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OPERATIONAL SYSTEM FOR PREDICTING THUNDERSTORMS TWO TO SIX HOURS IN ADVANCE

Silver Spring, Md.
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NOAA Technical Memorandum NWS TDL-64

OPERATIONAL SYSTEM FOR PREDICTING THUNDERSTORMS TWO TO SIX HOURS IN ADVANCE

Jerome P. Charba

Techniques Development Laboratory
Silver Spring, Md.
March 1977

UNITED STATES DEPARTMENT OF COMMERCE
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

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OPERATIONAL SYSTEM FOR PREDICTING THUNDERSTORMS TWO TO SIX HOURS IN ADVANCE

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ABSTRACT. We have developed and implemented in the National Weather Service an objective method yielding probabilities of thunderstorms 2-6 hr in advance. The probabilities are for square areas 40-45 nmi on a side which cover most of the United States east of the Rocky Mountains.

The probabilities are produced by multiple linear regression equations. The independent variables or predictors in these equations are derived from routinely-observed surface atmospheric variables, manually digitized radar data, localized climatic frequencies of thunderstorms, and large-scale numerical model output. Predictor quantities computed from these data are appropriately positioned relative to the predictand areas and "linearized" in order to enhance their correlations with the predictand.

Verification of 2-1/2 mo of operational spring season forecasts shows the forecasts to have considerable skill relative to forecasts of the climatic frequency and persistence of thunderstorms. Subjective examination of individual cases shows that the envelopes of high probability values match up well with the general patterns of thunderstorm occurrence.

1. INTRODUCTION

This report discusses a recently implemented operational prediction system that produces objectively derived thunderstorm forecasts. Computer-produced 2-6 hr probabilities of thunderstorms are transmitted to National Weather Service (NWS) stations and other users three times daily; the three forecasts span the period 1700-0300 GMT, the period of the diurnal maximum in thunderstorm frequency. The area covered by these forecasts includes most of the United States east of the Rocky Mountains.

The prediction scheme is based upon a hybrid combination of the classical statistical (Klein 1970) and model output statistics (MOS) (Glahn and Lowry 1972) approaches to objective weather forecasting. It involves use of multiple screening regression and generalized operator methods. In a previous report, Alaka, Charba, and Elvander (1975) discussed a preliminary prediction technique which showed a good deal of promise. In a subsequent redevelopment of the prediction system, we've expanded and improved the developmental procedure. For instance, we've (1) added some new predictors based upon new data sources, (2) increased the size of the developmental data sample, and (3) expanded the geographical domain. This report discusses the redevelopment of the spring season prediction equations, verification of the operational forecasts, and operational aspects of the forecasting program.

2. DEVELOPMENT OF EQUATIONS

Separate 2-6 hr thunderstorm prediction equations were derived for the periods 1700-2100 GMT, 2000-0000 GMT, and 2300-0300 GMT. In the development of these equations, thunderstorm occurrences within these periods for square areas 40-45 nmi on a side were determined from manually digitized radar (MDR) data. The MDR data, operationally available in the NWS, are integers ranging from 1 to 9 which describe the intensity and coverage of radar echoes within square areas 40-45 nmi on a side (see Moore, et al., 1974). A thunderstorm was assumed to have occurred within an MDR square when the MDR value was equal to or greater than 4 in accordance with the results found by Mogil (1974). Thus, the predictand was defined as an occurrence or nonoccurrence (1 or 0 value, respectively) of an MDR value $\geq$ 4 within a box for each of the 4-hr periods given above.

The geographical area covered by these predictand squares is shown in figure 1. The total number of squares within the area involved is 571. The developmental data sample was from the spring seasons (mid-March to mid-June) of 1974 and 1975. Because of the small size of this sample, we employed the generalized operator approach wherein all 571 predictor/predictand data pairs were pooled for the regression analysis.

Potential predictors were developed from four data sources, namely, basic surface variables observed hourly, Limited-Area Fine Mesh (LFM) model (Howcroft and Desmarais 1971) forecasts of basic upper air variables, MDR reports, and the predictand relative frequency of occurrence. The valid times of the various data relative to a predictand period are illustrated in figure 2 for the 2000-0000 GMT predictand. Hereafter, we shall refer to forecasts produced by the data inputs and valid times shown in figure 2 as the 1800 GMT forecasts since probabilities for 2000-0000 GMT are heavily dependent upon MDR data for 1735 GMT and observed surface data for 1800 GMT. Correspondingly, the 1500 GMT forecasts are for 1700-2100 GMT while the 2100 GMT forecasts are for 2300-0300 GMT. Therefore, for each of the three forecast cycles, the valid times of the input data relative to the beginning time of the predictand are these: MDR data approximately 2-1/2 hr earlier, observed surface data 5 and 2 hr earlier, and LFM forecasts 1 hr later*; the time of predictand frequency naturally corresponds to that of the predictand.

All potential predictors were evaluated at grid points located at the centers of the MDR (predictand) squares (see figure 1). Therefore, we first

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*It would have been preferred to have the LFM forecasts valid at the midpoint of the predictand period, but LFM forecasts could not be conveniently interpolated to the preferable time. However, since the LFM produces large-scale forecasts, a 1-hr discrepancy in valid time should have a negligible detrimental effect.

had to interpolate the observed surface and LFM forecast variables to these points. In the case of the observed surface data, this interpolation was performed with the Cressman (1959) objective analysis method complete with data-error checking. The interpolation of the LFM output to this grid involved standard biquadratic interpolation from the LFM grid.

The potential predictor variables derived from the grid point data are listed in table 1 along with the data source(s) from which each variable is based. Many of these variables are known from common use in thunderstorm forecasting, (e.g., see George 1960 and Miller 1972) and no discussion of them is necessary; a few others not previously documented are self-explanatory in the context of the list. However, some of the stability indices listed require elaboration. For instance, the K-index, K, (variable No. 29) is normally defined as :

$$K = T_{850} + T_{d,850} - (T_{700} - T_{d,700}) - T_{500}$$

where T is temperature and T_d is dew-point temperature at the pressure surfaces indicated in the subscripts. The modified K-index, K_{mod}, (No. 30) is defined as:

$$K_{mod} = \overline{T} + \overline{T}_d - (T_{700} - T_{d,700}) - T_{500})$$

where $\overline{T} = \frac{1}{2}(T_{sfc} + T_{850})$ and $\overline{T}_d = \frac{1}{2}(T_{d,sfc} + T_{d,850})$. In the case of the Total Totals index, TT, (No. 31) conventionally defined as:

$$TT = T_{850} + T_{d,850} - 2T_{500},$$

we replaced T_{850} by $\overline{T}$ and $T_{d,850}$ by $\overline{T}_d$ and, thus, defined the modified Total Totals index, TT_{mod} (No. 32). The Showalter index, SI, (No. 33) is conventionally defined as:

$$SI = T_{500} - T^*$$

where T* is the temperature of an air parcel lifted dry adiabatically from 850 mb to saturation, then moist adiabatically to 500 mb. In the definition of the modified Showalter index (No. 34), the parcel is lifted from the surface rather than 850 mb. In the case of each of these stability indices and in other derived predictor quantities where surface variables are involved in the computation, the surface variables are based upon observed surface data. Whenever a variable above the surface is involved, it is based upon an LFM forecast which, incidentally, is valid 3 hr later than the observed data (see figure 2). Note that the modifications to these indices lie in the incorporation of the latest observed surface temperature and dew point; therefore, in a sense we are correcting for errors in the LFM forecasts of these variables nearest the surface. As will be seen later, the modified stability indices are generally selected as predictors ahead of the conventionally defined indices.

Continuing the elaboration of other, perhaps unfamiliar, variables in table 1, the sign associated with variable No. 37 indicates whether the wind veers (positive sign) or backs (negative sign) with height. Variable No. 42, the 3-hr mean sea-level pressure change, is the only variable incorporating surface data observed 3 hr earlier. The MDR variables (No. 43) are defined later. The predictand relative frequency (No. 44) was computed for individual predictand boxes from the dependent sample data. Of course it would have been preferred to have available for use predictand frequencies computed from a long-term sample but such a sample was not available. In the procedure used, monthly frequencies were computed initially, then spatially smoothed, and finally interpolated timewise to the day. This procedure gave spatially-smooth daily-varying frequencies as desired. The main purpose for incorporating the predictand frequency as a predictor is that it could account for variability of thunderstorm occurrence on scales smaller than can be determined from currently available observed or forecast data.

