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Interaction of cold-air blocking and upper-level potential vorticity anomalies during lee cyclogenesis

By JOSEPH EGGER, *Meteorologisches Institut, Universität München, Theresienstr. 37, 80333 München, Germany*

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ABSTRACT

A two-dimensional model of the interaction of cold-air blocking by a mountain and of an anomaly of potential vorticity (PV) moving over the mountain during lee cyclogenesis, is presented. The model is based on the semigeostrophic equations for a three-layer atmosphere with piecewise constant distributions of potential vorticity. A geostrophic mean flow U normal to the mountain is imposed. Initially, an upper-level PV-anomaly is assumed above a cold layer confined by a surface front. The near-surface circulation is anticyclonic underneath the anomaly. Both the front and the anomaly move with speed $\sim U$ towards the mountain, where the cold air is blocked while the anomaly crosses the mountain and induces a cyclone in the lee.

1. Introduction

By now, it is well-known that blocking of cold air by a mountain is an important feature of lee cyclogenesis. For example, Mesinger and Pierrehumbert (1986), in their review on Alpine lee cyclogenesis, point out that the "prime effect of the Alps is to retard the southward advance of the cold air" (see also Zupanski and McGinley, 1989; Tafferner, 1990). The same appears to be true with respect to lee cyclogenesis at the Altai-Sayan massif (Chen et al., 1992) and also at the Atlas Mountains (Egger et al., 1995). However, blocking of air flow by a barrier is an intrinsically non-linear phenomenon and, therefore, difficult to include in a theoretical model of lee cyclogenesis.

Von Ficker (1920) considered blocking and deformation of low-level flow in his conceptual model of Alpine lee cyclogenesis. However, von Ficker's model is formulated at a descriptive level where nonlinearity does not pose a technical problem. Radinovic (1965) introduced blocking by the Alps in a quasigeostrophic two-level model by prescribing specific flow changes at the barrier. He was able to demonstrate for the first time quantitatively that deformation of low-level flow by the Alps is an important part of lee cyclone formation. Pierrehumbert (1985) considered a west-east oriented barrier cutting through an eastward moving linear baroclinic wave: cyclogenesis was found to occur. The mountain suppresses any meridional transport and, therefore, cold air blocking is mimicked to some extent. However, Pierrehumbert's model could not be verified against idealized and observed cases of Alpine lee cyclogenesis (Egger, 1988; VT, Tafferner and Egger, 1990). This failure is presumably due to the fact that a linear baroclinic wave is not close enough to the atmospheric flow state favourable for Alpine lee cyclogenesis. Mesinger and Pierrehumbert (1986) suggested quite a different approach to the problem. They assume a quasigeostrophic atmosphere with uniform potential vorticity. Such an atmosphere is governed by the motion of the isotherms at the ground (and at other boundaries). Mesinger and Pierrehumbert specify the temperature evolution at the ground in a manner reminiscent of cold air blocking by a mountain and are able to induce a "lee" cyclone this way.

In this paper, we take the idea of Mesinger and Pierrehumbert (1986) as a starting point. A two-dimensional semigeostrophic three-layer model will be used where the potential vorticity distribution and the location of the intersection of the isentropes with the ground determine the flow. Cyclone formation in the conceptual model of Mesinger and Pierrehumbert (1986) is due to a prescribed increase of the temperature in the lee. In our model, temperature (density) is a flow variable which is not specified independently. In particular, we predict the advance of the cold front towards the mountain and the ensuing blocking. There is one more point, where we wish to go a step beyond Mesinger and Pierrehumbert (1986). In recent years it has become increasingly clear that the flow state in the upper troposphere may be of crucial importance during lee cyclogenesis (Mattocks and Bleck, 1986; Zupanski and McGinley, 1989). If so, the assumption of uniform potential vorticity as in Mesinger and Pierrehumbert (1986) must be relaxed so that we can allow for the motion of "anomalies" of potential vorticity (PV) aloft over the lee side. The importance of such processes to lee-side development comes out clearly, for example, in Tafferner (1990), Lanzinger (1992) and Han et al. (1994). Correspondingly, the model will be designed such that it can handle piecewise constant PV-distributions. This model ought to help us in understanding the linkage of cold-air blocking and upper-level PV-distribution during lee cyclogenesis.

