NOAA Technical Memorandum NWS TDL-62

AUTOMATED PREDICTION OF THUNDERSTORMS AND SEVERE LOCAL STORMS

Techniques Development Laboratory
Silver Spring, Md.
April 1977

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AUTOMATED PREDICTION OF THUNDERSTORMS AND SEVERE LOCAL STORMS

Ronald M. Reap and Donald S. Foster

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CONTENTS

AUTOMATED PREDICTION OF THUNDERSTORMS AND SEVERE LOCAL STORMS

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ABSTRACT. Operational probability equations were developed for predicting general thunderstorm activity and more localized severe weather such as tornadoes, large hail, and damaging winds for periods up to 36 hours in advance. The statistical equations were derived by applying multiple screening regression techniques to predictors forecast by operational numerical models and to predictands tabulated from manually-digitized radar data and severe local storm reports.

Generalized forecast equations were developed to give thunderstorm probabilities for the April to September convective season. Key predictors in the thunderstorm equations were the stability and vertical motion fields below 700 mb and the boundary-layer wind field. The equations for severe local storms, developed for both spring and summer, predict the conditional probability of tornadoes, large hail, or damaging winds, given the occurrence of a thunderstorm. Predictors selected in the spring (April-June) equation strongly reflected the importance of low-level atmospheric circulation and dynamics to severe storm formation. The probability forecasts are routinely transmitted on facsimile and teletypewriter for use as guidance by operational forecasters.

1. INTRODUCTION

We have developed operational probability equations for predicting general thunderstorm activity and more localized severe weather such as tornadoes, large hail, and damaging winds. The statistical equations were derived by applying multiple screening regression techniques to model predictors archived on tape and to predictands tabulated from manually-digitized radar (MDR) data and severe storm reports. The approach used, called "Model Output Statistics" by Glahn and Lowry (1972), differs from older statistical techniques in that predictors in the developmental sample are forecast quantities from operational numerical models. Its advantage is that it uses the skill of dynamical models, taking into account biases in the models. Its disadvantage is that new equations must be developed for each new model or major model change.

Generalized operator equations were developed to forecast thunderstorm probabilities for the entire April to September convective season. However, for severe local storms, we found it desirable to develop separate generalized operator equations for the spring (April-June) and summer (July-September) seasons. In addition, the severe local storms forecasts are in the form of conditional probabilities contingent on the occurrence of thunderstorms. The predictand data used in the screening regression analysis was tabulated for the intervals ± 3 hours and ± 12 hours centered on 0000 GMT. As a consequence, the operational probability forecasts of thunderstorms and severe local storms are valid over two similar periods, a 6-hr and a 24-hr period centered on 0000 GMT, that is, for the intervals 21-27 hours and 12-36 hours after 0000 GMT initial time. All but one of the predictors in the operational probability equations were 24-hr model forecasts based on 0000 GMT initial data.

The chief purpose of these automated forecasts is to provide specific guidance to forecasters at the National Severe Storms Forecast Center (NSSFC), especially in the preparation of medium-range (12-36 hr) thunderstorm and severe local storm outlooks. They also provide general guidance to operational forecasters at the National Meteorological Center (NMC), field forecast centers, and air terminals. The probability forecasts are currently prepared once daily on the NOAA computer system and are transmitted over NWS facsimile and teletypewriter circuits.

2. PREDICTOR/PREDICTAND SAMPLE

The 1976 thunderstorm and severe local storm probability equations were developed from a two-year (1974-75) predictor/predictand sample. Predictors were generated by NMC's six-level primitive equation (PE) model (Shuman and Hovermale, 1968) and the Techniques Development Laboratory's (TDL) three-dimensional trajectory model (Reap 1972). Table 1 is a partial list of the basic and derived model predictors and climatic predictors screened by the regression procedure. Of the 150 predictors tested, most were 24-hr forecasts based on 0000 GMT initial data with a few 12-, 18-, and 36-hr forecast fields included. With the exception of one 36-hr predictor, all predictors in the operational probability equations were 24-hr model forecasts based on 0000 GMT initial data.

The predictand sample was based on MDR data, collected from hourly teletypewriter reports archived on magnetic tape, and on severe storm reports from NSSFC's archive tapes. The MDR data were tabulated for blocks approximately 65-70 km on a side; the area covered by these blocks is shown in figure 1. Both the echo intensity and coverage within each block were digitized in accordance with a code (table 2) that was originally developed by Moore and Smith (1972) for use in generating objective numerical precipitation guidance. This code also contains additive data indicating the presence of severe convective cells and line echoes. In effect, the MDR sample provides predictand data of a much higher resolution than those used in previous screening regression studies on thunderstorms and severe local storms (Bonner 1971; Reap 1974). Details of the procedures for editing and archiving the MDR data are given by Foster and Reap (1973).

Table 1.--List of basic and derived model predictors and climatic predictors employed in the screening regression procedure.

Predictor (level, if applicable)
Temperature (surface, 850-, 700-, 500-mb)
Potential temperature (boundary-layer)
Dew point (surface, 850-, 700-mb)
Relative humidity (surface, 850-, 700-mb)
Mean relative humidity (surface to 700 mb)
12-hr net vertical displacement (surface, 850-, 700-mb)
24-hr net vertical displacement (surface, 850-, 700-mb)
U horizontal wind component (boundary-layer, 850-, 700-, 500-mb)
V horizontal wind component (boundary-layer, 850-, 700-, 500-mb)
ω vertical wind component (boundary-layer, 650 mb)
Wind direction (boundary-layer, 500 mb)
Wind speed (boundary-layer, 850-, 500-mb)
Height of constant pressure surface (1000-, 850-, 500-mb)
18-24 hr height change (1000 mb)
Surface pressure
Convective instability (surface to 700 mb)
Convective instability x 12-hr 700-mb net vertical displacement
Trajectory convergence (surface, 850 mb)
Total Totals index
K index
Showalter index
Modified Showalter index
Modified Showalter index + 12-hr net vertical displacement (700 mb)
Temperature advection (850 to 700 mb, 850 mb)
Dew-point advection (850 to 700 mb, 700 mb)
Thunderstorm relative frequency distribution
Moisture divergence (boundary-layer)
Vector wind shear (boundary-layer to 500 mb)
Wind divergence (boundary-layer)
Relative vorticity (boundary-layer)
Geostrophic vorticity (1000-, 500-mb)
Thermal vorticity (1000 to 500 mb)
Vorticity advection (500 mb)
Temperature lapse rate (850 to 500 mb)
Thickness (850 to 500 mb)
Terrain-induced vertical velocity
Gradient of 12-hr net vertical displacement (700 mb)
Sweat index
Wet bulb potential temperature lapse rate (surface to 700 mb)
Height of wet bulb zero
Sine latitude
Cosine latitude
Solar altitude

