A Tutorial on Lateral Boundary Conditions as a Basic and Potentially Serious Limitation to Regional Numerical Weather Prediction

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ABSTRACT

Limited-area models (LAMs) are presently used for a wide variety of research and operational forecasting applications, and such use will likely expand greatly as the rapid increase in the performance/price ratio of computers and workstations makes LAMs more accessible to novice users. The robustness of these well-tested and documented models will make it tempting for many to consider them as turn-key systems that can be used without any experience or formal training in numerical weather prediction. This paper is intended as a tutorial and caution for such prospective model users, with the specific purpose of illustrating that, in spite of advanced physical-process parameterizations and high resolutions permitted by faster computers, and modern mesoscale data for initial conditions, there is still a basic limitation to predictability with a LAM—lateral boundary conditions (LBC). Illustrations are provided of previous work that show the serious negative effects of LBCs, and guidelines are provided for helping to minimize their negative impact on forecast quality.

1. Introduction

Increases in the performance/price ratio of computers and workstations have made it attractive for a growing number of government, commercial, and educational institutions worldwide to consider using limited-area (in contrast to global) numerical weather prediction models for a variety of research and specific operational applications. The present use of these models is wide-ranging, and evidence suggests that this use will expand greatly during the next decade. Even though it is easy to hypothesize that computing power will be so accessible and economical that global models will have sufficient resolution for any ap-

plication, history does not bear this out. Economic or political exigencies, as well as situations where local data are not available at central modeling facilities, will often exist such that special needs will generally, at least within the foreseeable future, be met through the use of locally run, limited-area models (LAMs). This unavoidable situation means that it is important and timely to review the known and major limitation of these LAMs that is related to their lateral boundary conditions (LBCs), especially because the forecasts will increasingly be likely used to make major decisions related to public safety, the economy, and the environment. Such a tutorial, or advice from "a modeler," is especially appropriate because LAMs are becoming more touted as "turn-key" systems and are accessible to many in the meteorological and nonmeteorological communities with little experience in numerical weather prediction (NWP) and knowledge of its limitations.

In addition to the numerous well-known research applications of LAMs, there are many LAMs that are run operationally. For example, they are employed for operational prediction of regional weather by the U.S. National Weather Service (the Eta, RUC, and NGM models—Black 1994; Benjamin et al. 1994) and by

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small nations who perceive that their special needs are not being met by the global forecasts that are available. They are being used by agricultural consulting companies for operational prediction of weather to which agriculture is sensitive. When coupled with air-quality models, they are applied to regional airsheds to help government and business develop strategies for managing regional air quality. Militaries employ regional models for producing specialized forecasts of weather that affects the conduct of their operations over the land and sea. LAMs are also used for planning emergency responses to the accidental release of hazardous chemicals and radioactive material, and are to be employed in the near future for nowcasting the existence of windshear near airports that is hazardous to aviation.

The above applications may become more widespread in the future, and a number of new ones are likely. For example, the large number of consulting companies that produce customized weather forecasts for clients may operate their own modeling systems that provide specialized regional products. Coupled with surface hydrologic–runoff models, the atmospheric models will almost certainly be used for flood prediction and management of water resources used for hydropower, human consumption, and recreation. When global models become sufficiently accurate to predict interseasonal and interannual climate change with some skill on the large scale, LAMs will be embedded within them to predict the regional effects. These regional forecasts may be used in the process of making major economic, social, and environmental decisions.

There is, of course, a variety of sources of forecast error that may make a particular limited-area modeling system unsuitable for a specific application. These include the physical-process parameterizations, the initial conditions, the numerical algorithms, and surface forcing. These limitations can be addressed through a variety of well-known methods. There is, however, one unique and unavoidable aspect of LAMs that will continue to represent a significant limitation to their utility for any application, regardless how much sophistication we use in limiting the other error sources: the lateral boundary conditions. A number of studies have demonstrated that the LBCs of LAMs can have a significant impact on the evolution of the predicted fields through the propagation of boundary errors onto the interior of the domain. These boundary errors originate from a variety of sources. The LBCs are obtained from coarser mesh models

with significantly poorer horizontal and vertical resolution and simpler physical process parameterizations, and the numerical techniques used for interfacing the two grids inevitably generate error that propagates onto the LAM grid. Thus, it is essential before one uses a LAM to have a good understanding of how the LBCs can negatively affect the predictive skill of the model and even entirely negate the benefits of high resolution and sophisticated physics. Section 2 will provide an initial discussion of the relevance of LBC effects to the practical application of LAMs. Section 3 will then summarize previous research that can provide us with insights relative to the potential seriousness of this problem, and section 4 will review current LBC formulations. In section 5 these experiences will be summarized and interpreted, and some general guidelines and cautions will be offered that will allow users of LAMs to configure their models in such a way as to minimize these problems in their particular application.

Note that this paper only provides a brief review of the various types of LBC formulations that can be employed in LAMs. This is a subject that has been discussed extensively in the literature, and the summary here is intended to direct the reader to more indepth descriptions elsewhere. Rather, the emphasis here will be on providing general guidance to LAM users, who perhaps have little formal NWP experience, regarding how to configure LAM systems to minimize the negative effects of LBCs on forecasts and simulations.

2. A pragmatic consideration of lateral-boundary effects

It should be recognized from the outset that LBC problems with LAMs are inevitable, and that our only realistic objective should be to understand the nature of the problems well and learn how to mitigate their negative effects to the extent possible for each particular model application. And, as we will see, the seriousness of their impact on a model solution can depend greatly on the specific circumstances of the model application. Thus, it is not possible or reasonable to apply the same few simple guidelines in all situations.

LBCs have an influence on the solution of a LAM that can be attributed to at least five factors.

• The LBCs are defined based on forecasts from coarser resolution models or analyses of data, de-

pending on whether the LAM is being used for operational or research applications. In either case, the horizontal, vertical, and temporal resolution of the boundary information is generally poorer than that of the LAM, and thus the boundary values interpolated to the LAM grid at every time step have the potential of degrading the quality of the solution.

- Even if the LBC-data resolution is hypothetically similar to that of the LAM, and there is little interpolation error, the quality of the LBC data may be erroneous for other reasons, especially if they are based on other model forecasts. That is, the forecast that provides the LBCs may simply be wrong in some important respect having nothing to do with its resolution. In any case, these errors will be transmitted to the LAM domain at the mesh interface.
- Because specified LBCs determine the computational-domain-scale variations to the meteorological fields, these longer wavelengths cannot interact with the model solution on the interior. This limited spectral interaction can effect the evolution of the LAM forecast because the LAM solution cannot feed back to the large scales.
- The specific LBC formulation used can produce transient nonmeteorological gravity-inertia modes on the LAM domain that, even though they are thought to not interact strongly with the meteorological solution, can complicate the interpretation of the forecast.
- The physical-process parameterizations may, sometimes out of necessity, be different for the LAM and the coarser-resolution model providing the LBCs. The resulting inevitable differences in the solution at the boundary may cause spurious gradients and feedbacks between the two grids, which can influence the interior of the LAM domain.

As noted above, these limitations are generally unavoidable. Thus, the problem reduces to determining how to anticipate the circumstances when they will represent a significant factor influencing the quality of the LAM solution and applying specific modeling strategies that will minimize their effect.

Conventional wisdom has been simply to move the lateral boundaries sufficiently far from the area of meteorological interest so that their effect is within acceptable limits during the period of an integration. However, the specific domain-size decisions made in this regard are, probably more often than one would hope, relatively arbitrary and based on "guesswork."

In some situations, computing-resource factors also play an important role in this decision. Nevertheless, this distancing of the lateral boundaries from the area of meteorological interest is the only possible solution to the problem, in addition to, of course, using LBC formulations that generate only minimal numerical artifacts in the solution. Thus, our primary objective here reduces to establishing guidelines on how distant the lateral boundaries must be in specific model applications in order that their negative effects be acceptable.

An important first question is related to how we gauge the acceptability of LBC error, given that we cannot eliminate it. Most model users would likely agree on the general condition that the LBC error is acceptable if it is not greater than the error associated with the other limiting factors—initial conditions, the numerical approximations, the physical-process parameterizations, and the surface forcing. However, this is not an especially easy criterion to apply from a practical standpoint because we rarely have the ability to quantify the individual contributions of any of these five sources of error, especially because they can be situation dependent. Thus, if we use this approach it will be necessary to make subjective judgments about the importance of LBC error relative to those from the other sources.

A subjective estimate of the relative importance of LBC error can be based on the degree to which the meteorology in a given case is dominated by initial conditions, local forcing, and advection–propagation of features from outside the area of interest on the model domain. If the model is being applied to a single meteorological case in a research setting, this judgment can be based on the prevailing meteorological conditions for that case. However, if the modeling system is being established for operational use, the decisions must be based on worst-case estimates of conditions that will prevail over an ensemble of meteorological situations. Given the above, the following concepts that are generally held to be true by modelers should be kept in mind when reading the next section containing actual examples of LBC impacts on LAM simulations. In the final section, these concepts and the experiences described in the next section will be synthesized into specific recommendations for limiting LBC effects to acceptable levels.

