

Low-Level Potential Vorticity and Cyclogenesis to the Lee of the Alps

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ABSTRACT

High-resolution numerical model simulations over the Alpine region are presented that reveal the presence of low-level elongated bands of potential vorticity (PV) downstream of high topography. These PV streamers (or PV banners) occur when the synoptic-scale wind turns into a direction across the Alps. Individual pairs of banners with anomalously positive and negative values of PV can be attributed to flow splitting, either on the scale of the whole of the Alps (primary banners), or on that of individual massifs and peaks of the model topography (secondary banners). The PV bands have amplitudes of up to -2.5 and $+5$ pvu, a width of 50–150 km, can attain a length of up to 1500 km, and extend in the vertical from the surface up to the 500-hPa level on occasions. The PV banners are associated with zones of enhanced horizontal wind shear. The analysis of daily output from the operational NWP model run of the Swiss Meteorological Institute also demonstrates that such PV streamers are a frequent feature and occur whenever there is appreciable flow past the Alps.

Low-level PV streamers may interact with the larger-scale flow, and thereby represent an intermediary between the (unbalanced) formation of an orographic vortex, and its (approximately balanced) interaction with the synoptic-scale environment. This process is analyzed for one particular case of Alpine lee cyclogenesis. Simulations show that PV streamers may wrap up and subsequently contribute to the low-level PV anomaly within the developing cyclone. It is suggested that the two phases of Alpine lee cyclogenesis can be interpreted in this way, that is, as the rapid formation of a low-level orographic vortex followed by its baroclinic and diabatic interaction with an approaching upper-level trough. To test this interpretation, sensitivity studies with dry dynamics, reduced surface friction, and idealized terrain are conducted.

1. Introduction

Recent theoretical studies have provided ample evidence for the existence of several regimes in stratified atmospheric flow past isolated topography. Assuming a stratified airstream of constant Brunt–Väisälä frequency N and velocity U , and a frictionless free-slip lower boundary condition, hydrostatic nonrotating flow undergoes a bifurcation-like transition from the “flow-over” to the “flow-around” regime when the dimensionless mountain height is raised past its critical value $NH/U \approx 1.2$ (Smolarkiewicz and Rotunno 1989; Smith and Grønås 1993). For mountains beyond the critical height, the flow field is characterized by the splitting of the incident flow below peak height and the formation of vertically oriented vortices to the lee (Smolarkiewicz and Rotunno 1989; Crook et al. 1990; Schär and Durran 1997). Recent studies also demonstrate that these lee vortices contain anomalies of potential vorticity, and that their generation is associated with dissipation, either by turbulence in hydraulic-jump-like regions of gravity wave breaking, by “slow diffusion” in the elongated

recirculating wake, or alternatively by turbulence in the planetary boundary layer (Schär and Smith 1993a; Thorpe et al. 1993; Schär 1993; Grubisic et al. 1995; Smith and Smith 1995; Schär and Durran 1997).

Several recent observational and numerical studies have analyzed mesoscale orographic effects in terms of the aforementioned mountain-flow regimes (Wilczak and Glendening 1988; Etling 1989; Smith and Grubisic 1993; Thorpe et al. 1993; Clark et al. 1994; Levinson and Banta 1995; Olafsson and Bougeault 1996, 1997; Buzzi et al. 1997). Most of this research has focused upon mesoscale aspects of flow near steep topography. However, to the extent that the synoptic-scale flow is approximately balanced (Hoskins et al. 1985), one also expects that orographically generated PV anomalies will subsequently be able to interact with the synoptic-scale environment, and thereby represent a conceptual intermediary between the (unbalanced) mesoscale formation of orographic flow anomalies, and their subsequent (essentially balanced) effects on the larger-scale flow. This interpretation appears particularly promising for cases of lee cyclogenesis. Topographic effects can here provide a low-level source of potential vorticity, which ultimately may play a similar role in cyclone formation as the well-documented diabatic PV source in cases of explosive maritime cyclogenesis (Whitaker et al. 1988; Reed et al. 1992).

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To study the importance of topographic PV streamers for cyclogenesis, an analysis is here undertaken of low-level potential vorticity in high-resolution numerical simulations of an Alpine lee cyclogenesis event. The synoptic setting of Alpine lee cyclogenesis is characterized by the progression of an upper-level trough and its associated cold front toward the Alps (Buzzi and Tibaldi 1978; Bleck and Mattocks 1984). Lee cyclogenesis takes place in two phases (Egger 1972; Buzzi and Tibaldi 1978; McGinley 1982). The first phase is associated with frontal retardation, a cold-air outbreak into the western Mediterranean, and the rapid formation of a shallow vortex over the Gulf of Genoa. During the second phase the growth rate drops to baroclinic values, and the structure of the growing cyclone approaches that of typical extratropical low pressure systems. Numerical simulations of this second phase support the descriptive interpretations based upon the concept of upper-level–lower-level vortex interaction (Hoskins et al. 1985; Tafferner 1990). The primary effect of the mountain is thus the first-phase formation of a low-level vortex (or amplification of a preexisting vortex), while the second phase can be interpreted as a mere modification of classical cyclogenesis.

The aforementioned resemblance of the second phase to classical cyclogenesis suggests the approximate validity of the balanced dynamics during that phase. It then follows from the invertibility principle that any low-level vortex structure able to contribute to the second phase must be associated with (i) a surface thermal anomaly and/or (ii) a low-level PV anomaly. An interpretation of the first phase must thus seek to explain the generation of either one or both of these two ingredients. A well-documented mechanism for the generation of anomalies of category (i) is the retardation of an approaching cold front. In effect it results in the generation of an Alpine-scale wake characterized by a warm surface anomaly. The orographic retardation also implies geostrophic (or balanced) adjustment of the heavily distorted baroclinic configuration, which induces a pressure drop through upper-level mass-flux divergence (Bleck and Mattocks 1984; Tafferner 1990) and vertical motion through Q-vector forcing (McGinley 1982). However, from the viewpoint of the balanced dynamics it is the warm low-level air by itself that constitutes the driving agent of the second phase.

Although some aspects of the cold-air retardation appear, in principle, amenable in terms of the quasigeostrophic dynamics (Smith 1984; Speranza et al. 1985; Pierrehumbert 1985; Schär 1990), more recent research on mountain flow regimes suggests that the associated processes are intrinsically nonbalanced as soon as flow-splitting occurs. For wide obstacles such as the Alps the critical mountain height is reduced by the effects of the earth's rotation somewhat below the value $NH/U \approx 1.2$ quoted above. For instance, for a circular obstacle with Rossby number $L_f/U = 1$, the critical mountain height is given by $NH/U \approx 1$ (Trüb 1993). This value can easily

be met by the Alpine setting, and—consistent with this theoretical analysis—there is observational evidence for low-level flow splitting in the Alpine region during events of frontal interception (Chen and Smith 1987; Binder et al. 1989).

The occurrence of flow splitting implies that lee vortices and, of particular interest in the current context, anomalies of PV might be generated to the lee of the Alps. The generation of such low-level PV streamers corresponds to a mechanism for the generation of balanced flow anomalies of category (ii). This mechanism is not entirely new, but aspects of it have been raised in several earlier studies. For illustration we reproduce in Fig. 1 an isentropic hand analysis first shown by Steinacker (1984) and later by Pichler and Steinacker (1987). It shows the Montgomery potential (dashed lines) and pressure height (full lines) of the 292-K isentropic surface. This isentropic surface is entirely within the troposphere in the domain of interest. At the time shown, there is strong northerly flow across the Alps. The associated effects to the lee of the Alps appear surprisingly similar to configurations seen in experiments of nonrotating flow past idealized topography (cf. Smolarkiewicz and Rotunno 1989; Schär and Durran 1997). There are two counterrotating vortices with reversed flow in between. This surprising resemblance with nonrotating flows might be helped by the excessively strong northerly flow of this particular event, which increases the effective Rossby number and thus makes the flow less rotational.

In agreement with Steinacker's analysis, several studies have noted that a pool of low-level vorticity near the southwestern tip of the Alps often precedes deep Alpine lee cyclogenesis (McGinley 1982; Frenzen and Speth 1986; Tafferner 1990; Lanzinger et al. 1991), but none of these studies have explicitly addressed the question whether and by what processes there is a violation of PV conservation along parcel trajectories. In contrast, in the tradition of laboratory experiments of salt-stratified flows, the generation of vorticity in the frictional boundary layer has been investigated and suggested as a mechanism for Alpine lee cyclogenesis (Boyer et al. 1987; Baines and Steinacker 1987). In light of the results of Smolarkiewicz and Rotunno (1989), who demonstrated that lee vortices can form in absence of surface friction, the interpretations advanced by these laboratory experiments might, however, require revision.

In this study we will examine in detail a case of Alpine lee cyclogenesis, and focus upon the generation of low-level PV streamers and their interaction with the synoptic-scale environment. The study will rely on high-resolution numerical simulations with a hydrostatic mesoscale model that is described in section 2. The standard experiment is then presented in section 3, and this is followed in section 4 by a range of sensitivity experiments. To reduce the complexity of the flow, an additional simulation with idealized topography but unchanged synoptic forcing will be analyzed in section 5.

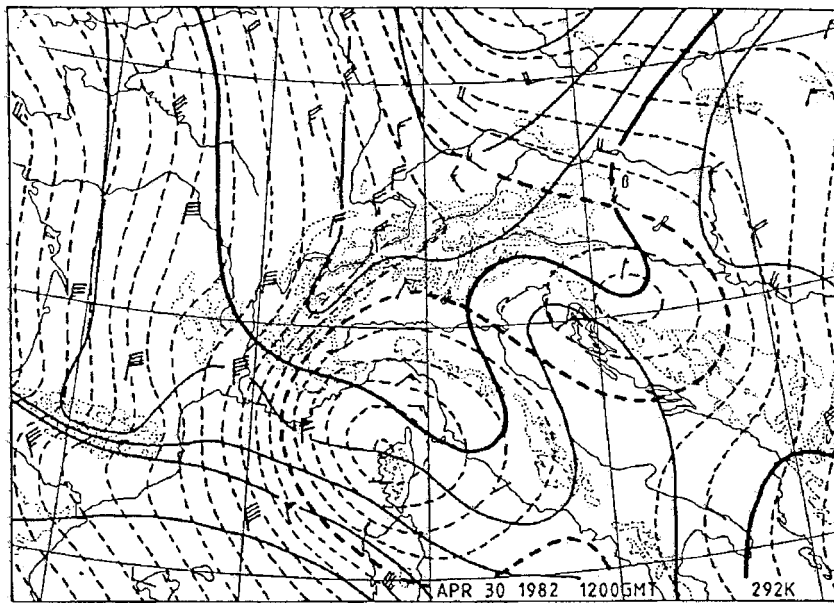


FIG. 1. Analysis of the flow around the Alps on the 292-K isentropic surface at 1200 UTC 30 April 1982. The diagram shows the Montgomery potential (dashed lines, interval 10 m) and the pressure height (full lines, interval 50 hPa). The bold line is the 700-hPa pressure contour. From Steinacker (1984).

Finally, using output of the operational numerical prediction runs of the Swiss Meteorological Institute we demonstrate in section 6 that PV streamers to the lee of the Alps are common and also occur in conjunction with flow phenomena other than lee cyclogenesis. Some further remarks follow in the concluding section 7.

2. Model and overview of numerical simulations

The simulations performed in this study were undertaken with the limited-area hydrostatic numerical modeling system originally developed by the German Weather Service (DWD). The low-resolution version of this model is referred to as Europa-Modell (EM). It has a horizontal grid spacing of 56 km and is used operationally by the DWD with a domain covering all of Europe as well as the northern Atlantic. The high-resolution model (HM) is one-way nested into the EM, has a horizontal resolution of 14 km, and has been derived from the EM in a collaboration between the DWD and the Swiss Meteorological Institute (SMI). These institutions run the HM to provide high-resolution short-range weather forecasts. A detailed description of the model can be found in Majewski (1991) and DWD (1995).

The model is based on the hydrostatic set of equations. In the horizontal, the atmospheric fields are discretized in rotated spherical coordinates with the respective resolutions of 0.5° (EM) and 0.125° (HM). The rotation of the geographic pole permits the use of a relatively isotropic grid in the geographical region of interest. In the vertical, a hybrid coordinate system is

adopted such that at low levels the computational surfaces are terrain following and thereafter transit with height to coincide at upper levels with pressure surfaces. The model's prognostic variables are surface pressure, the horizontal wind components, total heat, and total water content. The latter two quantities are converted into temperature, specific humidity, and liquid water content at each time step, assuming 100% relative humidity in clouds. The discretization is based on finite



FIG. 2. Horizontal domains for the low-resolution EM simulations (outer frame) and high-resolution HM simulations (inner frame). Shading shows EM topography with additional contours every 500 m.

