure-driven channeling. This form of channeling is quite different from pure deflection of synoptic-scale winds into an along-valley direction, which is called forced channeling and appears to be the dominating channeling mechanism in short and narrow valleys (Weber and Kaufmann 1998). The term dynamic airflow channeling is used here to cover both of these two processes. The wind speed in a valley caused by pressure-driven channeling 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. Good examples of channeled airflow in long, straight, and well-defined valleys are the upper Rhine Valley (Wippermann and Groß 1981; Fiedler 1983; Wippermann 1984; Vogel et al. 1986; Adrian 1988), the Swiss Middleland (Furger 1992), and the Tennessee Valley (Whiteman and Doran 1993; Eckman 1998).

In previous channeling 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 (all wind direction angles are given relative to north). For certain directions of the geostrophic wind at ridge height, the channeled flow in the valley is opposite to the along-valley wind component of the geostrophic wind at ridge height. This feature of pressure-driven channeling is called a countercurrent (see the left-hand side of the top panel in Fig. 1 and the right-hand side of Fig. 2). Channeling of the airflow in valleys also depends on atmospheric stability. On the one hand, stable stratification acts to decouple winds within the valley from the winds above the ridges, resulting in a higher frequency of channeling events in the valley (Kalthoff and Vogel 1992). On the other hand, unstable stratifi-

