NOTES AND CORRESPONDENCE

Can Sensitivity Studies Yield Absolute Comparisons for the Effects of Several Processes?

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ABSTRACT

The contribution of a particular process is shown to be strongly dependent upon the other processes under investigation because of synergistic contributions. In general, as the number of relevant factors being investigated increases, the role of any specific factor diminishes because the synergistic interactions with the new factors are extracted. This is illustrated with the variations of the topographic role in the impressive lee cyclone deepening event on 3–5 March 1982 during the Alpine Experiment. When latent heat release, latent heat flux, and sensitive heat flux enter into our comparative study, the topographic contribution to the surface pressure lee cyclone deepening gradually diminishes down to 50% or more.

1. Introduction

It has been recently illustrated (Stein and Alpert 1993, hereafter SA) how interactions among several processes being investigated can be isolated. Such synergistic interactions are significant (for example, Keyser and Uccellini 1987), and their calculation is a prerequisite for the proper comparison among the contributions of several factors or processes. This was demonstrated (SA) with two central factors, namely, the topography and surface fluxes, and their effect on the rainfall distribution for a cyclone evolution in the Eastern Mediterranean. Following the factor separation method additional examples on quite different scales were reported on the turbulence scale (Deng and Lilly 1992), meso-β scale mountain winds (Alpert and Tsidulko 1994), cloud scale (Khain et al. 1993), organized large boundary layer eddies (Levi 1993, personal communication), and others (Alpert et al. 1994). Although the foregoing discussion focuses on a mesoscale example, that is, processes that influence the deepening of a lee cyclone, it is not restricted to this scale. On the contrary, as illustrated by the aforementioned studies, synergism is significant on a wide range of atmospheric scales, from small-scale up to large-scale turbulence, and so are the implications to the present issue of comparing several processes. The purpose of this note is to quantitatively illustrate that the contribution of any factor is not unique and is strongly dependent on the particular set of factors or processes being chosen by the investigator. The case chosen for illustration is an impressive lee cyclogenesis event during the Alpine Experiment (ALPEX) and is described in the next section.

2. Cyclone development in the lee of the Alps

One of the most studied lee cyclogenesis events, both observationally (Buzzi et al. 1985; Buzzi et al. 1987) and by numerical simulations (Taffemer and Egger 1990; Tibaldi and Buzzi 1983; Bleck and Mattocks 1984; Dell'Osso 1984), is the 3–5 March 1982 ALPEX case. It was the most intense (Buzzi et al. 1985) lee cyclogenesis deepening during the ALPEX international special observational period aimed at the better understanding the role of mountains in weather. Figures 1a,b show the 1200 UTC 4 and 5 March analyzed surface maps based on ECMWF (European Centre for Medium-Range Weather Forecasts) initialized analyses. A deepening of 8.7 hPa (mb) in the lee of the Alps occurred within 24 h; most of the pressure fall (6.1 hPa) occurred within the last 12-h period. Higher horizontal resolutions analyses indicate even a somewhat larger pressure fall (Dell'Osso 1984). Model simulations were performed by several research groups in order to better understand the physical processes responsible for this extraordinary phenomenon. First, the topographic barrier that blocks the low-level cold front was suggested as being responsible for the first phase of rapid deepening (Buzzi and Tibaldi 1978). In addition, the convection and associated latent heat release developing in the lee were