What we exclude, however, are baroclinic processes. The model atmosphere is two-dimensional and gradients of flow variables normal to the flow direction are excluded. Of course, there is sample evidence that virtually all lee cyclogenesis events are linked to baroclinic waves moving over the related mountain massif. Both, the surface cold front and the upper-level PV-anomaly as represented in the model are features of such mature baroclinic systems. However, further baroclinic development is excluded in the model and eventual cyclone growth in the lee cannot be attributed to baroclinic instability. So we have here a minimum cyclogenesis model where many processes, which are known to be important, are excluded in order to explore and isolate the remaining mechanisms. A more thorough discussion of this point must be postponed till the details of the model have been presented.

2. The Model

Versions of the model are described to some detail in Egger (1992) and Egger and Hatt (1994),

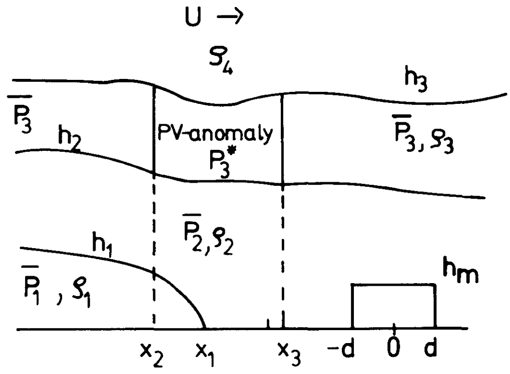

Fig. 1. Schematic of the model. Potential vorticity is uniform throughout layers 1 and 2 and piecewise constant in the upper layer where an anomaly P_3^* may be inserted. The width of the mountain is 2d, its height is h_m. See text for further details.

so that we can be brief. The model atmosphere is two-dimensional (Fig. 1) and consists of 3 homogeneous layers of constant density ρ_i $(i=1, 3)$. Layer 1 represents the cold air. The interface of layer 1 and 2 stands for the cold front. Its intersection with the ground at $x=x_1$ will be called surface cold front. There is a third layer which represents the upper troposphere. We assume a mountain with vertical walls.

The flow along the front is geostrophic:

$$v_i = -\frac{\partial p_i}{\partial x}(f\rho_i)^{-1} \tag{1}$$

(v_i meridional flow speed in layer i; f Coriolis parameter, constant; p_i pressure). The model atmosphere is hydrostatic, so that

$$p_i = \sum_{j=i+1}^{4} g_{ji} h_{j-1} \rho_i, \tag{2}$$

with reduced gravities $g_{ji} = g(\rho_i - \rho_j)/\rho_i$ and interface heights h_j. The prognostic model equations are

$$\frac{\partial v_i}{\partial t} + P_i M_i = fU, \tag{3}$$

$$\frac{\partial}{\partial t}(h_i - h_{i-1}) + \frac{\partial}{\partial x} M_i = 0, \tag{4}$$

where

$$M_i = (h_i - h_{i-1})\, u_i \tag{5}$$

is the volume flux in each layer with zonal velocity u_i, U is the geostrophic wind related to an imposed large-scale pressure field and

$$P_i = \left(\frac{\partial v_i}{\partial x} + f\right) \Big/ (h_i - h_{i-1}) \tag{6}$$

is potential vorticity (PV), which is conserved. It is understood in (4)–(5), that h_{i-1} equals the height of the terrain if layer i touches the ground.