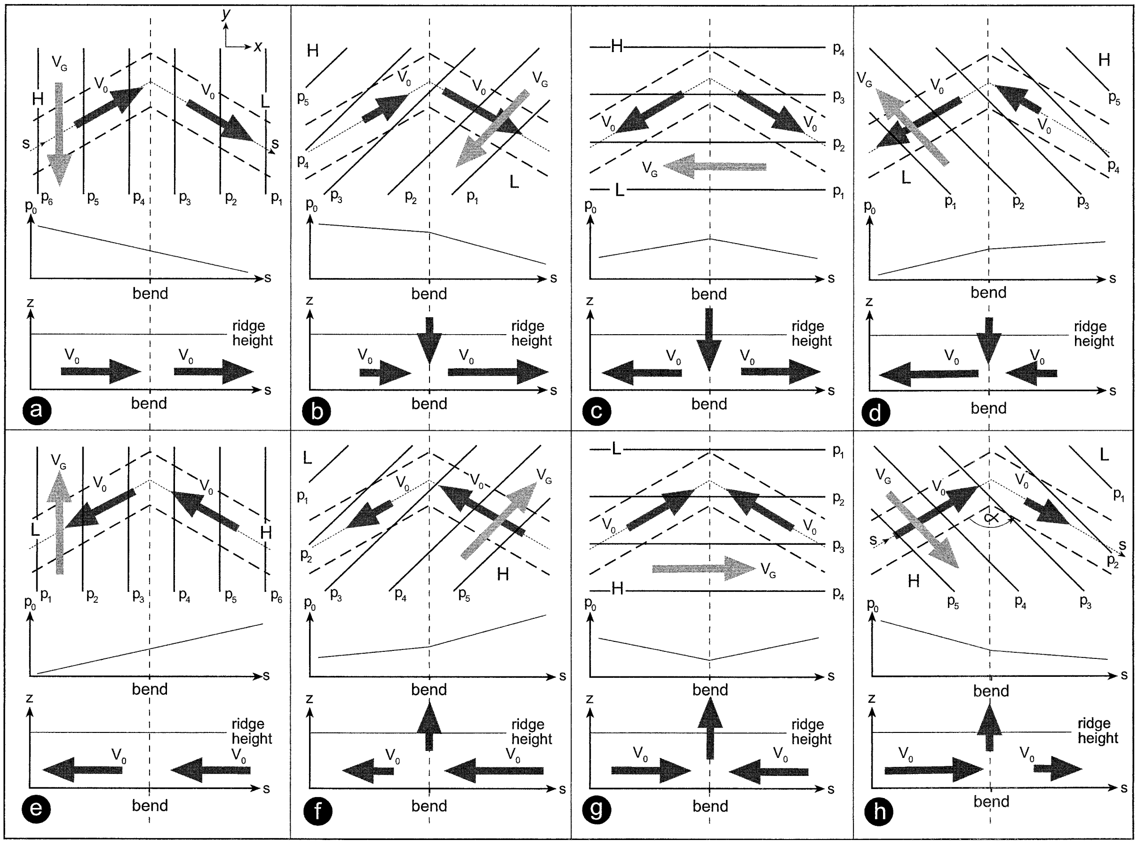

FIG. 3. Plan and cross-section representations of pressure-driven channeling in a bent valley with $\alpha = 120°$ and geostrophic wind directions from (a) north, (b) northeast, (c) east, (d) southeast, (e) south, (f) southwest, (g) west, and (h) northwest; *s* indicates the along-valley direction.

cation can lead to strong vertical momentum exchange between the flow in the valley and the flow above ridge height. Under such conditions upper-level winds can more easily penetrate downward into the valley, counteracting the development of channeled flow in the valley and increasing the probability of cross-valley flows. However, the vertical turbulent exchange of momentum also transports the momentum of the channeled air within the valley to higher levels. So in some cases, the vertical thickness of the layer containing channeled airflow in the valley can reach above the height of the surrounding ridges because of the upward transport of momentum (Fiedler 1983).

3. Channeling in bent valleys

For spatially invariant horizontal pressure gradients, the wind speed and direction in an idealized, long, and straight valley with homogeneous aerodynamic surface roughness is constant along the valley axis. In nature, however, valleys are often curved or bent, that is, composed of segments of different orientation. In these valleys, the along-valley component of the synoptic-scale pressure gradient differs from one segment of the valley to another. Figure 3 shows an example of such a bent valley with an angle of $\alpha = 120°$ between the two valley segments and the flow field in the valley resulting from pressure-driven channeling 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 (Figs. 3a and 3e). For geostrophic winds from directions between the bisection angle and the bisection angle $\pm\alpha/2$, the along-valley pressure gradient is of the same sign but of different magnitude in both parts of the valley (Figs. 3b, 3d, 3f, and 3h). This should result in convergence or divergence in the along-valley wind at the valley bend and therefore lead to mass-compensating vertical air motion. For the remaining geostrophic wind directions the along-valley pressure gradient changes its sign at the bend, which should result in a directional convergence or divergence in the along-valley wind component at the bend and associated mass-compensating vertical air motion. Special cases occur when the direction of the geostrophic wind is perpendicular to the bisection angle of the valley bend (i.e., easterly and westerly winds) (Figs. 3c and 3g). 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 convergence