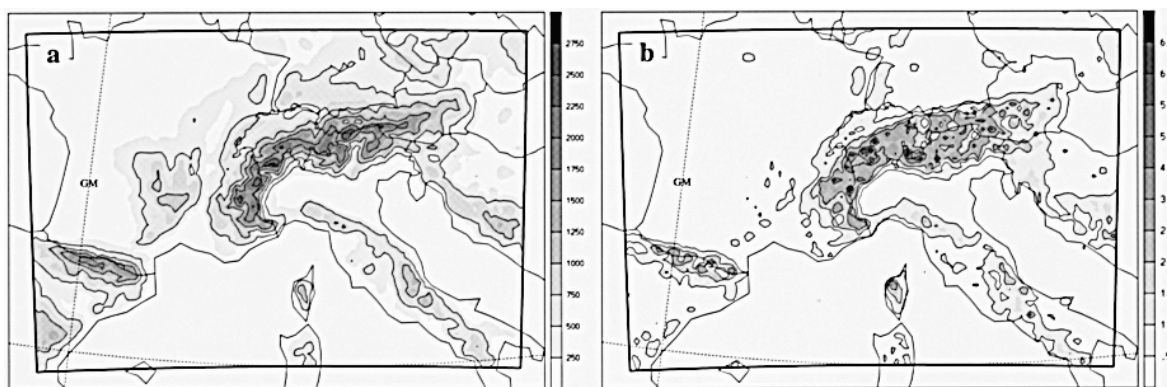


FIG. 3. Horizontal domain of high-resolution HM simulations with (a) topography in the same format as in Fig. 2, and (b) the roughness length parameter with contours at 0.5, 1.5, 2.5, 4.5, 5.5 m.

differencing with a semi-implicit time-stepping scheme. For this study, the model was run with Eulerian advection, a time step of 300 s (EM) and 75 s (HM), and with 30 computational layers. For the EM simulations, the top of the model domain is located at $p = 0$ hPa at which the vertical motion is set to zero. For the HM simulations, a KDB-type gravity wave absorber is employed at the $p = 20$ -hPa level (see Klemp and Durran 1983; Bougeault 1983). The implementation of this absorber in pressure coordinates is due to Herzog (1995).

Here relevant parameterizations include a surface-layer formulation (Louis 1979), a boundary layer and turbulence formulation with a second-order closure scheme of hierarchy level 2 (Mellor and Yamada 1974; Müller 1981), grid-scale cloud microphysics of Kessler type including a parameterization of the ice phase, moist convection in mass-flux formulation (Tiedtke 1989), a radiative transfer formulation (Ritter and Geleyn 1992), and a fourth-order horizontal diffusion scheme.

The domains used in this study are shown in Fig. 2 along with the low-resolution EM topography. The EM domain covers most of Europe and a large fraction of the North Atlantic, while the high-resolution HM domain zooms into the Alpine region. Figure 3 shows the standard setting (topography and roughness length) for the high-resolution HM runs. Both the EM and HM

topography are mean topographies. However, some smoothing was applied to the HM topography in order to reduce poorly resolved small-scale gravity wave activity. This smoothing led to a reduction of the maximum topographic height from 3132 m to 2806 m.

The atmospheric data fields for the initial and lateral boundary conditions for the EM are derived from initialized European Centre for Medium-Range Weather Forecasts (ECMWF) analysis fields. Details of the associated technical procedures are given in Majewski (1985). The HM is one-way nested into the EM. At the lateral boundaries the models are driven using relaxation boundary conditions (Davies 1976). The relaxation zones have a width of eight grid points, and the boundary updating frequencies are 6 h and 3 h for EM and HM, respectively.

The simulations discussed in this paper are listed in Table 1. For all HM runs, the EM standard simulation (EMS) was used for supplying initial and lateral-boundary data, except for the HM runs with idealized topography, which are driven by separate EM simulations. All diagnostic computations are carried out on model surfaces and are interpolated to horizontal and vertical sections for display. Most of the analysis was conducted at a temporal resolution of 1 h, but here attention is restricted to a selection of diagrams.

TABLE 1. List of simulations presented in this paper. Simulations with name-prefix EM and HM use horizontal resolutions of 56 km and 14 km, respectively. The two rightmost columns give the maximum topographic height and roughness length over the Alps.

Simulation	Driving model	Section	Purpose	h_{topo} (max)	Z0 (max)
EMS	ECMWF	3a	Standard simulation	2539 m	4.94 m
HMS	EMS	3b	Standard simulation	2806 m	7.45 m
HMD	EMS	4a	Dry dynamics	2806 m	7.45 m
HMM	EMS	4b	Smoothed topography	2138 m	4.34 m
HMR	EMS	4c	Reduced roughness length	2806 m	0.001 m
EMI	ECMWF	5	Idealized topography	2521 m	4.73 m
HMI	EMI	5	Idealized topography	2761 m	7.47 m
HMID	EMI	5	Idealized topography and dry dynamics	2761	7.47 m

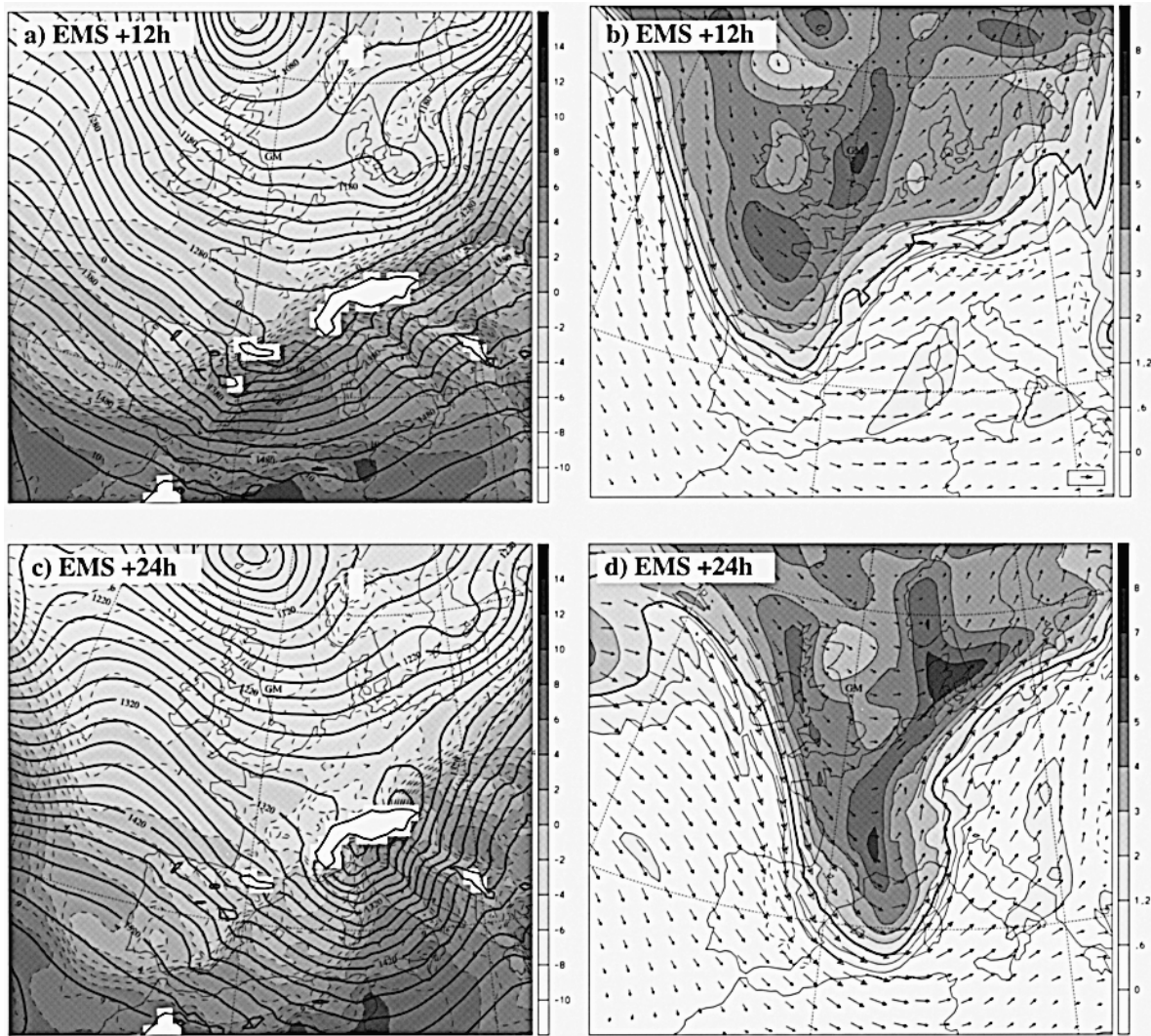


FIG. 4. The synoptic evolution depicted in terms of the EM simulation starting at 1200 UTC 4 December 1992. Left-hand panels show the 850-hPa geopotential (solid contours, interval 20 gpm) and temperature (dashed contours every 1 K and shading every 2 K). Right-hand panels show the wind vectors (plotted every third grid point) and potential vorticity on the 315-K isentropic surface. Contours of PV are drawn at 0, 0.6, 1.2, 2, 3, 4, 5, 6, 7, 8 pvu, and the 2-pvu contour indicating the tropopause is plotted heavy solid. The unit vector of 20 m s^{-1} is shown in a box at the bottom right of panel (b).

3. The standard simulation

Consideration is given to the Alpine lee cyclogenesis event on 4–6 December 1992. The event was selected for study since it shows a rapid and deep development of a lee cyclone within 24 h, and since there is a prolonged period of northerly flow past the Alpine massif following cyclogenesis. All simulations were initialized at 1200 UTC 4 December and integrated over 48 h. Here we proceed by discussing the synoptic-scale evolution in the 56-km resolution EMS standard simulation, comparing it with objective and operational hand analysis of the development, and then turn to the discussion of the 14-km HM standard simulation (HMS).

a. Synoptic-scale evolution

To illustrate the simulated synoptic-scale development of the EMS run, Fig. 4 shows the geopotential height and temperature fields on the 850-hPa level (left-hand panels), and the 315-K isentropic potential vorticity (right-hand panels). Diagrams are shown for forecast times 12, 24, 36, and 42 h. The last output time is selected for reference with later analysis.

At 0000 UTC 5 December, a mature cyclone is moving toward Scandinavia (Fig. 4a) and the associated cold frontal system is about to reach the Alps. This system is embedded in a large-amplitude upper-level trough, as illustrated by the PV distribution on the 315-K isentropic surface (Fig. 4b). The subsequent development is

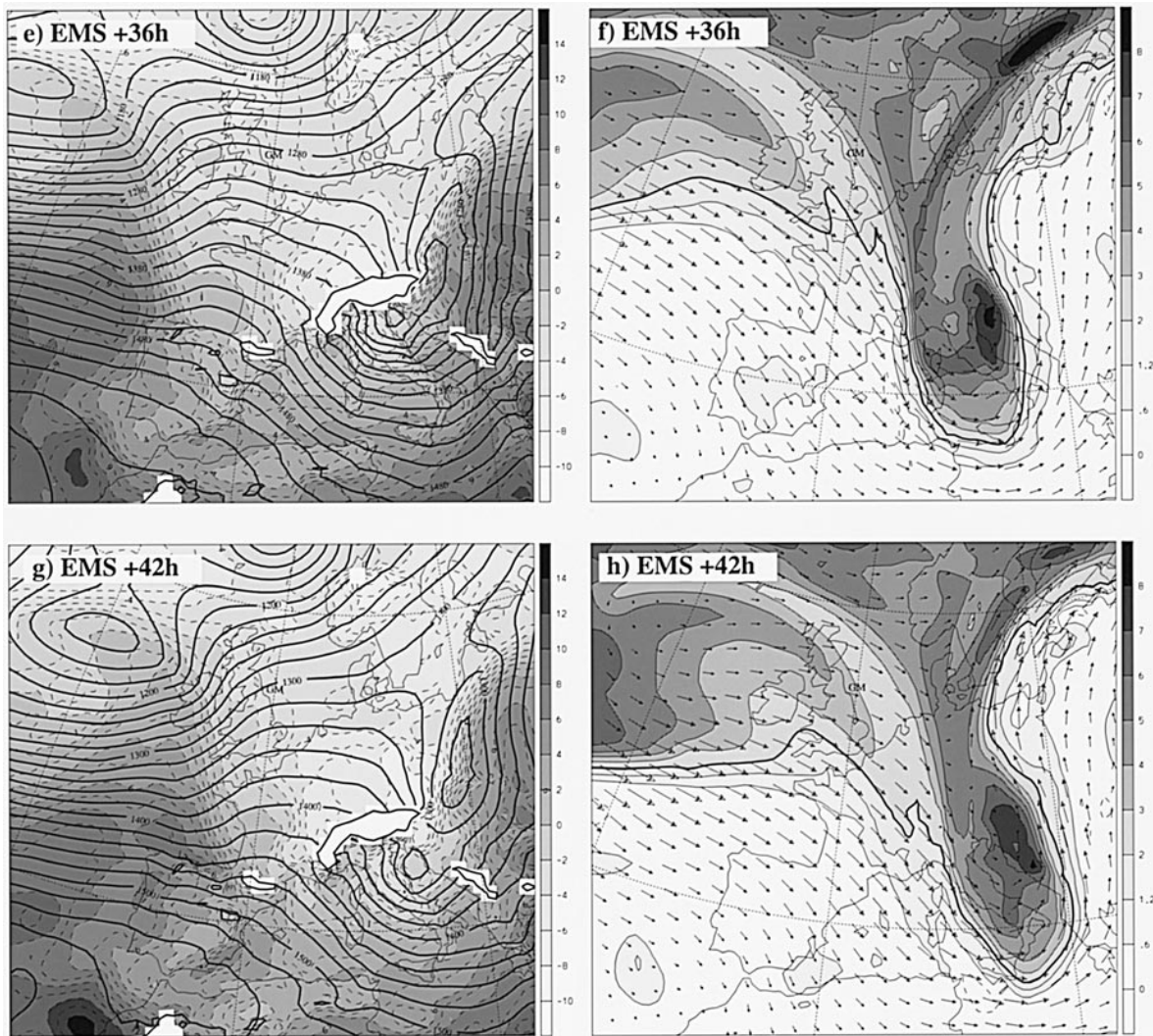


FIG. 4. (Continued)

associated with the deepening of the upper-level trough (Fig. 4d), a pronounced cold-air outbreak into the western Mediterranean Sea, and the formation of a cyclone in the 850-hPa geopotential (Fig. 4c). Initially isolated centers of the cyclone are visible in the geopotential on both sides of the Alps, suggesting that the cyclone is approximately centered over the main ridge. By 0000 UTC 6 December, the low-level cyclone to the south of the Alps has intensified and has moved eastward toward the Adriatic Sea (Fig. 4e). To the rear of the cyclone there is strong northerly flow past the Alps. At the same time, the upper-level PV streamer shows some signs of roll-up (Fig. 4f). Toward the end of the simulation, the secondary low pressure center to the north of the Alps strengthens and overpowers the one to the south (Fig. 4g).