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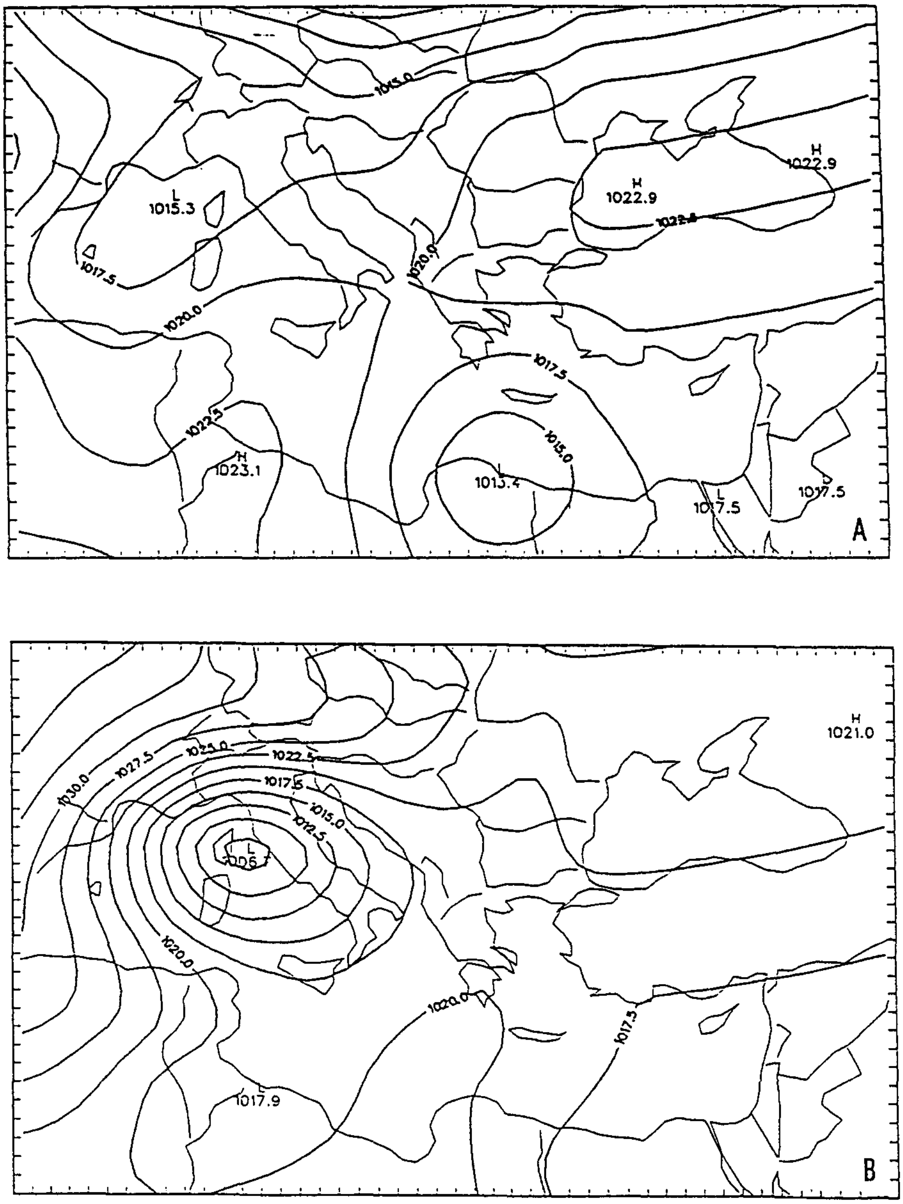

FIG. 1. Analyzed ECMWF surface synoptic charts over the Mediterranean region for (a) 4 March 1983 1200 UTC and (b) 5 March 1983 1200 UTC. Contour interval is 2.5 hPa.

related to the second-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, four factors were chosen: topography (*t*), surface latent heat flux (*l*), surface sensible heat flux (*s*), and latent heat release (*r*) in the deep clouds developing within the cyclonic system. In order to calculate the possible 16 (2^n) contributions, mesoscale simulations with the PSU/NCAR (The Pennsylvania State University/National Center for Atmospheric Research) mesoscale model version MM4 were performed. Horizontal resolution was 80 km with a 46 × 34 mesh and 16 levels up to ~12 km. Further details on model and simulations can be found in SA and Alpert et al. (1994). Initial time for simulations was 0000 UTC 4 March. 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 four "pure" contributions (*t*, *l*, *s*, and *r*), six double interactions, four triple interactions (*tsl*, *tsr*, *tlr*, *slr*), one quadro-interaction (*tslr*), and the residual contribution referred to as large scale. The residual (large scale) term was excluded from the discussion because only the local processes were investigated. In fact, the relatively large contribution of the large scale in this case led some authors (Tafferner and Egger 1990) to disregard this case as a strong lee cyclogenesis case.

The separation method was fully described in SA, but in order to further illustrate how the method works with four factors the formulas for the double and triple interactions (*tr* and *tlr*) are written as follows [Eq. (16) in SA]:

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

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

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 (that is, synergistic contribution), while f_{ijk} is the value of the predicted field for the simulation where only factors i, j, k are involved. The predicted field f when all factors are zero is f_0. Notice that the caret functions ($\hat{f}$) on the lhs of (1)–(2) are calculated from the model simulations output represented by f functions on the rhs.

