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NWS TDL 79

PERFORMANCE OF OPERATIONAL OBJECTIVE 0-6 H QUANTITATIVE PRECIPITATION FORECASTS RELATIVE TO MANUAL AND MODEL GENERATED FORECASTS: A PRELIMINARY ASSESSMENT

Techniques Development Laboratory
Silver Spring, MD
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U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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ABSTRACT

During the spring and summer of 1987, TDL's new, operational 0-6 h objective QPF product (OBJ) was verified and compared against three similarly verified NMC QPF products over the conterminous United States. The NMC products were a manually prepared QPF chart (MAN) issued 4-6 hours earlier than the OBJ and 6-12 and 12-18 h QPF maps from the NGM and LFM. All products were verified for two consecutive 6-h periods, 1800-0000 GMT (afternoon) and 0000-0600 GMT (evening). All products were verified both subjectively and objectively. Both verifications are preliminary primarily because verifying precipitation observations on a scale consistent with the OBJ QPF's were not available. However, upon careful consideration of the event defined in each QPF product and the nature of the verifying precipitation analysis, a useful performance comparison was obtained.

The principal findings from the verification are as follows: (1) The 0-6 h OBJ product scored better overall than manual and model generated products issued 4-12 hours earlier. The MAN and NGM products scored next best at nearly equal levels; the LFM scored poorest. (2) The OBJ product performed better for the evening than the afternoon period. The improved performance during the evening is believed to result from persistence of afternoon rainstorms into evening, which is accounted for in the OBJ model. Conversely, the MAN product exhibited slightly better performance for the afternoon period. (3) The OBJ and model-generated QPF's performed better during the spring of 1987 than during the following summer months, as expected. Unexpectedly, the MAN product appeared to perform at least as well during the summer as in spring. (4) The LFM QPF's performed rather poorly, particularly during the summer season. The LFM's poor summertime performance was associated with strong underprediction of the observed precipitation. The NGM performed substantially better and, in fact, scored as well as the shorter range MAN product.

1. INTRODUCTION

The Techniques Development Laboratory (TDL) has recently developed and implemented at the National Meteorological Center (NMC) an objective system that produces 0-6 and 3-9 h quantitative precipitation forecasts (QPF). The forecasts are currently issued three times daily after the 1200, 1800, and 0000 GMT surface data observation times during the spring, summer, and fall seasons. The forecasts are available on the National Weather Service's (NWS's) Automation of Field Operations and Services (AFOS) system in probability and categorical form, as described in National Weather Service (1987).

The objective QPF system was developed with standard statistical procedures with significant extensions (Charba, 1983; 1987). Predictors contained in the multiple regression (forecast) equations make heavy use of hourly surface and manually digitized radar reports (National Weather Service, 1978) and localized climatic frequencies of precipitation amount (Charba, 1985). Charba (1987) estimated that more than half the predictive information contained in the 0-6 h forecasts comes from these observational and climatic data, with the balance coming from forecasts from the Limited Area Fine Mesh Model (LFM) (Gerrity, 1977; Newell and Deaven, 1981). At the 3-9 h projection, the reverse is true with LFM forecasts providing slightly more than half the information. Because of the heavy reliance on observational data, this technique may be characterized as an updating procedure. That is, the latest hourly observations together with local climatology update and correct the large scale model forecasts issued earlier. A similar approach is applied in the operational system producing 2-6 h forecasts of thunderstorms and severe local storms (Charba, 1977; 1979) and for updating public and aviation weather elements in the TDL LAMP project (Glahn and Unger, 1986) presently under development and testing.

The objective QPF system was initially implemented in June 1986 on an experimental basis. Forecasts were issued once daily, following the 1800 GMT hourly observation time (1800 GMT cycle), with the real time forecasts being made available to a few local NWS weather offices. In May 1987, a 0000 GMT cycle was added and the forecasts became available nationwide on AFOS. In March 1988, a 1200 GMT cycle was added to 1800 and 0000 GMT cycles.

This paper consists of an evaluation of forecast performance of the 0-6 h operational objective QPF's[1] available during the spring and summer seasons of 1987. The forecasts were from the 1800 and 0000 GMT cycles, which are issued at about 1845 and 0045 GMT, and valid 1800-0000 and 0000-0600 GMT, respectively. The evaluation was also performed for forecasts issued during the fall 1986 but only for the 1800 GMT cycle.

The evaluation of the TDL objective QPF's was conducted by verifying the operational forecasts daily and comparing scores with three other centralized 6-h QPF's issued at the National Meteorological Center (NMC). The NMC products used for comparison consisted of a 6-h QPF product prepared subjectively (National Weather Service, 1983) and two numerical model 6-h QPF's, one from the new Nested Grid Model (NGM) (Hoke et al., 1985) and the other from the LFM. The NGM was developed and implemented quite recently while the LFM has been operational since the early 1970's. One of the primary motivations for development of the new NGM was to obtain improved model precipitation forecasts. Accordingly, 6-h QPF's from the NGM have recently become available to field forecasters in graphic form on AFOS. For the LFM, only 12-h QPF's are available.

The primary purpose of this study was to examine how the performance of the new TDL objective QPF's compared with the manual and model QPF's and, in essence, see whether these forecasts are able to improve on existing centralized QPF's by updating with the most recent observed data. A secondary

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[1]Evaluation of the 3-9 h forecasts was not conducted because verifying precipitation data are presently not available.

objective was to see how the NMC manual, LFM, and NGM QPF's performed relative to one another. This comparison should be valuable to field forecasters since these products are used in the preparation of public forecasts. The comparison will also benefit our future development work as we seek to improve the present objective QPF system by incorporating the best available input information.

2. QPF PRODUCTS AND VERIFYING PRECIPITATION ANALYSIS

A. QPF Products

Fig. 1 shows the issuance times of the four products verified relative to the 1800-0000 and 0000-0600 GMT valid times. In this figure, the objective forecasts are referred to as OBJ, the subjective as MAN (referring to the manual preparation), and the numerical model forecasts as NGM and LFM. (These terms are used henceforth in this paper.) Note that the forecast projection for each product is relative to the time of the most recent data injested in the particular forecast system. For example, the 0-6 h OBJ forecast for the 1800-0000 GMT period incorporates observed data for 1800 GMT.

Each of the four products give the amount of precipitation expected in a 6-h period. The forecasts, available in graphical form on AFOS (except the 6-h LFM forecasts), depict 0.25-, 0.50-, 1.00-, and 2.00-inch predicted isohyets. The OBJ product also includes a probability estimate associated with each isohyet, as well as the maximum point probability within each isohyet (National Weather Service, 1987). This information was not verified here since the NMC products do not contain probability information. Therefore, only the four isohyets noted above were verified for each product.

Although the four isohyets are issued for each of the QPF products verified, the precipitation amounts denoted for each product do not have precisely identical meanings. In the case of the OBJ chart, a predicted amount is for the maximum (or near maximum) amount at some point within a 40 x 40 n mi box (National Weather Service, 1987). The grid of all such boxes is shown in Fig. 2. In addition, this maximum refers to that observable by the high density climatic hourly precipitation data (HPD) network (Fig. 3). In the case of the MAN product, the predicted precipitation amounts indicated by the isohyetical field denote local areal averages (National Weather Service, 1983). The NGM and LFM QPF's should be similarly interpreted. Thus, there is a significant difference between the OBJ forecast isohyets and those for the other products, and this difference should be considered in a comparative verification.

The only 6-h verifying precipitation data available for this study consisted of the reports contained in conventional surface airways observations (SAO's). The present unavailability of the HPD data for the period verified is unfortunate since the number of SAO stations is only about one-third the number of HPD stations. Also, since the OBJ QPF's refer to maximum amounts defined by the high density HPD network, a verification for this product based on the more coarse SAO network will result in fictitious overforecasting.

B. Precipitation Analysis

Had the HPD data been available for verifying the different products, we could have defined one precipitation field for the OBJ forecasts and another for the NMC forecasts. That is, these data would have been used to specify a field of maxima within the valid boxes for the OBJ forecasts and a field of local areal averages for the NMC products. Since the sparse SAO data cannot resolve the local maximum amounts described by the OBJ forecasts, we felt such an elaborate procedure was not warranted. Instead, we chose to verify all products on the basis of an objective analysis of the SAO data that retained the greatest possible spatial detail. This analysis nevertheless depicts local averages of the point precipitation amounts. Thus, the verifying precipitation field would underrepresent the OBJ forecast amounts from the combination of two factors. One factor is the lower density of the observations and the other the areal smoothing of the maximum point amounts. While considerable fictitious overforecasting would therefore be expected for the OBJ forecasts, we felt the ensuing comparative verification could provide potential field users of the OBJ forecasts with an early indication of their relative performance. While such a performance assessment satisfies the primary objective of the study, the verification results must be regarded as preliminary.

The objective precipitation analysis was produced by a three-pass Cressman (1959) successive correction scheme applied to the 6-h SAO precipitation observations. The analysis grid, comprised of the centerpoints of the OBJ forecast boxes (Fig. 2), has a 40 n mi grid spacing. The scanning radius for the final pass in the objective analysis, which is data density dependent, was roughly 1.5 gridlengths.

In order to gain some appreciation of how the point precipitation observations relate to corresponding objectively analyzed values, an example case is provided. Fig. 4a shows the isohyetical precipitation analysis over the United States for 0000-0600 GMT August 17,1987. Fig. 4b gives an enlarged view of the analysis for the eastern Great Plains to lower Great Lakes region. Also included in Fig. 4b are the non-zero precipitation observations and a subset of the analysis grid. Clearly, the analysis underestimated the maximum point amounts, especially where a peak amount is surrounded by much lower adjacent amounts. For example, near the Illinois shore of Lake Michigan (Fig. 4b), the 2.75-inch observation is almost completely smoothed out in the contour analysis because of the influence of adjacent amounts under a half inch. Conversely the 2.42-inch amount on the eastern shore of Lake Michigan is well represented in the analysis since lower adjacent amounts are farther away. Other factors influencing the degree of retention of the peak amounts in Fig. 4 are the distances of peak observations from the nearest grid point, the spatial distribution of the observations, and, of course, zero amounts (which are not plotted in Fig. 4b).

C. Illustration of the Four QPF Products

The distinguishing properties of the OBJ product and the NMC products can be illustrated by examining the forecasts for a particular case. The case selected is for 0000-0600 GMT August 17, 1987, for which the observed precipitation field was discussed above (Figs. 4a and 4b). Fig. 5, which shows the NMC surface analysis for 0000 GMT August 17, features a squall line ahead of a cold front extending from northwest Texas to Wisconsin. Note the convergence of very warm moist air along the squall line especially in northeastern Illinois. Fig. 6, which is the 500-mb analysis for the same time, features a marked short wave trough moving northeastward over the Northern Plains states and a blocking 500-mb ridge over the Atlantic Coast.

The four QPF products for the 0000-0600 GMT period of August 17, 1987, are shown in Figs. 7a-7d. The OBJ QPF chart (Fig. 7a), as it appears on AFOS, shows a heavy compact isohyetical pattern centered in northeast Illinois, which reflects the observed surface features discussed above (Fig. 5). Note that the peak forecast isohyet in this case is 3.0 inches. (The 3-inch plus forecasted precipitation amounts indicated by this isohyet are based on the probabilities for $\geq$ 2.0 inches (the highest forecast interval), as described in the National Weather Service (1987)). Recall from Fig. 4b the analysis showed a small, closed 2.0-inch isohyet near the eastern shore of Lake Michigan, and some point observations over lower Lake Michigan were in the 2-3 inch range. The NMC MAN forecast (Fig. 7b) and the NGM and LFM QPF charts (Figs. 7c and 7d) generally show much lighter predicted amounts, especially the LFM. The lower amounts exhibited by the NMC forecast isohyetical patterns are typical, apparently reflecting the difference in the event forecast, as pointed to previously. (It should be noted the MAN chart also contains maximum point amounts forecast to occur within some of the heaviest isohyets (National Weather Service, 1983), as shown in Fig. 7b. This information is not considered in the verification since comparable information is not contained in the other products.) Another feature illustrated by this case, which is typical of all cases, is the OBJ and MAN products contain higher spatial resolution than the NGM and LFM forecasts. This higher detail results from the use of higher resolution observed data and climatic information in the former products. Finally, the very light amounts forecast by the LFM in this case is typical of the underforecasting by this model during the summer season, as will be seen in the next section.

3. VERIFICATION

A. Procedures

As noted in the previous section, the observed precipitation field used to verify all four QPF products was the spatially averaged isohyetical field provided by the Cressman objective analysis. On the basis of this verifying map, the verification was performed both subjectively and objectively over the conterminous United States. In both instances, the verification was performed in a comparative sense, meaning all products must have been available for the case to be included in the sample.