Although the pressure drop in the center of the lee cyclone is somewhat overestimated (see Fig. 5), the

simulated synoptic-scale development is consistent with observations. For illustration, operational ECMWF analysis fields are shown in Fig. 6 at 0000 UTC 6 December. These are to be compared with Figs. 4e,f of our simulation. Comparison reveals that the formation of the lee cyclone, its progression over Italy, and the subsequent phase of northerly flow is well captured by the model, except for some minor differences in the horizontal scale and strength of the low, and a slight displacement of the upper-level PV maximum toward the north. The simulated surface pressure distribution for the same time is shown along with the DWD surface chart in Fig. 7. The two pressure patterns and the frontal systems reveal good agreement. At upper levels, both the ECMWF analysis and the simulated 500-hPa field show the formation of a cut-off low at or shortly before 0000 UTC 6 December.

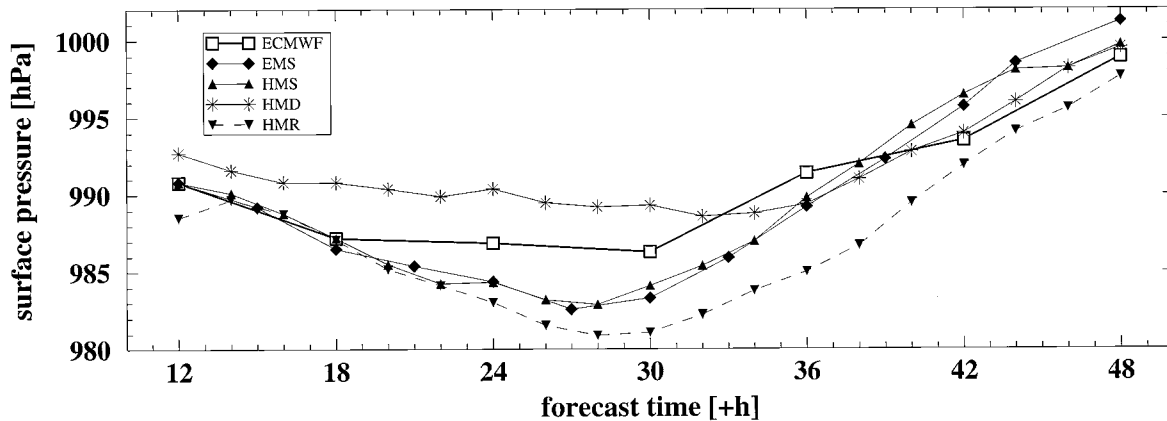


FIG. 5. Evolution of mean sea level pressure in the center of the developing cyclone for ECMWF analysis data (squares) and several simulations initialized at 1200 UTC 4 December 1992 (see code).

b. Mesoscale evolution

Next we now zoom into the inner computational domain and discuss the results of the 14-km resolution standard simulation HMS. Figure 8 shows the evolution of the 850-hPa geopotential height and temperature (left-hand panels) along with the distribution of the potential vorticity (right-hand panels) on the same level. The first row of panels is at simulation time +12 h and shows the cold front aligned roughly with the Pyrenees and the main Alpine crest. Hand analysis (Berlin weather map) shows the first closed low in the MSL pressure at the southwestern edge of the Alps on 0600 UTC 5 December, but the operational ECMWF analysis suggests—consistent with our simulation—that it occurred somewhat earlier and immediately to the east of the Pyrenees (cf. Fig. 8a). At about the same time, there is a cold-air outbreak into the Mediterranean associated with strong northerly Mistral to the west of the Alps. The associated

air parcels turn cyclonically over the Gulf of Genoa (Figs. 8c,d). Orographic mesoscale features worth noting include the foehnlike dips in the geopotential to the lee of the island of Corsica, the Apennine mountains in Italy, and the Dinaric Alps in Slovenia and Croatia. The isotherms in Fig. 8c also suggest that there is cold frontal retardation by the Alps and later by the islands of Corsica and Sardinia. Within the arch of the Alpine topography, a closed circulation is visible. Subsequently, the 850-hPa low strengthens and then moves eastward (Fig. 8e) until it reaches the Adriatic Sea (Fig. 8g). At the time of the last two panels, there is a tremendous pressure contrast across the Alps, which at 850 hPa amounts to 60 gpm.

The distribution of PV on the 850-hPa level is shown in the right-hand panels of Fig. 8. The dark shaded areas (full contours) indicate regions with $PV > 0.6$ pvu ($1 \text{ pvu} = 10^{-6} \text{ m}^2 \text{ K kg}^{-1} \text{ s}^{-1}$), which is well above typical tropospheric values, while light

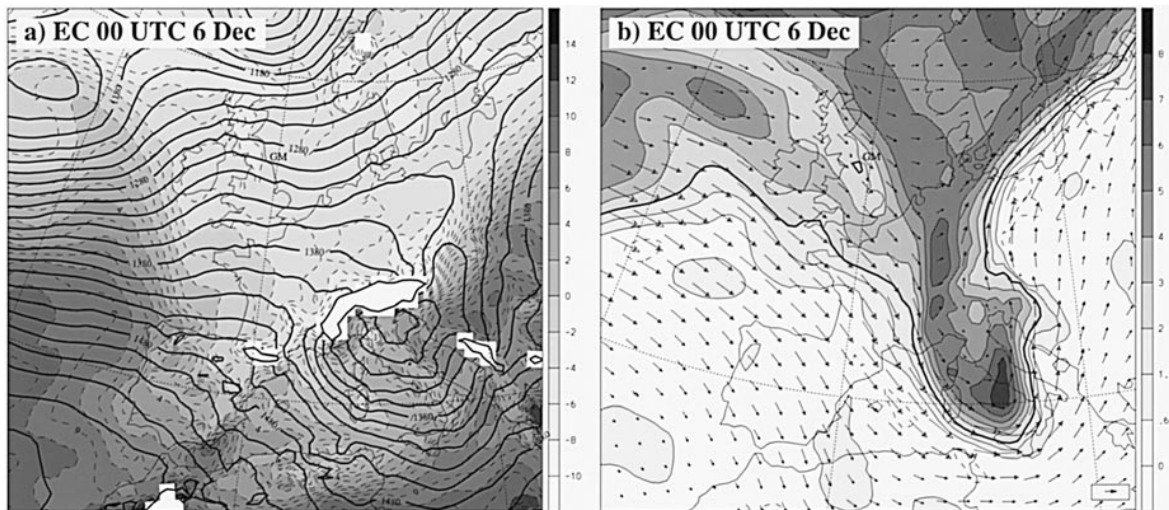


FIG. 6. As in Fig. 4e,f but for the verifying operational ECMWF analysis.

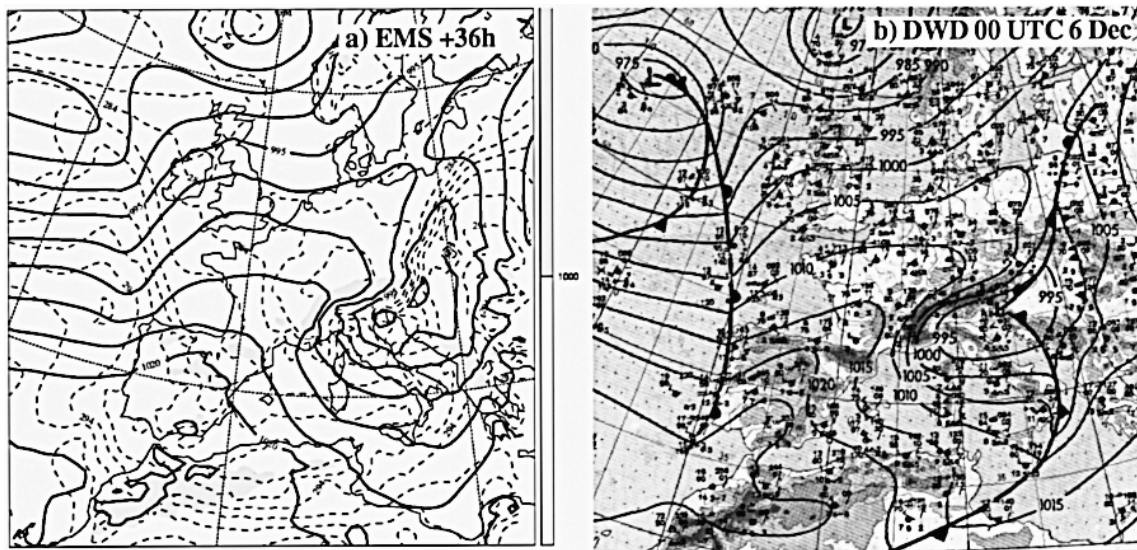


FIG. 7. Mean sea level pressure at +36 h according to (a) the EMS simulation and (b) the hand analysis of the German Weather Service. Contours are shown every 5 hPa. Dashed lines in (a) are 850-hPa isotherms with a contour interval of 2 K, and the shaded areas indicate topography above 1000 m.

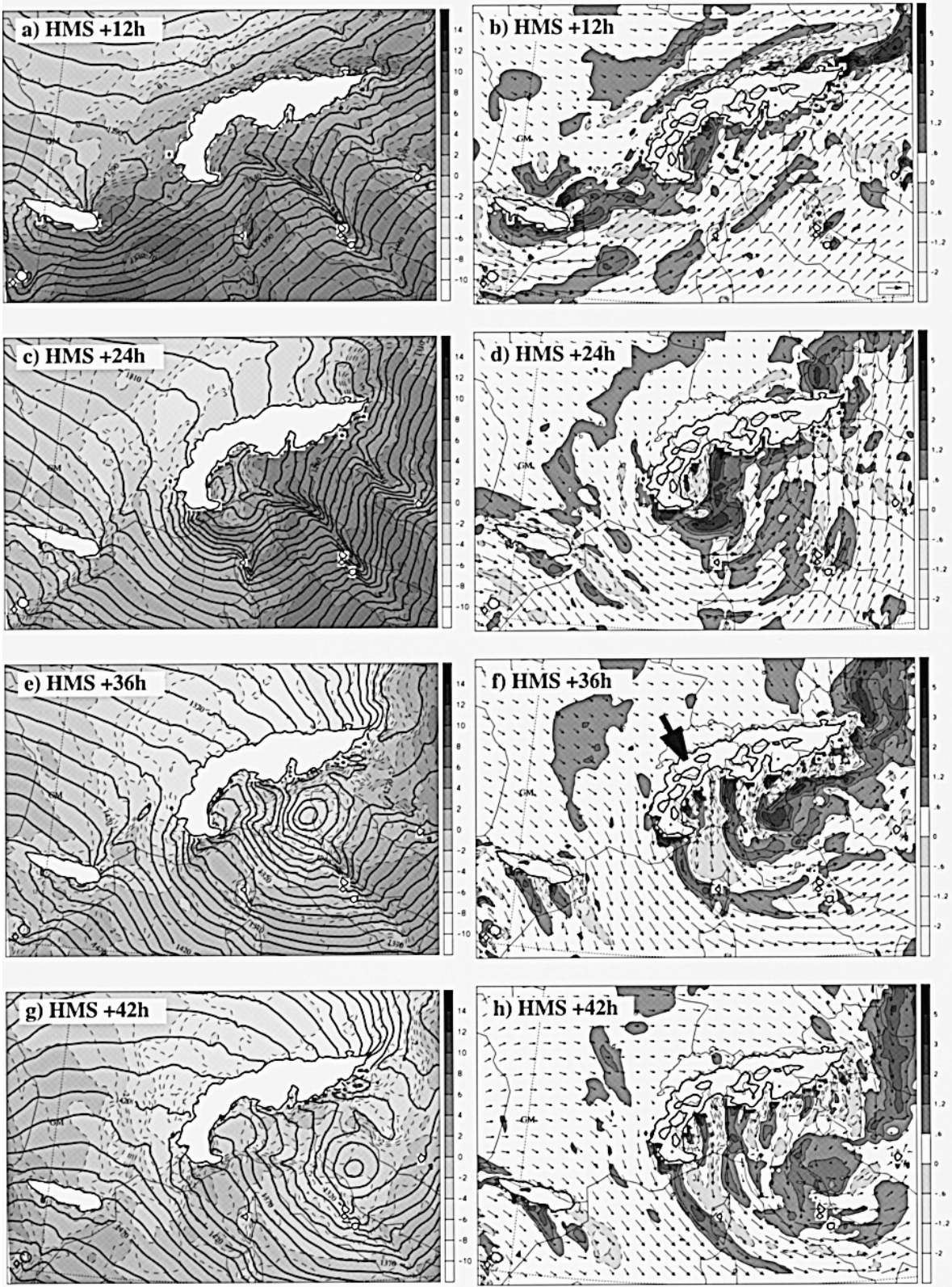
shaded areas (dashed contours) show regions with negative PV. In addition, 850-hPa wind vectors are superimposed. Three classes of PV anomalies can be identified. First, there are some cold frontal PV features (see in particular Fig. 8b) that are advected into the domain and are presumably of diabatic origin. Second, when the flow turns into a direction across the Alps or the Pyrenees (see Figs. 8f,h), elongated anomalies of positive and negative PV become apparent that are associated with flow splitting. Following Smith and Smith (1995), these will be referred to as “PV banners.” Third, toward the end of the sequence, the core of the cyclone is associated with a positive anomaly of PV (Fig. 8h) that is associated with diabatic processes (see later).