Each of the computed variables in table 1 was judiciously smoothed in a manner designed to remove wavelengths of 4 grid lengths (approximately 170 nmi) and less. A five-point hanning filter (Shuman 1957) was used.

For various causes, some well understood and others not, a predictor variable may correlate best with a weather phenomenon when it is positioned at some point other than where the phenomenon is occurring. For example, squall line thunderstorms are often found to the east of the thermal gradient and convergence zone characteristic of a cold front. The need for optimal positioning of predictors is especially important if the predictors are based upon data observed earlier, viz, the observed surface data.

We devised an objective procedure for determining the best position for each potential predictor. The best position was defined as that point for which the predictor had the highest linear correlation with the predictand from among 30 points surrounding the predictand box. The positions of ten of the more prominent variables are shown in figure 3. These positions, or offsets as we call them, were determined from the 1800 GMT data sample. These same offsets were also applied to predictor variables at 1500 and 2100 GMT.

Because fields of radar echoes are spatially very discontinuous, we decided to define several potential predictors from the MDR data. An individual potential predictor was defined as the MDR code for a particular MDR box in the vicinity of the predictand box. To determine what boxes (predictors) would be most useful, we made a special screening regression run in which 30 candidates were offered. The first seven MDR boxes selected (see figure 4) were chosen as the potential predictors to be screened in combination with the other variables in table 1.

The screening regression technique used to derive the prediction equations relates the predictand to a weighted linear combination of predictor variables. Of course, predictor variables are generally not related to the predictand frequency in a linear sense. In practice, some of the nonlinearity can be accounted for by converting the continuous variables into sets of binary variables and screening the latter in combination with the former (Glahn and Bocchieri 1976). However, this too has drawbacks; for instance, (1) one does not know, a priori, how to choose the binary limits, (2) the total number of potential predictors can become exceedingly large when the new binary variables are created, and (3) some of the information contained in a continuous variable is lost upon conversion into a discrete set of binary variables.

Our attempt to account for the nonlinearity of predictor/predictand relationships in the dependent sample involved transforming the predictor variables in such a way that the new variables are linearly related to the predictand. We went about this by first plotting on rectangular coordinate axes the predictand relative frequencies corresponding to small intervals along the predictor axis. The data used were from the dependent sample. Sample plots which show considerable nonlinearity are shown in figure 5.* A functional curve was then fitted to these points. Actually, we fitted the plotted data points exactly by connecting adjacent points with straight lines as shown in figure 5. Each predictor variable was then transformed or "linearized" by interpolating from these functions the predictand relative frequency (ordinate value) corresponding to each predictor value (abscissa value). The new variable to be screened in place of the original one is made up of the interpolated values. Among the variables in table 1, only the ones derived from observed surface data and LFM output were linearized. MDR variables were not linearized because of the small range and discreteness of the MDR code values. Also, the predictand frequency predictor was approximately linearly related to the predictand frequency by definition.

One possible pitfall in applying this linearizing technique lies in "overfitting" the dependent sample. This is especially dangerous when the dependent sample is small, because predictor/predictand curves based upon such a sample would generally not match up well with curves based upon other samples. Consequently, this could result in poor forecast performance on independent samples. As for the benefits of using linearized predictors (found in our previous work), the main ones are that they extend the range of the estimated probabilities and they can improve the skill on independent data.

In the development of the primary thunderstorm regression equations, all the variables in table 1 were screened together. However, we also derived "backup" equations for which the MDR variables in table 1 were withheld as possible predictors. During the operational usage, the backup equations are needed to produce forecasts at grid points where MDR data are nonexistent or happen to be missing.

Table 2 gives the reduction of variance and predictand relative frequency associated with the derivation of the primary equations for 1500, 1800, and 2100 GMT. Note that the predictand frequencies and the reductions of variance vary in a parallel manner. The reductions of variance for the backup equations (not shown) were generally lower. Strict comparisons of this quantity, however, are not meaningful because the sample sizes associated with the backup

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*Considerable care was taken to insure that the plot covered the entire range of the predictor variable but yet that each plotted point is based upon a sufficient number of cases so that it can be considered as approximately representative of the population.

equations were almost twice those of the primary equations. For instance, for 1800 GMT, the primary equation was based upon 31,536 cases while the backup equation was based upon 52,058 cases. The comparatively small size of the primary equation sample is due to the loss of cases that had missing MDR predictor data.

Typical of all equations derived are those for 1800 GMT. Tables 3a and 3b list the predictors and the cumulative reduction of variance for 1800 GMT primary and backup equations, respectively. The predictor variables are listed in the order in which they were selected during the screening regression and the data from which each predictor was computed is given in parentheses. In table 3a, the subscripts to the MDR variable names correspond to the convention adopted in figure 4. Note that the cumulative reduction of variance increases appreciably out to 16 terms for the primary equation and 15 terms for the backup equation. In fact, all the equations summarized in table 2 contain between 14 and 16 predictors. Of course, the only reliable method of determining the optimal number of predictors is to test candidate equations with different numbers of terms on an independent sample. We performed such a test on an independent sample (discussed in detail in the next section) which did not become available until after the equations in table 2 had become operationally implemented. A plot of the verification score, P, (discussed in detail in the next section) as a function of the number of predictors per equation for the 1800 GMT primary and backup equations is shown in figure 6. For the purpose of the present discussion, it will suffice to state that the lower the P-score the better the match between the probabilities and the observed predictand events. The plot shows that the best scores were obtained with equations that had 14 or 15 predictors. In applications of this regression method to other predictands the maximum number of predictors has generally been around 10 or 12 (e.g., see Bocchieri and Glahn 1972). The greater number of contributing terms found here is likely a reflection of the broad assortment of data sources upon which the predictors are based. That is, the different data sources likely contain independent information about occurrences of thunderstorms, and of course, this is reflected in the derived variables. Therefore, even similar variables, when based upon different data sources, contain independent information and thus add to the reduction of variance of the predictand.

In view of the shortness of the predictand projection it is interesting to compare the relative number of times observed and forecast data is incorporated into the predictors in tables 3a and 3b. For the primary equation, observed surface or MDR data appear in 13 of the 16 predictors; for the backup equation observed (surface) data appears in a lesser number of predictors (nine) but note that observed data, including predictand relative frequency, is contained in each of the first four predictors. As for the forecast variables from the LFM, they appear in five of the primary equation predictors and nine of the backup equation predictors. From this it is clear that, in general, observed data is the dominant data source and, in particular, the MDR predictors tend to preempt the LFM-based predictors in the primary equation.

As for the predictor variables contained in the primary and backup equations, note that the modified K index was selected first in both equations. Comparison of subsequently selected predictors between the two equations shows that the inclusion of two MDR predictors in the primary equation tended to minimize the importance of the surface moisture divergence which was selected second in the backup equation. Note also the high ranking of the modified Total Totals index and the predictand relative frequency in both equations. The high ranking of the predictand frequency is partly due to the fact that this quantity was derived from the dependent predictand sample, an unfortunate, though unavoidable circumstance. The 500-mb wind speed was selected 6th and 5th in the two equations; note that this predictor was negatively correlated with thunderstorm occurrence (see figure 3) as we would have expected. The remaining predictors in the equations generally involve MDR variables, additional stability indices, and quantities based upon equivalent potential temperature.

3. VERIFICATION

The spring season prediction equations discussed here were implemented operationally in mid-April 1976. Normally, most of the grid point probabilities within the forecasting domain (see figure 1) would be based upon the primary equations with the remaining part based upon the backup equations. Unfortunately, however, because of transmission difficulties, the MDR data were not available to the computer program in real time until the following June. Therefore, the backup equations were used exclusively for producing the operational forecasts for most of the spring season.

To properly test the predictive equations on independent data, we later recomputed the operational forecasts from archived data. The archived data were identical to the real-time data except that MDR data were included. The recomputed sample of "operational" forecasts from the spring season of 1976 contained 74 days, from the period 31 March to 14 June. With probability values at all 571 forecast points combined, the total number of cases was 33,012. Sixty-six percent of these probability values were computed from the primary equations and the rest from the backup equations. In this section we shall discuss verification scores from this independent sample. We shall also evaluate the performance of the probabilities from the standpoint of subjective verification of a few selected cases. Since the prediction equations for 1500, 1800, and 2100 GMT were similar, we shall only discuss the verification of the 1800 GMT probabilities for 2000-0000 GMT.

