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A multi-stage evolution of an ALPEX cyclone

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ABSTRACT

The rôles of topography, convection, sensible and latent heat fluxes in Alpine lee cyclogenesis are investigated. The adoption of a newly developed factor separation method allows the identification of the contributions of each of these processes as well as their synergistic effects. Topographical blocking is the dominant factor in the first and most rapid phase of the cyclone deepening. This is followed by the convection contribution at the 2nd but slower phase. Local moisture flux is dominant in the 3rd phase accompanied by a significant cyclolytic contribution by the Alps. Between the 1st and the 2nd phases of deepening, the synergistic effect of convection induced by the mountains plays an important rôle in the deepening at a time when the convection independent of mountains has not become yet so active. Coarser horizontal resolutions still capture these features, although to a lesser extent. Model simulation results are shown to be strongly dependent upon the chosen set of factors. As the number of factors increases, a specific contribution diminishes because synergistic terms with the new factors are extracted from the contribution of the specific factor under investigation. Another interesting conclusion is that the elimination of an important factor from the investigation will not remove its contribution. It will reappear and be attributed to another factor which is the most synergistic to the important factor. The spread of the cyclones' centers in the model simulations is shown to be a powerful tool in understanding the effects of different factors on the evolution of the model solutions. For instance, convection moves the cyclone to the east northeast while topography ties the cyclone to the lee of the Alps. The sea moisture fluxes tend to move the cyclone toward the warm bodies of water.

1. Introduction

A relatively large number of studies have been devoted to cyclogenesis with particular attention to the processes responsible for the lee cyclone generation. Early studies of lee cyclogenesis (LC hereafter) focused on observations and indicated the most concentrated regions with high frequencies (Petterssen, 1956). More recently, several theories were suggested to explain the LC features and they are frequently separated for convenience into 2 groups as follows: the modified (by the lower boundary layer) baroclinic instability approach as reviewed by Tibaldi et al. (1990) and Pierrehumbert (1985) and the directional wind shear suggested by Smith (1984).

Along with the theoretical approaches, numerical models have been exceedingly used, starting with the pioneering work at the Alps by Egger (1972), in order to both explain real cyclogenesis developments as well as to verify the simplified theories. The models became more recently the most realistic tools particularly with the full physics of the 3-D mesoscale models. Current numerical models seem to be very efficient in performing excellent simulations of complex LC developments. At the same time, the theoretical models are unable to really clarify the complex physical mechanisms for the LC, Egger (1988).

Several studies of Alpine LC, both observational (Buzzi and Tibaldi, 1978) and modeling

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(Dell'Osso and Radinović, 1984; Tosi et al., 1983), clearly indicate the existence of 2 distinct phases in development. The 1st is a rapid one typically less than 12 h that was attributed to the blocking of the low level cold front. The second deepening phase is a slower one (24 h) and better fits the typical growth-rates of baroclinic instability (Tibaldi et al., 1990).

Numerical simulations (Dell'Osso and Radinović, 1984) indicate that latent heat release is a major cyclogenetic contributor at the 2nd phase. Other important mechanisms particularly with regard to Alpine LC were suggested to be fluxes of latent and sensible heat (Emeis and Hantel, 1984). However, no numerical simulations were attempted in order to separate all the aforementioned contributions at different stages. One of the major reasons, besides the modeling complexity, is the existence of many synergistic interactions among these processes that complicate the sensitivity study. Recently, Stein and Alpert (1993, SA hereafter) have shown that for n factors being investigated, 2^n simulations are necessary in order to separate the contributions and all the possible interactions.

In the present study, we apply the factor separation method to the most impressive Alpine LC development observed on the 3–6 March 1982 during the Alpine Experiment (ALPEX). Quite a number of papers, mostly observational and through modeling, have dealt specifically with this case and the comparison of their results with those obtained here by the factor separation method will illustrate the power of this method. Furthermore, the choice of 4 factors, topography, convection#, latent and sensible heat fluxes will allow a direct comparison with the aforementioned studies. Another important mechanism is the potential vorticity (PV) advection that was found to be the important mechanism in some Alpine lee cyclogenetic cases (Bleck and Mattocks, 1984). It was not chosen as a factor here due to the complexity in switching the PV advection on/off. See further discussion in Section 3.

Section 2, describes the time variation of the factor-separated contributions to the lee cyclone deepening. Section 3 discusses a major limitation of sensitivity studies. Sections 4 discusses divergence of the solutions with time and the significance in understanding lee cyclogenesis. Section 5 summarizes our main findings.

