OBSERVATION AND MODELLING OF LEE CYCLOGENESIS

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Summary: Lee cyclogenesis, as observed in various parts of the world, is a well documented phenomenon which has posed difficult theoretical as well as forecasting problems. A review of recent advances in observational and numerical modelling is provided, with particular emphasis on Alpine lee cyclogenesis. This particular phenomenon, which is the most frequently observed manifestation of orographically induced cyclogenesis, has been thoroughly investigated in the context of the Alpine experiment of GARP. The observational and numerical achievements are discussed with reference to the progress made in the understanding of this phenomenon. Finally, the possible relationships between Alpine cyclogenesis and other types of orographic cyclogenesis are discussed.

1. INTRODUCTION

The concept that extra-tropical cyclones develop as a result of an intrinsic instability of the atmospheric circulation is widely accepted in dynamic meteorology. The leading process has been identified, after Charney (1947) and Eady (1949), as the baroclinic instability of a sheared current. The basic formulation of the theory has received substantial improvement over the last thirty years. While the linear problem has been generalized to more realistic basic state flows, the non-linear problem has been tackled with an increasing degree of complexity, including dynamical analysis of chaotic regimes. Numerical models have been used extensively to explore formulations of the baroclinic problem, inaccessible to analytical treatment.

The baroclinic instability problem essentially depends on the boundary conditions. Topographic variability enters the problem as a lower boundary condition. We shall see that orographic cyclogenesis is a phenomenological manifestation of the sensitivity of the baroclinic atmosphere to surface reliefs. In this paper, I will mainly consider the observational and numerical aspects of this phenomenon. The theory is examined by Speranza (1986, this Volume).

That terrain characteristics are important in determining cylogenesis and cyclone paths has long been recognized in synoptic meteorology (see, for example, Ficker, 1920) but progress in the understanding of the different processes associated with topography (flow diversion, roughness variations, elevated heat sources and sinks, etc.) has been rather slow. Mountains and ocean-continent contrast induce "stationary" planetary waves that destroy the zonal symmetry of the long-time mean flow. This asymmetry, in turn, affects the spatial distribution of cyclogenesis frequency and of cyclone tracks (see, for instance, Manabe and Terpstra, 1974). However, this is not the sole effect of mountains on cyclonic scale disturbances. Mountains have also a strong direct influence on baroclinic instability modes in the sense that they locally affect, through flow diversion and blocking, the spatial structure, rate of growth and propagation of these synoptic scale disturbances.

Due to unsatisfactory explanations, forecasting orographic cyclogenesis has long been a difficult task. The advent of numerical forecasting models did not substantially alleviate this problem until very recently, largely as a result of the difficulties encountered in properly representing orography in models (Mesinger, 1985).

An impressive indication of the impact of orography on cyclogenesis comes from Petterssen's (1956; Fig. 1) classical map of cyclogenesis frequency in the Northern Hemisphere during winter. While the frequency of cyclogenesis over the mid-latitude oceans is relatively high but rather uniformly distributed, definite peaks of limited spatial extension occur in proximity of the mountain ranges, generally from east to south of them. Examples of frequency maxima to the south of orography are noted in the Mediterranean and in the Gulf of Alaska. The similarity between these two types of cyclogenesis will be discussed below. Maxima of cyclogenesis tend to occur to the east of mountains when these extend in a mainly latitudinal direction, as in the case of the Rockies. Orographic influence cannot be excluded (although other factors, such as enhanced baroclinicity and oceanic heat source, are important) also for the cyclogenetic areas off the east coasts of Asia and North America, where mountain ranges of moderate height are aligned from north-east to south-west. Other authors have extended and refined these hemispheric statistics (Klein, 1957; Whittaker and Horn, 1982). For regional scale, more detailed statistics of cyclogenesis, see also Radinović and Lalic (1959, summarized in Kuettner, 1982) and Radinović (1965 a), for the Mediterranean; Chung, Hage and Reinelt (1976) for East Asia (where Petterssen's analysis suffers from data scarcity) and North America; Chung (1977) for South America.

It is worth mentioning that the statistics referred to above should be viewed with some caution because of the uncertainty and subjectivity in the definition of cyclogenesis (Speranza, 1975). This definition is based on the appearance of closed isobars at the surface, with different intervals between isobars chosen by different authors. The criterion appears in some cases too wide, so that, for example, shallow thermal lows not evolving into active cyclones might be mistaken for cyclogenesis. Nevertheless, a firm conclusion that can be derived from the above analyses is that the spatial distribution of cyclogenetic frequency is very unevenly distributed near mountains. This is equivalent to saying that mountains strongly influence the place (if not time) of development. The highest

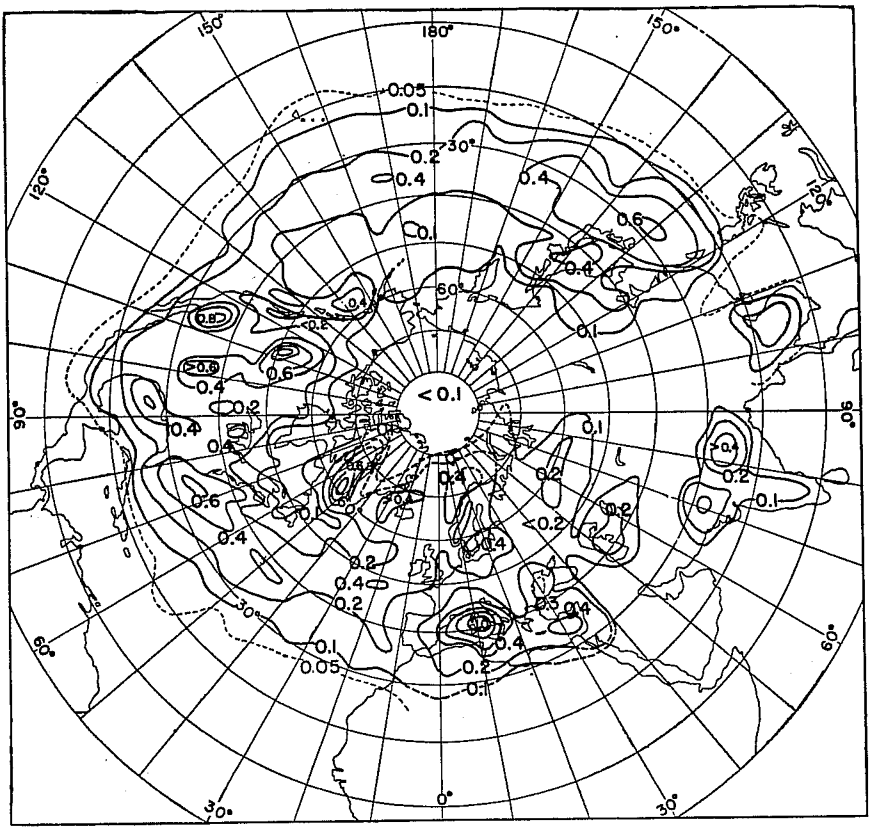

Fig. 1 Percentage frequency of cyclogenesis in squares of 100,000 km2 in winter (Petterssen, 1956).

frequency of cyclogenesis is observed "in the lee", where "lee" is usually intended with respect to some mean flow. This word needs further clarification in dynamical terms: for the moment, "lee cyclogenesis" will be used simply as a synonym of orographic cyclogenesis, meaning with this that the neighbouring orography is essential in determining location and/or timing of cyclone growth. In this definition, I have chosen to include cases of cyclonic re-intensification when passing over or near mountains, since lee cyclogenesis is often a secondary cyclogenesis, as will be discussed below. It is obvious that, to become operative, such a definition requires the existence of numerical models apt to run parallel experiments with and without mountains.

