The Relative Roles of Lateral Boundaries, Initial Conditions, and Topography in Mesoscale Simulations of Lee Cyclogenesis

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ABSTRACT

The contributions of *boundary* factors, which may be considered to be independent of the physics or the dynamics of the mesoscale model, are explored in a consistent approach for a widely investigated Alpine Experiment (ALPEX) lee cyclogenesis case. The roles of the lateral boundaries and the initial fields in conjunction with that of the topography, as well as their possible nonlinear interactions in various model settings, are calculated with the aid of the recently developed factor separation method. Focus is given to the influences of the extent of the model domain and of the running period prior to the climax of the lee cyclone development during 3–6 March 1982. It is shown that the initial conditions are dominant in the first 9–15 h, during which time the topography and lateral boundaries play negative roles because of the adjusting processes. The nonlinear interaction BI between lateral boundaries (B) and the initial conditions (I) was found to be the major contributor to the cyclone deepening during the adjustment period. For longer running periods, some equilibrium is reached in which both the BI interaction and the lateral boundary dominate. The topographic contribution to the lee cyclone deepening in this ALPEX case was indeed limited to about 20% only, as already indicated by earlier studies. Testing several distances of the western lateral boundary suggests the existence of an optimal distance for good results. Both too distant and too close lateral boundaries yield worse results. Testing with frozen boundary conditions shows that the update of the lateral boundaries at a specific time of +36 h was crucial to the development. The results are clearly dependent to some extent on the model type and the particular case under investigation, as well as on the boundary conditions, the initialization procedures, and other model characteristics. The current experiments, however, provide a quantitative approach for estimating the relative roles of the aforementioned boundary factors in mesoscale developments with the aid of the Pennsylvania State University–National Center for Atmospheric Research MM4 mesoscale model and The Florida State University regional system.

1. Introduction

Mesoscale numerical simulations are well known to be highly sensitive to boundary conditions because of the unavoidable necessity for a limited area when high resolution is required. Although the problem can be partly circumvented by enlarging the model domain or adopting nested grids, these boundary effects seem to still influence, to a varying degree, the model results. In addition, when high resolutions are required the common tendency is to shorten the period of prediction as far as possible, typically to 24–48 h. Consequently, the influence of the initial fields becomes strongly interrelated to the effects of the lateral boundary conditions. A third natural factor in the lee cyclogenesis problem is the topography and its contribution to the cyclone generation. The aforementioned three factors—that is, lateral boundary, initial fields, and bottom topography—share a common feature in that they are all boundaries, in space or time, in the problem under investigation. In addition, it seems that these three factors may be strongly interrelated, and that they may strongly influence the mesoscale model simulations.

It is the purpose of our present study to address the three *boundary* factors and their influence in a partic-

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ularly impressive lee cyclogenetic case during the Alpine Experiment (ALPEX), which covered the Gulf of Genoa development on 3–6 March 1982. We wish to focus on the role of each of these factors, and in particular on their nonlinear interactions, by applying the recently developed factor separation method of Stein and Alpert (1993, SA hereafter). This method was shown to allow the isolation of the nonlinear interactions among the factors under investigation. A relatively large number of studies concentrated on the 3–6 March 1982 case, which was the most impressive during the ALPEX special observational period (Tibaldi et al. 1990; Alpert et al. 1996). The focus was primarily on the potential physical mechanisms, such as topography (Dell'Osso 1984; Tafferner and Egger 1990), jet streak, or upper-level potential vorticity dynamics (Bleck and Mattocks 1984; Zupanski and McGinley 1989) and convection or surface fluxes (Alpert et al. 1995, 1996; Hantel et al. 1984). Indeed, some investigators pointed out that mesoscale model results are extremely sensitive to domain size and lateral boundary conditions [see, e.g., Pielke (1984)]. This was based on the finding by Anthes and Warner (1978), among others, that the flux of kinetic energy through the side walls of a mesoscale model crucially affects the solution in the interior. A similar conclusion was reached by Radinovic (1986) in investigating kinetic energy budgets for a number of ALPEX cases.

