THE SYNOPTIC SETTING AND MESOSCALE OROGRAPHIC SYSTEMS

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Summary : Consideration is given to the linkage between the nature of the ambient synoptic setting and the occurrence of orographically-related mesoscale systems. Some of the mechanisms that forge such a link are illustrated in the context of Alpine systems, and comments made on the implications for numerical weather prediction.

1. INTRODUCTION

Numerous mesoscale flow systems occur in the vicinity of major mountain chains. For example in the Alpine region there are distinct orographically-related mesoscale signatures associated with :- the diurnal variations in the boundary layer; the major wind systems of the Bise, Bora, Fohn and Mistral; the passage of a front; and the development of severe storms and lee-cyclones. A similar rich range of phenomena exist over other mountain chains (see e.g. Smith et al. 1997). The scale, nonlinearity and impact of these systems renders their theoretical understanding challenging and their accurate prediction desirous.

One important factor in determining the type of mesoscale orographic system realized at a given time is the ambient synoptic flow, and it is the link between the synoptic setting and the mesoscale system that forms the connecting theme of the present study. The emphasis is on the dynamics of various links, and the approach adopted is as follows :- to list the the ingredients that influence the form of the linkage (Section 2); to present a few prototype Alpine-related examples (Sections 3-5); and to comment on possible implications for numerical weather prediction (Section 6).

2. RUDIMENTS OF A CLASSIFICATION

A classification of mesoscale orographic systems would need to consider the following factors :

- the orographic-related mechanism(s) involved in generating the mesoscale system,
- the scale and configuration of the orography,
- the nature of the synoptic setting, and
- the character of the resulting system.

The *mechanisms* could be viewed in terms of the processes generating the system's buoyancy - surface radiative effects associated with the elevated terrain, advective effects as air moves up or down slope, and cloud-diabatic effects. Radiative forcing on the scale the orography would usually result in a buoyancy anomaly and a flow response on the same scale (e.g. mountain-plain circulations) rather than in an inter-scale linkage. Up-and down-slope flow in a stratified environment induce buoyancy and vorticity anomalies with the nature of the response related to the flow's space-time scale. Strong stratification can also inhibit such flow with the orography acting as a barrier. Contrariwise ascent arising from either the radiative or the advective effects can also trigger, or enhance pre-existing, cloud-diabatic effects.

The *scale and configuration of the orography* is crucial in determining whether the forementioned mechanisms are likely to be effective in generating a mesoscale response. Planetary and synoptic-scale mountain ranges would promote significant vorticity changes arising from up- and down-slpe flow and this could engender a mesoscale response by via nonlinear scale-contraction of the incident flow, or such a response could be linked to the mountain range's mesoscale features such as individual mountains or the lateral slopes. For mesoscale terrain there can also be a scale-differentiated response with meso-α scale terrain more favourable for a balanced flow response and meso-β and γ scale terrain more likely to parturate a non-balanced response.

For the *synoptic setting* one natural temporal sub-division is into the quiesecent, steady and transient categories. This categorization could be further refined to account for spatial characteristics of the incident flow field.

The *character* of the mesoscale system can take the form of a modification of a pre-existing incident system, a direct response to the forcing, an indirect response via an intermediate process, or an intrinsic instabilty of the ambient flow in the presence of orography.

In the following sections a sequence of less studied systems are selected based upon the underlying physical mechanisms, and used to illustrate a range of inter-scale linkages.

3. OROGRAPHICALLY-CONFINED WAVES

In principle orography can permit the occurrence of natural modes of atmospheric oscillation in the form of orographically-confined waves. Topographic Rossby waves are attributable to the buoyancy and vorticity created as air moves along meso-scale terrain slopes. They propagate along the contours of the terrain with the higher terrain to their right (- in the Northern Hemisphere), and their lateral and vertical scale are determined respectively by the width of the slope and the Rossby scale-height. Pseudo Kelvin-waves can arise when the orography acts as a barrier to the flow, and are often interpreted in terms of the dynamics of a mixed-layer. They propagate like a gravity-wave along the 'barrier' (also located on the right), whereas their lateral decay has a geostrophic character.

Simple physical considerations suggest that the frequency (ω) of these two types of waves, would be such that, for terrain orientated perpendicular to say the x-direction,

$$\omega \sim \{\eta_x N\}\ l \,/\, [k^2 + l^2]^{1/2} \qquad \text{for topographic waves,} \qquad (1)$$

where η_x denotes an uniform terrain slope, N the uniform stratification, and (k, l) are respectively the along- and across-slope wavenumbers, and

$$\omega \sim \{g^* H\}^{1/2}\ l \qquad \text{for Kelvin waves,} \qquad (2)$$

with g* and H denoting respectively a 'reduced gravity' and the depth of the mixed layer.

An important feature of these frequency relationships is that waves can be non-dispersive in the along-ridge direction - topographic waves for k>>l, and Kelvin-waves for all (l) values. The existence of such waves raises the possibility of distinctively different types of inter-scale links for different synoptic settings, and this is illustrated in the following sub-sections.

3.1 Quiescent Setting

Excitation of orographic-bound waves in a quiescent synoptic setting would be favoured if they had a frequency close to either that of the diurnal forcing in the PBL or to that of the planetary-scale (diurnal, semi-diurnal, etc. ..) tidal waves.

One possible example of such an effect is the asymmetry of the diurnal surface pressure pattern across the main east-west ridge of the Alps (Davies and Phillips, 1985; Frei and Davies, 1993). For clear-sky, quiescent synoptic conditions the primary feature on the northern side is a ~0.5 hPa semi-diurnal oscillation, and on the southern side it is a ~2.5 hPa diurnal oscillation (Fig.1). The prevalence of this asymmetry is confirmed by a long-term statistical climatology - the variation in the across ridge strength of the solar-diurnal (i.e. S_1) component is ~1hPa and it has a lateral scale away from the terrain of ~200 km.