Fig. 1 shows that the most prominent and best isolated maximum of cyclogenetic frequency corresponds to the area characterized by Alpine lee cyclogenesis, i.e. the Western Mediterranean. Observation and understanding of this particular phenomenon, together with the study of related orographic effects, were the main objectives of ALPEX, whose field phase took place in 1982. The observational, numerical and theoretical work related to ALPEX has led to substantial progress over the last few years. For this reason, Alpine cyclogenesis is the main subject of this review, with particular attention given to the post-ALPEX results (see also Mesinger and Pierrehumbert, 1986). Extensive reviews by Speranza (1975), Tibaldi (1980) and Buzzi and Speranza (1983) provided a good summary of the pre-ALPEX work (see also Kuettner, 1982).

Other types of orographic cylogenesis will be discusssed more briefly, emphasizing similarities with and differences from Alpine cyclogenesis.

2. BASIC PHENOMENOLOGY OF ALPINE CYCLOGENESIS

A considerable number of depressions form in each year near the surface in the region south or southeast of the Alps. As mentioned above, not all

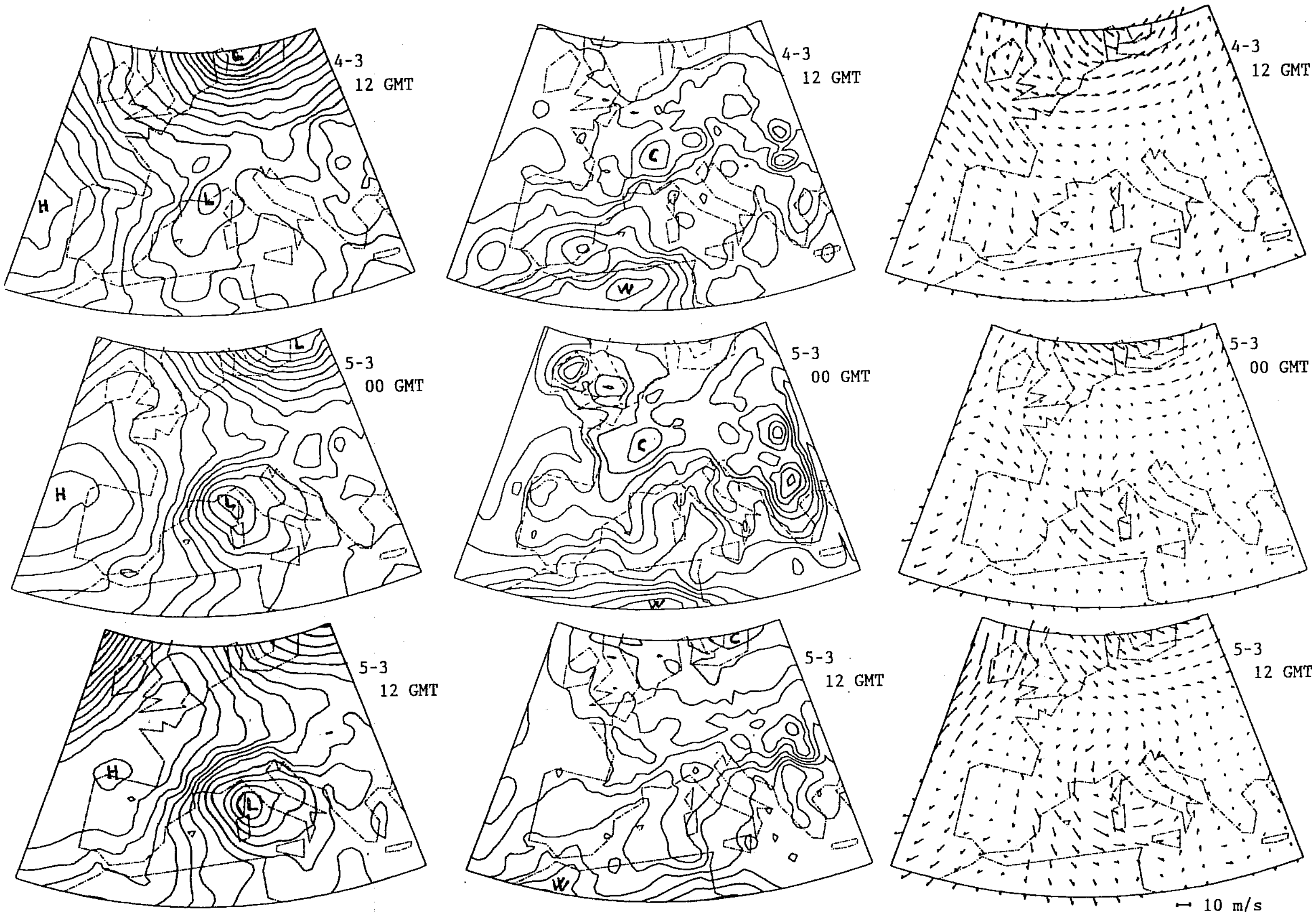

Fig. 2 Sea level pressure (2.5 hPa interval, left), sea level potential temperature (2 K interval, middle) and surface wind (plotted every 2 grid points, right) for the cyclogenesis of 4-5 March 1982.

cases can be classified as "true" lee cyclogenesis. For the 13 months of the extended ALPEX Observing Period, Pichler and Steinacker (1986) have counted 40 cases they consider, on an empirical basis, as orographically induced cyclogenesis, having excluded thermally induced lows and lows moving from south-west or south towards the Alps. Weak cases are, however, included in this classification. About ten to twenty cases per year can be considered (with some arbitrariness) as moderate or strong lee cyclones. During the ALPEX Special Observing Period (SOP: March-April 1982), 6 to 8 cases of orographically induced cyclones (an objective evaluation of the topographic effects is not yet available for all cases) occurred in the Alpine area (Radinović, 1985; Buzzi, 1986).