- *Strength of cross-boundary flow*—The strength of the cross-boundary flow in the upwind direction should be strongly correlated with the timescales

on which LBC error propagates and amplifies as it enters the interior of the domain. More specifically, the degree of the vertical coupling of the flow field, and the layers in the atmosphere containing the process to be simulated, will determine the levels for which the magnitude of the cross-boundary flow is most crucial. For example, if the model is being used to provide low-level terrain or thermally forced winds and stability for air-quality studies, and there is relatively small vertical dynamic coupling, the strength of the cross-boundary flow in the lower troposphere will be more important than that in the upper troposphere. In general, the speed of error propagation from the boundaries will be case, seasonally, and geographically dependent.

- *Strength of forcing at lateral boundaries*—The presence of strong forcing, such as associated with complex topography, convection, or an extratropical cyclone, at the lateral boundaries should be avoided when possible because the resulting large gradients and accelerations are not treated realistically by the LBCs. The inertia–gravity waves produced by the misrepresentation of the effects of these forcing mechanisms can propagate rapidly to the domain interior and sometimes make it difficult to interpret the meteorologically realistic component of the solution.

- *Strength of forcing on the domain interior*—The strength of the local forcing on the domain interior, resulting, for example, from terrain and differential surface heating, is important because sometimes the resulting mesoscale features are relatively insensitive to moderate errors in the large-scale fields that result from LBC error. For example, the time of onset of a coastal sea–breeze circulation is more strongly correlated with local thermodynamic effects than with the specific characteristics of the large-scale flow field and its LBC-related errors.

- *Sensitivity of the forecast to initial conditions*—If the model solution is strongly sensitive to the initial conditions, development of dominant meteorological features may take place early in the integration period. Once these features, such as an MCS or extratropical cyclone, are well established, their evolution may be less susceptible to LBC error that penetrates to the domain interior later in the integration.

- *Resolution consistency of LBC data and the LAM*—The horizontal and vertical resolutions of the coarse-mesh model providing the boundary conditions for the LAM should be as close as possible to those of the LAM. This will reduce the inconsistencies between the solutions of the two models, thus providing higher-quality LBC data entering the LAM domain and reducing gradients at the boundaries that can generate gravity–inertia waves. Unfortunately, the growing use of ensemble forecasting techniques for global coarse-mesh models will tend to exacerbate this problem because the global-model resolutions tend be poorer when ensembles are used, and it will be difficult to choose which single ensemble member to use for LBCs.

- *Physical-process parameterization consistency*—The physical-process parameterizations of the LAM and the coarser-mesh model providing the LBCs should be similar, if not identical. This will reduce gradients near the LAM boundaries that can generate gravity–inertia waves. Note that this recommendation is sometimes difficult to follow because some parameterizations, such as for convection, are very dependent on the model resolution.

- *Length of the integration*—When LAMs are used for both research and operational prediction, there are tradeoffs that determine the length of the integration. For example, if mesoscale initial data are sparse, it is wise to initialize the model well before the desired forecast period to allow the model internal dynamics to "spin up" mesoscale structures that are responsive to the large-scale and local forcing. However, this tactic allows more time for LBC error to penetrate to the domain interior. This tradeoff needs to be considered.

- *Interactive grid nesting*—LAMs often have the option of using a series of nested computational domains, where the horizontal resolution of the domains increases by a factor of perhaps 2 to 4 for each progressively smaller grid. The LBCs for the outermost (largest) grid are provided from another, generally global, modeling system or from analyses of data. In such nested grid systems, there is often the option of using an interactive interface or boundary condition in which each grid can influence the next coarser one as well as the next finer one. Even though it has not been confirmed by research, one would expect that this truly interactive interface should allow the model solution on the interior to interact with the longer domain-scale wavelengths. This improved spectral interaction should improve the evolution of the LAM forecast. Thus, interactive boundaries should be employed

where possible rather than one-way-specified boundaries.

- *LBC temporal resolution*—A potentially major source of LBC error is that associated with the use of LBC information from models or observations that has poor temporal resolution compared to the timescales of the meteorological features that must "pass through" the boundaries. The timescales of the cross-boundary fluxes must be assessed, and the temporal resolution of the LBCs should be defined accordingly.

- *LBC formulation*—LBCs for meteorological models are inherently ill-specified mathematically, and thus many engineering approaches have been devised to minimize the potentially serious numerical problems that can develop. Some algorithms are, understandably, better than others in particular situations. Even though meteorologists who are model users are often more concerned about physical-process parameterizations than the numerical aspects of models, they also need to be concerned about the LBC formulation that is being used.

- *Four-dimensional data assimilation (FDDA)*—The use of a preforecast FDDA period can have both a positive and negative effect on the LBC influence, whether continuous or intermittent assimilation techniques are utilized. On the one hand, the preforecast integration period will allow LBC errors to propagate closer to the domain center by the start of the forecast. Conversely, the data assimilated during the period will partially correct for errors of LBC origin that are within the influence region of the data. Variational data assimilation through the adjoint approach will have similar potential problems.

3. Summary of previous experience

Three general types of recent studies have been performed from which we can gain insight. One involves the application of model computational domains of different size to simulate meteorological cases, and from these simulations a direct determination is made of the effect of the proximity of the lateral boundaries on some measure of the veracity of the simulation. Another type can be grouped into the general category of mesoscale predictability studies wherein a control simulation is first performed with a LAM. Then, perturbations (errors) are imposed on the model initial conditions (or sometimes lateral bound-

ary conditions) and the differences between the model solutions with and without the perturbations are analyzed and ascribed to specific factors, including the LBCs. A third category of study uses an adjoint model from which actual sensitivity fields are produced directly. Relevant studies from which we can gain insight are grouped below into these three categories. Note that there are numerous early and recent works that describe various kinds of evidence of the potentially serious effect of LBC error on LAM forecasts (e.g., Miyakoda and Rosati 1977; Gustafsson 1990; Mohanty et al. 1990). However, for the sake of brevity, this review will be limited to selected investigations that use relatively state-of-the-science models and provide special insights that can help us avoid major problems with LBCs.

Before reviewing the literature that can provide us with guidance relative to this problem, it is worth first relating some anecdotal evidence. As one example, during the mid 1980s the NWP group at The Pennsylvania State University began running a meso-alpha scale LAM in real time on a daily basis for research and instructional purposes (Warner and Seamen 1990). This LAM, whose computational domain spanned the northeastern United States, was initialized with the same data used for initialization of the U.S. National Weather Service's (NWS) nested-grid model (NGM), and the lateral boundary conditions were driven by the NGM forecast. The model-physics parameterizations were generally superior to those of the NGM, and the horizontal grid resolution was a factor of 3 greater. Expectations were that it would easily outperform the NGM. However, even though the LAM forecasted exceptionally well many verifiable mesoscale features that were not contained in the NGM forecast, its overall *objective* skill during much of the year was worse than that of the NGM. The fact that the LAM skill was worse in the winter, when stronger baroclinity produced higher wind speeds at the upwind LAM boundary, pointed to the possibility that the coarse spatial and temporal resolution NGM solution was sweeping across the LAM domain and negating the benefits of the considerably better physics and resolution. This was inferentially confirmed by expanding the LAM computational domain to the west, which improved the model's performance statistics. The important point to be gained from this experience is that, if objective skill is a measure of the value of a model forecast to a forecaster (which is an open question that will not be addressed here), this relatively sophisticated, high-resolution LAM with its original domain con-

figuration sometimes provided poorer guidance to the operational forecaster than did the standard NWS product.

a. Domain-size sensitivity studies

One of the first studies of the effect of driving LAM LBCs with a coarser-resolution forecast was that of Baumhefner and Perkey (1982). A LAM (Valent et al. 1977) with a 2.5° latitude–longitude grid was embedded within, and obtained its LBCs from, a 5° lat–long hemispheric model (Washington and Kasahara 1970). Both models used the same vertical grid structure (6 layers) and physical-process parameterizations. LBC "error" was first assessed by comparing the solution from this nested system with that from a nonnested, 2.5° lat–long version of the hemispheric model. Figure 1 shows the midtropospheric pressure error (difference between LAM and hemispheric model solutions) associated with the LBCs for a 48-h forecast period. Large pressure errors with amplitudes of 5–10 hPa propagate rapidly onto the forecast domain at middle and high latitudes (and amplify), primarily from the west and north boundaries, with speeds of 20°–30° long day^{-1}. Comparison

of this error distribution with the location of synoptic disturbances (not shown) shows that the error maxima are associated with areas in which significant changes are taking place at the boundaries. The fairly inactive large-scale meteorological conditions in the subtropics and Tropics generate very little LBC error. In this case, the errors are primarily associated with an erroneous decrease in amplitude of the disturbances as they propagate onto the domain, in spite of the fact that the fine grid has twice the resolution of the coarse grid that supplies the LBCs. LAM simulations in which the LBCs were provided by a 2.5° lat–long hemispheric model (i.e., the LAM and hemispheric models had the same horizontal resolution) showed errors that were also large and that had a similar distribution, indicating that significant LAM errors in these regions resulted from the LBC formulation. Figure 2 summarizes the root-mean-square (rms) error growth in 500-hPa heights on the limited-area domain associated with the use of LBCs from the 2.5° (dotted curve) and 5° (dashed curve) lat–long global model. The solid curve shows the difference between the 2.5° and 5° grid, *hemispheric* simulations over the area of the LAM domain, and represents the error that is associated with the use of the 5° unbounded grid compared to the 2.5° unbounded grid. Height differences (m) are shown for the total domain (left) and subdomains that exclude the areas within 20° (middle) and 30° (right) of the boundary. The most rapid error growth is during the first 24 h. The fact that the error associated with the 2.5° LBCs begins to decrease rapidly after 24 h probably indicates that it is associated with rapidly propagating and damped transients generated at the lateral boundaries early in the simulation. In contrast, when the 5° LBCs are used there is a continuing propagation of coarse-resolution information throughout the entire period that causes the error to be generally larger throughout the forecast.