The subjective verification was performed by a simple scoring procedure whereby "points" for each mispredicted observed or forecast feature in the corresponding isohyetical pattern were subtracted from a perfect score of 10.0. The weight or "points" allocated to each observed or forecast feature ranged from 0.5 for a minor feature to 2.0 for a major feature. For a forecast and observed feature of a given size, less than the maximum amount was subtracted when the forecast and observed precipitation features were close to each other in amount and location. An illustration of the scoring for an imagined case is shown in Fig. 8. Note that 2.0 was subtracted for misforecasted major observed and forecasted features centered in North Carolina and Mississippi, respectively. Only 0.5 was subtracted for the moderate observed feature near Lake Michigan because of its close proximity (in location and amount) to a nearby forecast feature, and no penalty was exacted for features in northwest Texas because of an even closer matching. Conversely, no credit was given for the forecast feature in southern California because the nearest observed feature located in central Arizona was too far away. When all the points were subtracted for this case the score equals 3.5. This score is near the lower extreme for scores obtained for actual forecasts.

In practice, a person assigning the subjective scores must exercise considerable judgement in the assignment process. One reason is that actual forecast and observed configurations are often more complex than those illustrated in Fig. 8. Also, in the typical real case, most individual forecast features are rarely entirely correct or entirely incorrect. The built-in capability to give partial credit for close forecast and observed features was incorporated to cover such marginal situations. Another dubious aspect of the scoring system is that the score will usually decrease as the number of forecast and observed features on a map increases. We should note, however, that for a given day all products were scored together and strong emphasis was placed on consistency in scoring similar features for the separate products. Thus, the relative score among the products, not the absolute score, was stressed in the scoring process. To see if strong consistency was actually achieved, the next section, which discusses the verification results, will show scores assigned independently by the first and third authors of the paper.

The procedure for the objective verification of a given product was quite straightforward. The first step was to superimpose a grid comprised of the center-points of the grid boxes in Fig. 2 over the observed and forecasted isohyetical maps. Then, grid points falling within the observed and forecasted isohyets were tallied, as were those falling in forecast-observed overlap areas.[1] A grid point falling within a given forecasted isohyet was counted correct when the coincident observed amount equalled or exceeded the forecasted amount. The number of grid points forecast, the number observed, and the number of correctly forecast points over the conterminous United States were thereby obtained for each isohyet contained on the chart. From tabulations of these values over all forecast charts in the sample, standard scoring measures such as the critical success index (CSI) (Donaldson et al., 1975) and the bias were computed from forecast/observed contingency tables for each isohyet of each product. The CSI and bias are defined as

$$\mathrm{CSI} = \frac{C}{F+O-C} \qquad (1)$$

and

$$\mathrm{Bias} = \frac{F}{O}\,, \qquad (2)$$

where F is the number of forecast grid points, O is the number observed, and C is the number of correctly forecast points.

In the case of the objective scoring system, a subset of the full verification sample was formed for days when daily CSI's and bias's could both be computed for all products. Note from Eq. (2) the daily bias for a particular isohyet can be computed for all products only when the isohyet is observed. For the sample subset, standard deviations of the daily CSI's and bias's could be computed about the sample mean.

Beyond the subjective and objective natures of the two scoring procedures, several additional differences between the two scoring systems exist. (1) The subjective procedure gives partial credit for a "close" forecast, the objective

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[1] The assumption implied by this procedure is that when a grid box center-point falls inside an isohyet, at least half the area of the box is enclosed by the isohyet.

procedure does not. (2) The subjective procedure yields a single score that accounts for all aspects of forecast accuracy, whereas the objective procedure yields separate scores for the different precipitation amounts (isohyets) and more than one measure of accuracy, i.e., CSI and bias, for each amount. (3) The objective scoring system considered only the 0.50-, 1.00-, and 2.00-inch isohyets (to reduce the manual workload) while the subjective system also included the 0.25-inch isohyet.

B. Results and Discussion

Mean values of daily subjective scores assigned by the lead author for the four products over the contiguous United States are shown in Fig. 9. Also shown are standard deviations of the daily scores about the means. The sample was comprised of two daily forecasts for all products from 137 days[1] (274 forecast charts per product) over the period March 24-September 15, 1987. Fig. 9 indicates the OBJ forecasts performed best, the MAN and NGM performing second at roughly equal levels, and the LFM last. Note from the standard deviations, the daily variation of the OBJ scores about the mean was the smallest and that for the LFM was the largest. This indicates the performance of the objective forecasts was more steady than the other products.

One might question whether the differences in average scores in Fig. 9 represent significant differences in product performance, since the differences are small. Some light on this question is provided in Fig. 10 which shows the means of subjective scores assigned independently by the first and third authors of the paper over a short period during the fall of 1986. Note that even though the number of forecast maps in this sample is only 24 compared to 274 in Fig. 9, the product rankings based on the mean scores are about the same for the two scorers. Also, the product rankings are generally consistent with those in Fig. 9. Even the standard deviations about the means are roughly similar for the two scorers (Fig. 10) and for the two samples (Figs. 9 and 10). These results show that, even though the differences in the mean scores are small, they are significant in the sense that two independent scorers assigned similar values.

The tabulations and scores from the objective verification over the United States are shown in Table 1. The forecast sample is the same as that for the subjective scores in Fig. 9, except that the 0.25-inch isohyets were not considered, as previously noted. Table 1 shows the OBJ system forecast many more events than the other three products, particularly for the heavier precipitation intervals. Also noteworthy is the comparatively low number of LFM forecasts of $\geq$ 0.50 inches and the paucity of $\geq$ 1.00- and $\geq$ 2.00-inch forecasts by all three NMC products. Since the number of observed events for $\geq$ 1.00 and $\geq$ 2.00 inches is also small compared to that for $\geq$ 0.50 inches, the discussion here will emphasize the latter precipitation category.

The relative performance of the various products is best indicated in Table 1 by the number of correct forecasts for each precipitation interval, though this

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[1] The actual number of calendar days involved in the verification was greater than 137 since those days in which one of the two forecast cycles was missing was counted as a "half day." Also, a forecast cycle was included only when forecast charts for all products were available.

quantity is highly influenced by the number of forecasts for the interval. The largest number of correct forecasts was clearly obtained by the OBJ system, with the largest percentage improvement over the NMC products appearing for the heavier precipitation intervals. This result is also evident from the CSI scores in Table 1. On the other hand, the OBJ system forecast many more events than were observed while the NMC products, except for the ≥ 0.50-inch MAN forecasts, predicted fewer than the number observed. The overforecasting by the OBJ system increased with increasing precipitation amount, as clearly indicated by the bias values in Table 1. For instance, the OBJ system overforecast the number of ≥ 0.50-inch events by almost four times and the number of ≥ 2.00-inch events by eleven times. Considering the NMC products for ≥ 0.50 inches, the MAN product forecast almost twice the number observed, the LFM less than half the observed, and the NGM nearly equal the observed. For the heavier intervals, all NMC products greatly underforecast the corresponding observed events.

For easy performance comparison among the different products, the CSI's and biases in Table 1 for selected precipitation intervals are graphed in Figs. 11-14. For ≥ 0.50 inches, the CSI (Fig. 11) shows three performance levels among the four products, with the OBJ product the highest, the MAN and NGM about equal in the mid-range, and the LFM the lowest. The standard deviations of the daily CSI's about the sample means are roughly equal for the OBJ, MAN, and NGM and lower for the LFM. The lower standard deviation for the LFM is partly a result of the mean CSI for this product lying closer to the lower bound, which is zero. Conversely, the standard deviation for the OBJ product is reduced least by this artifact since the mean CSI is furthest from the lower bound. Fig. 12, which illustrates the CSI's for the ≥ 1.00-inch forecasts, shows results similar to that for ≥ 0.50 inches except the ranking of the NGM has increased to second and the MAN has fallen to third. The improved ranking by the NGM for ≥ 1.00 inches is also evident from Table 1. Note that the NGM achieved substantially more correct ≥ 1.00-inch forecasts than the MAN or LFM even though fewer forecasts were issued.

While we have just seen the OBJ system performed best in terms of the CSI, it was earlier noted this system exhibited considerable overforecasting. To illustrate this further, the biases for ≥ 0.50 inches are graphed for each product in Fig. 13. In this figure, two bias values are shown for each product, the higher one for only those days when the event was observed and the lower one for all days. For both samples, the figure illustrates the strong overforecasting by OBJ, lesser overforecasting by MAN, substantial underforecasting by the LFM, and near perfect bias for the NGM. The standard deviations of the daily biases are in rough proportion to the sample mean for each product but this quantity, as for the CSI, is affected by the bias's inherent lower bound of zero.

The strong overforecasting for the OBJ product indicated by the results in Table 1 and Fig. 13 confirms the expected fictitious overforecasting discussed in Section 2. As previously noted, it results from the known inconsistency between the event forecast by the OBJ system and the observed precipitation analysis. The bias seen here would be expected to essentially disappear with use of the proper (HPD) verifying data, and with the observed event defined in conformance with the event forecast. This expectation is based on bias values exhibited by the OBJ system on the dependent data. That is, when the system was applied to 7 or 8 full seasons of dependent data, the bias values over all precipitation intervals were nearly always in the range 1.2 to 1.4. Because the dependent sample was rather large, it seems quite unlikely that a substantial independent sample with consistent verifying data would produce the gross overforecasting indicated here. Also note from Fig. 13 the overforecasting by the OBJ system is greater for days when the event was observed. This result indicates the analyzed precipitation amounts were too low on the rainy days. Also note in Table 1 that the apparent overforecasting by the OBJ system increased with increasing precipitation amount. This result also reflects the discrepancy between the event forecast by the OBJ system--the maximum point amount in a 40 mi box--and the areal precipitation analysis. That is, the ery heavy rainfall amounts tend to be quite localized and, therefore, more susceptible to analysis smoothing than lighter amounts which have broader areal coverage. Another result supporting this conclusion is that during summer, when heavy amounts are even more spotty than in other seasons, the biases for the OBJ forecasts for $\geq$ 1.00 and $\geq$ 2.00 inches were 30-40% higher than they were in the spring.

Interestingly, Table 1 shows the number of events forecast by the OBJ system for a particular precipitation interval matches closely with the number of observed events in the next lower precipitation interval. For instance, the number of OBJ forecasts of $\geq$ 1.0 inches (2735) is close to the number of $\geq$ 0.50-inch observed events (2449) and the number of $\geq$ 2.00-inch forecasts (310) is near the number of $\geq$ 1.00-inch events (416).

For the NMC products, the bias values suggest the precipitation analysis is generally consistent with the precipitation amounts forecast. In fact, Table 1 shows that except for the $\geq$ 0.50 inch MAN forecasts, the NMC products generally underforecast the analyzed precipitation amounts. Thus, it appears the areal precipitation analysis is appropriate for these products.

It's interesting that each of the NMC products exhibited an increasing tendency to underforecast with increasing precipitation amount (Table 1). For the MAN product, this result can be explained by the fact that the maximum point precipitation amounts indicated on the forecast charts (see Fig. 7b) were not considered in the verification procedure. For instance, it's possible a forecaster's specification of a heavy peak amount within a comparatively light predicted isohyet could preclude his perception of the necessity of issuing an intermediate isohyet. Obviously, this does not explain the underforecasting by the NGM and LFM. Table 1 shows the underforecasting by the LFM was especially pronounced, with strong underforecasting appearing for all three precipitation intervals. In fact, the LFM underforecasting of precipitation amount during the warm season months is commonly known by NWS forecasters and even appears in documented literature (Gyakum and Samuels, 1987). The responsible underlying deficiencies in both of these NMC models likely involve inadequate modelling of physical/dynamical processes that produce mesoscale events and the use of oversimplified convective parameterization schemes.

Many previous studies have shown heavy precipitation exhibits a marked diurnal variation in most regions of the United States. During the spring and summer months the diurnal cycle consists of a morning minimum followed by an afternoon or nighttime maximum (e.g., see Winkler et al, 1987). Since the OBJ system uses current and antecedent precipitation as predictive input (as does the MAN system), it should be interesting to compare the forecast performance during the 1800-0000 GMT (afternoon) period with the 0000-0600 GMT (evening) period. Figs. 14a and 14b illustrate the CSI's for $\geq$ 0.50 inches for all products for the two periods. Note for the OBJ system the CSI increases substantially from the afternoon to the evening period. Thus, persistence of antecedent precipitation apparently plays a strong positive role in the forecast performance for this product. For the MAN product the persistence factor does not result in improved performance during the evening period. Presumably, this is because persistence has little positive benefit for lead times of 4-6 hours. In fact, the slightly higher MAN CSI for the 1800-0000 GMT period may partly stem from a forecast lead time which is 2 hours shorter than for 0000-0600 GMT. Another possible factor, which is unrelated to persistence, is that forecasters make extensive use of the 1200 GMT upper air analysis for the 1800-0000 GMT QPF. At the time of the 0000-0600 GMT QPF issuance, the 1200 GMT upper air analyses are more than 6 hours old and their utility is diminished. As for the LFM and NGM, the length of the two forecast projections apparently has no impact on forecast performance. This result is not unexpected since model instabilities during the first 12 hours following initialization presumably neutralize the normal advantage of the shorter forecast projection.