The earliest motivation for our present study was the finding that topography was not a dominant factor in the 3–6 March 1982 lee cyclogenesis development. This was indicated in several studies (Tafferner and Egger 1990; Tibaldi et al. 1990; Orlanski and Gross 1994; A. Buzzi 1992, personal communication) and was also noticed in our earlier results (Alpert et al. 1995). We therefore wanted to consistently investigate the role of the lateral boundaries and the initial fields in conjunction with that of the topography, as well as their possible nonlinear interactions in various model settings. In particular, focus is given to the extension of the model domain and the simulation time prior to the climax of the development, which was at 1200 UTC 5 March 1982 with 1004-hPa central lee cyclone pressure according to our subjective analysis or 1006.8 following the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis (Dell'Osso 1984). As illustrated next, this required a large number of mesoscale experiments (over 50) with various model settings. But obviously, the set of experiments was limited by our computing resources, and we hope that the preliminary conclusions here will motivate a more complete treatment of the complicated questions being raised.

Special attention should be given here to comparing our approach with that of Vukicevic and Errico (1990), who discuss the predictability of the same ALPEX cyclogenesis case, with similar emphasis on the roles of lateral boundary conditions, initial conditions, and topography. They investigated the same three "artificial" factors, indicating their major role, with the focus on predictability. In particular, they illustrated the effects of the domain scale, topography, and initial conditions and related these to explain the apparent contradiction in the literature on mesoscale predictability. Here, the perspective is different. We focus on one phenomenon—the ALPEX lee cyclogenesis—and point to the importance of the geographical distance of the lateral boundary from the development area (the Gulf of Genoa), even given the same domain area. In addition, the effect of the running period prior to the development is illustrated. The three artificial boundaries are examined for their contributions when acting in unison, just as in reality, by employing the factor separation to define the synergistic effects.

The model employed here is the Pennsylvania State University–National Center for Atmospheric Research (NCAR) mesoscale model version 4 (MM4) and is described along with the parameterizations by Stein and Alpert (1991, 1993). The Florida State University (FSU) regional model (see Krishnamurti et al. 1990) was also used for verification in this study only in Fig. 3, curve D. This is a semi-implicit semi-Lagrangian regional model that is run at 0.50° latitude–longitude resolution and 15 vertical layers. It includes a dynamic normal mode initialization procedure for the definition of the initial state. For comparison, an extended domain was used for the FSU experiment, and the lateral boundary conditions were derived from a global spectral model forecast, which was run at a resolution of T106. Further details on the FSU model appear in the above reference.

A comparison of our factor separation approach to the adjoint sensitivity method seems necessary here, since the adjoint method was also recently applied to the Alpine lee cyclogenesis problem (see Errico and Vukicevic 1992; Vukicevic and Raeder 1995). First, as indicated by the latter, a clear distinction should be drawn between the "impact method" and the "adjoint method." In the impact method the value of the input parameter(s) is changed and the model solution(s) are evaluated. For many parameters this requires many simulations, while the major advantage of the adjoint method is that only one adjoint model solution is required to determine the sensitivity of a particular forecast aspect or result to all input parameters. Now, the factor separation is clearly an impact method. Its main advantage is in the ability to calculate synergistic interactions among relevant processes that were predefined and chosen by the modeler. Also, it allows the effects of several processes to be quantitatively compared for the first time, along with the contributions by their potential interactions. All the contributions add up to 100% of the control run result. Moreover, as shown by Alpert et al. (1995), comparison of the contributions of several processes to a specific model result cannot be performed without a factor separation. In con-