This, of course, is not true forecast error because observa-

DAY .5   **DAY 1.0**
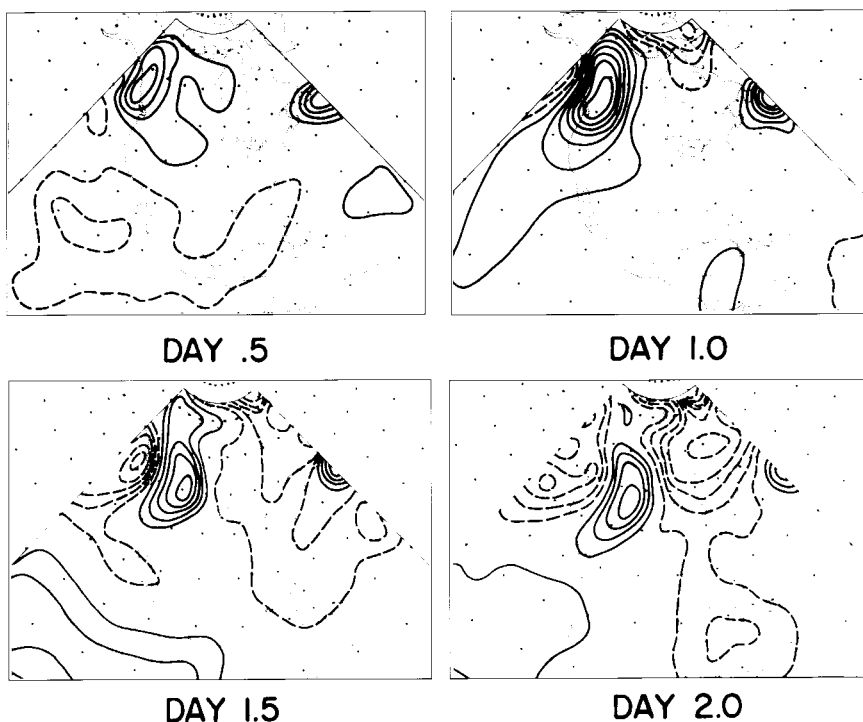
DAY 1.5   **DAY 2.0**

Fig. 1. Pressure difference at 6 km (about 500 hPa) between simulations from a 2.5° lat–long hemispheric model and a limited-area model with the same resolution embedded within a 5° lat–long hemispheric model. The differences are associated with boundary-condition errors. The area delineated is that of the LAM domain. The isobar interval is 1 hPa, and negative values are dashed. From Baumhefner and Perkey (1982).

tions are not being used as a reference. However, it is sobering to see that, when the global 2.5° simulation is used as a reference, the *global* 5° simulation shows smaller error than do either of the 2.5° LAM simulations containing the LBC error. That is, when using the 2.5-km global solution as a standard, higher accuracy is obtained by using only the coarse global model rather than the coarse global model with an embedded higher-resolution LAM. In another experiment (not shown), where the computational domain was extended by 20° of longitude at the east and
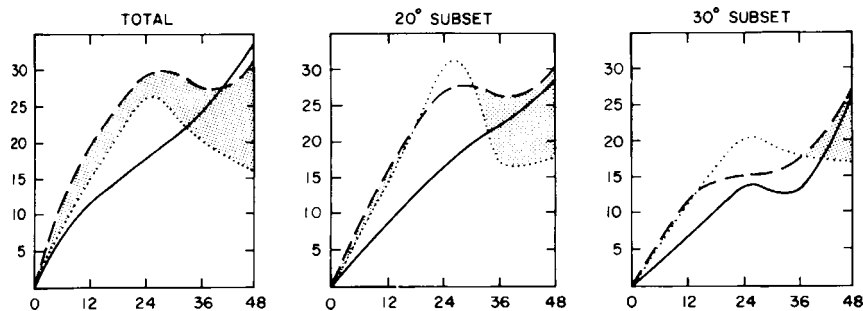

FIG. 2. Rms 500-hPa height differences (m) for the total domain (left) and subdomains that exclude the areas within 20° (middle) and 30° (right) of the boundary. The solid curve shows the difference between 5° and 2.5° hemispheric simulations, the dashed line shows the difference between the 2.5° hemispheric simulation and that from the 2.5° LAM whose LBCs are provided by the 5° hemispheric simulation, and the dotted line shows the difference between the 2.5° hemispheric simulation and that from the 2.5° LAM whose LBCs are provided by the 2.5° hemispheric simulation. The abscissa represents forecast hours. From Baumhefner and Perkey (1982).

west boundaries, the center of the domain was protected from LBC contamination for a longer period, but by 48 h the high central latitudes were contaminated from both the east and the west by error propagating inward at about 30° long day^{-1}. Baumhefner and Perkey state that "these experiments lead to the not too surprising conclusion that boundary locations should be determined from the forecast time frame selected and the typical boundary error propagation rate." Comparison of model simulation error *defined relative to observed conditions* for the 2.5° hemispheric model and the 2.5° LAM embedded within the 5° hemispheric model revealed that the LBCs increased the total simulation error by up to 50% after 24 h at high latitudes. That is, the total error growth from all non-LBC sources is about twice that which is related to the LBCs. Naturally, the relative contribution of the LBCs to the total error depends greatly on the overall predictive skill of the model. It is noteworthy that similar results were obtained using two totally different algorithms for specifying the LBCs.

Another well-controlled demonstration of this domain-size problem is described by Treadon and Petersen (1993), who performed a series of experiments with 80- and 40-km grid-increment versions of the NWS Eta Model (Black et al. 1993) on a winter and summer case. While maintaining the same resolution and physics, they progressively reduced the area coverage and documented the impact on forecast skill. The "control simulation" utilized the full computational domain of the Eta Model, while experimental simulations used collocated domains that were progressively smaller, with each having approximately

one-half of the area coverage of the next larger domain (Fig. 3). In each case, global spectral T-126 AVN previous-cycle forecasts were used for lateral boundary conditions. For a winter cyclogenesis case, the 80- and 40-km grid-increment models with the full domain produced a reasonably accurate forecast. However, the forecast on the smallest domain, which had its lateral boundaries close to the area affected by the storm, had 500-hPa rms height errors that were twice as large as those of the forecast on the full domain by only 12 h into the forecast period. In addition, the surface low pressure center was much weaker than observed and
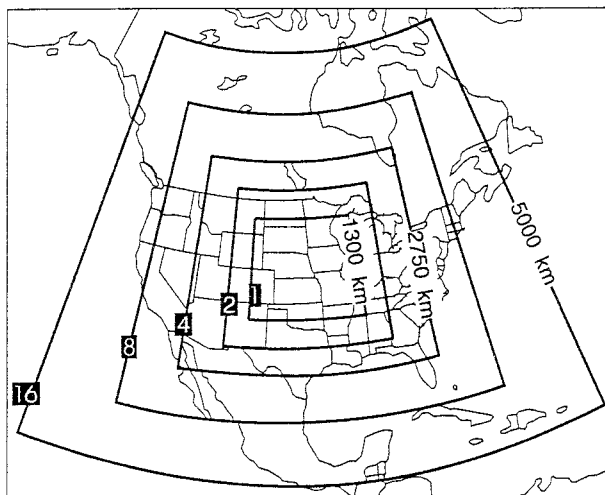

FIG. 3. Five collocated integration domains of the 80-km grid increment Eta Model used in the domain-size sensitivity study. The grid number corresponds to the factor by which the grid is larger than that of the smallest grid. From Treadon and Peterson (1993).

erroneously placed in the smallest domain forecast. Figure 4 illustrates the sensitivity of the simulation to domain size in terms of differences in the rms 500-hPa height forecasts between the largest domain and each of the smaller domains. For a summer case, with much weaker flow over the small domains, qualitatively similar results were obtained in term of error growth. In the latter case, rms 500-hPa height errors (relative to data analyses) were more than twice as large on the smallest domain than they were on the largest domain by the 36-h forecast time (Fig. 5). An example is shown in Fig. 6 of the rapid influence that the LBCs can have at upper levels, even when the cross-boundary flow is weak to moderate. For this summer case, Fig. 6 illustrates two 12-h simulations of 250-hPa isotachs from the 40-km grid-increment Eta model. Figure 6a shows a strong narrow jet streak simulated on the largest domain, while Fig. 6b shows that the same feature on the smallest domain has been considerably smoothed. The authors conclude that "small scale features develop within the integration domain only when the forcing mechanisms remain local to that domain" and that "difficulties arise when mesoscale development depends on large scale forcing."