Two quantities were computed as measures of the forecast performance, namely, the bias and skill scores. The bias was defined as the sum of all forecast probabilities divided by the sum of the predictand observations. Unbiased forecasts would therefore have a bias value of one. The skill score applied to the probability forecasts is based upon a quantity which is one-half the score defined by Brier (1950). This quantity, P, which has become commonly used in the NWS for verification of probability forecasts, is defined as:

$$P = \frac{1}{N} \sum_{i=1}^{N} (F_i - O_i)^2$$

where F_i is the forecast probability, O_i is the observed event (1 when the event occurs, 0 otherwise) for case i, and N is the number of forecasts. If

P_F and P_C are the P-scores for the operational probability and climatic frequency forecasts, respectively, then the skill score, SS, of the forecast is:

$$SS = \frac{P_C - P_F}{P_C} \times 100.$$

Thus, SS is the percentage improvement in P of the forecasts over that computed from the climatic frequency of the predictand. A negative score would mean the operational forecasts were inferior to climatology, and a positive score would mean the forecasts were better than climatology. In terms of fit to the observations, the best climatic frequency available for this verification was the predictand relative frequency for individual predictand boxes discussed in the previous section. Since this quantity was also selected as a predictor in all the operational equations, the skill score essentially measures the forecasting skill of other predictors.

The bias and skill score for the operational sample of forecasts discussed above was found to be 1.17 and 21.9%, respectively. This bias value indicates a slight tendency towards overforecasting. The forecast skill score shows the operational forecasts improved substantially upon forecasts of the climatic frequency of thunderstorms. Interestingly, when the dependent sample mean over all predictand boxes was used as the climatic frequency, the skill score of the operational forecasts increased from 21.9% to 23.6%. This result shows that the individual MDR-box frequencies computed from the dependent sample were harder to improve upon by the operational forecasts than the mean frequency of all boxes. In other words, the single box frequencies were a better approximation of the frequencies in the independent sample.

Since these forecasts project only to 6 hr in the future, it should be interesting to examine the forecast skill of persistence of the predictand. A persistence forecast for 2000-0000 GMT was defined identically to the predictand except that it was based upon MDR data for the period 1400-1800 GMT. Recall that the operational prediction equations incorporated only 1800 GMT MDR data. For the independent sample discussed earlier, the persistence forecasts gave a bias of 0.39 and a skill score of -14.6%. This negative skill score means these persistence forecasts were inferior to climatic frequency forecasts. The apparent reason for the poor performance of persistence is the short lifetime of thunderstorms and the diurnal variation in thunderstorm frequency (Wallace 1975). Note the low bias of persistence; this verifies the observed tendency for thunderstorms to develop during the afternoon, i.e., after 1800 GMT.

One goal that should be strived for in probability forecasting is that the probabilities be reliable. That is, when a certain probability value is stated on many occasions, it should agree closely with the relative frequency of occurrence of the event. Sanders (1967) has shown that minimizing the difference between the probability and the observed frequency will lower the P-score. A plot of the reliability for 5% probability intervals is shown in figure 7 for the 1800 GMT operational forecasts. The plot shows the probabilities were within 10% of the observed relative frequencies in all intervals except that for 95-100%.

Another kind of perspective into the performance of the probability forecasts can be gained by subjectively comparing individual cases with actual occurrences of thunderstorms. We did this for three cases picked from 7 days, randomly selected, except for the requirement that thunderstorms must have occurred somewhere in the forecast domain. The main factor that dictated our three choices was that coverage of the verifying MDR data was good in areas of thunderstorm development. Thus these cases (figures 8a, 8b, and 8c) did not necessarily produce the best verifications of the original seven.

Thunderstorms that actually occurred during the valid periods of the probability forecasts were superimposed in figure 8. A thunderstorm (or predictand) occurrence or nonoccurrence was defined in the same way it was in the developmental sample. Therefore, in figure 8, the predictand value is 1 where a T (for thunderstorm) appears and 0 otherwise. Areas delineated by dotted lines had missing MDR data; therefore, verification of the probabilities in these regions is not possible.

In general, figures 8a, 8b, and 8c illustrate that the general pattern of thunderstorm occurrence agrees well with the envelope of higher probabilities. On the other hand, the smaller scale probability maxima and minima do not consistently verify correctly although they appear to be correct at least as often as not. An apparent weakness in the probabilities as revealed in figures 8b and 8c is that, when thunderstorms occurred both in the Midwest and along the Gulf Coast, the probabilities were higher in the latter region. This deficiency, also seen in other cases not shown, is likely a consequence of deriving and subsequently applying a single prediction equation for the entire forecasting area. Predictor coefficients or even predictor variables appropriate for the Gulf Coastal states are not likely to be the same for the upper Midwestern states because prevailing air mass characteristics between these two regions are different. Therefore, a single equation applied to both regions is likely to result in forecast errors in both regions as suggested by these cases. Investigation of the magnitude of this problem and the methods of resolving it are currently in progress.

4. OPERATIONAL ASPECTS

This product is produced and transmitted operationally during the spring and summer seasons three times daily at about 1530, 1830, and 2130 GMT. The probabilities are transmitted to NWS and other users by teletypewriter. A sample teletypewriter bulletin with an overlay superimposed is shown in figure 9.

5. CONCLUSIONS AND RECOMMENDATIONS

The verification statistics for an independent sample have demonstrated that these 2-6 hr operational probability forecasts of thunderstorms improved considerably upon climatic frequency or persistence forecasts. Subjective verification of quasi-randomly selected cases showed the patterns of high probability matched up well with thunderstorm occurrences. From this we conclude the probabilities should be valuable to anyone concerned with short-range prediction of convective precipitation.

Admittedly, this thunderstorm predictand is rather general in that there are many weather elements directly associated with thunderstorms. Some thunderstorm related elements which are hazardous to human activities are low ceiling, poor visibility, lightning, and flash floods. Therefore, these probabilities could be used as guidance for issuance of short range forecasts or "watches" of these weather conditions. Two-to-six hr probabilities for severe thunderstorms accompanied by strong surface wind gusts, large hail, and tornadoes are produced separately (Charba 1977), but these general thunderstorm probabilities could complement that product as well.

Additional work in several areas, some already alluded to, would likely result in improvements to the current forecasts. (1) Better use could be made of the MDR data. Work now in progress shows that the frequency of thunderstorm occurrence (as determined from MDR data) in MDR boxes is highly correlated with the distances of the boxes from radar stations. This distance dependence is due to poor quality of radar data at large distances from the radar. Procedures should be incorporated to properly screen poor quality data from the dependent and independent samples. (2) Techniques should be incorporated to accommodate differences in predictor/predictand relationships from one MDR box to another. For instance, there is little reason to expect that a given predictor will have a similar relationship to the predictand in one section of the forecasting grid as in another. While the current procedure does not accommodate these differences, Charba (1977) has successfully done so in the case of 2-6 hr severe local storm prediction. (3) Another area that should result in a significant improvement lies in developing a better method of positioning predictors relative to the predictand box. In the current procedure, predictors are optimally positioned but only in a climatological sense. It may be profitable to investigate techniques that would position predictors differently for each day according to certain synoptic conditions. (4) The use of new data sources and longer samples which will become available in the future will also contribute towards improved prediction equations.

6. ACKNOWLEDGMENTS

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Table 1.--Potential thunderstorm predictor variables. The data source(s) for each variable is given in the right-hand column.