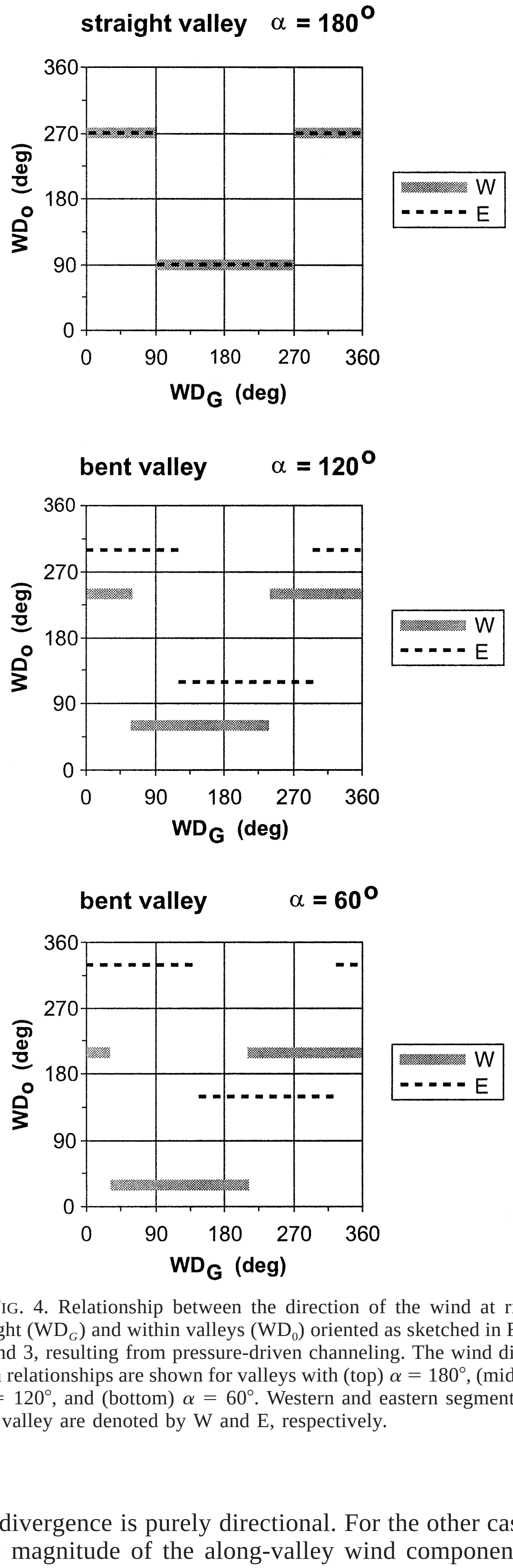

FIG. 4. Relationship between the direction of the wind at ridge height (WD_G) and within valleys (WD_0) oriented as sketched in Figs. 1 and 3, resulting from pressure-driven channeling. The wind direction relationships are shown for valleys with (top) $\alpha = 180°$, (middle) $\alpha = 120°$, and (bottom) $\alpha = 60°$. Western and eastern segments of the valley are denoted by W and E, respectively.

or divergence is purely directional. For the other cases, the magnitude of the along-valley wind component is of a 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 channeling on the wind direction in valleys as a function of the geostrophic wind direction is shown in Fig. 4 for a straight valley and bent valleys with $\alpha = 120°$ and $\alpha = 60°$. The occurrence of convergence or divergence of the along-valley wind component as a function of geostrophic wind direction is illustrated in Fig. 5. 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 sectors in which directional convergence or divergence occurs increase, and the sectors where convergence or divergence is caused purely by 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 normalized with the synoptic-scale pressure gradient force (PGF_N) is depicted in Fig. 6 for valleys with $\alpha = 150°$, $\alpha = 120°$, and $\alpha = 60°$. The formulas used to derive the curves in Fig. 6 are given below. These formulas are only valid for the given orientation of the valley.

For the west segment of the bent valley (W),

$$PGF_N = \cos\left(WD_G + \frac{180 - \alpha}{2}\right); \qquad (1)$$

for the east segment of the bent valley (E),

$$PGF_N = \cos\left(WD_G - \frac{180 - \alpha}{2}\right), \qquad (2)$$

where WD_G is geostrophic (or gradient) wind direction, and α is the angle between valley segments (i.e., the bend angle).

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 normalized pressure gradient force (ΔPGF_N) between the two parts of the valley (i.e., E–W), which is also shown in Fig. 6. The equation for the curve E–W that follows from (1) and (2) is given by

$$\Delta PGF_N = \cos\left(WD_G - \frac{180 - \alpha}{2}\right) - \cos\left(WD_G + \frac{180 + \alpha}{2}\right). \qquad (3)$$

As discussed earlier, the strongest and weakest horizontal convergence or divergence and vertical motion in bent valleys are expected for geostrophic winds blowing perpendicular (i.e., easterly and westerly) and par-