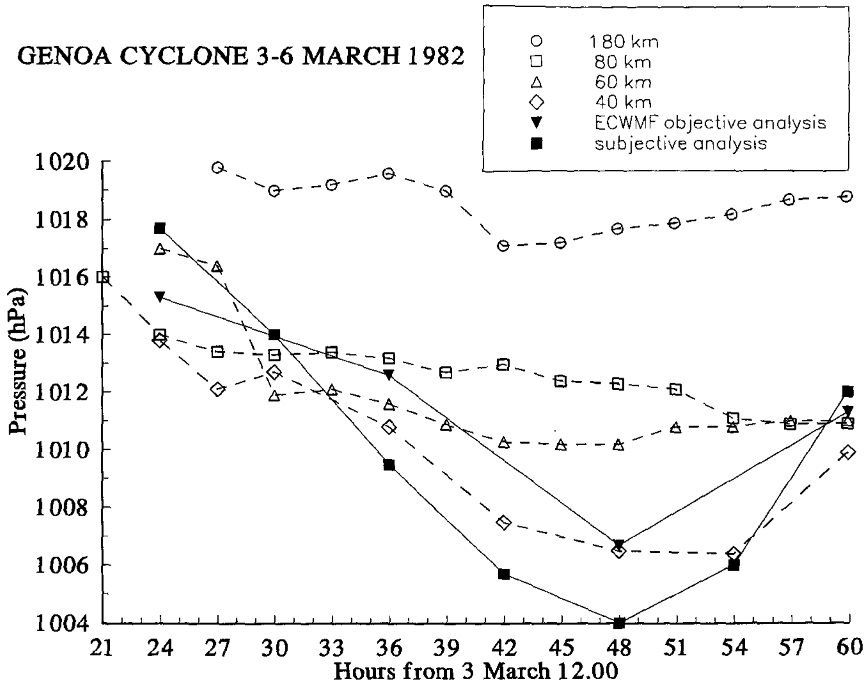

FIG. 1. The 3–6 March 1982 Genoa lee cyclone central pressure curves (hPa) for model horizontal resolutions of 180 (open circles), 80 (open squares), 60 (open triangles), and 40 km (rotated open squares) as functions of time. The observed deepening rates, based on our subjective analysis (full boxes) and the ECMWF analysis (full triangles), are also drawn.

trast to the adjoint method, no linear assumptions are made in the factor separation. The full nonlinear developments as represented by the model simulations are accounted for, and the nonlinear contributions are actually calculated and isolated as the synergistic terms, if the relevant processes were indeed chosen by the modeler. One weakness of the factor separation method—besides the heavy computation involved—is the sensitivity to the set of processes (or factors) chosen by the modeler. This is discussed in some detail by Alpert et al. (1995, 1996). However, the investigator is believed to frequently have a reasonably good estimate for the dominant processes (or factors) in the particular development he wishes to study.

The next section introduces the ALPEX 3–6 March 1982 case with four different horizontal resolutions and a comparison to the observed deepening profiles. The resolution experiments serve to verify our model simulations, but more importantly they illustrate that a comparison of different resolutions with different integration domains is not only very difficult to perform, but is inappropriate because of the varying distance of the lateral boundary from the relevant model development. Consequently, section 3 addresses the lateral boundary setting, while section 4 presents results for the factor separation experiments with the three "boundary" factors. The summary and conclusions are given in section 5.

2. Lateral boundary influences on the Genoa cyclone deepening

a. Varying the model resolution and domain

The lee cyclone deepening curves for horizontal resolutions of 180, 80, 60, and 40 km are presented as function of time in Fig. 1. In addition, the observed deepening rates, based on our subjective analysis (full boxes) and the ECMWF analysis (full triangles), are drawn. Indeed, as expected, the increase in resolution leads to better simulations. However, there is a hidden factor here—that is, the proximity of the lateral boundary conditions, which also influence the results to a varying degree since the domains for the various simulations were different due to computing limitations. In these experiments the same mesh—that is, number of grid points 73 × 41, was employed. The lateral boundary effect is clearly illustrated in Figs. 2 and 3 where the 80-km run is repeated with three different horizontal boundary locations. In the A setting, the western boundary is closest to the Genoa development (43°N, 10°E) and the deepening curve, Fig. 3, curve A, fits best to the observations, compared to analyses in Fig. 1. In both, the minimum is reached at 48 h. The increased distance of the western lateral boundary in settings B and C in Fig. 2 resulted in a significant delay in the maximum deepening, as shown in the corresponding curves in Fig. 3. With the more distant bound-

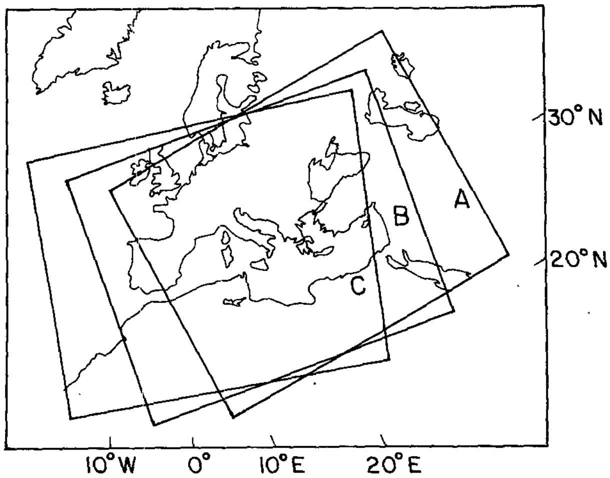

FIG. 2. The three different settings for the model domain. In the A setting, the western boundary is closest to the Genoa development at 43°N, 10°E.

ary in curve C in Fig. 3, this delay even reaches 10–12 h. This result, however, does not suggest that the closer the western boundary is, the better the simulation will be, as illustrated in the next experiment.

