Alpine Frontal Interception And Lee Cyclogenesis

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Chapter 1

INTRODUCTION

The passage of a strong baroclinic zone with a concomitant surface cold front onto the European Alpine complex illustrates the impact of a major mesoscale orographic feature upon an internally induced sub-synoptic flow system. Such an event is observed to engender, or is accompanied by, a rich variety of flow phenomena that can include pre-frontal Foehn and post-frontal blocking on the northern foreland, stark changes in frontal progression over and on the fringe of the orography, and the contemporaneous southward extrusion toward the Alps of a high level PV streamer and the comparatively rapid development of cyclogenesis on the southern lee-side. In recent years the detailed observation of these orographically induced effects has formed key ingredients of the field programmes of ALPEX (see e. g. Kuettner, 1982) and the Alpine Fronts Experiment (Hoinka and Volkert, 1987). These programmes in turn have resulted in the compilation of additional statistical-climatological surveys of such events, the preparation of numerous diagnostic case studies and the formulation or crystallization of several hypothesis for the generation of the lee-cyclones. It is these studies that form the core material for the present review. We focus here upon the lee cyclogenesis and consider the accompanying orographically induced phenomena only from the standpoint of their contribution to the cyclogenesis.

Chapter 2

DIAGNOSED FEATURES OF LEE-DEVELOPMENT

2.1 Climatology and Classification

The earlier statistical analyses of cyclone frequency for the Mediterranean region and for the entire northern hemisphere have been respectively updated by Pichler and Steinacker (1987) and Whittaker and Horn (1984). These studies differ somewhat in their criteria for cyclogenesis but they all demark the immediate Alpine south-side, in particular the Gulf of Genoa, as a geographically confined but major cyclogenetic region with the Autumn through to the Spring constituting the most productive period. By way of illustration note that 40 cases of in-situ generation occurred in or contiguous to the Gulf during the 13 months of the ALPEX Observing Period (AOP), and 9 cases during the two months (March - April 1982) of the Special Observing Periode (SOP).

However despite this remarkably high cyclogenetic frequency, only weak signals register in the seasonally averaged flow fields (see e.g. the climatological atlas of Lau et at ,1981). These anaemic signals are attributable in part to the comparatively small scale and localised occurrence of Alpine lee cyclones but also reflect their somewhat weak amplitude e.g. during the ALPEX AOP the pressure decrease accompanying cyclogenesis was $\sim 7\,\mathrm{hPa}$ in the mean with $21\,\mathrm{hPa}$ for the most extreme event (Pichler and Steinacker, 1987).

Classification of lee-cyclone events in terms of synoptic pattern demarks two main categories (see e.g. Pichler and Steinacker, 1987). These categories correspond essentially to, the approach from the western quadrant of a surface front closely followed by a broad large amplitude upper-level trough, and the passage of a short wave trough embedded in a northerly or north-westerly upper airstream with an accompanying southward excursion of cold air at the surface. There is however a strong resemblance in the development and structure of the cyclones in the two categories, and this suggests that the dominant dynamical processes might not be significantly different. Other possible classifications include the separation of the lee-events into shallow and deep categories, and, somewhat more esoterically, whether lee cyclogenesis would have occurred even in the absence of the Alps. In reference to the former classification note that slightly less than half the lee-events during the AOP produced a cut-off at 500 hPa.

2.2 Flow Features

We consider in sequence the flow features that accompany the lee developement. Advection of a frontal system toward the Alps will serve to disturb pre-frontal features such as a low-level jet. This jet can at first be deflected around the western perimeter (Kurz, 1984). The strong deformation of the incident front itself as it entcounters the Alpine foreland is clearly illustrated in displays of sucessive isochrones of the surface location of the front. In assessing the apparent retardation it should be remembered that elevated (i.e. mountain) stations would register a delayed arrival of the front even if there were no orography. On the northern rim of the Alpine chain the immediate post-frontal cold air can rapidly develop an orographically bounded pressure surge that propagates eastward (Davies, 1986) and leaves a narrow ($\sim$ 150 km) high pressure pillow on the Alpine northside (see Chen and Smith, 1987). A possibly related feature is the enhanced rate of progression of the near-Alpine portion of the surface front (Hoinka and Volkert, 1988).

