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NGM-Based MOS Thunderstorm and Severe Thunderstorm Probability Forecasts for the Contiguous United States

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This Technical Procedures Bulletin (TPB), which was written by J. Brent Bower of the Techniques Development Laboratory (TDL), describes new Nested Grid Model (NGM)-based Model Output Statistics (MOS) guidance for thunderstorms and severe thunderstorms. For AFOS users, the guidance is included under the FWC category as part of the NGM MOS matrix. For the Family of Services' Domestic Data Service subscribers, the guidance is included in the FOUS14 KWBC message. The thunderstorm and severe thunderstorm guidance have been available since the FWC/FOUS14 message was implemented on November 4, 1992 at 1200 UTC. It is also included in similar bulletins to all stations supported by the United States Air Force.

The NGM-based thunderstorm/severe thunderstorm MOS forecasts are generated twice daily around 0400 and 1600 UTC. The 6- or 12-h thunderstorm and severe thunderstorm probability forecasts are valid for periods ending 12 to 60 hours following 0000 and 1200 UTC. Equations for 24-h forecasts valid at 36 and 60 hours after 0000 UTC were also developed.

Operational users of the NGM-based guidance may be particularly interested in Section 5, entitled "Operational Considerations". It includes discussions of dependence of MOS guidance on the associated model, testing of the new equations, characteristics of the guidance, and sample cases.

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NGM-BASED MOS THUNDERSTORM AND SEVERE THUNDERSTORM PROBABILITY FORECASTS FOR THE CONTIGUOUS UNITED STATES

by J. Brent Bower, Techniques Development Laboratory

1. INTRODUCTION

The Techniques Development Laboratory (TDL) of the National Weather Service (NWS) has derived new regression equations to predict the probability of thunderstorms and conditional probability of severe thunderstorms by applying the Model Output Statistics (MOS) technique (Glahn and Lowry, 1972) to output from the Nested Grid Model (NGM) (Hoke et al., 1989). Data from radar, hourly surface aviation observations (SAOs), and Severe Local Storms (SELS) event logs from the National Severe Storms Forecast Center (NSSFC) were used to define the predictands. The 6- or 12-h thunderstorm and severe thunderstorm probability forecasts are valid for periods ending 12 to 60 hours following 0000 and 1200 UTC. Equations for 24-h forecasts valid at 36 and 60 hours after 0000 UTC were also developed. The prediction equations for thunderstorms were implemented on the NOAA/NWS computers in October 1991 and for severe thunderstorms in February 1992 for over 700 sites in the contiguous United States. Since then, NSSFC, along with U. S. Air Force (USAF) forecasters and supported customers, have received the forecasts. Other NWS personnel began receiving the guidance with the implementation of the new FOUS14 KWBC (FWC) message on November 4, 1992 (see Section 4).

The NGM-based MOS thunderstorm/severe thunderstorm guidance uses different predictand definitions than the guidance based on the Limited-area Fine-mesh Model (LFM). Most LFM-based guidance defines the thunderstorm predictand solely in terms of Manually Digitized Radar (MDR) data from weather surveillance radars (Reap and Foster, 1979) and the severe thunderstorm predictand solely in terms of SELS data. This LFM-based guidance includes the 0000 UTC 12- to 36-h forecast graphics of thunderstorm and severe thunderstorm probabilities (Reap, 1977) and the 12-h thunderstorm forecasts from the 0000 and 1200 UTC forecast cycles in the FOUS12 (Reap, 1983). However, special 6-h thunderstorm guidance available for the western U.S. (Reap, 1986), the northeast U.S. and the Kansas-Oklahoma areas (Reap, 1990), and under development for Florida, is based on lightning data.

2. METHOD

The MOS approach correlates predictand data (weather condition to be forecast) with predictor data (output from numerical models, surface observations, remotely-sensed observations, and geographical or climatic information). In the application of MOS described here, the forecast equations were developed by applying linear multiple regression techniques to relate the thunderstorm or severe thunderstorm predictand data to the predictors. Screening regression techniques select the set of predictors that yield the highest reduction of variance for the predictand.

3. DEVELOPMENT

3.1 Predictand

Data availability and suitability played a major role in determining how we defined the station-oriented thunderstorm and severe thunderstorm predictands. There are a number of possible sources of data with which to define the occurrence of a thunderstorm or severe thunderstorm. These sources include remote sensing information such as lightning detection and MDR data, SAOs, and reports from spotter networks in the NSSFC's SELS logs, which could be used to supplement the SAOs. One of the best ways of detecting and defining thunderstorms over large areas is with a lightning detection network (Reap and Orville, 1990). While we wished to use lightning data, the data were not available to us for the entire contiguous 48 states for the time period used for development. There were difficulties with the other sources of data as well. Radar echo intensity data have been shown to be related to thunderstorm activity. In Reap and Foster (1979), radar echoes at Video Integrator and Processor level 3 (VIP3) were used to indicate the occurrence of thunderstorms. Of course, VIP3 is not a 100% accurate indicator of thunderstorm occurrence; thunderstorms may not always occur with a VIP3 and, conversely, lower VIP levels may be associated with thunderstorms. In addition, radar coverage is rather poor in space and/or time in many areas, especially in the west. Surface observations probably report many fewer thunderstorms than actually occur, because thunderstorms are a subsynoptic event that can occur in the area around a station without being detected by direct observations at the station. Spotter networks may not have sufficient coverage for all stations and they only report severe thunderstorms, not general thunderstorms. In light of these limitations, we decided the best way to define the thunderstorm predictand was to combine SAOs with SELS and MDR data. In this way, we minimized the deficiencies of any one data source.

Spatial and temporal resolution are two other necessary considerations in defining a predictand. Note in Fig. 1 that MDR data are reported for grid blocks approximately 47 km (true at 60° North) on a side. Each station lies within an MDR grid block. Because a station may lie near a border or corner of a grid block, there may be a radar echo very near a station which is not reported in the station's block, but is reported across the border in an adjacent block. In order to avoid this "blind spot" in coverage, the eight surrounding grid blocks were included as the target area for thunderstorm occurrence. This 9-block area is approximately 115-135 km on a side, depending on latitude. The temporal resolution was specified by different intervals over which the reports were accumulated: 6 hours (0000-0600, 0600-1200 UTC, etc.), 12 hours (0600-1800 UTC, 1800-0600 UTC), and 24 hours (1200-1200 UTC). Note the 12-h periods are different from those of the LFM-based 12-h thunderstorm guidance, which are valid for the 0000-1200 and 1200-0000 UTC periods.

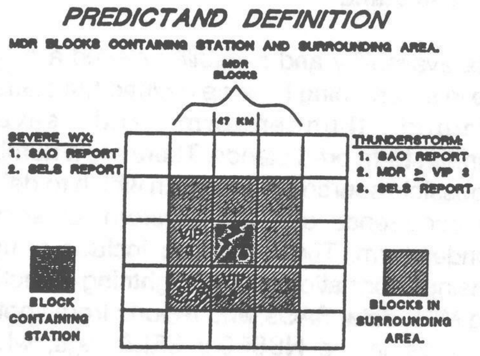


Figure 1. Schematic showing the definition of the NGM-based MOS thunderstorm and severe thunderstorm predictands.