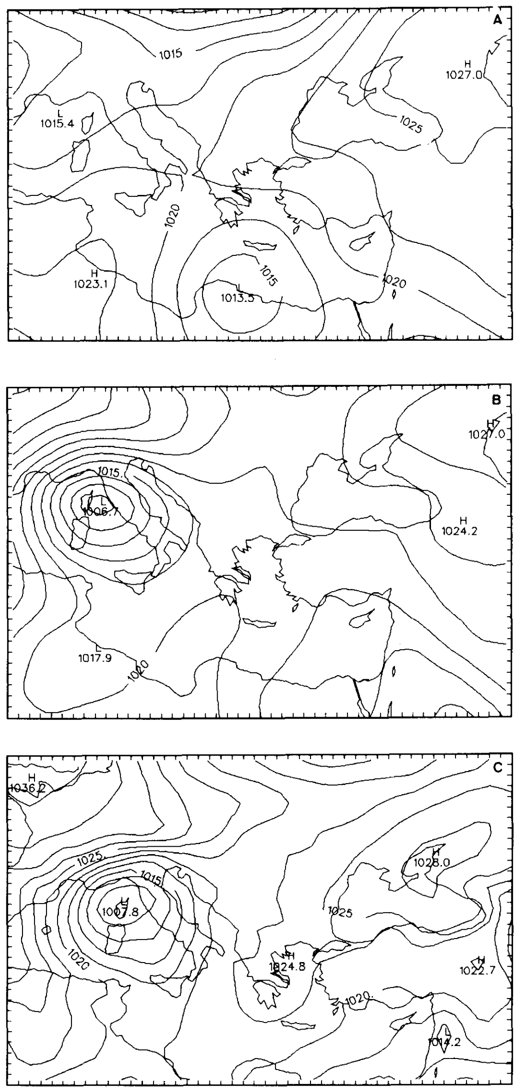

Fig. 1. Surface pressure charts for the ALPEX lee cyclogenesis on the 3–6 March 1982. (A) 4 March 1200 UTC ECMWF analysis; (B) 5 March 1200 ECMWF analysis; (C) 48 h model prediction for the 5 March 1200 UTC. (B) is the verifying analysis for model prediction in (C). The isobaric interval is 2.5 hPa. The mesh is due to plotting software.

It should be clarified that only the convective processes as formulated by the Anthes-Kuo cumulus parameterization scheme were switched on/off for testing the convection factor. This factor will be henceforth referred to as convection, having in mind latent heat release due to cumulus convection only.

Table 1. *Published literature on the 3–6 March 1982 ALPEX lee cyclogenesis; the specific factors and primary focus for each study, are listed*

Reference	Factors or fields	Focus
Bleck and Mattocks (1984)	1. potential vorticity	potential vorticity and lee cyclogenesis
Dell'Osso (1984)	1. topography 2. resolution	case study
Frenzen and Speth (1984)	1. kinetic energy budget 2. vorticity	diagnostics
Hantel et al. (1984)	1. absolute vorticity 2. kinetic energy budget 3. latent and potential heat budget	improvement of objective analysis scheme
Buzzi et al. (1985)	1. mass field 2. trajectories 3. vertical velocity	isentropic analysis
Frenzen and Speth (1986)	1. kinetic energy 2. vorticity	comparison of several studies
Johnson and Hill (1987)	1. mass and angular momentum balance	quasi-lagrangian diagnostics
Zupanski and McGinley (1989)	1. topography 2. jet streak 3. low-level baroclinicity	role of upper versus lower dynamics
Tafferner and Egger (1990)	1. topography	verification of theories
Trevisan and Giostra (1990)	1. topography 2. baroclinic wave	dynamical balance