Coincident with the arrival of the front in the Alpine region the pressure in the lee begins to decrease and an incipient cyclone develops within the warm air ahead of the front. It has been mooted (Messinger and Pierrehumbert, 1986) that diabatic effects are probably of secondary importance during this phase since it is not usually linked to active cloud systems and significant precipitation. Also the across-ridge meridional flow tends to be comparatively weak (Radinovic, 1986; Binder et al, 1989). Case study (see e.g. McGinley, 1982; Steinacker 1984 b,c) and composite (Radinovic,1986) analyses indicate that the development in this phase is linked to the orographically induced deformation of the incident front with convergence and ascent in the warm air. There is also evidence (Reimer, 1986; Frenzen and Speth, 1986; Pichler and Steinacker, 1987) of a vorticity dipole aligned E-W across the Alps at this time with positive vorticity on the western flank. Another occasional occurrence during this phase is the development north of the Alps of a distinct wave feature on the transiting surface cold front (Kurz, 1984; Schar and Davies, 1989 a).

The second phase of the development is characterised by an upper level trough/potential vorticity streamer that propagates without retardation toward the Alps (Buzzi and Tibaldi, 1978; McGinley, 1986; Bieck and Mattocks, 1984). Under continued extension, the streamer cuts-off to form an isolated pool. A strong vertical coupling of the ageostrophic field occurs when the region of divergence on the foreward flank of the pool moves to overlie the low-level surface convergence zone. If the pool itself becomes aligned over the surface low then the disturbance acquires a vertically coherent cyclonic structure. Vorticity budget analyses of the cyclogenesis (Frenzen and Speth, 1986; McGinley, 1986) confirm the strong advective import of mid- and upper-level vorticity during this second stage, and likewise energy budget computations (Hantel, 1987) point to strong contributions of mesoscale diabatic effects.

Chapter 3

MECHANISMS AND MODELS

Bergeron (see Chromow,1940) commented that there were various competing theories to account for the generation of lee cyclogenesis. The situation has not changed. Here we first catalogue a range of possible cyclogenetic mechanisms and then proceed to discuss the various hypotheses.

3.1 Mechanisms

Let us assume that the main aspects of the lee-cyclogenesis are adequately, or at least qualitatively captured, by the dynamics of balanced-flow. The bravado of this assumption is transparent - the response to steady incident flow upon the Alpine scale topography is itself not yet clearly understood. Consider then the processes capable of generating stream function patterns of closed cyclonic circulation. A local maximum of relative vorticity will herald such a pattern provided the induced velocity can somewhere fully offset the ambient mean flow. (Note, as a benchmark reference, that to counter a $10\,\mathrm{ms}^{-1}$ airstream a circular region of uniform vorticity (ζ) and a diameter 800 km requires $\zeta \geq 2.5f$!)

Mechanisms for the generation of such a local maximum include

(i) vortex stretching either due to the internal dynamics or to orographic forcing,

(ii) redistribution of the PV distribution so as to form a local PV pool. The pool would need to be disentangled from a larger reservoir such as the stratosphere, a large scale warm surface anomaly, or a strip PV distribution associated with, say, a front or pre-frontal low-level jet,

(iii) internal diabatic heating with positive PV generation beneath the maximum in the diabatic heating rate, and

(iv) frictional effects (e.g. the possibility of PV generation associated with orographically induced flow separation).

Further note that in the vincinity of orography a low-level closed stream function pattern can develop locally even in the absence of a maximum of relative vorticity if: -

(v) flow blocking effects prevail below the crest level of the orography, and in effect induce 'mirror-image' vorticity effects.

The realized lee-cyclogenesis will involve some, or all, of these mechanisms.

3.2 Models

There is a current spate, if not surfeit, of hypotheses relating to Alpine lee cyclogenesis. The most long-standing is a conceptual model comprising of various embellishments or reclading of the schematic of von Ficker (1920). It is phenomenological in character with low-level blocking and unimpeded progress of the upper-level trough/PV streamer being regarded as the salient features. It is inferred (e.g. using **Q** vector arguments) that the blocking will induce low-level development within the warm air on the secluded lee side of the orography, and this feature is subsequently augmented by, and indeed enhances the effect of, the arrival of the upper-level PV streamer (Mattocks and Bleck, 1986). This sequence involves mechanisms (i) and (ii) and is reminiscent of and can be viewed as an adjunct of a Type B development (Petterson and Smebye, 1971). The formation of the incipient surface cyclone sometime ($\sim 12\,\mathrm{hr}$) prior to the arrival of the elevated PV pool constitutes the quintessential difference. It is difficult to gainsay such a palpably observationally based model but this qualitative description does not provide insight on the dynamics of the first stage nor account for the seemingly immanent timely breakaway of a PV streamer directly toward the Alpine region. Another conceptual model gives preeminence, by analogy with smaller scale flow systems and laboratory analogue experiments, to possible flow separation (Mechanis (iv)) and the shedding of cyclonic lee vortices on the western Alpine fringe (Boyer et al 1987; Baines and Steinacker, 1987). In this context it is necessary to distinguish between frictionally induced and apparent inviscid flow separation.