Specifically then, the predictand--that is, occurrence of a thunderstorm--was defined as either an SAO report of a thunderstorm at the station, an MDR report of VIP3 or greater anywhere in the station's 9-block area, or a SELS log report of a severe thunderstorm occurrence within the station's area during one of the specified time periods. Similarly, the definition of a severe thunderstorm was either an SAO report of a severe thunderstorm at the station or a SELS log report of a severe thunderstorm within the station's area during one of the specified time periods. Fig. 1 is a graphical depiction of the thunderstorm and severe thunderstorm predictand definitions. MDR data were not used for defining severe thunderstorm events.

It is important to realize that the difference in the predictand definition between the NGM- and the LFM-based guidance affects the characteristics of the forecasts. The LFM-based thunderstorm/severe thunderstorm guidance was essentially developed by using a predictand extracted from four MDR blocks with the station located <u>anywhere</u> within that area. Thus, the forecast for the station is the probability of the event occurring within the four MDR block area containing the station. In contrast, the NGM-based guidance was developed by using a predictand extracted from a nine-MDR block area with the station located within the center block. Thus, the predictand area for the NGM-based guidance is 2.25 times as large as the predictand area for the LFM-based guidance. This difference has several implications. First, with a larger predictand area, there were more events detected for each station. For rare events like severe thunderstorms, this helped in developing the equations. Second, it probably is more realistic to forecast for a larger area when using a synoptic-scale model to predict a subsynoptic-scale event. The predictability of a synoptic-scale model does not extend down to the mesoscale. Third, the most obvious result to users is that the NGM-based probabilities will be higher than the LFM-based probabilities for a given situation [see Murphy (1991) and Schultz (1991) for a discussion of probabilities and event definitions]. In fact, the NGM-based thunderstorm probabilities can go up to 100% for many stations. This will be discussed further in Section 5.4.

3.2 Predictors

The potential predictors available to derive the thunderstorm/severe thunderstorm forecast equations were geographic variables, climatic variables, and NGM forecasts interpolated to stations. The following predictors were included:

NGM forecasts

- precipitation amount
- relative humidity
- dew point
- equivalent potential temperature
- K-index, lifted index, Total Totals index, SWEAT index
- modified lifting condensation level
- advection of K-index by 700 mb wind
- wind and moisture divergence
- wind speed shear
- geostrophic vorticity, vorticity advection
- divergence of Q-vectors
- temperature difference between levels
- sea level pressure
- geostrophic wind components

Geographic and climatic predictors

- station elevation, latitude, and longitude
- sinusoidal functions of the day of the year
- extraterrestrial radiation
- hours of sunshine

In addition, several new interactive predictors were created: vertical velocity multiplied by the K-index, the Total Totals index, or the relative humidity; and relative humidity multiplied by the K-index or the Total Totals index. Many of the predictors were available in both binary and continuous form. The most important predictors chosen in the thunderstorm equation development were mean relative humidity (from the surface to approximately 500 mb) times the K-index, the lifted index, and the equivalent potential temperature. The most important predictors for the severe thunderstorm equations were the 500- to 850-mb temperature difference, the SWEAT index, and the sea level pressure. Note that observations were not used as potential predictors in this development.

3.3 Seasons

Developmental data were stratified into three seasons: spring (March 16-June 30), summer (July 1-October 15), and cool (October 16-March 15). Four seasons of data (1987-1990) were used to develop the summer thunderstorm equations; five seasons of data (1987-1991) were available for the summer severe thunderstorm and the spring thunderstorm and severe thunderstorm equations. The cool season equations also used five seasons of data (October 1986-March 1991).

3.4 Equation Development

The thunderstorm and severe thunderstorm equations were developed for the following projections from 0000 and 1200 UTC:

6-h periods	12-h periods	24-h periods (0000 UTC only)
6-12 hours		
12-18 hours	6-18 hours	
18-24 hours		
24-30 hours	18-30 hours	
30-36 hours		12-36 hours
36-42 hours	30-42 hours	
42-48 hours		
48-54 hours	42-54 hours	
54-60 hours		36-60 hours

These 12-h periods were used instead of the traditional 0000-1200 and 1200-0000 UTC because thunderstorms tend to reach a maximum frequency around 0000 UTC in most parts of the country, and we wanted to isolate the typical diurnal trend in the 12-h period.

The equations for the 6- and 12-h periods were developed simultaneously to enhance (but not ensure) forecast consistency. Forecasts are inconsistent when a 12-h probability is less than one of the concurrent 6-h probabilities or when the 12-h probability exceeds the sum of the two concurrent 6-h probabilities. In a simultaneous development, predictors are selected for multiple predictands during the same screening regression. Thus, for instance, we developed the 6-h equations for the 6-12 and 12-18 h periods and the 12-h equation for the 6-18 h period in the same regression. The result of simultaneous development is that the equations share the same predictors, but have unique regression constants and coefficients. The 24-h equations were developed separately.

Equations were developed by using the regional approach in which data for a group of stations were combined in order to increase the sample size. One equation was then derived for all the stations in the region. The size of each region was driven by the number of events needed to derive a stable equation. Based on geography, relative frequencies, and each station's correlation of the predictand with important predictors, we divided 431 stations in the contiguous 48 states into regions for both the spring and summer thunderstorm equations as shown in Fig. 2a. The cool season thunderstorm regions (Fig. 2b) are similar.

For severe thunderstorms, because the frequency of occurrence was dramatically different between the day and night periods, we chose to treat the development of the daytime and nighttime equations differently. Thus, for the spring season, the contiguous U. S. was divided into six regions for the afternoon/evening (p.m. period, 1800-0600 UTC) and two regions for the late-night/morning (a.m. period, 0600-1800 UTC) as shown in Figs. 3a and 3b, respectively. For the summer season equations, we used six regions (Fig. 4a) for the p.m. period and one region for the a.m. period. For the cool season, two regions (Fig. 4b) were used for the p.m. period and one region for the a.m. period. The cool season p.m. period equations were developed by using the stations in the enclosed region in Fig. 4b for one set of equations, and by using the data for all 431 stations for the second set of equations. When the forecasts are made, however, the equations for the enclosed region are applied only to stations within that region. The second set of equations is applied to the remaining stations.

The conditional severe thunderstorm equations were developed by using cases when thunderstorms occurred. The severe thunderstorm forecast probabilities are conditional on a thunderstorm occurring. Therefore, the probabilities only have meaning when a thunderstorm occurs or is expected to occur.

4. MESSAGES AND SCHEDULES

Since its implementation, the thunderstorm/severe thunderstorm guidance has been disseminated in bulletins to all stations supported by the USAF. In addition, NSSFC accesses the forecasts and creates Automation of Field Operations and Services (AFOS) graphics for use by the NSSFC forecasters. In November 1992, the NWS began to disseminate this guidance to NWS field offices as part of the complete NGM MOS package (Dallavalle et al., 1992).