The results of the lee cyclone deepening curves in Fig. 3 also include for verification the FSU model result, curve D. The pressure drops rapidly in the first 36 h, and thereafter the rate of drop is slower. At hour 60 the central pressure reaches 1008 hPa. Results in the FSU run or in run D are closer to the settings A and C through almost 44 h of forecast. No pressure minimum is achieved in the FSU run.

Experiments A–D performed so far suggest that setting A is best when examined with a relatively coarse 10° interval of the domain longitudinal location. Next, a finer interval of 2° longitudinal translation is investigated by moving the domain in both the east and west directions to the A setting. In Fig. 4 the deepening curves are drawn for six experiments in which only the longitude of the domain center was changed by 2° intervals from 19° to 29°E (E1 to E6, respectively). The center's latitude was kept constant at 40°N. The domain with the center at 25°E (E4, open squares dashed line in Fig. 4) nearly fits the A setting in Fig. 3. The mesh size for this and subsequent runs was 31 × 46, which explains the slight differences between experiment E4 and experiment A in Fig. 3. It is interesting to see that the experiment with the closest proximity of the western boundary to the development—that is, 29°E (E6, full triangles dash–dotted line)—yields the second worst result, with a minimum central pressure of about 1011 hPa. The worst result is with the boundary farthest from the development, where the center of the model domain is at 19°E (full circles line). This suggests the existence of an optimal distance of lateral boundary; a close boundary interferes with the inner model dynamical evolution, while a boundary too far away also has a negative effect. Obviously, this negative effect is due to the *exact* analyzed information enforced at the boundaries; for operational models where analyzed information does not exist as forecast proceeds, the optimal distance of the boundaries is as far as possible.

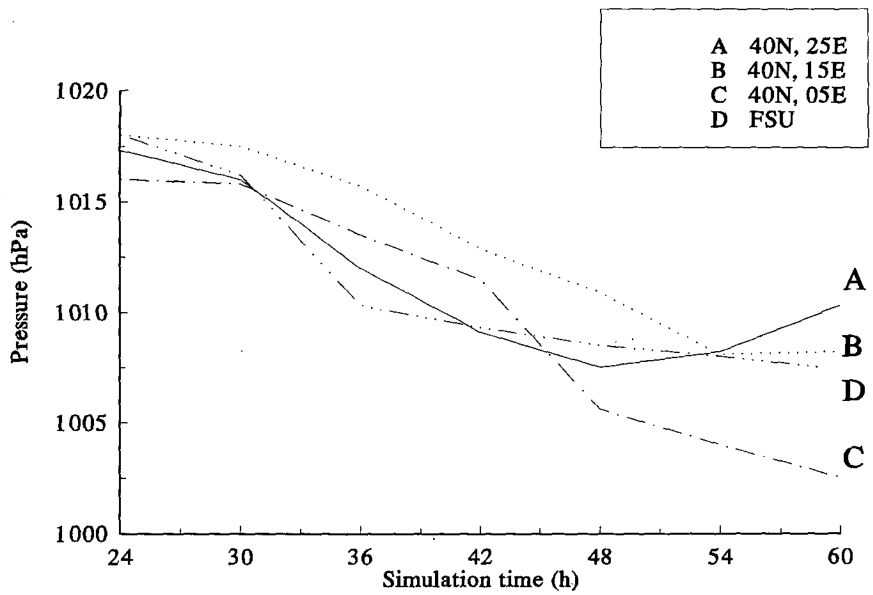

FIG. 3. The central pressure (hPa) curves as functions of time for the model settings A, B, and C from Fig. 2. Model resolutions are 80 km. Latitude and longitude are indicated for the domain center in each setting.

