LEE CYCLOGENESIS AND ITS NUMERICAL MODELLING

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1. INTRODUCTION

It is a well known fact that the earth's topography, with its wide variety of features, plays a very important role in exciting atmospheric perturbations involving all scales of motion. The importance of extensive mountain complexes in forcing quasi-stationary planetary-scale perturbations, which account for a large fraction of the global transfer of energy and momentum in the westerly flow, has been recognised in the late forties-early fifties (e.g. Charney and Eliassen, 1949, Bolin, 1950).

On the small scale, mountainous terrain may force very strong local variations of boundary layer properties and of different meteorological parameters as wind, temperature, latent and sensible heat fluxes or directly of weather phenomena, such as precipitation.

At intermediate (synoptic) scales the influence of mountains is well-known to weather forecasters, and at these scales both the shape and the position of the topographic obstacles relative to the atmospheric flow play a significant role. In this last respect the Alps represent a striking example of how important the profile and the location of a mountain can be in influencing the weather.

Due to their shape and orientation, the Alps affect differently the behaviour of the synoptic-scale flow according to different meteorological situations and to the overall "cross-section" that they present to the oncoming flow. The gap between them and the Pyrenees can also produce flow chanelling effects (e.g. mistral).

Although the volume of the Alpine chain is not particularly large compared to other synoptic-scale obstacles, their WSW-ENE orientation, together with the presence just south of them of the source of moisture and heat from the Mediterranean Sea, enhances the meridional air mass contrast, preventing NW-SE advection to a certain degree. The high cross-section they present to the frontal systems coming from N and NW makes this mountain chain an ideal source of flow perturbations; the obstacle is in fact, "seen" by the oncoming Atlantic systems as a semicircular convex barrier, with a mean profile elevation of 2500-3000 meters.

The final product of the "strong interactions" between the synoptic scale flow and the mountain may be a secondary cyclone that sheds from the obstacle.

The complex phenomenology of this, and of other, lee-cyclogeneses is still not fully understood and numerical models show a limited ability in reproducing these atmospheric developments.

Some progress has been made during the last few years and the purpose of this lecture is to describe the phenomenon and to review some of the numerical simulations. For a comprehensive bibliography on orographic effects in atmospheric dynamics, see U.K. Meteorological Office, 1978.

2. PHENOMENOLOGY OF LEE CYCLOGENESIS

Let us try to describe the main factors controlling cyclogenesis.

Suppose we have a baroclinically unstable fluid in motion, with a certain amount of available potential energy (APE) that could be converted into kinetic energy (KE) of the fluid parcels via "slantwise convection"; let us also suppose that we can introduce a perturbation of a certain amplitude in the flow. Because the fluid is baroclinically unstable, the perturbation will start growing, converting APE into KE.

If the perturbation was "impulsive", i.e., a packet localized in space and time, its scale will start to change. This is due to the fact that the "perturbation" has its own characteristic spectrum, and each single wave will start to grow more or less independent from the others (at least until the amplitudes become large and nonlinear interactions become important). The growth rate will be larger for some wavelengths than for others and this will produce a change of scale of the growing eddy.

Since the "corrugations" at the atmosphere's lower boundary act as continuous sources of perturbations, we are faced with the problem of explaining why we do not see baroclinic eddies continuously pouring out of mountainous regions.

Although steady flow over a synoptic-scale obstacle tends to produce higher pressure before and over the mountain and lower pressure in the lee, the small amplitude of the phenomenon and the continuous variations of the basic flow reduce the cyclogenetic efficiency of such a mechanism at least for isolated mountains. In addition, the atmosphere may not be sufficiently unstable all the time.

Figure 1 shows, nevertheless, that such a coincidence is not a rare event in the earth's atmosphere, and this is the main reason why we would like to improve our ability to model successfully and subsequently forecast such meteorological phenomena.

Orographic cyclogenesis occurs in the lee of both synoptic scale mountain ridges, such as the Rockies, and synoptic (and even sub-synoptic) scale isolated massifs, such as Greenland and the Alps.

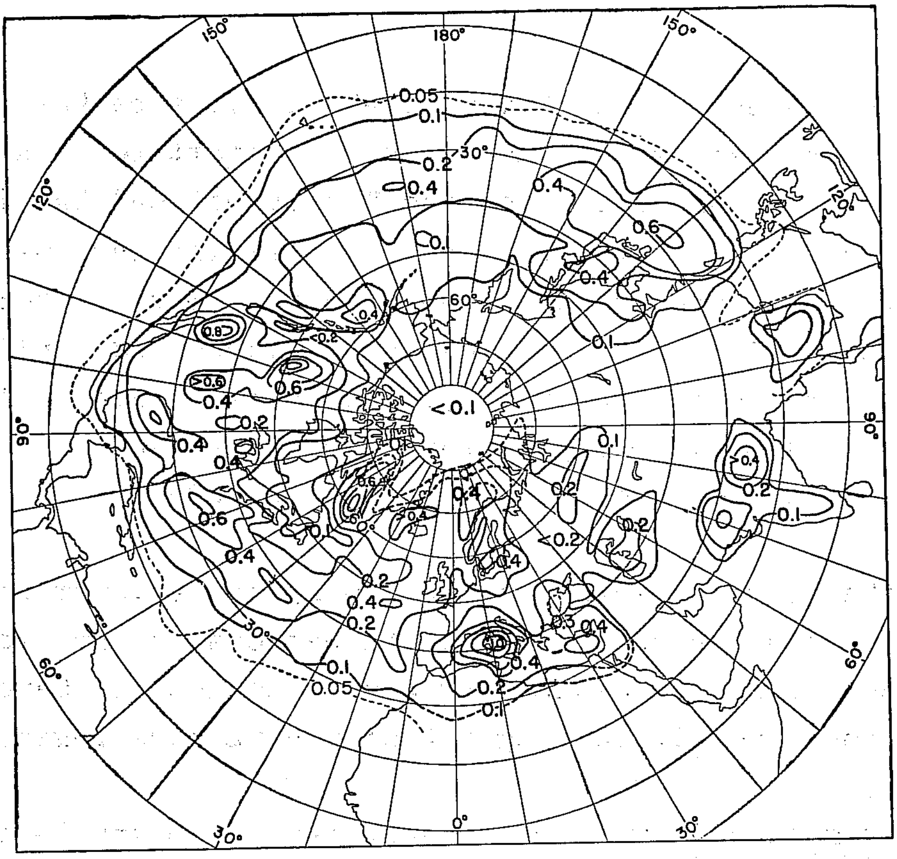

Fig. 1 Percentage frequency of occurrence of cyclogenesis in squares of 100,000 km^2 in winter (1899 to 1939). After Petterssen (1956).

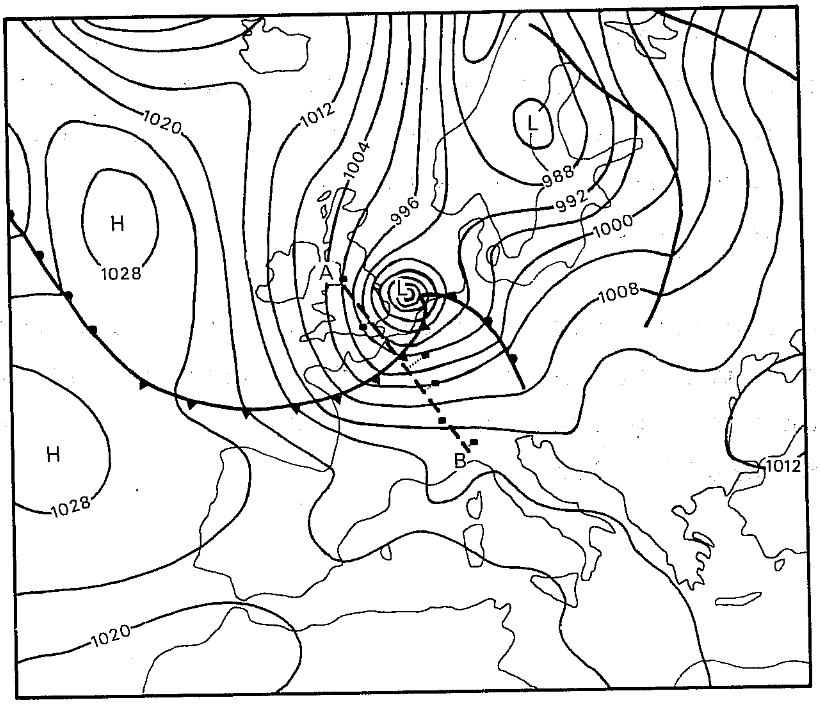

Fig. 2 MSLP, 2 April 1973, 1200 GMT. After Buzzi and Tibaldi (1978).

Cyclogenesis in the lee of the Alps has been investigated for many years (v. Ficker, 1920). For a review of the earlier results the reader is referred to Speranza (1975). More recently, some cases have been made the object, either of detailed case studies (CENFAM, 1961-65, CNR, 1973, Buzzi and Rizzi, 1975, Pichler and Steinacker, 1976, Buzzi and Tibaldi, 1978, Pümpel, 1978, Fons, 1979), or of statistical investigations (CENFAM 1961-1965, Radinović, 1962, 1965a, 1965b).

The applicability of the conclusions from these studies the cyclogenesis in the lee of other isolated mountains should be taken with great care.

Even within the restricted class of Genoa Cyclogenesis there is a wide variety of categories, but for the great majority of intense and rapidly developing disturbances, the original perturbation is provided by the interaction between the Alps and a north-westerly low- and mid-tropospheric cold front embedded into a larger scale planetary trough moving across Northern Europe (see Figure 2). As this cold front starts impinging on the mountain ($t = t_o$) several events take place.

The low-level cold advection, with its associated convergence pattern, is retarded in the mountain region, until most of the cold air has started to flow around (instead of over) the obstacle (Figure 3). This also produces a pronounced deformation of the low-level thermal field increasing the baroclinity in the region; at this point, a low-level, small-scale, shallow baroclinic vortex is initiated in the lee area ($t = t_o + 6h$).