Analytic solutions to the model equations can be derived if the potential vorticity P_i is assumed to be piecewise constant in each layer. Here we consider the situation depicted in Fig. 1 where $P_1 = \overline{P_1}$ and $P_2 = \overline{P_2}$ are uniform while an anomaly P_3^* is embedded in the upper layer so that $P_3 = P_3^*$ for $x_2 < x < x_3$ and $P_3 = \overline{P_3}$ elsewhere. We prescribe $\overline{P_i} = f/(H_i - H_{i-1})$ where H_i is the upstream height of interface i. Note, that (6) with (1), (2) is a set of linear equations for every interval $-\infty < x < x_2$, $x_2 < x < x_1$, $x_1 < x < -d$, $-d < x < d$, $x > d$ (to take one example). Solutions are of the type

$$h_i = \sum_j A_{ij} \exp(\pm \lambda_j x), \qquad \text{where} \quad j = 1, \cdot, 3(1, 2)$$

for the 3 (2)-layer situation, A_{ij} are amplitude factors and the radii λ_j^{-1} must be determined from (6) for each interval separately. Given $\overline{P_i}$, x_i and the orography, it is then straightforward to solve (6) for the heights h_i under the boundary conditions $h_i \to H_i$ for $x \to -\infty$, $h_{2,3} \to H_2 - H_1$, $H_3 - H_2$ for $x \to \infty$, as implied by continuity, and $h_1 = 0$ at $x = x_1$, if the cold air has not yet reached the mountain. If, on the other hand $x_1 = -d$ then $h_1 = h_w$, where h_w is the depth of the cold air at the wall. It is simple to find solutions to (1), (2) and (6) for every interval $-\infty < x < x_2$, $x_2 < x < x_1$, $x_1 < x < -d$, $-d < x < d$, $x > d$ (to take one example). The factors A_{ij} are obtained by matching solutions at $x = x_2$, $x = x_1$, $x = -d$, $x = d$ requiring continuity of h_i and v_i. These procedures are described more fully in Egger (1992), where two surface fronts are admitted, but no PV-anomaly.

Prediction of the flow evolution requires only a forecast of the position of the points x_j. A standard procedure (Davies, 1984) is to solve the volume flux equations which are derived from (1)–(5) by imposing the geostrophic constraint (1) on the tendencies of v_i and h_i. The solution to these flux equations is obtained using the same analytic techniques as for the height field and the matching conditions as in Egger and Hatt (1994; continuity of M_i at all x_j; continuity of $\partial M_i/\partial x$ at x_2, x_3; continuity of $(\partial M_1 + M_2)/\partial x$ and of $\partial M_3/\partial x$ at $x = x_1$). If all $M_i(x_j)$ are known, we have

$$\begin{aligned} u_1(x_1) &= \frac{\partial M_1}{\partial x} \Big/ \frac{\partial}{\partial x}(h_1 - h_m)\big|_{x=x_1}, \\ u_3(x_{2,3}) &= M_3/(h_3 - h_2)\big|_{x=x_{2,3}}. \end{aligned} \tag{7}$$

Note, that the derivatives in (7) are evaluated analytically. Finally,

$$\frac{\mathrm{d}x_j}{\mathrm{d}t} = u(x_j) \tag{8}$$

is the forecast equation for the points x_j. Given the positions x_j, the model provides us with analytic expressions for the heights h_i and the fluxes M_i. However, the integration of (8) is carried out in a stepwise approximate form. Runs are terminated when the cold air reaches the crest, i.e., if $h_w = h_m$.

Although our model atmosphere is baroclinic, baroclinic instability is excluded. One way to allow for baroclinic wave growth is to suppose mean gradients $\partial \overline{P_i}/\partial y$ of the potential vorticity in y-direction (normal to x-axis). However, potential vorticity conservation requires

$$\frac{\partial P_i}{\partial t} + u_i \frac{\partial P_i}{\partial x} + v_i \frac{\partial \overline{P_i}}{\partial y} = 0$$

in that case. Potential vorticity can no longer be assumed uniform in a layer and, therefore, our analytical approach breaks down. Another possibility is to consider a threedimensional atmosphere where uniformity of PV in layers and baroclinicity may be combined. Again the simplicity of our approach would be lost. A price must be paid for adopting such a simple model. Both the cold front and the upper level PV-anomaly are part of a baroclinic system. Correspondingly, their motion ought to be governed by baroclinic wave dynamics, but not, as in our model, by a barotropic mean flow U. A rather brief description of a grid point version of this model is presented in Egger et al. (1995). The analytic model described here is, of course, superior to a grid point model, in particular so, if it comes to handling the motion of the surface front.