The NGM-based thunderstorm/severe thunderstorm MOS forecasts are generated twice daily around 0400 and 1600 UTC. The guidance is disseminated in alphanumeric form on AFOS for the stations given in Technical Procedures Bulletin (TPB) No. 408 (Dallavalle et al., 1992). The guidance is also disseminated on military communication circuits for the stations given in TPB No. 399 (Miller, 1993). On AFOS, the thunderstorm/severe thunderstorm guidance is available in the FWCxxx product, where xxx are the call letters of the station requested. The guidance is also available on the Family of Services' Domestic Data Service in the FOUS14 KWBC product. An example of the thunderstorm/severe thunderstorm forecasts as part of the complete FWC/FOUS14 message is shown in Fig. 5. In this example, the product is for Washington, D.C. (DCA) for the 0000 UTC

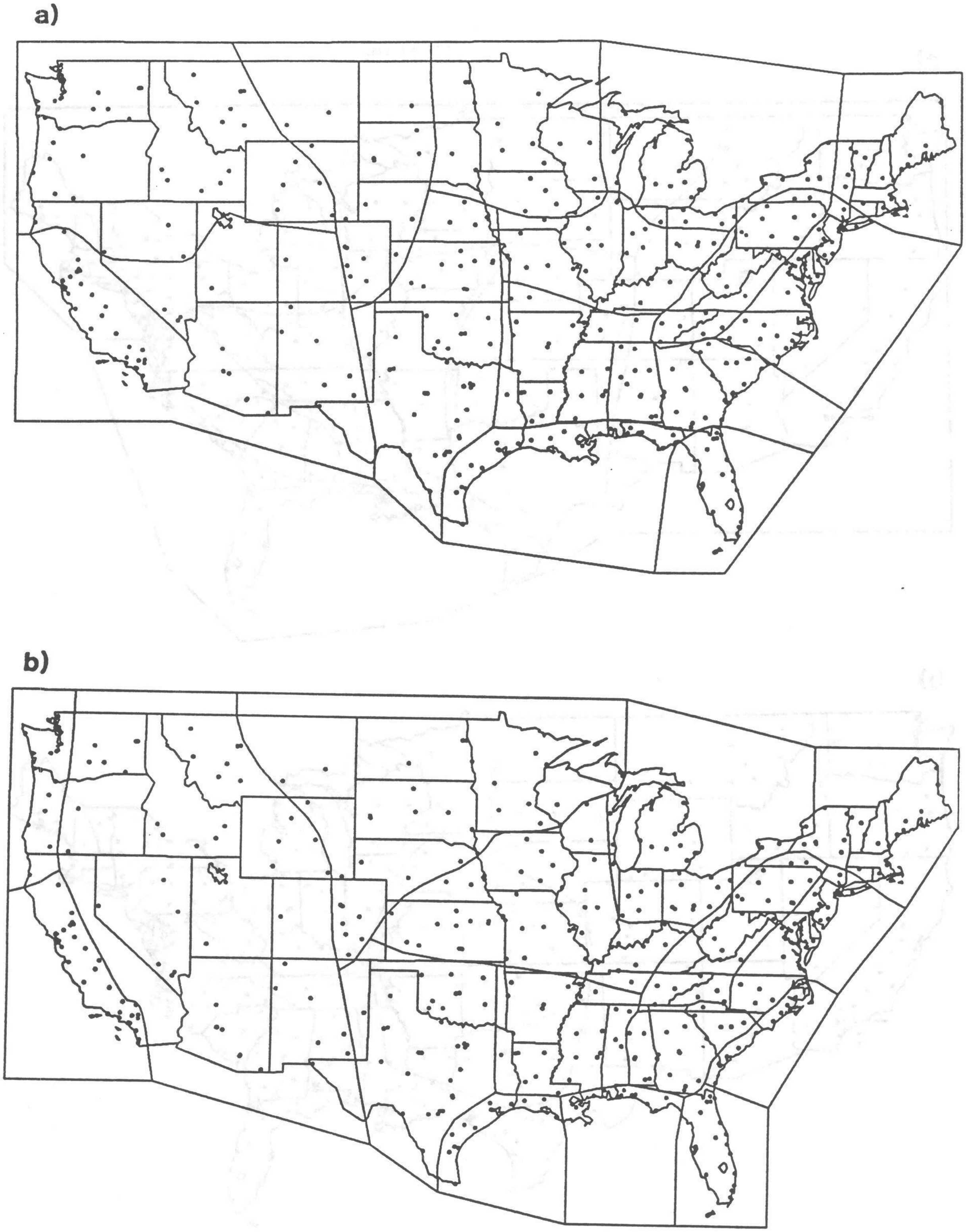
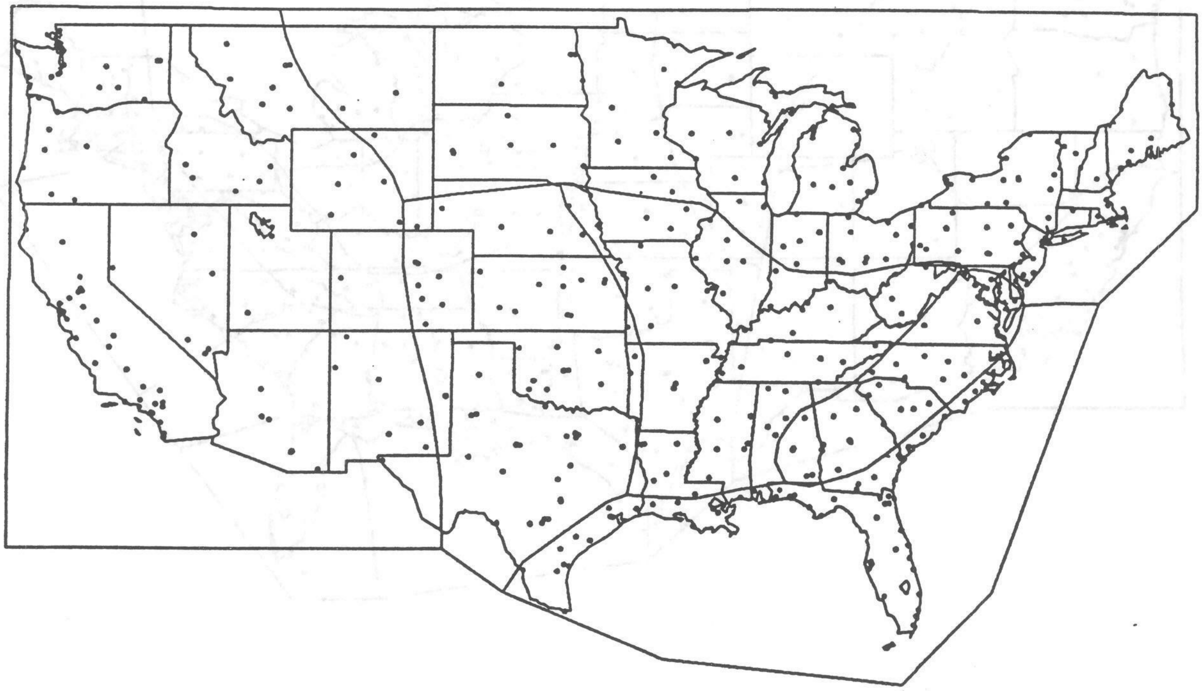


Figure 2. Regions and stations used in development of thunderstorm forecast equations for the (a) spring and summer seasons and (b) cool season.

a)



b)