	Variable	Data Source(s)
1.	Sfc u-component	Sfc obs
2.	Sfc v-component	Sfc obs
3.	BL u-component	LFM
4.	BL v-component	LFM
5.	850-mb u-component	LFM
6.	850-mb v-component	LFM
7.	500-mb u-component	LFM
8.	500-mb v-component	LFM
9.	MSL pressure	Sfc obs
10.	700-mb vertical velocity	LFM
11.	Sfc mixing ratio	Sfc obs
12.	850-mb mixing ratio	LFM
13.	700-mb mixing ratio	LFM
14.	850- to 500-mb mean mixing ratio	LFM
15.	850- to 500-mb mean temp.-dew point spread	LFM
16.	Sfc equiv. pot. temp.	Sfc obs
17.	Sfc equiv. pot. temp. x horizontal gradient of sfc equiv. pot. temp.	Sfc obs
18.	850-mb equiv. pot. temp.	LFM
19.	700-mb equiv. pot. temp.	LFM
20.	850- to 700-mb mean equiv. pot. temp.	LFM
21.	(Sfc minus 700-mb) equiv. pot. temp.	Sfc obs + LFM
22.	(850-mb minus 700-mb) equiv. pot. temp.	LFM
23.	Sfc equiv. pot. temp. advection	Sfc obs
24.	850-mb equiv. pot. temp. advection	LFM
25.	700-mb equiv. pot. temp. adevction	LFM
26.	Sfc moisture divergence	Sfc obs
27.	BL moisture divergence	Sfc obs + LFM
28.	850-mb moisture divergence	LFM
29.	K index	LFM
30.	Modified K index	Sfc obs + LFM
31.	Total Totals index	LFM
32.	Modified Total Totals index	Sfc obs + LFM
33.	Showalter index	LFM
34.	Modified Showalter index	Sfc obs + LFM
35.	500-mb wind speed	LFM
36.	Mag. of 850- to 500-mb wind shear	LFM
37.	Signed mag. of 850- to 500-mb wind shear	LFM
38.	(500-mb minus 850-mb) wind direction.	LFM
39.	BL vorticity	LFM
40.	500-mb vorticity	LFM
41.	500-mb vorticity advection	LFM
42.	Three-hr MSL pressure change	Sfc obs
43.	MDR variables (see Fig. 4)	MDR data
44.	Predictand relative frequency	Predictand data

Table 2.--Reduction of variance and predictand frequency associated with the primary thunderstorm regression equations.

Predictor Time (GMT)	Reduction of Variance (%)	Predictand Frequency (%)
1500	24.0	8.4
1800	28.2	10.1
2100	25.8	8.6

Table 3a.--Predictor variables selected for inclusion in the 1800 GMT primary thunderstorm regression equation. The variables are listed in the order they were selected; the cumulative reduction of variance with each additional term is given in the right hand column. The data from which each variable was computed is shown in parenthesis.

	Variable	Cumulative Reduction of Variance (%)
1.	Modified K index (Sfc obs + LFM)	18.7
2.	MDR_1 (MDR)	20.9
3.	Modified Total Totals index (Sfc obs + LFM)	22.3
4.	MDR_2 (MDR)	23.6
5.	Predictand relative frequency (Predictand data)	24.2
6.	500-mb wind speed (LFM)	24.9
7.	Sfc moisture divergence (Sfc obs)	25.5
8.	850-mb equiv. pot. temp. (LFM)	25.9
9.	Sfc equiv. pot. temp. advection (Sfc obs)	26.3
10.	MDR_5 (MDR)	26.6
11.	MDR_4 (MDR)	26.9
12.	MDR_3 (MDR)	27.2
13.	Modified Showalter index (Sfc obs + LFM)	27.4
14.	Sfc mixing ratio (Sfc obs)	27.7
15.	Sfc equiv. pot. temp. (Sfc obs)	28.0
16.	500-mb v-component (LFM)	28.2

Table 3b.--Same as Table 3a for the 1800 GMT "backup" thunderstorm regression equation.

	Variable	Cumulative Reduction of Variance (%)
1.	Modified K index (Sfc obs + LFM)	18.5
2.	Sfc moisture divergence (Sfc obs)	19.8
3.	Predictand relative frequency (Predictand data)	20.6
4.	Modified Total Totals index--binary (Sfc obs + LFM)	21.3
5.	500-mb wind speed (LFM)	22.0
6.	Sfc equiv. pot. temp. advection (Sfc obs)	22.4
7.	850- to 500-mb mean mixing ratio (LFM)	22.8
8.	500-mb v-component--binary (LFM)	23.1
9.	Showalter index (LFM)	23.4
10.	850-mb mixing ratio (LFM)	23.6
11.	Sfc equiv. pot. temp. x horizontal gradient of equiv. pot. temp. (Sfc obs)	23.8
12.	Modified Total Totals index--binary (Sfc obs + LFM)	24.0
13.	850-mb equiv. pot. temp.	24.1
14.	Sfc mixing ratio--binary (Sfc obs)	24.3
15.	Modified Showalter index (Sfc obs + LFM)	24.5

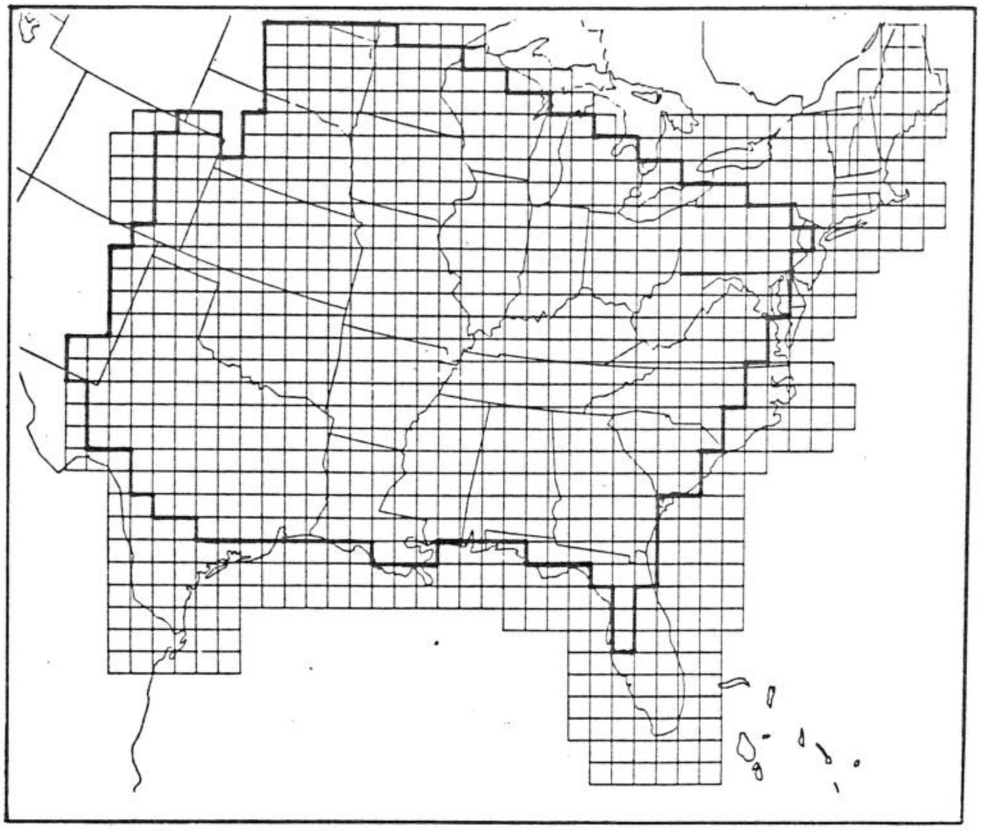

Figure 1.--The general thunderstorm predictands were defined within that region of the United States enclosed by the heavy line. The individual predictand boxes correspond to the MDR squares shown; predictors are evaluated at the centers of these boxes.

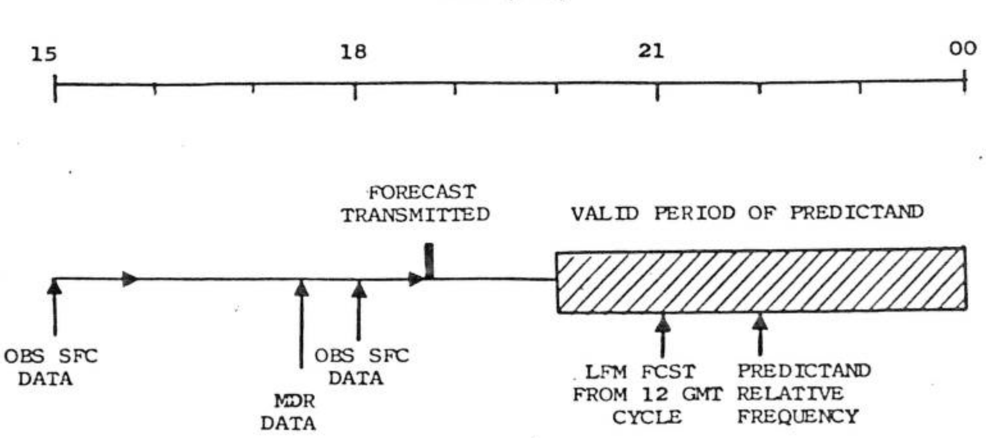

Figure 2.--Types of input data and their valid times relative to the valid period of the predictand for the 1800 GMT forecast cycle.