The amplitude and prevalence of the anomaly suggests that it might be attributable to the Alpine modification of the planetaray S_1 tide. Support for this hypothesis has been derived from a heuristic theoretical model that represents the dynamics of the mixed layer flow around an idealized cylindrical Alpine massif as shallow water flow under "reduced gravity" (Fig. 1). For this model the terrain-induced modification takes the form of a mesoscale, terrain-trapped Kelvin wave that interfers destructively (constructively) with the global S_1 signal to the north (south) of the terrain. In essence a Kelvin wave circumnavigates the orographic feature in approximately one day and resonates with the global S_1 tide.

Likewise a possible example of free topographic-waves has been associated with some Antarctic flow structures (Egger and Fraedrick, 1987).

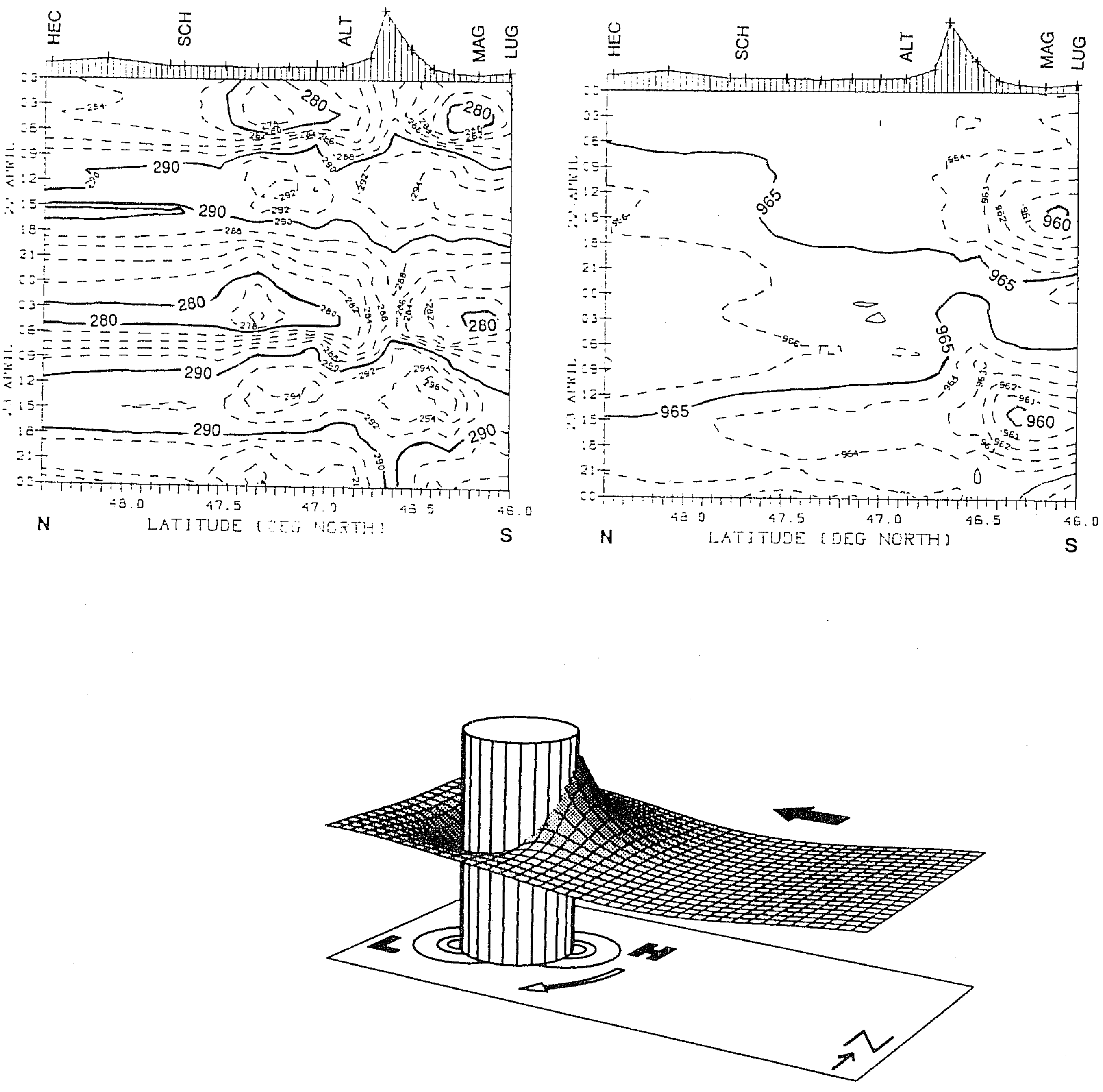


Fig. 1 Upper panels are space-time displays along the Gotthard section of the Alps for 22-23 April 1982.
Left Panel : the scaled static energy, $T_S = T + gz/c_p$, with contour intervals 2K.
Right Panel : a standardized surface pressure at 1hPa intervals. (Adapted from Frei and Davies, 1993).
Lower Panel is a schematic of the idealized model configuration and indicates the nature of the flow response.

3.2 Quasi-steady Setting

An airstream aligned along an elongated terrain would modify the propagation velocity of orographically-confined waves. Consider for example a configuration comprising an airstream incident tangentially upon an elongated mountain and splitting to flow along the two-sides of the terrain. In this configuration a steady orographic-bound wave would be brought to rest on the right-hand side of the terrain (- looking downstream) if the flow speed matched the phase speed of the bound-wave. No such possibility would exist on the opposite slope.

A possible Alpine example occured during the ALPEX field phase when a weak easterly flow persisted for several days (Paegle et al, 1984). It resulted in a strong jet-like structure at the top of the mixed-layer on the Alpine northside, but not on the southside. Both the jet and the strength of the inversion exhibited a strong diurnal variation, and Fig. 2 provides an indication of the flow's structure at midnight on two successive nights.