The mobility of the lee cyclones is variable, but usually those which grow in place or move very slowly attain the largest strength and vertical extension (Illari et al., 1981), as occurred in the ALPEX event of 4-5 March 1982 (Fig. 2). In these as in other similar cases (see Illari et al., 1981; Tibaldi and Buzzi, 1983), the mature stage is associated with the establishment of a split westerly flow over Europe. In the initial stage of growth, the apparent displacement of lee cyclones near the surface tend to be very small in any case (Radinović, 1985).

As already observed by the earlier investigators, the initial depression appears in the lee of the Alps ahead of,rather than on, a cold front, reaching the mountain range from a direction between west and north. The first stage of growth is also not associated with extensive cloud systems and precipitations; usually, these gradually develop together with the cyclone growth. As noted by Mesinger and Pierrehumbert (1986), these factors seem to eliminate sensible heat flux, frontal instability and latent heat release as main factors in initiating the development.

A feature which does seem to be important in the initiation of the lee cyclone is the interaction of the cold front with topography, resulting in cold air "damming" on the windward side of the Alps, retardation of cold advection in the lee and distortion of the frontal structure, with frontogenesis above the mountain and a positive thermal anomaly forming in the lee at low levels (Radinović, 1965 b; Buzzi and Tibaldi, 1978). A deepening trough aloft, associated with an upper level jet maximum pointing towards the Western Mediterranean, was also identified as another key feature conducive to deep lee cyclones (Reiter, 1963; Danielsen, 1973; Buzzi and Tibaldi, 1978, to quote a few). Rapid pressure fall near the surface occurs when the front-left quadrant of the advancing jet is located above the region between the Alps and the Pyrenees. The upper level flow is altered, in turn, by the orographic influence: in the growth stage, jet splitting tends to occur north-west of the Alps, even at high tropospheric levels, and a cut off low over the Mediterranean is often the end product of strong lee cyclogenesis.

It is significant that both cold front and upper jet are usually part of the same pre-existing synoptic scale system: an approaching, often growing, cyclonic disturbance, possibly with various degrees of vertical organization. That is to say that Alpine lee cyclogenesis appears almost invariably as a secondary cyclogenesis, requiring the existence of a primary disturbance interacting with the Alps (Buzzi and Tibaldi, 1978; Buzzi and Speranza, 1983). In this respect, lee cyclones are more similar to a wave scattering process than to lee waves or vortexes created by an obstacle in an incident parallel flow. Lee cyclogenesis should not be confused with quasi-stationary, mesoscale disturbances of the "lee wave" type which are frequently observed when the basic low level flow is perpendicular to the mountain range (Buzzi and Tibaldi, 1978). This notion is the basis of the recent progress in our understanding of the process.

Buzzi and Tibaldi (1978), with simple scale evaluations, found two different stages in the growing process of the lee cyclone they analyzed. In the first, more rapid stage, the process is mesoscale in character and the orographic action is more evident. In the second, they recognized a more conventional process of baroclinic instability, during which a coherent cyclone develops on the synoptic scale. Buzzi and Tibaldi acknowledged the importance of the latter baroclinic stage in characterizing organized lee cyclones as opposed to shallow and short living depressions. They failed, however, to identify the role played by orography also in this stage. This role was first demonstrated by Tosi et al. (1983) as a result of extensive numerical experimentation in idealized conditions: the mountain was shown to be essential to determine location and strength of cyclone formation even after the initial stage associated with frontal deformation.

Here, it is worth noting that, starting from the pioneering work of Egger (1972), the contribution made to our understanding of Alpine cyclogenesis by the numerical experimentation is intimately related to that of the observational studies. For example, the identification of lee cyclogenesis with an essentially baroclinic process was already empirically noted by Egger (1972) and Trevisan (1976) in their numerical simulations. The importance of baroclinic conversion was then quantitatively evaluated, still in numerical experiments, by Tibaldi et al. (1980), and confirmed by McGinley (1982) diagnosing real data. Another important result of the numerical experiments is the identification of the scale and shape of the mountain-induced anomaly in cases of cyclogenesis. This anomaly appears in the geopotential field as a relatively simply structured dipole with high pressure north or northeast of the mountain and low pressure on the other side (see Speranza et al., 1985, and references thereafter). This is an example of a typical result which cannot be entirely derived from the observations but which has allowed substantial theoretical advances.

3. DISCUSSION OF RECENT OBSERVATIONAL RESULTS

ALPEX has provided an extensive data base, suitable, in principle, for quantitative analysis and diagnostics of lee cyclogenesis. In order to extract meaningful information, it is necessary to employ appropriate analysis schemes that can provide a consistent three or, possibly, four-dimensional description of the atmospheric states on scales at least of the order of the meso-α. Particular care is required to ensure an accurate evaluation of the effects of orography in the mass and wind fields (flow blocking and separation, divergence, pressure and temperature perturbations etc.). No satisfactory and well established analysis schemes existed to offer "official" gridded data of the so called III-b type to the scientific community. The development of suitable analysis schemes is part of the research connected with ALPEX. A brief summary of different analysis characteristics and methods is given here.

Isentropic analysis has been adopted by several researchers (see, e.g., Steinacker, 1984; Bleck and Mattocks, 1984; Buzzi et al., 1985; Reimer, 1986) in view of its advantages in describing mesoscale structures like fronts and jets and allowing direct computation of trajectories and potential vorticity. While Bleck and Mattocks (1984) and Reimer (1986) apply the optimum interpolation scheme, Buzzi et al. (1985; also Trevisan et al., 1985) use a simple univariate variational method, concentrating their efforts on producing an accurate description of wind and mass fields near steep mountains. The two latter schemes attain the finest resolution, with 50-60 km of mesh width.

Some degree of readjustment between mass and wind is generally applied, but no specific "initialization" procedure has been attempted to provide dynamically consistent analyses. An exception is the variational analysis scheme proposed by McGinley (1986; see also McGinley, 1984), which links the interpolated variables using nearly complete set of equations. This scheme utilizes pressure coordinates and, in the latest formulation, "step mountain" representation (Mesinger, 1984, 1985). Simultaneous satisfaction of the continuity equation, as a strong constraint, and of the momentum equations, as a weak constraint, are imposed to represent the mountain barrier effect and to minimize unrealistic momentum residuals. The velocity time tendencies are evaluated from 6-hourly ALPEX observations, but the "first guess" vertical motion has to be estimated from a form of the omega equation.