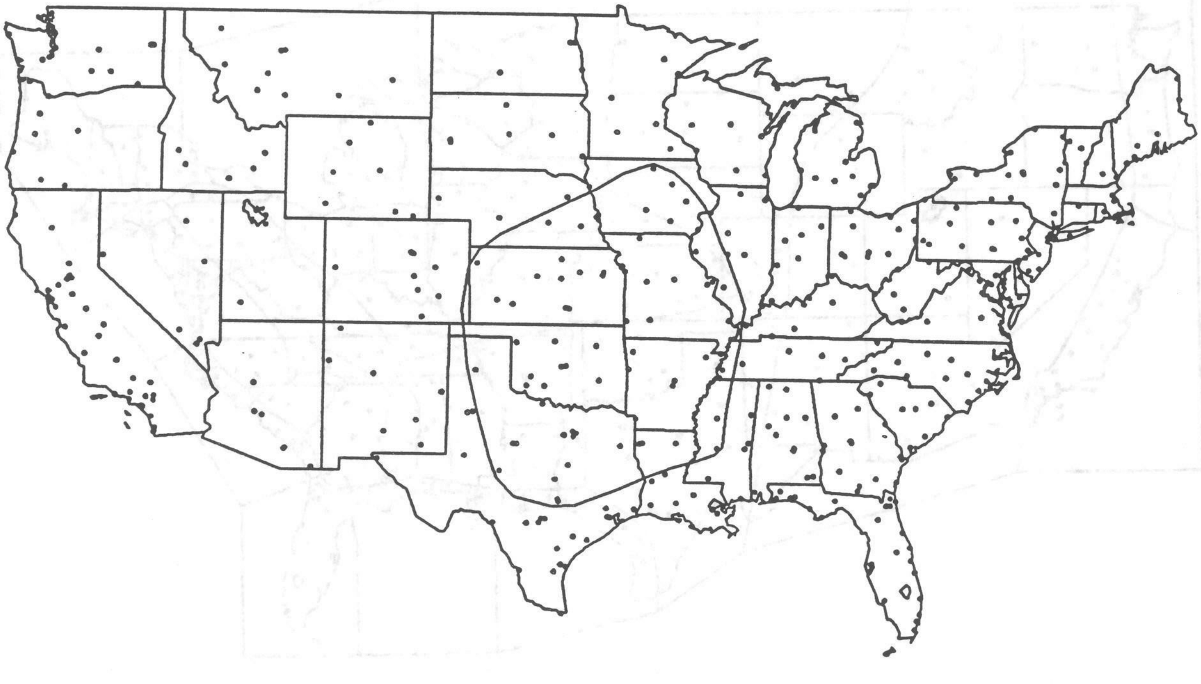
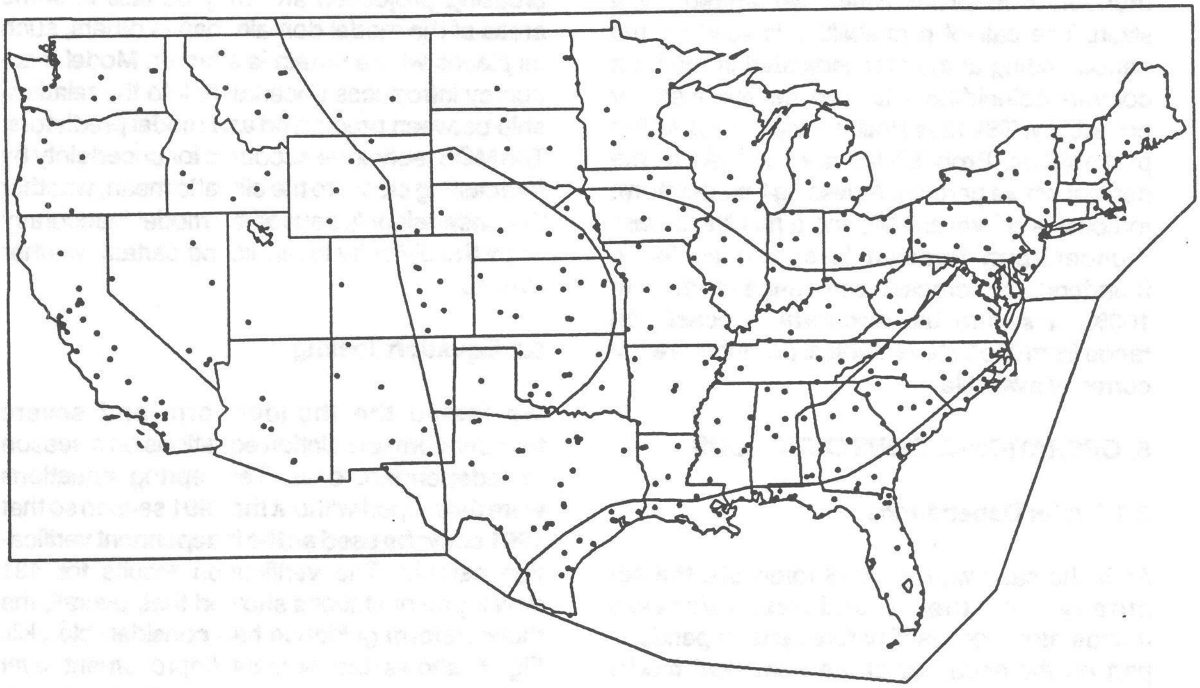


Figure 3. Regions and stations used in development of severe thunderstorm forecast equations for the spring season (a) p.m. period (1800-0600 UTC) and (b) a.m. period (0600-1800 UTC).

a)



b)

Figure 4. Regions and stations used in development of severe thunderstorm forecast equations for the (a) summer season p.m. period and (b) cool season p.m. period.

forecast cycle on March 6, 1991. The line labeled TSV06 lists the 6-h probabilities for thunderstorms followed by the severe thunderstorm probabilities, separated by a slash. The pair of probabilities is valid for the period ending at the time indicated in the hour column coinciding with the severe weather probability. TSV12 is similar except for the 12-h probabilities. Probabilities are rounded to the nearest whole percent. A missing thunderstorm forecast is shown as 999, and a missing severe thunderstorm forecast is shown as 99. A thunderstorm forecast can range from 0 to 100%; a severe thunderstorm forecast can range from 0 to 98%. Graphical products are not currently available.