The deformation of the lower-tropospheric thermal structure, together with the almost undisturbed advection processes taking place at upper level, can be interpreted in terms of a local distribution of cyclonic vorticity combining

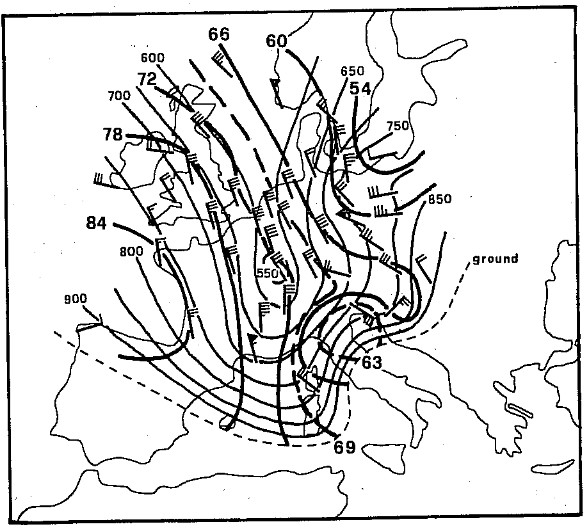

Fig. 3 Isentropic analysis, $\theta=285$K 3 April 1973, 12 GMT; thin lines: pressure in mb; thick lines: Montgomery streamfunction isolines at 60×10^{5} cm^{2} s^{-2} windknots. After Buzzi and Tibaldi (1978).

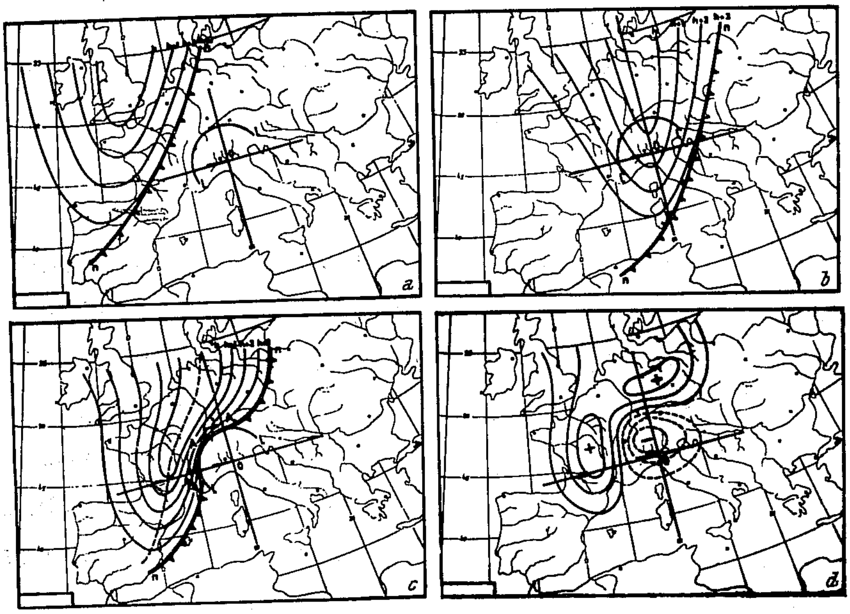

Fig. 4 Schematic figures showing the orographic effect of the Alps. a) Idealized thickness trough approaching the mountain; b) The position of the thickness trough over the Alps area in the idealized case when mountain ranges do not exist; c) Showing deformation of the thickness trough on meeting the mountain barrier of the Alps; d) Showing schematic distribution of vorticity corresponding to the thickness trough in c). After Radinović (1965).

the hydrostatic equation and the definition of the vertical component of geostrophic vorticity into the relationship:

$$\frac{\partial \zeta}{\partial \ell n p} = - \frac{R}{f} \nabla^2 T$$

(ζ vert. comp. of geostrophic vorticity, T temperature, p pressure, f Coriolis parameter and R gas constant).

The modification of the low-tropospheric temperature advection due to the mountain acts in such a way as to produce negative values of $\nabla^2 T$ in the lee region, and it is thus possible to account for the presence of cyclonic vorticity at low levels. This cyclonic circulation, in turn, advecting warmer air from the SW, enhances the deformation of the frontal structure. This feed-back mechanism proceeds at the expense of the APE: warm air is ascending on the eastern edge of the obstacle and cold air is descending in the western lee area; the baroclinic eddy has been formed.

The importance of the horizontal deformation of the temperature advection as a fundamental dynamical ingredient for this kind of development, confirmed in recent case studies, has been proposed a number of years ago by Radinović (1965) (see Figure 4). The fact that, in the early stages, the fast growth of the baroclinic disturbance seems to be confined to the lower half of the troposphere, and is only subsequently reinforced by the development aloft, has been stressed recently by Buzzi and Tibaldi (1978), see Figure 5.

The upper-level vorticity advection, associated with the movement of the planetary scale trough will reach the genesis region later ($t = t_o + 12h$, see Figure 6). The overlapping of high-level vorticity advection with a low-level baroclinic area is well known to be favourable to cyclone development (Sutcliffe, 1947, Petterssen, 1956)

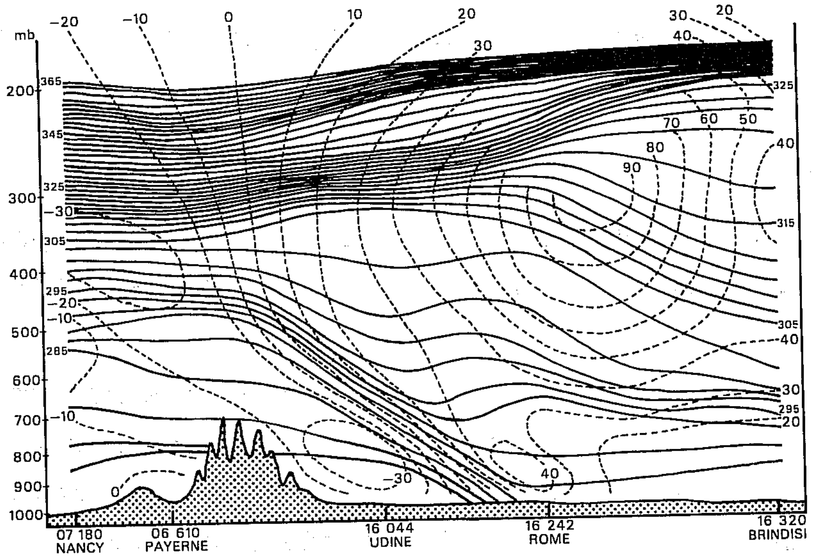

Fig. 5. Cross-section along the line E-F of Fig. 6; 3 April 1973, 1200 GMT. Full lines: isentropes (^{o}K); dashed lines: isotachs of normal wind component (knots). After Buzzi and Tibaldi (1978).

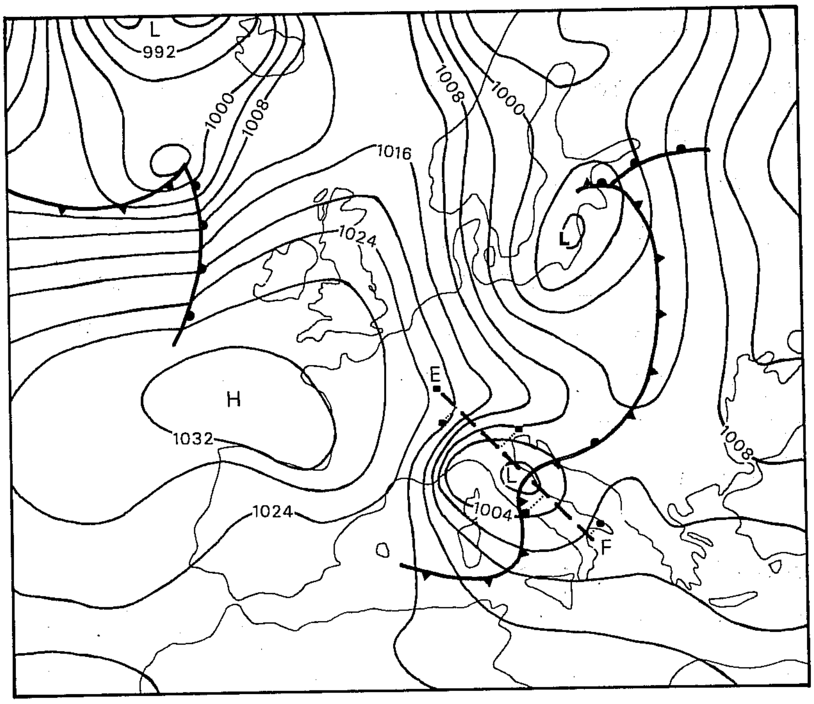

Fig. 6. MSLP, 3 April 1973, 1200 GMT. After Buzzi and Tibaldi (1978).

and can qualitatively account for the depth reached in some cases, in which the whole troposphere is later occupied by a coherent vortex. From this time the cyclone will assume more and more vertical coherence, progressively increasing its horizontal scale; it will also start drifting, very slowly in the beginning, then more rapidly, south-eastward, undergoing the "normal" development one would expect from a mid-latitude disturbance (see Figure 7).

During the early stages of the development, the growth rate of the disturbance is very fast (e-folding time of about 6 hours) then it progressively approaches the growth rate typical of normal-mode linear baroclinic instability theory (e-folding time of about 30 hours), well in agreement with recent results on initial value baroclinic instability (Simmons and Hoskins, 1979), of which lee cyclogenesis is indeed a very pertinent example.