The large imbalances shown by McGinley (1986) to be present in the fields before the adjustment procedure is applied indicate the danger of attaching stringent physical significance to fields derived from univariate methods. On the other hand, further research is needed to test multivariate methods that include "initialization" procedures on the mesoscale. At present, quantitative diagnostics derived from objective (and subjective) analysis methods suffer from serious uncertainties when higher order quantities are evaluated on sub-synoptic scales. Moreover, no highly comprehensive diagnostic studies, based on ALPEX data, have yet been published. As a consequence, I have the impression that a well established and physically consistent observational picture of lee cyclogenesis has not up to now emerged from post-ALPEX diagnostics, though some confirmation of previous results and some new findings have come out. The case-to-case variability, well represented also in the limited ALPEX sample of lee cyclones (Frenzen and Speth, 1986; Buzzi, 1986), tends to obscure the common characteristics and to hinder the construction of a phenomenological model of general validity, particularly if the interpretation does not rely upon a theoretical scheme to be validated. For all these reasons, I adopt the theory proposed by Speranza et al. (1985; with also subsequent developments and extensions in Buzzi and Speranza, 1986; Malguzzi and Trevisan, 1986) as a working hypothesis for the critical examination of some of the observational results. I hope that the loss in "objectiveness" will be compensated by a more rational treatment.

As regards typological differences, Pichler and Steinacker (1986) identify two basic types of Alpine lee cyclogenesis (with the reservation that intermediate cases may also occur), according to the direction of the (local) upper level wind: a "south-westerly" type and a "north-westerly" type (see Fig. 3). In the first case we have an upper trough moving to the east in a large-scale mean westerly flow. The orographic action on

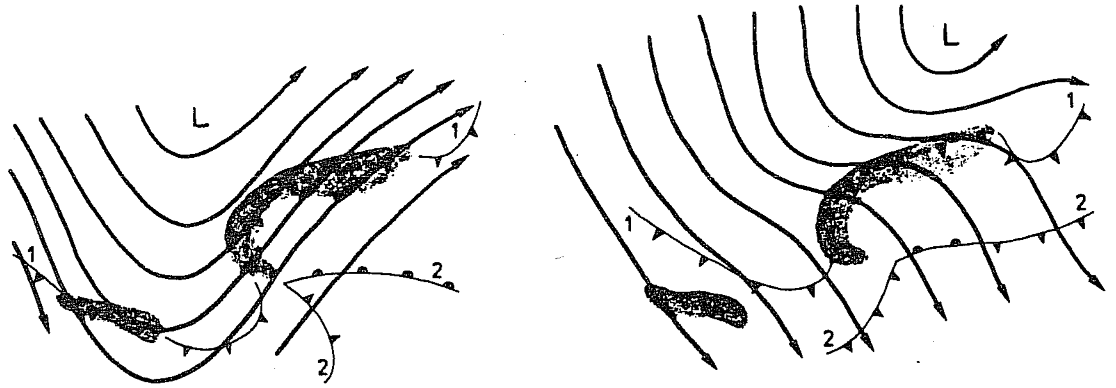

Fig. 3 Schematic patterns of upper level contour lines for the "south-westerly" (left) and "northwesterly" (right) types of Alpine cyclogenesis, after Pichler and Steinacker (1986). Alps and Pyrenees are shaded.

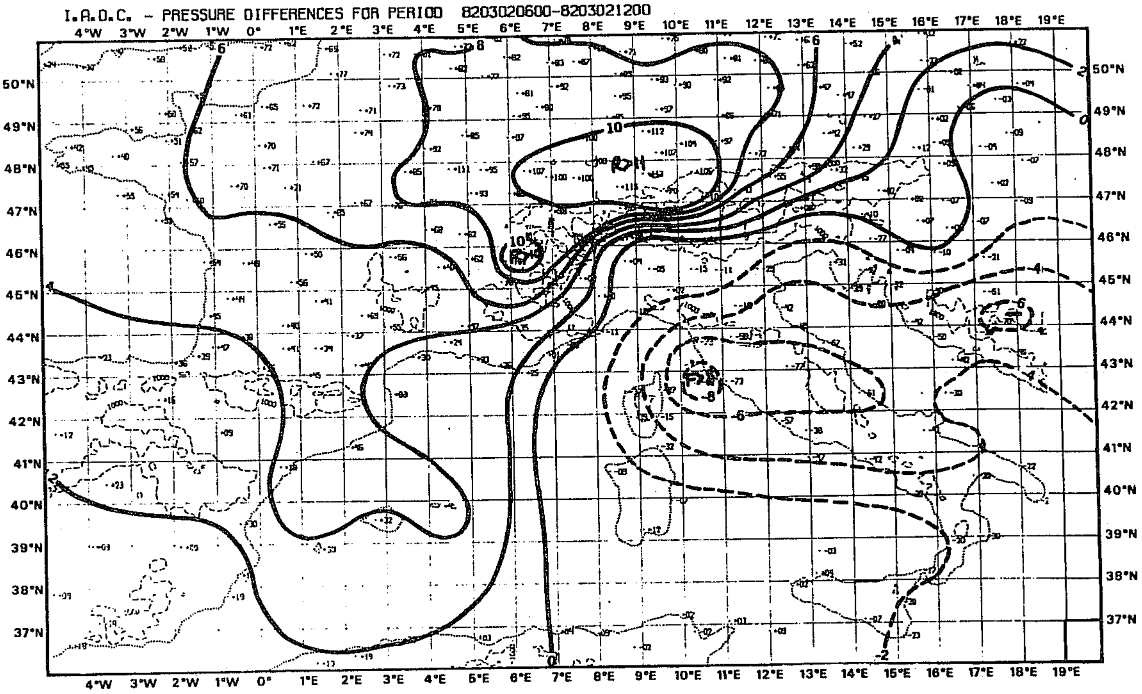

Fig. 4 Change in sea level pressure between 12 GMT and 06 GMT, 2 March 1982. Intervals of 2 hPa. (Radinović, 1985).

cyclogenesis is particularly evident if the trough is slow moving, as, for example, in the case of 4-5 March 1982 (Fig. 2; see also Dell'Osso and Tibaldi, 1982). In the second case, we have an upper disturbance travelling in a north-westerly, large-scale mean flow. Several ALPEX cases were of this latter type, as, for example, those of 20-21 March and 30 April 1982.

In the light of the theory mentioned above, these two types may be interpreted essentially by changing the direction of the mean large scale flow (or, more properly, thermal wind) with respect to the orientation of the mountain chain. The strongest orographic modification is predicted when the wave velocities are nearly perpendicular to the principal axis of the mountain, that is in the "south-westerly" type, in agreement with the observations. This is the type for which the theory of Speranza et al. seems most relevant, also because the primary wave moves rather slowly and, therefore, is under the orographic influence (not only of the Alps, but also of the Pyrenees: see Jansa and Ramis, 1982) for a longer time. At the opposite extreme, in a case of a wave embedded in an almost northerly basic flow (and northerly thermal wind - a situation typically associated with North Atlantic blocking), the disturbance is not expected to have strong interaction with the Alps, which are oriented essentially in the zonal direction. Such a case occurred during ALPEX SOP (24-25 April). Though a cyclone formed in the Gulf of Genoa, the role played by orography on its development, in accordance with the experiments performed by McGinley and Goerss (1986), appears to be marginal.