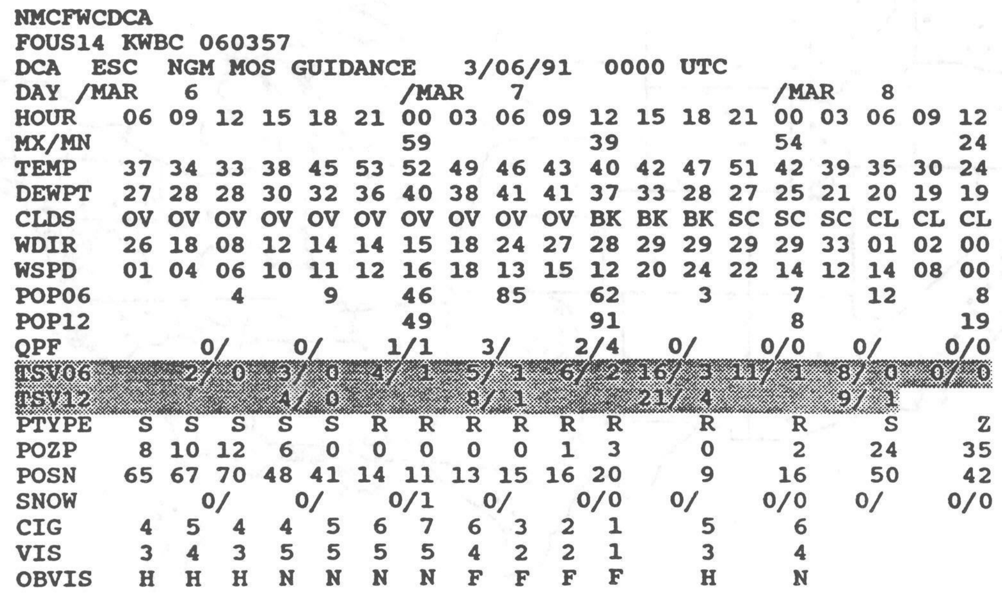
5. OPERATIONAL CONSIDERATIONS

5.1 Model Dependence

As is the case with all MOS forecasts, the accuracy of the thunderstorm/severe thunderstorm probability forecasts depends in part on the accuracy of the numerical model used as input. While the MOS technique can account for some systematic biases in the NGM, MOS cannot correct for poor model forecasts. Model accuracy decreases with increasing projection and may be less in some areas of the model domain than in others, such as places where terrain is a factor. Model inaccuracy introduces uncertainty into the relationship between predictand and model predictors. The MOS technique accounts for uncertainty by forecasting closer to the climatic mean, whether the uncertainty is caused by model inaccuracy or by the difficulty in predicting certain weather events.

5.2 Equation Testing

We tested the thunderstorm and severe thunderstorm prediction equations on a season of independent data. Test spring equations were developed without the 1991 season so that 1991 could be used as the independent verification sample. The verification results for 431 development stations showed that, overall, the thunderstorm guidance had considerable skill. Fig. 6 shows the percent improvement over climate in the Brier score of 6-h thunderstorm



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NMCFWCDCA
FOUS14 KWBC 060357
DCA  ESC  NGM MOS GUIDANCE   3/06/91   0000 UTC
DAY /MAR 6              /MAR  7                 /MAR  8
HOUR   06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06 09 12
MX/MN                    59          39          54          24
TEMP   37 34 33 38 45 53 52 49 46 43 40 42 47 51 42 39 35 30 24
DEWPT  27 28 28 30 32 36 40 38 41 41 37 33 28 27 25 21 20 19 19
CLDS   OV OV OV OV OV OV OV OV OV OV BK BK BK SC SC SC CL CL CL
WDIR   26 18 08 12 14 14 15 18 24 27 28 29 29 29 29 33 01 02 00
WSPD   01 04 06 10 11 12 16 18 13 15 12 20 24 22 14 12 14 08 00
POP06         4     9    46    85    62     3     7    12     8
POP12                    49          91           8          19
QPF         0/    0/    1/1   3/    2/4   0/    0/0   0/    0/0
TSV06      2/ 0  3/ 0  4/ 1  5/ 1  6/ 2 16/ 3 11/ 1  8/ 0  0/ 0
TSV12            4/ 0        8/ 1       21/ 4        9/ 1
PTYPE   S  S  S  S  S  R  R  R  R  R  R     R     R     S     Z
POZP    8 10 12  6  0  0  0  0  0  1  3     0     2    24    35
POSN   65 67 70 48 41 14 11 13 15 16 20     9    16    50    42
SNOW        0/    0/    0/1   0/    0/0   0/    0/0   0/    0/0
CIG     4  5  4  4  5  6  7  6  3  2  1     5     6
VIS     3  4  3  5  5  5  5  4  2  2  1     3     4
OBVIS   H  H  H  N  N  N  N  F  F  F  F     H     N
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Figure 5. Sample FOUS14 KWBC (FWC) message for Washington, D.C. (DCA) for the 0000 UTC cycle on March 6, 1991. The line labeled TSV06 is the 6-h thunderstorm/severe thunderstorm guidance. The line labeled TSV12 is the 12-h guidance.

probability forecasts. Climate forecasts were based on equations using only geographic or climatic predictors. Skill levels showed a strong diurnal cycle, with much greater skill for p.m. period forecasts (especially the 1800-0000 UTC period) than for the a.m. period forecasts. This diurnal cycle mirrors the diurnal cycle in the thunderstorm relative frequency. The scores (not shown) for the conditional severe thunderstorm forecasts indicated a similar diurnal pattern, but with less skill than the thunderstorm forecasts. In fact, the a.m. period severe thunderstorm forecasts showed very little skill. Although we had hoped for better, this result was not too surprising since severe weather during the a.m. period is very rare, difficult to predict, and perhaps more influenced by mesoscale factors than the synoptic-scale environment.

Reliability is the correspondence between the probability forecast and the relative frequency of the event. In other words, for all probability forecasts of 60%, we would want the event to occur 60% of the time; for all 20% probability forecasts, we would want the event to occur 20% of the time. The reliability of the 6-12 h probability forecasts from the 1200 UTC cycle is shown in Fig. 7. The reliability of the thunderstorm forecasts was good. The reliability (not shown) of the severe thunderstorm forecasts was similar.

5.3 Guidance Characteristics

This section provides specific information that general verification scores cannot give. This information is based on what TDL has learned through tests and monitoring of the operational guidance. Since the thunderstorm predictand can "verify" simply with the occurrence of a VIP3 echo, a heavy convective rain is a verifying event as much as a true thunderstorm. This is especially important to remember during the cool season when we suspect a large number of the "thunderstorm" occurrences in the predictand sample were heavy rain events without lightning. Hence, high probabilities in the cool season may indicate a heavy rain event as much as a thunderstorm. On the other hand, in the spring and summer there will be occasions when the forecast thunderstorm probability for a station is much greater than the probability of precipitation for that same station. The main reason for this is the difference in the predictands: the probability of a thunderstorm is for a large area while the probability of precipitation is for getting measurable precipitation in the rain gauge at the station.

In evaluating the guidance, we created graphics of the thunderstorm/severe thunderstorm forecasts by plotting the probabilities on a U.S. map background. We found it quite useful to look for areas of relative maxima in the probabilities. For example, we looked at a number of cases when a slow-moving, well-developed cyclonic system tracked across the country over the course of several days. These systems brought outbreaks of thunderstorms and severe thunderstorms each afternoon and into the night. During these situations, the relative maximum of 12-h thunderstorm probability forecasts was slightly ahead of the observed thunderstorm occurrences. Thus, instead of the axis of the relative maximum of thunderstorm probabilities being in the center of the thunderstorm occurrences, with the number of events decreasing away from the axis, the axis of highest probabilities was near the eastern extent of the thunderstorm area. This apparent tendency for the 12-h MOS forecasts (presumably MOS is interpreting what the NGM is predicting) to indicate thunderstorm activity ahead of the actual observed activity may occur with other synoptic situations as well.

