Eta Model Precipitation Forecasts for a Period Including Tropical Storm Allison

FEDOR MESINGER

UCAR Visitor Scientist Program, National Meteorological Center, Washington D.C.

THOMAS L. BLACK, DAVID W. PLUMMER AND JOHN H. WARD

National Meteorological Center, Washington, D.C.

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ABSTRACT

A step-mountain (eta) coordinate limited-area model is being developed at the National Meteorological Center (NMC) to improve forecasts of severe weather and other mesoscale phenomena. Precipitation forecasts are reviewed for the 20-day period 16 June–5 July 1989. This period was chosen not only because of intense warm-season precipitation, including that of Tropical Storm Allison, but also because two sets of forecasts from NMC's nested grid model (NGM) were available for comparison, one using the operational Kuo convection and the other using the eta model's Betts-Miller convection scheme. Thus, a three-way model comparison was possible.

Particular attention is paid to the forecasts of precipitation maxima. With verification performed on accumulated 24-h amounts averaged over the limited fine mesh (LFM) model grid boxes, the eta model shows skill at the highest observed precipitation category in 14 out of 58 verification periods, about one fourth of all cases. The forecasts also show a high degree of consistency in that successful forecasts starting from different initial times are produced for the same verification period.

Although the eta model was less successful than the NGM in predicting the lightest precipitation category, it demonstrated noted improvement in the 0.50-inch and greater categories, regardless of the convection scheme used in the NGM. Evidence is presented which indicates that the greater accuracy of the eta model is primarily a result of its space differencing schemes.

1. Introduction

Difficulties in achieving progress in quantitative precipitation forecasts, and in particular in forecasting intense warm-season precipitation, have been frequently emphasized. For example, Ramage (1982) has found negligible increases in a 12-yr (1966–77) sample of nonwinter precipitation forecasts made at National Weather Service (NWS) forecast offices. Since that time encouraging simulations of convective weather using state-of-the-art mesoscale research models have been published in a number of papers (see, e.g., Koch 1985; Koch et al. 1985; Maddox et al. 1986). A recent example is the simulation of an intense squall line by Zhang et al. (1989).

While successful simulations of individual cases of intense convective systems are very gratifying, the results of these simulations may not be directly applicable for assessing the prospects for progress in real-time operational forecasting. For example, the research systems are not limited by the time constraints inherent to an operational environment. These research-oriented simulations often have the advantage of using analyzed rather than forecast lateral boundary conditions. In addition, while individual case results can be extremely promising, a statistical analysis of a sample containing numerous forecasts of a large range of day-to-day convective systems is needed to evaluate the performance of a candidate operational model.

This note presents a systematic analysis of a series of warm-season precipitation forecasts produced in a quasi-operational configuration using forecast boundary conditions. A sample will be analyzed consisting of 39 48-h numerical forecasts covering a 20-day verification period. The forecasting model used for the experiment is the so-called "eta model". The eta model has been developed at the National Meteorological Center (NMC) based on a prior "minimum physics" version of the code written and tested at the Federal Hydrometeorological Institute and Belgrade University (the HIBU model) and at the Geophysical Fluid Dynamics Laboratory of Princeton University. The model was set up so that the required computational effort was comparable to that of the nested grid model (NGM), the current U.S. operational regional model. The idea is to assess progress, if any, relative to the NGM which is due to the design of the eta model and

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Corresponding author address: Thomas L. Black, National Meteorological Center, W/NMC 22, World Weather Building, Room 204, Washington, DC, 20233.

not to a larger computing effort. Wherever appropriate, advantage will be taken of the availability of forecasts from the NGM using the eta model's Betts-Miller convection scheme. For simplicity in this study "skill" is equated to positive threat scores, although one may argue that they may not be synonymous.

Specific objectives of this exercise include

1) Evaluating the skill in forecasting the location and intensity of the precipitation maxima using a verification area covering the eastern two thirds of the contiguous United States; examining the skill with respect to the choice of the convection scheme (Betts-Miller vs. Kuo) and of the model (eta vs. NGM-Betts); and examining the consistency of successful forecasts starting from different initial conditions;
2) Demonstrating the skill and consistency in the eta model forecasts of the location and intensity of the precipitation associated with Tropical Storm Allison; and
3) Identifying possible reasons for the increased accuracy of the eta model and providing guidance for further development of the model by making a three-way model comparison (i.e., eta vs. NGM, and eta vs. NGM-Betts).

2. The models and the verification procedures

a. Model characteristics

The numerical and physical parameterization schemes of the eta model have been described at some length in papers by Janjić (1984, 1990) and Mesinger et al. (1988). Since the eta model precipitation forecasts will be compared to those of the NGM, the main differences between the two models will be summarized. Concerning their space differencing schemes:

The eta model uses

- the eta vertical coordinate (Mesinger 1984) which permits step-like representation of mountains and quasi-horizontal coordinate surfaces;
- an Arakawa E grid; and
- the Janjić (1984) horizontal advection scheme which imposes a strict control on false energy cascade (e.g., Janjić and Mesinger 1984; Fig. 3.12).

The NGM uses

- the sigma vertical coordinate;
- an Arakawa D grid; and
- the Lax-Wendroff horizontal advection scheme (Phillips 1979; see also Mesinger and Arakawa 1976) with additional periodic filtering of 2 to $4\Delta x$ waves.

Both models include comprehensive physics packages (see Janjić 1990 for the eta model physics; Tuccillo 1988 for the NGM physics). One major difference in these is the Mellor-Yamada turbulence closure scheme of the eta model as opposed to the more conventional bulk formulation of the NGM. Another is the Betts-Miller convection scheme used in the eta model (Betts 1986; Betts and Miller 1986) as opposed to the Kuo scheme used in the operational version of the NGM. As already pointed out, the NGM was also run with the Betts-Miller scheme in an attempt to identify the effect of the different convective parameterizations.