Radinović (1985) presents composite diagnostics based on eight cases of cyclogenesis ocurring during the ALPEX SOP. The "signal" obtained is probably partially masked by the averaging over different types, in accordance with the discussion above, including perhaps pseudo-orographic events. Nevertheless, Radinović identifies the following typical characteristics of these cyclones:

a) convergence in the lowest layers and upward motion dominate near cyclone centres in the developing stage.

b) thickness generally decreases in all layers, except in the low layers at the beginning where cold advection is obstructed below the mountain level. Warm air is drawn into the forward side of the cyclone, but a warm front can hardly be identified; the cold front, on the contrary, intensifies over the Alps, creating regions of large thermal gradients (see also Buzzi et al., 1985); later, however, baroclinicity decreases.

c) pressure tendency near the surface is opposite north and south of the Alps, exhibiting strong tendency gradient across the relief (Fig. 4).

d) kinetic energy increases in a fixed volume embracing the cyclone, the main contribution being the net flux from the boundaries.

e) the low level vorticity increase starts when cold air deflection around the obstacle and augmentation of baroclinicity produce negative thickness vorticity below mountain top level; the vorticity advection aloft is small initially but rapidly increases when the upper trough moves over the region of the low level cyclone.

Some of these features (b and e, in particular) are identified by Radinović as being distinctive of orographic cyclogenesis with respect to types A and B of mid-latitude cyclogenesis of Petterssen and Smebye (1971). Point d (but see also Frenzen and Speth, 1984) might seem problematic for the theory of Speranza et al., which implies that the kinetic energy of the disturbance comes from the mean available potential energy. However, the energy budget in a limited volume extending to the upper troposphere is largely dominated by the passage through this volume of the upper level jet, representing a large influx of kinetic energy which can mask other conversion processes. This kind of spatial inhomogeneity is not described by that theory, except for the local deformation induced by an isolated topography (Buzzi and Speranza, 1986). Features b and c, on the other hand, are in agreement with the theory. In particular, the pressure tendency exhibits the same dipolar structure identified in the numerical models as characteristic of the orographic perturbation. The tendency conserves the structure of the "orographic perturbation" while this grows on the pre-existing wave.

It is, in any case, difficult to extract from the observations those features that are specific of the orographic action. The theory is illuminating in this respect, showing that, even in a very idealized case, the action of the topography does not remain confined to the topographic scale alone but affects the spatial structures on the synoptic scale on which the baroclinic instability manifests itself. The lee cyclogenetic process is viewed as a readjustment of the free mode atmospheric growing disturbance (the parent cyclone) to a change, along its path, of the lower boundary condition (the topography). The synoptic scale change is, therefore, macroscopic, but is catalized by a smaller scale boundary effect. A spatial rearrangement of fields is predicted, but without a dramatic change of the basic internal conversion processes from the no-mountain balance. For instance, vorticity and energy budgets in the cyclone volume are not expected to differ markedly from those of the other extratropical cyclones, with all their complications and variability.

As an example, we consider budgets of vorticity, an appropriate indicator of low level cyclogenesis, for individual cases. ALPEX studies focusing on vorticity and related quantities have been presented, among others, by Mattocks (1982), Bleck and Mattocks (1984), Frenzen and Speth (1984 and 1986), Reimer (1986), Pichler and Steinacker (1986), McGinley (1986).

Frenzen and Speth (1984) analyze individual terms of the vorticity equation in isobaric coordinates for the case of 4-5 March 1982, using Reimer's isentropic analysis interpolated on pressure surfaces. Positive advection of relative vorticity is found at all levels, peaking at 300 hPa, throughout the growing stage. Vorticity production by convergence is observed to peak also at upper levels, but to become more and more important at lower levels in the later stages of vorticity increase. Budgets were made over a fixed large area. In a second paper (1986), Frenzen and Speth compare various ALPEX cases, trying to identify common and different features in the vorticity (and kinetic energy) budgets. The positive vorticity advection into the developing cyclone and mass convergence at mid levels, preceding cut-off formation, are noted as common features, although not very distinctive of orographic action. An indication of the latter is found in the pattern of relative vorticity near the Alps, positive to the west (or south-west) and negative to the east (or north-east), consistent with the theory of finite-amplitude, three-dimensional mountain of Buzzi and Speranza (1986).

McGinley presents similar budgets but for smaller areas following the movement of the surface cyclone ("quasi-Lagrangian"), for three ALPEX cases (one is shown in Fig. 5). Individual terms are evaluated at four isobaric levels, using a flux form of the vorticity equation. Two of the three cases are similar to each other because both were characterized by short travelling upper waves embedded in a general north-westerly stream, accompanied by jet streak penetrating over the Western Mediterranean. Vorticity budgets also appear similar in the developing stages, being dominated by vorticity advection in the upper layers and by absolute vorticity convergence in the lower layers. Tilting and vertical transport seem to play a secondary role. This kind of vorticity budget is reminiscent of the type B cyclogenesis identified by Petterssen and Smebye (1971); the orographic effect, on the other hand, is not easily appreciated, though the sensitivity of the budget to the presence of the orographic barrier in the analysis scheme is evaluated by McGinley and appears to be quite strong.

Steinacker (1984) and Pichler and Steinacker (1986) adopt a different approach to vorticity diagnostics, considering the evolution of absolute