Similar sensitivities to LAM domain size were documented by Dickinson et al. (1988) in their development of a version of The Pennsylvania State University–NCAR mesoscale model (Version 4; MM4) (Anthes and Warner 1978; Anthes et al. 1985) to be used for mesoclimate studies. Simulations of 72-h duration were performed with MM4 for a winter precipitation event in the western United States where orographic modulation of the precipitation was important. Three different domain sizes were used, where the smallest had its upwind lateral boundary near the coastline at the western margin of the precipitation area. In each case the grid increment was 60 km and the lateral boundary conditions were defined from a large-scale analysis of the observations. This analysis had a horizontal resolution that was similar to that of the global climate model within which the LAM was to be embedded. The smallest domain covered an area that was approximately one-ninth that of the largest domain. Because the model was to be used for regional climate simulation rather than for operational prediction, the authors chose to compare the structure of the orographically modulated precipitation fields from the three simulations with each other rather than show objective verification statistics. Figure 7 depicts the 72-h precipitation totals for the three domains, where the area shown represents the coverage of the smallest domain. The boundary of the largest grid is 1200 km removed from this area, and for the medium-sized grid it is removed by a distance of 600 km. It is
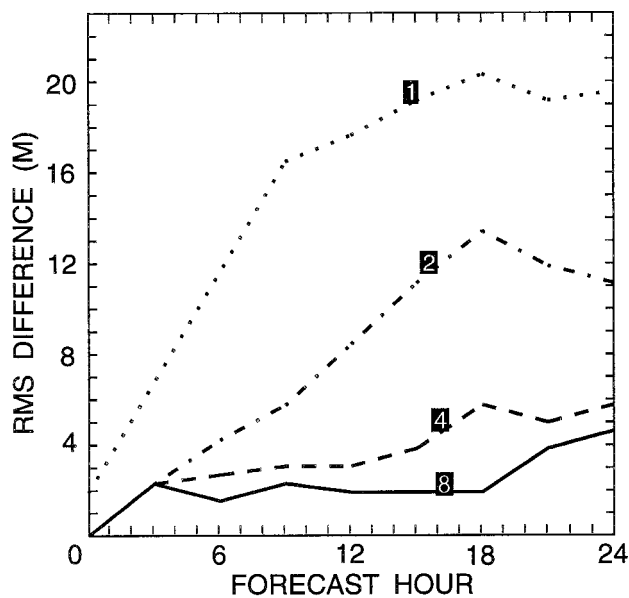

FIG. 4. Temporal evolution of the rms difference in the 500-hPa height forecasts between the largest domain and each of the smaller domains for a forecast initialized at 1200 UTC 7 January 1992. The grid number corresponds to those defined in Fig. 3. From Treadon and Peterson (1993).
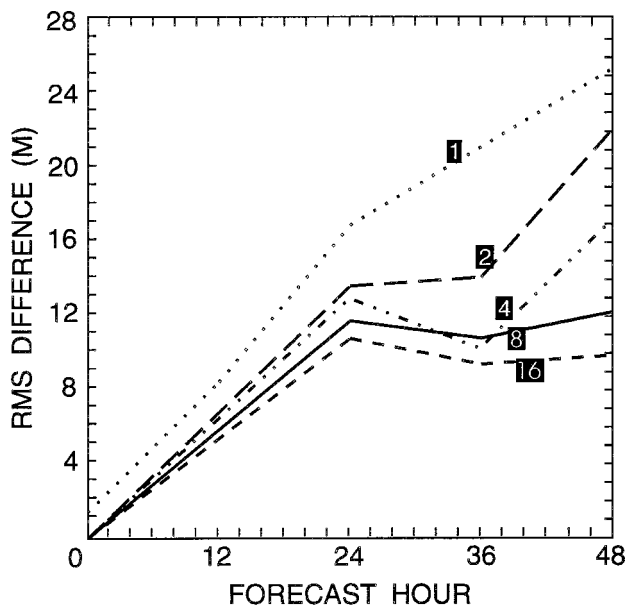

FIG. 5. Temporal evolution of the rms 500-hPa height errors (relative to data analyses) for each of the five computational grids for a forecast initialized at 0000 UTC 3 August 1992. The grid number corresponds to those defined in Fig. 3. From Treadon and Peterson (1993).
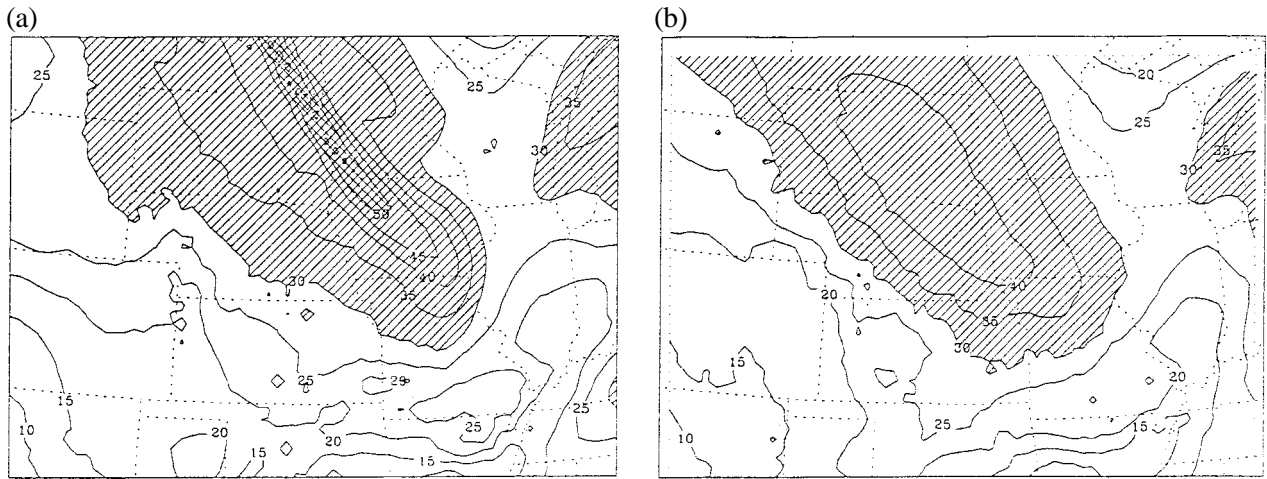
FIG. 6. Simulated 250-hPa isotachs (m s^{-1}) from the 40-km grid increment Eta Model initialized at 1200 UTC 3 August 1992 for the largest computational domain (a) and the smallest (b). The isotach interval is 5 m s^{-1}. From Treadon and Peterson (1993).

clear that the orographically forced structure to the precipitation field is strongly dependent on the distance of the lateral boundaries from the forcing. For example, the dominant precipitation maximum of over 6 cm that exists in northern Arizona for the smallest domain is barely discernible when the largest domain is employed. An additional experiment (not shown) confirmed that the use of an even larger domain had little significant impact on the structure of the precipitation fields for a simulation of this duration. Because there are many similarities in the precipitation patterns of the large- and medium-sized domains, the authors decided to accept the computational expense and to use a domain for their future work that had the lateral boundaries displaced by 900 km from this area of orographic forcing.

b. Mesoscale predictability studies

Predictability studies with mesoscale LAMs have demonstrated that error growth is much different than that which has been documented for global models (Anthes et al. 1985; Errico and Baumhefner 1987; Vukicevic and Paegle 1989; Warner et al. 1989). When small perturbations (errors) are added to the initial conditions (but not the boundary conditions) of a mesoscale LAM, the simulation from the perturbed initial state and that from the unperturbed control initial state do not diverge as they would with an unbounded model. The error growth here is affected by a number of processes, but the LBCs have a definite major impact on the solution that can be attributed to at least some of the factors noted earlier. For example, the perturbed atmosphere on the domain interior is ad-

vected out of the limited domain at the outflow boundaries, and the use of identical LBCs in the two simulations causes unperturbed atmosphere to be swept in at the inflow boundaries.

In a predictability study that is very revealing of LBC effects, Vukicevic and Errico (1990) used a relatively coarse resolution version of The Pennsylvania State University–NCAR mesoscale model (MM4) with a grid increment of 120 km for a 96-h simulation of Alpine cyclogenesis. LBCs were defined for MM4 using data analyses and simulations from the NCAR Community Climate Model-Version 1 (CCM1) that was initialized at the same time as the LAM.