One should note that the Betts-Miller schemes of the two models were not identical. A number of parameters differed due to testing aimed at refining the scheme which included adjusting its performance to the remaining components of the physics packages of the models. The largest difference regards the decision of whether or not to carry out shallow convection in cases when the instability condition is satisfied for the deep convection but when insufficient moisture is present to produce precipitation according to the deep convection algorithm of the scheme. This replacement of the deep convection by the shallow one was performed in the eta model (along with the presence of a viscous sublayer, e.g., Pielke 1984; see also Black and Mesinger 1989), and was not performed in the NGM. The differences resulting from such changes in the parameters of the scheme were found to be far less than the differences between the performance of the Kuo and the Betts-Miller scheme in any of these versions (e.g., Plummer et al. 1989). Thus these differences should not have had a substantial effect on the model results to be discussed.

Still another difference to note is the treatment of the boundary conditions. Lateral boundary conditions of the eta model are prescribed in a one-way mode using the results of the NMC global medium-range forecast (MRF) model. They are taken from the 12 hours earlier MRF (aviation) run in order to simulate an operational situation in which the short-range model is run prior to the medium-range one. Boundary conditions are prescribed at the single outermost line of grid points, shown in Fig. 1. The NGM on the other hand is a two-way triply nested hemispheric model with its highest resolution domain perhaps slightly larger than that of the eta model (Hoke et al. 1985; Hoke et al. 1989).

The eta model as used here has been set up to mimic the computational effort of the NGM considering both the execution time and the horizontal and vertical resolution. It is run with the grid increments of $^{15}\!/_{26}\,^{\circ}$ and $^{14}\!/_{26}\,^{\circ}$ of its rotated longitude and latitude, respectively, which results in about an 80-km grid distance (79.6 km along the model's southern and northern boundary, and 87.7 km at its equatorial grid line). There are 16 layers in the vertical with values of $\Delta\eta$ equal to the NGM's values of $\Delta\sigma$.

b. Verification procedures

The scores examined are the threat score

$$T = \frac{CF}{F + O - CF} \tag{2.1}$$

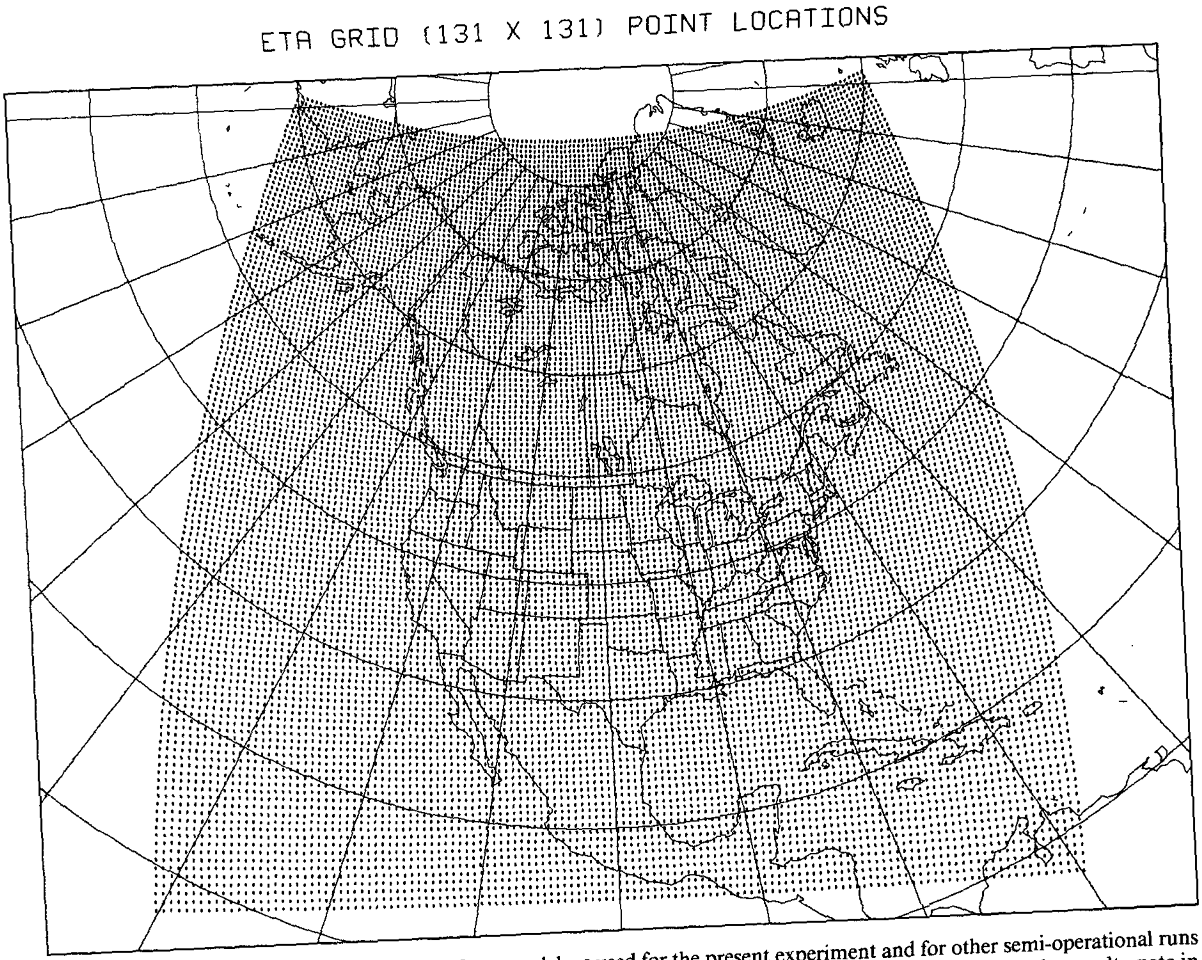

FIG. 1. Domain and grid points of the NMC eta model, as used for the present experiment and for other semi-operational runs of the model during spring and summer of 1989. Since the model is using the Arakawa E grid the grid points shown alternate in each row and column between the mass and the wind points.