The first notable PV banner on the 850-hPa level is located to the east of the Pyrenees (Fig. 8b), and coincides with the initial closed surface low referred to above. The location of this banner and the associated surface low is in a preferred region for the formation of mesoscale Mediterranean vortices (Jansà et al. 1994). Later the associated PV feature merges with the strongest PV banner that starts near the southwestern edge of the Alps and curves cyclonically around the developing low-pressure system (Figs. 8d,f). At later times, when the synoptic wind turns into a direction across the Alps, numerous additional banners form (Fig. 8h). Analysis of space–time continuity at high temporal resolution shows that the conservation of potential vorticity along parcel trajectories is violated in comparatively small regions over the topography, and that the streamers are the result of essentially adiabatic advection of PV anomalies by the ambient wind. The PV banners reach their full

extent 42 h after the start of the simulation (Fig. 8h). At this time they attain a length of up to 800 km and have a width of about 50 km. This width corresponds to about four grid points, and is thus determined by the numerical resolution of the model. This critical aspect will further be discussed in the concluding section. Similarly, the number of PV banners depends on the resolution of the model topography. It is thus useful to distinguish between the outermost major PV banners, which encompass the Alpine wake and are the result of Alpine-scale flow splitting, and the additional banners, which result from flow splitting (and wave breaking) at smaller-scale topographic features. These two types of banners will subsequently be referred to as “primary” and “secondary” banners, respectively.

Individual pairs of positive and negative PV banners can be attributed to peaks in the model topography. Note for instance the banners leading away from the Monte Rosa massif, whose location is indicated with an arrow in Fig. 8f. Looking downstream, a negative (positive) banner of PV formed to the left (right) of the massif. The underlying processes of formation will further be addressed in the next section. The PV banners as described above are not only observed to the lee of Alpine peaks, but also near other topographic obstacles, for instance, to the lee of the Pyrenees (see Fig. 8f) or the island of Corsica (see Fig. 8d).

It is of interest to compare the above results with the operational ECMWF analysis with spectral resolution T213, and an effective resolution which is about five times smaller than that of our HM simulations. The relevant ECMWF fields are shown in Fig.



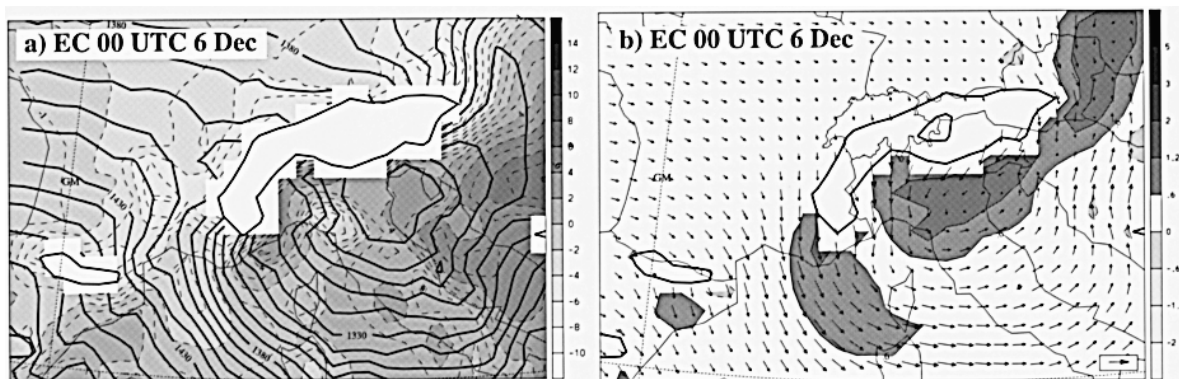


FIG. 9. As in Fig. 8e,f but for the verifying operational ECMWF analysis.

9 at 0000 UTC 6 December, in the same format as in Fig. 8. The larger-scale patterns of the surface pressure distribution compare well (cf. Fig. 9a and Fig. 8e), but the mesoscale features and associated pressure gradients (e.g., those associated with foehn-like flow over the Apennine mountain range) are much weaker developed in the ECMWF analysis. The distribution of PV in the ECMWF fields agrees with the HMS simulation concerning the location and approximate shape of the positive PV anomaly in the center of the low, and the primary PV banner forming at the southwestern Alpine tip (cf. Fig. 9b and Fig. 8f). However, as a result of the smaller resolution, the secondary PV banners are not resolved.

To gain further insight into the three-dimensional structure, the upper panels of Fig. 10 show zoomed views of the potential vorticity distribution at the same time as Fig. 8h, but on the 900- and 700-hPa levels, respectively. The strongest positive banner is the primary banner, which emanates from the southwestern Alps. It separates the strong northerly mistral wind to the west (with velocities up to 24 m s^{-1}) from the wake fluid to the east (with vanishing or slightly reversed flow, see Fig. 10a). Note also the flow past the model's representation of the Gotthard gap of the Alpine topography (indicated by the arrows in Figs. 10a,b). The north foehn within and to the lee of this gap is much stronger than in the regions shielded by higher topography (see Fig. 10b). The "Gotthard jet" is associated with a positive (negative) banner of PV to the left (right) when looking downstream, and it

can be tracked downstream on the 700-hPa level for several hundred kilometers, both in terms of the wind and the PV fields. The positive banner to the left spirals into the center of the cyclone and thus appears to feed the associated cyclonic low-level PV anomaly.

Consider next the vertical section in Fig. 10d, which is aligned in the W–E direction and cuts across the western portion of the Alps and approximately perpendicular across several PV banners. The banners have maximum strength at levels between 850 and 900 hPa, but the PV anomalies extend up to the 600-hPa level. Away from the topography, the maximum amplitudes of the banners correspond to between -2.5 pvu and $+5 \text{ pvu}$. The section also shows that the banners tilt westward with height, which is a result of differential advection.

The S–N cross section in Fig. 10c cuts along the positive PV banner associated with the Gotthard gap. The flow in the section is from right to left. The isentropic distribution suggests strong north-foehn descent of upper-level air to the south of the Alps. Further to the lee, the isentropes relax approximately to their original level in a hydraulic-jump-like fashion, indicating strong gravity wave activity and possibly breaking (or the model's representation of this process). Most of the PV banners originate approximately from mountaintop height or somewhat below, suggesting that the PV is primarily generated in conjunction with flow splitting. The presence of some notable PV anomalies at even higher levels (see also Fig. 10b), however, indicates that gravity wave breaking in the free troposphere (over the adjacent mountain peaks of the section in Fig. 10c) contributes to their generation as well. The vertical sections in Fig. 10 also depict the upper-level stratospheric intrusion associated with the PV trough earlier discussed in Fig. 4h.

4. Further analysis and sensitivity experiments

In this section we present a range of sensitivity experiments that are designed toward identifying the

FIG. 8. The low-level mesoscale evolution in the HMS simulation. Left-hand panels show the 850-hPa geopotential (solid contours, interval 10 gpm) and temperature (dashed contours and shading). Right-hand panels show wind vectors (plotted every fourth grid point) and potential vorticity (shading) on the 850-hPa surface. Light shaded areas and dashed contouring indicates negative PV values (contours at -2 , -1.2 , -0.6 , 0 pvu), while contours with $PV > 0.6 \text{ pvu}$ are dark shaded with solid contouring (at 0.6 , 1.2 , 2 , 3 , 4 , 5 pvu). The heavy lines denote topographic height at 1000 and 2200 m.

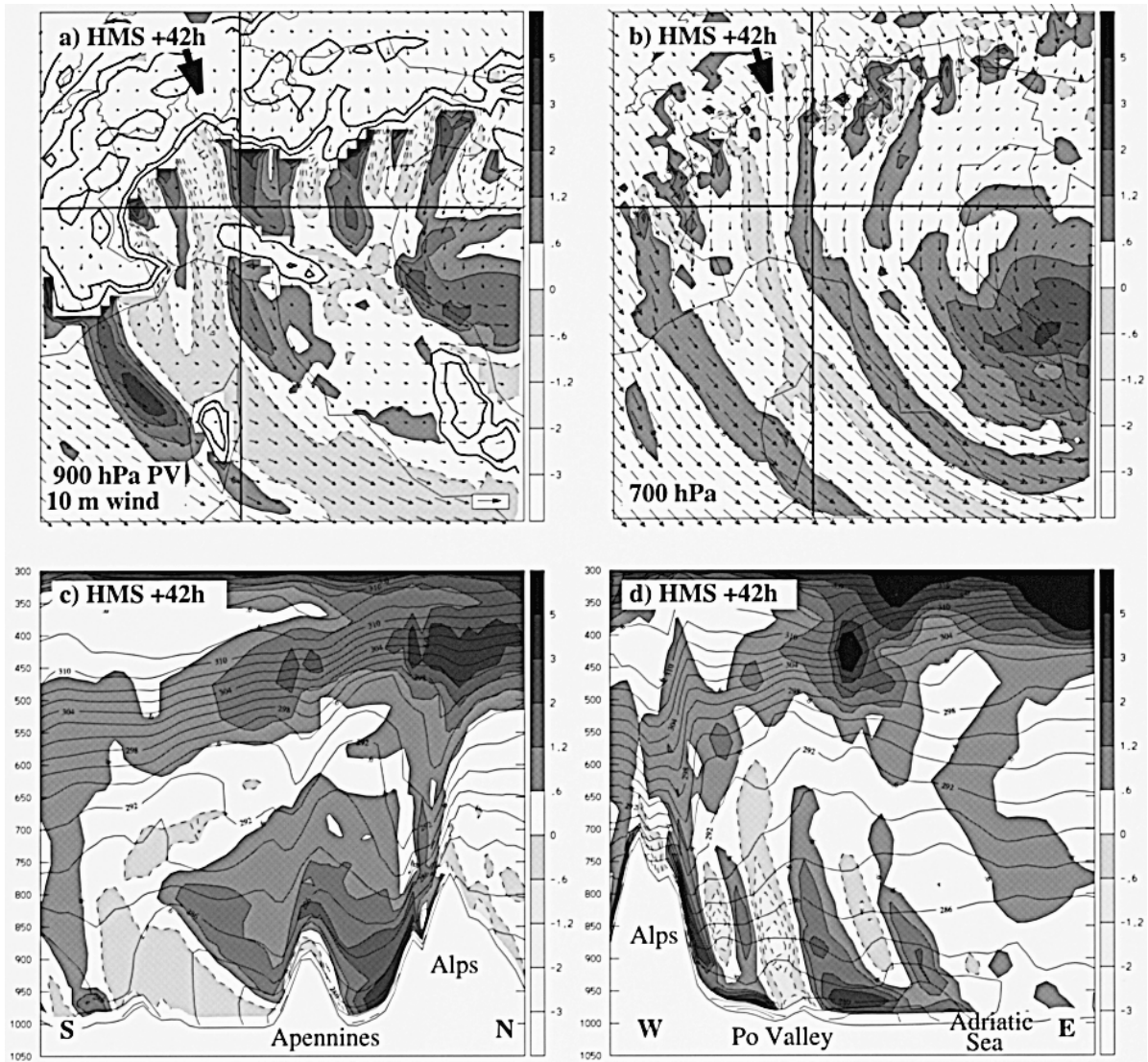


FIG. 10. Horizontal sections as in Fig. 8h but in a zoomed format and on (a) the 900-hPa level with winds on 10 m, and (b) on the 700-hPa level. Wind vectors are shown every second grid point. Lower panels show vertical sections for (c) a south–north cross section and (d) and a west–east cross section. Vertical sections also show potential temperature (contour interval 2 K). For locations of sections see panels (a) and (b).

dynamical processes responsible for the formation of the PV banners. The major questions relate to the effects of condensation, surface friction, and hydraulic-jump-like dissipative processes associated with flow past complex topography.

a. Effects of moist dynamics

It has been recognized for some time that latent heating can induce the formation of low-level PV anomalies and thereby contribute to and interact with frontogenesis and cyclogenesis (Emanuel et al. 1987; Hoskins et al. 1985). Here we thus determine the contribution of moist dynamics to the low-level PV distribution found in the previously discussed simulation

results. We start by giving consideration to the moist aspects of the HMS simulation. To this end, Fig. 11 shows simulated and observed 24-h accumulated precipitation fields prior to 0600 UTC 6 December. The objective analysis in Fig. 11b is based on a preliminary version of a high-resolution Alpine-wide precipitation dataset (Frei and Schär 1997). This dataset contains several thousand rain gauge observations with daily resolution. Overall the simulation agrees well with the analysis, thus suggesting that the moist aspects are sufficiently well simulated to address their effects upon the low-level distribution of PV. Pertinent features to note in Fig. 11 include the fairly dry conditions to the north, and the precipitation maximum in the southeastern Alps. This precipitation max-

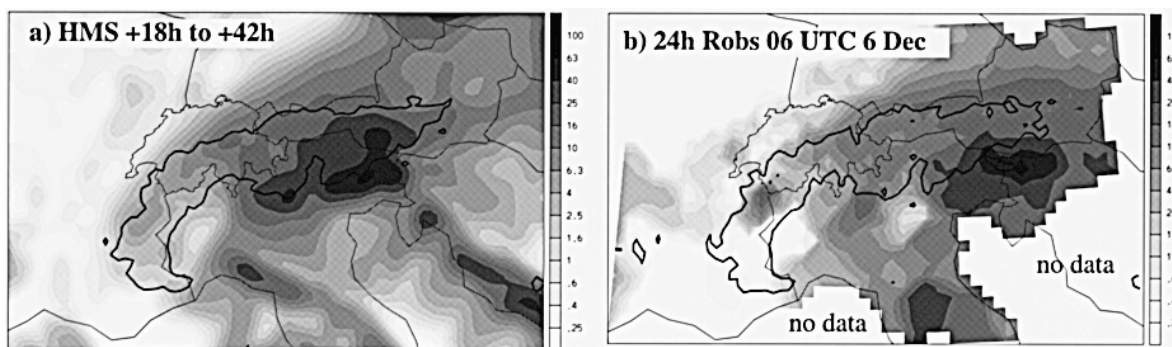


FIG. 11. Accumulated 24-h precipitation prior to 0600 UTC 6 December for (a) simulation HMS and (b) an objective analysis from a network of ~ 3000 rain gauge stations (see Frei and Schär 1997). The output of the model has been smoothed in order to be compatible with that of the objective analysis (i.e., 0.25°). Note that the diagrams cover only a part of the computational domain.

imum is associated with a southerly stream of moist air ahead of the lee cyclone and is typical for Alpine lee cyclogenesis events in the autumn and early winter season. The amplitude of the maximum is well captured by the model, but it is displaced somewhat westward. Note the absence of strong precipitation in the western Alps. The absence of moist processes to the south of the Alps except ahead and in the immediate vicinity of the lee cyclone is also confirmed by the relative humidity field (see Fig. 12). It shows humid conditions to the north and east of the Alps, and the relative humidity in the core of the developing cyclone is near saturation. However, most of the Alpine wake is associated with relative humidity values $< 40\%$. Note also that the dry wake is not confined to the west by the westernmost positive PV banner (cf. Fig. 8f) but does extend farther west. This configuration is the result of adiabatic warming and drying within the descending north foehn over the main ridge and the western flank of the Alpine topography. The PV banners behind the cyclone thus almost exclusively formed in the dry foehn area to the lee of the Alps, suggesting that moist processes played a minor role in their formation.