In one experiment, a control simulation was first performed with MM4, and then the initial conditions were perturbed and the model was again integrated. LBCs were based on analyses of data and were thus "forecast-error free" and the same for both simulations. Figure 8a shows the 96-h 500-hPa geopotential-height differences between the two simulations. In order to infer the LBC effects on limiting error growth in the above LAM experiment, Fig. 8b shows the 96-h 500-hPa difference between the solutions from unbounded, global CCM1 simulations with perturbed and unperturbed initial condition for the same area (i.e., no LAM was used). Even though there is some similarity to the patterns on the downwind (eastern) side of the domain, the amplitudes and patterns are quite distinct. Because the model resolutions and physics parameterizations are not the same, the differences must be viewed qualitatively. Nevertheless, it is very likely that much of the difference is due to the aforementioned effects of the LBCs. Thus, if the
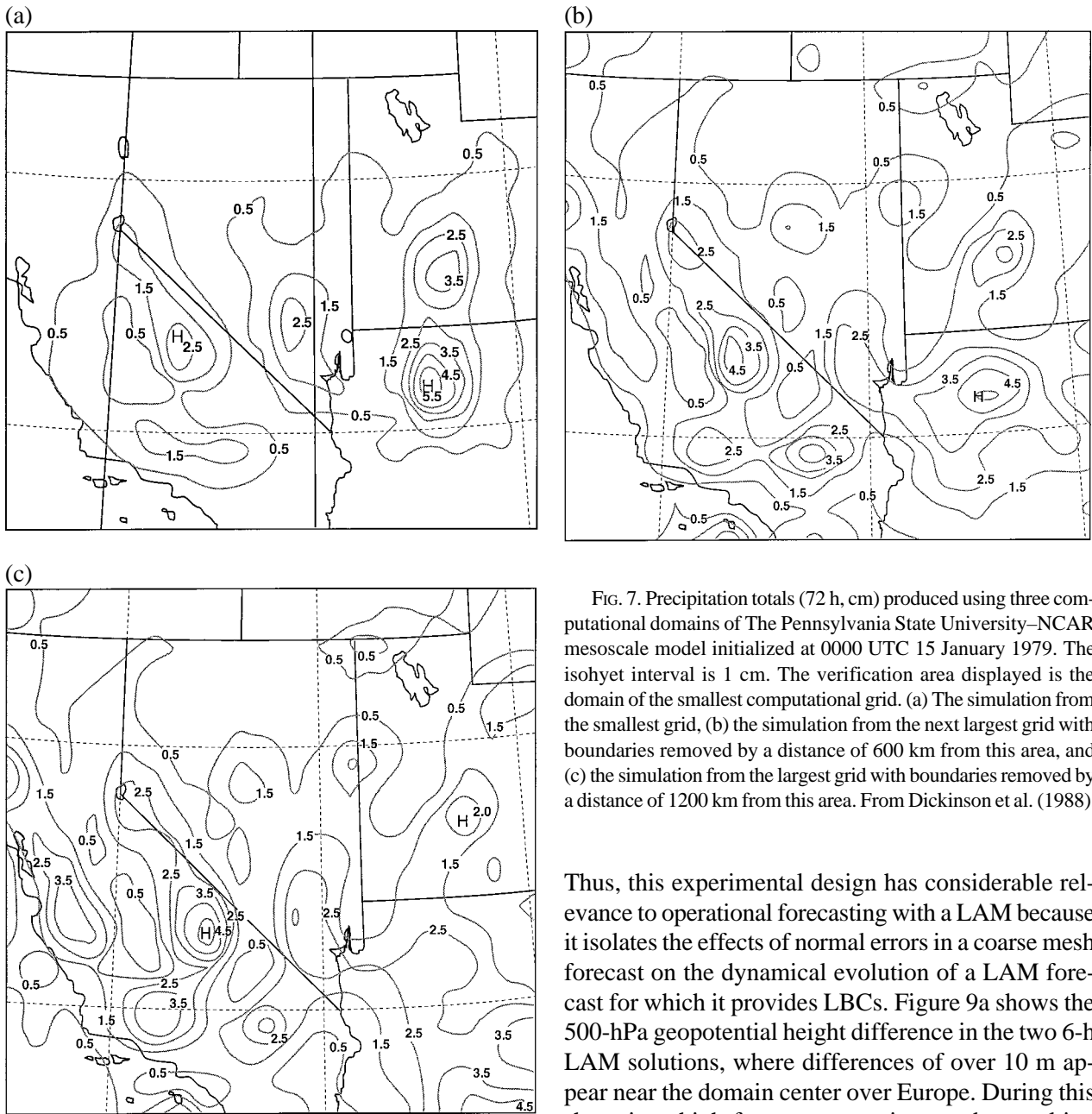
(a)

(b)

(c)

Fɪɢ. 7. Precipitation totals (72 h, cm) produced using three computational domains of The Pennsylvania State University–NCAR mesoscale model initialized at 0000 UTC 15 January 1979. The isohyet interval is 1 cm. The verification area displayed is the domain of the smallest computational grid. (a) The simulation from the smallest grid, (b) the simulation from the next largest grid with boundaries removed by a distance of 600 km from this area, and (c) the simulation from the largest grid with boundaries removed by a distance of 1200 km from this area. From Dickinson et al. (1988).

MM4 LAM were being used to produce an actual forecast of cyclogenesis on this limited domain, the natural dynamical evolution of the model atmosphere would be seriously affected by the LBCs.

To gain further insight about LBC effects on the LAM solution, an additional experiment used control and perturbed-initial-condition CCM1 forecasts to define the LBCs of a corresponding pair of MM4 forecasts that had initial conditions that were identical and equal to those of the control CCM1 simulation. The perturbed CCM1 initial conditions were defined so as to emulate expected operational measurement errors.

Thus, this experimental design has considerable relevance to operational forecasting with a LAM because it isolates the effects of normal errors in a coarse mesh forecast on the dynamical evolution of a LAM forecast for which it provides LBCs. Figure 9a shows the 500-hPa geopotential height difference in the two 6-h LAM solutions, where differences of over 10 m appear near the domain center over Europe. During this short time, high-frequency transient modes resulting from the LBC formulation have contaminated the entire domain. Figure 9b shows the same field after 96 h, by which time 25–30 m short-wave amplitude differences exist over the Mediterranean. In order to compare this error growth on the LAM domain that is associated with only LBC errors, with the error growth that results from errors that originate on the LAM domain, another experiment was conducted. Now the two LAM simulations used the same LBCs obtained from the CCM1 control run, but the LAM initial conditions were defined by interpolating the CCM1 control and perturbed initial conditions to the LAM grid. Thus, the previous experiment used perfect initial con-

ditions on the LAM domain but had realistic LBC errors, whereas this subsequent experiment had perfect LBCs with realistic initial-condition error. Figure 9c illustrates that after 96 h the initial condition error alone produced less overall error in the LAM simulation than did the LBC error alone (Fig. 9b). The major differences are at high latitudes in the northwest and northeast quadrants of the domain where the CCM1 alone had its greatest error (see Fig. 8b). It is important to recognize that the LAM domain employed here has perhaps four times the area of many typical LAM domains, and thus the LBC error effects would normally be felt on considerably shorter timescales. Based on these results, Vukicevic and Errico state that "medium range forecasts with nested limited-area models may not significantly reduce rms errors relative to the same forecasts performed with global models."

As noted earlier, it is intuitive that, in some situations, strong local forcing mechanisms may cause a model simulation to show more skill, in spite of LBC errors, than it otherwise would. The existence of such forcing-related predictability increases may be an important criterion in determining whether a particular LAM configuration can be used successfully without unacceptable dominance of the solution by LBC effects after a period of time. Even though Vukicevic and Errico did not directly evaluate the influence of local forcing on error originating at the LBCs, they did evaluate its effect on the growth of initial-condition error. These results can be enlightening in the context of our problem because the effects of local forcing on predictive skill should be qualitatively similar regardless of whether the errors in the meteorological area of interest (that is, in the vicinity of the forcing) originated locally from initial conditions or propagated from the lateral boundaries. The results from two pairs of experiments were compared. One pair included a control simulation and a simulation with perturbed initial conditions, where both used a realistic representation of the orography of the Alps at the lower boundary. Another pair was identical except that no orography was used. After 96 h of simulation, the vertically averaged rms geopotential height errors (differences between the control and the perturbation runs) were twice as large in the pair with no orographic variation, thus confirming the hypothesis.

c. Adjoint sensitivity studies

Recently, variational techniques employing an adjoint model have been used to investigate the sen-
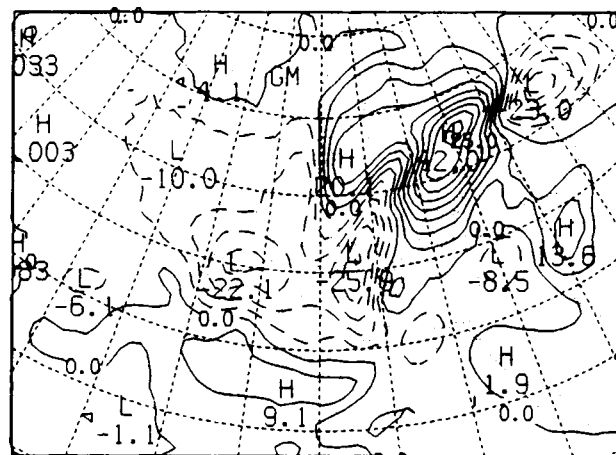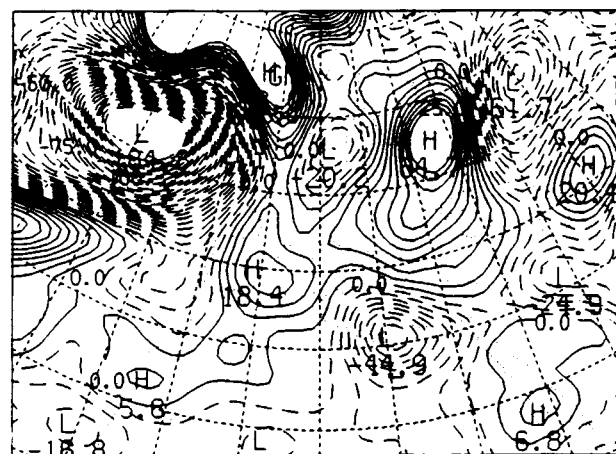