For various reasons, it should be interesting to compare how the four QPF products performed during the spring season relative to the summer season. Figs. 15a and 15b illustrate the CSI for all products during the spring (March 24 - June 15) and summer (June 16-September 15) separately for ≥ 0.50-inch forecasts with the two daily forecast periods combined. The figure shows the CSI for all products except MAN dropped significantly from spring to summer. The deterioration of the LFM CSI is especially pronounced. Interestingly, the poor CSI exhibited by the LFM during summer is associated with gross underforecasting. For instance, the bias for ≥ 0.50 (≥ 1.00)-inch forecasts was 0.70 (0.77) during spring and only 0.22 (0.19) during summer. Clearly, the LFM has considerable difficulty predicting summer convective precipitation. The NGM, on the other hand, performed relatively well during both seasons, with deterioration in CSI from spring to summer relatively slight. Also the NGM did not suffer from underforecasting during summer. In fact, for ≥ 0.50 inches the NGM bias for summer (0.98) was higher than it was for spring (0.78).

The slight improvement in CSI of the MAN product from spring to summer seen in Figs. 15a and 15b is rather remarkable. Forecasting precipitation is known to be more difficult in summer (e.g., see Charba and Klein, 1980) since resolvable synoptic and subsynoptic controls are weak and unresolvable mesoscale controls predominate. In concert with this rationale, the level of performance of the OBJ, NGM, and LFM products diminished from spring to summer.

So, the question that arises is, why did the summertime MAN forecasts show a slight improvement over the corresponding spring season forecasts? Clearly, the sizable spring and summer samples underlying Figs. 15a and 15b would tend to preclude the notion the anomalous MAN performance trend was a chance result. Lacking other plausible explanations, we feel compelled to draw attention to the possible role of "forecaster feedback." To elaborate, in mid-June 1987, verification scores for the period March 24 to June 10, 1987, which were essentially identical to those for the full spring season (see Fig. 15a), were provided to NMC. It seems natural to surmise the forecasters' response to the results in Fig. 15a was to diligently strive to improve their performance standing by whatever means available, i.e., making better use of the available information, especially the NGM guidance. The verification results for the following summer months (Fig. 15b) indeed shows the forecasters' ranking improved. We believe this improvement is in fact linked to the feedback provided.

4. SUMMARY AND FUTURE PLANS

During the spring and summer of 1987, TDL's new, operational 0-6 h objective QPF product (OBJ) was verified and compared against three similarly verified NMC QPF products over the conterminous United States. The NMC products were a manually prepared QPF chart issued 4-6 hours earlier and 6-12 and 12-18 h QPF maps from the NGM and LFM. All products were verified during two consecutive 6-h periods, 1800-0000 GMT (afternoon) and 0000-0600 GMT (evening). All products were verified both subjectively and objectively. Both verifications are preliminary, however, because needed high density climatological hourly precipitation data (HPD) were not available. Instead, precipitation data from the conventional hourly surface observations (SAO) network were used. The verifying precipitation map consisted of an objective analysis of the 6-h SAO precipitation amounts.

Results from both the subjective and objective analysis showed the following:

(1) The 0-6 h OBJ product scored better overall than manual and model-generated products issued 4-12 hours earlier. The MAN and NGM products scored next best at nearly equal levels; the LFM scored poorest.

(2) The OBJ product performed better for the evening than the afternoon period. The better performance during the evening is believed to result from persistence of afternoon rainstorms into evening, which is accounted for in the OBJ model. Conversely, the MAN product exhibited slightly better performance for the afternoon period. This is believed due to a slightly shorter forecast projection for the afternoon (4 hours versus 6 hours for the evening) and to more extensive forecaster use of the morning upper-air analyses.

(3) The OBJ and model-generated QPF's performed better during the spring of 1987 than during the following summer months, as expected. Unexpectedly, the MAN product appeared to perform at least as well during the summer as in spring. Lacking other explanations, we suggest the strong summertime performance of the MAN product resulted from forecaster adjustments following our provision to them of comparative verification scores for the spring season.

(4) All four QPF products exhibited deterioration of forecast performance with increasing precipitation amount. The OBJ product showed less degradation than all NMC products, and the MAN showed the most. The larger degradation of the NMC products was manifested as increasing underprediction with increasing amount.

(5) The OBJ product exhibited a strong overforecasting bias relative to the areally-averaged precipitation analysis. However, the bias resulted from the inconsistency between the maximum point amounts specified by the forecasts and areal amounts resulting from the objective precipitation analysis. The NMC products, for most precipitation intervals, did not exhibit overforecasting, indicating the areal precipitation amounts were consistent with the forecasts.

(6) The LFM QPF's performed rather poorly, particularly during the summer season. The LFM's poor summertime performance was associated with strong underprediction of the observed precipitation. The NGM performed substantially better and, in fact, scored as well as the shorter range MAN product.

The results of this study point to two areas of planned future work. One is a more rigorous verification based on the high-density HPD data is needed to better establish the performance of the OBJ product relative to other QPF products. With this higher density precipitation data, verifying precipitation fields appropriate to amounts specified by each product can be defined. Another area of work spurred by the study is the planned redevelopment of the OBJ system with inclusion of NGM forecasts. Commencement of effort in this area will soon be possible as adequate samples of stable NGM output are now becoming available.

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REFERENCES

Charba, J.P., 1977: An operational system for predicting thunderstorms two to six hours in advance. NOAA Technical Memorandum NWS TDL-64, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 24 pp.

_____, 1979: Two to six hour severe local storm probabilities: An operational forecasting system. Mon. Wea. Rev., 107, 268-282.

_____, 1983: Experiments in 0-9 hour objective quantitative precipitation forecasting. Preprints Fifth Conference on Hydrometeorology, Tulsa, Amer. Meteor. Soc., 269-278.

_____,1985: Climatological relative frequencies of six-hour precipitation amount over the conterminous United States. Preprints Sixth Conference on Hydrometeorology, Indianapolis, Amer. Meteor. Soc., 1-8.

_____, 1987: Features of an operational objective 0-6 and 3-9 h system for forecasting heavy precipitation amounts. Preprints Seventh Conference on Hydrometeorology, Edmonton, Amer. Meteor. Soc., 137-142.

_____, and W. H. Klein, 1980: Skill in precipitation forecasting in the National Weather Service, Bull. Amer. Meteor. Soc., 61, 1546-1555.

Cressman, G. P., 1959: An operational objective analysis system. Mon. Wea. Rev., 87, 367-374.

Donaldson, R. J., Jr., R. M. Dyer, and M. J. Kraus, 1975: An objective evaluator of techniques for predicting severe weather events. Preprints Ninth Conference on Severe Local Storms, Norman, Amer. Meteor. Soc., 321-326.

Gerrity, J. F., 1977: The LFM model--1976: A documentation. NOAA Technical Memorandum NWS NMC-60, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 68 pp.

Glahn, H. R., and D. A. Unger, 1986: A local AFOS MOS program (LAMP) and its application to wind prediction. Mon. Wea. Rev., 114, 1313-1329.

Gyakum, J. R., and K. J. Samuels, 1987: An evaluation of quantitative and probability of precipitation forecasts during the 1984-85 warm and cold seasons. Weather and Forecasting, 2, 158-168.

Hoke, J. E., N. A. Philips, G. J. DiMego, and D. G. Deaven, 1985: NMC's regional analysis and forecast system results from the first year of daily, real-time forecasting. Preprints Seventh Conference on Numerical Weather Prediction, Montreal, Amer. Meteor. Soc., 444-451.

National Weather Service, 1978: Weather radar observations. Federal Meteorological Handbook, No. 7, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, pp. 6-1 thru 7-6.

_____, 1983: Quantitative precipitation forecast program. National Weather Service Forecasting Handbook, No. 1 Facsimile Products, Supplement No. 2, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 7-9 to 7-16.

_____, 1987: Zero-to-six and three-to-nine hour objective forecasts of heavy precipitation amount. NWS Technical Procedures Bulletin No. 370, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 14 pp.

Newell, J. E., and D. G. Deaven, 1981: The LFM-II model--1980. NOAA Technical Memorandum NWS NMC-66, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 20 pp.

Winkler, J. A., B. R. Skeeter, and P. D. Yamamoto, 1987: Seasonal variations in the diurnal characteristics of heavy precipitation. Preprints Eleventh Conference on Hydrometeorology, Edmonton, Amer. Meteor. Soc., 147-150.

Table 1. Forecast performance of four QPF products for three precipitation intervals over the conterminous United States. The sample, which is the same as that for Fig. 9, was based on 274 forecast maps for each product for the nation. The sample for each product was formed from two forecast maps per day on most days over the period March 24-September 15, 1987.

Product (Projections)	Precipitation Interval (Inch)	Number of Events Forecast	Observed	Correct	CSI	Bias
0-6 H OBJ	≥ 0.5	9258	2449	1095	0.103	3.78
	≥ 1.0	2735	416	130	0.043	6.58
	≥ 2.0	310	28	6	0.018	11.07
4-10 H MAN	≥ 0.5	4593	2449	400	0.060	1.88
6-12 H MAN	≥ 1.0	173	416	11	0.019	0.42
	≥ 2.0	3	28	0	0.000	0.11
6-12 H NGM	≥ 0.5	2223	2449	257	0.058	0.91
12-18 H NGM	≥ 1.0	106	416	17	0.034	0.26
	≥ 2.0	5	28	0	0.000	0.18
6-12 H LFM	≥ 0.5	961	2449	114	0.035	0.39
12-18 H LFM	≥ 1.0	172	416	7	0.012	0.41
	≥ 2.0	5	28	0	0.000	0.18

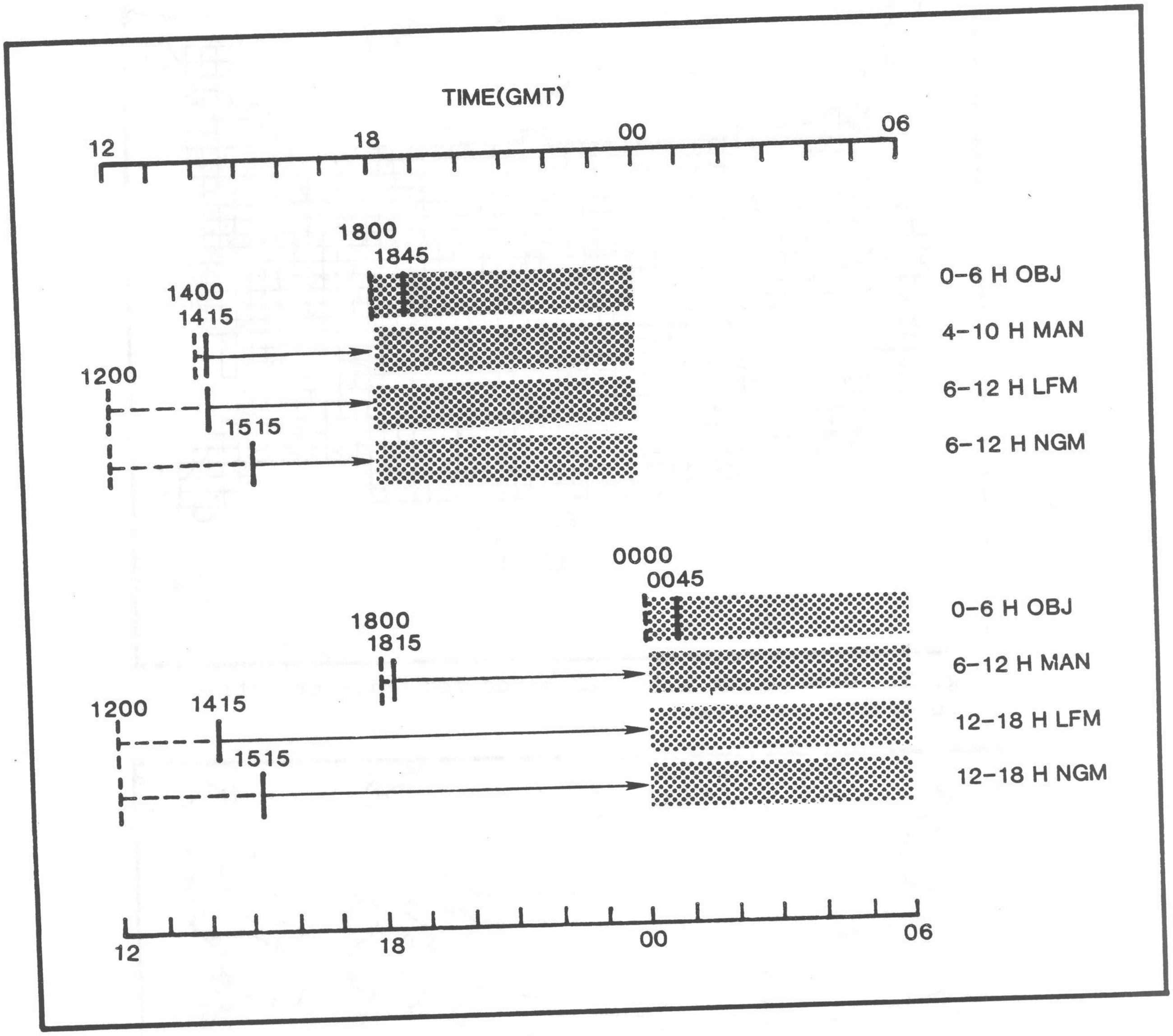

Fig. 1. Forecast issuance and projection times for the four QPF products indicated at the right. The forecast valid period for each product is denoted by the stippled bar. Preceeding each bar (left edge of bar for OBJ product), the first vertical line segment (dashed) denotes the observed data cutoff time, and the second one (solid) the forecast issuance time. The forecast projection given at the right is relative to the data cutoff time.