Cyclogenesis in the lee of large scale mountain ridges, e.g. the Rockies, has many characteristics in common with cyclogenesis in the lee of isolated massifs (Newton, 1956, McClain, 1960, Hage, 1961, Chung and Reinelt, 1973, Chung et al., 1976, Chung, 1977). The characteristics of the "basic state" and of the development phase appear to be substantially the same. The mechanism that generates the original perturbation, may differ from the isolated obstacle case. Because the air cannot flow around a long ridge and is therefore forced to flow over the mountain, the generation of cyclonic vorticity, through stretching of the vortex tubes, is thought to be the leading source of perturbation for the flow (Newton, 1956). The fact that the majority of lee cyclones still tend to form near a surface front is probably due to the fact that low-level frontal systems are very good indicators of baroclinic areas anyway.

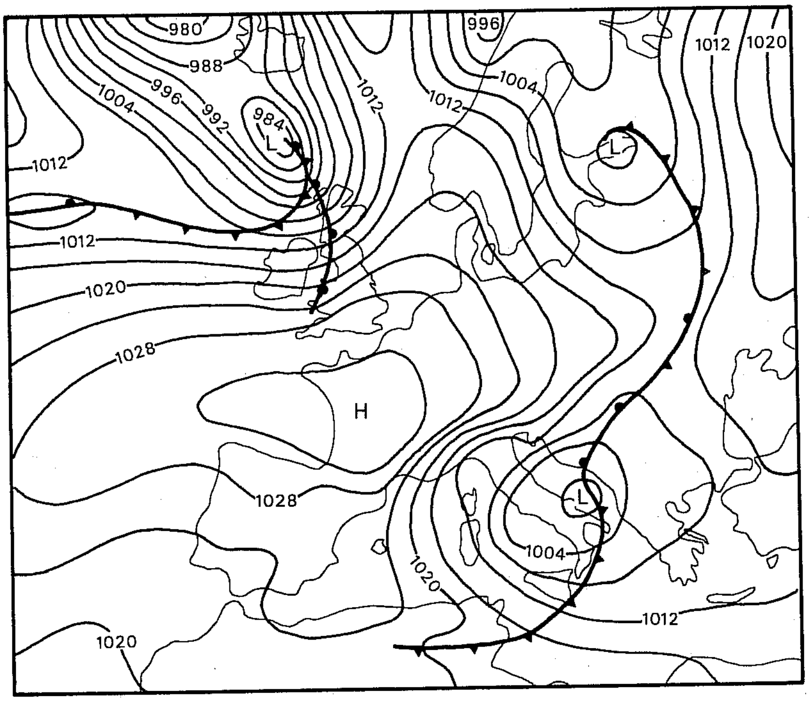

Fig. 7 MSLP, 4 April 1973, 0000 GMT. After Buzzi and Tibaldi (1978).

In subsequent stages, after the initial lee-low (and associated cyclonic circulation) has been formed, low-level convergence processes seem to be partially inhibited by the presence of the ridge; this allows the baroclinic development to take over completely, throughout the troposphere.

The role played by the upper-levels vorticity (and divergence) advection processes seems to be greatly reduced in these ridge cases (Egger, 1974).

3. NUMERICAL MODELLING: IDEALISED SIMULATIONS

The first, and for a long time the only, noteworthy attempt to model lee cyclogenesis is due to Egger (1972). He used a modified version of Edelmann's numerical model (Edelmann, 1963), a six-level, primitive equation sigma model, with a simple parameterization of surface friction and horizontal diffusion. The grid-length was 380 km and the time-step 13 minutes.

Instead of allowing the sigma surfaces to follow the profile of the mountains, Egger took the approach of representing steep mountains with bulks of stagnant air, applying blocking conditions ($V_\perp \equiv 0$) at the vertical walls.

In his first paper, he chose to model cyclogenesis in the lee of the Alps and used idealized initial conditions, choosing fields "sufficiently close to those which are known from statistical and synoptic investigation". Figures 8a, b and c show the result of one of his experiments.

From his diagnosis it can be deduced that the major reason for his success in reproducing a cyclone in the lee of the Alps was due to the correct representation of the blocking of low-level advection exerted by the mountain and

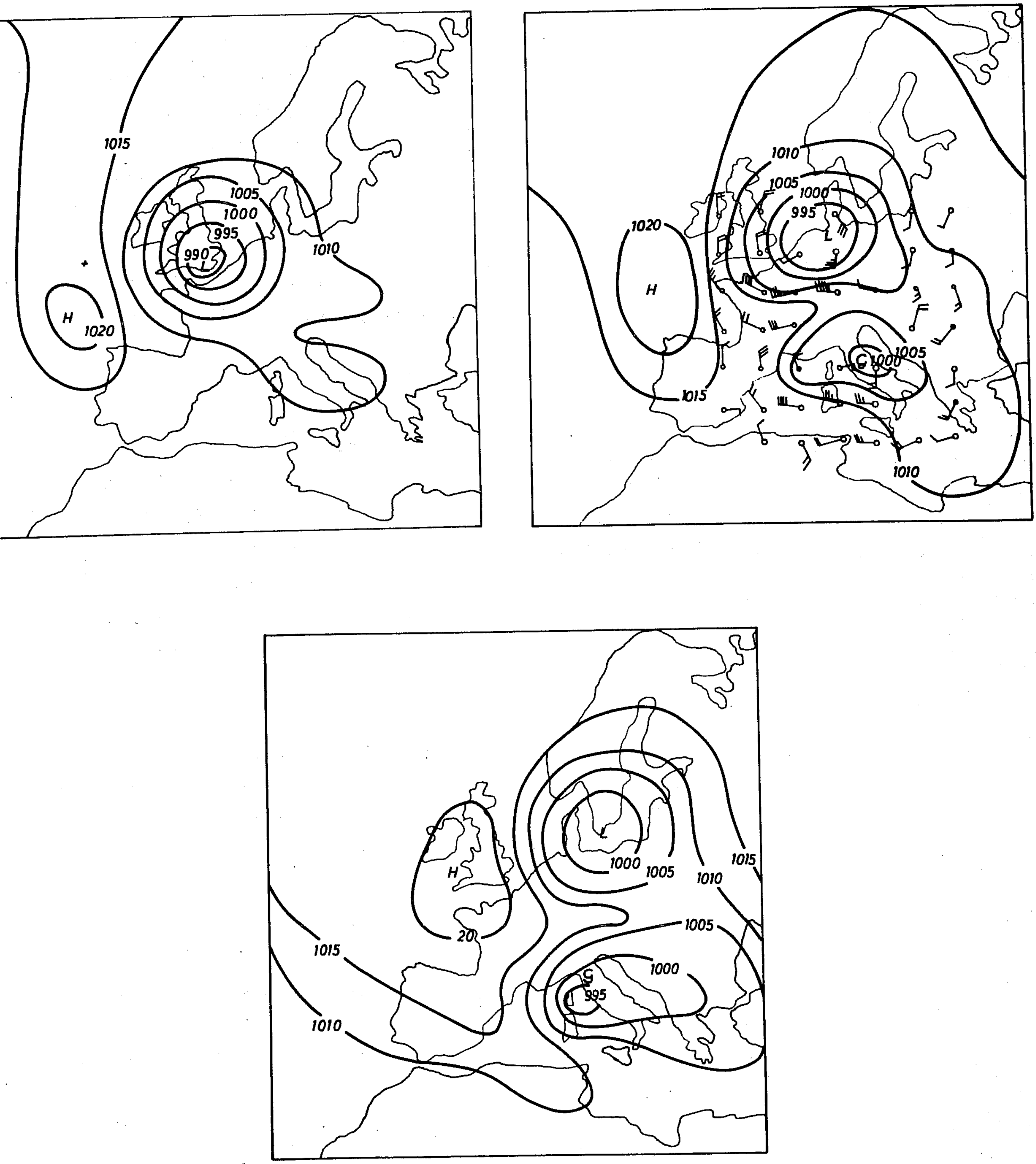

Fig. 8 a) Surface pressure (mb) after 24 h in Egger's numerical experiment. The cross marks the initial position of the centre of the low L. b) Surface pressure and wind after 36 hr. c) Surface pressure at 48 h. After Egger (1972).

the consequent deformation of the thermal field (or, in Radinović's words, of the "thickness advection"). The advection of divergence (and vorticity) aloft, associated with the propagation of the large scale wave, was, on the contrary, left undisturbed.

Another possible role played by the low-level deformation of the thermal field in deviating the upper-level jet was pointed out by Trevisan (1976); this deformation would localize in situ the upper level, and usually otherwise spontaneous, development (cut-off low). This possibility of orographic localisation of an upper level development was first proposed, in a similar interpretation, by Danielsen (1973). In his phenomenological picture of lee cyclogenesis, the obstacle is, in fact, held responsible for the early splitting of the upper-level jet.

We will now turn our attention to a more recent simulation experiment that confirms some phenomenological hypotheses previously put forward exploring, at the same time, the possibility of improving the routine forecast of such meteorological phenomena.

The model used is a channel version of the PE, 6-level, HIBU model (Janjić, 1977; Mesinger, 1977). It is a primitive-equation model with a simple surface friction parameterization and dry convective adjustment. The grid length is about 160 km at 45°N; in this version it was run as a 6-level model, and the time-step was 360 seconds.