and the bias score

$$B = \frac{F}{O} \tag{2.2}$$

(e.g., Anthes 1983), where CF is the correctly forecast, F is the total forecast and O is the observed area, respectively, of the accumulated precipitation above a given amount. Threat scores and bias scores can routinely be obtained at NMC for 24-h precipitation accumulations verifying at 1200 UTC. The fine-mesh precipitation analyses are obtained over the eastern ⅔ of the United States (Nierow 1985) and then averaged over grid boxes of the LFM model (190 km × 190 km at 60° lat on stereographic projection). The averaging of the predicted 24-h precipitation from the eta model's and NGM's grids to the common verification grid is done in such a way that the total rainfall is conserved. Scores are calculated for categories of 24-h precipitation accumulations with inch measurements equal to and greater than 0.01, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.50, 3.00, 3.50 and 4.00.

The period under investigation is 1200 UTC 16 June–5 July 1989. During that time a) there was no change in the semioperational version of the eta model run twice per day, and b) results of the NGM run with the Betts-Miller convection scheme were also available. Condition a) was not satisfied prior to 16 June and condition b) not after 5 July, so that the considered 20-day verification period is the longest for which both conditions were satisfied and the three-way model comparison was possible.

The period 16 June–5 July 1989 was exceptionally wet over the eastern two-thirds of the continental United States. On two occasions average LFM grid-box precipitation of over 4 inches in 24 hours was recorded. On only five occasions was the maximum precipitation less than 1.75 inches. A large portion of the heavy precipitation was produced by Tropical Storm Allison which slowly approached the Texas-Louisiana coastline at about the middle of this period. Although its center moved over land, the storm remained near the Gulf Coast for about four days causing heavy rains and flooding in the regions around the Texas-Louisiana border.

3. Verification of precipitation maxima

Since correctly forecasting the location of precipitation maxima is of special interest and is not something for which numerical models are yet famous, the considered sample was searched for cases in which the models retained skill greater than zero through the highest category of the "observed" precipitation. Two forecasts from all of the models were not accessible to the verification code because of archiving problems. The sample thus consisted of 39 forecasts from each of the three models. The forecasts starting at 1200 UTC were each verified for two of their forecast periods, 00–24- and 24–48 h; and those starting at 0000 UTC for one, the 12–36-h forecasts. The two inaccessible forecasts were those starting at 0000 UTC. Thus, within the 20 verification periods there are verifications for 58 accumulated precipitation forecasts for each of the three models.

The operational NGM retained skill greater than zero through all of the precipitation categories observed over 2 periods; the NGM with the Betts-Miller convection (NGMx, for experimental) over 12 periods; and the eta model over 14 periods.

The extent to which these numbers are a result of the biases of the models for heavier precipitation amounts varies significantly between the models. For the NGM the effect is large. Its Kuo scheme showed a severe bias in the sense of being deficient in forecasting heavier precipitation amounts. For example, of the 58 24-h verifications the NGM never produced LFM grid-box amounts of 3.5 inches and greater even though the amounts of 4 inches and greater were observed during two 24-h periods, that is, for 6 verification periods. With the Betts-Miller scheme the NGM's precipitation patterns are much more concentrated (see also Plummer et al. 1989) as are those of the eta model. Therefore the ability of the NGM to retain skill through all of the categories observed is much improved with the Betts-Miller scheme.

In order to assess the possibility of benefiting from overforecasting the precipitation amounts in the two models using the Betts-Miller scheme, consider only those bias scores which accompanied the 12- and 14 periods with positive threat scores for all observed categories. Suppose a model had a bias of 1 when the calculation includes all forecasts. If the bias is recalculated, after excluding forecasts for which the highest verifying rainfall amounts were predicted to be zero by the model, the new bias score would be greater than 1. The larger this score, the more serious is the overforecasting of the heaviest rain for the remaining forecasts. The same type of increase occurs if the value of the bias score for all forecasts is not 1. The ratios of the number of forecast and observed LFM grid boxes ("points") at the highest observed category for the 12 forecasts of the NGMx were

$$\frac{2}{1},\frac{2}{2},\frac{1}{1},\frac{2}{1},\frac{10}{2},\frac{3}{3},\frac{5}{3},\frac{2}{2},\frac{2}{1},\frac{5}{1},\frac{5}{1},\frac{5}{1}, \qquad (3.1)$$

with an average value of 2.64. The ratios for the 14 forecasts of the eta model were

$$\frac{2}{2},\frac{2}{1},\frac{1}{1},\frac{3}{1},\frac{3}{1},\frac{4}{2},\frac{3}{2},\frac{13}{2},\frac{1}{1},\frac{2}{1},\frac{2}{1},\frac{2}{3},\frac{4}{3},\frac{3}{3}, \qquad (3.2)$$

with an average of 1.96. If, on the other hand, the average value of the bias score is calculated by dividing the sum of all forecast points by the sum of all observed points, the values obtained are 2.32 and 1.88, respectively. In either case, these average values indicate that the slightly higher number of hits of the eta model, 14 versus 12, did not result from overforecasting the highest precipitation amounts. Both models underforecast the highest precipitation amounts, the eta model somewhat more than the NGMx, as one can demonstrate by calculating the averages over all 58 verifications. Using the former of the two calculation methods, one obtains averages of 0.55 for the NGMx and 0.47 for the eta model.