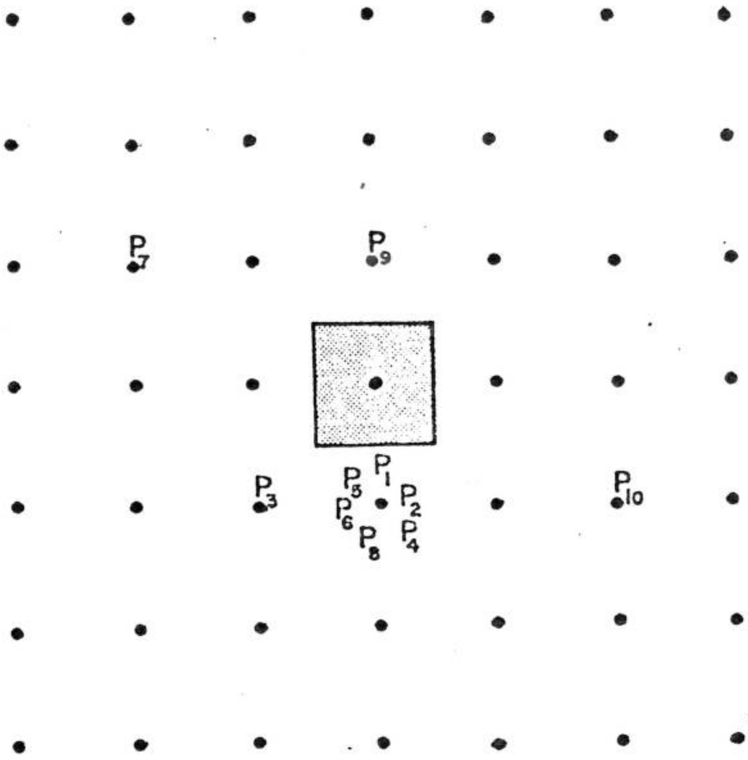

Figure 3.--The P's denote grid point positions of different predictor variables relative to the predictand box. The position of each variable was determined from the field of space-lagged linear correlation coefficients where the correlation is between that variable and the predictand; the highest correlation specified the position or offset of the variable relative to the predictand box (shaded). The subscripts to the P's are in the order of decreasing magnitude of the linear correlation coefficients. Each variable is identified below; the trailing information in parentheses gives the sign of the correlation coefficient and the data from which the variable was computed:

P_1 - Modified K index (+; Sfc obs + LFM)
P_2 - Showalter index (-; LFM)
P_3 - Modified Total Totals index (+; Sfc obs + LFM)
P_4 - 850-mb mixing ratio (+; LFM)
P_5 - 850- to 500-mb mean mixing ratio (+; LFM)
P_6 - Sfc moisture divergence (-; Sfc data)
P_7 - Equiv. pot. temp. x horizontal gradient of equiv. pot. temp (+; Sfc data)
P_8 - Sfc equiv. pot. temp. advection (+; Sfc data)
P_9 - 500-mb v-component (+; LFM)
P_{10}- 500-mb wind speed (-; LFM)

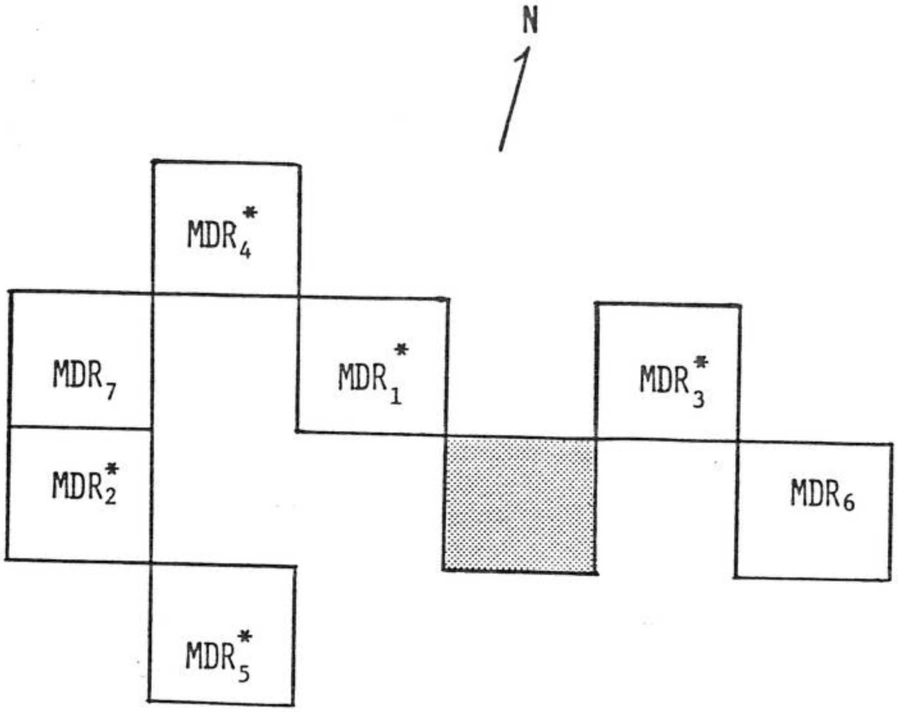

Figure 4.--Potential predictors defined from MDR data. The subscripts denote the order of selection of seven MDR predictor boxes in a special screening regression run wherein 30 MDR boxes surrounding the predictand box were offered. The predictor boxes selected for inclusion into the 1800 GMT equation are indicated by asterisks. The predictand box is indicated by shading.