In summary, optimal boundaries should not be too far away in order to have an effective update or control of the mesoscale model, nor too close in order to avoid interference with the dynamical evolution. It should be cautioned that the position of the optimal boundary is to some extent dependent on the resolution, model, or analysis.[1]

b. Freezing the boundary conditions

Another series of experiments that also indicates both the significance and the subtle role played by the lateral boundary was performed in order to identify the contributions of local factors versus advected effects, such as upper-level PV advection. In their factor separation study for the same ALPEX case, Alpert et al. (1995, 1996) have already noticed that even when all four local cyclogenetic factors were switched off—that is, topography, latent heat release, and latent and sensible heat fluxes—a weak lee cyclone (about 50% of the deepening, see Table 1) was simulated. This experiment, entitled in an approximated manner "large-scale (LS) only," suggests that either the updated boundaries with the ECMWF analyses retain some memory of the lee cyclone development or that features such as upper-level PV advection were highly influential in the interior development. The mesoscale model boundaries were updated at every time step based on 12-h intervals from the ECMWF analyses. In order to establish the relationship between the lateral boundaries and the lee cyclonic development, the boundary conditions in the LS-only experiment were fixed at specific times, which varied 48, 36, and 24 h from the initial time. Indeed, as shown in Table 1, when the boundaries were frozen too early, at +24 h, no cyclone was developed at all. If the boundaries were frozen only from 48 h onwards, results were as in the LS-only experiment. However, if these boundaries' "freezing" took place at +36 h, the cyclone continued its deepening even to values quite close to the full run with all factors switched on—that is, 1008.2 hPa as compared to 1007.7 hPa (see Table 1). This clearly suggests that of the boundary conditions available, those at +36 h were critical to the cyclone development. This is even further illustrated in another LS-only experiment in which the 36-h update was skipped. As may have been expected, this experiment yielded no cyclone at all (see the last column of Table 1). Another interesting feature is the delay of about 12 h in the deepening of the cyclone when only the 36-h lateral boundaries were operated at all times past +36 h. This delay was determined by the time separation of the pressure minimum in the +36-h run, compared to that in the full control run. This time lag is clearly related to the advection time of the "LS signal" from the lateral boundary to the Genoa region, as illustrated in the next section using the factor separation method.

[1] The optimal boundary distance is reminiscent of the optimal influence of a supervisor (parent) in the control of his student (child). In both, the optimal distance goes to infinity as the additional *knowledge* of the *boundary* in respect to the inside *development* goes to zero.

3. Factor separation experiments

The aforementioned experiments point to a complex interrelationship among the three following factors in contributing to the development of the ALPEX lee cyclone on 3–6 March 1982: the lateral boundaries, the initial fields, and the topography. We have, therefore, chosen to study the roles of the lateral boundaries (hereafter B), and the initial fields (I) in conjunction with that of the topography (T), as well as their potential nonlinear interactions in various model settings, by applying the factor separation method as introduced by SA. The method requires the switching on/off of each of the factors involved and also performing all possible experiments (here, eight) in case one is interested in all the nonlinear interactions among the factors. Without the separation of the various interaction terms involved here—that is, BT, IB, IT, and IBT—four experiments will suffice. In order to explain this, a brief review of the factor separation method is given below.

The factor separation method is fully described in SA, but for illustration on how the method works with three factors, the formulas for the double and triple interactions (BT and IBT, for instance) are written as follows [Eq. (16) in SA]:

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

and

$$\hat{f}_{ibt} = f_{ibt} - (f_{ib} + f_{it} + f_{bt}) + (f_i + f_b + f_t) - f_0, \qquad (2)$$

where $\hat{f}_{ijk}$, $i, j, k \in \{i, b, t\}$ is part of the predicted field f (pressure in this note), dependent solely on the combination of the factors i, j, and k—that is, a synergistic contribution—while f_{ijk} is the value of the predicted field for the simulation where only factors i, j, and k are switched on. The predicted field when all the chosen factors are zero is f_0. Notice that the "hat" functions ($\hat{f}$) on the lhs of (1) and (2) are calculated from the model simulations output represented by f functions on the rhs. The lhs functions $\hat{f}_{bt}$ and $\hat{f}_{ibt}$ will be hereafter referred to, for brevity, as BT and IBT contributions.