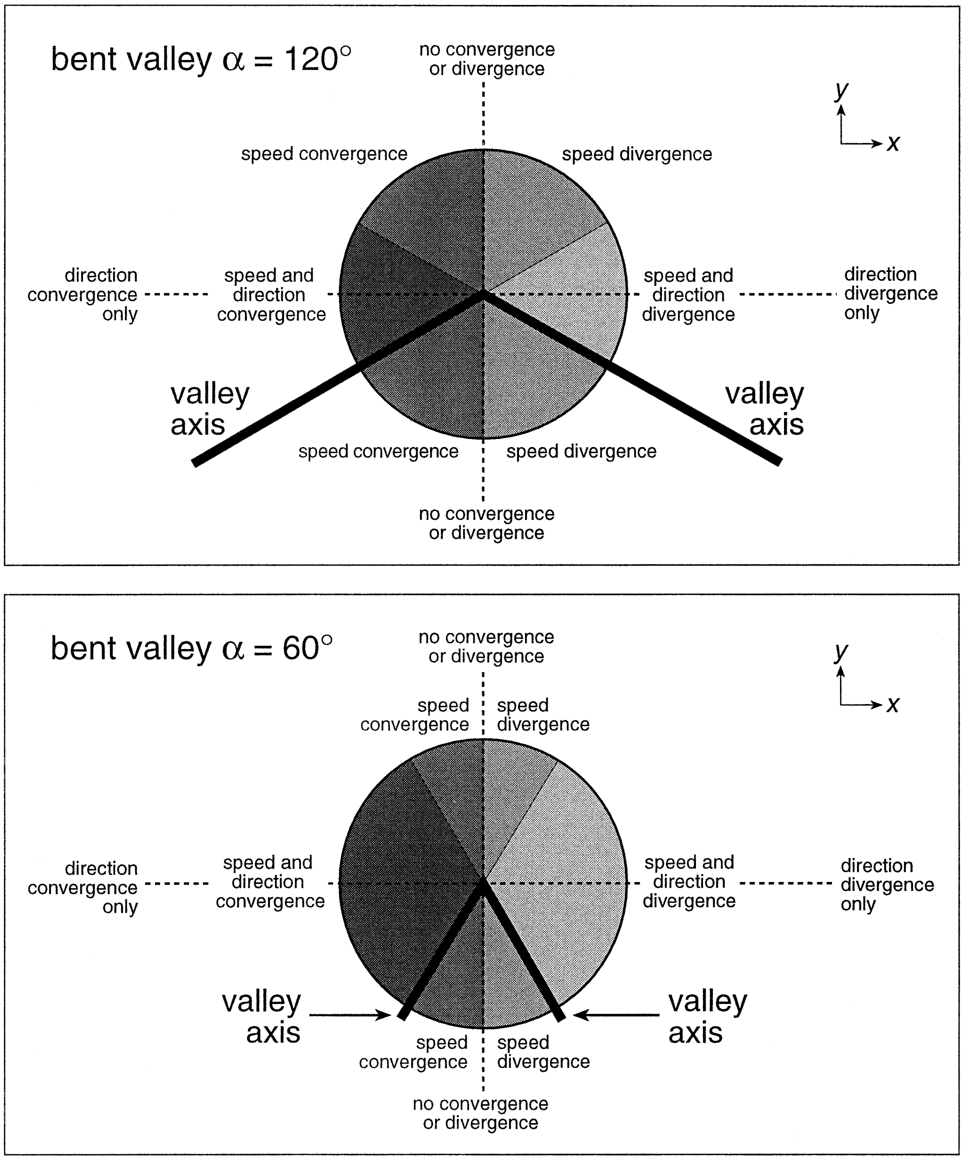

Fig. 5. Occurrence of convergence or divergence in the along-valley wind component because of pressure-driven channeling in bent valleys with $\alpha = 120°$ and $\alpha = 60°$ as a function of the geostrophic wind direction.