Fig. 8. The 500-hPa 96-h geopotential-height difference between a control simulation with MM4 and a parallel one with perturbed initial conditions (a). The contour interval is 5 m. The LBCs were identical and based on analyses of observations. For the same area (b) the difference between two unbounded CCMI simulations after the same 96-h period is shown, one with initial-condition perturbations over its entire domain and one without. From Vukicevic and Errico (1990).

sitivity of LAM forecasts to initial conditions and boundary conditions. The adjoint operator produces fields that indicate the quantitative impact of any small, but arbitrary, perturbation in initial conditions, boundary conditions, or model parameters on a particular aspect of the forecast. This approach has the advantage over the traditional types of predictability studies discussed above in that the resulting dependencies are not sensitive to the specific perturbations applied to the initial or boundary conditions. Actual metrics of sensitivity are produced, and the results apply to any arbitrary set of perturbations, provided
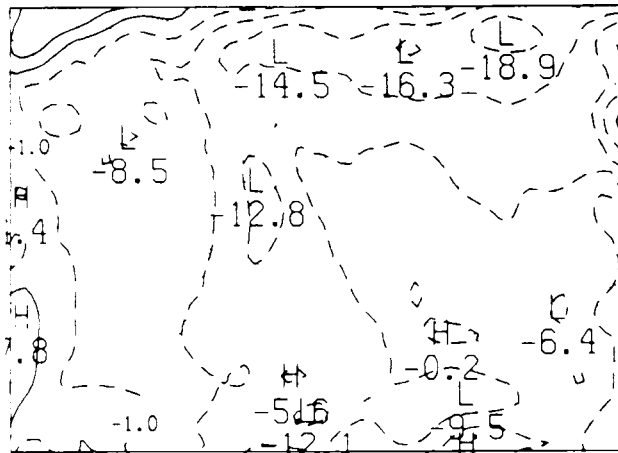
(a)
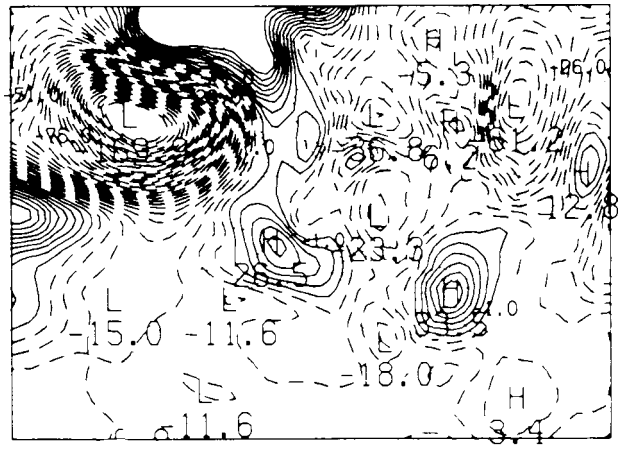
(b)
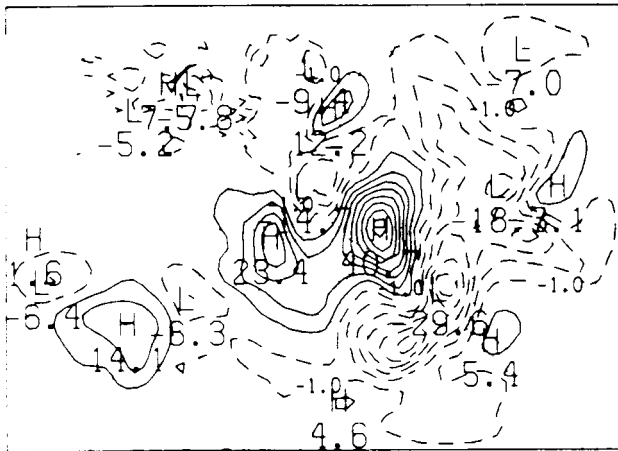
(c)

FIG. 9. Difference in (a) 6-h and (b) 96-h 500-hPa geopotential height between two MM4 simulations. The contour interval is 5 m. Control and perturbed-initial-condition CCM1 forecasts were used to define the LBCs of a corresponding pair of MM4 forecasts that had initial conditions that were identical and equal to those of the control CCM1 simulation. The perturbed CCM1 initial conditions were defined so as to emulate expected operational errors. In (c), the 500-hPa 96-h difference field is from two LAM simulations that used the same LBCs obtained from the CCM1 control run, but the LAM initial conditions were defined by interpolating the CCM1 control and perturbed initial conditions to the LAM grid. From Vukicevic and Errico (1990).

that they are not too large. For a more in-depth discussion of this technique, the reader should consult Errico and Vukicevic (1992) and Hall and Cacuci (1983).

Errico et al. (1993) applied this approach to investigate the sensitivity of LAM simulations to conditions on the domain interior and LBCs. A dry version of The Pennsylvania State University–NCAR MM4 model and its adjoint were employed, where the model had a grid increment of 50 km and 10 computational layers. LBCs were provided by linear temporal interpolation between 12-h T42 analyses (resolution equivalent to about a 300-km grid increment) from the European Centre for Medium-Range Weather Forecasts. The sensitivity was tested in 72-h simulations of both a summer and a winter case. A number of aspects of the simulations were investigated relative to their sensitivity to initial and boundary condition. We will concentrate on the influence of the LBCs on the 72-h relative vorticity for the 29 grid points at all

computational levels that are within 150 km of the center of the domain.

Figure 10 shows the sensitivity of the 72-h relative vorticity in this limited area in the center of the domain to perturbations of the 400-hPa v component of the wind on the domain interior for the winter case. (For further discussion of the sensitivity metric, see Errico et al. 1993.) The four panels indicate the areas and the extent to which the 72-h vorticity in this area is sensitive to the v wind component on the domain interior at various times between the initialization and the 72-h time. For comparison, Fig. 11 illustrates the sensitivity of this vorticity average to the v component of the wind on the lateral boundaries. Again, the four panels show the sensitivity of the 72-h vorticity to the LBCs of v at various prior times during the simulation period. The LBC-sensitivity metric extends over four rows and columns of grid points near the boundary because the LBC formulation in this model is such that LBCs are defined at all four points closest to the boundary. Note that the isopleth intervals differ greatly between Figs. 10 and 11 and among the different panels within each figure (see captions). Table 1 summa-

rizes the maximum value of the sensitivity metric on the domain interior and on the lateral boundaries at these times.

Table 1 indicates that, as expected, the sensitivity of the 72-h vorticity to conditions on the domain interior decreases as the initial time of the simulation is approached. That is, the 72-h vorticity simulation tends to "forget" the impact of the perturbations to instantaneous meteorological conditions as these conditions become more temporally removed. In terms of the effect on the 72-h simulation, the 48-h LBCs are more important than those at other times (see Table 1) because the 24-h difference is the time required for the LBC signal to propagate to the center of the domain at this level. It is interesting that the 72-h forecast is less sensitive to initial condition (h = 0) perturbations (1.4 units) than it is to boundary-condition perturbations at any time (8-150 units). The results for lower levels (i.e., perturbations below 400 hPa) with weaker winds are qualitatively similar except that it naturally requires more time for LBC effects to penetrate to the center of the domain. For the summer case, the weaker wind speeds cause a factor-of-2 slower propagation of the sensitivity.
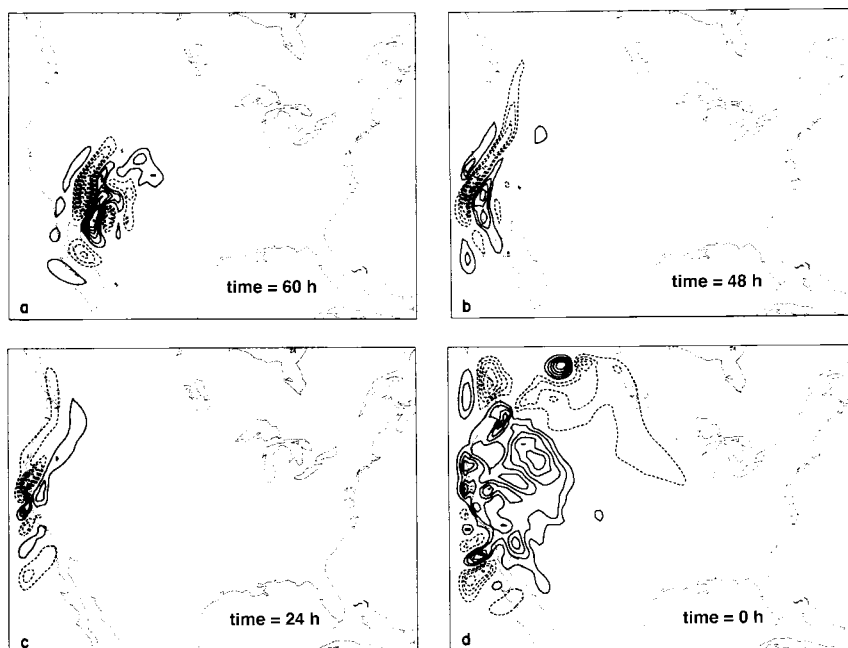

Fig. 10. Sensitivity of the 72-h relative vorticity in the limited volume in the center of the domain to perturbations of the 400-hPa v component of the wind on the domain interior for the winter case. The four panels indicate the areas and the extent to which the 72-h vorticity is sensitive to the v-wind component on the domain interior at the times indicated during the simulation. Maximum absolute values are 93, 76, 18, and 1.4 units, respectively, for (a)–(d). Isopleth intervals are 10, 10, 2.5, and 0.25 units, respectively, for (a)–(d). From Errico et al. (1993).