Deductive models of lee-cyclogenesis based upon an examination of the orographic modification of conventional baroclinic instability have been advanced by Pierrehumbert (1985) and Sperenza and his colleagues (see e.g. Sperenza et al, 1985; Buzzi et al 1987). In the first study the barrier effect of the orography is modelled by inserting a vertical slot at low-levels. This obstacle is shown to force a tangentially incident baroclinic trough-ridge wave train to generate successively low (high) cut-off features on the southern (northern) side of the slot. (The generation of these features has been attributed by Davies and Schär (1986) to the action of Mechanism (v)). The second type of study (e.g. Sperenza et al, 1985) indicates essentially that for low orography and their considered flow configuration the modifying effect experienced by the baroclinic wave comprises the generation of additional positive (negative) relative vorticity within the wave train where the flow is directed off (onto) the orography. Note that here the orographically induced vorticity changes are due to vortex stretching and shrinking (mechanism (i)) as individual air parcels traverse either on or off the terrain, and that in a more general context the response would be influenced by the necessity for individual air parcels to ride both on and off the mountain. Upstream blocking and lee descent is a possible, but not always realized, way of circumventing this restriction. In the context of lee cyclogenesis the rationale for examining the modifying influence of orography upon classical growing baroclinic waves is weakened if the environment is that of a mature or decaying wave or is more akin to a Petterson Type B situation.

Another deductive model applied to lee cyclogenesis is that of Smith (1984, 1986). The core ingredient is that balanced flow response of a steady baroclinic airstream incident upon orography can include a stationary lee-side trough if the flow has a backward shear. The synoptic conditions that accompany a front moving from the NW quadrant toward the Alps with an associated NE-SW aligned baroclinic zone match, at least transiently, the requirement of backward shear.

State of the art numerical weather prediction models and mesoscale research models have also proved to be fruitful tools in the study of lee cyclogenesis. For instance simulations undertaken with the NWP models using real data suggest that the orography is not always a key component in some lee-cyclogenesis events (Mesinger and Strickler, 1982; Pham,1986; McGinley and Goerss, 1986), parameterised cloud-diabatic effects modulate rather than dominate the development (Dell'Osso and Radinovic, 1984; Tibaldi and Dell'Osso, 1986), the orographic contribution induces a synoptic scale high-low dipole pattern across the Alps (see e.g. Tibaldi and Buzzi, 1983). Also the seemingly successful simulation of the cyclogenesis with over-broad (but reasonably high) representations of the Alps is an indicator that the development might not depend sensitively upon hyper-ageostrophic effects.

Again the research models have helped underline the significant contribution of the orographic barrier effect and/or shape of the orography (see e.g. Dell'Osso, 1984). These non-linear numerical models also serve as a tool for examining the various hypotheses associated with the forementioned conceptual and deductive models. Tafferner (1986, 1988) and Mattocks and Bieck (1986) provide examples of the development toward vertical co-alignment of the surface circulation and the upper-level PV distribution. Again the simulation of lee cyclogenesis with essentially inviscid research models suggests that the observed lee-side flow separation is not necessarily a frictionally induced effect. Also Egger (1989), Schär and Davies (1989b), Bratseth and Breivik (1988) examined the efficiency in the finite-amplitude regime of the foregoing deductive hypotheses. Egger simulated a lee-cyclone using a level primitive equation model and then in a series of experiments adjusted the initial conditions to match respectively the three deductive-theoretical models. In each of these cases his simulations failed to produce a lee-cyclone of significant amplitude. Schär and Davies used a quasi-geostrophic model to trace the response of the orography upon an incident baroclinic zone and reproduced a two phased lee development. In the first phase there was substantial frontogenesis to the south west with mild but rapid surface development. Non-linear effects and the finite lateral width of the baroclinic zone served during this time to substantially enhance the response due to the backward shear effect. In the second phase there was further development that linked upper and lower level cyclonic features in the model and the associated growth rate exeeded that of conventional baroclinic instability theory. Discrepancies between the results of different numerical models are a salutory reminder that none of the foregoing numerical models can provide a definitive reproduction of the observed flow sequence. The assessment of the resulting simulations should be tempered accordingly.

The significance of the sequence of flow phenomena that accompany the passage of a cold front onto the European Alpine complex lies in the example it provides of large amplitude, intricate, inter-related synoptic and sub-synoptic dynamical processes. The various hypotheses for lee cyclogenesis point to the rich range of possible orographic effects, and illustrate neatly the form and limitations of three current general approaches to the study of atmospheric dynamics.

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