allel (i.e., northerly and southerly) 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 westerly winds (such as the midlatitudes) and an orientation as given in Figs. 3–6, the area around the valley bend should frequently experience dynamically induced lifting and, hence, weaker atmospheric stability, fewer sunshine hours, and increased convective cloud and precipitation occurrence when compared with other parts of the valley (Fig. 7). The same bent valley located in a climate dominated by easterly synoptic-scale winds is expected to frequently experience dynamically induced subsidence, stronger atmospheric stability, and possibly more sunshine hours and less precipitation in the area near the bend than in other parts of the valley. The left panel of Fig. 7 shows cloud-free (high pressure) synoptic conditions over the valley area, in which surface heating and moisture levels are mostly insufficient to cause the development of cumulus clouds. However, near the bend the channeling-induced lifting causes air parcels to reach condensation level, resulting in the formation of convective clouds and precipitation. The right panel illustrates a closed stratus cloud cover that is assumed to have been advected over the valley area by the mean (synoptic) wind, and the channeling-induced subsidence causes the clouds to dissolve near the bend.

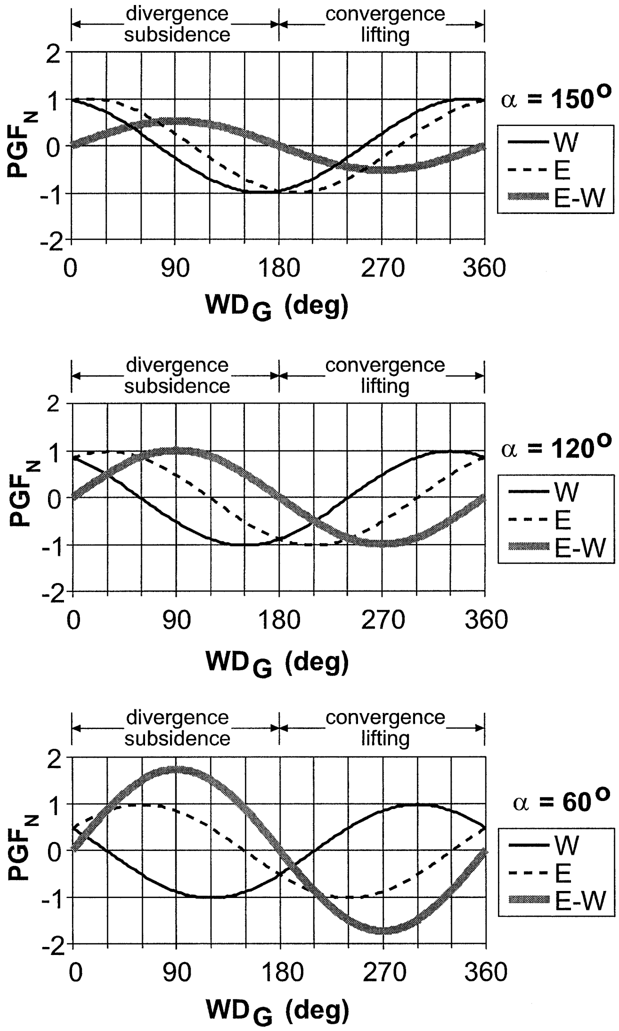

FIG. 6. Normalized along-valley pressure gradient force (PGF_N) as a function of the geostrophic wind direction (WD_G) in the east (E) and west (W) segment of bent valleys with (top) $\alpha = 150°$, (middle) $\alpha = 120°$, and (bottom) $\alpha = 60°$. Negative values indicate an along-valley PGF_N oriented in minus s direction. A magnitude of ± 1 is equivalent to the strength of the synoptic-scale PGF. Furthermore, the difference between the normalized along-valley pressure gradient force in the differently oriented valley segments (i.e., E–W) is shown to illustrate the expected relative intensity of flow convergence or divergence and compensating lifting or subsidence as a function of the geostrophic wind direction.