Note, that the scenario envisaged here is "orthogonal" to that presented recently by Orlanski and Gross (1994; their Fig. 17). These authors consider a cold front approaching an west-east oriented mountain from the west. The front is oriented normal to the mountain. Cyclogenesis occurs after the cold front arrives at the southern flank of the mountain. Here, the front is oriented parallel to the mountain and the lee cyclone forms before the cold air reaches the lee.

3. Results

It is helpful for an understanding of the flow evolution to discuss simple cases first. In particular, if there is no mountain, the flow state does not change in time in a coordinate system moving with speed U. We show in Fig. 2 the heights h_i and the surface pressure (dashed) linked to a positive

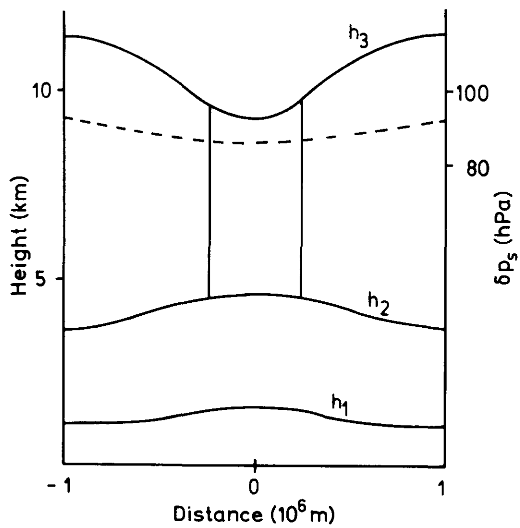

Fig. 2. Interface heights h_i (full) and surface pressure deviation δp_s from reference value (hPa; dashed) linked to a PV-anomaly in the upper layer confined by the vertical lines; no mountain. Parameters: $H_1 = 1000$ m; $H_2 = 3500$ m; $H_3 = 12000$ m; $P_3^* = 5\overline{P_3}$, $g_{11} = 1.2$ m s^{-2}, $g_{22} = g_{33} = 0.6$ m s^{-2}.

PV-anomaly. The height deviations are familiar from more complex PV-inversion models (Hoskins et al., 1985). There is a trough above the anomaly and two ridges underneath. The circulation (not shown) is cyclonic in all layers. While the anomaly has a diameter of 500 km, the scale of the surface low is much larger. The interpretation of Fig. 2 is simple: the pressure field due to the upper level trough induces cyclonic vorticity in layers 1 and 2. Thus the thickness of these layers must be relatively large in order to ensure uniformity of potential vorticity. The scale of the surface low reflects the radii λ_{ij}^{-1}.

If there is a mountain but no PV-anomaly and no surface front one obtains the well known pattern of steady semigeostrophic flow over a mountain with a symmetric ridge on top of the mountain. The magnitude of the height perturbations decreases with increasing layer index.

We consider now a case without upper-level PV anomaly where the surface front is located initially 300 km upstream of a narrow mountain. The flow in the cold air is anticyclonic. With $U = 10$ m s^{-1}, the front arrives after about eight hours at the foot of the mountain. From then on the cold air is piling up at the wall and the surface pressure is rising. For example, we observe a surface pressure jump of more than 10 hPa at the wall at $t = 17$ h. The cold air continues to pile up at the mountain. At $t = 25$ h (Fig. 3a), the vorticity in the lowest layer is cyclonic near the wall. Note that there is no mechanism available in a semigeostrophic model to affect the inflow profile far upstream. The surface pressure in the lee is decreasing with increasing x but there is no surface pressure minimum and no lee cyclone.