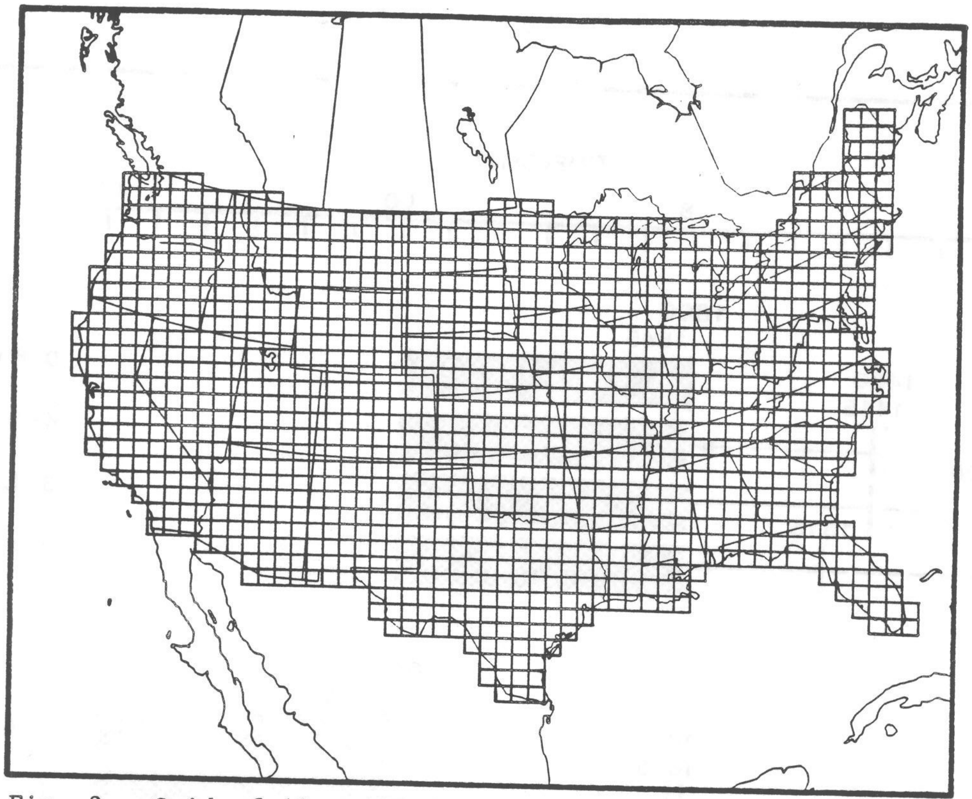

Fig. 2. Grid of 40 x 40 n mi boxes for which objective forecasts are issued.

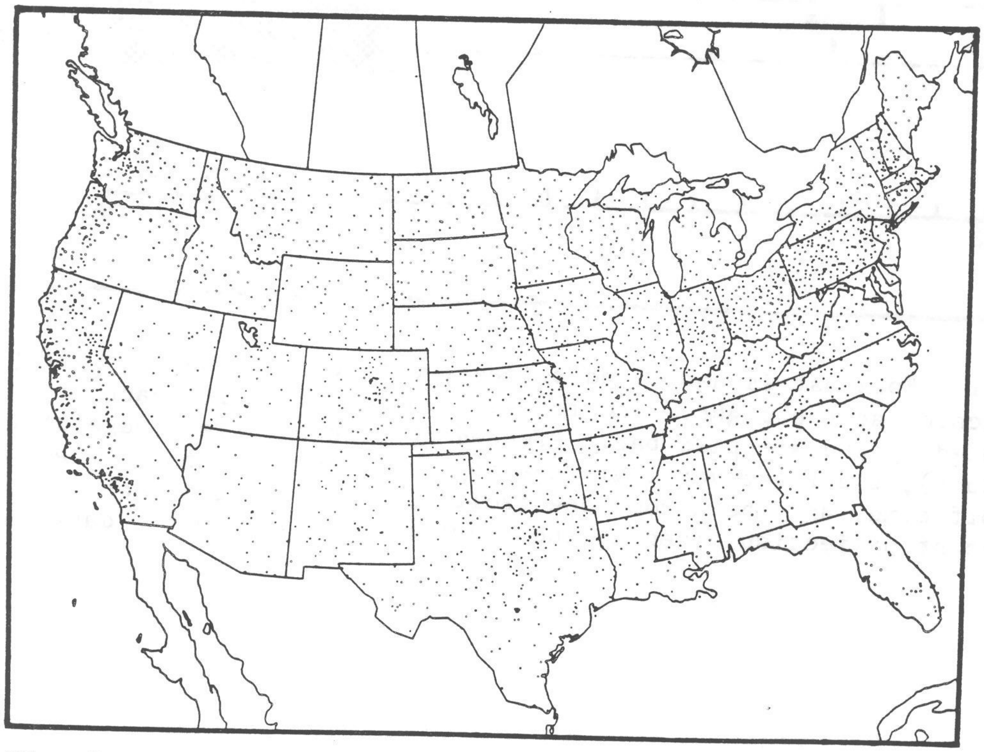

Fig. 3. Station locations (dots) of the climatic hourly precipitation data network.

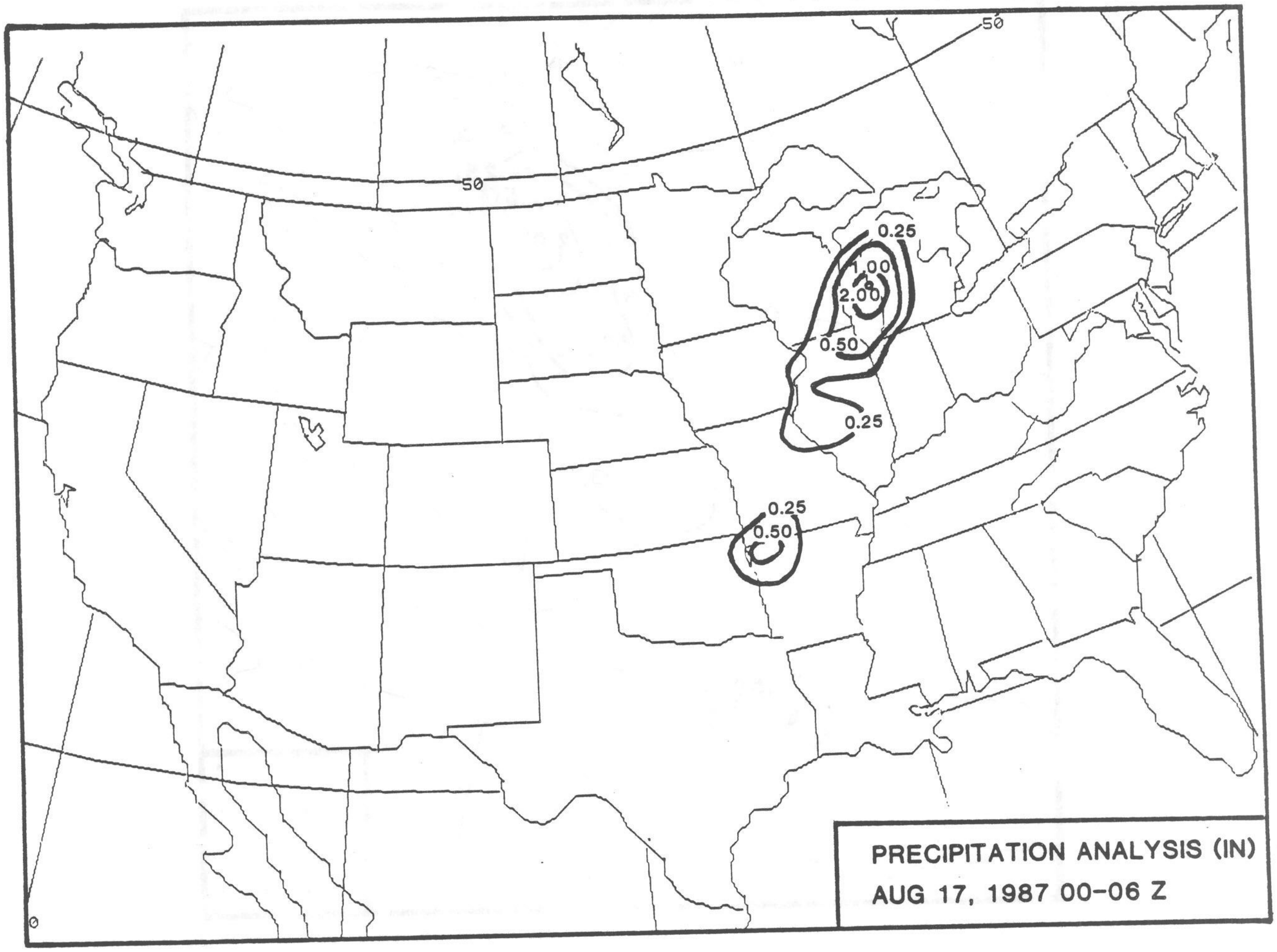

Fig. 4a. Objective precipitation analysis (inch) for 0000-0600 GMT August 17, 1987.

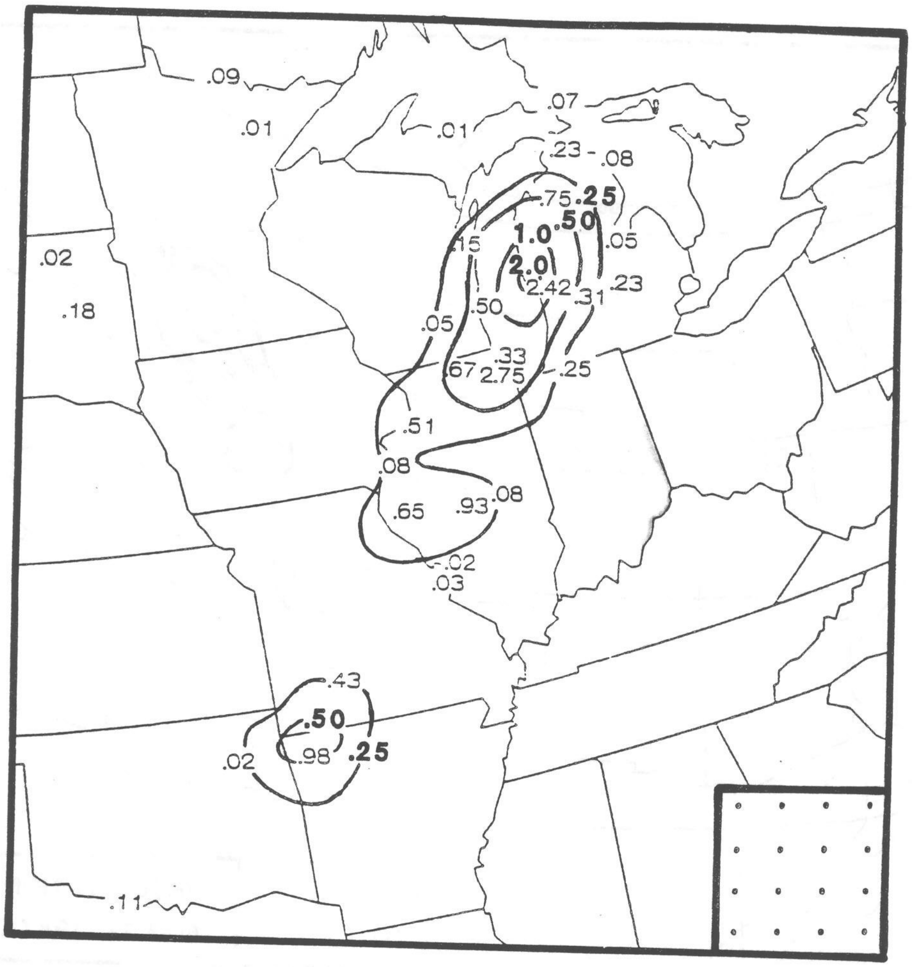

Fig. 4b. Enlarged view of the objective precipitation analysis in Fig. 4a. Non-zero precipitation observations are plotted (inch). The analysis gridpoints, depicted in the lower right corner, occupy the center points of the gridboxes in Fig.2.