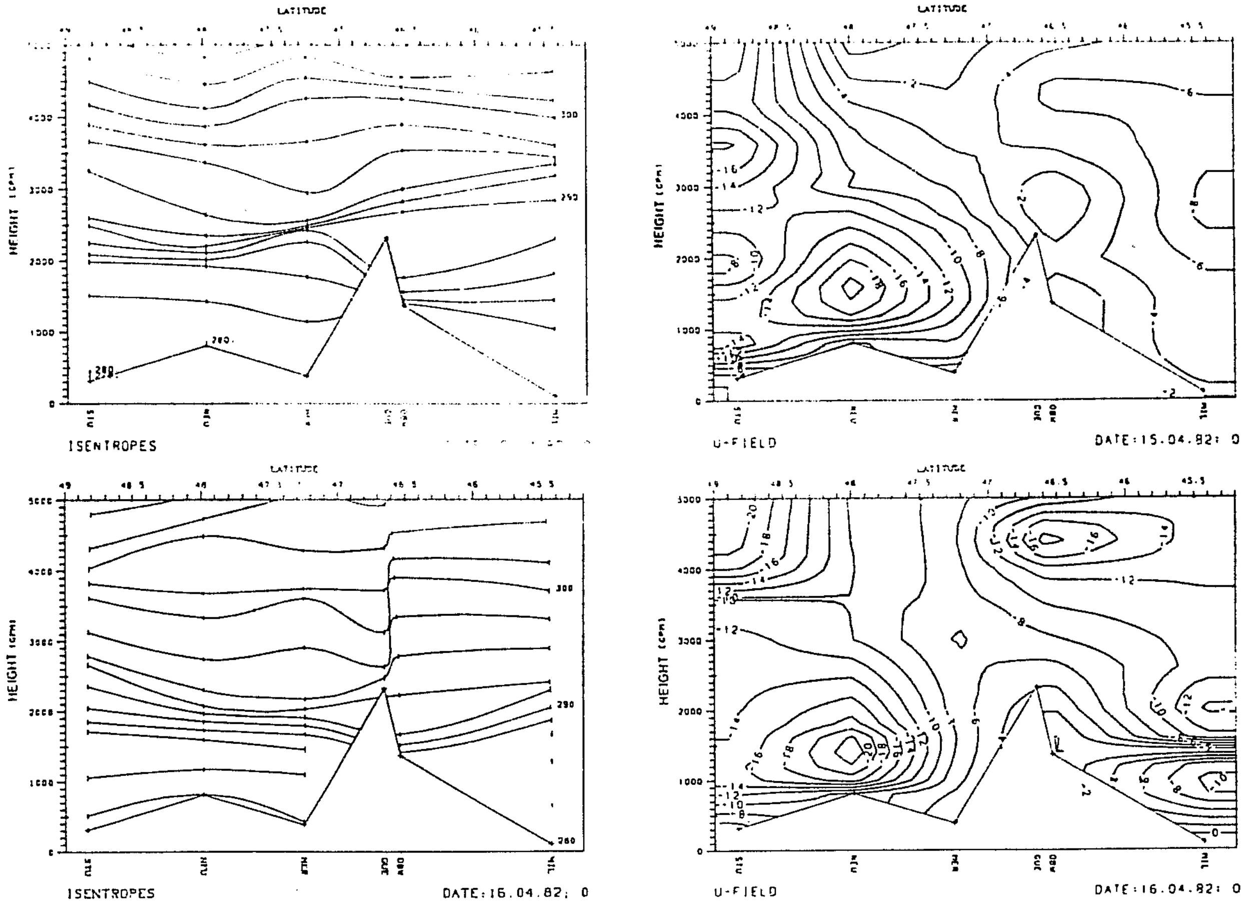


Fig.2 North-South sections across the Gotthard part of the main Alpine ridge showing the isentropic pattern (le panels) and the distribution of the easterly flow component (right panels) at 00Z on the 15 and 16 April 198 Each panel is based upon data from from six radiosonde acents (Adapted from Horn and Davies, 1989).

An idealized a "shallow-water" model of the flow (Horn and Davies, 1989) again captures the essensce of the non-linear response (Fig. 3).

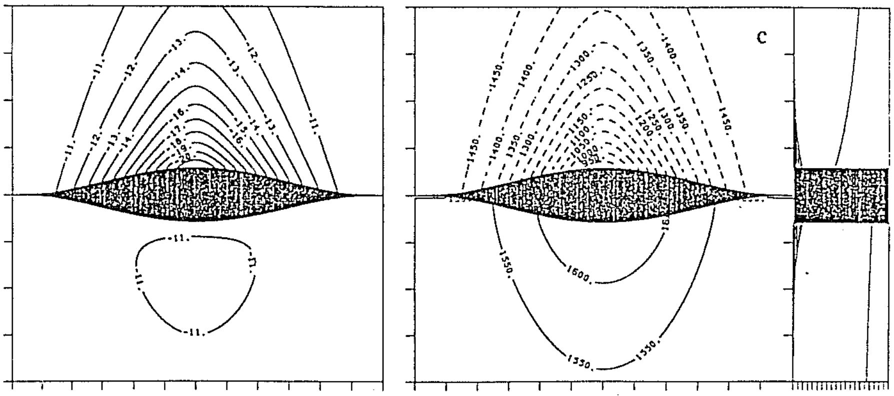


Fig. 3 Left and centre panels display the horizontal distribution of the easterly flow component (in ms^{-1}) and the height of the mixed layer (in m) as derived from the idealized model. Prescribed upstream conditions are a 10 $m\ s^{-1}$ flow and a mixed layer depth of 1500m. The right panel is a (roptated) central cross-section. Note the across-ridge asymmetry of the response. (For further details see Horn and Davies, 1989).

A geostrophic along-mountain flow within the mixed-layer speeds-up abreast of the terrain as a result of the splitting and concomitantly draws down (elevates) the height of the inversion on the northside (southside) inducing a positive (negative) feed-back upon the strength of the flow on the north (south) side. In effect there is a steady, non-linear Kelvin-wave on the model's Alpine north-side.

3.3 Transient Setting

In a transient setting an incident flow system can act to excite a free, or yield a forced, orographically-confined wave response. An incident synoptic system flowing onto a smaller-scale terrain slope would trigger topographic Rossby waves which could then propagate quasi non-dispersively (k>>l) along the terrain. In effect the terrain slope acts to modify the low-level wave-guide and deflect the incident system. This inference is supported by statistical analysis of observational data (Hsu and Wallace, 1985; Hsu, 1987; Wallace et al, 1988), and these studies indicate that the preferred regions for such an effect are the eastern slopes of the Rockies, the north and north-east of the Tibetan plateau and western and northern coasts of Greenland (Fig. 4).