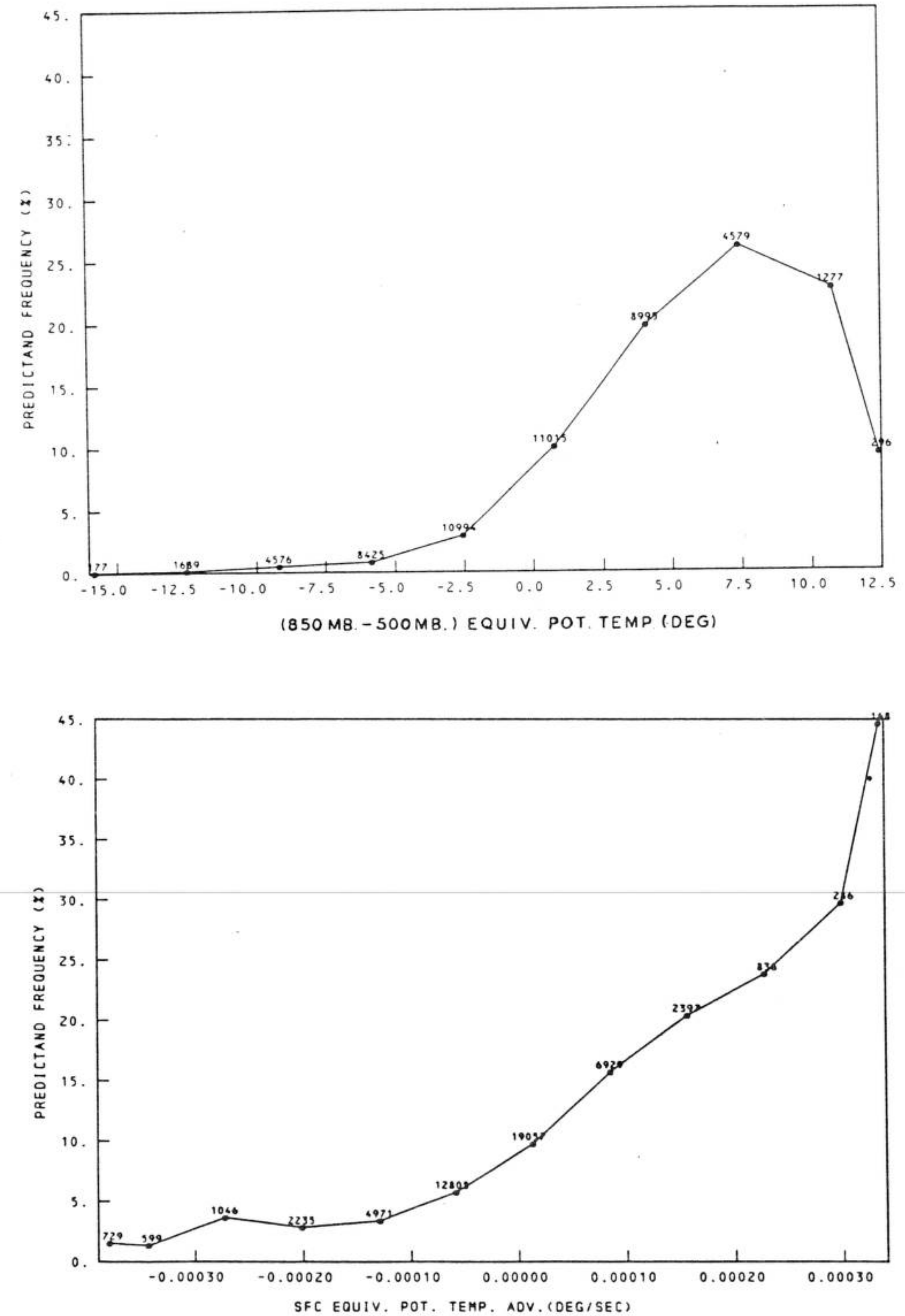

Figure 5.--Plots of predictand relative frequency versus selected potential predictor variables as determined from the dependent data sample. Among the variables in table 1, these exhibited the greatest non-linearity. The number above each plotted point is the number of predictor/predictand data pairs used to define the point.

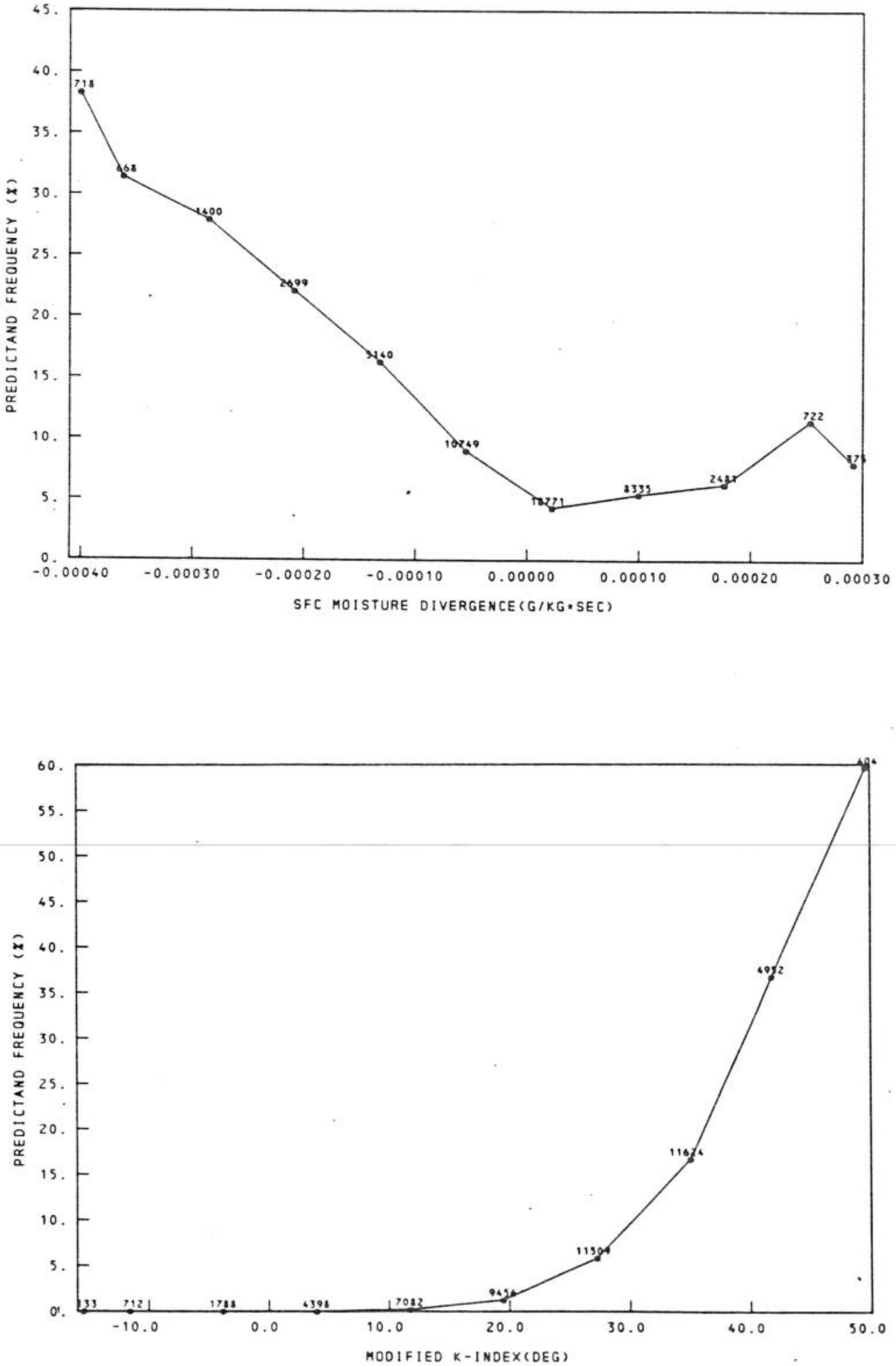

Figure 5.--Continued.

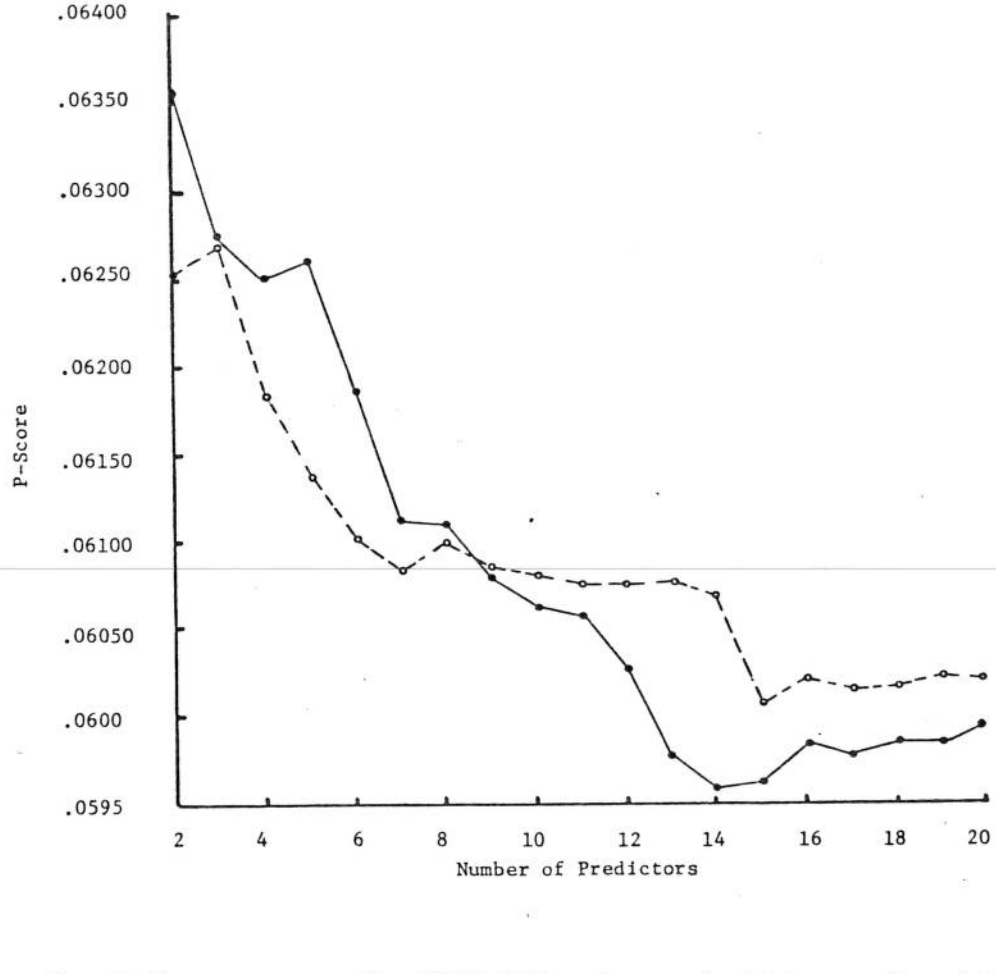

Figure 6.--P-Score versus the 1800 GMT primary (solid curve) and backup (dashed curve) thunderstorm regression equations of varying numbers of predictors. The operational primary and backup equations had 16 and 15 predictors, respectively.