Another important point concerns the distribution of the cases with positive threat scores at the highest observed category only in the eta model forecasts. This distribution, along with the maximum categories observed, is displayed in Table 1.

A remarkable feature of this table is the tendency of the 14 hits to occur for the same verification periods irrespective of the initial times. Of the 18 periods when it was possible to show skill at the highest observed category for all three forecast periods, this occurred three times. Two of the remaining five hits occurred for the same verification period. Given that the overall probability of a realization of skill in a given verification is equal to 14/58, and that the total number of realizations is 14, then the probability of such clustering by chance is less than 3/10,000. This is a strong indication that the model with its present resolution, nu-

TABLE 1. Forecast periods within the sample of 58 verifications for which the eta model has skill at the highest observed precipitation category, and values of these highest categories.

Verification date	Forecast period (h)			Highest category observed (inches/24 h)
16 June	00–24 h			3.00
17 June			24–48 h	2.00
24 June	00–24 h	12–36 h	24–48 h	1.75
26 June	00–24 h	12–36 h	24–48 h	1.50
27 June	00–24 h	12–36 h		4.00
29 June			24–48 h	2.50
1 July	00–24 h	12–36 h	24–48 h	2.00

merical schemes and physics, is not forecasting the location of the precipitation maxima by chance.

4. Examples: tropical storm Allison

Examples of precipitation forecasts are shown for two of the verification periods of Table 1. One is of the three forecasts verifying at 1200 UTC 27 June. They are shown in the upper right and in the two lower panels of Fig. 2. Analyzed precipitation verifying at the same time is shown in the upper left hand panel of the same figure. The verification performed over approximately the eastern two-thirds of the continental United States includes calculation of values for near-shore ocean points based on radar data if they are available, although the reliability of these values is not high. The period of Fig. 2 is the first verification period for which the center of precipitation due to Tropical Storm Allison was located over land and is also the period of Table 1 with the highest observed precipitation. The ratios (3.2) of forecast and observed LFM points at the maximum category are written in the same order as the forecast periods of Table 1. One can locate in this sequence the ratios of forecast and observed LFM points of 1/1 and 2/1 of the 00–24- and 12–36-h forecasts shown in the figure, respectively. In both cases the eta model correctly forecasts the single LFM gridbox with precipitation over 4 inches in 24 hours and in the 00–24-h forecast this was the only point of that precipitation category that was predicted.

Following landfall, the center of accumulated precipitation from Allison moved east and was located over south central Louisiana at the next verification time. Subsequently while reducing in intensity, Allison moved back to the Texas-Louisiana border and at 1200 UTC 29 June was located north of its position seen in Fig. 2. During the following 24 hours, while slightly weakening further, the storm moved back toward the south to about the same position as on 27 June. Finally after another 24 hours the center moved north-northeast so that at 1200 UTC 1 July it was located at the Arkansas-Louisiana border. The three forecasts verifying at that time are the second example shown in Fig. 3. Note that this is the first verification time for which the precipitation center had moved further inland after staying at or close to the Gulf Coast for the preceding four to five days and that in all three forecasts this movement was predicted.

5. Average scores: the three-way model comparison

In Fig. 4 the threat scores for the three models averaged for all 58 verifications are shown. "Averaging" is performed by first summing all points observed within each category, all points correctly forecast, and the total number of points forecast, prior to inserting these sums into (2.1). In this way, incorrectly forecast points in categories above the maximum observed will penalize the average score. This would not be the case if the threat scores had been calculated for individual verifications first and then averaged over only those categories for which precipitation was observed.

Comparison of the eta and the NGM results is shown in the upper panel of Fig. 4. The eta model performed worse in the lightest precipitation category of 0.01 inches and greater. This is related to a bias problem of the Betts-Miller scheme to be discussed shortly. The eta bias score in this category was only 0.74 compared to 1.10 for the NGM while the bias of the NGMx (using the Betts) was even worse at only .64. The model performances for the next higher category of 0.25 inches and greater were nearly equivalent. The eta model outperformed both versions of the NGM in the remaining categories by a gradually increasing margin for larger precipitation amounts. At the higher categories, the reduced performance of the NGM is mainly a result of the bias problem in that model's Kuo convection scheme. For example, at 2.00 inches and greater, the NGM had a bias score of only 0.62 compared to 1.11 for the eta model.

Differences seen in the lower panel of Fig. 4 are to a larger extent due to the effects of different finite-differencing procedures since both the NGM and eta models in this comparison are using the Betts-Miller scheme. The eta model wins all of the categories for the light and for the intense precipitation.

The average bias scores of the three models are shown in Fig. 5. The bias problem noted earlier in the eta model for the light precipitation categories is even more severe in the NGMx, indicating that the problem is the result of the convection scheme and not of the space discretization of the models. The results also demonstrate the dominant effect of the convection scheme on the bias scores in that the character of the two NGM plots is radically changed with the replacement of the Kuo by the Betts-Miller scheme. Note that although the errors remain substantial, they are generally of the opposite type, i.e., over-rather than underforecasts. Except for the highest categories, the eta/NGMx comparison in the lower panel again reflects the higher accuracy of the eta model compared to the NGM, convection schemes being the same. The problem of the excessive biases of the eta model at the highest precipitation categories will be addressed later in this section.