The basic idea of the channel experiment was to set up a baroclinically unstable westerly flow, insert a perturbation, let it grow for 96 hours to a large amplitude, with consequent development of a frontal system, and use this situation as an "initial condition". A mountain vaguely resembling the Alps, and of the same steepness, is then

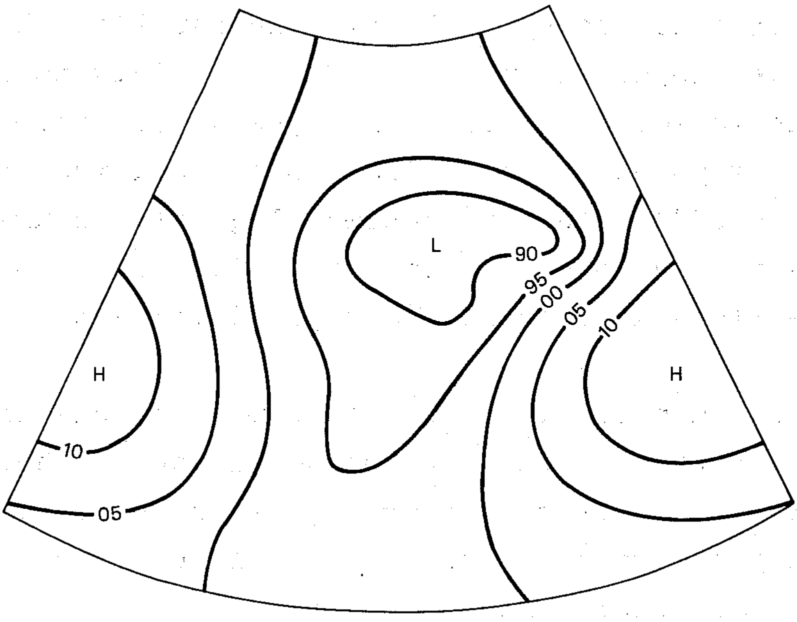

Fig. 9 Initial situation T = 00+92h, MSLP, for the idealized channel experiment with the HIBU model. The thick black line indicates the ridge of the idealized Alps that will grow in the following eight hours. After Buzzi, Malguzzi and Tibaldi (1979).

allowed to grow smoothly just in front of the oncoming frontal system, with a growth time-scale of about eight hours, to allow for progressive geostrophic readjustment.

Figure 9 shows the "initial condition" (96 hours after the small perturbation was inserted) and the position of the mountain that is about to grow in the oncoming 8 hours. Figures 10 and 11 show the situation as it develops 36 and 60 hours later. The temperature structure at 850 mb is shown in order to facilitate the positioning of the low-level frontal system.

The main characteristics of this simulation are the surprisingly realistic "look" of the low-level baroclinic disturbance, and the comparatively slow development at 500 mb.

Detailed model diagnostics confirmed that the cyclonic circulation in the lee region is initiated by the mountain-induced deformation of the front. At 850 mb, in the lee area, immediately before cyclogenesis, there was positive correlation between upward vertical motion and cold temperature and downward motion and warm temperature. The blocked thermal advection process further enhances this phenomenon in the upwind mountain region increasing the temperature gradient. Baroclinity is therefore locally enhanced by the front-obstacle interaction. This numerical simulation also confirms that the low-level and the high-level processes are likely to be, in the early stages at least, distinct. We are, in fact, left with the question as to why the model showed an upper-tropospheric development slower than that which is usually observed in real cases, where the cut-off low is produced only a few hours after the surface development.

We have many possible reasons: the initial state could be "unsuitable" for the development of a cut-off; the

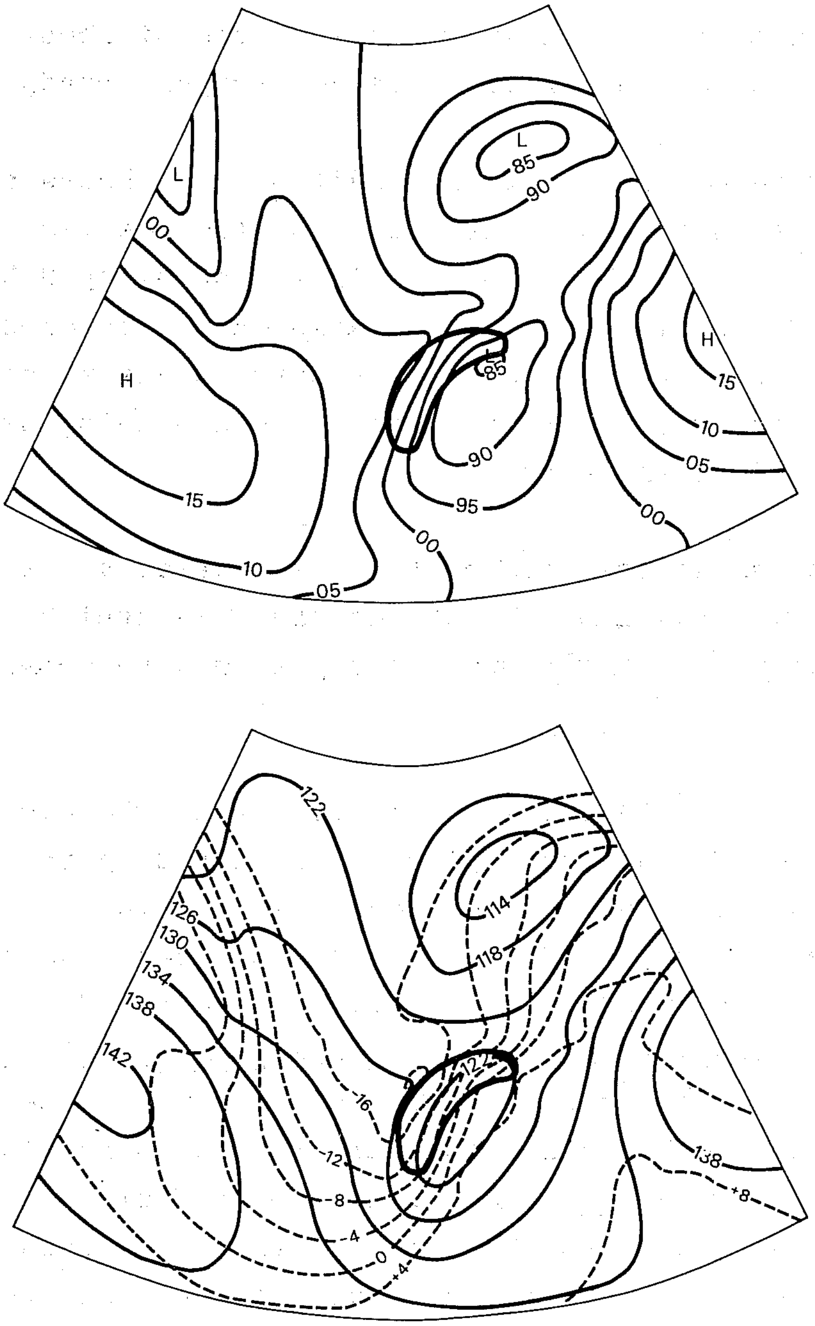

Fig. 10 Situation at T = 00+92+36h for the idealized channel experiment with HIBU model. a) MSLP; b) 850 mb height (continuous lines) and temperature (dashed lines). After Buzzi, Malguzzi and Tibaldi (1979).

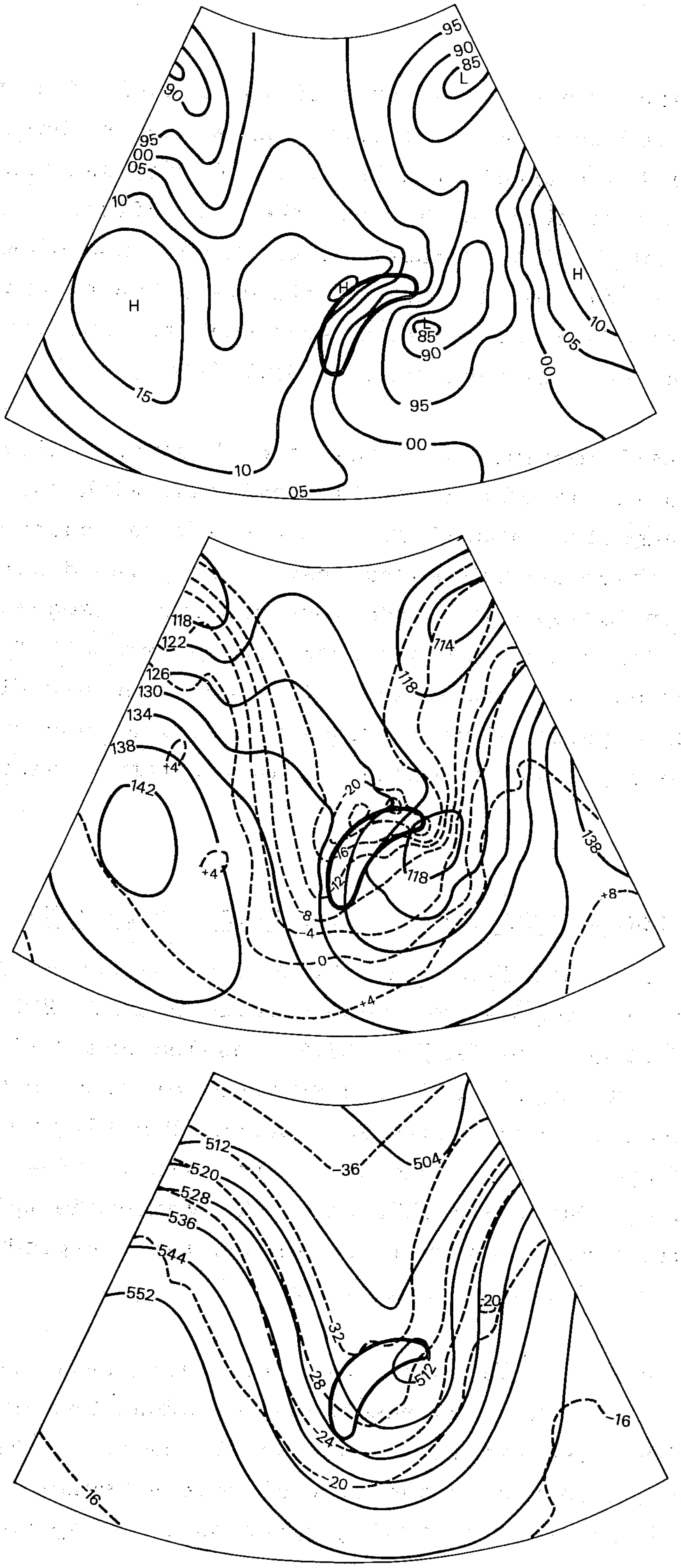

Fig. 11 Situation at T = 00+92+60 h for the idealized channel experiment with HIBU model. a) MSLP; b) 850 mb height (continuous lines) and temperature (dashed lines); c) 500 mb height (continuous lines) and temperature (dashed lines). After Buzzi, Malguzzi and Tibaldi (1979).

latitudinal width of the channel is probably too small to allow a correct growth of very long waves and both the depth of the channel (top level at 200 mb) and the low vertical resolution could have the same effect; the absence of physical parameterization may also slow down the growth rate of the baroclinic disturbance, and concentrate the APE-KE conversion near the surface, as shown in the numerical work by Gall (1975).