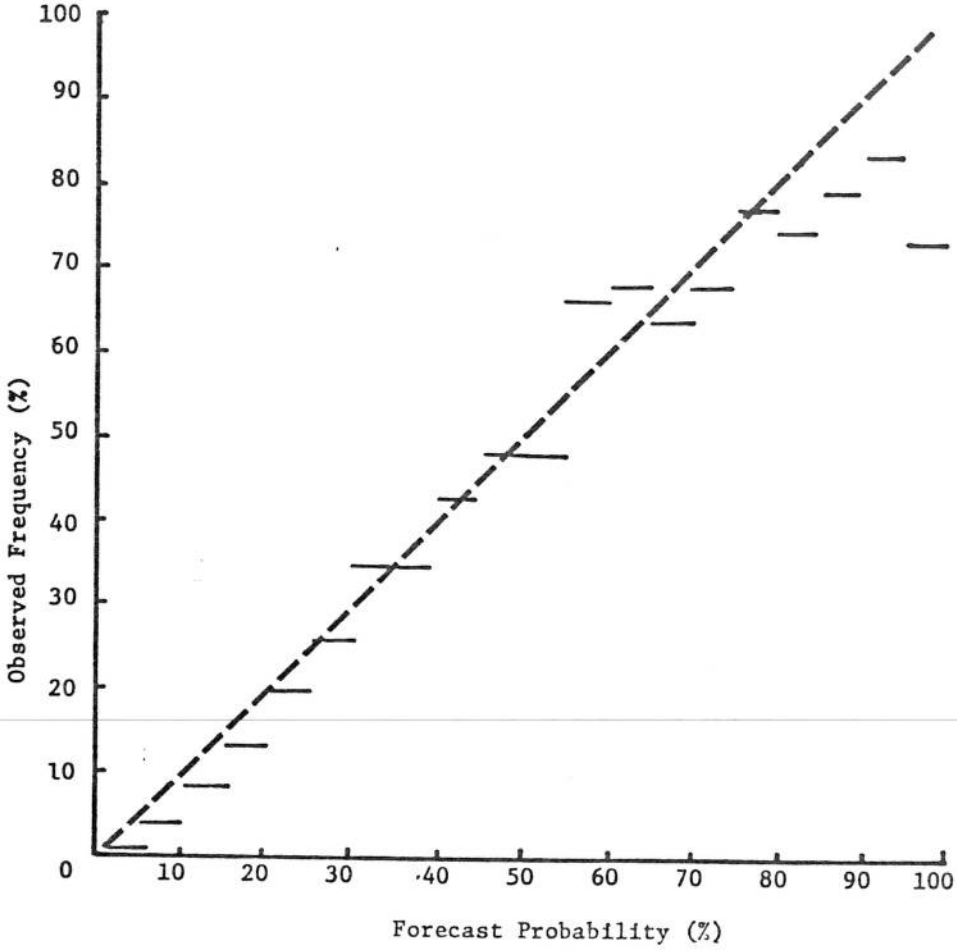

Figure 7.--Reliability of the probability forecasts at 1800 GMT within 5% intervals. Perfect reliability is indicated by the dashed line.

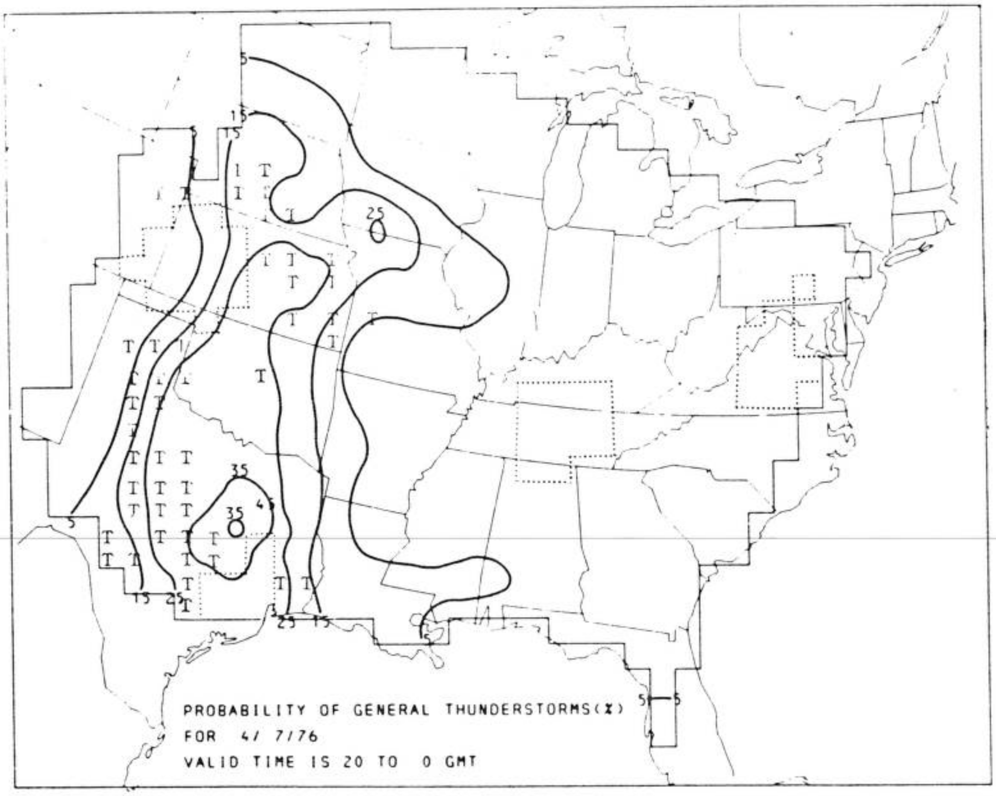

Figure 8a.--Sample operational probability forecast with actual occurrences of thunderstorms superimposed. The probabilities were produced by the 1800 GMT primary and backup equations. Thunderstorm occurrences, as determined from MDR data, for the valid period of the forecast are indicated by T's. Within areas enclosed by dotted lines, MDR data were missing and, therefore, verification of the probabilities is not to be considered.

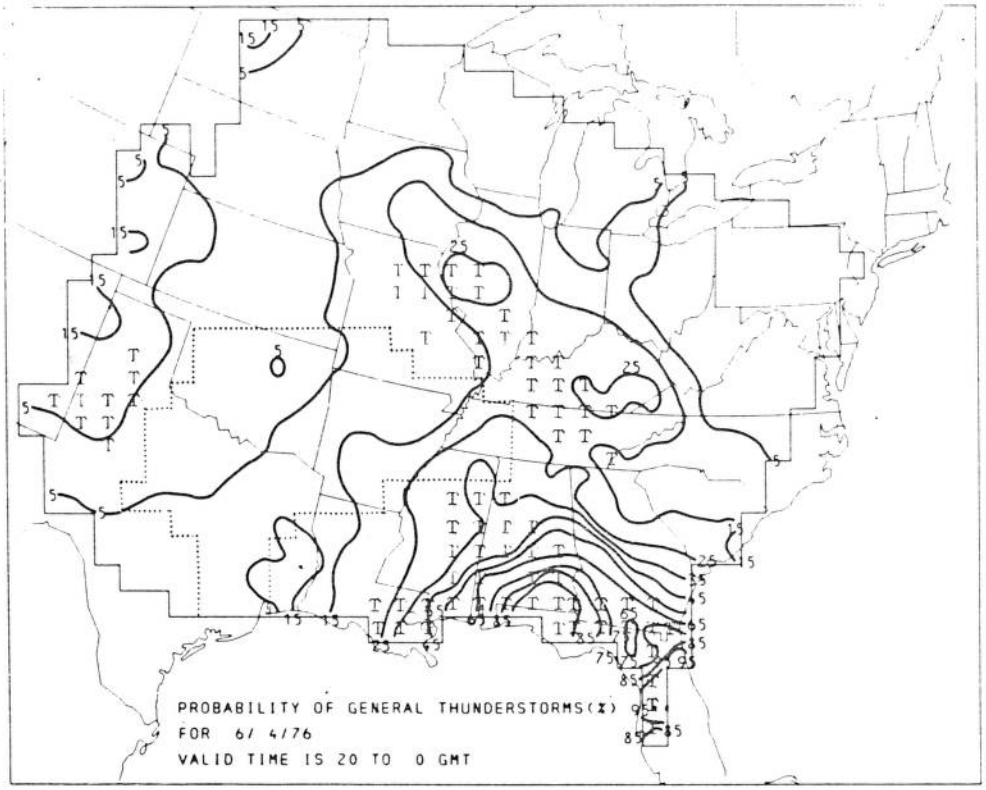

Figure 8b.--Same as 8a.