Other possible reasons may also contribute to the increased accuracy of the eta model compared to the NGMx. The different treatment of the boundary conditions might be suspected of having a significant influence on the forecasts. However, the lateral boundaries (see Fig. 1) are generally fairly distant from the verification area and therefore the impact of the differences in the treatment of the boundary conditions should grow as the forecast progresses, becoming more visible in the 24–48 than in the 00–24-h forecasts.

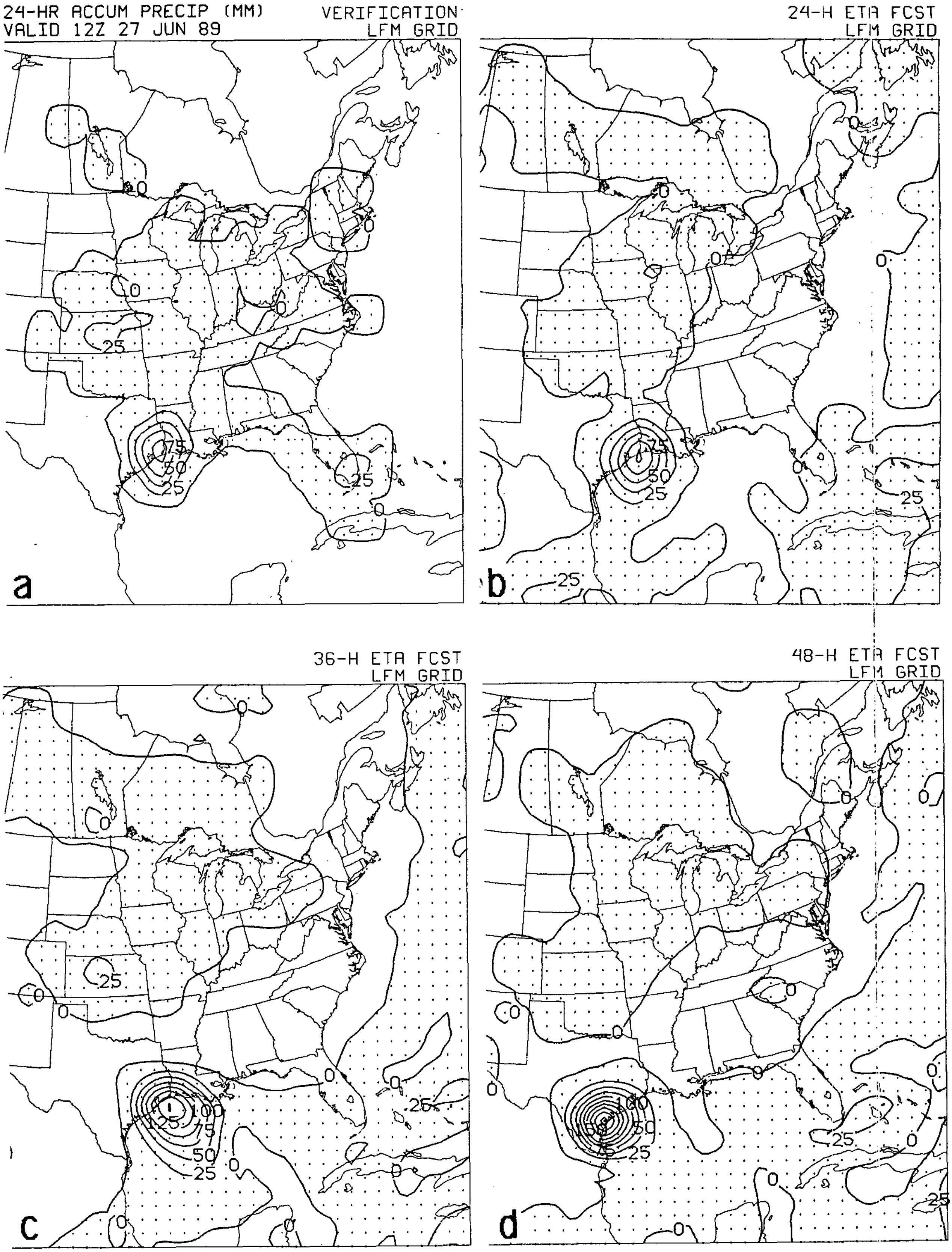

FIG. 2. 24-h accumulated precipitation (mm) verifying at 1200 UTC 27 June 1989: a) NMC analysis; b) 00–24-h, c) 12–36-h, and d) 24–48-h eta model forecast, respectively.