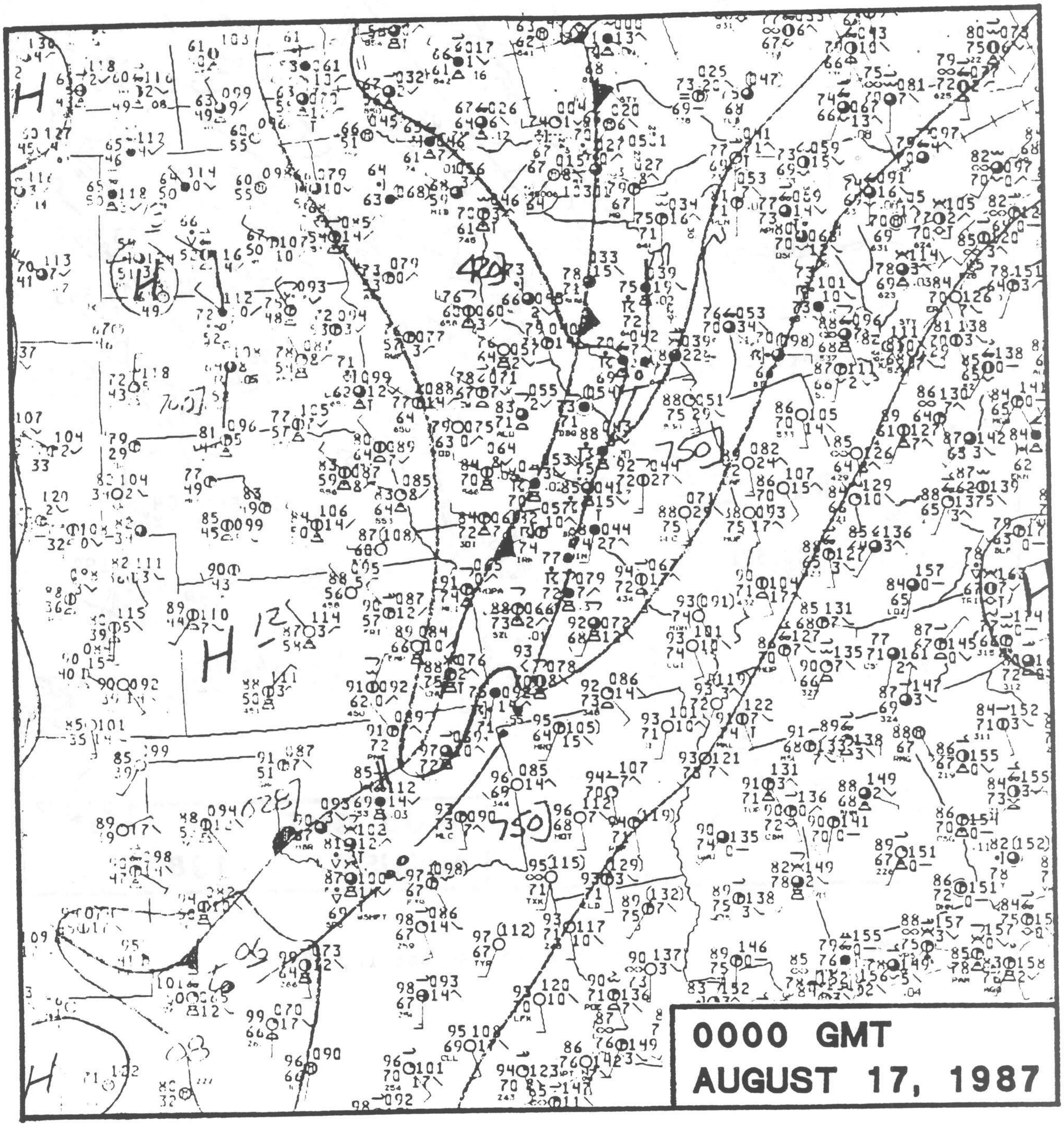

Fig. 5. NMC surface analysis for 0000 GMT August 17, 1987.

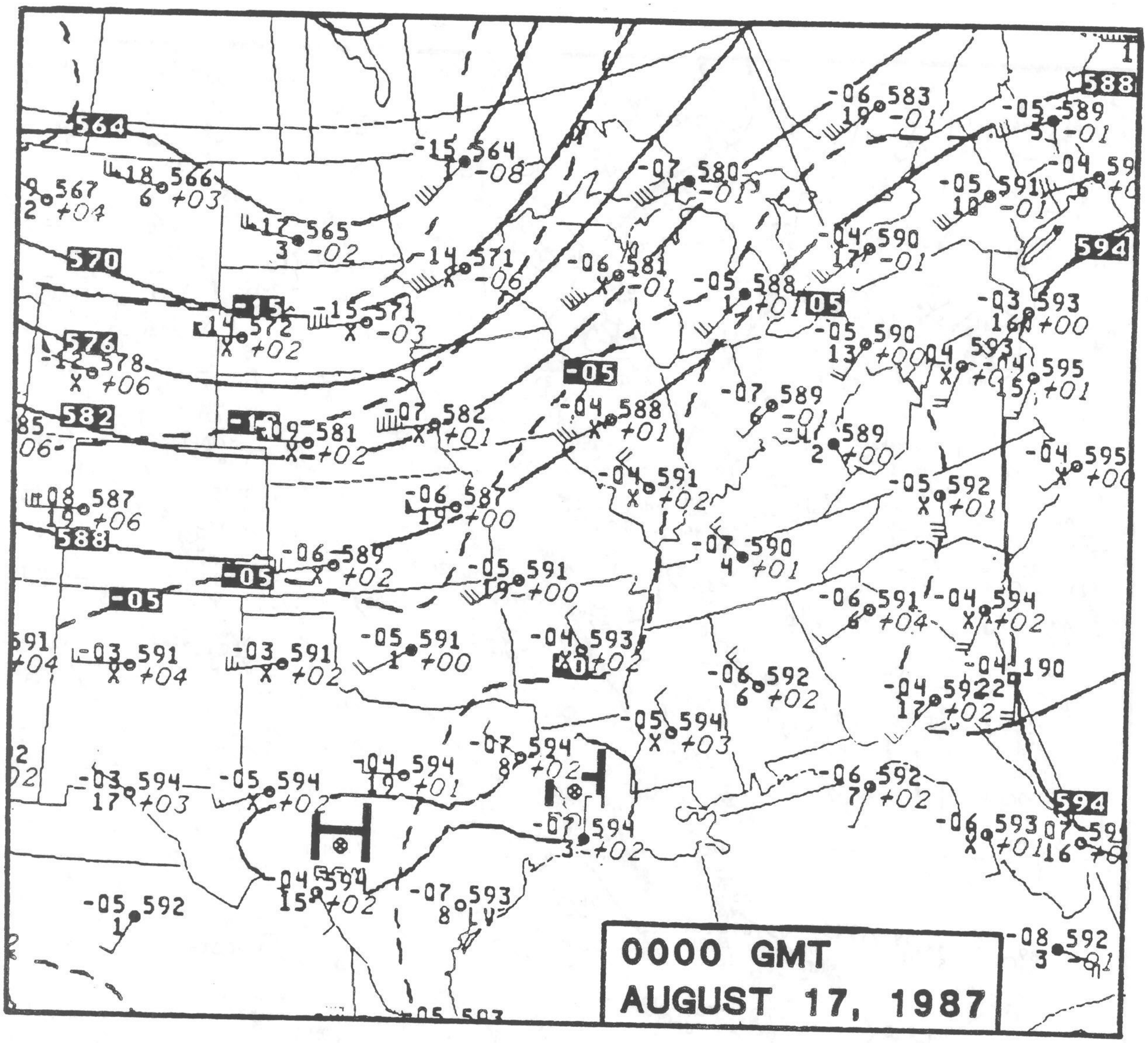

Fig. 6. NMC 500-mb analysis for 0000 GMT August 17, 1987.

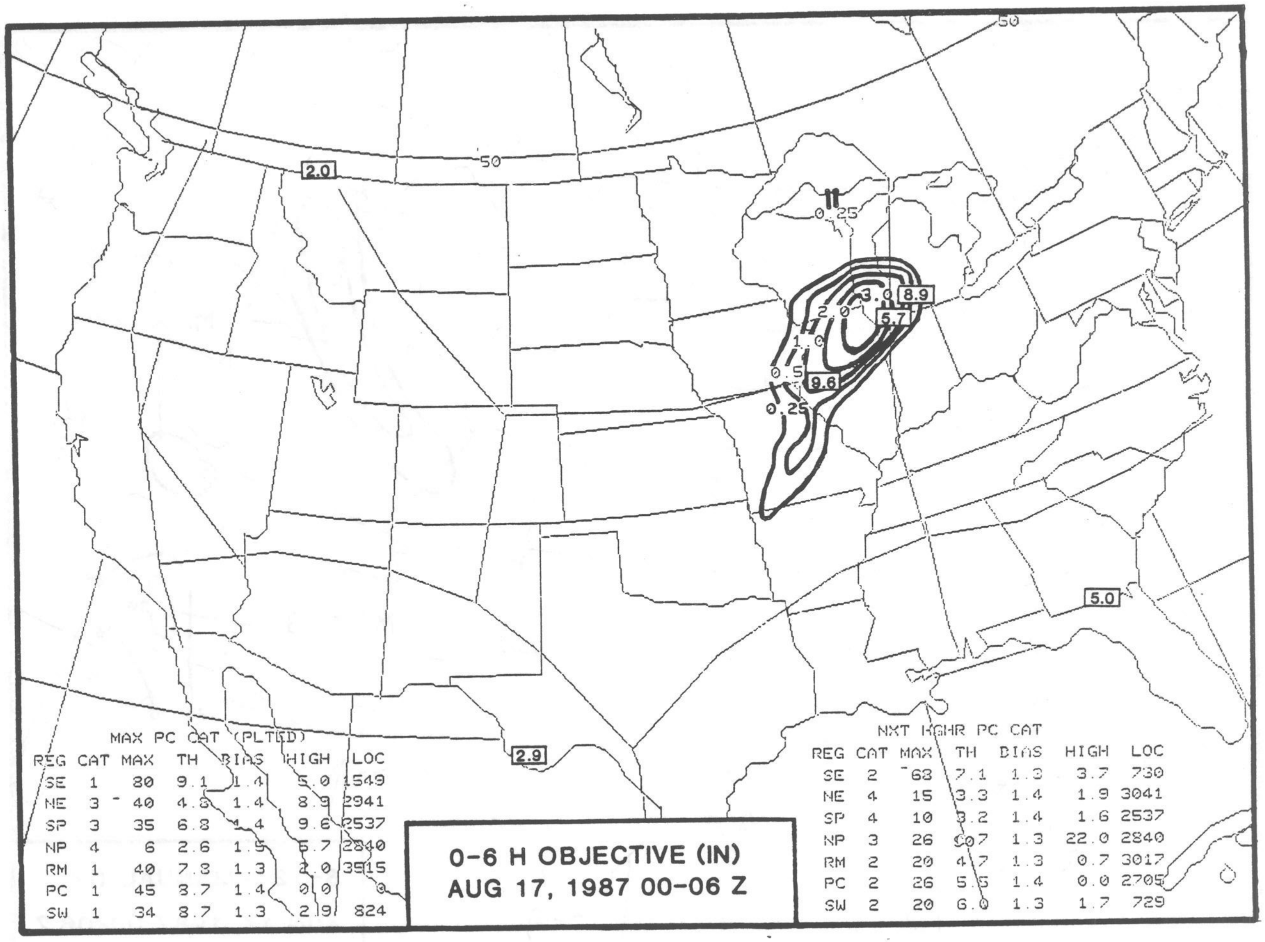

Fig. 7a. Zero-six hour objective (OBJ) QPF valid 0000-0600 GMT August 17, 1987. Heavy solid contours are predicted isohyets in inches. Other items in the AFOS graphic relate to forecast probabilities for precipitation amounts within the various geographical regions, as described in National Weather Service (1987).