2. The 3–6 March 1982 lee cyclone development

One of the most studied lee cyclogenesis both observationally (Buzzi et al., 1985; Buzzi et al., 1987) and by numerical simulations (Tafferner and Egger, 1990; Tibaldi and Buzzi, 1983; Bleck and Mattocks, 1984; Dell'Osso, 1984) is the 3–5 March 1982 ALPEX case. A summary of some of the published literature and main objectives is presented in Table 1. It was the most intense (Buzzi et al., 1985) lee cyclogenesis deepening during the ALPEX international special observational period aimed at a better understanding of mountain rôle in weather. Figs. 1A, B show the 4 and 5 March 1200 UTC analyzed surface maps based on ECMWF (European Centre Medium Range Weather Forecasts) initialized analyses. An 8.7 hPa (mb) deepening in the lee of the Alps occurred within 24 h, most of the pressure fall (6.1 hPa) within the last 12-h period. Our 48-h model simulation (to be discussed later) is shown in Fig. 1C and its verifying analysis in Fig. 1B. Model simulations were performed by several research groups in order to better understand the physical processes responsible for this impressive phenomenon. First, the topographic barrier which blocks the low-level cold front was suggested as responsible for the first phase of rapid deepening (Buzzi and Tibaldi, 1978). In addition, the convection and the associated latent heat release developing in the lee were related to the 2nd phase deepening (Dell'Osso and Radinovic, 1984). The effects of the surface latent and sensible heat fluxes from the sea region located in the lee were also suggested as contributing to the cyclone's formation (Tibaldi et al., 1990). Consequently, 4 factors were chosen, topography (t), surface latent heat flux (l), surface sensible heat flux (s) and the latent heat release (r) in the deep clouds developing within the cyclonic system. In order to calculate the possible 16 (2^4) contributions, mesoscale simulations with the PSU/NCAR mesoscale model version MM4 were performed. Horizontal resolution was 80 km with a 46×34 mesh and 16 levels up to ~ 16 km. Further details on model and simulations can be found in SA. Initial time for simulations was 3 March 1200 UTC. The sea-level pressure change at the center of the control run cyclone was then partitioned into contributions by each process or combination of processes. These included 4 "pure" contributions (t, l, s and r), 6 double interactions, 4 triple interactions (tsl, tsr, tlr, slr), one quadruple interaction ($tslr$) and the residual referred crudely[#] to as the "large-scale contribution". This term was excluded from the following discussion because only the local processes were investigated. In fact, the relatively strong contribution of the large-scale in this case was noticed by other authors (Tafferner and Egger, 1990). Indeed, in our simulation, the large-scale run with all factors switched off yields a weak cyclone, with a cyclone central pressure value of 1011.2. This is about half of the deepening and is also contributed to by the model lateral boundaries as indicated in further experiments not discussed here.

The separation method was fully described in SA but in order to further illustrate how the method works with 4 factors, the formulae for the double and the triple interactions (tr and tlr) are written as follows, eq. (16) in SA:

$$\hat{f}_{tr} = f_{tr} - (f_t + f_r) + f_0, \quad (1)$$

$$\hat{f}_{tlr} = f_{tlr} - (f_{tl} + f_{tr} + f_{rl}) + (f_t + f_l + f_r) - f_0, \quad (2)$$

where $\hat{f}_{ijk}$ $i, j, k \in \{t, l, r\}$ is part of the predicted field f (pressure in this note) dependent solely on combination of the factors i, j and k (i.e., synergistic contribution), while f_{ijk} is the value of the predicted field for the simulation where only factors i, j, k are on. The predicted field f when all factors are zero is f_0. Notice that the "hat" functions ($\hat{f}$) on LHS of (1)–(2) are calculated from the model simulation output represented by f functions on the RHS.

Fig. 2 presents the time evolution for all the 15 local contributions illustrating the dominant processes at each stage for the Genoa cyclone deepening. Fig. 2A focuses on major 5 contributions to be later discussed in more detail while Figs. 2B, C show the rest of the contributions.

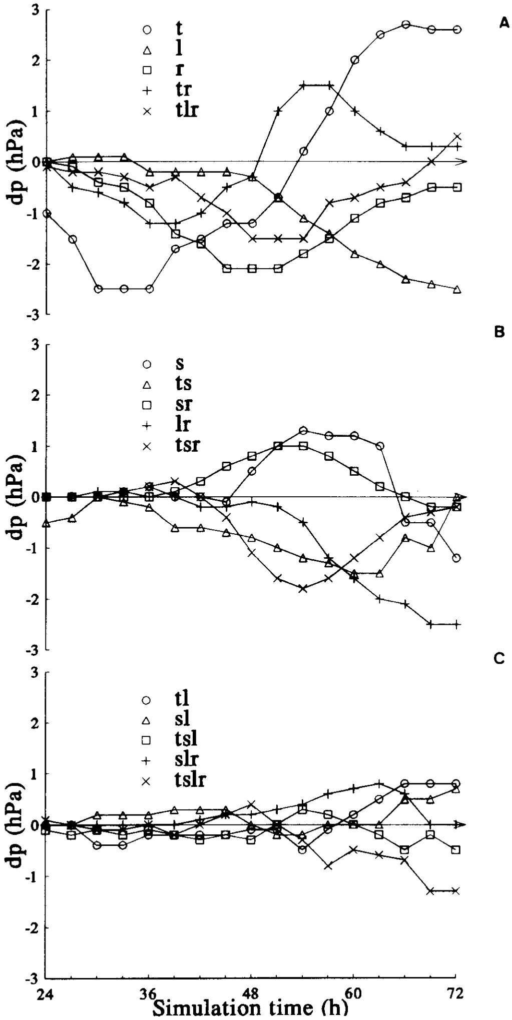

Fig. 2. The 48 h time evolution for all the 15 local contributions to the ALPEX cyclone deepening (hPa) following 24 h of simulation. The interaction synergistic contribution are indicated by the letters of their parent factors. (A) First 5 major contributors; (B) next 5 contributors; (C) last 5 contributors.