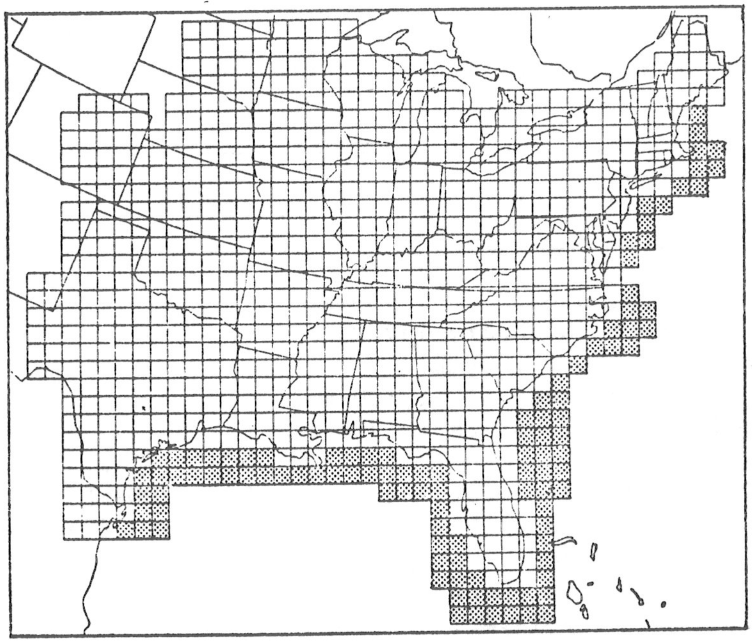

Figure 1.--MDR grid region. Data from shaded overwater blocks were not used in the screening regression procedure.

The MDR predictand sample consisted of data for 335 days from April 1 to September 30, for the years 1974 and 1975. Code values of 4 or greater (Mogil 1974) within the periods ± 3 hours and ± 12 hours from 0000 GMT were used to identify thunderstorm occurrences for both the general thunderstorm equations and the severe local storm equations. As a result, the 6-hr and 24-hr probability forecasts developed from this sample are valid for the periods 21-27 hours and 12-36 hours, respectively, after 0000 GMT initial time for each block in the MDR grid region shown in figure 1.

The predictand data for localized severe weather consisted of reports of tornadoes, surface hail ≥ 1.9 cm in diameter, and wind gusts ≥ 93 km/hr and/or wind damage. These reports were extracted from archive tapes edited at NSSFC to eliminate any identifiable sources of error such as redundant, misplotted, or false reports.

3. THUNDERSTORM PROBABILITY

Generalized forecast equations were developed to give 6-hr and 24-hr thunderstorm probabilities for the April to September period for the entire MDR grid region; no attempt was made to stratify the data by geographical region. The total sample size, or number of comparisons between model forecasts and MDR data, was 249,909 (761 blocks times 335 days with some missing data) for the 6-hr thunderstorm probability equation. Frequency of thunderstorm occurrence, defined by MDR code values of 4 or greater within the interval ± 3 hr of 0000 GMT, was 16.9% for the two spring-summer periods covered by the sample. The predictors selected by the screening procedure

Table 2.--Manually Digitized Radar (MDR) code. VIP1, VIP2, etc. are time-averaged echo reflectivity values obtained from the operational video integrator and processor unit which is standard in the NWS radar network.

Code No.	Coverage in Box	Intensity Category	Rainfall Rate In/Hr
0			
1	Any VIP1	Weak	< .1
2	≤ 1/2 of VIP2	Moderate	.1 - .5
3	> 1/2 of VIP2		
4	≤ 1/2 of VIP3	Strong	.5 - 1
5	> 1/2 of VIP3		
6	≤ 1/2 of VIP3 and 4	Very Strong	1 - 2
7	> 1/2 of VIP3 and 4		
8	≤ 1/2 of VIP3, 4, 5, and 6	Intense or Extreme	> 2
9	> 1/2 of VIP3, 4, 5, and 6	Intense or Extreme	> 2

and their contributions to the 6-hr thunderstorm probabilities are summarized in table 3. Predictors are listed in order of their selection. The six predictors shown in table 3 gave a total reduction of variance of 15.0% (a multiple correlation coefficient of 0.39).

The total sample size for the 24-hr thunderstorm probability equation was 251,674 cases, which represents a slight increase over that found for the 6-hr equation. This difference arises from blocks with data missing for the 6-hr period, but with valid reports elsewhere during the encompassing 24-hr period. Frequency of thunderstorm occurrence was 28.5% for the 24-hr period. Table 4 lists predictors for the 24-hr equation. The eight predictors shown gave a total reduction of variance of 24.5% (a multiple correlation coefficient of 0.49).

As in earlier regression studies (Bonner 1971; Reap 1974), the leading predictor in both the 6-hr and 24-hr thunderstorm equations was found to be a truncated form of George's K index (1960):

$$K = (850 \text{ Temp} - 500 \text{ Temp}) + 850 \text{ Dew Pt} - (700 \text{ Temp} - 700 \text{ Dew Pt}),$$

where $5 \leq K \leq 32$. Within this range, the relationship between the K index and thunderstorm frequency is approximately linear. Other predictors include the terrain pressure forecast by the PE model and the convective (layer) instability, Θ^*, given by the lapse rate of equivalent potential temperature, Θ_E, where,

$$\Theta^* = \Theta_E(700) - \left[\Theta_E(\text{surface}) + \Theta_E(850)\right]/2.$$

Table 3.--Thunderstorm probability equation for period April 1 to September 30. Six-hr probabilities are valid within the interval 21-27 hours after 0000 GMT initial time. All predictors are 24-hr model forecasts.

Predictor	Model	Equation Coefficient	RV (%)
Equation constant	---	-111.8	---
K index ($5 \leq K \leq 32$)	TJ/PE	0.996	12.10
Convective instability (°C)	TJ	-0.524	1.22
Terrain pressure (mb)	PE	0.086	0.70
Boundary-layer wind divergence (10^5/sec)	PE	-4.136	0.37
Boundary-layer wind speed (m/s)	PE	-0.715	0.39
Cosine of the latitude	---	34.81	0.21
Total			14.99

Table 4.--Thunderstorm probability equation for period April 1 to September 30. 24-hr probabilities are valid within the interval 12-36 hours (1200 to 1200 GMT) after 0000 GMT initial time. All predictors are 24-hr model forecasts, except for the 36-hr mean relative humidity field.