One good way for forecasters to use the guidance effectively is to learn the characteristics of the probabilities in their particular area for the different seasons. As was mentioned earlier, the NGM-based thunderstorm probabilities will tend to be greater than what forecasters expected with the LFM-based guidance. In fact, since many forecasters likely have a sense of the usual range of values for the LFM-based guidance, this is very important to know. To see some of the characteristics of the NGM-based guidance, we looked at the critical success index (CSI) for a range of thunderstorm probabilities. We discovered that, in general, the higher the observed relative frequency of

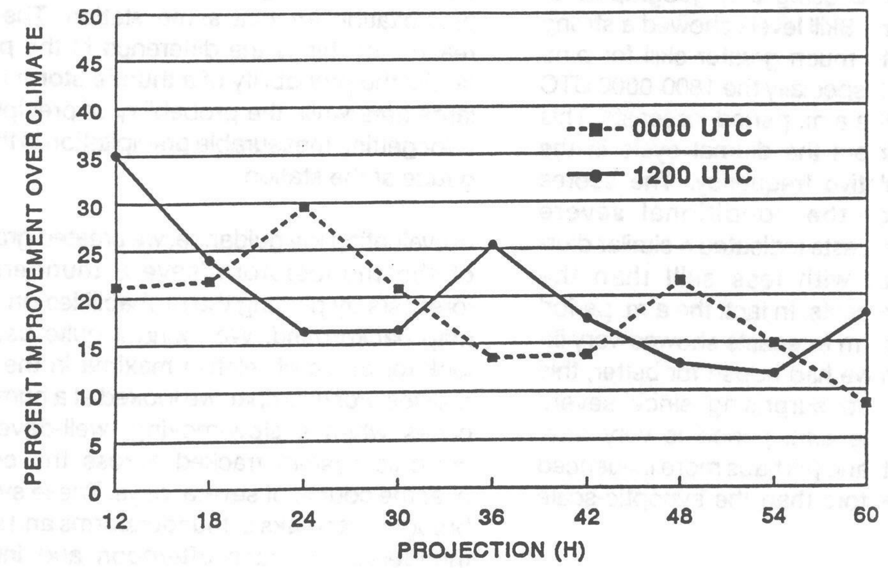

Figure 6. Percent improvement over climate of the Brier scores for 6-h thunderstorm forecasts made from 0000/1200 UTC NGM output for March 16-June 30, 1991.

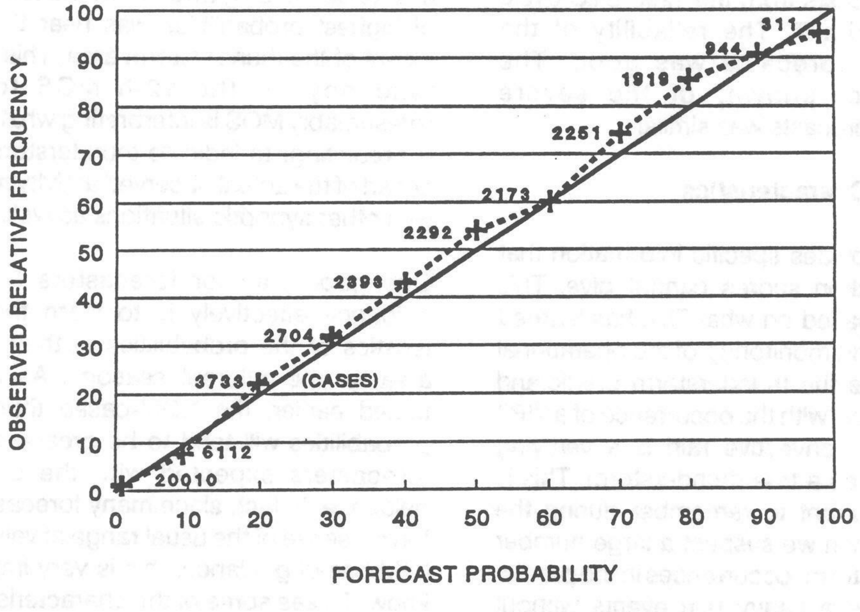

Figure 7. Reliability of 6-12 h thunderstorm forecasts made from 1200 UTC NGM output for March 16-June 30, 1991. Probability and relative frequency are in percent. The numbers plotted at each point are the number of forecasts of each probability rounded to the nearest 10%.

thunderstorms, the higher the MOS forecast probability that maximized the CSI. This probability is called the threshold probability. In our evaluations, CSIs (not shown) were maximized with threshold probabilities of 35-45% for regions with high relative frequencies of thunderstorms. For regions with the lowest relative frequencies (west of the Rocky Mountain Front Range), the maximum CSI scores were achieved with threshold values of 20-25%. From daily monitoring of the forecasts, we found that the forecaster should closely watch areas with probabilities at these thresholds for the spring and summer seasons.

A summary of probability values that have been observed during our monitoring efforts is shown in Fig. 8. The values in the summary are only preliminary because they are based on a limited sample of cases. As experience is gained on the local level, users may want to modify the values and fill in those not yet determined. At probabilities of 75-100% east of the Front Range, thunderstorms were likely to occur. West of the Front Range, high thunderstorm probabilities were closer to 40-60%; probabilities above 75% were not seen. For the cool season, critical probability values appeared to be 10% to 20% lower than for the spring and summer seasons. Note that the range of forecasts extends from 0% to 100%, so that even the low 10-15% probabilities can't be ignored. Reliability was quite good for the lower probabilities.

There was some concern that with the thunderstorm definition being based on MDR data, SAOs, and the SELS logs, all of which have poor or sparse coverage west of the Front Range, the thunderstorm guidance there might not be very useful. What we have seen has convinced us otherwise. There indeed is good information in the guidance in the West. See Section 5.4 for a sample case.

We have been able to monitor the severe thunderstorm guidance only since the equations were completed at the end of February 1992. Therefore, we know much less about its characteristics. For the spring season, the maximum conditional probabilities were around 60% (30%) for p.m. periods in the east (west) and 30% (15%) for a.m. periods. When the thunderstorm probabilities were negligible, severe thunderstorms rarely occurred regardless of how high the conditional severe thunderstorm probabilities were. When the thunderstorm probabilities were low to moderate (the range is regionally and seasonally dependent) and the conditional severe thunderstorm probabilities were relatively high (see Fig. 8), experience with the guidance indicated scattered thunderstorms occurred with a few isolated severe thunderstorms. If both the thunderstorm and severe thunderstorm probabilities were high (see Fig. 8), wide-spread thunderstorms with more numerous severe thunderstorms (severe weather "outbreaks") occurred.

5.4 Example Cases

The following cases illustrate how the threshold probabilities discussed in Section 5.3 might be used in real situations. The first case was from June 25-26, 1991. The 12-h thunderstorm and severe thunderstorm forecasts were produced by test spring equations for the 6-18 hour period after 1200 UTC June 25. The forecast valid time ended 0600 UTC June 26. Fig. 9 shows contoured thunderstorm and severe thunderstorm probability forecasts along with the thunderstorm and severe thunderstorm occurrences.