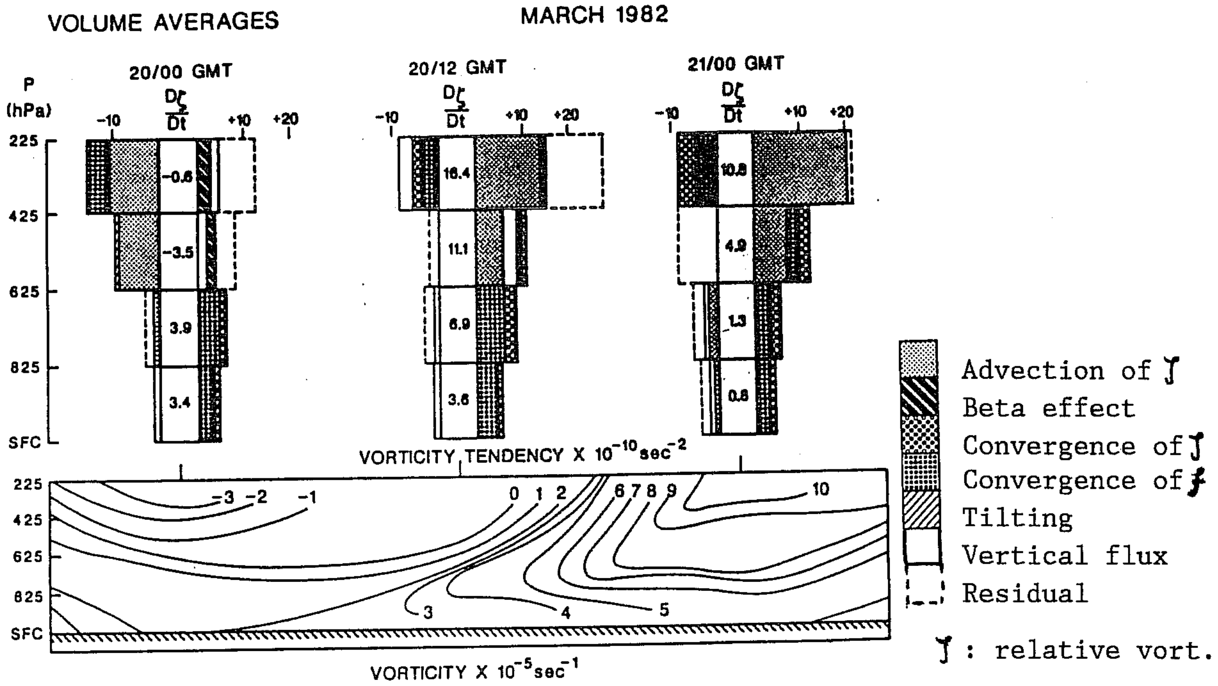

Fig. 5 Vorticity budgets for three times, labelled at top of figure. Budgets are computed for a small volume, moving with the low level cyclone from north France to the Tyrrenian sea. 12 h observed vorticity changes are plotted in the middle of each block; terms contributing to vorticity increase (decrease) are plotted to the right (left). Bottom figure indicates averaged vorticity for each pressure level, versus time. (McGinley, 1986).

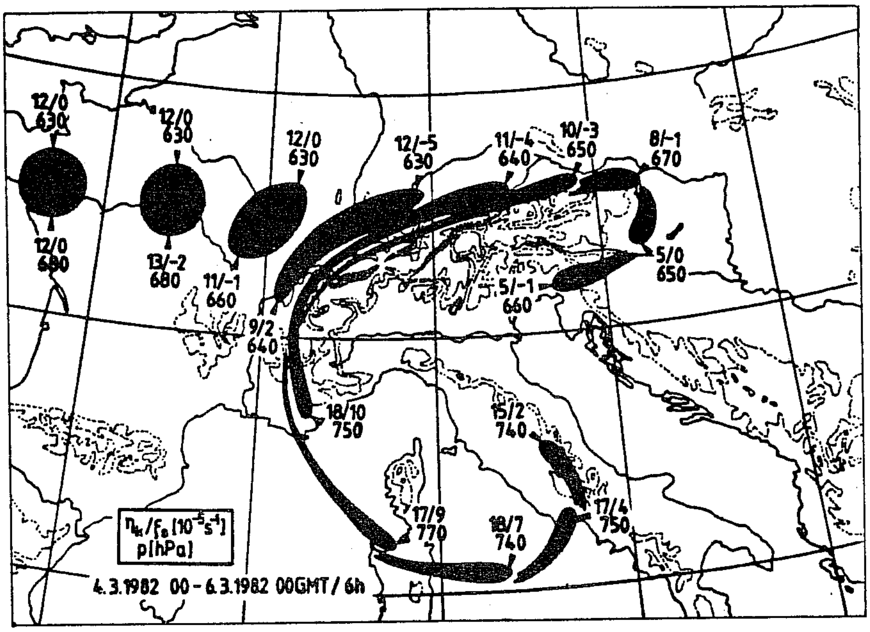

Fig. 6 Deformation of an isentropic surface, during a case of Alpine cyclogenesis, plotted every 6 hrs, between 4 March, 00 GMT, and 6 March, 00 GMT, 1982. At the northern and southern sides of the area, absolute curvature vorticity, relative shear vorticity and pressure are plotted (Pichler and Steinacker, 1986).

vorticity on isentropic surfaces. They consider total vorticity as being split into (relative) shear vorticity and (absolute) curvature vorticity, having noted, after accurate wind and trajectory analyses, that substantial exchanges between relative and curvature vorticity take place along trajectories passing near the Alps (Fig. 6). Pichler and Steinacker show that, while the total vorticity increases in the cyclone core over the Western Mediterranean (because of flux convergence), the shear vorticity along trajectories passing west of the Alps initially increases, associated with the deflection of the massif, and is then trasformed into curvature vorticity when air parcels enter the cyclonic vortex. This result emphasizes the strong mesoscale deformation induced by orography and its role in producing vorticity in a preferred location. The development of strong winds, such as Mistral and Bora, very often associated with lee cyclogenesis, can be viewed as a local aspect of the process.

Recalling the theory of Speranza et al., we can say that it is not inconsistent with the existence of strong shear and deformation near the mountain (shown, for instance, in the three-dimensional mountain cases of Speranza et al., 1985, and Buzzi and Speranza, 1986), but that non-geostrophic dynamics is required (as in the extension of Malguzzi and Trevisan, 1986) for internal consistency. Even in the quasi-geostrophic case, however, the large scale features of the flow deformation are realistically represented.

Bleck and Mattocks (1984) approach the diagnostic problem more synthetically, looking at the Ertel potential vorticity fields near the tropopause. They emphasize the correlation between cyclogenesis and positive potential vorticity advection in the upper layers, showing that lee cyclogenesis is anticipated by a southward displacement of a nucleus of high potential vorticity from the polar low stratosphere moving towards the Alpine region (see also Tibaldi and Trevisan, 1973). Minor or transient developments were found to be associated with "streamers" of potential vorticity injected into the Alpine region from troughs passing north of the Alps, while intense cyclogenesis occurred when potential vorticity maxima moved directly over the barrier. The use of potential vorticity as a powerful diagnostic quantity is illustrated by Hoskins et al. (1985). What needs further investigation, in cases of Alpine cyclogenesis, is the role of orography in modifying the evolution of the potential vorticity field itself. The tendency of deep lee cyclogenesis to produce upper cut-off lows seems to indicate that the associated cut-off of potential vorticity maxima may be one aspect of the same process.

Other diagnostic studies have concentrated upon particular aspects of lee cyclogenesis on the subsynoptic scale, such as, to quote only some, frontogenesis (Buzzi et al., 1985), stratospheric ozone descent (Buzzi et al., 1984), fluxes of latent and sensible heat (Emeis and Hantel, 1984), vorticity components and ageostrophic motions in isobaric layers (Reimer, 1986), mountain drag (Hafner and Smith, 1985; Davies and Phillips, 1985). Again, some are qualitatively accounted for by the aforementioned theory (frontogenesis, form drag) and some are not, but an assessment of their relative physical importance at the various scales is still needed.