Predictor	Model	Equation Coefficient	RV (%)
Equation constant	---	-140.9	---
K index ($5 \leq K \leq 32$)	TJ/PE	1.674	18.91
Modified Showalter index plus 700-mb 12-hr net vertical displacement (°C mb/12 hr)	TJ/PE	0.105	1.79
Terrain pressure (mb)	PE	0.114	1.52
Boundary-layer wind divergence (10^5/sec)	PE	-6.344	0.72
K index	TJ/PE	-0.727	0.42
Surface to 400 mb mean relative humidity (%)	PE	0.220	0.53
Boundary-layer "V" wind component (m/s)	PE	-0.593	0.34
Cosine of the latitude	---	47.10	0.27
Total			24.50

The second predictor in table 4 combines the modified Showalter index and the trajectory model 700-mb 12-hr net vertical displacement in an attempt to delineate regions where unstable layers are superimposed on large-scale lifting. The modified Showalter index is computed by using an averaged value of temperature and dew point at the surface and 850 mb in place of the 850-mb values normally used in computing this index.

4. SEVERE LOCAL STORM CONDITIONAL PROBABILITY

The 6-hr and 24-hr equations for severe local storms predict the conditional probability of tornadoes, large hail, or damaging winds, given the occurrence of a thunderstorm (MDR values of 4 or greater). Initially, severe convective cells, indicated by the MDR additive data, were included as predictand data in deriving the probability equations. However, in a study relating MDR data to severe storm reports, Foster and Reap (1975) found that most radar-observed severe convective cells were not associated with tornadoes, hail, or strong wind gusts at the surface. This was especially true along the Gulf Coast and Florida in the summer. Therefore, we derived the final operational equations by using only severe local storm reports as predictand data. In addition, the probability equations were derived separately for the spring and summer seasons because of the marked decrease in the frequency of severe local storms in summer.

In contrast to the general thunderstorm equations given by tables 3 and 4, most predictors for the severe local storm equations were in categorized or binary form. This was done to better capture the highly nonlinear relationships that often exist between model predictors and severe storm events.

A. Spring Equation (April-June)

Predictors selected by the screening procedure and their contributions* to the spring 6-hr conditional probability forecasts are listed in table 5. Predictors are listed in order of their selection. Sample size, or the number of blocks with MDR values of 4 or greater, was 16,888 cases. Frequency of occurrence of severe local storms was 8.4% in the 1974-75 spring sample. Total reduction of variance with nine predictors was 8.5% with a corresponding multiple correlation coefficient of 0.29.

The total sample size for the 24-hr severe local storm probability equation was 30,897 cases. Frequency of severe storm occurrence was 8.2% for the 24-hr period. Predictors for the 24-hr equation are listed in table 6. The 12 predictors shown gave a total reduction of variance of 6.9% with a multiple correlation coefficient of 0.26.

Interpreting the equations given by tables 5 and 6 in a physical sense, we see that maximum conditional probabilities for tornadoes, large hail, and damaging winds generally exist in regions where:

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* Binary predictors are created by assigning a value of 1 (or 0) to a predictor if its original value is less than (or equal to or greater than) the category limits shown in tables 5-8. In the resulting forecast equations, binary predictors with a value of 1 give the percentage contributions shown in tables 5-8 and 0 otherwise.

Table 5.--Spring conditional probability equation for tornadoes, 1.9 cm or larger hail, or wind gusts greater than 93 km/hr and/or wind damage. Six-hr probabilities are valid for the interval 21-27 hours following 0000 GMT initial time. Limit of forecast probability is 0 to 27.3% at 30°N and 0 to 35.4% at 45°N.

Predictor	Model	Category	Contribution (%)	RV (%)
Equation constant	---	---	-7.51	---
1000-mb height	PE	< 70 m	4.00	4.57
850-500 mb temperature lapse rate	TJ/PE	< 29°C	-5.71	1.27
Boundary-layer to 500 mb wind shear	PE	< 14 m/s	-5.53	0.70
Modified Showalter index	TJ/PE	< 1°C	3.89	0.37
Sine of the latitude	---	(continuous)	39.21 x sin lat	0.59
Surface temperature	TJ	< 23°C	-4.35	0.35
850-mb temp advection	TJ/PE	< 3 x 10^{-5}°C/s	-3.69	0.23
1000-mb height	PE	< 30 m	4.54	0.21
700-mb relative humidity	TJ	< 30%	2.76	0.17
Total				8.46

Table 6.--Spring conditional probability equation for tornadoes, 1.9 cm or larger hail, or wind gusts greater than 93 km/hr and/or wind damage. 24-hr probabilities are valid for the interval 12-36 hours (1200 to 1200 GMT) following 0000 GMT initial time. Limit of forecast probability is 0 to 26.2% at 30°N and 0 to 33.9% at 45°N.

Predictor	Model	Category	Contribution (%)	RV (%)
Equation constant	---	---	-7.75	---
1000-mb height	PE	< 70 m	2.46	3.36
850-500 mb temperature lapse rate	TJ/PE	< 29°C	-3.13	1.03
500-mb wind speed	PE	< 12 m/s	-2.99	0.48
Modified Showalter Index	TJ/PE	< 1°C	3.97	0.52
Sine of the latitude	---	(continuous)	37.27 x sin lat	0.40
1000-mb height	PE	< 30 m	4.84	0.30
Boundary-layer to 500 mb wind shear	PE	< 16 m/s	-3.70	0.26
Height of zero wet bulb temperature	TJ	< 2600 m	-2.95	0.16
Modified Showalter index	TJ/PE	< -2°C	2.28	0.11
700-mb relative humidity	TJ	< 30%	1.75	0.10
Surface temperature	TJ	< 27°C	-1.94	0.08
850-500 mb temperature lapse rate	TJ/PE	< 30°C	-3.20	0.08
Total				6.88

(1) the boundary-layer is warm and moist with low surface pressure and

(2) the lower troposphere is characterized by positive temperature advection, unstable lapse rates of temperature and moisture, significant wind shear, and a strong zonal wind component.

The sine of the latitude represents a climatic contribution. This term gives a greater probability of severe local storms in the northern portion of the MDR grid area for a given set of predictors from the numerical models.