The overall impression is that the phenomenological picture sketched in the literature is consistent with the results of the numerical modelling, because all the phenomenological characteristics that have been pointed out as important (steepness of the mountain and consequent blocking effect, deformation of the flow and temperature fields, distinction into two separate low-level and high-level processes, progressive increase of vertical and horizontal scale, etc.), can be recognised in the numerical simulation as well.

4. NUMERICAL MODELLING: REAL DATA SIMULATIONS

Amongst the real data simulations that have been performed, with various degrees of success (e.g. Bleck, 1977, Mesinger, 1976, Mesinger and Janjić, 1977, Capaldo and Finizio, 1977, Tibaldi and Janjić, 1977 and Mesinger et al., 1979), we will consider three examples: Bleck, Tibaldi and Janjić, and Mesinger et al.; the first two refer to the April 1973 case, (Buzzi and Tibaldi, 1978) while the third is a real data simulation that has successfully reproduced the upper-level development as well.

Bleck's model is an isentropic, 11 level, 2-way nested model with coarse-mesh resolution of about 380 km at 60 °N and ¼ fine mesh resolution on the Alpine area. The Alps are about 2800 m high and of realistic steepness. The model, in order to control generation of noise both by

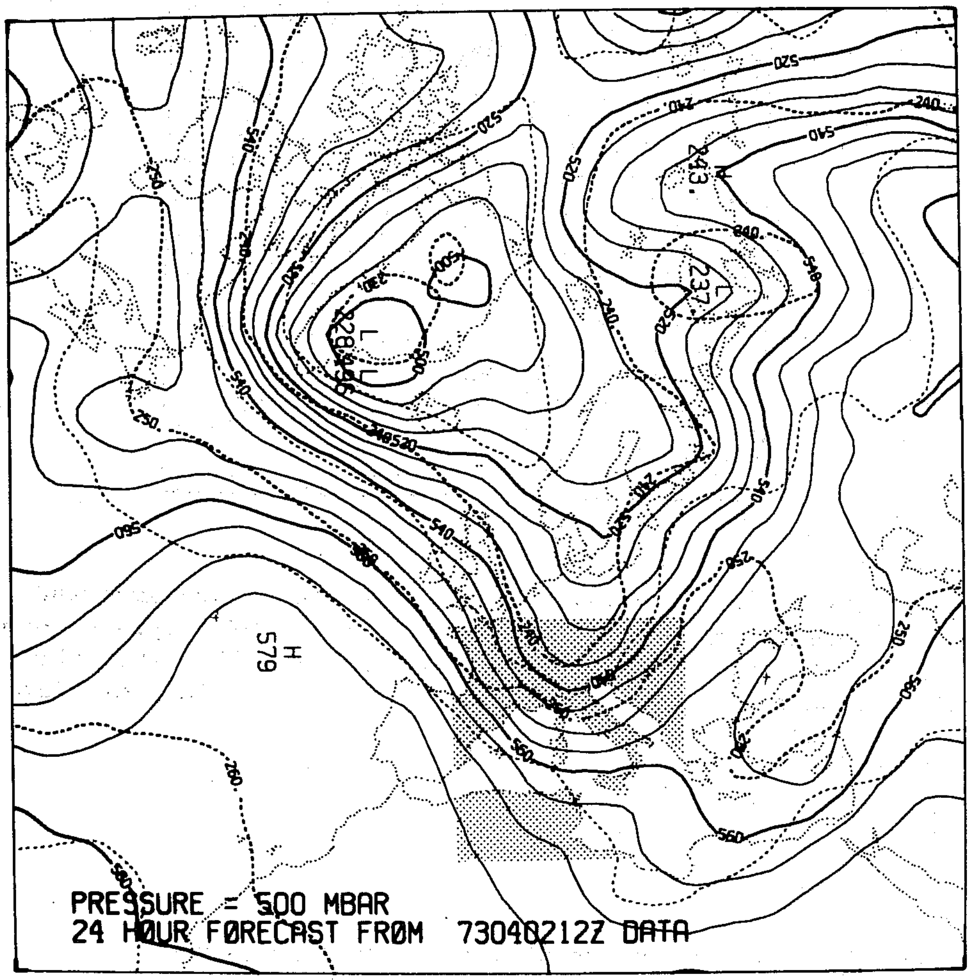

Fig. 12 Coarse mesh 24h prediction of 500 mb height (solid) and temperature (dashed), verifying at 1200 GMT 3 April 1973. After Bleck (1977).

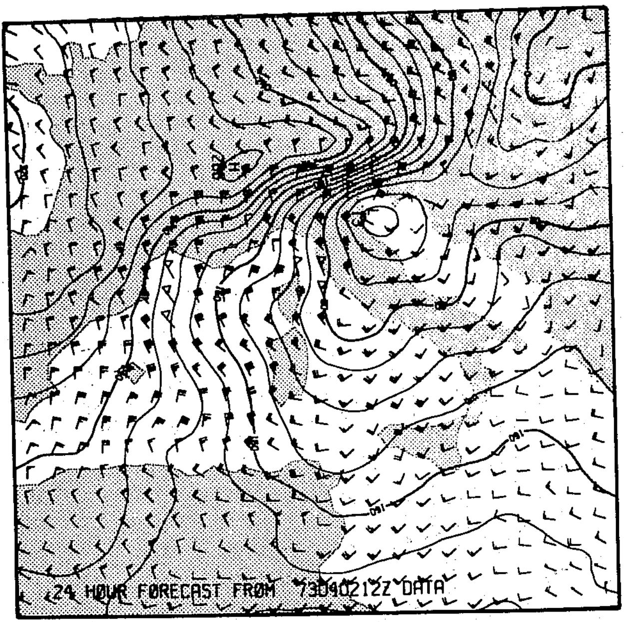

Fig. 13 Fine mesh 24h prediction of sea level pressure and surface wind verifying at 1200 GMT 3 April 1973. Cyclone central pressure 1001.3mb. Contouring interval 2 mb. Short wind barbs, 2.5ms^{-1}; long barbs, 5ms^{-1}; triangles 25ms^{-1}. After Bleck (1977).

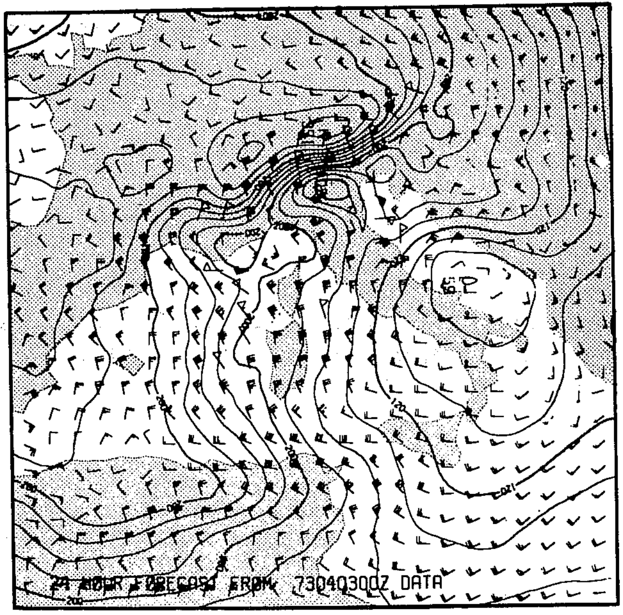

Fig. 14 As in Fig. 13 except for 000 GMT 4 April 1973. After Bleck (1977).

the mountains and by the nesting technique, has to resort to a very strong filtering procedure. The surface friction, in order to simulate the increased drag exerted by the mountain on the flow, is made proportional to the mountain height. The initial conditions (12 GMT 2nd April 1973) were obtained by an isentropic objective analysis system. For more details, see Bleck (1977).

The model used by Tibaldi and Janjić is the limited area version, with constant lateral boundary conditions, of the HIBU model. The grid and the time step were the same as in the channel version run mentioned before, that is 6-level, 160 km grid length at 45 °N and 360 seconds time step. In the example shown here, the surface friction intensity was made proportional to the mountain height, as in Bleck's example. Lateral boundaries of the integration region were 35W, 40E, 30N and 66N, and the maximum height of the Alps was about 3000 meters. One of the main numerical features of this model is that it uses a differencing scheme (Mesinger, 1973 and Janjić, 1979) that prevents the generation of false two-grid-interval waves in the height field, and does not, therefore, need any filtering or damping of the divergent part of the flow. The objective analysis that provided the initial conditions (OOGMT 3 April 1973) was very crude and, furthermore, a few reports were missing from the data set. Figures 12 to 14 show the result of Bleck's experiment and Figures 15 and 16 of Tibaldi and Janjić's experiment.