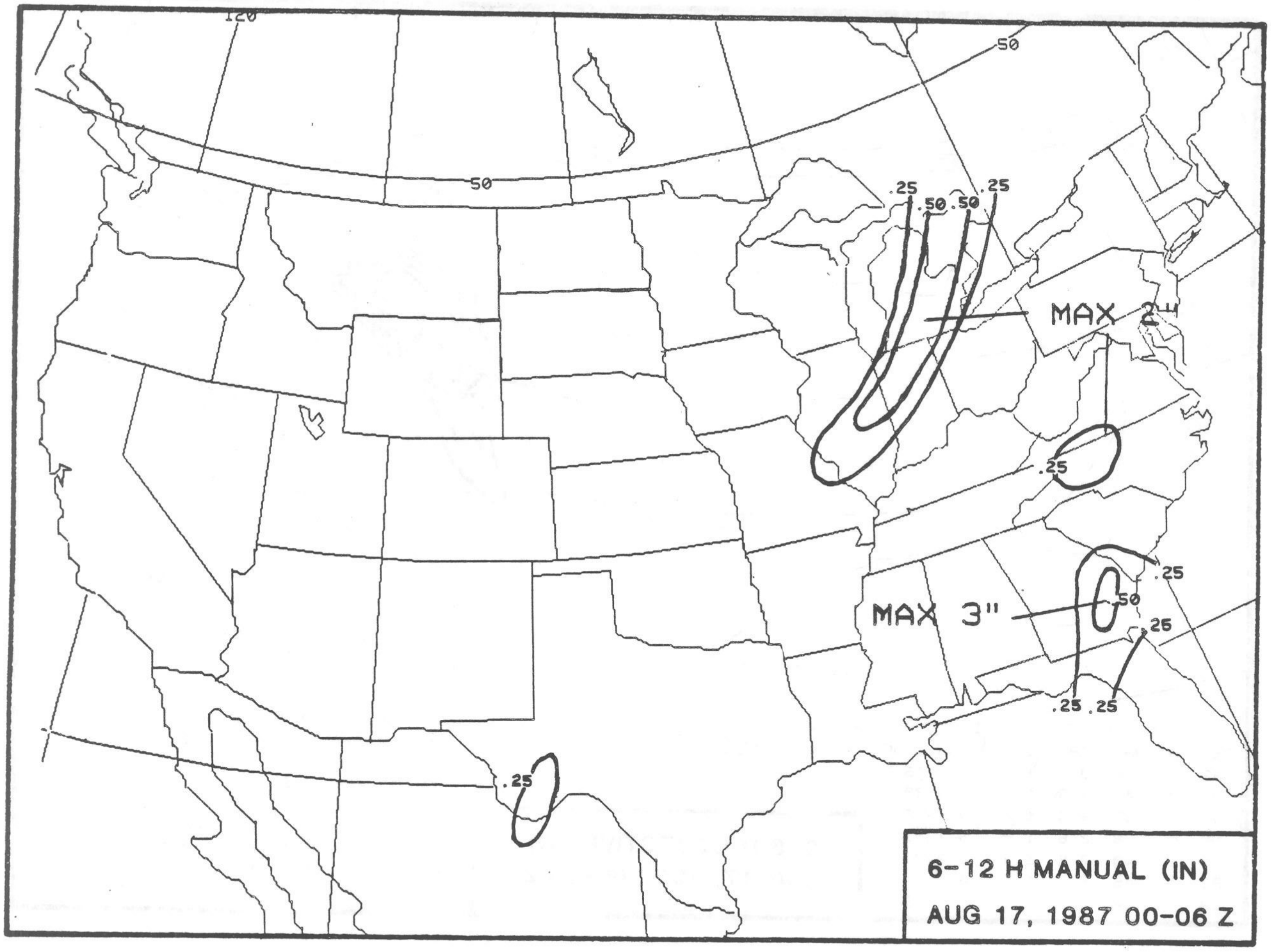

Fig. 7b. As in Fig. 7a except 6-12 h manual (MAN) QPF. The "MAX" values appearing in the AFOS graphic refer to maximum point rainfall amounts expected within the isohyets indicated (see National Weather Service, 1983).

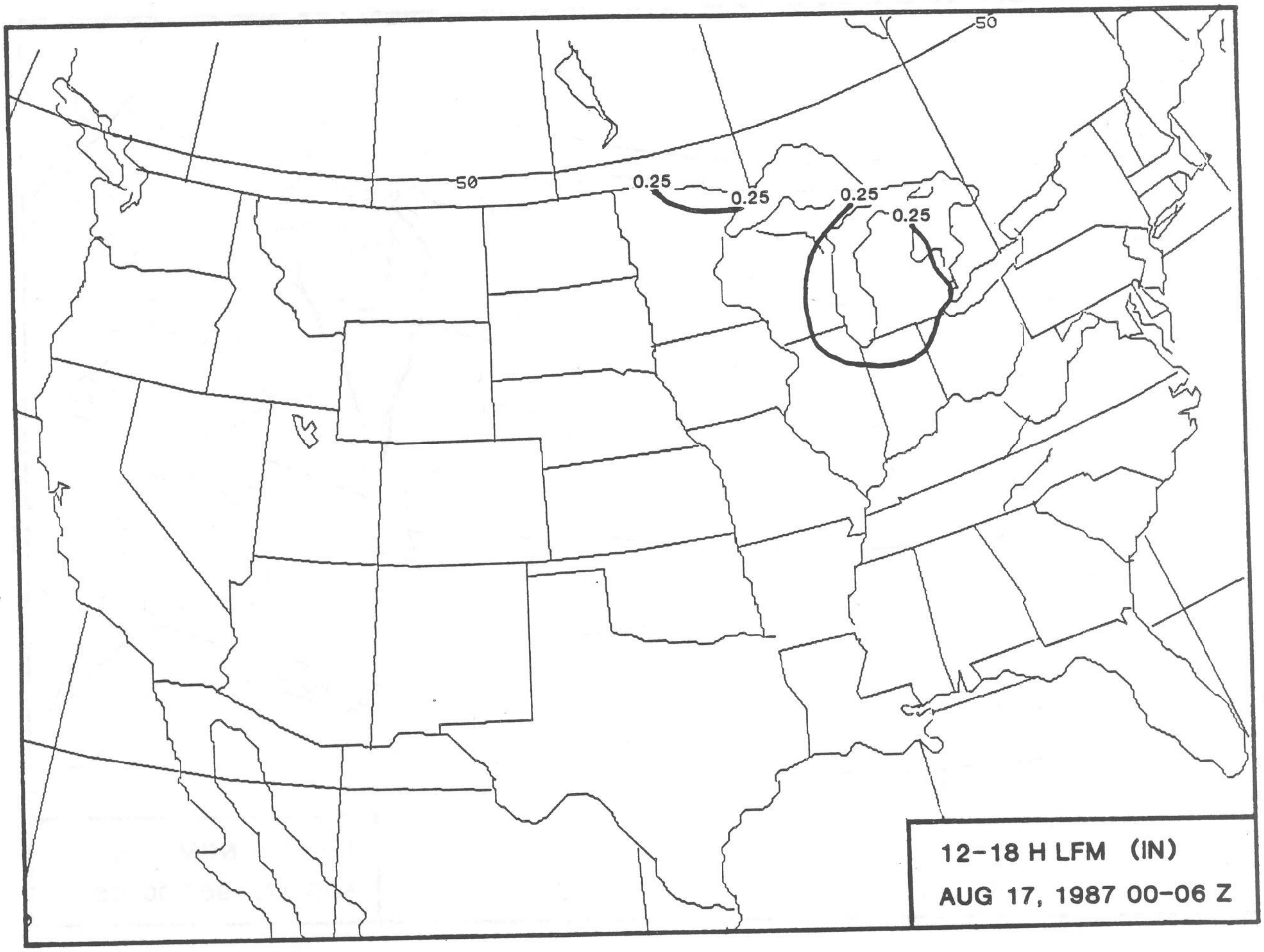

Fig. 7c. As in Fig. 7a except 12-18 h LFM QPF.

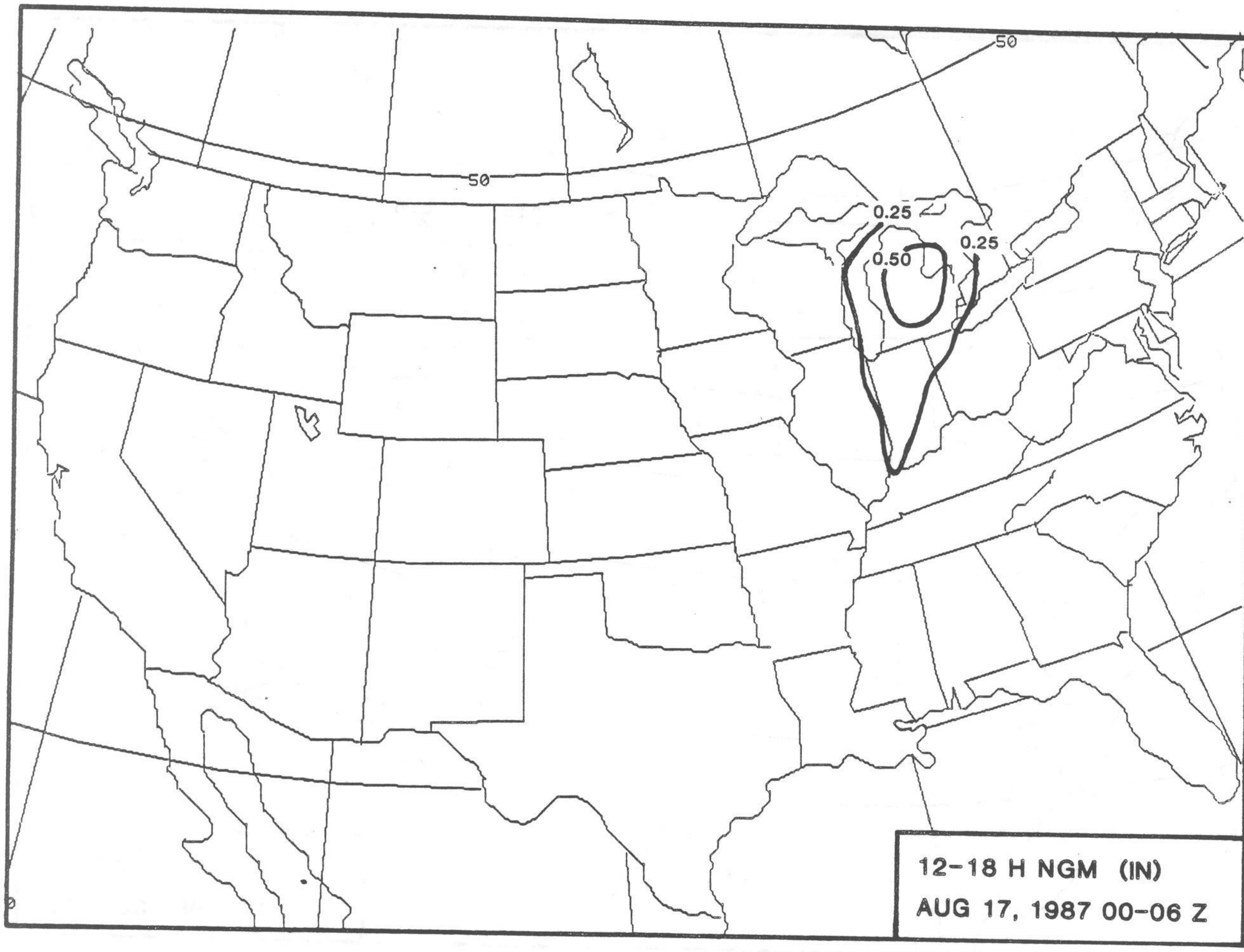

Fig. 7d. As in Fig. 7a except 12-18 h NGM QPF.