B. Summer Equation (July-September)

Predictors selected for the 6-hr summer probability equation and their contributions to the conditional probability forecast are listed in table 7. Sample size was 25,016 cases. Frequency of occurrence of severe local storms in the 1974-75 summer sample was 2.4% for the 6-hr period, a considerable reduction from that observed in the spring. The ten predictors in table 7 gave a total reduction of variance of 3.6% with a multiple correlation coefficient of 0.19.

Total sample size for the 24-hr summer probability equation was 40,120 cases. Frequency of severe storm occurrence was 2.8% for the 24-hr period. Table 8 lists predictors for the 24-hr forecasts. The twelve predictors shown gave a total reduction of variance of 3.1% with a multiple correlation coefficient of 0.18.

In keeping with the weak large-scale flow patterns in summer, the predictors in tables 7 and 8 place more emphasis on the thermodynamic properties of the atmosphere.

5. OPERATIONAL ASPECTS OF PROBABILITY FORECASTS

Since the beginning of the 1972 severe local storm season, thunderstorm and severe local storm probabilities have been routinely transmitted to NSSFC to guide operational forecasters in preparing their convective outlook charts. The probability forecasts are transmitted once-daily from April through September on National Weather Service (NWS) facsimile circuits FOFAX (Slot F040C), NAFAX (Slot N73), and NAMFAX (Slot A114N). A sample facsimile chart is shown in figure 2. Probabilities from the forecast equations are also available on the Federal Aviation Administration's request/reply system with headings FXUS50-51 for severe local storms and FXUS60-61 for general thunderstorms. These messages are in the form of probability values plotted in the correct geographical location. Figure 3 illustrates a sample FXUS bulletin with appropriate background geography and MDR grid blocks superimposed. The 6-hr thunderstorm probabilities shown for the eastern United States were valid for the interval $\pm$ 3 hr centered at 0000 GMT on June 18, 1975. The two parts of each FXUS bulletin, when held side by side, cover the entire MDR grid region. Note that most of the MDR blocks over water do not contain probability values. These

Table 7.--Summer conditional probability equation for tornadoes, 1.9 cm or larger hail, or wind gusts greater than 93 km/hr and/or wind damage. Six-hr probabilities are valid for the interval 21-27 hours following 0000 GMT initial time. Limit of forecast probability is 0 to 13.3% at 30°N and 17.4% at 45°N.

Predictor	Model	Category	Contribution (%)	RV (%)
Equation constant	---	---	32.47	---
Cosine of the latitude	---	(continuous)	-26.11 x cos lat	1.73
Surface temperature	TJ	<31°C	-4.66	0.71
Total Totals index	TJ/PE	<48	-1.50	0.29
Surface temperature	TJ	<27°C	-1.73	0.23
500-mb wind speed	PE	<12 m/s	-1.38	0.19
1000-mb height	PE	<90 m	1.39	0.14
700-mb temperature	TJ	<4°C	-3.67	0.11
500-mb temperature	PE	<-7°C	1.17	0.09
500-mb wind speed	PE	<16 m/s	-2.23	0.08
1000-mb height	PE	<130m	0.85	0.06
Total				3.63

Table 8.--Summer conditional probability equation for tornadoes, 1.9 cm or larger hail, or wind gusts greater than 93 km/hr and/or wind damage. 24-hr probabilities are valid for the interval 12-36 hours (1200-1200 GMT) following 0000 GMT initial time. Limit of forecast probability is 0 to 12.2% at 30°N and 0 to 16.1% at 45°N.

Predictor	Model	Category	Contribution (%)	RV (%)
Equation constant	---	---	28.74	---
Cosine of the latitude	---	(continuous)	24.01 x cos lat	1.45
Surface temperature	TJ	<27°C	1.92	0.51
500-mb wind speed	PE	<16 m/s	-3.96	0.30
Total Totals index	TJ/PE	<46	-0.82	0.29
Surface temperature	TJ	<31°C	-2.74	0.14
Convective instability	TJ	<-6°C	1.50	0.10
1000-mb height	PE	<90 m	1.22	0.09
500-mb wind speed	PE	<8 m/s	-1.06	0.09
700-mb temperature	TJ	<4°C	-2.14	0.05
500-mb temperature	PE	<-7°C	0.86	0.04
1000-mb height	PE	<130 m	0.72	0.04
Total Totals index	TJ/PE	<44	-0.68	0.03
Total				3.13

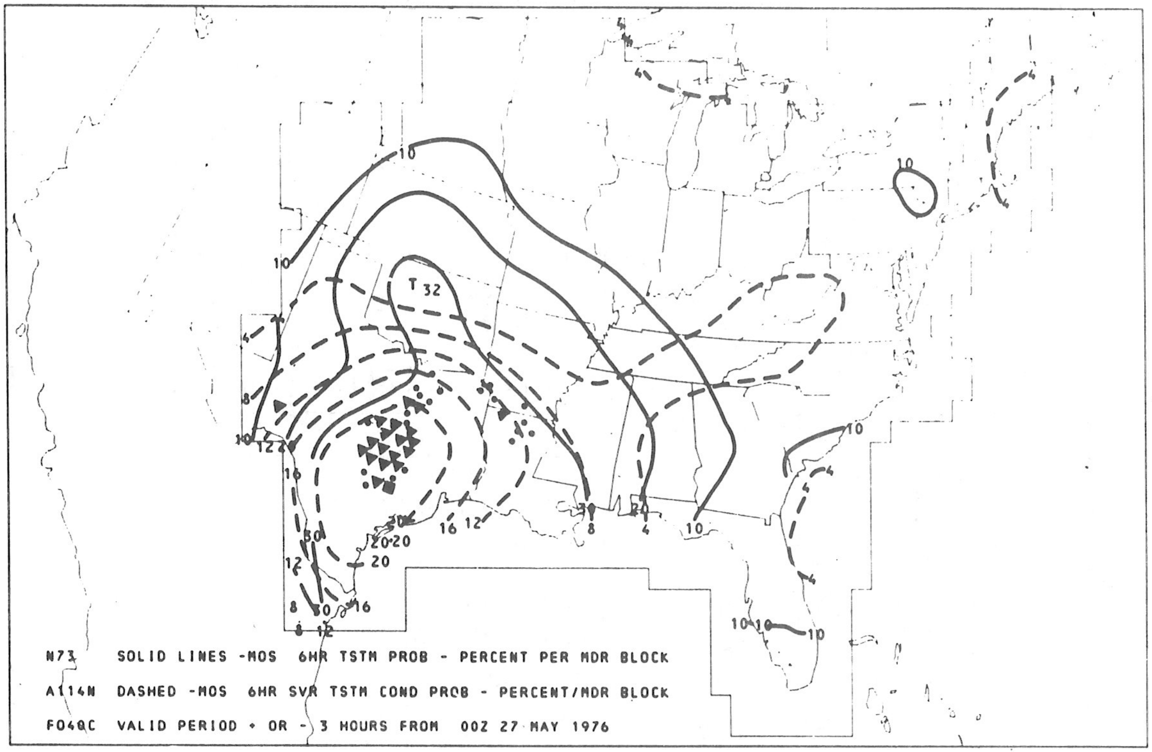

Figure 2.--Computer-drawn map of thunderstorm probability (solid) and conditional probability of tornadoes, large hail, or damaging winds (dashed). The probabilities are valid for each MDR block during the 21-27 hr interval following 0000 GMT initial time, or ± 3 hrs from 0000 GMT the next day. Observed tornadoes = ▼, hail = •, and damaging winds = ■.

were excluded from the developmental sample because thunderstorms occur mainly at night over water rather than late afternoon near 0000 GMT as is the case over land.