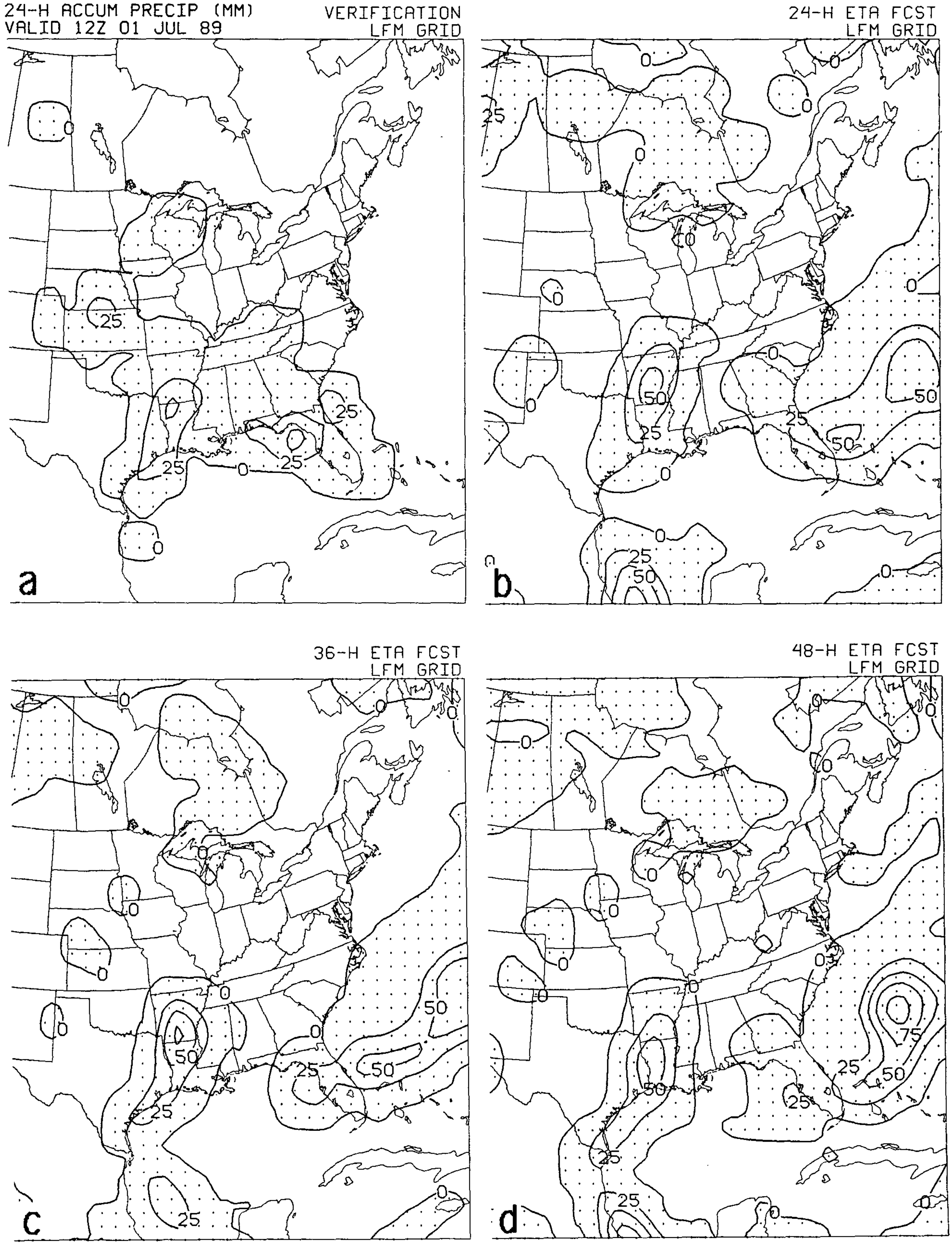

FIG. 3. 24-h accumulated precipitation (mm) verifying at 1200 UTC 1 July 1989: a) NMC analysis; b) 00–24-h, c) 12–36-h, and d) 24–48-h eta model forecast, respectively.

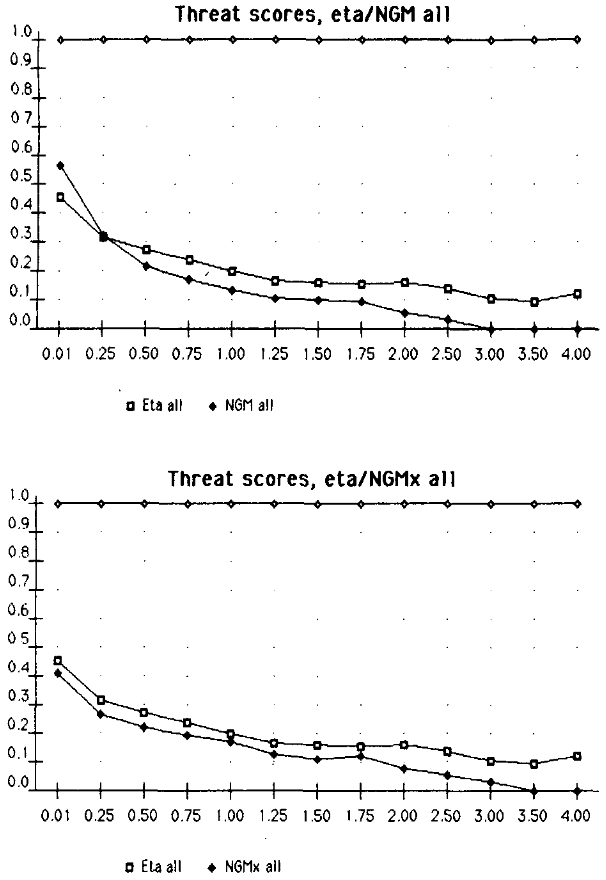

FIG. 4. Threat scores for various precipitation categories (inches) of 24-h accumulated precipitation of the eta model, the NGM, and the NGMx (NGM with the Betts-Miller convection scheme) for 58 forecasts verifying every 1200 UTC within the period 16 June–5 July 1989. See text for additional details. Eta model and NGM, upper panel; eta model and NGMx, lower panel.

While the appearance of such an impact could, in principle, be masked by an opposing effect, it is hard to see which of the remaining major differences between the two models could lead to such a situation. Specifically, no effort is made to initialize the eta model. In this regard, it should not have an advantage over the NGM early in the forecasts which would be maintained through the later stages of the forecasts due to possible beneficial effects of the different treatment of the boundary conditions. The difference between the scores for the two mentioned periods is in itself of interest by indicating the rate of the loss of skill of the models as the forecast period is increasing.