An incident synoptic system that does not surmount the terrain would not yield a topographic wave of appreciable amplitude. However if the incident balanced system is confronted with an orographic-barrier then the 'balanced' response to a cyclone and anticyclone would be a deflection in opposite directions. (Hsu (1987) did not detect a significant difference in the response of these two types of systems.)

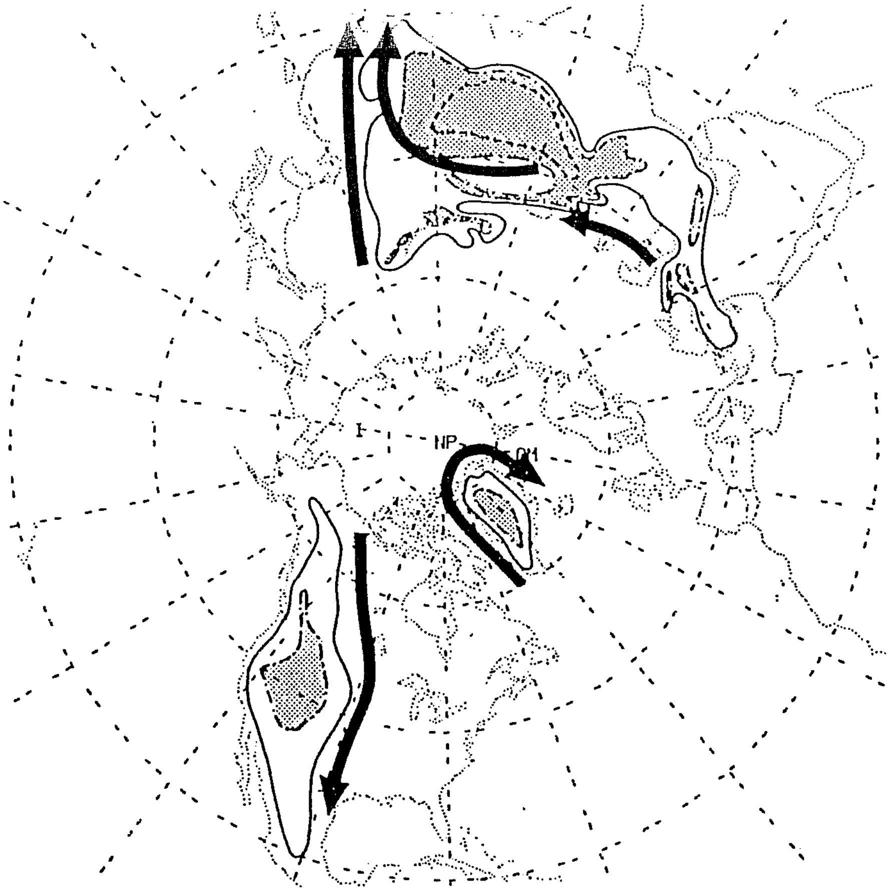


Fig.4 Location of observed topographic waveguides in the Northern Hemisphere. (From Hsu, 1987).

A flow with mesoscale characteristics (low-level jet or surface front) incident upon a high mountain is more likely to trigger Kelvin waves, and in their non-linear phase such waves can transit to a gravity-current like pattern. Kelvin-waves and gravity currents have been linked with several storm systems that propagate along coastal mountain ranges and possess surge-like features, e.g. coastal lows in South Africa (Preston-Whyte and Tyson, 1973; Gill 1977) and southerly busters along the south-east coast of Australia (Baines, 1980; Coloquhoun et al , 1985).

4. OROGRAPHIC BREAKDOWN OF BALANCED FLOW

The flow incident upon a mountain is generally in a state of quasi-balance, but the response to meso-β scale orography can have a significant non-balanced buoyancy wave component. In effect there is an inter-scale linkage whereby the balanced synoptic-scale incident flow acquires via direct orographic forcing an unbalanced mesoscale wave response.

Boyancy waves play a role in the vertical transport of momentum, and the parameterization of the associated gravity wave-drag is an ingredient of many weather prediction and climate models. In turn the parameterization schemes are based, for the most part, upon heuristic idealized model studies. For example such studies usually assume a steady non-rotating setting, and thus the schemes do not incorporate a time-lag effect and eschew (perhaps justifiably) consideration of the inter-scale link arising from the modification of balanced flow incident upon synoptic-scale orography. The former limitation might be alleviated in an ad-hoc fashion, and the latter provides the motivation for the following remarks.

An airstream of uniform velocity and stratification incident upon an isentropic ridge has a balanced flow reponse that is characterized by : an evanescent structure in the vertical; a slackening of the wind up- and down-stream of an orographic crest; and a speed-up and strengthening of the stratification over the terrain itself (Pierrehumbert, 1985; Davies and Horn, 1988).

The intensity of these features is prescribed by the dimensionless parameter (R_oF), where R_o and F are respectively Rossby and inverse Froude numbers defined by,

$$R_o = (U/fL) \qquad \text{and} \qquad F = (NH/U) \ .$$

with U and N denoting the upstream velocity and stratification, and L and H signifying the ridge's half-width and height. The intensity of the features increase with R_oF and become singular for $(R_oF) = (R_oF)_{crit}$ (see Table 1).

TABLE 1

Terrain Profile $\eta\ (x)$	Across-ridge Velocity $\{u_B\ (x, \theta)\}$	Breakdown Criterion Value of $(R_oF)_{crit}$
$\cos x$	$\{1 - (R_oF) \sin x\, [e^{-(RoF)\,\theta}]\}^{-1}$	1
$1/\{1 + x^2\}$	$\{1 - (R_oF)\, (\delta^2 - x^2)/(\delta^2 + x^2)^2\}^{-1}$	1
$(1/\pi)\{\tan^{-1}[(x + 1)/a]$ $- \tan^{-1}[(x - 1)/a]\}$	$\{1 - (1/\pi)(R_oF)[(x + 1)/\{\alpha^2 + (x + 1)^2\}$ $- (x - 1)/\{(\alpha^2 + (x - 1)^2\}]\}^{-1}$	$\sqrt{2}$ for $a >> 1$ $\pi/2^{3/2}$ for $a = 1$ $2\pi a$ for $a << 1$
$x/\{1 + x^2\}$	$\{1 - 2\, (R_oF)\, x\, \delta/(\delta^2 + x^2)^2\}^{-1}$	$8/3^{3/2}$

Formulae for the semi-geostrophic across-ridge velocity field and the breakdown criteria for various terrain profiles. The parameters " δ" and "a" are defined by $\delta = \{1 + (R_oF)\, \theta\}$ and $\alpha = \{a + (R_oF)\, \theta\}$.