The mechanical effect of the Alpine topography (t) is the first to generate the rapid deepening within 6 h, Fig. 2A, while all other contributions are still much smaller. This corresponds well to the aforementioned 1st phase. In the 2nd phase, the latent heat release (r) or "convection only" becomes the dominant contributor (42–54 h) while the "pure" topographic contribution quickly

[#] Indeed not all the small scale contributions were included in the considered four factors.

Table 2. *Primary and secondary cyclogenetic processes as well as major cyclolytic contributors and their time evolution, based on the factor separation for sea-level pressure at the cyclone's center*

Stages in lee cyclogenesis 3–6 March 1982

Time (h)	0 ——— 12 ——— 24 ——— 36 ——— 48
primary process	← topography blocking (*t*) → ← convection (*r*) → ← (*tsr*) → ← local moisture flux (*l*) →
secondary process	← *ts* → ← *tr* → ← *r* → ← *t* → ← *tlr* → ← *tsr* → ← *r* → ← *tsr* → ← *lr* → ← *l* →
cyclotonic	← none → ← *tr* → ← *t* →

tlr: mountains convection induced by local moisture fluxes.
tsr: mountains convection induced by sensible heat fluxes.
ts: mountains heating.
tr: mountains convection.
lr: convection due to local moisture fluxes.

diminishes to become later a major cyclolytic (destruction of cyclone) factor. This is probably due to the cyclone's motion beyond the favorable lee region. Of interest here is the considerable contribution of the synergistic double and triple interactions. For instance, the mountain-induced convection (*tr*) is the 2nd contributor at the 1st stage (27–36 h). Each of the synergistic terms can be associated with a specific meaning shedding light on the complex physical mechanisms under investigation. The triple interaction *tlr*, quite important at the 45–60 h phase, for instance, represents the contribution to the deepening by the terrain-induced convection with local moisture (synergism of terrain, convection and surface latent heat flux). Table 2 summarizes the primary and secondary cyclogenetic processes as well as major cyclolytic contributors that emerge from the surface pressure analysis. Obviously, the results here, as well as in the other examples, are valid only to the extent that all the model simulations represent the real atmosphere.

One way to address the sensitivity of our factor-separated results to the particular model setting is to repeat such an experiment with a different resolution. Fig. 3 presents the 5 major contributions for such an experiment with a coarser horizontal resolution of $\Delta x = \Delta y = 180$ km, i.e., a horizontal interval which is more than double. Comparing Fig. 3 with Fig. 2A, one finds that again the topography (*t*) is the first to generate the rapid deepening, but about 12 h earlier. Later, it becomes the major cyclolytic factor. The differences may be attributed to the less detailed representation of the Alps by the 180 km compared to 80 km horizontal interval. The cyclone deepening with the coarser grid of 180 km was indeed significantly weaker, i.e., 7–8 hPa higher central pressure. The other factors show similar general trends although the magnitudes and phases, not unexpected, are different. In particular, the triple interaction *tlr* becomes the major contributor to the phase II deepening and significantly exceeding that of *tr* for the 80 km run. This implies that a horizontal interval of 180 km is inadequate for simulating such an Alpine lee cyclogenesis. Section 3 deals with the sensitivity to the set of factors being chosen for investigation.

3. Absolute comparisons for effects of several processes

In Section 2, 4 factors were chosen. Alpert et al. (1995) address the sensitivity of the factor

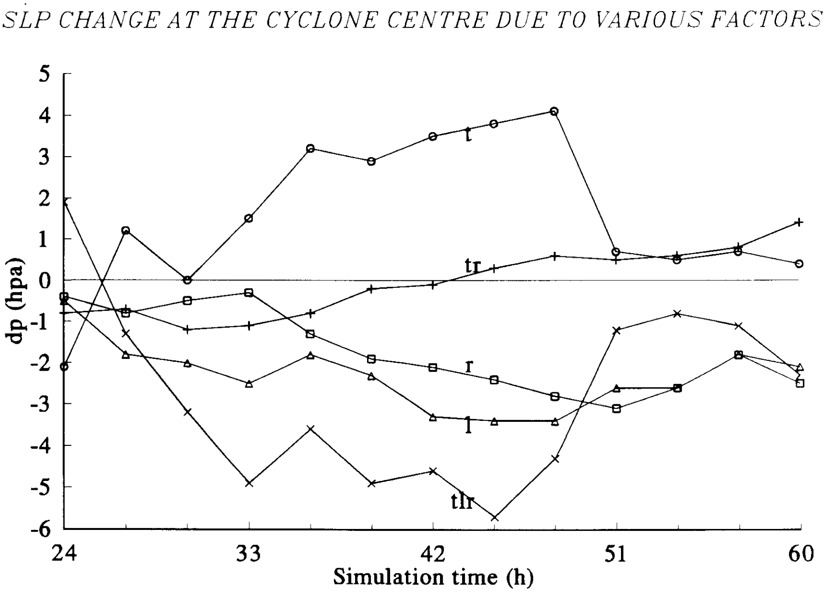

Fig. 3. As in Fig. 2A, but for coarser model horizontal resolution of $\Delta x = \Delta y = 180$ km.