The eta and the NGMx threat and bias scores averaged for the twenty 00–24-h forecasts, and for the twenty 24–48-h forecasts, are shown in Fig. 6 and in Fig. 7, respectively. The deterioration of skill in both models as the forecast range increases is clearly visible when comparing the plots of the two figures. The advantage of the eta model is retained in both forecast periods but is not significantly different on the second compared to the first day of the forecast. This would seem to eliminate the treatment of the boundary conditions as a possible major reason for the higher scores of the eta model.

The difference between the two models in their parameterizations of the boundary layer and the free atmosphere turbulence also does not appear to have a major impact on the accuracy of the precipitation forecasts. Varying selectable parameters of the Mellor-Yamada closure in a large number of sensitivity experiments produced only small changes in the precipitation forecasts.

The difference in space discretization schemes summarized in Section 2 is thus left as the apparent main reason for the improved scores. Accordingly the results shown in the preceding plots can be viewed as additional evidence in favor of the space discretization features of the eta model compared to those of the control model (e.g., Mesinger and Janjić 1989).

The problem of the excessive biases of the eta model at the highest precipitation categories, a problem of the

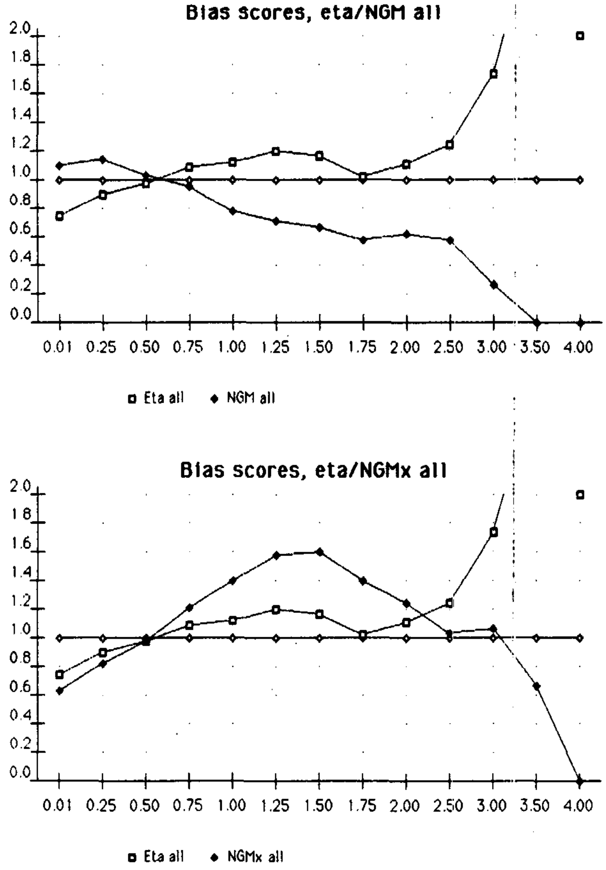

FIG. 5. As in Fig. 4 except for bias scores. The eta value equal to 2.83 at the category of 3.50 inches and greater is not plotted for better resolution of the range shown.

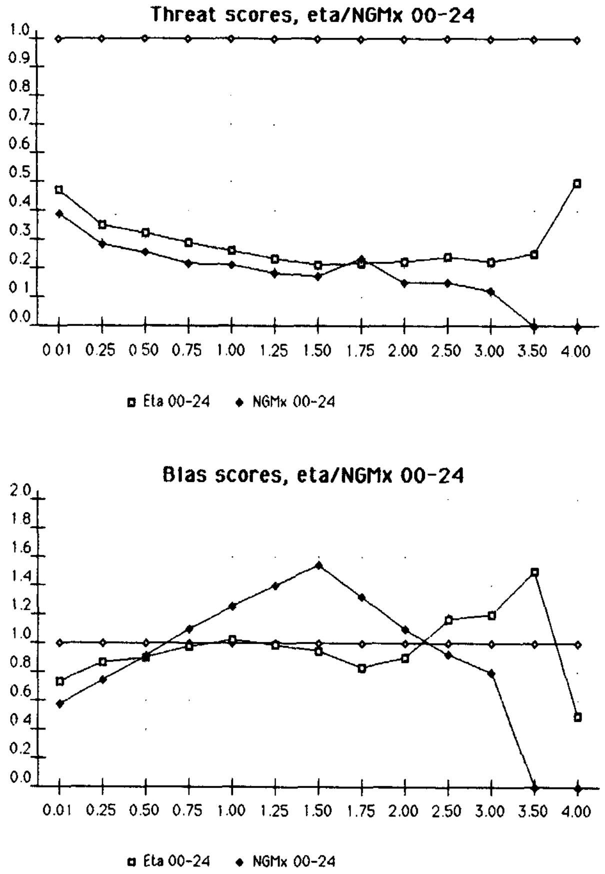

FIG. 6. Threat scores (upper panel) and bias scores (lower panel) for various precipitation categories (inches) of 24-h accumulated precipitation of the eta model and the NGMx (NGM with the Betts-Miller convection scheme) for 20 00–24-h forecasts verifying every 1200 UTC within the period 16 June–5 July 1989.