If there is a PV-anomaly above the cold air initially (Fig. 3b), we see the bulge of h_2 underneath the upper-level PV-anomaly as in Fig. 2. However, now there is no surface pressure minimum underneath the anomaly because the height profile of the lowest layer near the surface front dominates the surface pressure distribution. This initial state resembles to some extent that chosen by Gross (1990) in his investigations of the motion of PV-anomalies over a mountain. However, Gross' anomaly extends far upstream so that the meridional wind fields exhibit a southerly jet ahead of the PV-center but no northerlies. Moreover, the ground is an isentropic surface in Gross' model so that there is no surface front. Cold-air blocking is

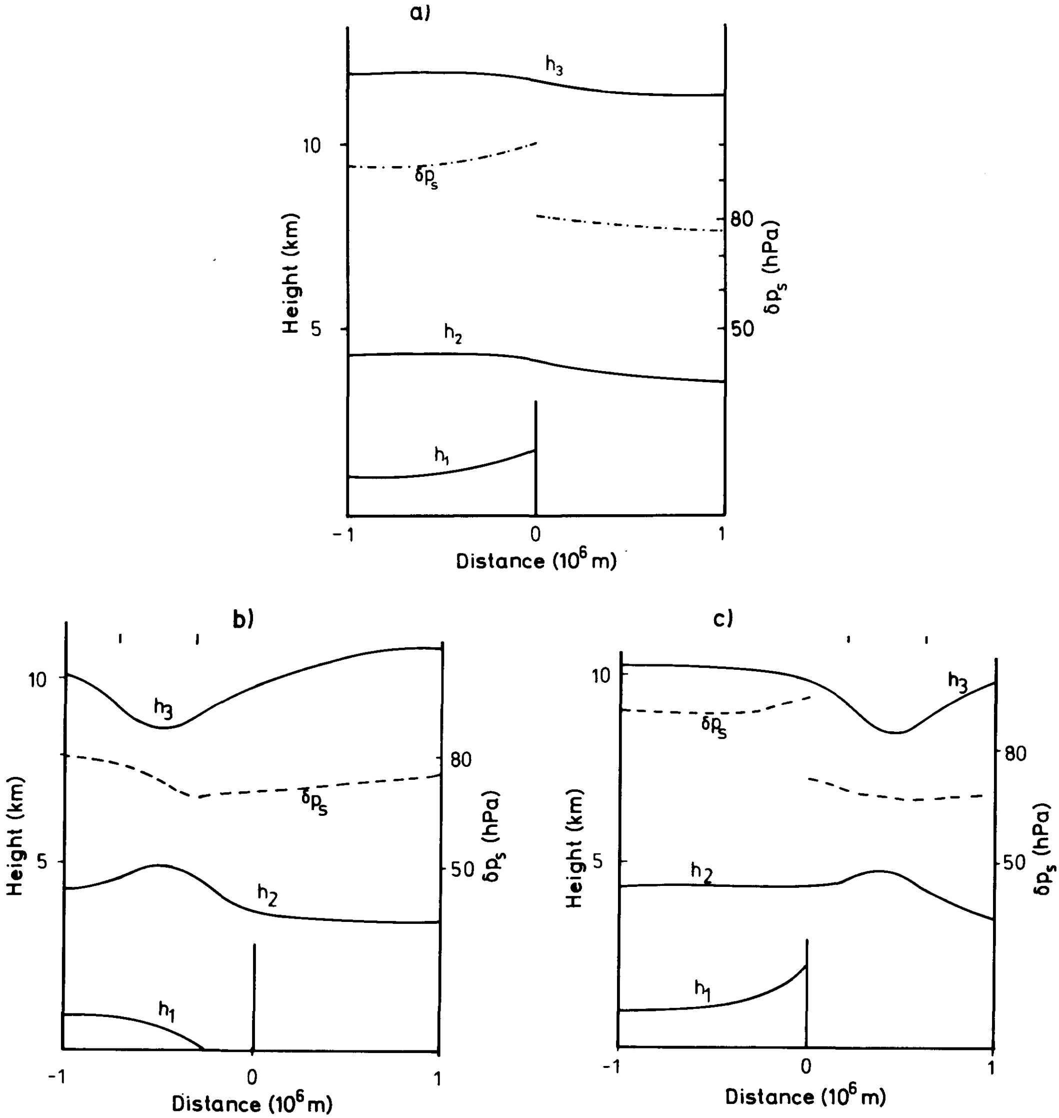

Fig. 3. Interface heights h_i (m; full) and surface pressure deviation δp_s (hPa; dashed) for a situation without (a: $t = 25$ h) and with (b: $t = 0$ h), (c: $t = 25$ h) PV-anomaly and a narrow mountain. Parameters: $H_1 = 1000$ m, $H_2 = 4500$ m; $H_3 = 12000$ m, $P_3^* = 5\overline{P_3}$, $g_{11} = 1.2$, $g_{22} = g_{33} = 0.6$ m s^{-2}. Mountain height 3000 m; $d = 10$ km; $U = 10$ m s^{-1}. The tick marks give the position of the PV-anomaly in (b), (c).

excluded a priori and, correspondingly, lee cyclogenesis does not occur. However, we may see Fig. 3b as a simplified version of the initial cros-section in Fig. 3b of Mattocks and Bleck (1986).

At $t = 25$ h (Fig. 3c), the h_1-profile is quite similar to that in Fig. 3a. The upper-level trough and even the bulge of interface 2 crossed the barrier. The depth of the lower layer underneath the anomaly is larger in the lee and, therefore, the cyclonic circulation is more vigorous. There is now a surface pressure minimum in the lee. The pressure difference between the wall and the minimum is 5 hPa. This is quite a realistic value for a lee cyclone in the incipient stage. What is not so realistic is the horizontal scale of the new cyclone which is almost as large as that of the low in Fig. 2. We have $\lambda_1 = 3 \times 10^5$ m and $\lambda_2 = 8 \times 10^5$ m outside the anomaly.