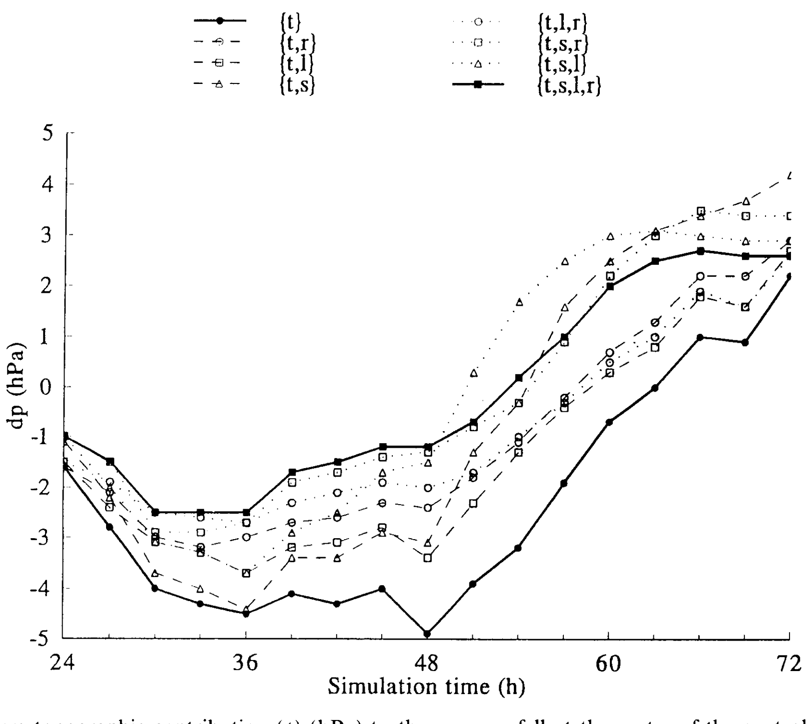

Fig. 4. The pure topographic contribution (t) (hPa) to the pressure fall at the center of the control cyclone as a function of the simulation time. Each curve represents one of the 8 possible sets of factors (see text). Heavy lines indicate the minimum choice of one factor only $\{t\}$ and the maximum choice of 4 factors, i.e., $\{t, s, l, r\}$.

separation results to the number and type of factors to be selected. They show that the increase in the number of factors diminishes the individual contribution of a particular factor. If, for instance, topography, which is a crucial factor, is included in each of the 8 potential sets $\{t\}$, $\{t, s\}$, $\{t, l\}$, $\{t, r\}$, $\{t, s, l\}$, $\{t, s, r\}$, $\{t, l, r\}$ and $\{t, s, l, r\}$, its contribution varies significantly from case to case as shown in Fig. 4. Notice that the notation with $\{\ \}$ refers to a potential numerical experiment for which the chosen factors or processes to be tested are listed within the parentheses as a group. This notation *should not be confused* with that of a specific contribution isolated for a particular experiment. For instance, the triple interaction *tlr* in the preceding section was isolated in an experiment for which 4 factors were chosen, i.e., the experiment $\{t, s, l, r\}$. Of course, each set is a legitimate choice for a modeler who investigates the rôle of topography (t) in the lee cyclogenesis and such examples are found in the literature, see SA. In Section 2, we have chosen the specific set with all 4 factors included, i.e., $\{t, s, l, r\}$. Fig. 4 presents the "pure" topographic contribution to the cyclone deepening for each of the 8 possible sets of factors to be investigated. It is not unexpected that the topographic contribution is largest when only one factor $\{t\}$ was considered, and the smallest, at least until the 48th hour of simulation was reached, when the largest set of factors $\{t, s, l, r\}$ was chosen, since, as the number of factors increases, synergistic contributions between the new factors and topography are extracted out from the original t contribution. In the extreme case where only topography was chosen as a factor, all synergistic contributions with the topography are tacitly assumed to be part of the topographic contribution making it the largest-bottom curve in Fig. 4. For instance, the cyclogenetic contribution of the latent heat release synergism with topography (*tr* in Fig. 2A) is associated with the topography in the case when r is not an investigated factor.