Clear plastic overlays, with appropriate background geography and MDR block configuration for the FXUS bulletins, may be used to identify the location of the probability values and are available upon request from TDL.

6. VERIFICATION OF PROBABILITY FORECASTS FOR 1975

To gain some insight into the general performance of the thunderstorm and severe local storm probability forecasts, we have tabulated verification statistics for the 1975 forecast equations. Although the 1975 equations differ somewhat from the 1976 equations given in tables 3 through 8, we believe that the statistical results are fairly representative for both years. Note that only 6-hr probability forecasts were produced in 1975.

There are a number of verification statistics and scores available for measuring the accuracy of the thunderstorm and severe local storm probability forecasts. We chose two scores that we believe provide sufficient information for a comprehensive analysis of the forecasts. One score, F, may be considered a measure of bias or forecast reliability. The other

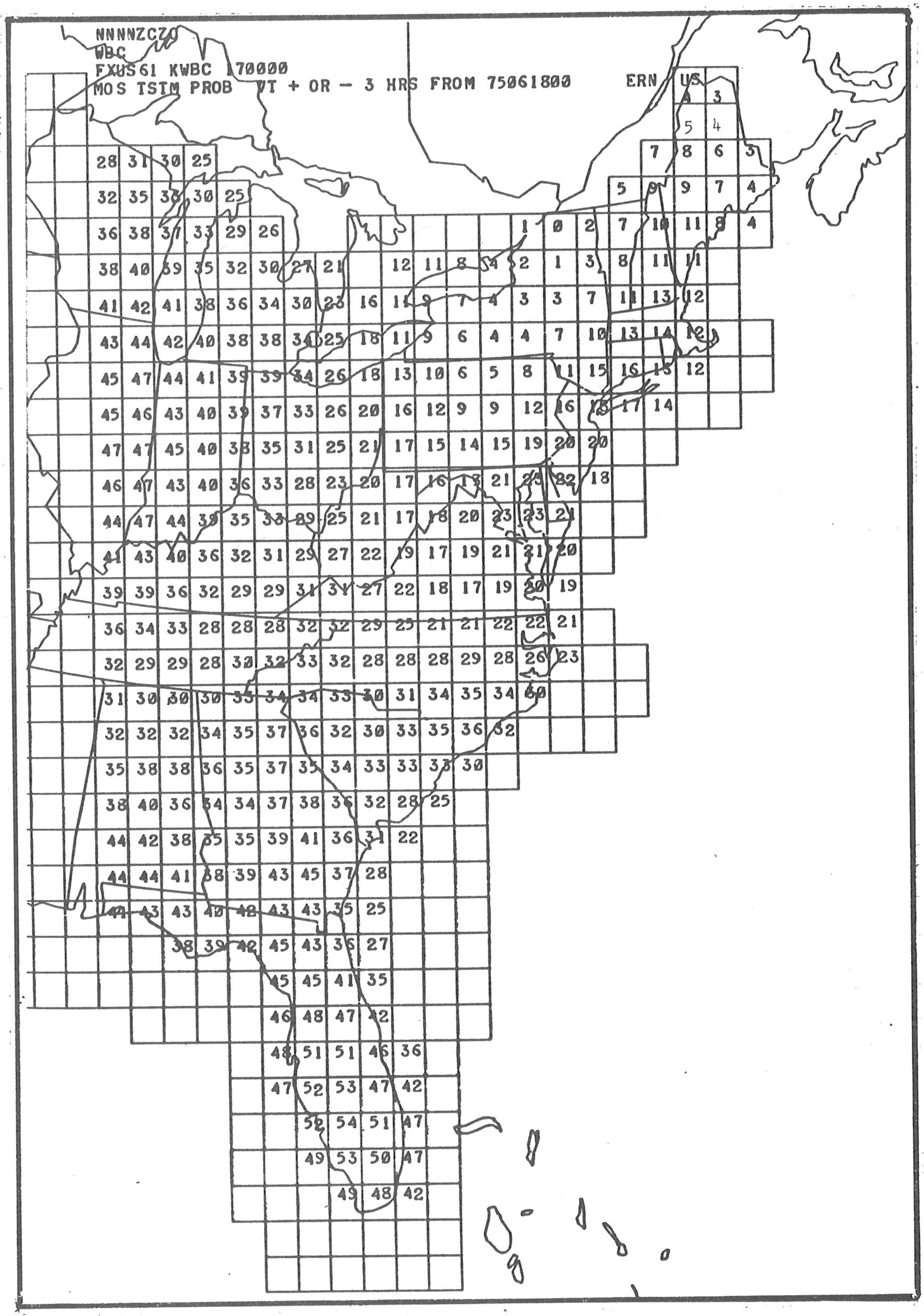

Figure 3.--Sample FXUS61 teletypewriter bulletin with appropriate background geography and MDR grid blocks superimposed.

score, P, is one-half the probability score defined by Panofsky and Brier (1958) and measures the mean squared error of the forecasts. It is a measure of both the reliability and the resolution of the forecasts. Resolution means the extent to which the individual probability forecast approaches the correct values of zero or one.

The F and P scores were computed for individual MDR blocks for each of 10 probability categories, for each MDR block for all categories combined, and for the whole MDR grid for all categories. Limits of the 10 probability categories were as follows: 0.00 to 0.09, 0.10 to 0.19, 0.20 to 0.29, ..., and 0.90 to 0.99. The basic tabulation consisted of the number of thunderstorm cases or forecasts and the number of severe local storm cases for each MDR grid block and for each category. Note that the conditional probability forecasts are verified against thunderstorm cases since they were developed from a similar sample. The F score is defined as:

$$F_i = \frac{(N_i \times R_i) - O_i}{N_i}.$$

For the thunderstorm equation,

N_i = Number of forecasts in category i,
R_i = Average probability for N_i forecasts, and
O_i = Number of thunderstorms in N_i forecasts.