A large number of additional runs has been performed, but the overall sequence of events as displayed in Fig. 3 is fairly robust to changes of the parameters. The intensity of the lee cyclone can be increased by strengthening the PV-anomaly. However, the ratio $P_3^*/\overline{P_3} = 5$ as chosen in the standard experiment would be characteristic of a relatively strong anomaly (e.g., Lanzinger, 1992) and we are not free to enhance P_3^* substantially. The scale of the lee cyclone can be altered by choosing different "stabilities" g_{ij}. We may assign a constant potential temperature θ_j to each layer, so that $g_{ij} \sim g(\theta_j - \theta_i)/\theta_j$. Our choice of g_{ij} in the standard experiment implies an increase of θ_j by about 60 K throughout the depth of the model atmosphere. This is a reasonable value. A substantial increase of g_{ij} to reduce the scale would not be justified.

The mountain is rather narrow. With $d = 100$ km, say, it takes the PV-anomaly about three hours to cross the barrier and there would be less time left for cyclone formation till the cold air reaches the top of the mountain, when compared to the standard experiment. One could extend the integration time by allowing for cold air flow over the plateau. Then one would witness lee cyclone formation just as in the standard experiment. However, the present formulation of the model does not allow for the motion of the front over the mountain.

One may choose the initial position of the PV-anomaly ahead of the cold front. In that case, a surface cyclone moves towards and over the mountain. Lee cyclogenesis is absent.

4. Conclusion

Altogether, a rather simple concept emerges. Both the upper-level PV-anomaly and the cold air move with approximate speed U towards the mountain. There is cyclonic circulation above the cold air, but anticyclonic flow in the lowest layer. The cold air is masking the impact of the upper-level PV-anomaly on the near-surface circulation as long as the anomaly is above the cold air. It is the mountain which allows the PV-anomaly to overtake the cold air. Once the PV-anomaly is ahead of the surface front, a low-level cyclone is established. This is the lee cyclone. The flow patterns in the intermediate and upper layer associated with the PV-anomaly change relatively little when the anomaly passes over the mountain to arrive in the lee. The cyclonic circulation in the upper layer passes over the mountain to arrive in the lee. The cyclonic circulation in the layer underneath the anomaly is but slightly more intense than upstream of the mountain.