Although these two models are basically different and the actual "shape" of the lee cyclone in both forecasts is not the same, there are two common points that are worth stressing and that may throw some light on the phenomenology of lee cyclogenesis. They are:

(i) Both models show a good low-level baroclinic disturbance in the right position and of almost

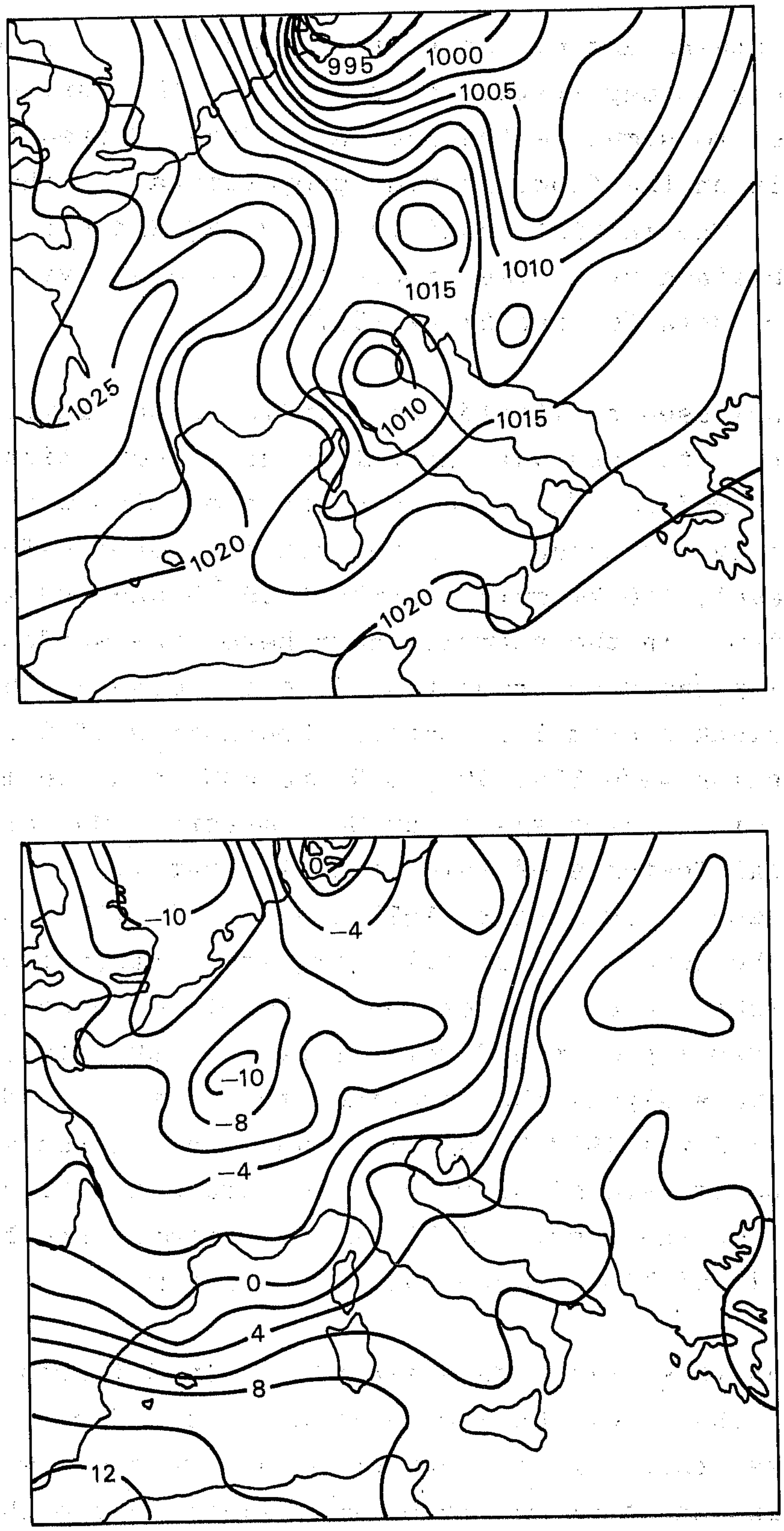

Fig. 15 12h numerical forecast of the same April 1973 cyclogenesis case verifying at 1200 GMT 3 April 1973. The model used is Mesinger and Janjić's HIBU model; a) MSLP; b) 850 mb temperature. After Tibaldi and Janjić (1978).

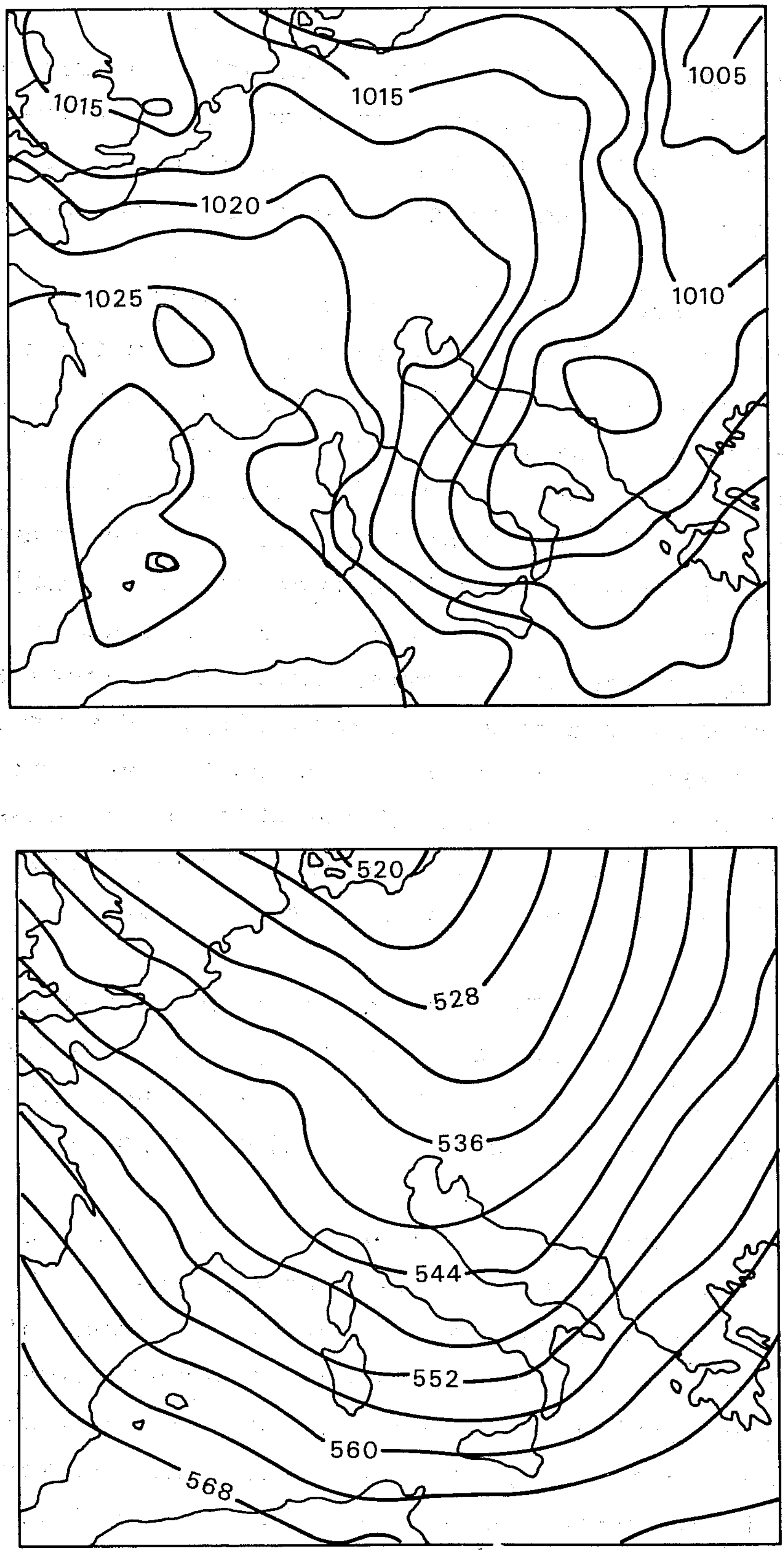

Fig. 16 36h forecast verifying at 1200 GMT 4 April 1973 (see also Fig. 15); a) MSLP: b) 500 mb height. After Tibaldi and Janjić (1978) the right intensity. The orographic origin of the disturbance is confirmed by the fact that both models fail to develop a lee cyclone at all if mountains are not present (control experiments).

(ii) Both models fail to describe correctly the development aloft (cut-off low). This failure to represent in a realistic way the upper tropospheric development is a common characteristic of almost all numerical simulations of lee cyclogenesis. To understand and isolate its causes amongst the many possible factors is the major goal of future research in this field, because it is likely to increase substantially our understanding of atmospheric numerical modelling. The problem is, however, further complicated by our limited understanding of some of the physical processes that are likely to contribute to the partial failures of these numerical simulations.

Mesinger et al., (1979) have very recently reported a real data numerical simulation of a case of lee-cyclogenesis that shows a very realistic development, not only at low levels, but also in the mid- and high-troposphere.

The model is the same as described above (Janjić, 1977, Mesinger, 1977), but, in this version, was further developed by Mesinger in a number of directions. Among other features, it now had the possibility to use observed (time dependent) boundary conditions (to overcome some of the limited area problems), to have physical parameterizations included (GFDL), to run with "double" resolution (grid length of 81 km at 45 ^{o}N), and to use fourth (instead of second) order horizontal advection; it also had 9 levels in the vertical.