To further examine the effects of latent heating, a

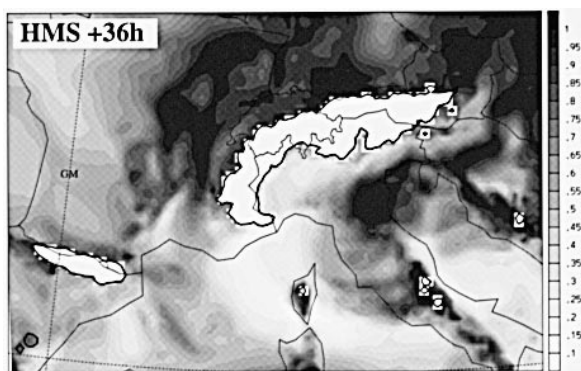


FIG. 12. Relative humidity on the 850-hPa level for simulation HMS.

dry numerical experiment was conducted. For this purpose all moisture was completely removed from the initial and lateral boundary conditions. Otherwise the dry simulation (HMD) is driven by the EMS simulation; thus the PV features entering the domain are as in the HMS simulation. Results from the dry experiment are shown in Fig. 13 at time $t = 24$ and 36 h. Comparison with Fig. 8 shows that cyclogenesis is substantially stronger in the moist simulation. This is also confirmed by the time-trace of the core pressure (cf. Fig. 5). At the same time, the dry lee cyclone follows a track somewhat farther south as compared to its moist counterpart.

Figure 13b shows that also in the dry simulation a primary PV banner was generated at the southwestern Alpine tip. Comparison with Fig. 8 does, however, show that it is substantially weaker than in the standard run. Consistent with this, Fig. 13d shows that at a later time the pronounced low-level PV anomaly in the core of the cyclone is absent in the dry simulation (cf. with Fig. 8f). Together this clearly demonstrates that moist processes play an important role in the spinup of the cyclone and in the formation of its low-level PV reservoir, although it is not the primary mechanism since the cyclone forms also in the dry experiment. This finding is in agreement with other numerical experiments that have demonstrated the importance of moist dynamics for Alpine lee cyclogenesis (e.g., Dell'Oso and Radinovic 1984; Kuo et al. 1995).

In contrast to the cyclone itself, the PV banners that develop in the northerly flow behind the cyclone are not appreciably affected by moist processes. In the dry simulation, their horizontal length scale is substantially reduced as compared to the HMS run, but this is a mere side effect of the weakened synoptic-scale circulation across the Alps and is not linked to moist processes in the formation of the PV banners itself.

b. Effects of complex topography

The results in section 4 suggest that each pair of positive-negative PV banners is associated with a peak

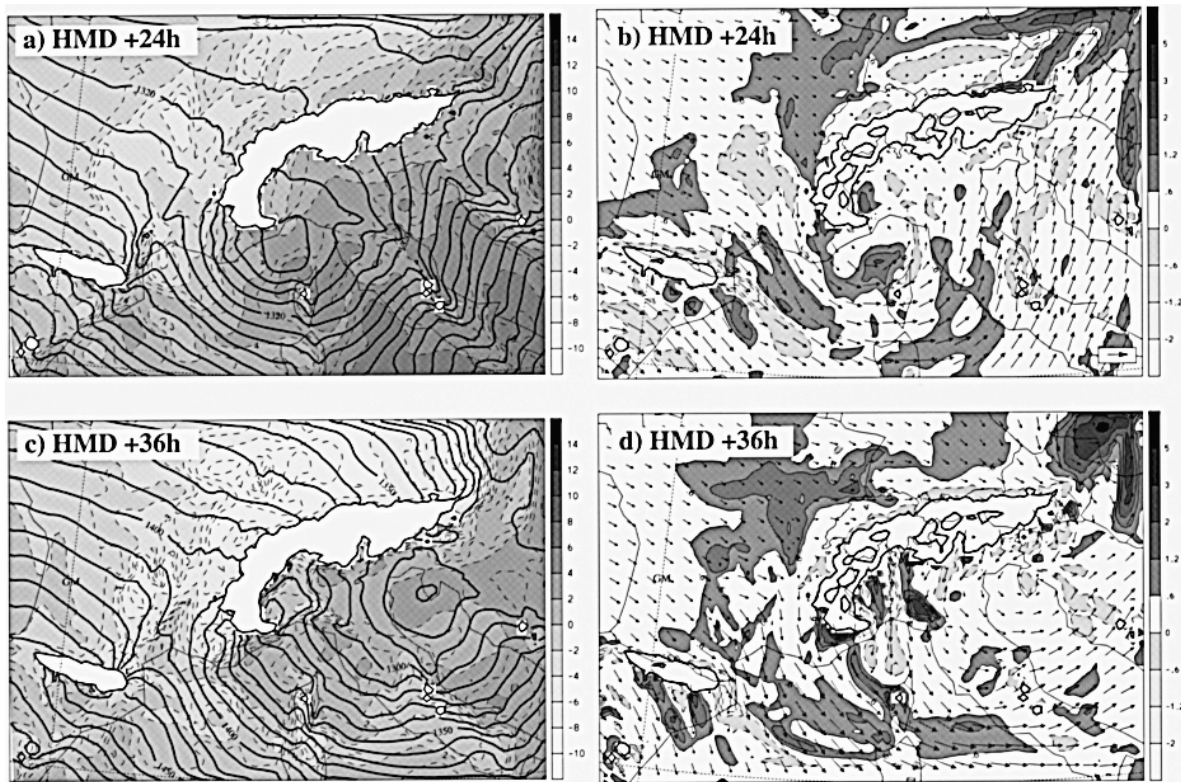


FIG. 13. As in Figs. 8c–f but for simulation HMD with dry dynamics.

in the model topography. To verify this hypothesis, an additional high-resolution simulation (HMM) was carried out. This simulation is identical to the standard run HMS except for the topography, which was subjected to some smoothing with a mass-conserving operator. The purpose of the smoothing was to simplify the terrain and reduce the number of model peaks. After 16 applications of the standard first-order smoothing operator, the resulting terrain is similar to the one used in the EM simulation, and only two shallow peaks remain in the topographic body of the Alps with a maximum altitude of 2138 m (cf. to 2806 m in HMS). The roughness length was smoothed in the same manner as the topography leading to a maximum value of 4.34 m over the Alps. In the HMM integration (not shown) the large number of PV banners of Fig. 8f is reduced to two pairs, each consisting of one positive and one negative banner. Each of the two pairs of banners is associated with one of the two remaining model peaks. However, the evolution and the movement of the lee cyclone as well as the shape and extent of the PV in its center is in good qualitative agreement with the standard HMS simulation, although the reduced height of the Alps leads to a slightly weaker development.

The experiment with smoothed topography thus supports the idea that the production of the PV banners is related to flow splitting at individual peaks in the model topography. In addition, the good agreement between

the lee cyclones of the HMM and HMS simulations suggests that the development of the cyclone is not overly affected by the secondary PV banners. However, the primary PV banners form irrespective of the details in the underlying topography, and—as to be discussed in section 6—can provide low-level PV to the growing cyclone.

c. Effects of surface friction

The formation of orographic vortices and shear lines was originally related to surface friction, where vorticity and potential vorticity is created at the intersections of isentropic surfaces with the topography, and reaches the interior of the flow by the separation of the frictional boundary layer (see, e.g., Snyder et al. 1985; Wilczak and Glendening 1988; Thorpe et al. 1993). However, numerical studies with idealized obstacles show that vertically oriented vorticity can be generated to the lee of the mountain by the tilting of baroclinically generated vorticity into the vertical, and in absence of surface friction (Smolarkiewicz and Rotunno 1989). This mechanism would lead to vorticity anomalies free of potential vorticity, but potential vorticity anomalies can be created by hydraulic-like effects (Schär and Smith 1993a; Schär and Durran 1997).

The relative contribution of the frictional and hydraulic processes was studied in the context of shallow-

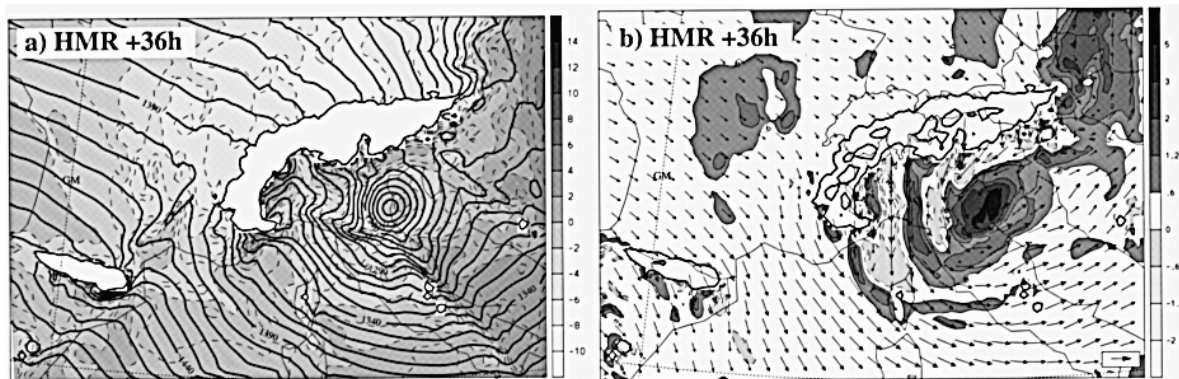


FIG. 14. As in Figs. 8e,f but for simulation HMR with reduced roughness length.

water flow (Grubisic et al. 1995; Smith and Smith 1995). For this simplified flow system, the effects of surface friction scale with a dimensionless parameter that is proportional to the horizontal scale of the mountain. Frictional (hydraulic) effects thus dominate the flow response for obstacles of large (small) horizontal extent. For typical atmospheric parameters, break even between the two processes is at a horizontal scale of approximately 1000 km. On the one hand, this critical length scale corresponds roughly to that of the Alps, and one might conclude that PV in flow past the Alps is heavily affected by turbulence in the frictional boundary layer and momentum exchange with the underlying surface. On the other hand, however, our model topography is characterized by numerous small-scale topographic features, and the analysis of Grubisic et al. thus suggests that the PV banners in our simulation could primarily be related to hydraulic-like effects.

In order to determine the source of the orographic PV, the HMS simulation was repeated but the roughness length over land was reduced to a constant value of

0.001 m. This value corresponds to that of a calm sea surface and is smaller by several orders of magnitude than that employed in the standard simulation (see Fig. 3b). Results from the corresponding experiment (HMR) are shown in Fig. 14 at forecast time +36 h. With reduced roughness length, the core pressure of the developing cyclone is substantially lower and its structure is of smaller scale (cf. Fig. 14a with Fig. 8e). This aspect can also be observed in the time trace of the surface pressure minimum earlier shown in Fig. 5. The positive and negative PV features in Fig. 14b nevertheless show a remarkable similarity with those of the HMS simulation (Fig. 8f), although they are in general somewhat stronger with amplitudes up to 9 and -5.5 pvu, respectively.