Switching off the topography is a common tool in the investigation of lee cyclogenesis, but switching off the initial fields or boundary conditions is a much subtler matter and not so frequently performed. Here this is suggested to smooth the initial fields at each level a large number of times—a few hundreds—in order to achieve a realistic switching off of this factor. This was performed with the five-point smoother [see, e.g., Shuman 1957), his Eq. (7)]. The corresponding variances

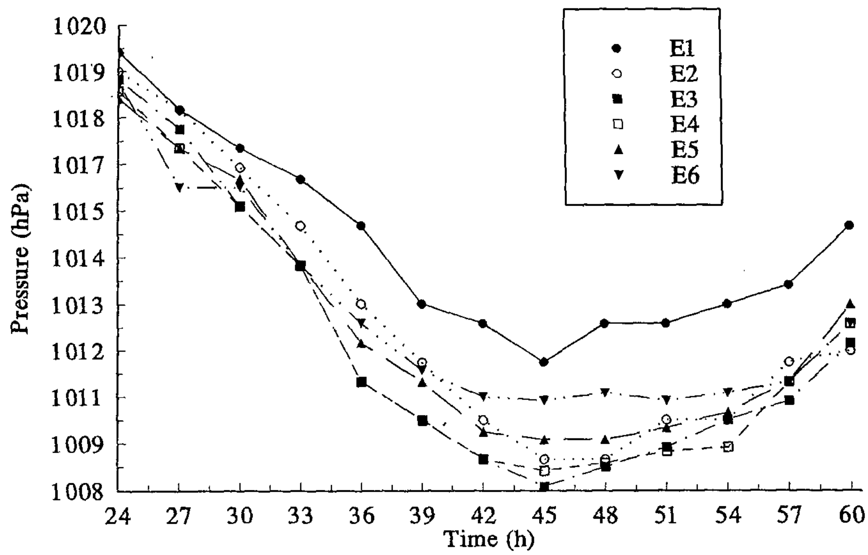

FIG. 4. As in Fig. 3 but for six model settings in which only the longitude of the domain center was changed by 2° intervals from 19° to 29°E (see inset table). The center's latitude was kept constant at 40°N. The domain with the center at 25°E (E4, open squares dashed line in Fig. 4) nearly fits the A setting in Fig. 3. The mesh size for this and subsequent runs was 31 × 46.

drop to their equilibrium minimum values as shown, for instance, in Fig. 5, for the 500-hPa height and wind fields and for the sea level pressure. The reason for the existence of such minima is found in the enforced lateral boundaries, which were kept unchanged. Similarly, the lateral boundary conditions were switched off by a linear time interpolation from the initial time directly to 0000 UTC 6 March 1982, which is past the time of maximum cyclone deepening.

The pure contributions to the total cyclone deepening of the initial fields (I), the lateral boundary conditions (B), the topography (T), and the synergistic interactions (S) were all calculated at the location of the control cyclone center at 0900 UTC 5 March, the time of the maximum deepening. The S term represents any of four synergistic terms involved here—that is, BT, IB, IT, IBT, or a combination thereof. In order to test the effect of the running period prior to the climax of the deepening at 0900 UTC 5 March (see Fig. 4), five such periods were tested: 9, 21, 33, 45, and 57 h. The 45-h run corresponds to the experiments in the former sections, with the initial time of 1200 UTC 3 March. The other experiments are with intervals of 12 h approach-

TABLE 1. Pressure at the lee cyclone center for several runs, indicated by the last digits in 10*XX.X*. The first column shows the full control run, and the second row is for the large-scale-only experiment. The next three columns are for LS only, with frozen lateral boundary conditions starting at +48, +36, and +24 h from the initial time of 1200 UTC 3 March 1982. The last column to the right presents the LS only in which the +36-h data was skipped in the updating of the lateral boundaries. The blank boxes represent cases where a cyclone did not exist in the simulation.

	Run					
			Fixed BC from			
Hour	Control full	Control LS only	+48	+36	+24	LS only (skip 36 h)
24	15.1					
30	12.6	15.5	15.5	15.5	15.7	16.3
36	9.8	13.4	13.4	13.4	15.2	16.0
42	7.7	11.6	11.6	10.7		15.7
48	7.8	11.2	11.2	8.5		15.3
54	8.9	11.7	11.4	8.2		15.2
60	9.7	12.7	11.8	8.2		15.4