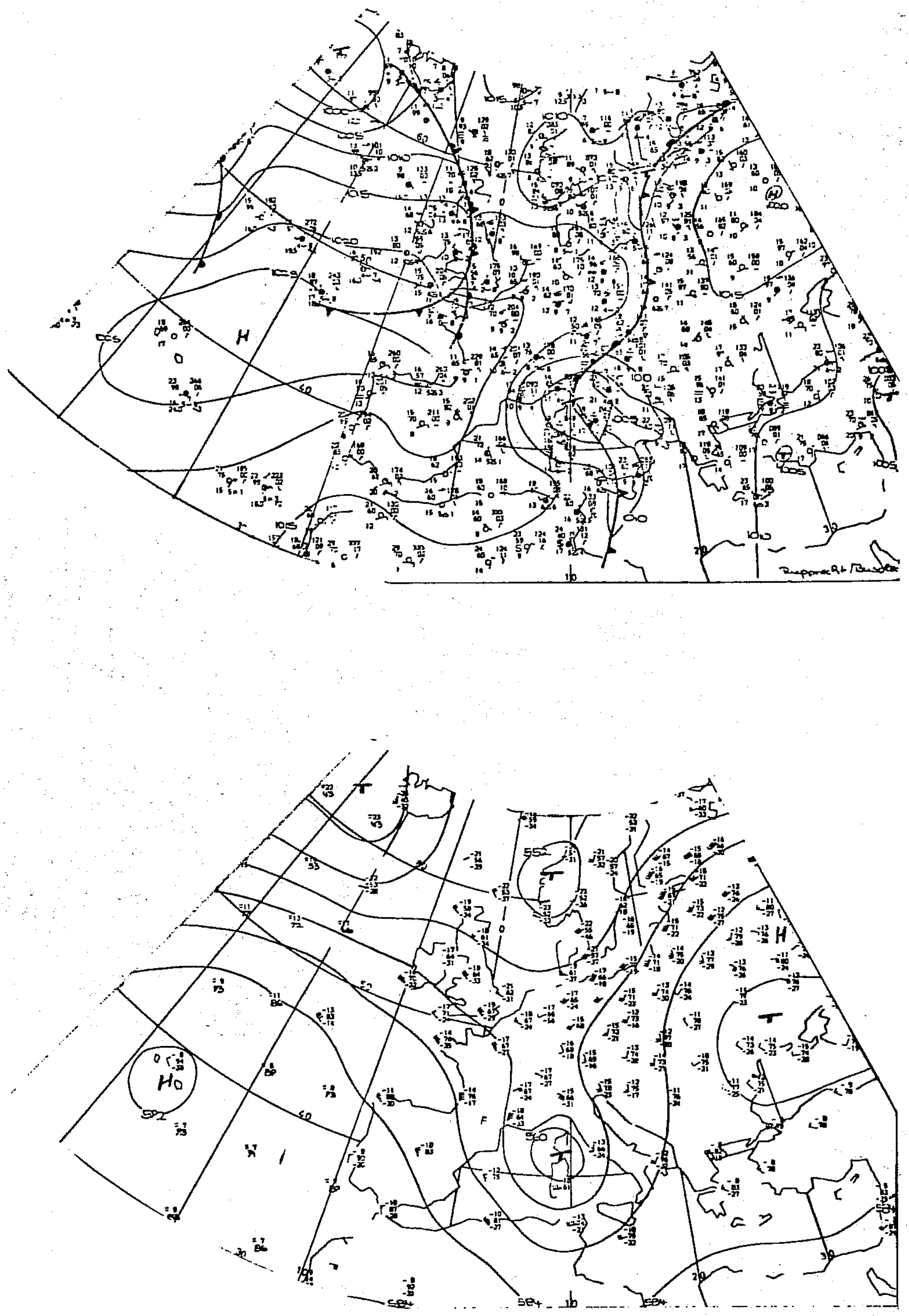

Fig. 17 00GMT 24 August 1975; a) MSLP; b) 500 mb height. Analysis of the German Weather Service.

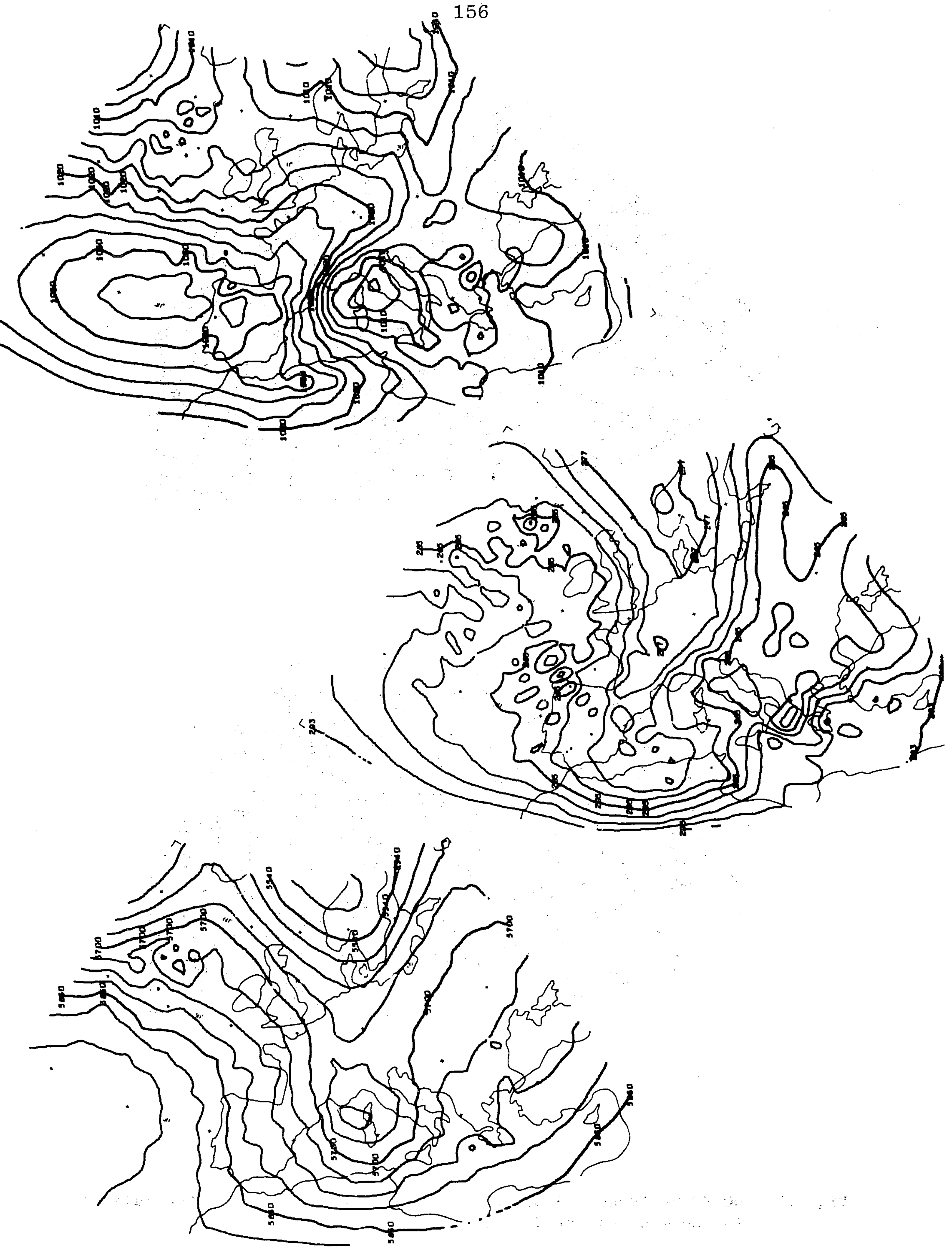

Fig. 18 OOGMT 24 August 1975; a) MSLP; b) 850 mb temperature; c) 500 mb height; 48 hour forecasts obtained by the GFDL staggered grid, enstrophy and energy conserving limited area model. Constant boundary conditions, "fourth" order horizontal advection, "adiabatic" ("minimum physics") version model, 51x19x9 points (1.5 x 1 degrees latitude x longitude) resolution. After Mesinger et al. (1979).

The initial data came from the NMC DST-5 analyses for 00GMT 22 August 1975; the mountains were lower (maximum height of the Alps 1940 meters) and also slightly smoother than in Tibaldi and Janjić's experiment.

The most successful simulation so far has been obtained using "double" resolution with second-order horizontal advection (compare Figures 17, 18 and 19), while the sole influence of having time dependent boundary conditions (not shown) did not seem to be quite as important.

With "physics" (not shown) the 500 mb cut-off is intensified, and is just about as fast as it apparently should be. The surface low is also deeper, but generally, at the sea level, "physics" did not improve dramatically the results of the low-resolution, time-dependent boundary conditions run.

As can be seen from Figure 20, the cyclogenesis takes place irrespective of the presence of the topography (which did not happen in the previous two cases), although the topographical modifications are very conspicuous (compare Figures 18 and 20) and quite well simulated by the model. In the experiment with mountains, the ridging at sea level northwest and southwest of the low and the ridging at 500 mb north of the cut-off (which could be the mechanism through which the mountains enhance the speed of the cut-off process in the upper troposphere) are particularly well captured.

With respect to this last point, it is perhaps revealing to look at the 850 mb temperature maps in Figures 18c and 20c. The region covered by temperatures below 279K in central Europe north and west of the Alps is much greater with mountains than it is without mountains. The point marking 10E longitude and 50N latitude is seen, for example, to have a temperature about 4-5K less with mountains than without mountains, and this is just about the region where