Figure 15 shows vertical sections of PV and potential temperature. Overall, the situation is qualitatively similar to the HMS simulation (cf. Fig. 10), but the PV banners have a tendency to be closer to the ground in the HMR simulation. The low-level wind speeds are substantially increased, which in turn leads to more pro-

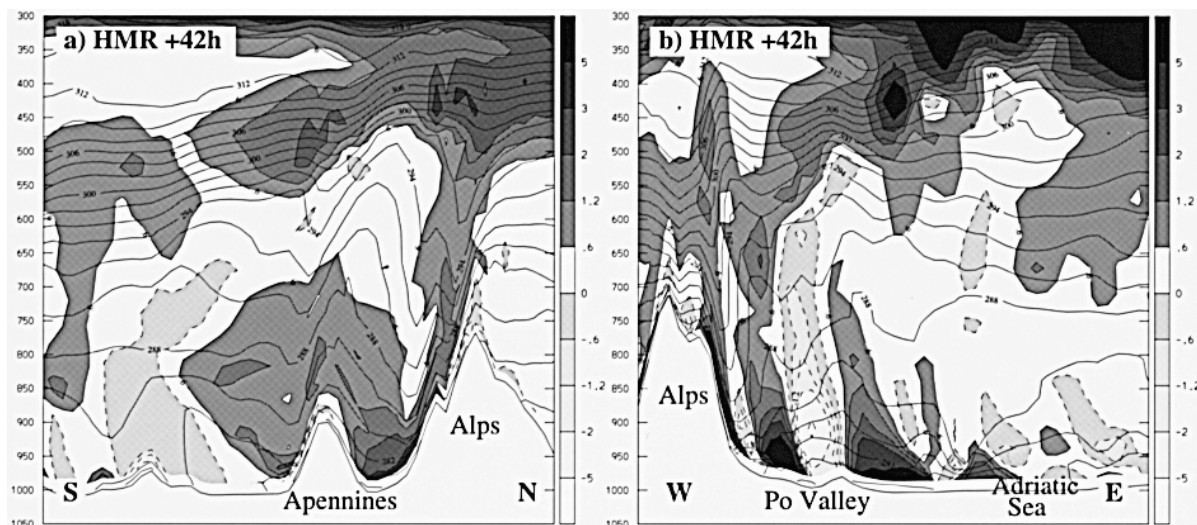


FIG. 15. As in Fig. 10c,d but for simulation HMR with reduced roughness length.

nounced gravity wave activity and foehn features. Note, for instance, how the hydraulic-jump-like structure in Fig. 15a is displaced farther downstream as compared to Fig. 10c.

The substantial enhancement of the foehn flow with reduced surface friction is consistent with idealized numerical simulations of the phenomenon (cf. Richard et al. 1989; Miller and Durran 1991). Miller and Durran demonstrated that the inclusion of surface friction into a numerical experiment with free-slip lower boundary conditions leads to a drastic reduction of the foehn region, a result that is in good qualitative agreement with our results for reduced surface friction. Georgelin et al. (1994) also provided evidence that observed gravity wave amplitudes are substantially overestimated throughout the troposphere when a too low roughness length is employed, and they suggest one should parameterize effects of subgrid-scale topography by using a dynamically adjusted roughness length.

In our simulation with reduced surface friction, the strength of the low is substantially overestimated, suggesting that the spindown of orographic vortices and lee cyclones is sensitive to the formulation of the surface fluxes of momentum. Interestingly, however, an additional simulation with an increased roughness length beyond the values used in the HMS run leads to negligible changes in the strength of the surface low.

An additional experiment was also performed using a free-slip lower boundary condition, where all the surface fluxes were completely switched off. This experiment confirmed the sensitivity of the foehn flow, but produced very similar PV banners as in simulation HMM with reduced roughness length. Overall this suggests that the PV banners form irrespective of the presence of a boundary layer, and thus by a hydraulically dominated mechanism (see Schär and Smith 1993a; Schär and Durran 1997).

The results from the above sensitivity study can be compared with Thorpe et al. (1993). The low-level PV features in their numerical experiments of flow past an idealized and smooth obstacle of Alpine size showed a much stronger sensitivity with respect to the formulation of the lower boundary condition than in our experiments. There are at least two reasons that could possibly account for these qualitative differences. First, Thorpe et al. used smooth idealized topography, free of small-scale details. According to the results of Grubisic et al. (1995), one would thus expect a substantially stronger frictional impact. Second, the experiments of Thorpe et al. were carried out near the bifurcation-like regime-boundary between the flow-over and flow-around regimes, possibly increasing the sensitivity of the flow response with respect to small changes of the control parameters.

5. Idealized topography and relation to lee cyclogenesis

The real-case numerical experiment discussed in section 4 suggests that orographically generated low-level

PV contributes to the formation of the initial low-level lee vortex. The resulting feedbacks on the synoptic-scale circulation might be described in terms of the balanced dynamics. However, a complicating factor is the presence of a large number of small-scale PV streamers. Since the balanced far-field effects of two neighboring streamers of opposite sign cancel one another, one expects that the initial low-level development of the lee cyclone is affected by the primary PV streamers, which emanate at the flanks of the Alpine-scale topography irrespective of its resolution, rather than by the secondary streamers associated with finescale topographic detail. The purpose of this section is to study the effects of the primary PV streamers in isolation. To this end, an idealized simulation was undertaken where the topography is replaced by smooth elliptic bodies representing the Alps and the Pyrenees, but the simulation is still driven by the observed lateral boundary conditions as derived from the ECMWF analysis. In effect, this procedure retains the synoptic-scale evolution, but removes the secondary orographic PV streamers and some other small-scale features observed in the simulations of section 4.

The idealized topography of the Alps and the Pyrenees is based on suitably aligned bell-shaped elliptic topographic bodies. To represent the elongated ridge and the steep slopes that rise abruptly from the European continent, the top and bottom part of the smooth bell-shaped topographies were cut off. This yields

$$z = \min \left\{ h_{\text{top}}, \max \left[\frac{h}{(1 + (x/a)^2 + (y/b)^2)^{3/2}} - h_{\text{bottom}}, 0 \right] \right\},$$

where the selected parameters for the Alps (the Pyrenees) are $h_{\text{top}} = 2770$ m (2000 m), $h_{\text{bottom}} = 1600$ m (2000 m), $h = 5700$ m (4700 m), $a = 23^\circ$ (13°), and $b = 4.5^\circ$ (3.3°). The resulting obstacles measure at their base 1020×207 km (422×120 km). The kinks in the so-defined model topography were smoothed with five applications of the standard filter, thus leaving a final height of the topography as listed in Table 1. The roughness length over land was chosen proportional to the topographic height with a maximum value of 7.47 m.

Since the topography in the HM domain is appreciably changed, the initial and lateral boundary data for the high-resolution run HMI were supplied by a corresponding low-resolution run EMI with essentially the same idealized topography, rather than the standard low-resolution run EMS.

The results of experiment HMI are shown in Fig. 16. With idealized topography, the development of the lee cyclone is qualitatively similar as in the standard experiment shown in Figs. 4 and 8. Cyclogenesis takes place at the western portion of the idealized Alpine topography, and the cyclone then propagates into a south-

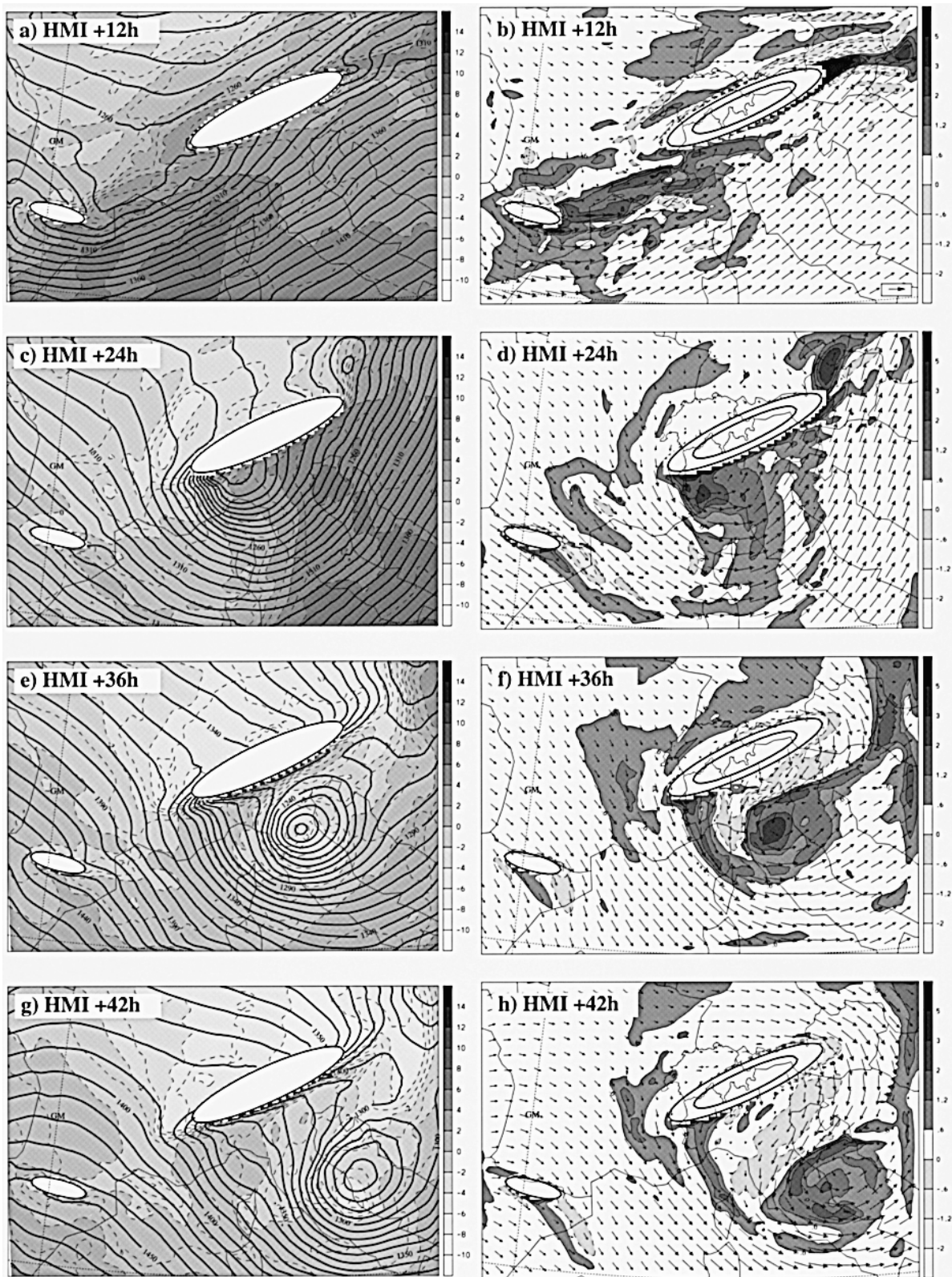


FIG. 16. As in Fig. 8 but for simulation HMI with idealized topography.

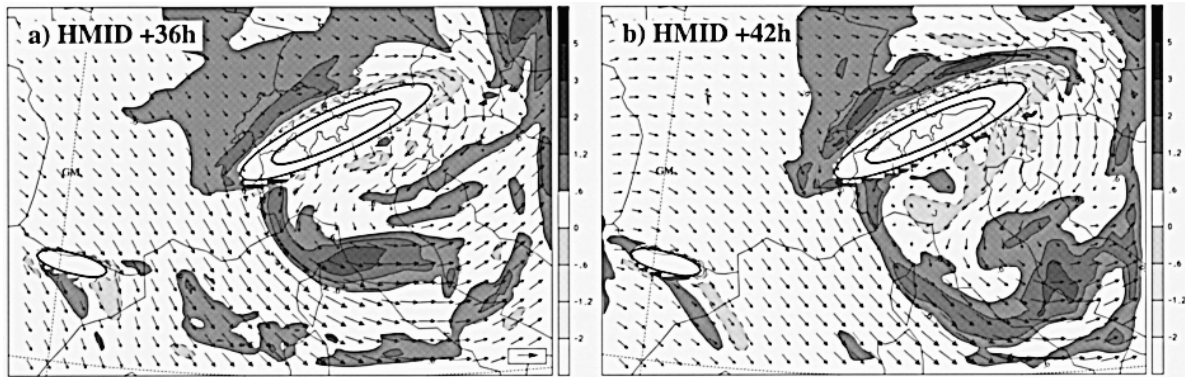


FIG. 17. As in Fig. 16f,h but for the simulation HMID with idealized topography and dry dynamics.

eastern direction toward the Adriatic Sea. The HMI development is slightly stronger than in the standard HMS simulation. The simplified topography facilitates the interpretation of the low-level PV field. In particular, the large number of PV banners observed in the standard simulation (cf. Fig. 8, right-hand panels) has vanished. The remaining primary PV banners are associated with flow-splitting past the whole of the idealized Alpine topography. At $t = +12$ h, there is a positive PV banner trailing downstream from the Pyrenees that contributes to the low-level PV distribution. At $t = +24$ h additional orographic PV from the western flank of the idealized Alpine topography contributes to the low, and is finally shed into the flow ($t = +36$ h) while further growing by diabatic processes (see below). Following this stage of minimum central MSL pressure, the lee cyclone weakens as it drifts toward the Adriatic Sea, but it maintains a well-defined core of positive PV.

To isolate the effects of dry orographic PV generation, an additional integration was conducted using the idealized topography but dry dynamics (experiment HMID, see Fig. 17). In qualitative agreement with the discussion in section 4a, the low-level circulation in the dry cyclone is substantially weaker than in its wet counterpart (on the 850-hPa level by ~ 50 gpm), and the second-phase high PV air found in the center of the moist cyclone is primarily of diabatic origin (cf. Fig. 16f,h). However, even in the dry simulation there is a pronounced PV banner emanating from the southwestern tip of the idealized topography that is of substantial strength and horizontal extension. The power of orographic processes is also demonstrated by the presence of pronounced negative PV banners (see Figs. 16f,h and Figs. 17a,b), since negative low-level PV cannot be generated by diabatic heating.

The numerical experiments thus show that orographically generated PV anomalies contribute to the PV anomalies present within or near the low pressure center of the developing cyclone. It is also worth noting that Figs. 16f,h show a remarkable qualitative resemblance with depictions of vortex shedding in idealized numerical experiments, although background rotation, baro-

clinity, and diabatic processes are important factors for the present development. As discussed in the introduction, several observational and theoretical studies have viewed Alpine lee cyclogenesis as the result of a two-phase mechanism. Here we interpret the first phase as being associated with the (unbalanced) formation of an orographic vortex in a fashion that is qualitatively comparable to vortex formation in barotropic flow past isolated topography, while the second phase of cyclogenesis is dominated by the (balanced) baroclinic interaction of the first-phase orographic low-level PV anomaly with the preexisting upper-level PV anomaly that enters the Alpine region.