For the severe local storm equation,

N_i = Number of thunderstorm cases in category i,
R_i = Average conditional probability for N_i thunderstorm cases, and
O_i = Number of severe local storm cases in the N_i cases.

For example, if there were 100 thunderstorm cases within the 0.50 to 0.59 conditional probability category with a mean conditional probability of 0.55 and there were 55 severe local storm cases, the F score would be 0% (perfect reliability) for the severe local storm equation. If there were no severe storm cases, the F score would be +55% (overforecast). If the average conditional probability in a category was 0% and there were 55 severe local storm cases, F would be -55% (underforecast). The range of F is from -100% to +100%, with 0% being a perfect score, i.e., no bias.

The P score as used here is defined as

$$P = \frac{1}{N} \sum_{i=1}^{N} (R_i - I_i)^2,$$

where R_i is the absolute or conditional probability for the i^{th} forecast and I_i is the observation. I_i is 1 if a thunderstorm or severe local storm event was observed and 0 otherwise.

A statistical summary for the 6-hr thunderstorm probability forecasts is given in table 9. The results are tabulated for each forecast category for the entire MDR grid area. The verification includes a few test runs made in early June followed by a fairly complete set of operational forecasts from June 12 to September 30, 1975.

Of the 81,234 forecasts made, 19,706 had thunderstorm occurrences. This resulted in an average probability of occurrence of 24%. The average forecast probability was 23% or 18,658 forecasts expected to be accompanied by thunderstorms. The overall F score was -1% (slightly underforecast) and the total P score was 0.15. For the whole grid, the thunderstorm probability forecast equation performed quite well. However, when examining the F score on a regional basis, underforecasting was found over the southern States. P scores were also higher for the same area. Table 9 shows that forecasts in categories between 0.40 and 0.69 would have verified better if they had been one or two categories higher, especially in the southern States.

Verification statistics for the 6-hr severe local storm conditional probability forecasts are given in table 10. F scores of +1 for the month of June and -1 for July through September 1975 indicate good overall forecast reliability. The average forecast probabilities of 0.08 and 0.02 were very close to the actual probabilities of occurrence of 0.06 and 0.03. Even more important was the fact that during June we were able to forecast severe local storm probabilities as high as 30-39% with good reliability, as shown in table 10, even though the climatological probability for the same period was only 6%. A broad glance indicates that the forecast equations performed satisfactorily. However, on a day-to-day and block-by-block basis, large fluctuations were observed in the F and P scores indicating the need for improved resolution in the operational models that generate the predictors. For example, the probability forecast shown in figure 2 for May 27, 1976 was outstanding in delineating the region where most of the severe local storms were later observed. In contrast, figures 4, 5, and 6 illustrate a case where improved resolution in the forecasts of low-level temperature, moisture, and winds would be extremely helpful in isolating the potential convective "hot spots". Figure 4 depicts a large trough at 500 mb dominating the central United States. Associated with this trough is a broad frontal zone extending from southern Texas to a low-pressure area in Canada (figure 5). The forecast probabilities of severe local storms (figure 6) lie along a similarly broad band more or less parallel to the front. Yet the actual severe storm activity, consisting of large hail in southern Texas and one tornado along the Oklahoma-Texas border, was concentrated in a few active pockets along this band. To accurately predict the location and intensity of isolated severe convective activity, we obviously have to predict the small-scale features which are important to severe storm formation, e.g., low-level jet streams, localized zones of intense convergence, moisture gradients associated with dry lines, dry-air intrusions at mid levels, etc. Current operational models cannot provide this degree of resolution because of the coarse forecast grids and fairly heavy smoothing employed. We obviously require high-resolution forecasts of temperature, moisture, and wind such as may be obtained from an advanced boundary-layer model. We anticipate that forecasts from a first-generation operational boundary-layer model, under development at TDL (Shaffer and Long 1975), will become available by late 1977.

Table 9.--Verification summary of 6-hr thunderstorm probability forecasts for period June 1 through September 30, 1975.

Probability Category	Number of Forecasts	*Expected Number of Thunderstorms	Observed Number of Thunderstorms	Average Forecast Probability	Observed Probability of Thunderstorms	F Score	P Score
0.90 - 0.99	0	0	0	0	0		
0.80 - 0.89	0	0	0	0	0		
0.70 - 0.79	0	0	0	0	0		
0.60 - 0.69	294	182	244	0.62	0.83	-21	.18
0.50 - 0.59	2443	1325	1612	0.54	0.66	-12	.24
0.40 - 0.49	5752	2544	3411	0.44	0.59	-15	.26
0.30 - 0.39	12491	4293	5182	0.34	0.41	-7	.24
0.20 - 0.29	23175	5739	6009	0.25	0.26	-1	.19
0.10 - 0.19	24600	3634	2752	0.15	0.11	4	.09
0.0 - 0.09	12479	941	487	0.08	0.04	4	.04
Total	81234	18658	19706	0.23	0.24	-1	.15

*The expected number of thunderstorms is computed by multiplying the average probability for each category by the number of forecasts.

Table 10.--Verification summary of 6-hr severe local storm probability forecasts for Spring and Summer of 1975.

Probability Category	Number of Thunderstorm cases	*Expected Number of Severe Cases	Observed Number of Severe Cases	Average Forecast Probability	Observed Probability of Occurrence	F Score	P Score
			Spring (June 1 - June 30)				
0.90 - 0.99	0	0	0	0	0		
0.80 - 0.89	0	0	0	0	0		
0.70 - 0.79	0	0	0	0	0		
0.60 - 0.69	0	0	0	0	0		
0.50 - 0.59	0	0	0	0	0		
0.40 - 0.49	0	0	0	0	0		
0.30 - 0.39	41	14	13	0.34	0.32	2	.22
0.20 - 0.29	238	57	59	0.24	0.25	-1	.18
0.10 - 0.19	512	75	43	0.15	0.08	6	.08
0.0 - 0.09	1931	67	59	0.03	0.03	0	.03
Total	2772	214	174	0.08	0.06	1	.06
			Summer (July 1 - September 30)				
0.90 - 0.99	0	0	0	0	0		
0.80 - 0.89	0	0	0	0	0		
0.70 - 0.79	0	0	0	0	0		
0.60 - 0.69	0	0	0	0	0		
0.50 - 0.59	0	0	0	0	0		
0.40 - 0.49	0	0	0	0	0		
0.30 - 0.39	0	0	0	0	0		
0.20 - 0.29	1	0	1	0.20	1.00	-80	.64
0.10 - 0.19	262	33	25	0.13	.10	3	.09
0.0 - 0.09	11425	205	280	0.02	.02	-1	.02
Total	11688	238	306	0.02	0.03	-1	.02

*The expected number of severe local storm cases is computed by multiplying the average probability for each category by the number of thunderstorm cases.