5. Discussion and outlook

The channeling processes were discussed for situations in which 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 Figs. 3–7. 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 channeling in nonstraight valleys.

For cases in which different wind speeds occur in the two segments of a bent valley (Figs. 3b, 3d, 3f, and 3h) inertia effects may cause the zone of flow convergence or divergence to be displaced into the segment with the lower wind speed, rather than being centred on the valley bend. It should be noted that only a few studies (e.g., Smedman et al. 1996) have actually investigated the effects of geostrophic wind direction on the expected wind speed due to dynamical airflow channeling, even in straight valleys.

Under baroclinic conditions the pressure gradient (and hence geostrophic wind speed and direction) at ridge level is not necessarily representative of the valley floor, particularly in deep valleys. Also, 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 (Eckman 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. Recent research by Weber and Kaufmann (1998) suggests that there is a critical valley size (width and length) below which forced channeling becomes the dominating channeling mechanism, instead of pressure-driven channeling. However, this critical valley size has not yet been investigated in detail.

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 idealized 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/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 modeling studies to investigate these questions. A parameterization of the orographical 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 future work.

Acknowledgments. This research was supported by the New Zealand Marsden Fund under contract UOC602 and the New Zealand Public Good Science Fund under contract C01X0011. The help of Dean Aldridge from

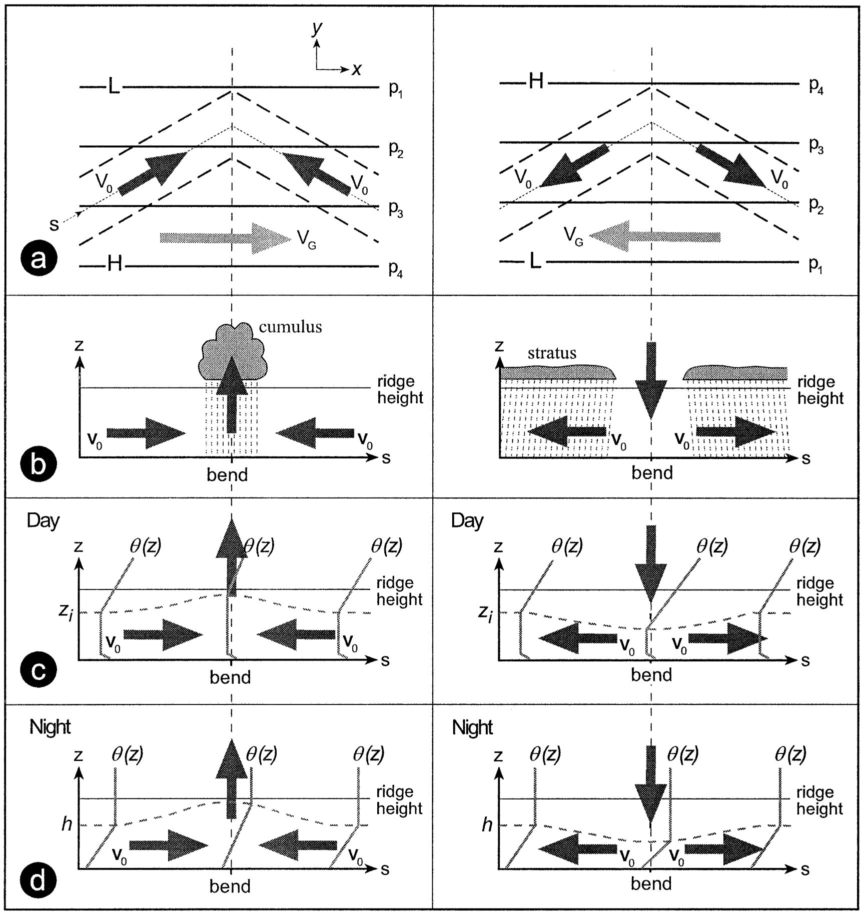

FIG. 7. Idealized sketches of possible channeling effects in bent valleys under (left) westerly and (right) easterly flow conditions: (a) plan view of airflow above and within the valley, (b) effects on cloudiness and precipitation, (c) effects on thermal stratification during daytime, and (d) effects on thermal stratification during nighttime; $\theta(z)$ denotes vertical profiles of potential temperature, z_i is the height of the mixed layer capping temperature inversion during daytime; and h is the height of the top of the nocturnal surface temperature inversion.