6. Analysis of low-level PV from high-resolution NWP runs

In the previous section we have analyzed in some detail one particular case of Alpine PV banners. In the current section, evidence is presented that the formation of low-level PV anomalies in flow past the Alps is neither a rare phenomenon at all, nor is restricted to cyclogenetic conditions. As an ideal data source, the output of the operational NWP runs of the Swiss Meteorological Institute is employed. The raw data of the output has generously been provided by the SMI, and has been analyzed at our institute on a daily basis since January 1995. The underlying model is the same HM model as that used in the previous sections, but it is used with a substantially larger domain, driven by the operational EM run of the DWD, makes use of the semi-Lagrangian advection scheme, and does not employ the upper-level gravity wave absorber. The integration time for these simulations corresponds to 48 h.

Here we restrict the discussion to the four spectacular cases shown in Fig. 18, all of which occurred between January and April 1995. The panels are in the same format as the earlier low-level PV diagrams. The orographic banners observed in the operational HM simulations develop within the first 6 h of integration time, which is the time the models needs to develop its small-scale structures from the initial lower-resolution analysis

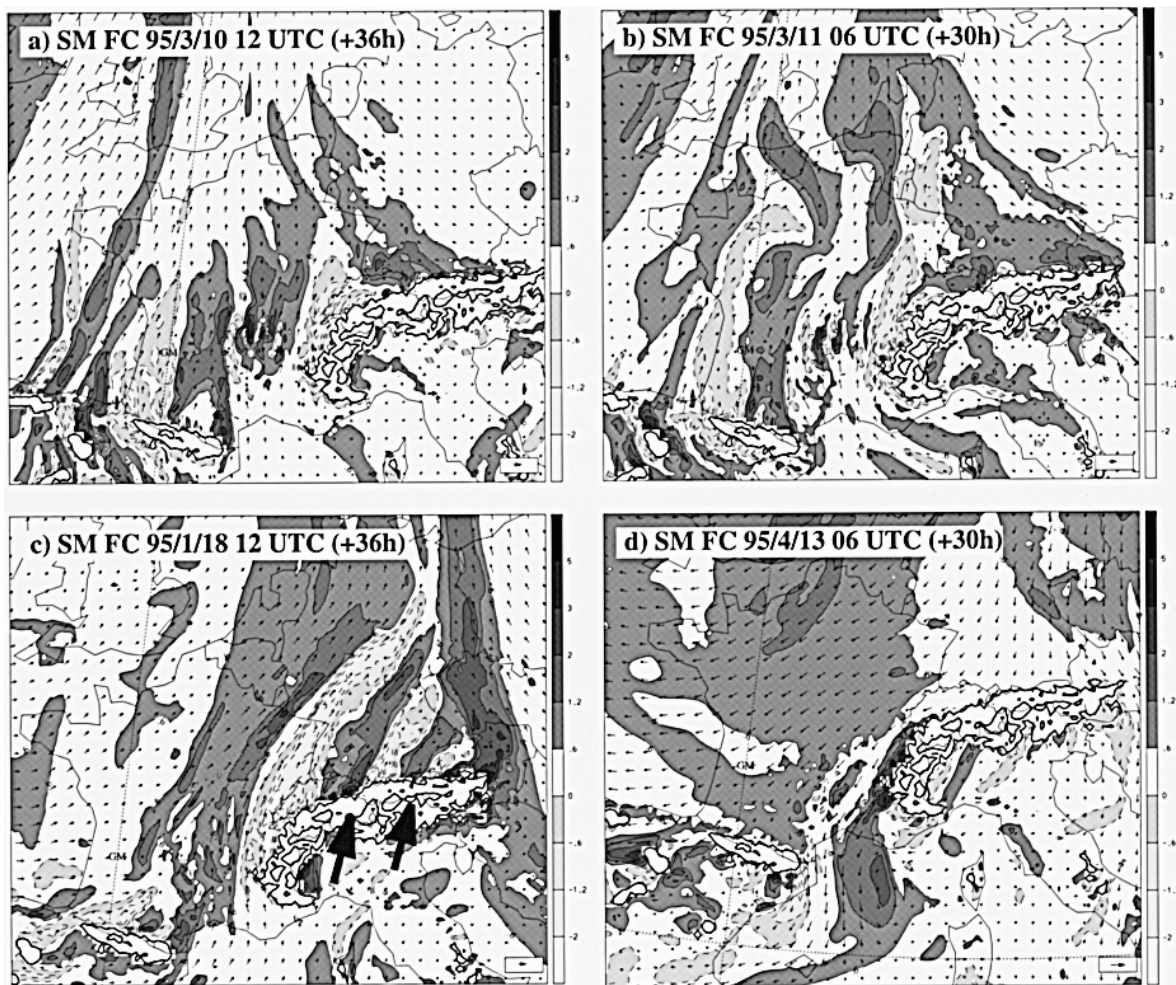


FIG. 18. The PV field and wind vectors on 850 hPa for selected situations from the operational HM simulation of the Swiss Meteorological Institute. The panels show (a) an elongated positive PV banner originating from the Pyrenees and extending as far as Scotland, (b) wavelike structures in a pair of PV banners originating at the Pyrenees, (c) PV banners to the north of the Alps associated with a strong foehn event, and (d) a PV banner at the southwestern edge of the Alps associated with strong Mistral immediately prior to the formation of a lee cyclone. The contouring is the same as in Fig. 8.

data. Once the banners are formed they grow, depending on the incident flow at the topography. In general the 36-h forecast and the 12-h forecast of consecutive NWP runs reveal reasonable agreement, but the 36-h forecast exhibits longer bands as a result of the longer advection time.

The first case shown in Fig. 18a illustrates the situation at 1200 UTC 10 March, when a north–south-oriented cold front associated with an upper-level PV streamer enters the computational domain. To the west there is an extremely long PV streamer with a length of more than 1500 km extending from the Spanish coast all the way to Scotland. The banner originates at the Cantabrian Mountains. The development started 24 h prior to the time shown, when a pair of positive and negative PV banners formed in a southwesterly flow to the lee of the coastal mountains. At 0000 UTC 10 March, both banners had an equal length of 300 km.

Then, in a successively stronger flow, the development of the positive banner becomes much more pronounced. The increased strength of the low-level flow is associated with the approaching cold front. Portions of the elongated banner roughly coincide with a surface cold-frontal signature, and its development is probably also associated with diabatic processes. Additional banners are visible at the Pyrenees, the Massif Central in central France, and at the Alps.

Roughly 24 h later, another spectacular pair of banners is seen to the lee of the Pyrenees (see Fig. 18b), still located in a strong southerly flow. The cold front mentioned above has slightly weakened and is now aligned between Portugal and Scotland. The pair of PV banners to the lee of the Pyrenees shows a wavelike pattern over northern France. This pattern might be associated either with a shedding instability, or may have been triggered by a synoptic-scale perturbation. The

positive PV banner starting to the east of the Pyrenees also separates humid Mediterranean air to its east from much drier air in the wake of the Pyrenees.

Figure 18c relates to a case of strong south foehn on 18 January 1995 and is associated with the progression of a deep upper-level trough toward the Alps. The low-level PV signature of the associated cold front corresponds to the westernmost PV band visible in Fig. 18b. Ahead of the cold front there is southerly flow across the Alps. The Alpine-scale splitting of the incident flow leads to the generation of a negative (positive) PV banner at the western (eastern) edge of the Alpine topography. The negative band is characterized by an extended region with PV values as low as -1.5 pvu. Both the primary bands extend up to northern Germany. The secondary PV banners within the Alpine wake are associated with foehn flow across two major gaps in the model topography, which correspond to the upper Rhine Valley along the border of Austria and Switzerland, and the Brenner Pass in Austria. The locations of these gaps are marked with arrows in the diagram. The formation of the wake pattern started on 17 January around noon, and the pattern did persist until the cold front passed the central Alpine region in the evening of 18 January.

Figure 18d shows a situation that is somewhat similar as the case discussed in the previous sections. Within the cold northeasterly flow, a strong PV banner is generated at the southwestern Alpine tip. A weak low-level depression coincides with this banner. However, in this case deep cyclogenesis does not take place, but rather the low-level vortex is advected off into the Mediterranean and decays. The lack of cyclogenesis appears to be related to the lack of appreciable baroclinicity and upper-level PV advection. The case is representative for the large number of cases in which a shallow first-phase lee depression forms without succeeding cyclogenesis, emphasizing the importance of upper-level PV advection for the second-phase deep development.

7. Conclusions

Results from high-resolution numerical simulations of an Alpine lee cyclogenesis event were analyzed with particular regard to the distribution of potential vorticity at lower levels. Positive and negative PV banners evolved after some simulation time when the winds turned into a direction across the Alps or Pyrenees. The banners evolve and grow downstream when the orographically generated PV anomalies are advected downstream. In this way, some of the banners attained a length of up to 1500 km. The results from the sensitivity studies with smoothed and idealized topography demonstrate that the banners usually occur as pairs of positive–negative PV anomalies, which can be attributed to peaks in the model topography. The generation of the banners is mostly associated with flow splitting, though the model's representation of gravity wave breaking appears to contribute to some lesser extent as well. Ad-

ditional simulations with reduced roughness length and with dry dynamics also suggest that the bands are not associated with diabatic effects and only weakly sensitive to the formulation of the boundary layer.

The width of the simulated banners corresponds to about 50–150 km and seems to be mainly determined by the model resolution. Indeed, pseudoinviscid shallow water theory suggests that the width of the banners decreases to that of a discontinuity in the limit of infinite Reynolds numbers (Schär and Smith 1993a), and very sharp atmospheric shear lines have been observed to the lee of the Big Island of Hawaii (Smith and Grubisic 1993) and the Colorado Front Range (Levinson and Banta 1995). The mechanism that halts the scale collapse is likely to operate at a scale of a few kilometers, and could for instance be related to boundary-layer processes and/or the dynamical stability properties of the shear lines. The real wake of the Alps could thus look far more complex than represented in the current study. The representation of higher and thus more realistic Reynolds numbers would presumably lead to narrower PV bands, and possibly to the generation of shedding eddies. Shallow water and continuously stratified theory suggests that eddy shedding should occur whenever there is appreciable reversed flow between the shearlines (Schär and Smith 1993b; Grubisic et al. 1995; Schär and Durran 1997). This situation is rarely met in our simulations, thus possibly explaining the absence of shedding instabilities. If the real Alpine wake should support shedding eddies, their interaction might also provide a source for horizontal divergence and mesoscale ascent, which might in turn be relevant for the triggering of convective activity remote from the Alpine slopes.

The validation of the simulated PV banners currently appears not feasible for the lack of high-resolution data in the lower troposphere. The inability to validate simulations is quite typical for current-day high-resolution forecasting models, which have reached a resolution beyond that of the operational observational networks. This issue is addressed within the Mesoscale Alpine Programme (MAP, see Binder and Schär 1996). One central aim of MAP is to provide high-resolution datasets for the validation of mesoscale numerical models in complex terrain, and this could also yield interesting observational data on the structure of the Alpine wake.

Consistent with the aforementioned limitations, we have sought to focus the interpretation primarily upon the larger-scale aspects of the PV banners, and in particular upon their approximately balanced interaction with the ambient synoptic-scale flow. The inversion operation inherent to such an interpretation sees the PV distribution with the smoothing eyes of an inverted Laplacian operator, and is thus not sensitive to the smaller-scale details in the low-level PV field. Our analysis suggests that the first phase of Alpine lee cyclogenesis is at least partly related to the generation of a strong PV banner at the southwestern edge of the Alps (or possibly

sometimes a similar banner at the eastern edge of the Pyrenees). The banner provides a low-level source of potential vorticity, and its roll-up implies a growth in horizontal scale and some pressure drop through subsequent geostrophic (or higher-order balance) adjustment. During the second phase, the low-level PV anomaly can interact and couple with the incipient upper-level PV trough much as in cases of cyclogenesis over flat terrain (Bleck and Mattocks 1984; Tafferner 1990; Hoskins et al. 1985). The suggested mechanism is supported by our simulation with idealized terrain, which showed the formation and shedding into the Alpine wake of a notable orographic PV anomaly immediately prior to deep lee cyclogenesis. Such a precursor appears to be fairly common and was observed in numerous operational NWP runs of Alpine lee cyclogenesis events (Aebischer 1996).

In addition to orographically generated PV, the low-level thermal anomaly associated with frontal retardation, and the diabatically generated PV anomaly associated with condensation, can contribute to the formation of a balanced low-level vortex. The effects of these three low-level processes are similar to the extent that surface thermal and shallow low-level PV anomalies are dynamically equivalent in the framework of the balanced dynamics (Bretherton 1966). In the current study we did not attempt to determine the relative contribution of the three aforementioned mechanisms. The attribution of the second-phase vertical interaction to either one or a combination of the three low-level ingredients, and the demonstration that it occurs by an essentially balanced mechanism, could possibly be accomplished with ideas that were developed in the context of maritime cyclogenesis (cf. Davis and Emanuel 1991), although the characteristic horizontal scales of Alpine lee cyclogenesis suggest that such an analysis might require some higher-order balance rather than quasigeostrophy (see, e.g., Raymond 1992). The efficacy of quasi-balanced interactions between features of comparatively small horizontal scales is also suggested by PV interactions in frontal cyclogenesis (see Appenzeller and Davies 1996).