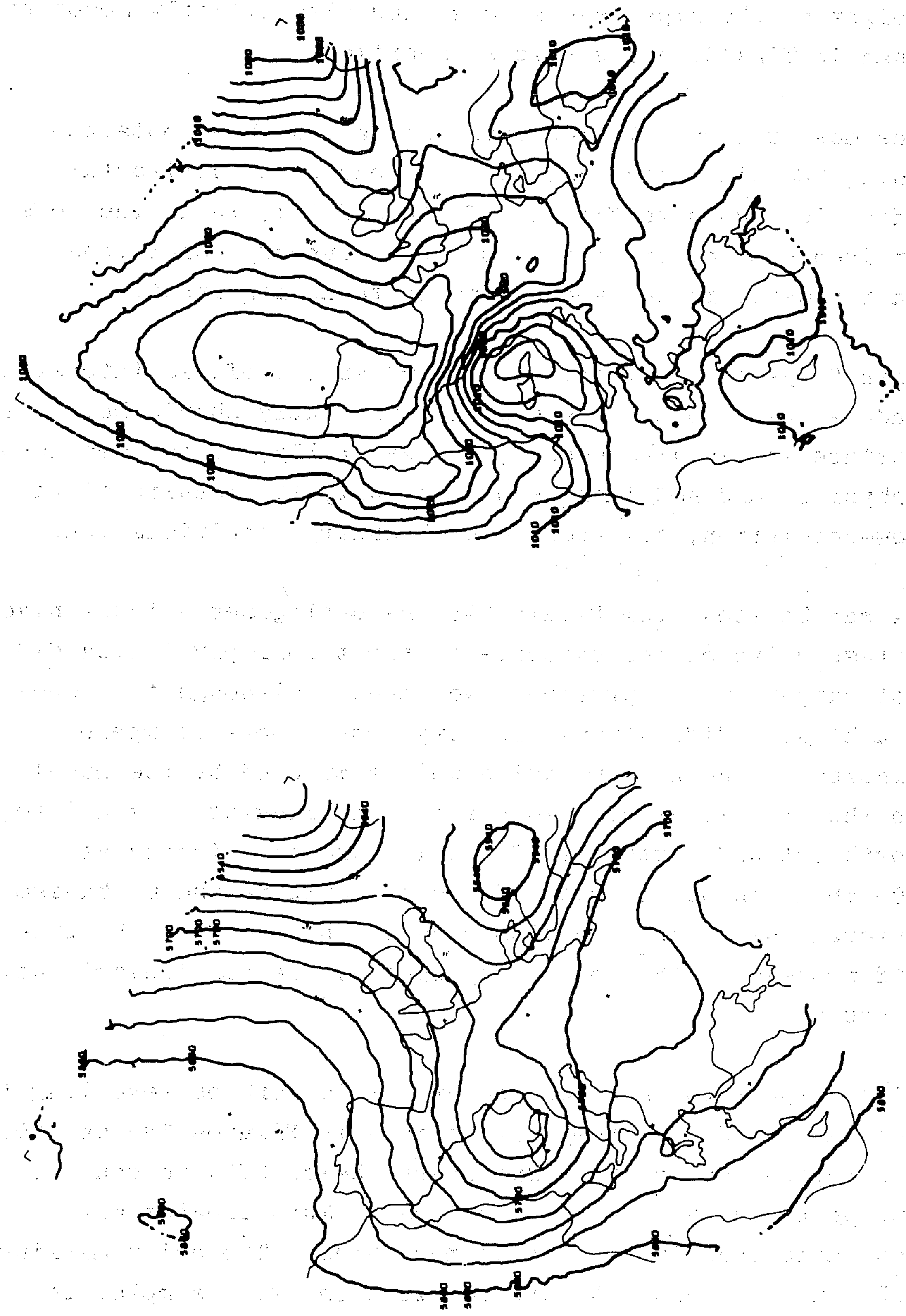

Fig. 19 Same as 18, but with double horizontal resolution (101x37x9 points, 0.75x0.5 degrees latitude x longitude) order horizontal advection schemes and observed boundary conditions; a) MSLP; b) 500 mb height. After Mesinger et al. (1979).

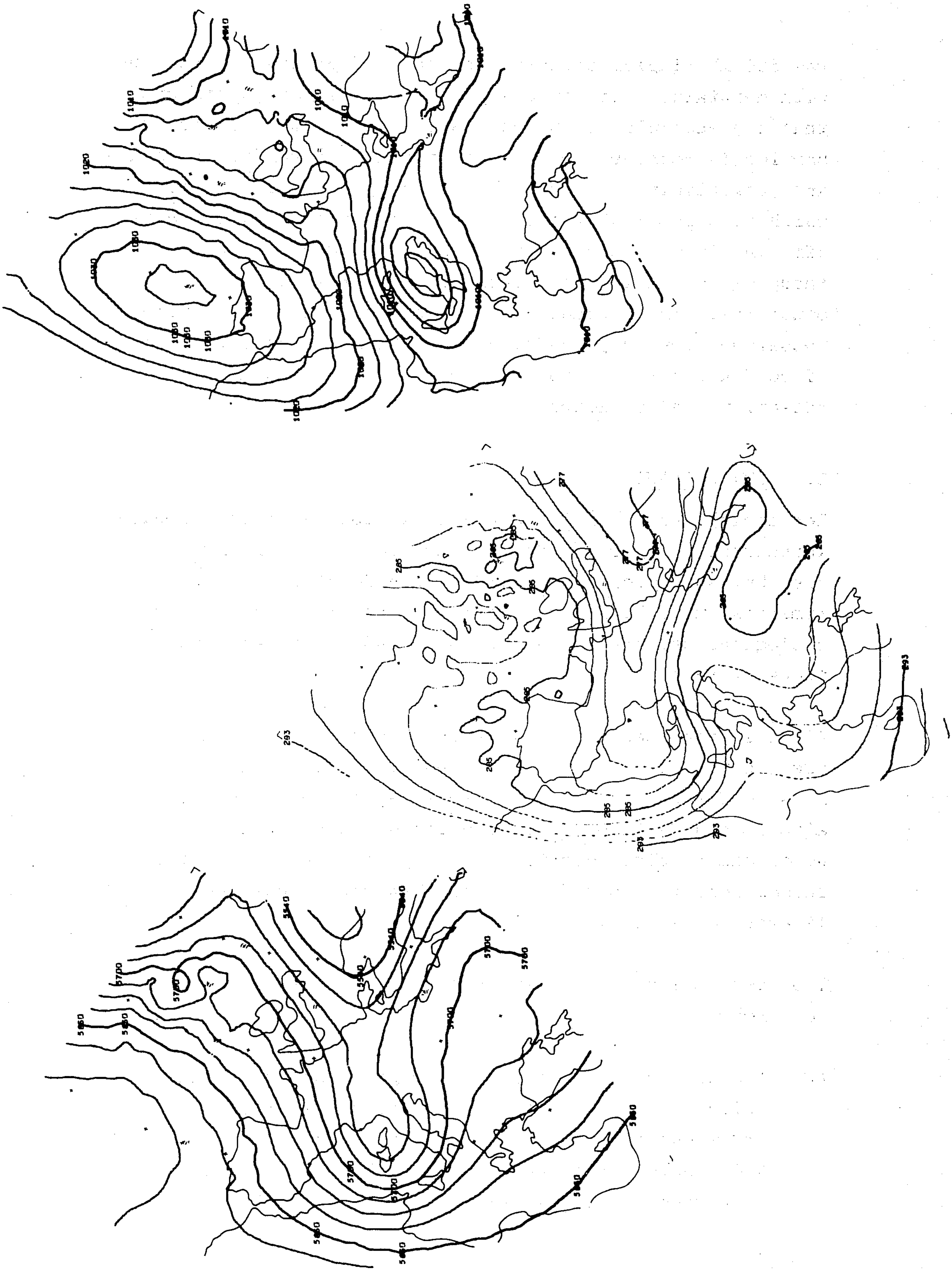

Fig. 20 Same as 18, but with no mountains. After Mesinger et al. (1979).

the 500 mb ridging executes the cut-off process in the run with mountains. It would appear, as Mesinger points out, that the accumulation of cold air north of the Alpine barrier is responsible for the increase in surface pressure, and, relatively speaking, also of geopotential heights, which then remarkably accelerates (in this case) the cut-off, and in some other cases possibly makes it occur even though it would fail to occur, in this region, without mountains. In agreement with this view, in the run with "observed" boundary conditions in which the accumulation of cold air north of the Alps happened to be slower, the cut-off was also slower.

5. CONCLUSIONS

Lee cyclogenesis remains a challenge for the meteorological forecaster in general, and in particular for the European one, but some progress towards its understanding and its numerical modelling has been made since the early phenomenological hypotheses by Radinović and numerical simulations by Egger.

All the idealized numerical simulations and limited area "real data" forecasts of cyclogenesis in the lee of the Alps so far produced show various degrees of success, but also common failures. An encouraging point is that the numerical results seem to be fairly consistent with the phenomenological picture of the phenomenon that the literature has so far outlined.

The numerical experimentation seems, in particular, to confirm:

(a) the distinction between a "trigger" phase, during which a low-level flow perturbation is produced and whose details can be different from case to case, and a baroclinic phase, during which this perturbation grows into a mid-latitude cyclone. The former is very often characterised by an intense deformation of the low-level thermal advection field caused by pronounced blocking effects due to the mountain and consequent flow of the cold advection mainly around the obstacle, while the flow aloft is left virtually undisturbed. The baroclinic phase is characterised by very fast growth-rates during its early stage, and by a progressive increase of the horizontal scale of the perturbation and of its vertical coherence, being this well in accord with theory and numerical experimentation on baroclinic instability as an initial value problem.

(b) The separation of the phenomenon in two distinct lower-tropospheric and upper-tropospheric developments (the first apparently easier to model numerically than the second). The overlapping of these two developments is a fundamental ingredient to produce deep and long-lasting cyclones, as opposed to shallow and short-lived lee-lows that are soon dissipated away (see also Speranza, 1975).

Although the numerical experimentation about lee cyclogenesis in general, and about cyclogenesis in the lee of the Alps in particular, has been, up to now, limited to few attempts, it is hoped that the existence, now official, of a GARP mountain sub program (ALPEX) will draw more attention and more resources on this problem. The rate of occurrence of this meteorological phenomenon in the sole Alpine region (10-20 full-size cases per year) makes very worthwhile any effort made towards its better understanding and numerical modelling, in terms of improved short- and medium range numerical weather forecasts.

Numerical case studies (carried out in parallel with careful production of detailed verification analyses and cross-sections) should try to investigate primarily:

(a) the dynamics of possible "trigger" mechanisms (interaction between the obstacle and the low-level circulation);

(b) the dynamics of the upper-level development, its possible localisation in-situ by the mountain (interaction between the obstacle and the upper-level circulation) and the origin of the difficulties that limited area models have encouraged in modelling it;

(c) the details of the energy conversion budget and the importance on both the trigger and the development phases of the diabatic (e.g. latent heat release) and sub-grid scale physical mechanisms (e.g. surface friction and wave drag parameterization) in order to assess their relative importance for an accurate forecast of the phenomenon.

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