At sub-critical flow settings and in the hydrostatic Boussinesq limit it can be shown (Horn and Davies, 1988; Davies, 1995) that the non-balanced residual flow response satisfies, on neglecting its self interaction, the following equation

$$\{(R_o^2\, u_B^3)\, m'_{xx} + m'\}_{\theta\theta} + (R_oF)^2\, m'_{xx} = -\tfrac{1}{2}\, (R_oF)^2\, R_o (u_B^2)_{xx} \ , \tag{3}$$

subject to the lower boundary condition,

$$m'_{\theta}(x, y, \theta_{bottom}) = 0 \tag{4}$$

Here potential temperature (θ) is the vertical coordinate, the suffixes x and θ signify derivatives, and m is the system`s non-dimensional equivalent of the Montgomery streamfunction.

Eq. (3) is a forced steady-state wave transmission equation that includes the modification of the refractive index due to the non-uniform flow field, and its non-homogeneous term corresponds to the forcing of residual flow by the balanced-flow. The structure of this forcing is evanescent in the vertical (see Table 1), and its horizontal structure (see Fig. 5) exhibits substantial scale-contraction relative to the terrain whilst its amplitude increases rapidly as $R_oF \rightarrow R_oF_{crit}$

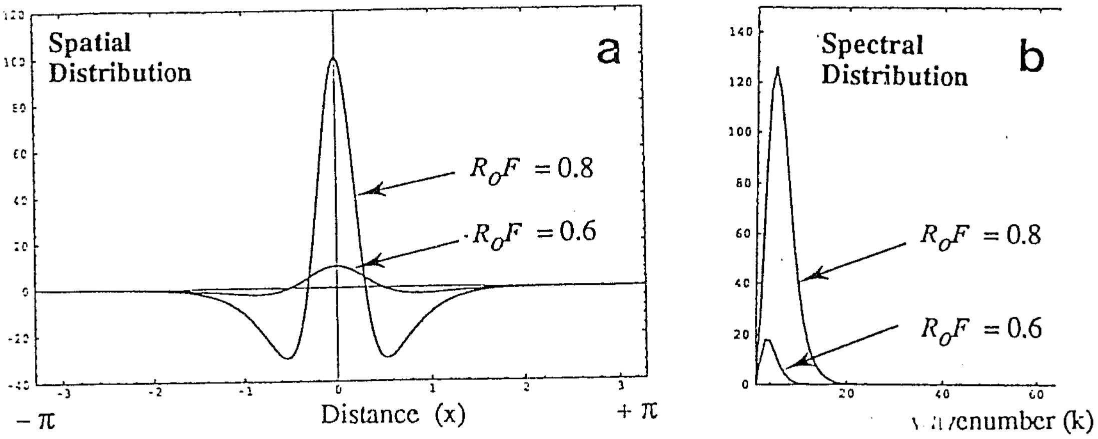


Fig.5 Surface distribution of the $\{-1/2\,(u_B^2)_{xx}\}$ component of the residual equation`s forcing term for flow over cos (x) topography. Depictions in (a) physical and (b) Fourier-space for two values of R_0F.

Intrinsic to the solution of Eq.(3) is a component sustaining vertically propagating inertia-buoyancy waves and quasi-horizontally propagating near-inertial waves. This follows from noting that the horizontal scale-contraction results in forcing of residual flow in the buoyancy wave part of the spectrum, and that the modified transmissivity due to the strong low-level speed-up can substantially broaden that wavenumber band locally amenable to vertical propagation. As a wave in the latter band propagates through the low-level region of reverse shear it will encounter a critical location $U = U_{crit}$, where $(kL) = fL/U_{crit}$. In the process its amplitude increases and thereafter will advance quasi-horizontally downstream as an inertial wave (c.f. Eliassen, 1968; Eliassen and Thorsteinsson, 1984), and moreover each wave attains criticality at a different location.

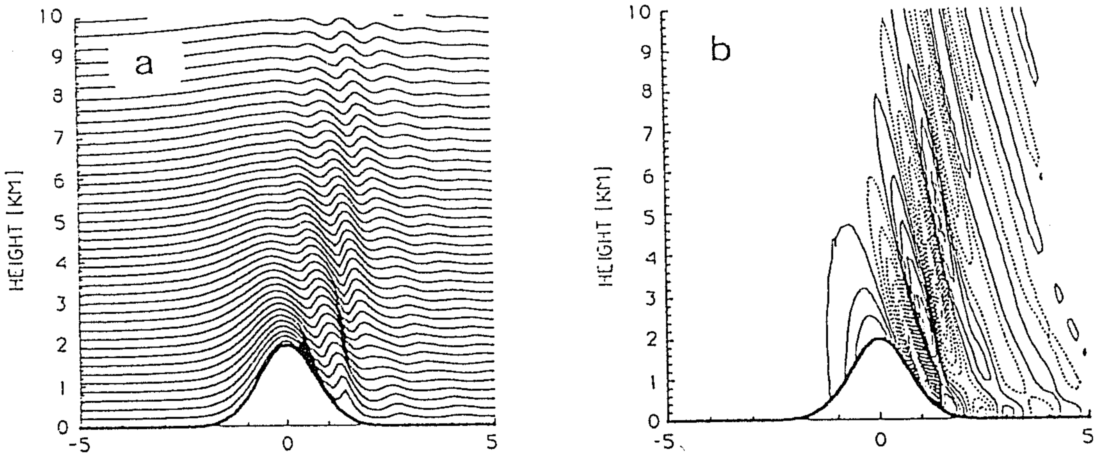


Fig.6 Quasi-steady flow over a bell-shaped ridge for the parameter setting of (Ro, F) = (1/4, 2). Displayed are the cross-sectional distribution of : - (a) the isentropic displacement field, and (b) the divergence patterns. (For this terrain profile $R_0F_{crit} = \pi^{1/2}/2$ - Pierrehumbert, 1985)

These inferences are supported by simulations performed with a nonlinear numerical model, and Fig.6 depicts results for flow over a Gaussian shaped ridge at a near-critical parameter setting. Two significant non-balanced flow components are evident - a steeply-inclined inertia-buoyancy wave-train tracking into the interior away from the neighbourhood of the crest, and a low-level near-inertial wave component. Thus there is appreciable buoyancy wave generation emanating from a terrain whose length-scale ($R_0<<1$) is indicative of balanced flow.