Figure 2 presents the time evolution for the five largest local contributions illustrating the dominant processes at each stage of the Genoa cyclone deepening. The mechanical effect of the Alpine topography (t) is the first to generate the rapid deepening within 6 h, while all other contributions are much smaller. This corresponds well to the aforementioned first phase suggested by Buzzi and Tibaldi (1978). In the second phase, the latent heat release (r), or convection only, becomes the dominant contributor (42–54 h), while the pure topographic contribution quickly 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 second contributor at the first stage (27–36 h). Each of the synergistic terms can be associated with a specific meaning shedding light on the complex physical mechanisms. 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). 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.

3. Discussion

In the preceding section four factors were chosen. Obviously, the number and type of factors to be se-

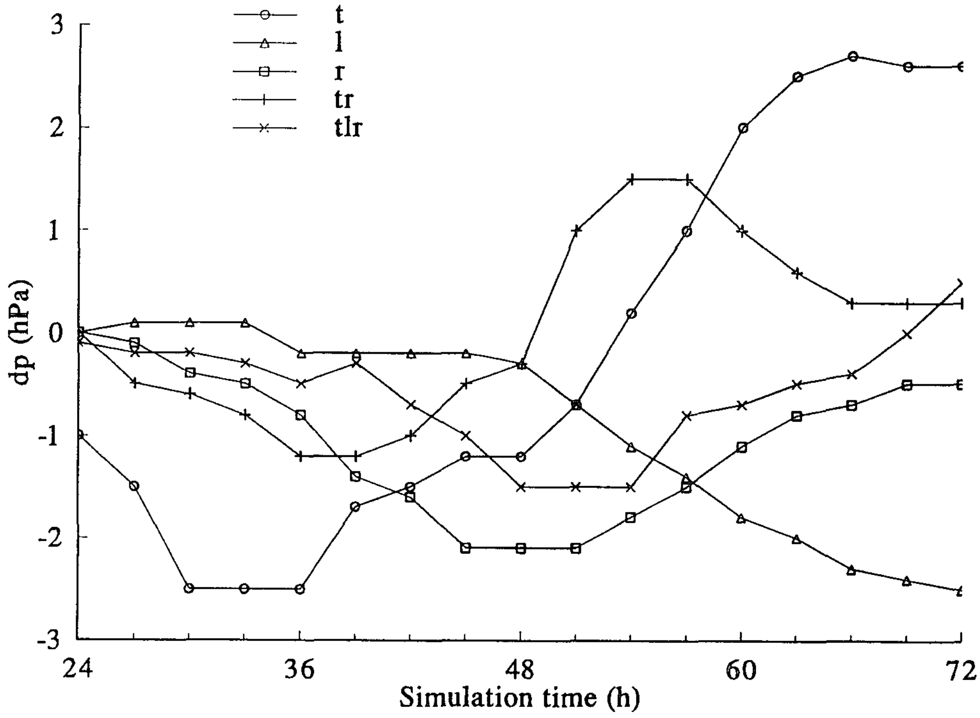

FIG. 2. Five (out of 16) contributions to the pressure deepening at the cyclone center. The factors are denoted by t—topography, l—latent heat flux, s—sensible heat flux, and r—latent heat release. The interaction terms are denoted by the letters of their parent factors.

lected could vary. Having the same four factors in mind, eight different sets of factors could have been chosen if one crucial factor like topography (t) is included in each set. The potential sets are then $\{t\}$, $\{t, l\}$, $\{t, r\}$, $\{t, s\}$, $\{t, l, r\}$, $\{t, s, r\}$, $\{t, s, l\}$, and $\{t, s, l, r\}$. Notice that in this notation with { } we refer to a potential numerical experiment for which the chosen factors or processes to be tested are listed within these braces 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 four factors were chosen, that is, the experiment $\{t, s, l, r\}$. Of course, each set is a legitimate choice for a modeler who investigates the role of topography (t) in the lee cyclogenesis, and such examples are found in the literature (see SA). In the preceding section we have chosen the specific set with all four factors included, that is, $\{t, s, l, r\}$. Figure 3 presents the pure topographical contribution to the cyclone deepening for each of the eight possible sets of factors to be investigated. It is not unexpected that the topographical contribution is largest when only one factor $\{t\}$ was considered and the smallest—at least until hour 48 of the simulation was reached—when the largest set of factors $\{t, s, l, r\}$ was chosen. As the number of factors increases, synergistic contributions between the new factors and topography are extracted from the original t contribution. In the extreme case where only topography was chosen as a factor, all synergistic contributions are tacitly assumed to be part of the topographical contribution to make it the largest (bottom curve in Fig. 3).