the Geography Department of the University of Canterbury with the drawing of figures is gratefully acknowledged. Special thanks are given to Dr. Dave Whiteman from Pacific Northwest National Laboratory in Richland, Washington, for his continuing encouragement to publish the conceptual model described in this paper.

REFERENCES

Adrian, G., 1988: Synthetic wind climatology evaluated by the nonhydrostatic numerical mesoscale model KAMM. *Environmental Meteorology,* K. Grefen and J. Löbel, Eds., Kluwer Academic, 397–411.

Eckman, R. M., 1998: Observations and numerical simulations of winds within a broad forested valley. *J. Appl. Meteor.,* **37,** 206–219.

Fiedler, F., 1983: Einige Charakteristika der Strömung im Oberrheingraben (Some characteristics of the airflow in the upper Rhine Valley). Wissenschaftliche Berichte des Meteorologischen Instituts der Universität Karlsruhe, Vol. 4, 113–123. [Available from Institut für Meteorologie und Klimaforschung, Universität Karlsruhe/Forschungszentrum Karlsruhe, Kaiserstrasse 12, D-76128 Karlsruhe, Germany.]

Furger, M., 1992: The radiosoundings of Payerne: Aspects of the synoptic dynamic climatology of the wind field near mountain ranges. *Theor. Appl. Climatol.,* **45,** 3–17.

Geiger, R., 1961: *Das Klima der bodennahen Luftschicht.* Friedrich Vieweg and Sohn, 646 pp.

Kalthoff, N., and B. Vogel, 1992: Counter-current and channeling effect under stable stratification in the area of Karlsruhe. *Theor. Appl. Climatol.,* **45,** 113–126.

Kaufmann, P., 1996: Regionale Windfelder über komplexer Topographie (Regional windfields over complex topography). Ph.D. dissertation. Paul Scherrer Institut, Villigen, Switzerland, 147 pp. [Available from Information Services, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland.]

Kossmann, M., and A. P. Sturman, 2002: Dynamic airflow channelling effects in bent valleys. Preprints, *10th Conf. on Mountain Meteorology,* Park City, UT, Amer. Meteor. Soc., 319–322.

Smedman, A.-S., H. Bergström, and U. Högström, 1996: Measured and modelled local wind fields over a frozen lake in a mountainous area. *Contrib. Atmos. Phys.,* **69,** 501–516.

Vogel, B., G. Groß, and F. Wippermann, 1986: MESOKLIP (First special observation period): Observations and numerical simulation—a comparison. *Bound.-Layer Meteor.*, **35,** 83–102.

Weber, R. O., and P. Kaufmann, 1998: Relationship of synoptic winds and complex terrain flows during the MISTRAL field experiment. *J. Appl. Meteor.*, **37,** 1486–1496.

Whiteman, C. D., 1990: Observations of thermally developed wind systems in mountainous terrain. *Atmospheric Processes over Complex Terrain, Meteor. Monogr.*, No. 45, Amer. Meteor. Soc., 5–42.

——, and J. C. Doran, 1993: The relationship between overlying synoptic-scale flows and winds within a valley. *J. Appl. Meteor.*, **32,** 1669–1682.

Wippermann, F., 1984: Air flow over and in broad valleys: Channelling and counter-current. *Contrib. Atmos. Phys.*, **57,** 92–105.

——, and G. Groß, 1981: On the construction of orographically influenced wind roses for given distributions for the large-scale wind. *Contrib. Atmos. Phys.*, **54,** 492–501.