Another example for the effect of the particular choice of factors is given in Fig. 5, but here for the latent heat release (r), or convection. In all of the 8 experiments, the same contribution which is due to convection only, is represented in Fig. 5. Again, the increase in the number of factors diminishes, at least till about 36 h, the individual contribution of convection, more and more along with the production of new synergistic terms (not

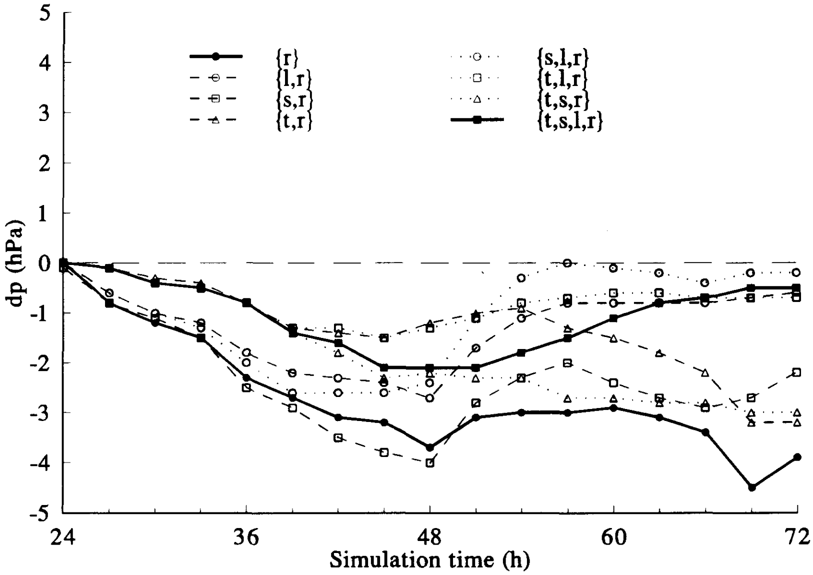

Fig. 5. As in Fig. 4, but for the contributions to the cyclone deepening due to the latent heat release (r), or convection.

shown) that are associated with the new factors. Later on, there are several curves outside the range bounded by $\{r\}$ and $\{t, s, l, r\}$ because of negative synergisms as well as error increases in the model with time. Fig. 5 illustrates that the unavoidable introduction of synergism prohibits a quantitative comparison for the effects of several processes, which is independent of the particular choice of the factors. The more meaningful result may therefore be the calculation of the variations in the contributions of a specific factor for several relevant groups of factors, e.g., Figs. 4, 5. In contrast to the topographic contribution which could be of either sign (Fig. 4), convection is a positive contributor to cyclone deepening, independent of the stage of development or the set of factors, Fig. 5.

It is interesting to note that the particular set $\{s, l, r\}$, which does not include topography, yields a convection contribution which is quite similar to the (tr) contribution in Fig. 2A. This is explained by the fact that since topography was not chosen in the $\{s, l, r\}$ set, its contribution was associated with the convection (r) through the hidden synergism between topography and convection, i.e., (tr). This leads to the following important lesson regarding the choice of factors. *If a dominant process or factor was not chosen by the modeler#, its effect will be identified with a different process or factor which is the most synergistic with the not chosen factor.* This may not be regarded as erroneous since one can, in a more general view, also associate with a particular factor all its synergistic contributions with the not chosen factors. This is a reasonable choice as long as one is aware of the fact that this study is focused on a particular set of factors and their inner interactions only. Another example to illustrate this point is the factor of the PV-advection that was indeed shown by several investigators to be the important mechanism in some LC cases (Pichler and Steinacker, 1987; Bleck and Mattocks, 1984; Tafferner, 1990). Since PV-advection was not chosen here as a factor, the induced convection due to the PV-advection clearly becomes a hidden synergism which is related, in our study, to the more general definition of convection. This is a reasonable choice as long as we are aware of the fact that our focus is on the relations among the chosen factors only, and we accept the further weight given to convection by the hidden synergism with the important PV-advection.

Similar results apply to a study of a synergistic contribution with several choices for the sets of factors. Fig. 6 presents the *tr* contribution where 4 set choices are presented. The increase in the number of factors in the set tends to diminish the individual contribution of *tr* till about 50 h, since, as the number of factors increases, the synergistic contributions between the new factors and *r* or *l* or both (double and triple synergism) are extracted. For longer simulation periods, negative synergistic terms and increasing errors seem to strongly modify this behaviour.