4. Summary of types of LBC formulations

As noted elsewhere in this paper, there are two basic approaches for providing lateral boundary values to LAMs that must respond to temporally and spatially varying larger-scale meteorological conditions. One involves the simultaneous integration of the LAM and a coarser-mesh model within which it is embedded, where the information flow between the domains is in both directions. See Harrison and Elsberry (1972), Phillips and Shukla (1973), and Staniforth and Mitchell (1978) for a historical discussion of such techniques. In the other approach, lateral boundary values are prescribed based on the output from a pre-

vious integration of a coarser-mesh model or an analysis of data. The development of these techniques is described in Shapiro and O'Brien (1970), Asselin (1972), Kesel and Winninghoff (1972), and Anthes (1974). The first approach is called two-way interactive nesting, and the latter is called one-way, or parasitic, nesting. In both cases, meteorological information from the coarser-mesh domain must be able to enter the fine-mesh domain, and gravity–inertia and other waves must be able to freely exit the fine-mesh

TABLE 1. Maximum values of the sensitivity metric of the relative vorticity near the center of the domain to the 400-hPa v-wind component on the lateral boundaries and on the domain interior (from Errico et al. 1993).

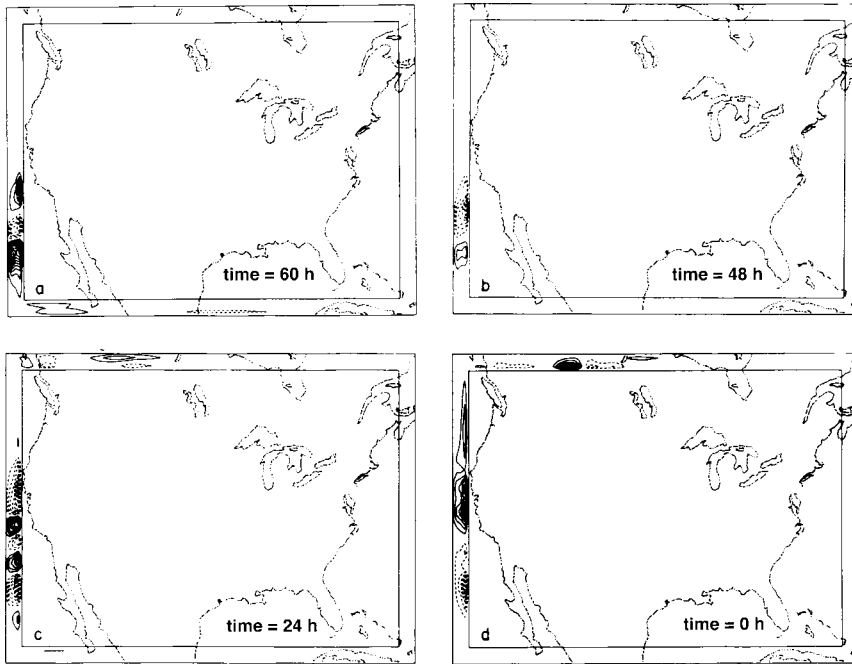|	Simulation time (h)			
	0	24	48	60
Lateral boundary sensitivity	8	40	150	52
Interior sensitivity	1.4	18	76	93

FIG. 11. Sensitivity of the 72-h relative vorticity in the limited volume in the center of the domain (circle, Fig. 10a) to perturbations of the 400-hPa v component of the wind on the lateral boundaries for the winter case. The four panels indicate the extent to which the 72-h vorticity is sensitive to the v-wind component on the lateral boundaries at the times indicated during the simulation. Maximum absolute values are 52, 150, 40, and 8 units, respectively, for (a)–(d). Isopleth intervals are 5, 25, 5, and 1 units, respectively, for (a)–(d). From Errico et al. (1993).

small scales in the fine-mesh solution near the boundary (Perkey and Kreitzberg 1976; Kar and Turco 1995). For example, in the Perkey and Kreitzberg approach, a wave-absorbing or sponge zone near the lateral boundary prevents internal reflection of outward-propagating waves through an enhanced diffusion as well as truncation of the time derivatives. In these approaches, the fine grid is forced with large-scale conditions through a relaxation or diffusion term (Davies 1976, 1983; Davies and Turner 1977).

5. Discussion and summary

The experiences described in the previous section are illuminating because of their conclusions about the potentially serious influences that LBCs can have on LAM forecasts. Even though none of these studies were ideally constructed for addressing the particular concerns of this discussion, this consistent, albeit qualitative, message that they convey is perhaps the most important knowledge that should be derived from them. Before suggesting some general guidelines for minimizing LBC-related errors, a review will be provided of the "lessons learned" from the modeling experiences described in the previous section.

domain. With the two-way interacting boundary conditions, the information from the fine mesh can affect the solution on the coarse mesh, which can feed back to the fine mesh. An example of the desirability of this approach is provided in Perkey and Maddox (1985), who use numerical experiments to show that a convective precipitation system can influence its large-scale environment, which can then feed back to the mesoscale. Note that LAMs that employ a two-way interacting nested grid system must generally obtain LBCs for their coarsest resolution domain from a previously run global model or from analyses of data. Thus, whether or not a two-way interacting nesting strategy is employed, the use of a one-way interacting interface condition is almost always necessary.

For the interface condition between domains of a two-way interacting nest, a variety of approaches are successfully used for interpolating the coarser-grid solution to the finer grid and for filtering the finer-grid solution that is fed back to the coarser grid (Zhang et al. 1986; Clark and Hall 1991). For one-way interacting grids, techniques are common that filter or damp

- Lateral-boundary error propagates toward the domain interior at a range of speeds. Deep gravity–inertia waves generated by geostrophic imbalances at the lateral boundaries can contaminate the domain interior within a few hours (Fig. 9a), whereas slower waves moving at near-advective speeds can penetrate inward on the domain at rates of 20°–30° day^{-1} in middle and high latitudes (Baumhefner and Perkey 1982).
- Lateral-boundary-error advective speeds are generally going to be slower at low latitudes because the conditions are more barotropic and the cross-boundary flow is weaker (Fig. 1). Another latitu-

dinal effect is that the observed gradients are weaker at lower latitudes, and this will mean that advective effects may be smaller in magnitude than those related to other physical processes (Baumhefner and Perkey 1982).

- Strong local dynamic forcing at the surface may reduce the dominance of errors that originate from lateral boundaries (Vukicevic and Errico 1990). However, even in these situations, LBC error can be significant (Dickinson et al. 1988).
- The more barotropic conditions during meteorological summer in middle and high latitudes will favor a slower rate at which lateral boundary error influences a forecast, compared to the faster rate that will prevail during typical winter baroclinic conditions where cross-boundary flow is stronger (Treadon and Petersen 1993; Errico et al. 1993).
- LBC errors can be sufficiently damaging to LAM forecast quality such that more accurate predictions can sometimes be obtained from the coarser-resolution models with less sophisticated parameterizations that are used to provide the boundary conditions for a LAM (Baumhefner and Perkey 1982).
- Errors generated by the LBC formulation alone, in addition to those associated with interpolation or errors in the forecast providing the LAM LBCs, can have long-term, significant-amplitude effects on forecast quality (Baumhefner and Perkey 1982).
- LBC-related forecast error averaged over the LAM domain grows approximately linearly in time until reaching a point where it becomes more temporally uniform (Baumhefner and Perkey 1982; Treadon and Petersen 1993). The growth in the domain-average error likely reflects the increase in the fraction of the domain influenced by the LBCs. The growth rate diminishes after the entire domain is affected.
- LBC errors can be more damaging to forecast quality than initial-condition errors of a similar magnitude, especially for longer simulation times (Vukicevic and Errico 1990; Errico et al. 1993).

The experiences described in the last section and summarized above, and the basic tenets of NWP related to LBCs that are listed in section 2, will now be synthesized into recommendations for how LBC effects can be minimized in any LAM application.

1) *Utilize a lateral-boundary buffer zone*

The LBC errors that reach the central part of a LAM domain are *sometimes,* unavoidably, so egre-gious as to render the LAM forecast to be of lesser, or at least no more, value than that of the coarser-mesh model that is producing the LBCs. In this situation, the only remedy is to remove the lateral boundaries a sufficient distance from the area of meteorological interest on the computational domain.

If sufficient computational resources are available, the lateral boundaries can be distanced from the central part of the computational domain so that LBC errors do not penetrate to this region during a forecast with the desired duration. Alternatively, a standard domain area can be employed and the forecast duration can be limited so as to prevent penetration of the LBC errors into the central area of meteorological interest. To illustrate the ramifications of this need for a buffer zone, a typical LAM configuration will be assumed, and the useful length of the forecast will be calculated. In this example, the lateral boundaries are removed in each direction from the area of meteorological interest (having length scale *L*) by a distance equal to one-half *L*. For example, if the computational domain has 100 grid points in each direction, the area of meteorological interest on the model domain is represented by the central subset of 50×50 points. Most modelers would agree that this is a reasonable compromise, even though there are three times as many computational points in the buffer-zone region *outside* the area of interest than there are in it. This seemingly large computational "overhead" is generally accepted as unavoidable. The useful period of the forecast is defined here as the time required for LBC influences to advect to the central forecast area. Also calculated is the lateral boundary displacement, in units of *L* (the length scale of the inner "protected" forecast area of the domain), required to produce a forecast of "standard" duration without LBC-error penetration to the domain interior. In addition, for each of these "extended" domains is computed the ratio of the number of buffer-zone grid points to the number of interior forecast-area grid points, which serves as a metric of the computational overhead resulting from the need for a buffer zone.