This highly idealised flow configuration illustrates the generation of unbalanced flow in a low Rossby Number setting, although the response could be significantly modified by planetary boundary layer effects.

5. INCIDENT SYSTEMS, CONVECTIVE SYSTEMS AND OROGRAPHY

In the previous two sections examples were presented of comparatively transparent 'synoptic-mesoscale' links. The physical mechanisms were related predominantly to buoyancy generation via advective effects, and cloud-diabatic effects were not pre-eminent. In contrast many orographically-related mesoscale systems involve an interplay of many mechanisms, and are often dominated by convective processes. It is systems of this kind that are considered in this section, and the two examples both involve heavy precipitation on the Alpine southside.

5.1 A Synoptic Precusor of a Mesoscale Storm

Heavy precipitation events on the Alpine southern slopes are invariably preceded at upper-levels by a distinctive upper-level precursor pattern (Massacand et al., 1997). It takes the form of an elongated and deep PV-streamer extending quasi-meridionally to the western Mediterranean. The streamer's evolution is characterized by a slow eastward translation (Fig. 7), and heavy precipitation ensues as the streamer approaches the Alpine ridge. The mean potential vorticity in the 500-150 hPa layer immediately prior to three severe precipitation events is shown in Fig. 8 (from Massacand et al., 1997). There is a striking case-to-case similarity in the PV-pattern, and this is corroborated by the examination of numerous further events.

There are distinctive dynamical links between the PV-streamer and the Alpine precipitation event. First the Alps are located at the south-eastern extremity of the Atlantic storm track, and are thus at a location that is favourable for the occurrence of the forementioned form of streamer. Secondly the streamer can play a dual role in instigating the convective event. Its strength, depth, temporal coherency and slow westward drift connotes a significant and sustained mesoscale enhancement of the low-level, southerly, pre-frontal airflow impinging upon the main Alpine ridge (c.f. lower panels of Fig. 8), and there is a predilection for ascent to develop on its forward flank.

The foregoing suggests that the PV-streamer is an ubiquitous and dynamically active precursor of rain-storms on the Alpine southside.

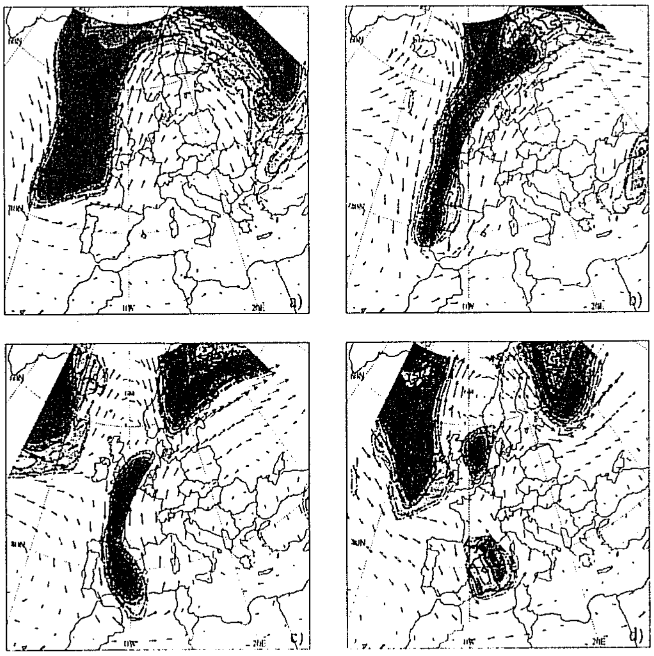
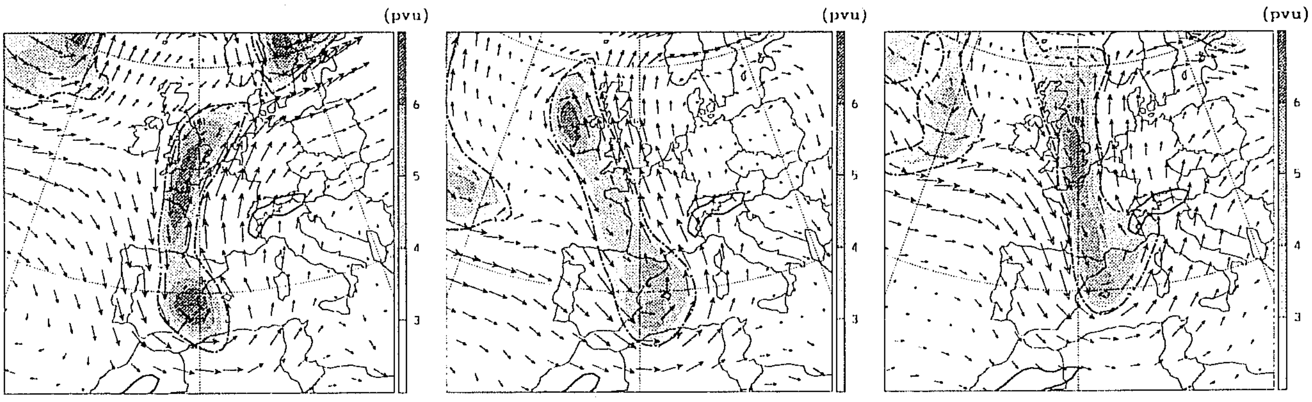


Fig. 7 A sequence of 320K isentropic charts (at 12 hourly intervals from 00UTC Sept. 21) depicting the potential vorticity pattern and wind field in the run-up to the heavy precipitation associated with the Brig storm.