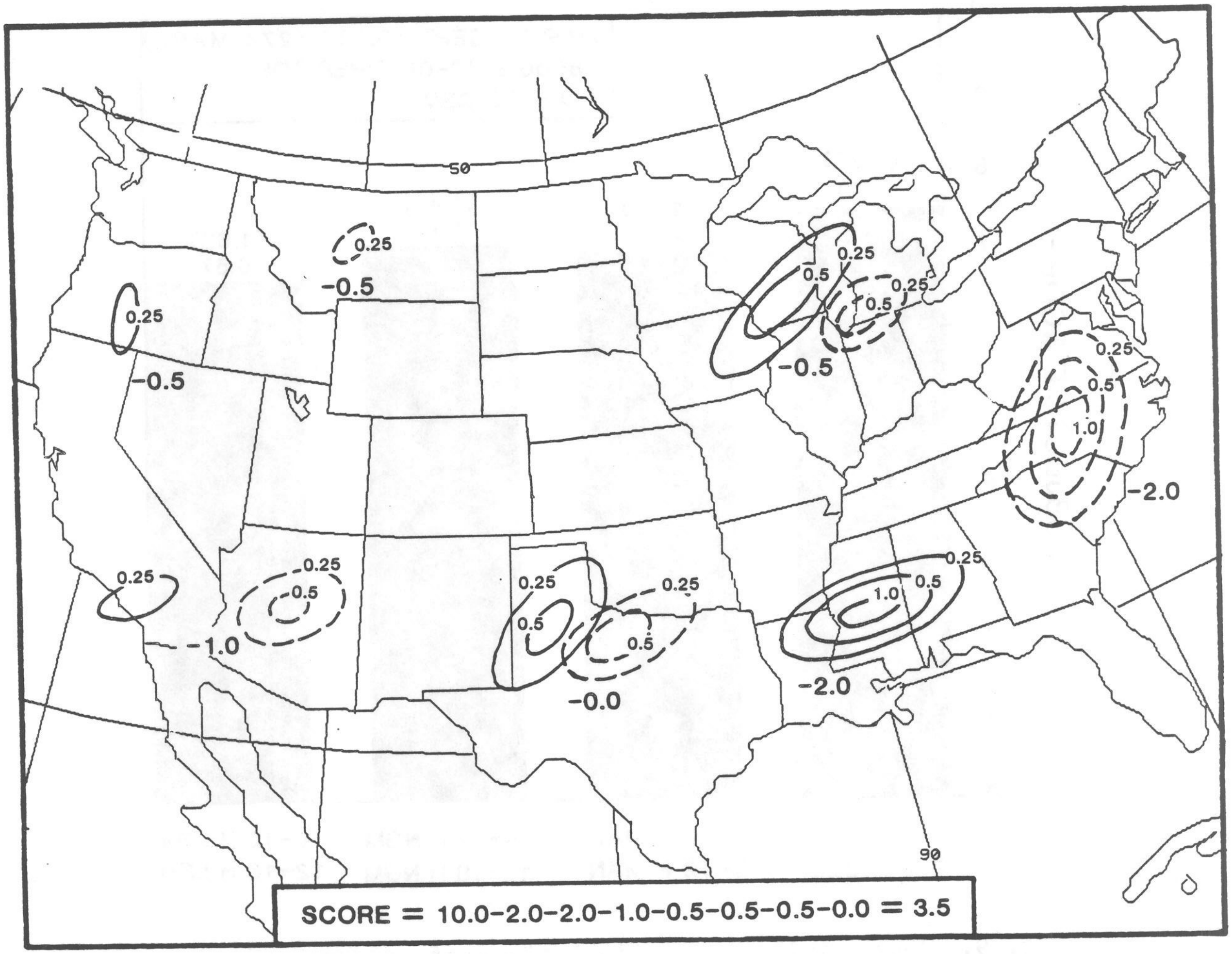

Fig. 8. Illustration of subjective scoring procedure for imagined forecast (solid) and observed (dashed) precipitation patterns (inch). A perfect score is 10.0. The amount subtracted from 10.0 for each incorrect forecast feature or each observed feature not forecast is indicated.

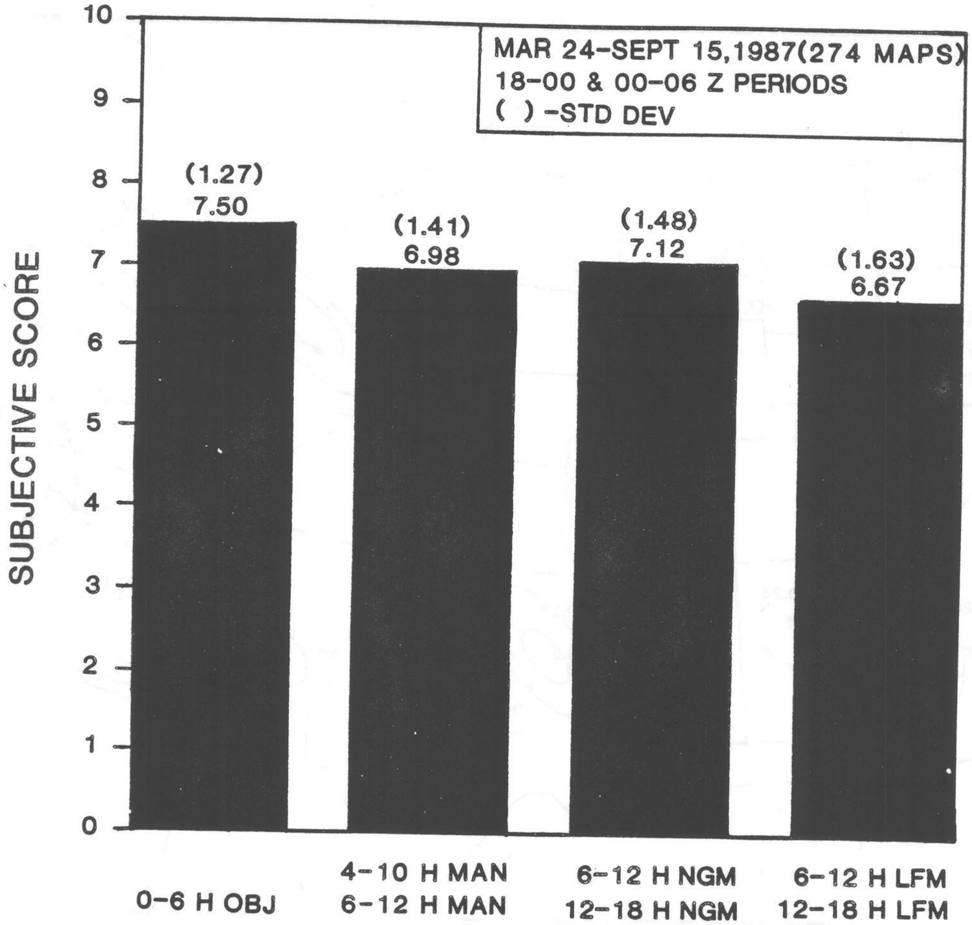

Fig. 9. Means and standard deviations of subjectively assigned scores for four QPF products over the conterminous United States. The sample for each product consisted of 274 forecast maps for the nation. The sample was formed by combining two daily maps on most days over the period March 24-September 15, 1987.

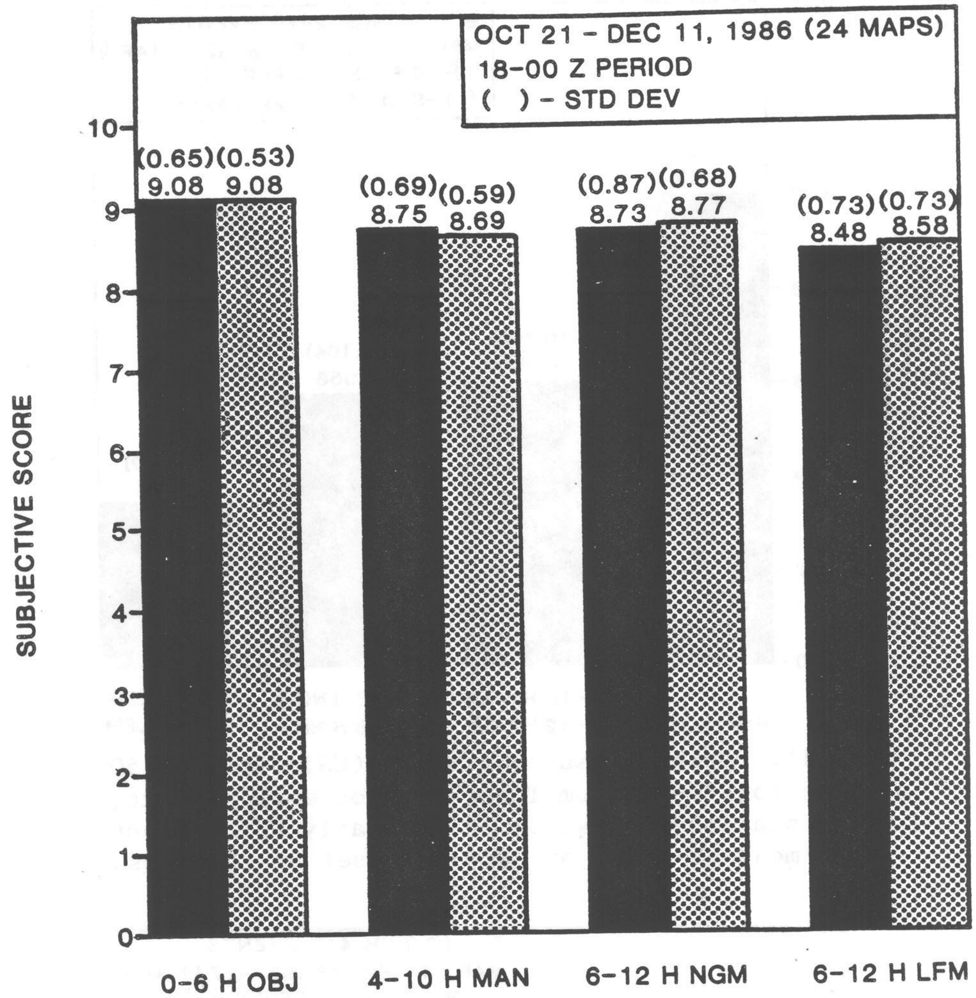

Fig. 10. As in Fig. 9 for scores assigned independently by the lead author (heavy shading) and the third author (light shading). The sample consisted of one forecast daily on 24 days during October 21-December 11, 1986.

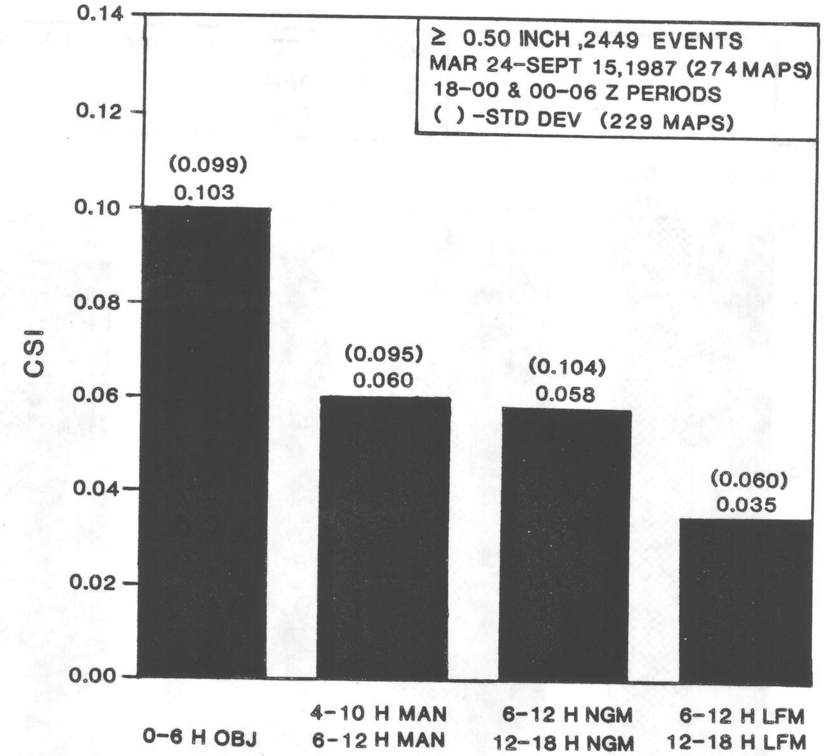

Fig. 11. Critical success index (CSI) for ≥ 0.50 inch forecasts from Table 1. For each product, the standard deviation of the daily CSI's about the mean is based on sample subset of 229 maps.