4. Spread of the model simulations

In Section 2, an experiment with a set of 4 factors was described. The factor separation method therefore required $16 = 2^n$ different simulations with all possible combinations of factors switched on/off. Obviously, in each simulation, the cyclone center may have a different location, which reflects the specific dynamical evolution due to the contribution of factors switched on. Fig. 7 presents the 16 different locations of the cyclone center following 45 h of simulation time. In this notation, the factors switched on are listed, so TLR, for instance, indicates the simulation where only the factors *t*, *l*, and *r* were operating while *s* was switched off.

A remarkable feature in the spread presented in Fig. 7 is the tendency of the factors to attract the cyclone center toward different regions. The convection (r) drifts the cyclones to the east-northeast while topography does similarly but to the north-northwest and the latent/sensible heat fluxes (l and s) move the cyclone toward the sea; a southern tendency. This feature is even more pronounced as the spread of the solutions with time is analyzed. Fig. 8 presents the cyclone centers, as in Fig. 7, but at 30, 45 and 60 h of simulation time. As time evolves, and the cyclone

Note that this dominant factor will be active in *all* the tests with the chosen factors, since the words "was not chosen by the modeler" are not equivalent to "switch off". In contrast, an unchosen factor is never switched off by the modeler in the particular set of factors he has chosen because this factor was not chosen for the factor separation.

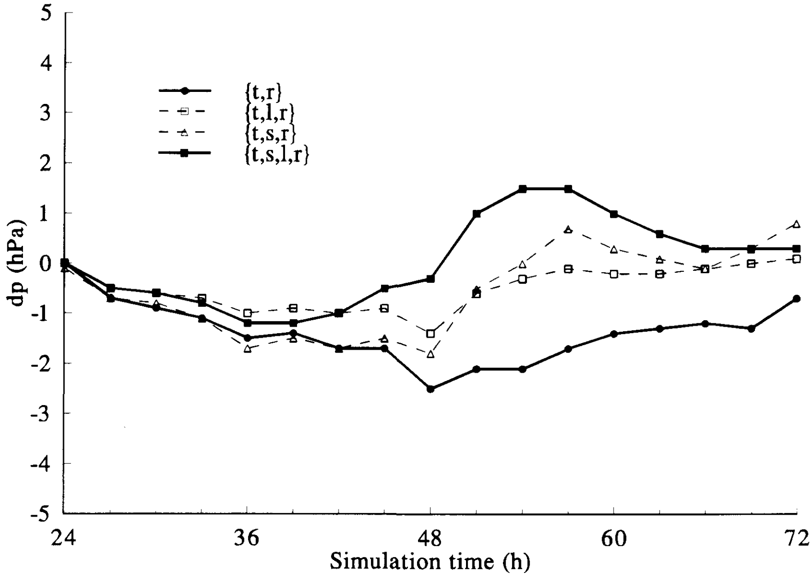

Fig. 6. As in Fig. 4, but for the contributions to the cyclone deepening due to the synergism (tr) between topography and latent heat release for 4 choices for the set of factors.

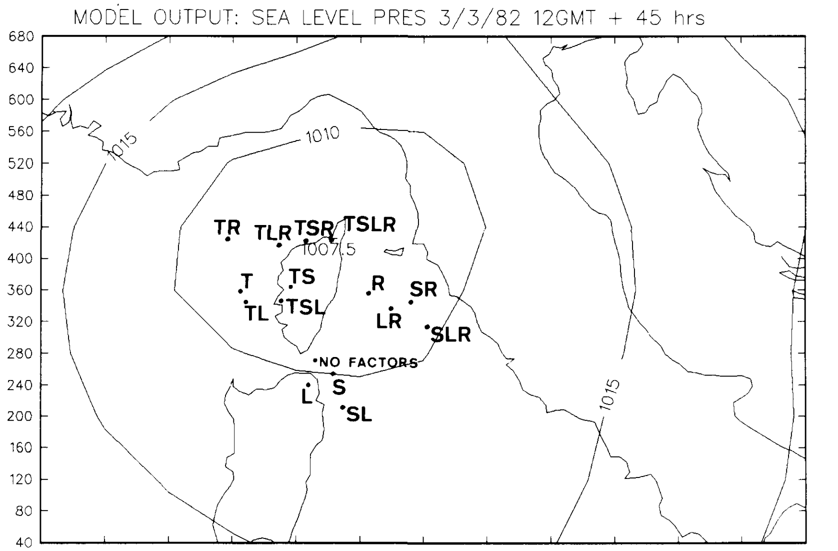

Fig. 7. The 16 locations of the cyclone center following 45 h of simulation for the 16 simulations with all possible combinations of factors switched on/off. In this notation, the factors switched on are listed: hence, TLR, for instance, indicates the simulation where only the factors t, l and r were operating while s was switched off.