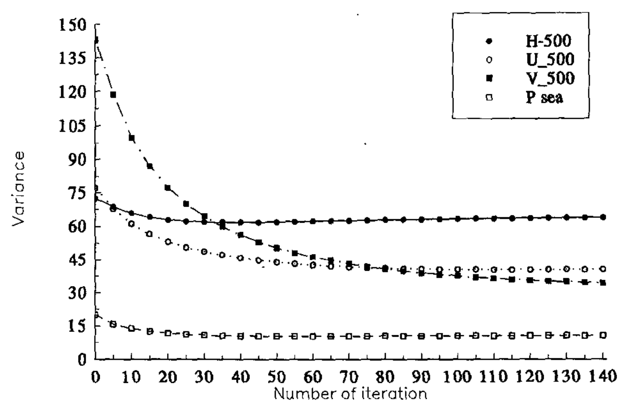

FIG. 5. The average variances over the model domain for the 500-hPa height and wind fields and sea level pressure as functions of the number of iterations. Units are dekameters squared for *H*, square meters per second squared for *U* and *V*, and hectopascals squared for sea level pressure *P*.

ing or moving away in time from the climax of the deepening at 45 h. The separation of the contributions requires eight (four) experiments for each running period if the synergistic terms are (not) separated (Stein and Alpert 1993). In this way, one can follow the contributions of I, B, T, and S as functions of the running period to the maximum of development. Figure 6 presents the normalized contributions of I, B, T, and all the nonlinear interaction terms S as functions of the interval between the initial time and the maximum deepening time. The four contributions always add up to −1, reflecting the total deepening in each case. At running period zero, the total deepening is obviously fully determined by the initial fields so that the contributions by the other factors—the lateral boundaries, the topography, and the synergistic interactions—are all identically zero. As the running period toward the maximum deepening increases, the contribution of I drops quickly, while other terms increase their share. Within 30 to 42 h it seems that some equilibrium is reached. The contribution of the initial fields then goes to zero, while the contributions to the total deepening of the cyclone are shared among the topography T (16%), the lateral boundary B (34%), the initial condition I (5%), and the synergistic terms S (45%). The major contribution by S is actually distributed among the four synergistic terms BI (−0.54), TB (−0.13), TI (0.10), and IBT (0.12). Hence, the interaction between lateral boundaries and the initial conditions is the major contributor to the cyclone deepening for running periods longer than the period of adjustment. The actual pressure (hPa) contributions are given in Table 2.

TABLE 2. Normalized pressure contribution of the nonlinear interactions at the adjusting stage with a running period of 21 h and at the near equilibrium stage with a running period of 45 h. The value in parentheses is the actual pressure (hPa) contribution for each case.

Running period	Interaction term BI	TB	TI	IBT	Total S
+21 h	−0.91 (−14.6)	−0.06 (−0.9)	−0.31 (−4.9)	+0.56 (+8.9)	−0.72 (−11.5)
+45 h	−0.54 (−9.2)	−0.13 (−2.2)	+0.10 (+1.8)	+0.12 (+2.0)	−0.45 (−7.6)

The cyclolytic contributions of the lateral boundary and the topography, with the shortest running period of 9 h only, as expressed by the positive values in Fig. 6, probably reflect the transitional perturbation of the adjusting period. This is also in agreement with the earlier discussion of a frozen lateral boundary at 36 h (Table