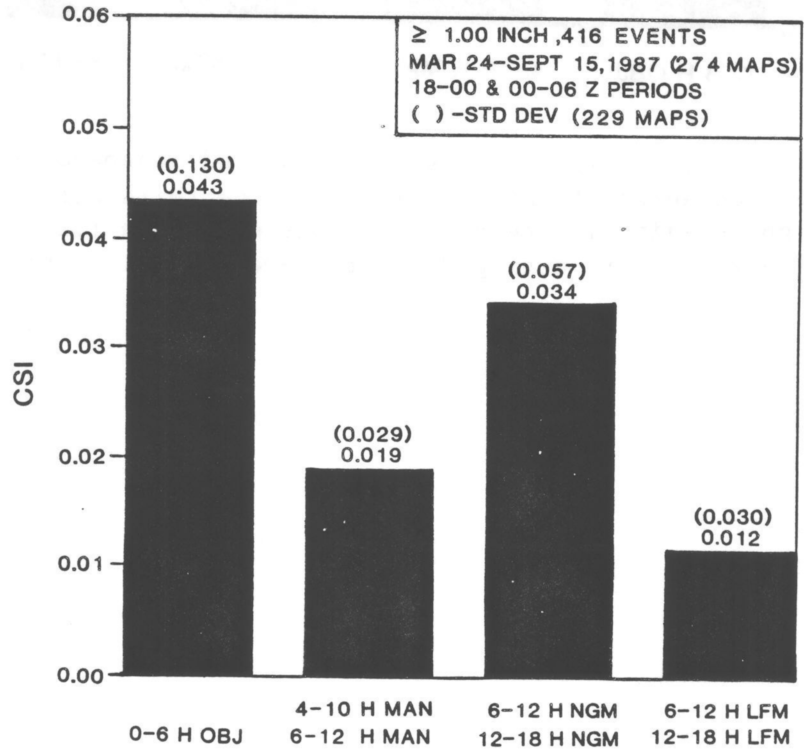

Fig. 12. As in Fig. 11 for ≥ 1.00 inch forecasts.

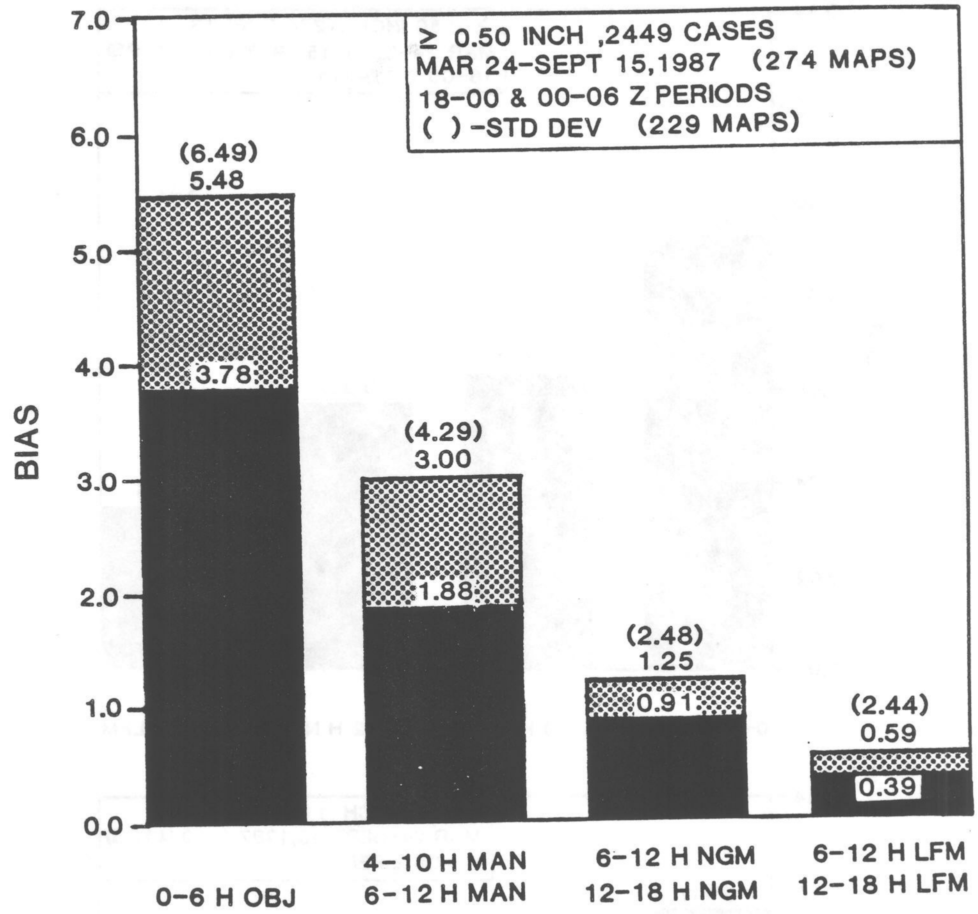

Fig. 13. Forecast bias for ≥ 0.50 inch forecasts. The bias based on all days (274 maps) is indicated by heavy shading and that based on days when the event was forecast and/or observed (229 maps) by light shading. Otherwise same as Fig. 11.

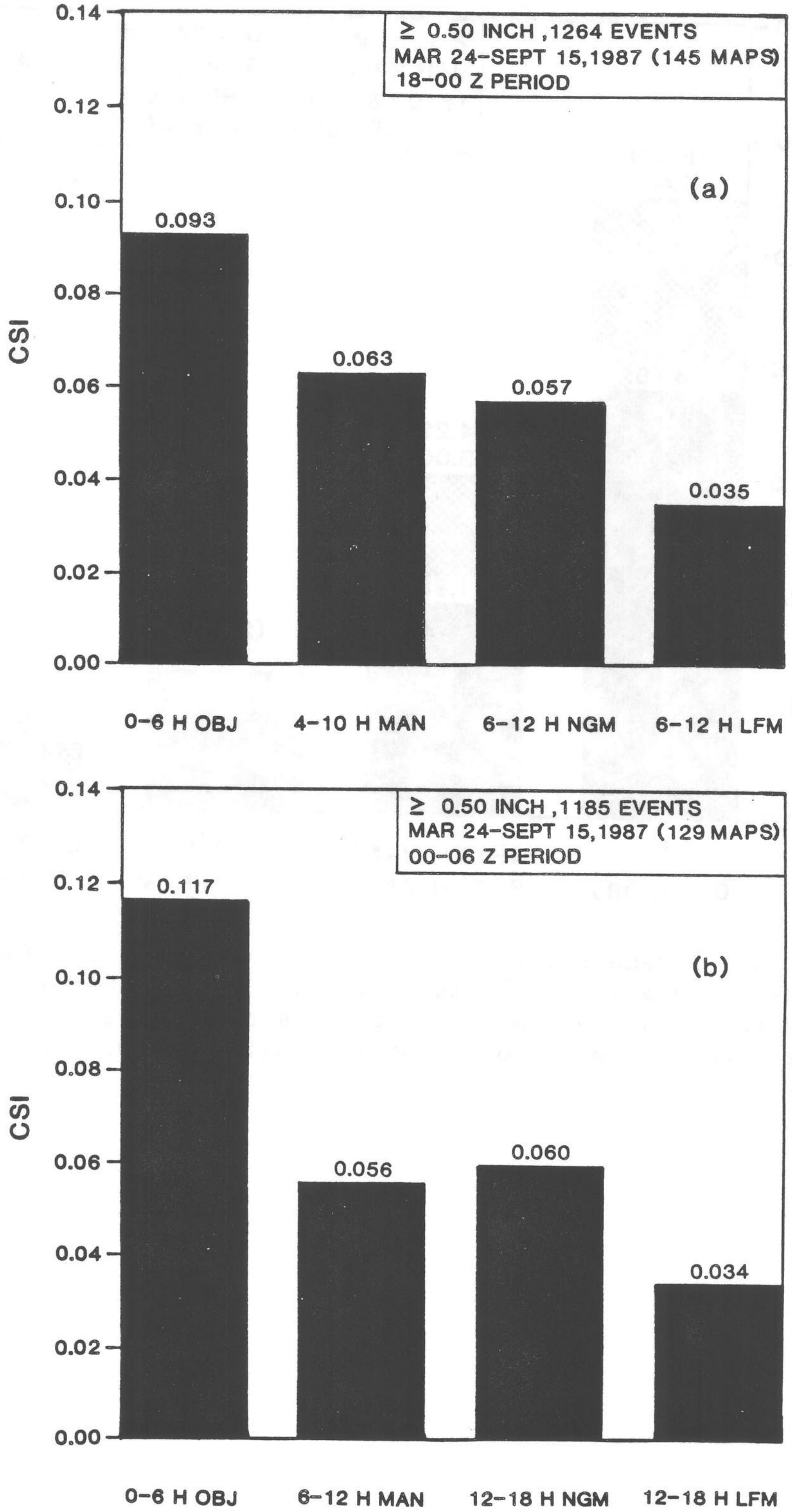

Fig. 14. As in Fig. 11 for the 18-00 GMT (a) and 00-06 GMT periods (b) separately. The sample size for (a) is 145 maps, for (b) 129 maps.

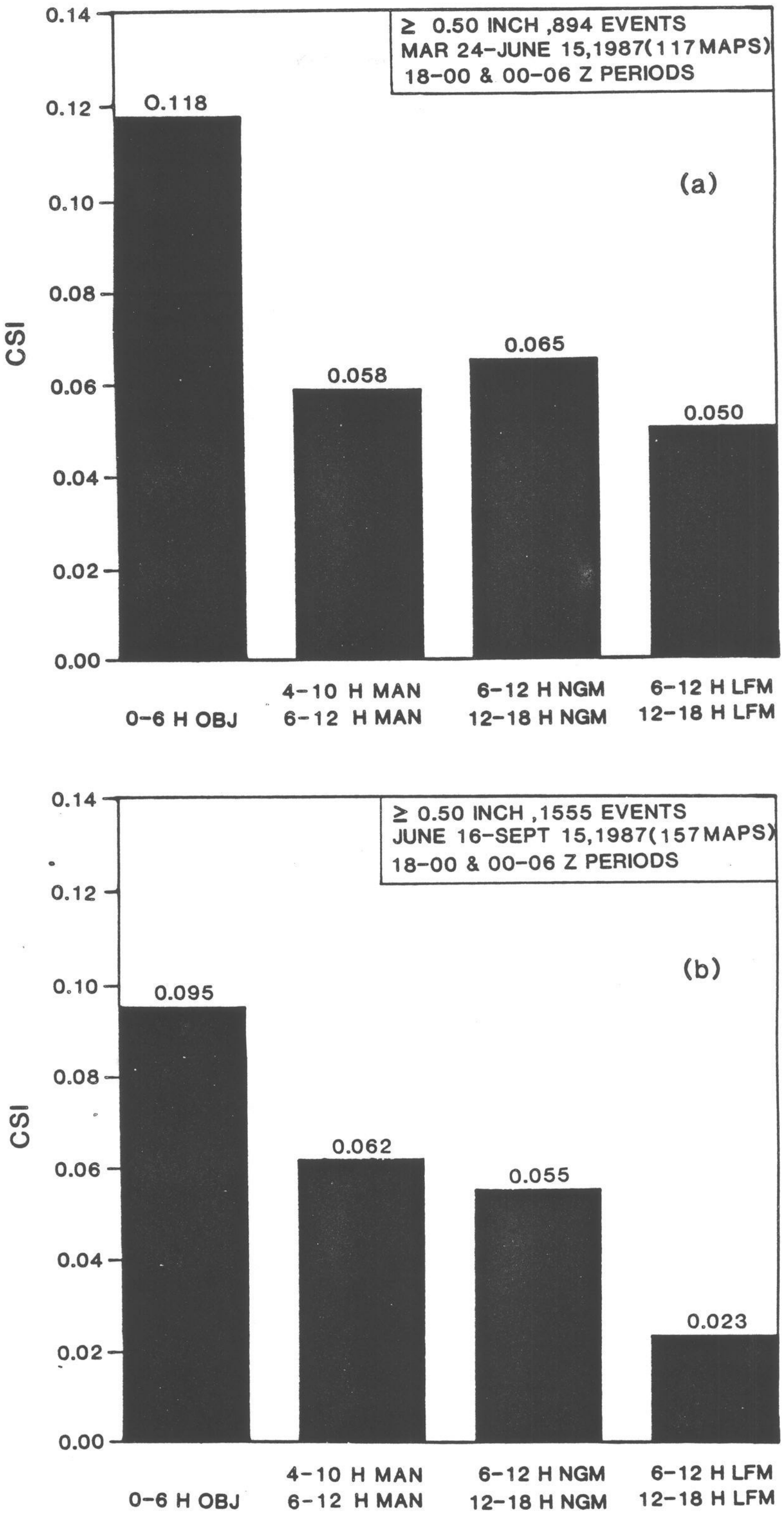

Fig. 15. As in Fig. 11 for the spring (a) and summer seasons (b) separately.

(Continued from inside front cover)

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