later and not the earlier forecast times (Figs. 6 and 7), is now examined in more detail. None of the 00–24- or 12–36-h average bias scores is greater than 1.5 so the large values of averages for all forecast times in the three highest categories (Fig. 5) are entirely due to the large bias values for 24–48 hours (lower panel of Fig. 7). The largest of these is the value of 5.5 in the category of 3.5 inches and greater. It is a result of 11 points predicted (on the LFM grid) even though 2 points were observed, one on 27 and one on 28 June. None of the predicted points were at observed locations. The most damaging eta forecast is the one shown in the lower right hand panel of Fig. 2 which is responsible for 5 of the 11 points. Another two points were forecast on 28 June and all other forecasts contributed a total of four points. The excessive and incorrectly placed rain of the 24–48 h forecast verifying 27 June is an example of a problem encountered repeatedly over warm water later in the year. This precipitation results from a quasi-steady state reached by the convection scheme later in the forecast in which large evaporative flux is being converted into rain with no effective stabilization provided by the scheme. Reduced severity of the problem in the NGMx model is probably a consequence of a reduction of the evaporation over water in that model to one half of the value given by the bulk parameter schemes used (Phillips, personal communication). Since the time of the experiments presented here, the problem has apparently been greatly reduced in the eta model by a generalization of the convection scheme. The adjustment procedure now allows for a decreasing role of the convective rain under some circumstances as well as a possibility for the convection to depart toward differing reference states (Janjić, pers. comm.). Plans are in place to report on this work at a later occasion.

6. Conclusions and comments

The following points perhaps stand out as the major conclusions of this work

1) The National Meteorological Center's eta model has been shown to produce quantitative precipitation

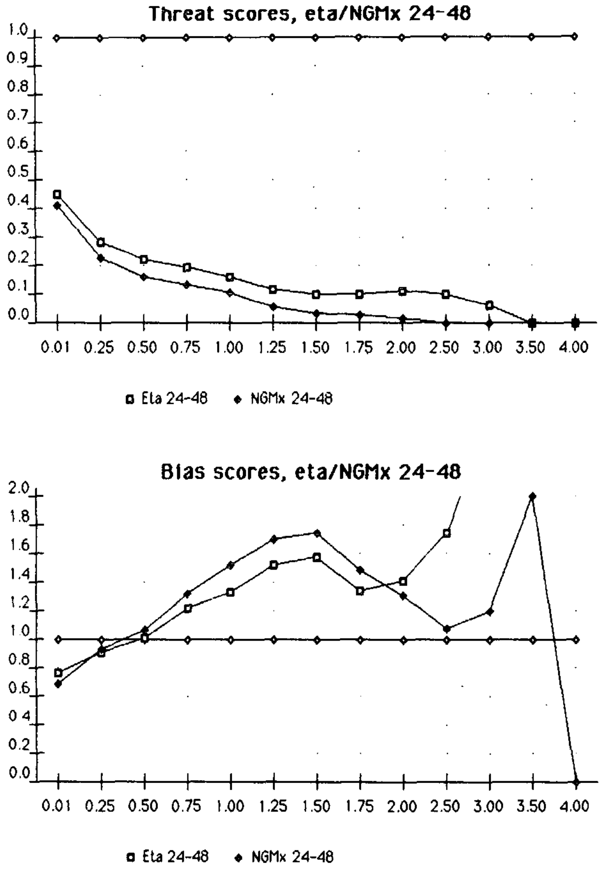

FIG. 7. As in Fig. 6, except for 24–48-h forecasts. The eta bias score values at the categories of 3.00, 3.50, and 4.00 inches and greater, equal to 2.6, 5.5, and 4.0, respectively, are not plotted for better resolution of the range shown.

forecasts which are substantially more accurate than those of the operational regional model (NGM) given the same convection scheme, the same initial conditions, and about the same domain and horizontal and vertical resolution. This result points to progress being made in the prediction of precipitation patterns, a longstanding concern in numerical weather prediction.

2) The three-way model comparison shows that, while causing some problems and particularly that of insufficient coverage of light precipitation, the eta model's Betts-Miller convection scheme appears to be an important reason for improving the numerical forecasts of heavier precipitation.

3) The eta model was successful in forecasting both the location and the intensity of the centers of precipitation patterns in about 25% of all cases in a period during the warm season when considerable intense convection occurred.

4) These successful numerical forecasts of the centers of precipitation patterns were very consistent in terms of independence of the initial conditions. Successful forecasts tended to occur for all three (in one case two) available forecasts verifying during the same period. This is seen as a demonstration of the model's ability to forecast the location of the precipitation maxima because of its ability to simulate certain situations given its present resolution, numerical schemes and physics. With improvements of some or all of these components it is expected that the range of situations in which the model's forecasts of heavy precipitation show significant skill will increase.

5) There is a strong indication that the major cause underlying the improvement in the accuracy of precipitation forecasts achieved by the eta model is its space discretization schemes summarized in Section 2. The philosophy of these schemes is one of accurately treating the smallest resolvable scales in terms of chosen physical principles, as opposed to damping and/or filtering these scales on the grounds that they contain large errors. Schemes are available which go still further in that direction (e.g., Carpenter et al. 1990; see also Mesinger and Janjić 1989) and a variety of improvements of current methods such as those used in the eta model is possible, including increased resolution. We are thus confident of continued progress in the prediction of weather phenomena where greatest advances may occur in areas of present difficulties of which mesoscale precipitation systems are an excellent example.

Acknowledgments. We are grateful to Alan Betts for numerous suggestions regarding choices of various parameters in the formulation of the convective parameterization scheme. Zaviša Janjić who originally implemented the scheme in the eta model has also made several suggestions including one to incorporate the viscous sublayer which has significantly helped the precipitation forecasts over regions of warm water. Support and encouragement of Drs. William Bonner and Eugenia Kalnay were vital for the success of a project as comprehensive as the substantial part of the development and the semi-operational implementation of the eta model. We appreciate the many useful suggestions offered by Zaviša Janjić, Louis Uccellini, and Ralph Petersen while writing this manuscript. Work of the first author on some of the material presented has been partly supported by the Science Association of Serbia; and by the Serbian Academy of Sciences and Arts, Belgrade.

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