(a) Brig (b) Piedmont (c) South Ticino

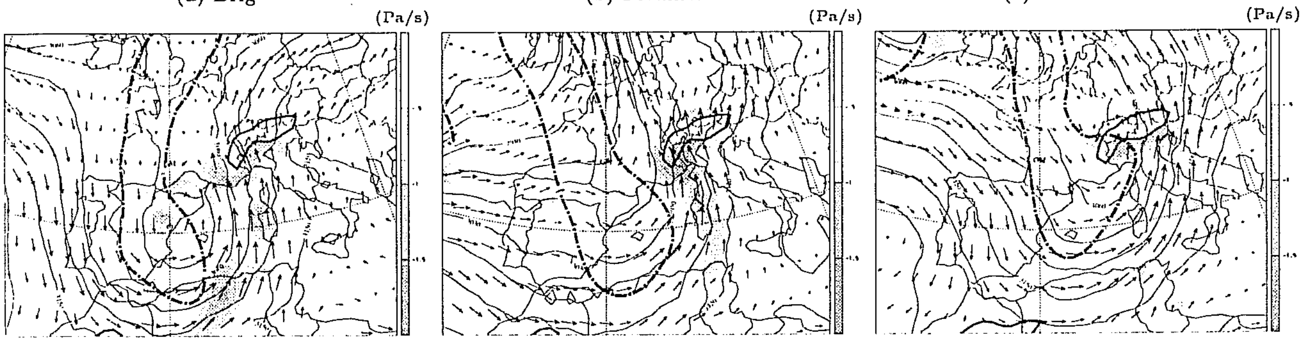


Fig.8 Pre-storm patterns over Europe pror to Brig, Piedmont and South Ticino events.

Upper Panels : mean potential vorticity in the 500-150 hPa layer and the airflow at 200hPa. Lower Panels: the wind field, geoptential height distribution and regions of significant ascent at 700hPa. The thick dash-dotted contour is the 3pvu isoline of the mean potential vorticity. (From Massacand et al, 1997).

5.2 An Multi-Component Linkage

The narrow quasi-meridionally aligned PV-streamers considered in the previous sub-section often cut-off to form isolated PV-anomalies (Appenzeller et al., 1996). Moreover such cut-off features often accompany Alpine lee-cyclogenesis (see e.g. Bleck and Mattocks, 1984; Pichler et al., 1990).

A streamer's break-up can result from a self-development of the streamer in the mature or post-mature phase of a baroclinic wave (Thorncroft and Hoskins, 1990), or from a balanced flow instability associated with the presence of an elongated maximum of potential vorticity on an isentropic surface (Appenzeller and Davies, 1992). However the frequent development of upper-level PV-anomalies in the near vicinity of the Alps also prompts the speculative inference that the break-up could be a 'synoptic-mesoscale' link involving orography.

To pursue this idea further a study was made of a break-up in the vicinity of the Alps and numerical model experiments undertaken of the event (Morgenstren and Davies, 1996). A 12-hourly sequence of the PV-distribution on the 315K isentropic surface from 00 UTC 9 June 1994 (Fig. 9) suggests that the streamer's southern extremity detaches to form an isolated anomaly over the western Mediterranean whilst the remainder of the streamer withdraws somewhat to the north.

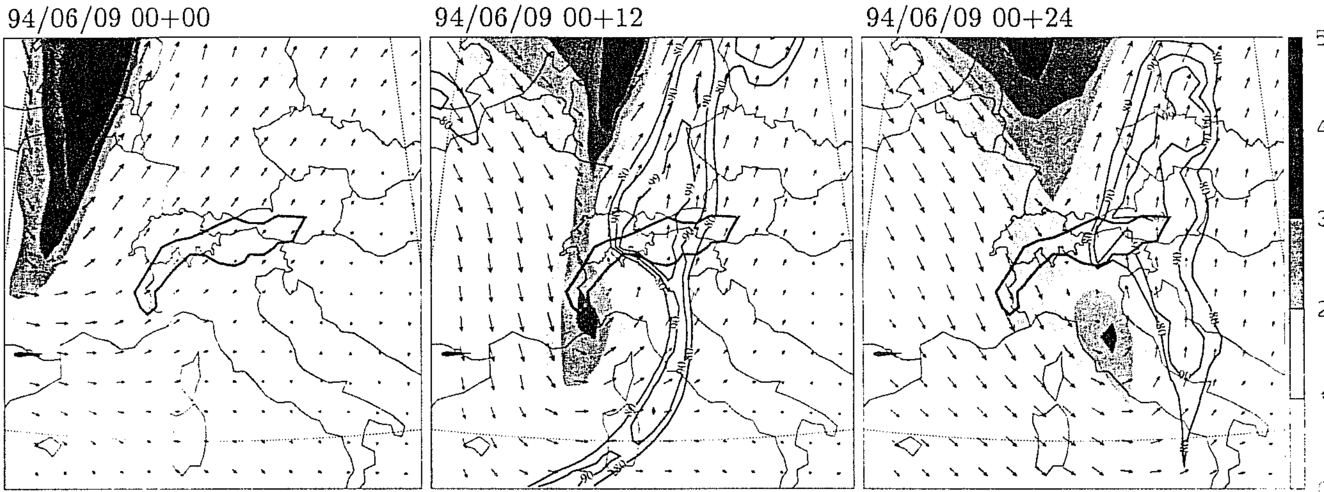
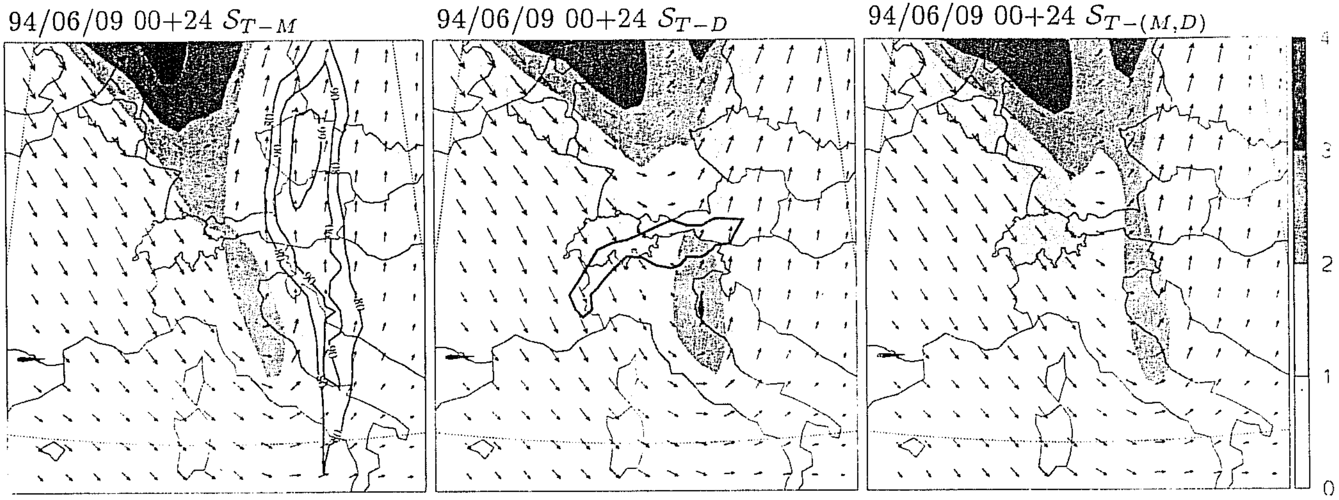