In Fig. 9a, the thunderstorm probabilities were much greater than those usually seen in the LFM-based MOS guidance, as shown by the large area with 100% or near 100% probabilities. There was a relative maximum of forecast thunderstorm probabilities in the southeastern states with an axis running from northern Alabama to southern Ohio. Nearly all of the stations with forecasts of 80% or higher probabilities had verifying thunderstorms. There was a gap in the thunderstorm events throughout Tennessee, northern Alabama, northern Georgia, and western South Carolina. Note the extension of lower probability contours into this area. In fact, the thunderstorm events tended to occur in a similar pattern as the probability contours. However, the axis of higher probabilities appears to be located east of the occurrences. In the northern high plains and west of the Rocky Mountain Front Range, using 20-25%

FORECAST TYPE		HIGH PROBABILITY	MAXIMUM PROBABILITY
Thunderstorm			
Spring (March 16-June 30)			
East		≥70%	100%
West		≥40%	75%
Summer (July 1-October 15)			
East		≥70%	100%
West		≥40%	65%
Cool (October 16- March 15)			
East		≥55%	100%
West		≥30%	60%
Severe Thunderstorm			
Spring (March 16-June 30)			
East	A.M.	ND	30%
	P.M.	≥20%	60%
West	A.M.	ND	15%
	P.M.	≥15%-20%	30%
Summer (July 1-October 15)			
East	A.M.	ND	30%
	P.M.	≥20%	60%
West	A.M.	ND	15%
	P.M.	≥15%-20%	30%
Cool (October 16-March 15)			
East	A.M.	ND	15%
	P.M.	ND	50%
West	A.M.	ND	10%
	P.M.	ND	30%

Figure 8. Probability values of interest from the NGM-based MOS thunderstorm and severe thunderstorm forecast systems. High probability is the level above which the event is most likely to occur. Maximum probability is the greatest probability observed at TDL prior to September 1992, but is not necessarily the greatest probability that can occur. ND is for values that were not yet determined. The dividing line for West and East is the Rocky Mountain Front Range.

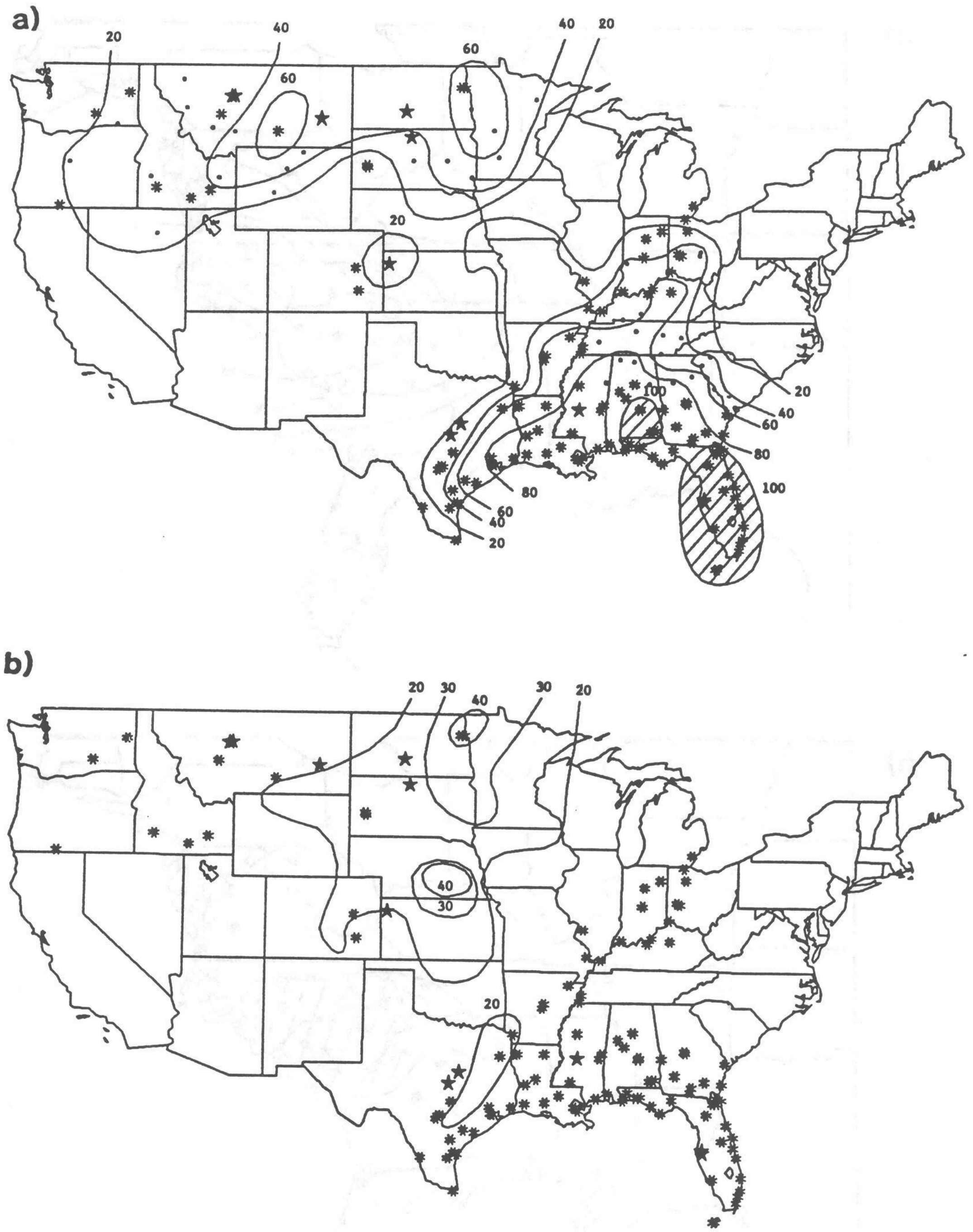

Figure 9. Contour map of (a) forecast thunderstorm and (b) forecast conditional severe thunderstorm probabilities for the June 25-26, 1991 case. Asterisks represent observed thunderstorms, stars represent severe thunderstorms, and dots represent stations that did not report thunderstorms but were within an appropriate threshold thunderstorm probability contour. For stations west of the Rocky Mountain Front Range and in the northern high plains, 20% was used as the threshold; 40% was the threshold used for the rest of the U.S. The lowest contour shown in (b) is 20%. The hatched areas in (a) are where thunderstorm probabilities are equal to 100%.