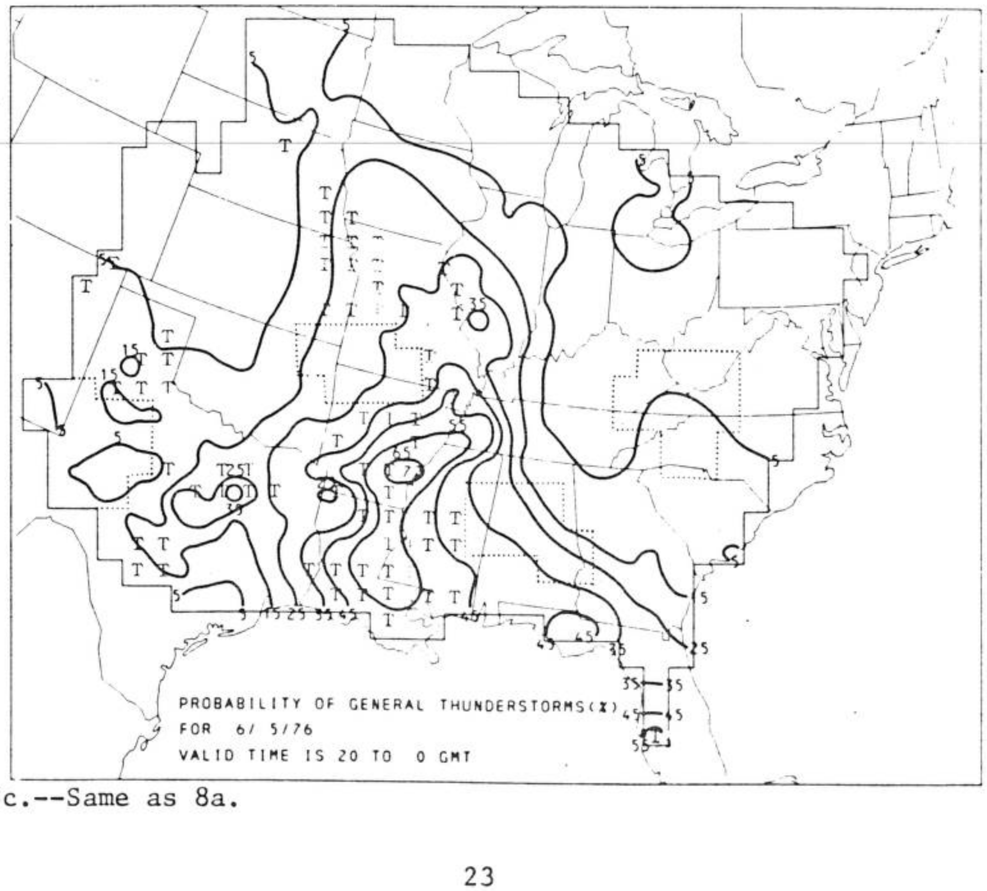

Figure 8c.--Same as 8a.

GEN TSTM PROB FCST VT 07/28/20-00 GMT

26 PCT OF FOLLOWING 571 FCST PTS BASED ON BACKUP EQNS

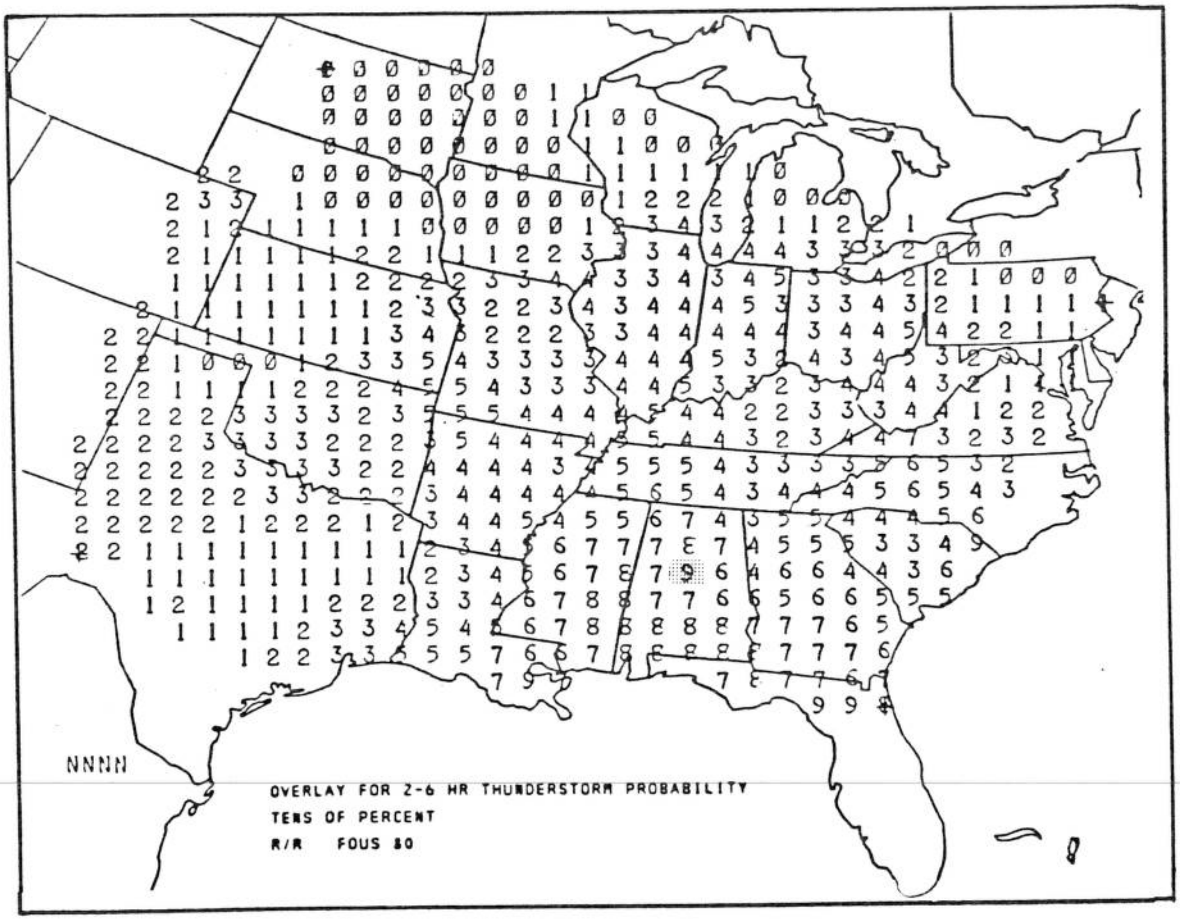

Figure 9.--Sample thunderstorm probability teletypewriter bulletin transmitted under the heading of FOUS80. A plastic overlay containing geographical boundaries has been superimposed. As indicated in the bulletin heading, the forecast is valid for July 28 (of 1976), 2000-0000 GMT. The backup equations are prediction equations not containing MDR predictors. The numbers are probabilities rounded to the nearest 10% with the ones digit left off. For example, the 9-value in Central Alabama represents an 85-94% likelihood of an occurrence of thunderstorms for a square area indicated by the shading.

(Continued from inside front cover)

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