Although in all eight experiments, the *same* contribution—due to topography only—is presented (Fig. 3), the differences among the curves are quite significant. Basically, this implies that any sensitivity study of several factors is strongly dependent on the particular set being selected in that specific study. Since the different processes are in general not independent, the further increase in the number of factors diminishes the individual contribution of topography more and more, along with producing new synergistic terms associated with the new factors. Hence, the unavoidable introduction of synergism prohibits a quantitative comparison for the effects of several processes that are independent

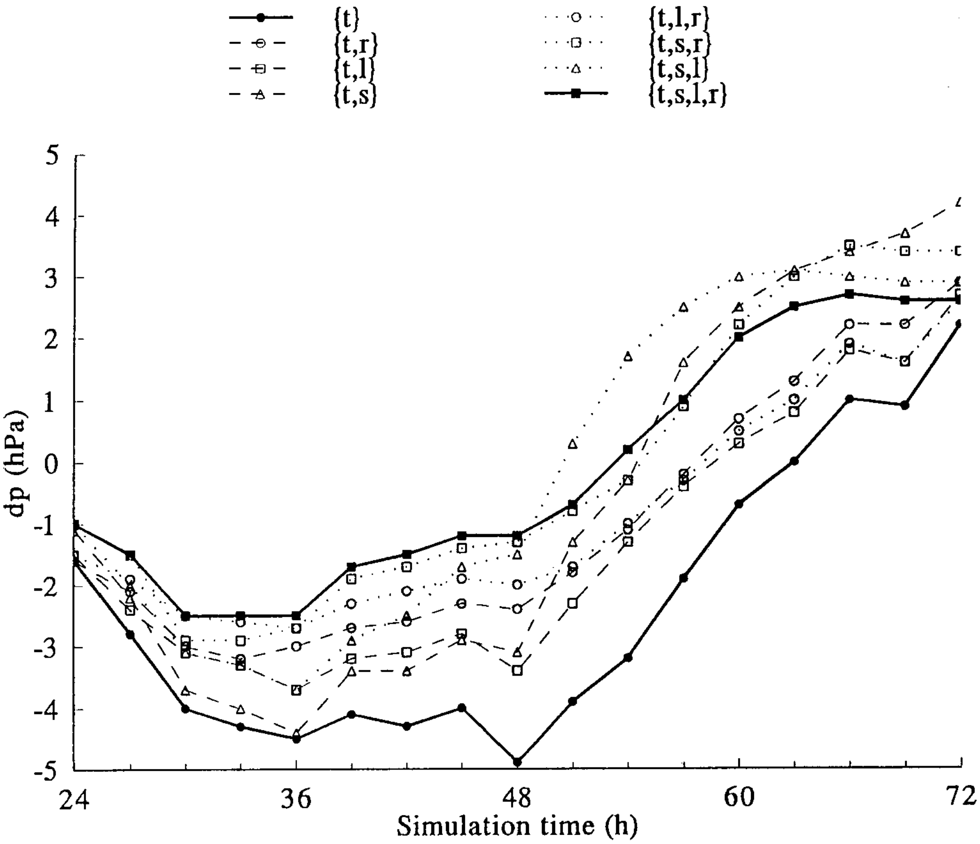

FIG. 3. The pure topographic contribution (t) in hPa to the pressure fall at the center of the control cyclone as a function of the simulation time. Each curve represents one of the eight possible sets of factors (see text). Heavy lines indicate the minimum choice of one factor only $\{t\}$ and the maximum choice of 4 factors, that is, $\{t, s, l, r\}$.

of the particular choice of factors. The more meaningful result may therefore be the calculation of variations in the contributions of a specific factor for several relevant groups of factors (for example, Fig. 3).

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