4. NUMERICAL MODELLING RESULTS

The earlier published simulations of lee cyclogenesis were based on idealized initial conditions and simple orographic representations. Using vertical wall mountains in a low resolution, primitive equation model, Egger was able not only to simulate Alpine cyclogenesis (1972) but also cyclogenesis in the lee of north-south barriers like Greenland and the Rocky Mountains (1974). The importance of a baroclinic mean flow and of the direct interaction of the pre-existing low with the topography were clearly stated in Egger's works. Subsequent experiments (Trevisan, 1976) showed that more conventional, finite slope mountains of sufficiently large volume could also induce simulated lee cyclogenesis. Bleck (1977), introducing simulations based on observed initial conditions and realistic topography, showed that acceptable results could be obtained only with high resolution (85 km of grid spacing) and mountain enhancement with respect to the grid average. Bleck's experiments were comparatively more successful in simulating the low level, initial development stage rather than the baroclinic stage leading to full upper development. Similar difficulties were experienced by other real data modellers, as, for instance, Mesinger and Strickler (1982), who firstly presented a systematic comparison between experiments made with and without mountains. They showed that, together with "true" orographic cases, there are others in which the modification introduced by the model orography is only minor: caution is needed, threfore, when cases are evaluated on a purely observational basis.

In the meantime, controlled experimentation continued, with the primary objective of testing theoretical hypotheses and diagnosing dynamical fields rather than evaluating different numerical schemes and parameterizations (Tibaldi et al., 1980; Tosi et al., 1983). These experiments were at least as important as the observations for the subsequent theoretical developments. Concepts related to the role exerted by the orography in energy conversions at various development stages, to the absolute versus convective instability (Illari et al., 1981) as a function of the initial state characteristics, to the dipolar nature of the "mountain-induced disturbance", rotated with height (see also Tibaldi and Buzzi, 1983, and Speranza et al., 1985), received clarification from controlled experiments. A review including these as well as other numerical experiments, made with different models (at different resolutions, on global as well as limited area domains), is given in Buzzi and Speranza (1983).

Recent numerical works have been devoted to integration tests based mainly on ALPEX cases. One exception is the case study presented by Mesinger (1985) and Mesinger and Pierrehumbert (1986), simulating the "refractory" case (3-4 April 1973) analyzed by Buzzi and Tibaldi (1978). A new mountain representation ("step" or "eta") was compared with the more conventional sigma. Results indicate less noisy fields and better simulation of the 500 hPa cut-off low in the new version, stressing the sensitivity to mountain specification at resolutions of the order of 100 km.

Sensitivity to orographic representation in terms of different terrain definitions at different resolutions, using versions of the ECMWF model, has been tested in a series of papers by Dell'Osso and Tibaldi (1982), Dell'Osso (1983), Dell'Osso and Radinović (1984), Dell'Osso (1984), Tibaldi and Dell'Osso (1986). The introduction of an "envelope orography" (Wallace et al., 1983) has been found to have a positive impact on the forecast not only of the planetary waves but also of transients like lee cyclones, as shown by Jarraud et al. (1986). They confirm Tibaldi and Buzzi's (1983) observation that errors in forecasting Alpine cyclogenesis, typical of smooth mountain representation, tend to propagate downstream over large areas of the Northern Hemisphere and increase in time because of mid-latitude instability. With respect to mountain representation, a result of the aforementioned experiments, conducted on different ALPEX cases, is that subgrid mountain parameterization with envelope orography is beneficial at low resolution, although "the requirement of an envelope-like parameterization decreases with increasing resolution" (Dell'Osso, 1984). Two and three day forecast experiments with a nested limited area model at resolutions up to about 50 km of grid distance (N192), with slight or no enhancement of terrain height, gave good results when applied to ALPEX cases, not only with respect to cyclone intensity and position but also to mesoscale temperature, wind (Fig. 7) and even, to some extent, precipitation structures.

The role of condensational processes has been tested by Dell'Osso and Radinović (1984) in a high resolution experiment on the ALPEX case of 18-19 March (a "true" orographic case, according to their experiments). Latent heat release was found more important in upper levels and at later stages of development, while the initiation of the lee cyclone was almost unaffected by it. More experiments on this effect, reported by Tibaldi and Dell'Osso (1986), confirm this general view, though the latent heat release

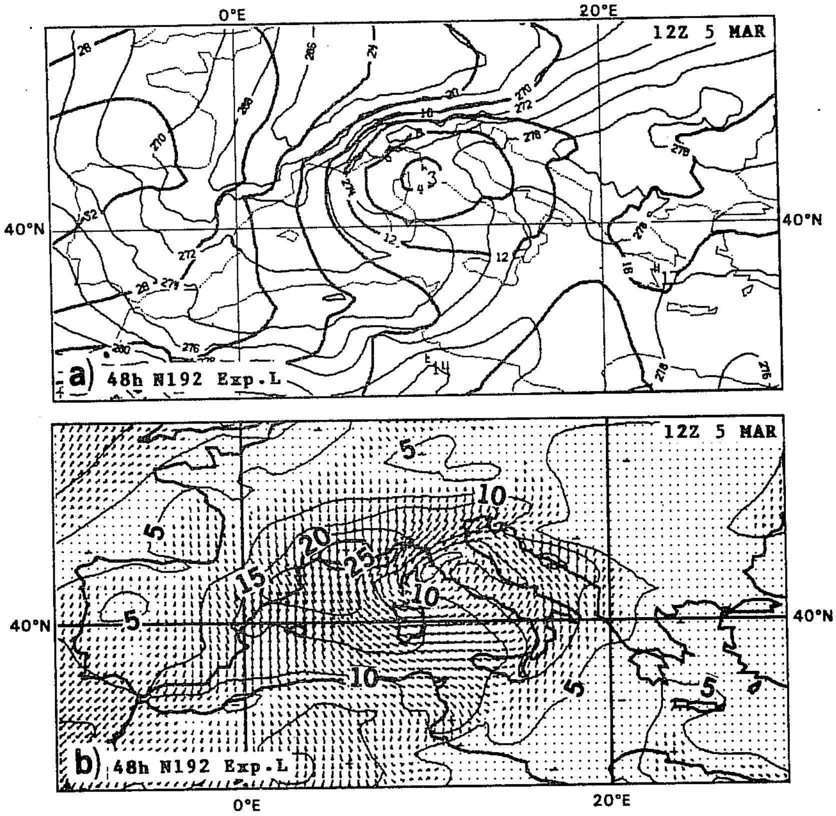

Fig. 7 Geopotential height and 850 hPa temperature (top) and 1000 hPa wind (bottom), in a high resolution, 48 h forecast experiment by Dell'Osso (1984).