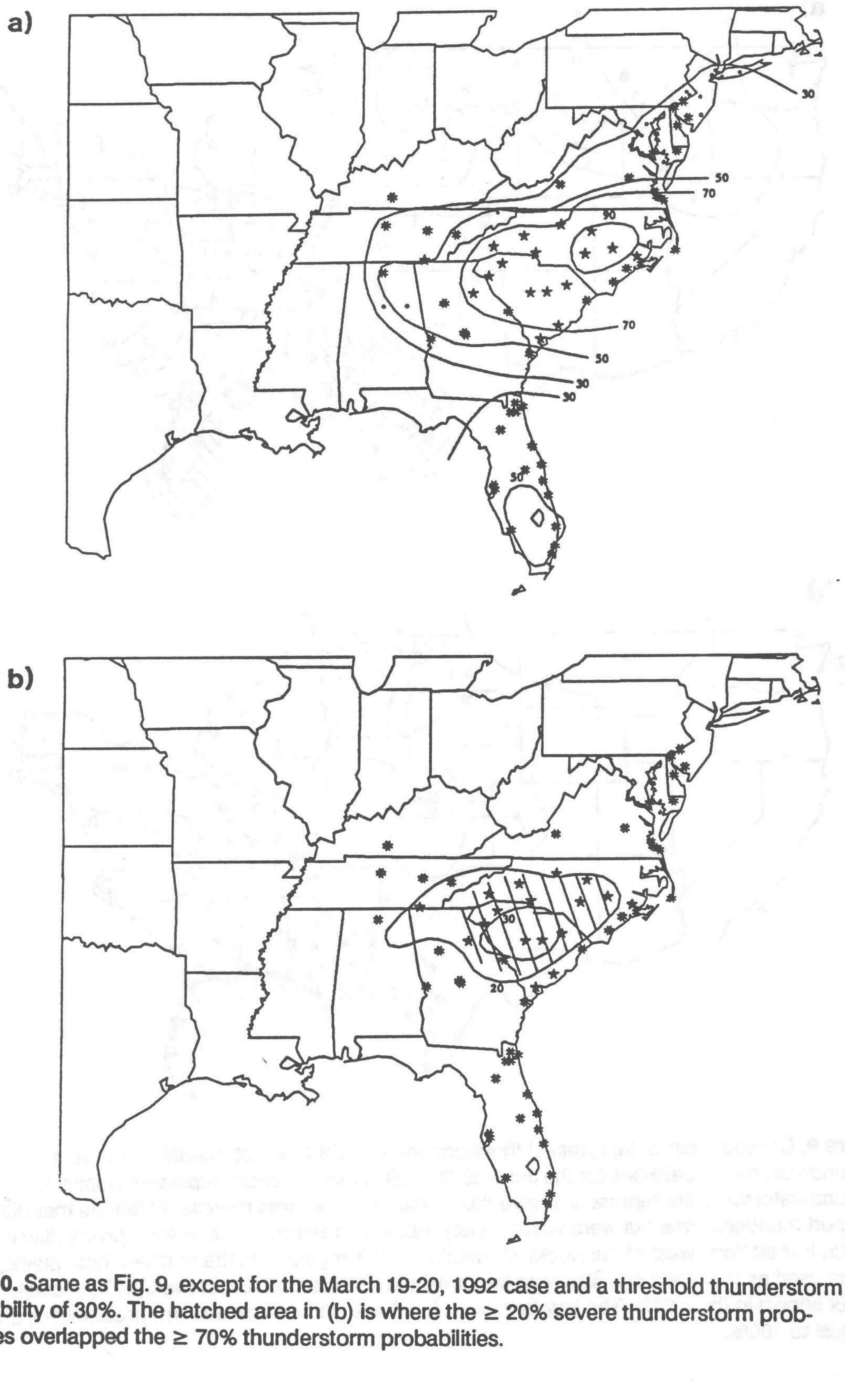

Figure 10. Same as Fig. 9, except for the March 19-20, 1992 case and a threshold thunderstorm probability of 30%. The hatched area in (b) is where the ≥ 20% severe thunderstorm probabilities overlapped the ≥ 70% thunderstorm probabilities.

probabilities for the thunderstorm threshold worked reasonably well in delineating the thunderstorm activity.

Fig. 9b shows the thunderstorm and severe thunderstorm occurrences for the same case plotted with the contours of the conditional severe thunderstorm probabilities. Most of the severe thunderstorm occurrences were scattered across the northern high plains where the higher thunderstorm probabilities (greater than 20% threshold for this area) overlapped with severe thunderstorm probabilities of 20% or more. The highest severe thunderstorm probabilities (40% or greater) were in eastern North Dakota and southern Nebraska. Maximum probabilities for both thunderstorms and conditional probabilities for severe thunderstorms overlapped in eastern North Dakota. While thunderstorms did occur, they were not severe in that immediate area. However, just to the west, there were severe thunderstorms. By contrast, southern Nebraska was an area with fairly low thunderstorm probabilities. No thunderstorms occurred, therefore, no severe thunderstorms were possible. The severe thunderstorms in central Texas occurred in an area where severe thunderstorm probabilities were just under 20%. There was no indication in the forecasts for the scattered severe events in Mississippi, Florida, and Montana.

The second case was from March 19-20, 1992. Here, the thunderstorm/severe thunderstorm forecasts were produced by the operational equations for the 6-18 h period after 1200 UTC March 19. The valid time ended 0600 UTC March 20. Thunderstorm forecasts in Fig. 10a showed relatively confined areas of high probabilities in the Carolinas and Florida. The thunderstorm occurrences were also concentrated in those same areas. Thunderstorms were more scattered in the lower probability areas around Maryland, Virginia, New Jersey, and eastern Tennessee than near the maximum probabilities. The maximum conditional severe thunderstorm forecast of 39% was located in central South Carolina in an area of thunderstorm probabilities around 85% (Fig. 10b). A number of tornadoes occurred in this area. Most of the severe events occurred where thunderstorm probabilities were greater than 70% and severe thunderstorm probabilities were greater than 20% (hatched area in Fig. 10b). In this case, the area with the highest severe thunderstorm probability forecasts coincided with the highest thunderstorm probabilities, as seen in Fig 10b. This pattern of a large area of high thunderstorm probabilities coincident with high conditional severe thunderstorm probabilities has been noticed in connection with several severe weather outbreaks. This is statistically reasonable since multiplying the highest thunderstorm probability by the highest conditional severe thunderstorm probability equals the highest unconditional probability for severe thunderstorms. In areas with lower thunderstorm and severe thunderstorm probabilities, the severe thunderstorm occurrences were more widely scattered. Severe thunderstorm events along the Carolina coasts were associated with severe thunderstorm probabilities of less than 10%. Part of the reason that the coastal stations had much lower probabilities than the inland stations was that the forecasts were produced by a different set of equations. The coastal region, in fact, has a very low climatic frequency of severe thunderstorms and, hence, tends to have low forecast probability values. Just how high the severe thunderstorm probabilities might get in this area in a strongest-case situation is unknown at this time.

6. REFERENCES

Dallavalle, J. P., J. S. Jensenius, Jr., and S. A. Gilbert, 1992: NGM-based MOS guidance - the FOUS14/FWC message. NWS Technical Procedures Bulletin No. 408, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, 16 pp.

Glahn, H. R., and D. A. Lowry, 1972: The use of Model Output Statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11**, 1203-1211.

Hoke, J. E., N. A. Phillips, G. J. DiMego, J. J. Tuccillo, and J. G. Sela, 1989: The regional analysis and forecast system of the National Meteorological Center. *Wea. Forecasting*, **4**, 323-334.

Miller, D. T., 1993: NGM-based MOS wind guidance for the contiguous United States. NWS Technical Procedures Bulletin No. 399, NOAA, U.S. Department of Commerce, 19 pp.

Murphy, A. H., 1991: Notes and correspondence: Reply. *Wea. Forecasting*, 6, 575.

Reap, R. M., 1977: Thunderstorms and severe weather probabilities based on Model Output Statistics--No. 5. NWS Technical Procedures Bulletin No. 199, NOAA, U.S. Department of Commerce, 5 pp.

____, 1983: FOUS12 MOS thunderstorm probability forecasts. NWS Technical Procedures Bulletin No. 331, NOAA, U.S. Department of Commerce, 5 pp.

____, 1986: New 6-h thunderstorm probability forecasts for the West. NWS Technical Procedures Bulletin No. 362, NOAA, U.S. Department of Commerce, 6 pp.

____, 1990: Six-hour thunderstorm probability forecasts for Kansas-Oklahoma and the northeast United States. NWS Technical Procedures Bulletin No. 385, NOAA, U.S. Department of Commerce, 6 pp.

____, and D. S. Foster, 1979: Automated 12-36 hour probability forecasts of thunderstorms and severe local storms. *J. Appl. Meteor.*, 18, 1304-1315.

____, and R. E. Orville, 1990: The relationship between network lightning locations and surface hourly observations of thunderstorms. *Mon. Wea. Rev.*, 118, 94-108.

Schultz, P., 1991: Comments on "Probabilities, odds, and forecasts of rare events." *Wea. Forecasting*, 6, 573-574.