Notwithstanding the aforementioned uncertainties, there are indications that low-level orographically generated PV anomalies often substantially contribute to or even dominate the early stages of Alpine lee cyclogenesis: in particular, this mechanism appears the only one that is able to explain initial cyclone formation according to climatology, namely, in comparatively small geographical areas near the southwestern Alpine tip and the eastern tip of the Pyrenees (see Jansà et al. 1994). In contrast, the retardation of the cold front produces a warm anomaly of Alpine scale, and is thus unable to explain the preferred geographical location of initial vortex formation. On the other hand, diabatic heating has in principle some potential to explain the geographical distribution of Alpine lee cyclogenesis for its proximity to the warm Gulf of Genoa, but the first phase of

most Alpine lee cyclogenesis events is reasonably well captured by the dry dynamics (see, e.g., Tafferner 1990). Nevertheless, to the extent that all the aforementioned processes appear to act in concert, and are of different relative importance at different stages of the development, and during different seasons, analysis of further cases will be needed to make any final conclusions.

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REFERENCES

- Aebischer, U., 1996: Low-level potential vorticity and cyclogenesis to the lee of the Alps. Ph.D. dissertation, Eidgenössische Technische Hochschule Zürich, 127 pp. [Available from Atmospheric Science ETH, 8093 Zürich, Switzerland.]
- Appenzeller, C., and H. C. Davies, 1996: PV morphology of a frontal-wave development. *Meteor. Atmos. Phys.*, **58**, 21–40.
- Baines, P. G., and R. Steinacker, 1987: Flow separation and vortex shedding as a mechanism for cyclogenesis in the lee of the Alps. Unpublished manuscript, 10 pp. [Available from Prof. Reinhold Steinacker, Institut für Meteorologie, Universität Wien, Silbergasse 45/7, 1190 Vienna, Austria.]
- Binder, P., and C. Schär, 1996: *The Mesoscale Alpine Programme: Design Proposal*. 2d ed. MAP, 77 pp. [Available from MAP Programme Office, c/o SMA, 8044 Zürich, Switzerland.]
- , H. C. Davies, and J. Horn, 1989: Free atmosphere kinematics above the northern Alpine foreland during ALPEX-SOP. *Contrib. Atmos. Phys.*, **62**, 30–45.
- Bleck, R., and C. Mattocks, 1984: A preliminary analysis of the role of potential vorticity in Alpine lee cyclogenesis. *Contrib. Atmos. Phys.*, **57**, 357–368.
- Bougeault, P., 1983: A non-reflective upper boundary condition for limited-height hydrostatic models. *Mon. Wea. Rev.*, **111**, 420–429.
- Boyer, D. L., R. Chen, and P. A. Davies, 1987: Some laboratory models of flow past the Alpine/Pyrenean mountain complex. *Meteor. Atmos. Phys.*, **36**, 187–200.
- Bretherton, F. P., 1966: Critical layer instability in baroclinic flows. *Quart. J. Roy. Meteor. Soc.*, **92**, 325–334.
- Buzzi, A., and A. Tibaldi, 1978: Cyclogenesis in the lee of the Alps: A case study. *Quart. J. Roy. Meteor. Soc.*, **104**, 271–287.
- , R. Cadelli, and P. Malguzzi, 1997: Low-level jet simulation over the Southern Ocean in Antarctica. *Tellus*, **49A**, 263–276.
- Chen, W.-D., and R. B. Smith, 1987: Blocking and deflection of airflow by the Alps. *Mon. Wea. Rev.*, **115**, 2578–2597.
- Clark, T. L., W. D. Hall, and R. M. Banta, 1994: Two- and three-dimensional simulations of the 9 January 1989 severe Boulder

- windstorm: Comparison with observations. *J. Atmos. Sci.*, **51**, 2317–2343.
- Crook, N. A., T. L. Clark, and M. W. Moncrieff, 1990: The Denver cyclone. Part I: Generation in low Froude number flow. *J. Atmos. Sci.*, **47**, 2725–2724.
- Davies, H. C., 1976: A lateral boundary formulation for multi-level prediction models. *Quart. J. Roy. Meteor. Soc.*, **102**, 405–418.
- Davis, C. A., and K. A. Emanuel, 1991: Potential vorticity diagnostic of cyclogenesis. *Mon. Wea. Rev.*, **119**, 1929–1953.
- Dell’Osso, L., and D. Radinovic, 1984: A case study of cyclone development in the lee of the Alps on 18 March 1982. *Contrib. Atmos. Phys.*, **57**, 369–379.
- DWD, 1995: Dokumentation des EM/DM-Systems. Deutscher Wetterdienst, 550 pp. [Available from Deutscher Wetterdienst, Zentralamt, 63004 Offenbach am Main, Germany.]
- Egger, J., 1972: Numerical experiments on the cyclogenesis in the Gulf of Genoa. *Contrib. Atmos. Phys.*, **45**, 320–346.
- Emanuel, K. A., M. Fantini, and A. J. Thorpe, 1987: Baroclinic instability in an environment of small stability to slantwise moist convection. Part I: Two dimensional models. *J. Atmos. Sci.*, **44**, 1559–1573.
- Etiling, D., 1989: On atmospheric vortex streets in the wake of large islands. *Meteor. Atmos. Phys.*, **41**, 157–164.
- Frenzen, G., and P. Speth, 1986: Comparative study of several cases of Alpine lee-cyclogenesis: Kinetic energy and vorticity. *Contrib. Atmos. Phys.*, **59**, 216–230.
- Frei, C., and C. Schär, 1997: A precipitation climatology of the Alps from high-resolution rain-gauge observations. *Int. J. Climatol.*, in press.
- Georgelin, M., E. Richard, M. Petitdidier, and A. Druilhet, 1994: Impact of subgrid-scale orography parameterization on the simulation of orographic flows. *Mon. Wea. Rev.*, **122**, 1509–1522.
- Grubisic, V., R. B. Smith, and C. Schär, 1995: The effect of bottom friction on shallow-water flow past an isolated obstacle. *J. Atmos. Sci.*, **52**, 1985–2005.
- Herzog, H.-J., 1995: Testing a radiative upper boundary condition in a nonlinear model with hybrid vertical coordinate. *Meteor. Atmos. Phys.*, **55**, 185–204.
- Hoskins, B. J., M. E. McIntyre, and A. W. Robertson, 1985: On the use and significance of isentropic potential vorticity maps. *Quart. J. Roy. Meteor. Soc.*, **111**, 877–946.
- Jansà, A., A. Genovés, M. A. Picornell, J. Campins, D. Radinovic, and P. Alpert, 1994: Mediterranean cyclones: Subject of a WMO project. *Proc. Int. Conf. on the Life Cycles of Extratropical Cyclones*, Vol. II, Bergen, Norway, University of Bergen, 26–31.
- Klemp, J. B., and D. R. Durran, 1983: An upper boundary condition permitting internal gravity wave radiation in numerical mesoscale models. *Mon. Wea. Rev.*, **111**, 430–444.
- Kuo, Y.-H., J. R. Gyakum, and Z. Guo, 1995: A case of rapid continental mesoscale cyclogenesis. Part I: Model sensitivity experiments. *Mon. Wea. Rev.*, **123**, 970–997.
- Lanzinger, A., H. Pichler, and R. Steinacker, 1991: ALPEX-Atlas: Case studies of ALPEX-SOP cyclones in the western Mediterranean. 2d ed. Oesterreichische Beiträge zur Meteorologie und Geophysik, Heft 4, ZAMG-Publ. No. 338. [Available from Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte, 1191 Vienna, Austria.]
- Levinson, D. H., and R. M. Banta, 1995: Observations of a terrain-induced mesoscale vortex and Canyon drainage flows along the Front Range of Colorado. *Mon. Wea. Rev.*, **123**, 2029–2050.
- Louis, J. F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound.-Layer Meteor.*, **17**, 187–202.
- Majewski, D., 1985: Balanced initial and boundary values for a limited-area model. *Contrib. Atmos. Phys.*, **58**, 147–159.
- , 1991: The Europa-Modell of the Deutscher Wetterdienst. *Proc. ECMWF Seminar on Numerical Methods in Atmospheric Models*, Vol. 2, Reading, United Kingdom, ECMWF, 147–191.
- McGinley, J., 1982: A diagnosis of Alpine lee cyclogenesis. *Mon. Wea. Rev.*, **110**, 1271–1287.
- , 1986: Vorticity budgets for Alpine lee cyclogenesis with and without the forcing of the terrain. *Proc. Conf. on Results of the Alpine Experiment*, Venice, Italy, World Meteorological Organization, 265–280.
- Mellor, G. L., and T. Yamada, 1974: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.*, **31**, 1791–1806.
- Miller, P. P., and D. R. Durran, 1991: On the sensitivity of severe downslope windstorms to the asymmetry of the mountain profile. *J. Atmos. Sci.*, **48**, 1457–1473.
- Müller, E., 1981: Turbulent flux parameterization in a regional-scale model. *Proc. ECMWF Workshop on Planetary Boundary Layer Parameterization*, Reading, United Kingdom, ECMWF, 193–220.
- Olafsson, H., and P. Bougeault, 1996: Nonlinear flow past an elliptic mountain ridge. *J. Atmos. Sci.*, **53**, 2465–2489.
- , and —, 1997: The effect of rotation and surface friction on orographic drag. *J. Atmos. Sci.*, **54**, 193–210.
- Pichler, H., and R. Steinacker, 1987: On the synoptics and dynamics of orographically induced cyclones in the Mediterranean. *Meteor. Atmos. Phys.*, **36**, 108–117.
- Pierrehumbert, R. T., 1985: A theoretical model of orographically modified cyclogenesis. *J. Atmos. Sci.*, **42**, 1244–1258.
- Raymond, D. J., 1992: Nonlinear balance and potential-vorticity thinking at large Rossby number. *Quart. J. Roy. Meteor. Soc.*, **118**, 987–1016.
- Reed, R. J., M. T. Stoelinga, and Y.-H. Kuo, 1992: A model-aided study of the origin and evolution of the anomalously high potential vorticity in the inner region of a rapidly deepening marine cyclone. *Mon. Wea. Rev.*, **120**, 893–913.
- Richard, E., P. Mascart, and E. C. Nickerson, 1989: The role of surface friction in downslope windstorms. *J. Appl. Meteor.*, **28**, 241–251.
- Ritter, B., and J. F. Geleyn, 1992: A comprehensive radiation scheme for numerical weather prediction with potential applications in climate simulations. *Mon. Wea. Rev.*, **120**, 303–325.
- Schär, C., 1990: Quasi-geostrophic lee cyclogenesis. *J. Atmos. Sci.*, **47**, 3044–3066.
- , 1993: A generalization of Bernoulli’s theorem. *J. Atmos. Sci.*, **50**, 1437–1443.
- , and R. B. Smith, 1993a: Shallow-water flow past isolated topography. Part I: Vorticity production and wake formation. *J. Atmos. Sci.*, **50**, 1373–1400.
- , and —, 1993b: Shallow-water flow past isolated topography. Part II: Transition to vortex shedding. *J. Atmos. Sci.*, **50**, 1401–1412.
- , and D. R. Durran, 1997: Vortex formation and vortex shedding in continuously stratified flows past isolated topography. *J. Atmos. Sci.*, **54**, 534–554.
- Smith, R. B., 1984: A theory of lee cyclogenesis. *J. Atmos. Sci.*, **41**, 1159–1168.
- , and A. Grønås, 1993: Stagnation points and bifurcation in 3-D mountain airflow. *Tellus*, **45A**, 28–43.
- , and V. Grubisic, 1993: Aerial observations of Hawaii’s wake. *J. Atmos. Sci.*, **50**, 3728–3750.
- , and D. F. Smith, 1995: Pseudoinviscid wake formation by mountains in shallow-water flow with a drifting vortex. *J. Atmos. Sci.*, **52**, 436–454.
- Smolarkiewicz, P. K., and R. Rotunno, 1989: Low Froude number flow past three dimensional obstacles. Part I: Baroclinically generated lee vortices. *J. Atmos. Sci.*, **46**, 1154–1164.
- Snyder, W. H., R. E. Thompson, R. E. Eskridge, I. P. Lawson, J. T. Castro, J. T. Lee, J. C. R. Hunt, and Y. Ogawa, 1985: The structure of strongly stratified flow over hills: Dividing streamline concept. *J. Fluid Mech.*, **152**, 249–288.
- Speranza, A., A. Buzzi, A. Trevisan, and P. Malguzzi, 1985: A theory of deep cyclogenesis in the lee of the Alps. Part I: Modifications of baroclinic instability by localized topography. *J. Atmos. Sci.*, **42**, 1521–1535.
- Steinacker, R., 1984: The isentropic vorticity and the flow over and around the Alps. *Riv. Meteor. Aeronaut.*, **43**, 79–83.

- Tafferer, A., 1990: Lee cyclogenesis resulting from the combined outbreak of cold air and potential vorticity against the Alps. *Meteor. Atmos. Phys.*, **43**, 31–47.
- Thorpe, A. J., H. Volkert, and D. Heimann, 1993: Potential vorticity of flow along the Alps. *J. Atmos. Sci.*, **50**, 1573–1590.
- Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parametrization in large-scale models. *Mon. Wea. Rev.*, **117**, 1779–1800.
- Trüb, J., 1993: Dynamical aspects of flow over Alpine-scale topography: A modeling perspective. Ph.D. dissertation, Eidgenössische Technische Hochschule Zürich, 140 pp. [Available from Atmospheric Science ETH, 8093 Zürich, Switzerland.]
- Whitaker, J. S., L. W. Uccellini, and K. F. Brill, 1988: A model-based diagnostic study of the rapid development phase of the Presidents' Day cyclone. *Mon. Wea. Rev.*, **116**, 2337–2365.
- Wilczak, J. M., and J. W. Glendening, 1988: Observations and mixed-layer modeling of a terrain-induced mesoscale gyre: The Denver cyclone. *Mon. Wea. Rev.*, **116**, 2688–2711.