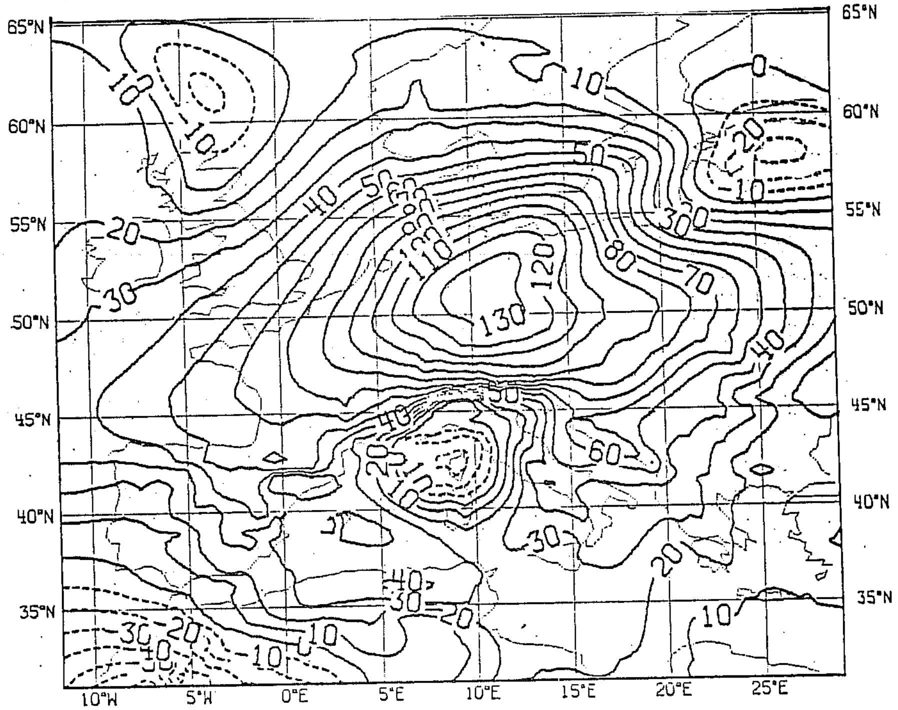

Fig. 8 Mean orography minus zero orography difference map for 1000 hPa geopotential height, for a 48 h high resolution, limited area forecast, valid 5 March 1982, 12 GMT (after Tibaldi and Dell'Osso, 1986).

may have different effects in different cases.

Progress in model performance in the forecasting of Alpine cyclogenesis, when sufficient resolution is employed, is also reported by a number of investigators, e.g., Pham (1982 and 1986), Tafferner (1986), McGinley and Goerss (1986), Hortal et al. (1986). It is too early to attempt drawing more general conclusions regarding model performance in simulating lee cyclogenesis in terms of coordinates (sigma, pressure and theta have been used), resolution, mountain representation etc. More systematic experimentation and evaluation is needed.

Returning to the theoretical considerations, we recall that the dipolar nature of the orographic pertubation in the geopotential field near the mountain is ubiquitous, having been found in high resolution experiments with real data (Hortal et al., 1986; Tibaldi and Dell'Osso, 1986; McGinley and Goerss, 1986; see Fig. 8). However, the simple Eady type model of instability, modified by the orography, though capable of accounting for the basic characteristics of lee cyclogenesis, does not seem to be fully adequate to represent those cases of lee cyclogenesis that more closely resemble, in the initial conditions, type B of Petterssen and Smebye. Idealized controlled experiments, such as those recently performed by Bleck and Mattocks (1986), stressing the role of potential vorticity "anomalies", are useful to clarify this aspect.

5. OTHER TYPES OF LEE CYCLOGENESIS

In accordance with the above discussion, it is an obvious step to look for other types of lee cyclogenesis in other parts of the world, where mid or high latitude mountain complexes extend mainly in the zonal direction. Remaining in the Mediterranean area, we find that the Pyrenees, the Atlas and the Anatolian mountains present this characteristic. Cases of secondary cyclogenesis occurring "in the lee" of these mountains are well documented (see U.K. Met. Office, 1962).

However, the theory of Speranza et al. (1985) predicts that the maximum response in the interaction of baroclinic waves with mountain chains occurs when the "basic" thermal wind is aligned more or less parallel to the main axis of the ridge. This means that also non-zonal mountains, under conditions of non-zonal flow, are expected to produce cyclogenetic effects similar to those of the Alps. That this is the case has been shown by Buzzi et al. (1986) in a paper dealing with the generalization of the aforementioned theory to different types of orographic cyclogenesis. Utilizing numerical results obtained with the ECMWF model (see also Speranza, 1986, this Volume), they show that cyclogenesis in the Gulf of Alaska, occurring under local north-westerly sheared mean flow, has basic features very similar to Alpine cyclogenesis. The Rocky mountains play a crucial role in focusing the cyclonic development over the Gulf of Alaska and in maintaining the cyclone on their western side until mature stage.

A typical example of this development is described by Winston (1955): in a general situation of dipolar blocking over the Pacific Ocean, a developing baroclinic trough moves along the north-westerly branch of the jet which flows parallel to the northern portion of the Rocky Mountains. In the course of a few days the cyclone grows in horizontal size and depth, becoming a major perturbation on the synoptic scale. Winston stressed the importance of the heat exchange betweeen the atmosphere and the sea, but the effect of topography was apparently overlooked. The vorticity budget of these eddies, confined by the orography to the Pacific side of the Rockies, and their feedback on the mean "blocked" flow, have been studied recently by Mullen (1986).

Buzzi et al. (1986) also consider classical cyclogenesis in the lee of the Rockies, in the more usual meaning of cyclonic development on the continental side of the Cordillera, in the presence of westerly mean flow. Also on the basis of previous analyses, they identify the following typical characteristics:

a) the existence of a precursor low in the Pacific;

b) the deceleration, northward curve and filling of this low near the surface as it approaches the American coast, just prior to lee cyclogenesis;

c) the disappearance of the parent low above the Cordillera, associated with the growth of a distinct trough in the lee, already initiated before the Pacific low centre reaches the west coast;

d) the development of the lee cyclone further south of the region of incidence of the parent low;

e) the slow southeastward movement of the lee cyclone, as long as it remains close to the mountainous region, and its subsequent northeastward acceleration as it drifts away from the mountain, possibly associated with reintensification.

These characteristics are captured by simply considering a baroclinic wave interacting with a north to south oriented large scale mountain. These results indicate that, in spite of the apparent differences, dynamical analogies exist among the various types of orographic cyclogenesis, confirming the validity of Egger's earlier approach in designing his numerical experiments (1972, 1974).

6. CONCLUSIONS

Lee cyclogenesis commonly occurs in various parts of the world, showing different characteristics that can be, to a large extent, interpreted as orographic modifications induced on baroclinic cyclonic transients, under different flow conditions and mountain geometries.

Alpine cyclogenesis has received much attention over recent years as one of the most striking and frequent examples of orographic cyclogenesis. Peculiar chracteristics have been identified on the observational basis, but controlled numerical experiments have been of great help in isolating the basic features of the orographic disturbance which are not confined to the mesoscale.

Numerical forecasts of Alpine cyclogenesis have been shown to improve dramatically, with better mountain representation and increased resolution. More systematic investigation is still needed, however, in terms of analysis and initialization schemes (for both diagnostic and modelling purposes) and of intercomparison of different models and numerical schemes.

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