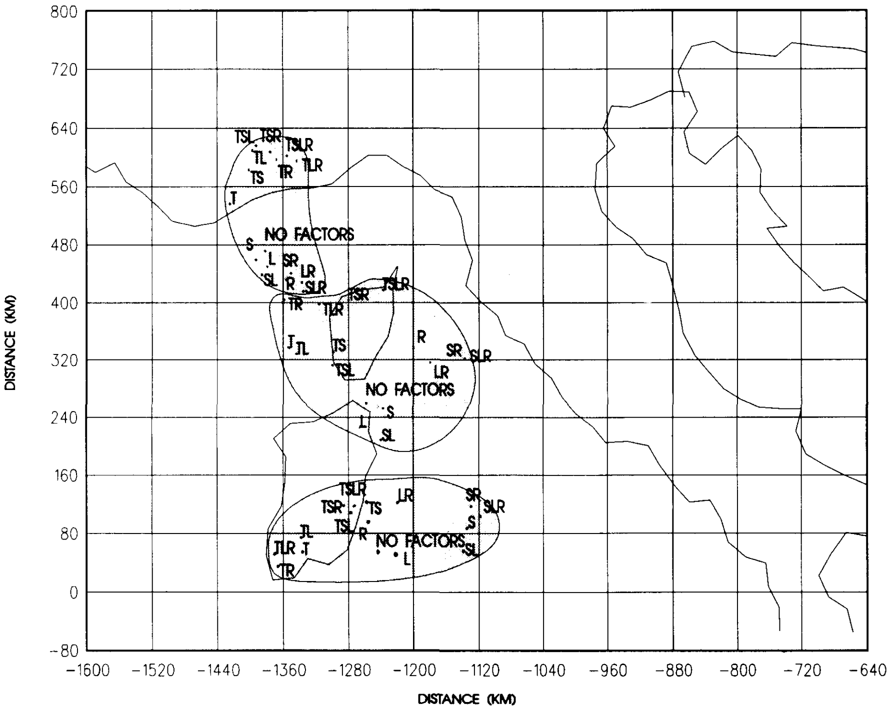

Fig. 8. As in Fig. 7, but for at 30, 45 and 60 h of simulation time in the north, central and south sections of the model domain. The cyclone spread region is denoted by shading.

spread region (shaded in Fig. 8) moves away from the lee cyclogenetic area, at 60 h, a clear change of the aforementioned tendencies takes place. The topographic factor delays the cyclone at the west over Sardinia while sea fluxes move the cyclone to the east where a larger and warmer body of water dominates.

The spread of the cyclones' centers in the model simulations raises the question whether the aforementioned pressure-separated results presented in Figs. 2–6 are valid for the points which are located off the cyclone center in the control run. The latter refers to the point TSLR where the factor separation was actually applied earlier in Sections 2, 3. Consequently, we have reproduced the pressure contributions, but for another point within the "cloud" of cyclone centers and this has yielded similar evolutions for the different processes as in Fig. 2 (not shown). It is expected, however, that for longer range predictions (beyond 60–70 h) where the spread of the cyclone centers increases even further, such a separation may not be valid any more.

5. Summary

The rôles of topography, convection, sensible and latent heat fluxes in Alpine lee cyclogenesis are investigated. The adoption of newly developed factor separation methods allows the identification of the contributions of each of these processes as well as their synergistic effects. Topographical blocking is the dominant factor in the 1st and most rapid phase of the cyclone deepening. This is followed by the convection contribution at the 2nd but slower phase. Local moisture flux is dominant in the 3rd phase accompanied by a significant cyclolytic contribution by the Alps. Between the 1st and 2nd phases of deepening, the synergistic effect of convection induced by the mountains plays an important rôle in the deepening at a time when the convection independent of mountains has not become yet so active. Coarser horizontal resolutions still capture these features, although to a lesser extent.

It should be noted that the 3–6 March 1982 cyclone exists even when all factors were switched off. Its development is in part attributable to the model lateral boundaries which are too close to the region where the cyclone is generated, and in part attributable to the so-called "large-scale contributions". This is the subject of a separate investigation not included here. The influence factors chosen therefore only modify a cyclone which is also occurring without the factors.

Model simulation results are shown to be strongly dependent upon the chosen set of factors. As the number of factors increases, a specific contribution in general diminishes because synergistic terms with the new factors are extracted from the contribution of the specific factor under investigation. Another interesting conclusion is that the elimination of an important factor from the investigation will not necessarily remove its contribution. It may reappear and be attributed to another factor which is the most synergistic to the important factor. The spread of the cyclones' centers in the model simulations is shown to be a powerful tool in understanding the effects of different factors on the evolution of the model solutions. For instance, convection moves the cyclone to the east northeast while topography delays the cyclone at the lee of the Alps. The sea moisture fluxes tend to move the cyclone toward the warm bodies of water.

6. Acknowledgements

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