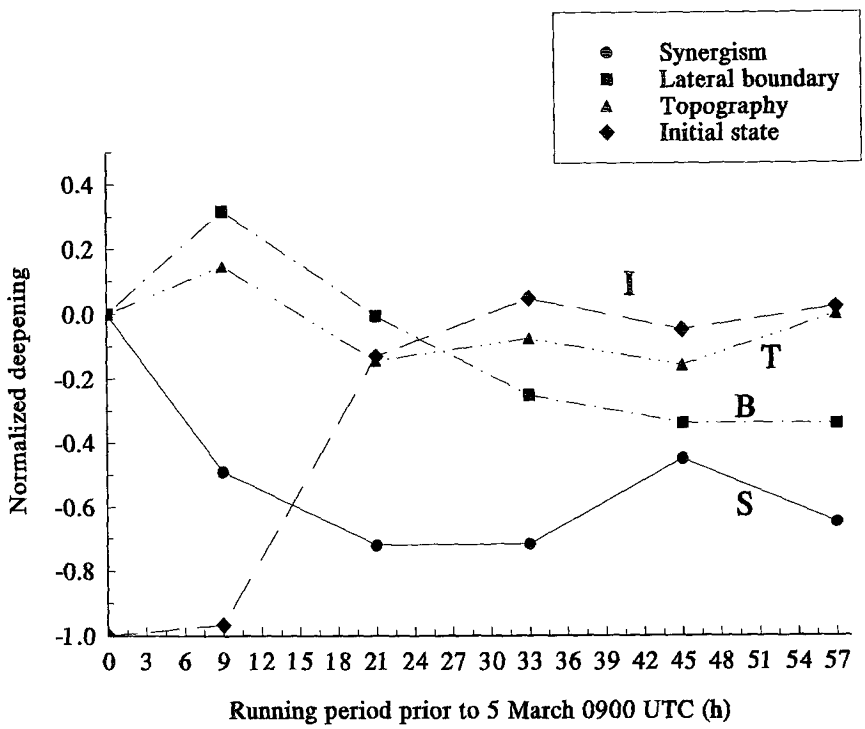

FIG. 6. The normalized contributions of I, B, T, and all the nonlinear interaction terms S to the cyclone deepening as functions of the running period prior to the maximum deepening time, which was at 0900 UTC 5 March. The four contributions always add up to −1, reflecting the total deepening in each case. At running period zero, the total deepening is fully determined by the initial fields so that the contributions by the other factors are identically zero.

1), where the boundary effect reached the development region only within 12–24 h. As expected, the boundary contribution increases with increasing running period on account of the initial fields contribution. That is, B increases and I decreases during the first 20–30 h. At the running period of 21 h (Fig. 6) the dominant interaction contribution, S = −0.72, is in fact distributed among the four synergistic terms BI (−0.91), TB (−0.06), TI (−0.31), and IBT (+0.56). Again, the interaction between the lateral boundaries and initial conditions is the major term, followed by the interaction between topography and initial conditions. The relatively large triple cyclolytic contribution (IBT) clearly indicates that the model is still in its adjusting stage, compared to the triple contribution at 45 h (12%) (see Table 2).

4. Summary

The present study clearly indicates that topography was not the direct[2] dominant contributor to the cyclone deepening on 3–6 March 1982. The factor separation method applied here allows the isolation of the contributions of boundary factors, which are normally considered independent of the physics or dynamics of the model. As illustrated here, the boundary factors play a crucial role in common mesoscale settings, a role which seems to have been underestimated, in our opinion, in mesoscale modeling primarily because of two reasons. First, the normal focus of the modeler is on the physics or dynamics of the mesoscale development. Second, the technical difficulties that are usually involved with the testing of the effects due to boundaries, such as changing the model domain or resolution, are often more cumbersome than switching off some physical parameterization like latent heat release would be.

The contributions of boundary factors independent of the physics or the dynamics of the mesoscale model are investigated in a consistent approach for a widely investigated ALPEX lee cyclogenesis case. The models employed here are the PSU–NCAR mesoscale model version 4 (MM4) and The Florida State University regional model. The roles of the lateral boundaries and the initial fields in conjunction with that of the topography, as well as their possible nonlinear interactions in various model settings, are calculated with the aid of the recently developed factor separation method. Focus is given to the influences of the extension of the model domain and of the running period prior to the climax of the lee cyclone development on 3–5 March 1982. It is shown that the initial conditions are the dominant factor in the first 24–30 h, a time when topography and lateral boundaries play even negative roles because of the adjusting processes. For running periods prior to the lee cyclone maximum deepening, which are longer than the adjusting period, the nonlinear interaction between lateral boundaries and the initial conditions was found to be the major contributor to the cyclone deepening. As the running period toward the maximum deepening increases, the contribution of I drops quickly while other terms increase their share, as was expected. Within 30–42 h, it seems that some equilibrium is reached. The contribution of the initial fields then goes to zero, while the contributions to the total deepening of the cyclone are shared among the topography T (16%), the lateral boundary B (34%), and the synergistic terms S (50%). The major contribution by S is actually distributed among the four synergistic terms BI (−0.54), TB (−0.13), TI (0.10), and IBT (0.12). Hence, the interaction between lateral boundaries and the initial conditions (BI) is the major contributor to the cyclone deepening for running periods longer than the adjusting period. The topographic contribution to the lee cyclone deepening in this case was indeed found to be limited to about 20% only, as already indicated in earlier studies.

The results presented here are clearly dependent to a varying extent on the model type and the particular case under investigation, as well as on the boundary conditions, the initialization procedures, and other model characteristics. The current experiments, however, provide a quantitative approach for estimating the relative roles of the aforementioned boundary factors in mesoscale developments.

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