It is assumed here that the advective speed represents a conservative estimate of the maximum speed with which LBC error penetrates the LAM domain by non-gravity–inertia modes. LBC errors may be reflected in the characteristics of nonadvective waves such as Rossby waves; however, such nonadvective waves generally propagate more slowly than do the advective waves.

Table 2 shows the useful forecast periods for four different computational areas with different scales and

for four different meteorological regimes. Average midtropospheric wind speeds (*S,* indicated) are used in the advection-time calculation for midlatitude winter and summer regimes, and for the tropical regime. For the midlatitude-uncoupled regime, it is assumed that there is weak vertical coupling and that the dominant meteorological processes are forced by lower-tropospheric effects. The smallest domain has the size of a large city, the next larger one spans an area equivalent to the coverage of a WSR 88D, the next larger one covers about a quarter of a typical continent, and the largest one covers an entire continent.

The forecast-duration limits for the domains with a standard buffer zone will be discussed first. For the metropolitan area domain, the forecast is hardly more than a "nowcast," regardless of the regime. The radar-range and regional domains are of a scale that might be appropriate for regional weather prediction for small to moderate size countries, but unless they are in the Tropics the forecast period is generally limited to considerably less than one day. Only for continental domains can useful forecasts have durations beyond a day.

If the buffer zone width is increased for the small domains to allow for forecasts with a longer, more operationally useful, duration, the computational overhead generally becomes quite large. For example, to obtain a 6-h forecast in winter with the metropolitan-area domain could require an overhead factor of between 500 and 1000. Figure 12 is based on the data in Table 2 and graphically shows the large computational overhead that is associated with protecting the smaller domains from LBC effects using a buffer zone. Often it is possible to anticipate an asymmetry in the speed/direction correlation of the prevailing wind and thus increase the width of the buffer zone more in the direction of stronger prevailing flow. Using available computational resources wisely by asymmetrically protecting the domain interior is recommended, but this will likely only permit an increase in the useful duration of the forecast by less than 50% compared to the use of a symmetric buffer zone with the same number of grid points.

Because the limitations to LAM applications implied by these calculation are quite significant, it is appropriate to reiterate that it has been assumed that the LBC error is sufficiently large such that it overwhelms the forecast accuracy when the error penetrates to the domain interior. However, there are measures that can be taken to control the amplitude of the LBC

TABLE 2. For four different computational areas and four different meteorological regimes: [a]useful range of forecasts for a standard domain; [b]width of buffer zone required (in units of *L*) for forecasts of "standard" duration; and [c]ratio of buffer-zone grid points to central forecast-area grid points for forecasts of "standard" duration.

Forecast domain size	Interior-forecast-area length scale (*L*)	"Standard" forecast duration	Meteorological regimes			
			Winter mid lat $S = 30$ m s^{-1} (~60 kt)	Summer mid lat $S = 15$ m s^{-1} (~30 kt)	Tropical $S = 8$ m s^{-1} (~15 kt)	Mid lat uncoupled $S = 5$ m s^{-1} (~10 kt)
Metropolitan area	50 km	6 h	[a]13 min [b]13.0 *L* [c]728	27 min 6.5 *L* 195	54 min 3.5 *L* 63	1.4 h 2.2 *L* 27
Radar-range area	500 km	18 h	2.3 h 3.9 *L* 76	4.5 h 1.9 *L* 22	9.0 h 1.0 *L* 8	13.5 h 0.6 *L* 4
Regional area	2000 km	36 h	9.0 h 1.9 *L* 23	18.0 h 1.0 *L* 8	35.9 h 0.5 *L* 3	53.9 h 0.3 *L* 1.7
Continental area	5000 km	72 h	22.5 h 1.6 *L* 16	44.9 h 0.8 *L* 6	89.8 h 0.4 *L* 2	134.7 h 0.3 *L* 1.3

errors (described later). Moreover, the dominance of LBC error is likely to be less if the phenomena to be forecast are related to local forcing from surface effects such as terrain and differential heating; an example might be terrain-forced convection.

2) *Utilize compatible numerics and physics with LAM and model providing LBCs*

The actual magnitudes of LBC errors will depend on a number of factors including the quality of the coarse-mesh forecast that is producing the LBCs and the magnitude of the error associated with the spatial and temporal interpolation from the coarse mesh to the LAM domain at the lateral boundaries. The latter error that is associated with the interpolation between the two grids can be mitigated through appropriate modeling-system-design decisions such as the use of LAM and coarse-mesh models with horizontal and vertical resolutions that are not greatly different, and the frequent passage of LBC information from the coarse-mesh model to the LAM. In addition, the use of reasonably consistent physical-process parameterizations (convection, cloud microphysics, turbulence, and radiation) on the two grids will minimize the unrealistic gradients that develop at the interface and propagate onto the LAM domain through advection and gravity–inertia waves.

3) *Employ well-tested and effective LBC formulations*

The LBC formulation should and can be sufficiently well tested and designed so that it does not generate *significant*-amplitude, gravity–inertia waves that can move toward the central area of the domain at much greater than advective speeds. Even though some of the examples presented in the previous section demonstrate that this error can be significant, the use of appropriately engineered LBC algorithms can generally limit the amplitude of this mode of error propagation to acceptable levels.

4) *Allow for effects of data assimilation on LBC impact*

When using FDDA, its influence on LBC effects must be allowed for. Because the preforecast integration period will allow LBC errors to propagate closer to the domain center by the start of the forecast, the influence of the assimilated observations in the buffer zone must be sufficiently great to control the LBC errors. If there is a data void in the upwind direction, the width of the buffer zone must be increased to account for the preforecast integration period.
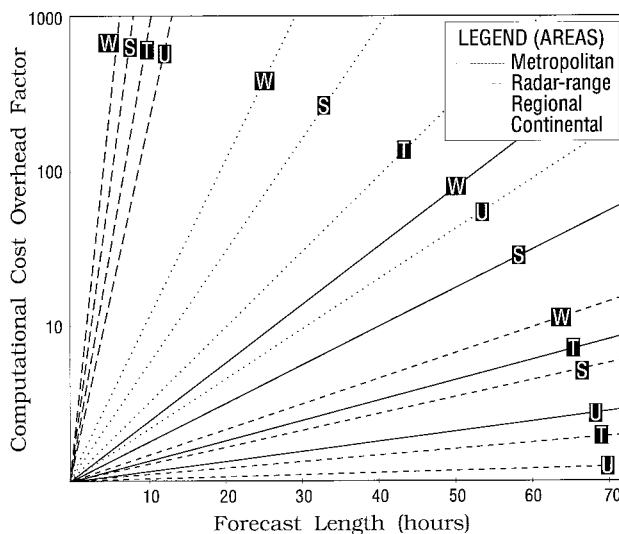

FIG. 12. Computational overhead associated with using a buffer zone to protect the domain interior from LBC effects. The ordinate is the ratio of the number of buffer-zone grid points to the number of grid points on the useful domain interior required to protect forecasts of various durations (abscissa) from LBC effects. Relationships are shown for the different forecast domains and for the different meteorological regimes (W—winter, S—summer, T—tropical, U—vertically uncoupled). The relationships are based on the data provided in Table 2.

5) *Account for importance of local forcing*

If strong local forcing mechanisms generally prevail and dominate the local meteorology, the forecast quality may not be as strongly affected by LBC errors as it would otherwise be. Thus, if the LBC errors are not especially large, the need for a wide buffer zone to protect the domain interior may not be essential. However, many locally forced phenomena can be quite sensitive to errors that can originate at the lateral boundaries.

6) *Avoid strong forcing at the lateral boundaries*

Strong dynamic forcing at the lateral boundaries can create numerical problems with many LBC formulations. Even though it is not possible to avoid the passage of transient high-amplitude meteorological phenomena through the boundaries, it is possible to avoid the collocation of the lateral boundaries with known regions of strong surface forcing such as associated with steep topography and surface-forced temperature gradients.

7) *Utilize interactive grid nests when possible*

When a LAM cannot influence the solution of the coarser-mesh model that provides its boundary values, the scale interactions of the LAM-resolved waves and

those on the large scale are inhibited. In addition, the use of a two-way interactive interface can, but will not necessarily, reduce the development of spurious gradients at the boundaries.

8) With any new model application, perform sensitivity studies to ascertain the LBC influences

After considering the experiences described in the last section, it should be clear that LBC sensitivity studies should be performed for any new application of a LAM, especially if the aforementioned recommendations regarding the buffer-zone width are not taken literally. These sensitivity studies should include the testing of the dependence of forecast accuracy on buffer-zone width, the sensitivity of the forecast quality to different LBC formulations, and a comparison of the LAM skill to that of other operational modeling systems that have unbounded domains. If the LAM is to be used operationally, the forecasts naturally should be evaluated for LBC sensitivity over a wide range of events within all seasons.

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