There appears to be ample observational support for the statement that the simple mechanism of the lee cyclone generation outlined above is playing a rôle during many cases of lee cyclogenesis. Some of the relevant references are quoted in the introduction. Most recently it has been suggested by Egger et al. (1995), that the generation of so-called Sharav cyclones in the lee of the Atlas mountains can be understood partly by invoking this mechanism. Many of these Sharav cyclones come into existence when a cold-air outbreak from the northwest is blocked by the Atlas mountains, while an upper-level trough or a cut-off low is moving over the barrier. However, this kind of observational support is not fully satisfactory. One could claim that our concept is verified whenever cold-air blocking by a mountain and upper-level motion of a PV-anomaly over a mountain coincide during lee-cyclogenesis, i.e., for many observed cases. However, the underlying dynamic mechanisms may differ considerably from what we propose here. In other words, tests ought to be carried out to make sure that we capture here a basic mechanism of lee cyclogenesis.

Three theories of lee cyclone formation are exposed to a test in VT and in Tafferner and Egger (1990). The basic idea is to repeat a successful simulation of a case of lee cyclogenesis but modified such that the assumptions of the theory to be tested are satisfied. If cyclogenesis occurs despite these modifications the theory is accepted. However, the theories tested in VT are linear while our concept with its moving surface front is nonlinear in the sense that the full evolution of the flow cannot be interpreted as a linear perturbation with respect to a basic state. It is difficult to use the techniques of VT in such a situation. Nevertheless, some attempts have been made to test the conceptual model somewhat along the lines of VT. However, our twodimensional model is so highly idealized that we were not able to design a convincing test. An alternative test could presumably be achieved by resorting to piecewise PV inversions of the form advocated by Davis and Emanuel (1991). This approach has not been pursued.

It remains to relate our results briefly to the literature on the theory of lee cyclogenesis, where the vast majority of papers is concerned with the impact of orography on synoptic perturbations resembling Eady waves. Hayes et al. (1993) and Orlanski and Gross (1994) are most recent examples in this category. Although sharp fronts may form in numerical simulations of Eady waves provided the numerical resolution is good enough (Schär, 1990), distinct fronts are absent in linear theories of lee cyclogenesis like those of Buzzi et al. (1987). Isolated PV-anomalies are not represented in these approaches. In that sense, our conceptual model concentrates on dynamical features which are normally excluded in theories of lee cyclogenesis. The model is akin (as has been mentioned above) to the model of Gross (1990). However, a lee cyclone does not form in Gross (1990) presumably because there is no cold front.

Our approach is perhaps closest to that of Mattocks and Bleck (1986) who investigate the role of orographic blocking of cold air and advection of upper-level PV-anomalies across a barrier in idealized three-dimensional simulations of Alpine lee cyclogenesis. The anomaly moves from the west towards the Alps and a lee-side depression is generated ahead of the PV-maximum. Although Mattocks and Bleck (1986) propose to interpret their results in terms of a geostrophic adjustment mechanism where cyclogenesis is thought to occur in the forward left quadrant of the jet linked to the PV-anomaly, the more simple explanation as described in this paper is compatible with the flow evolution as presented by Mattocks and Bleck (1986).

In conclusion, we can state that the conceptual model provides some useful guidance in interpreting observations and numerical results. It appears to shed some light on the flow evolution during the "trigger" phase (Buzzi and Tibaldi, 1978). However, the concept is too simple to be acceptable as a theory of lee cyclogenesis. It does not capture the often observed deepening of the upper-level trough nor does it include the flow around the mountain, features which are important.

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