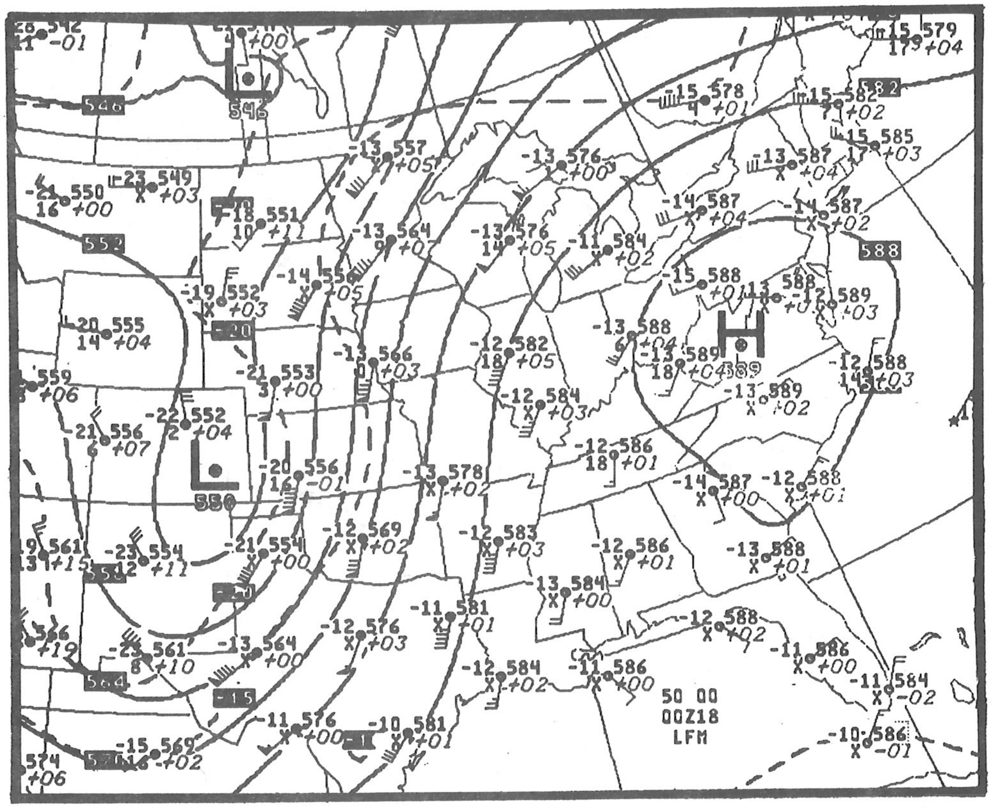

Figure 4.--500 mb analysis for 0000 GMT on April 18, 1976.

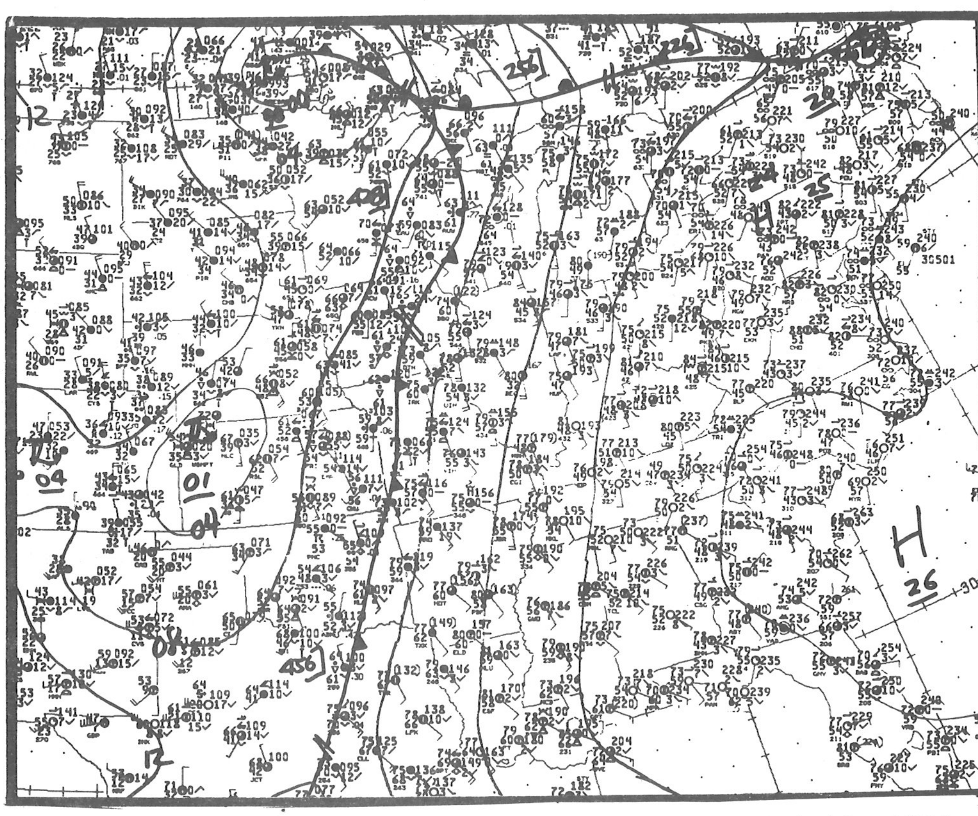

Figure 5.--Surface analysis for 0000 GMT on April 18, 1976.