Fig.9 A 12-hourly sequence (from 00 UTC 9 June 1994) depicting the PV-distribution (shaded), the wind field, and relative humidity (80, 90, 100% contours) on the 315K isentropic surface.

In this case again warm moist air is advected north-eastward toward the Alps in the lower troposphere and there is a prolonged period of deep convection and heavy precipitation over the southern Alpine slopes.

The accompanying model experiments were designed to test the hypothesis that the approach of the streamer toward the Alps triggers a chain of events that favour the streamer's break-up (Morgenstern and Davies, 1996). First the streamer contributes to the advection of warm moist low-level airflow toward the Alps, and the resulting orographically-locked deep convection generates a sustained mid-level positive PV anomaly. Secondly the induced anomaly the incoming PV-streamer, and in particular prompts the further distention of the filamentary structure.

The experiments comprise a sequence of 24-hour simulations with a version of the EM limited area model of the DWD, and the PV-patterns displayed in Fig. 10 are from simulations undertaken with a reduced representation of the orography and / or the absence of diabatic processes.


94/06/09 00+24 S_{T-M}

94/06/09 00+24 S_{T-D}

94/06/09 00+24 $S_{T-(M,D)}$

Fig. 10 The equivalent of Fig (9c) but derived from 24 hour numerical model simulations performed with : -
(a) reduced orography; (b) dry model physics; and (c) both of the foregoing effects.

Both reduced orography and dry physics appear to inhibit the formation of a strong cut-off, and their combined effect contributes significantly to the formation of the cut-off. Further support for this intricate inter-scale link has been gleaned from additional simulations performed with a starkly idealized model incorporating (or omitting) the key orographic and diabatic ingredients.

6. SOME IMPLICATIONS FOR NWP

The dynamics of the orographically-related mesoscale phenomena discussed in the previous three sections is not well established, but it is nevertheless of interest to examine possible implications of these systems for the design of numerical weather prediction suites.

For the *orographically-confined waves* (Section 3) the requisites are that : the models should have an adequate resolution to represent the height and gradient of the terrain, the observational data should be adequate to capture the flow systems, and the initialization procedure should retain them. The horizontal resolution of present day high resolution models should be adequate, whereas the observation and analysis of low-level highly evanescent structures is not without its difficulties, and the task of accomodating large mesoscale pressure gradients in assimilation procedures is certainly challenging.

To illustrate the foregoing points consider the pseudo Kelvin-wave signal in the Alpine environment. In quiescent, but potentially unstable convective, conditions the modification that this wave would induce to the depth of the well mixed layer could contribute to the onset of convective activity and influence both the timing and location of such outbreaks. If the phenomenon can instigate weather then the forecast model would need to incorporate the global tidal signal (via the boundary and initial data) and simulate its orographic modification. Moreover the system's lateral pressure gradient is ~1 hPa per 100 km (- a geostrophic wind of 10 m s^{-1}).

The consideration of a *balanced flow's breakdown* (Section 4) as it impinges upon planetrary or synoptic scale orography might be construed to be adequately simulated by current models since both the flow and the orography are well represented in the models. However the nature of the breakdown has two other implications. First it indicates that balanced flow might not prevail even over synoptic-scale high terrain, and this might need to be acknowledged in the design of a mesoscale assimilation scheme. Secondly the breakdown occurs in a thin low-level layer, and it has the potential for generating significant vertical momentum transfer between atmospheric layers in addition to, or instead of, the traditional contribution to gravity wave-drag. The direct representation of the breakdown would require high vertical resolution. (Note that the representation of near-inertial waves require a very large value for the ratio between vertical to horizontal grid lengths!).

It could be argued, with some justification, that the realization of this form of flow breakdown requires the synoptic setting to remain steady for a significant time and that the breakdown might be accomodated by adjustments in the turbulent processes within the planetary boundary layer. (Caveats that also pertain to the establishment of traditional gravity wave drag patterns).

For the *Alpine precipitation system* considered in Section 5 there are prediction- and parameterization-related implications. The recognition that an upper-level PV-streamer is a precursor of Alpine southside rain storms invites the conjecture that "an adequate delineation of the strength, location and evolution of the streamer might be a prerequisite for the accurate prediction of the storm". This conjecture has been given some credence by the results of numerical model experiments that incorporated modifications to the initial structure of the streamer.

The hypothesis of an inter-scale linkage leading to a cut-off in the PV-streamer and involving the cloud-diabatially produced, orographically-tied, PV-tower is of some interest. For the Alpine region such a process would contribute directly to lee-cyclogenesis, but it could also be an integral feature of extratropical fronto- and cyclo-genesis. For extratropical cyclones and fronts the sustained, but propagating, region of ascent ahead of a surface front induces a PV-band in the lower troposphere, and this band would then interact with upper-level undulations and streamers of potential vorticity. For NWP the critical issues are that the parameterization of the cloud convection produces a 'balanced' PV-tower with the appropriate form and on the correct time scale.

Acknowledgments
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