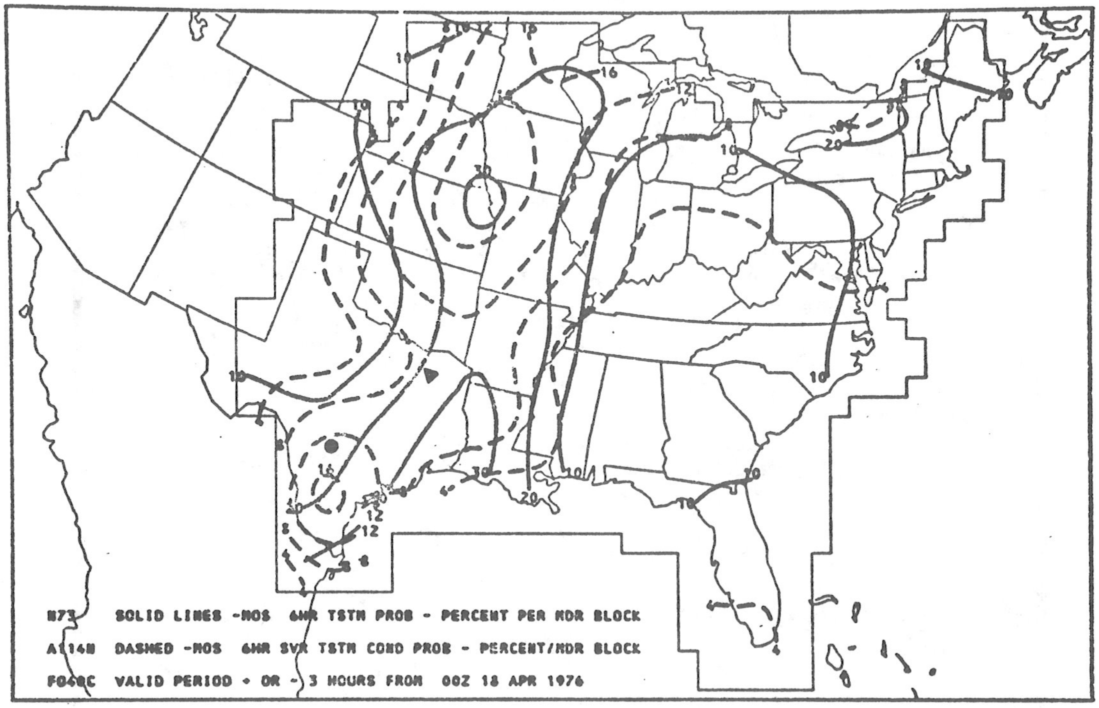

Figure 6.--Same as Figure 2 except for April 18, 1976.

7. SUMMARY AND FUTURE PLANS

Key predictors in the general thunderstorm equation were found to be the stability and vertical motion fields below 700 mb and the boundary-layer wind field. As expected, the spring equation for tornadoes, hail, and wind damage indicates the importance of predictors that reflect large-scale atmospheric circulation and dynamics, e.g., temperature advection, wind shear, zonal wind component, etc. In the summer, when the circulation is weak, the thermodynamic conditions become predominant factors.

The thunderstorm probability forecasts, when verified for the entire MDR grid for the entire June to September convective season, were generally quite good. When studied on a regional basis, the probabilities were somewhat low over the States bordering the Gulf of Mexico where thunderstorm frequencies are high resulting from sub-synoptic scale processes.

We were also satisfied with the overall verification statistics for the severe local storm conditional probability forecasts. However, on a day-to-day and a block-by-block basis, fluctuations from the overall scores indicate considerable room for improvement in the forecast equations, reflecting the need for improved resolution in the operational numerical models that generate the predictors.

In the 1977 probability equations, we plan to introduce an interactive thunderstorm predictor in which the effect of climatology is modulated by the synoptic situation. The role of this predictor will be to simulate the seasonal and regional variations in thunderstorm occurrence. Such variations are often related to sub-synoptic scale processes which are not adequately resolved by large-scale model predictors. Examples of such processes are land-sea breeze and terrain effects which are very often important to thunderstorm formation. The interactive predictor will be formed by combining the large-scale K stability index with thunderstorm relative frequencies obtained from MDR data. Initial probability estimates will then be obtained for individual MDR grid blocks by screening regression techniques. These probability estimates will then be included in the final regression run to develop a generalized equation for the entire MDR grid.

We also plan to develop separate probability equations for tornadoes and large hail. The geographical distribution of these severe weather events differs enough to warrant such an investigation.

In addition, we plan to incorporate predictors from NMC's Limited-Area Fine Mesh (LFM) model (Howcroft 1971) in our developmental sample. Eventually, we will use detailed forecasts of low-level temperature, moisture, and wind from a boundary-layer model currently under development at TDL (Shaffer and Long 1975). Obviously, the use of high-resolution model forecasts will require a careful formulation of new derived predictors to adequately capture small-scale features important to severe local storm formation, e.g., low-level jets, convergence zones, moisture gradients (dry lines), dry-air intrusions, etc.

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REFERENCES

Bonner, W. D., R. M. Reap, and J. E. Kemper, 1971: Preliminary results on severe storm prediction by screening regression using forecast predictors. Preprints Seventh Severe Local Storms Conf., American Meteorological Society, Boston, Mass., 36-41.

Foster, D. S., and R. M. Reap, 1973: Archiving of manually-digitized radar data. TDL Office Note 73-6, 5 pp.

______, and ____, 1975: Thunderstorm and severe local storm frequency distributions for 1974 derived from manually-digitized radar data and severe local storm reports. Preprints Ninth Severe Local Storms Conf., American Meteorological Society, Boston, Mass., 58-63.

George, J. J., 1960: Weather forecasting for aeronautics. Academic Press, New York, New York, 673 pp.

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

Howcroft, J. G., 1971: Local forecast model: present status and preliminary verification. NMC Office Note 50, 22 pp.

Mogil, H. M., 1974: Evaluation of severe weather and thunderstorm forecasts using manually-digitized radar data and the SELS severe weather log. Preprints Fifth Conf. on Forecasting and Analysis, American Meteorological Society, Boston, Mass., 270-275.

Moore, P. L., and D. L. Smith, 1972: Updating of numerical precipitation guidance. Journal of Applied Meteorology, 11, 1293-1298.

Panofsky, H. A., and G. W. Brier, 1958: Some applications of statistics to Meteorology. The Pennsylvania State University, University Park, Pennsylvania., 224 pp.

Reap, R. M., 1972: An operational three-dimensional trajectory model. Journal of Applied Meteorology, 11, 1193-1202.

_____, 1974: Thunderstorm and severe weather probabilities based on Model Output Statistics. Preprints Fifth Conf. on Forecasting and Analysis, American Meteorological Society, Boston, Mass., 266-269.

Shaffer, W. A., and P. E. Long, 1975: A predictive boundary-layer model. NOAA Technical Memorandum, NWS TDL-57, 41 pp.

Shuman, F. G., and J. B. Hovermale, 1968: An operational six-layer primitive equation model. Journal of Applied Meteorology, 7, 525-547.

(Continued from inside front cover)

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