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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

Computer Prediction of Precipitation Probability for 108 Cities in the United States

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Systems
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COMPUTER PREDICTION OF PRECIPITATION PROBABILITY FOR 108 CITIES IN THE UNITED STATES

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COMPUTER PREDICTION OF PRECIPITATION PROBABILITY FOR 108 CITIES IN THE UNITED STATES

William H. Klein

ABSTRACT

The "perfect prog" method of combining numerical and statistical weather prediction is applied to develop an automated system for forecasting the probability of precipitation at 108 cities on the mainland of the United States during daytime and nighttime periods from 12 to 60 hours in advance. Multiple regression equations are derived from a 4-5 year sample of data for each city and each season of the year by screening twice-daily geographical arrays of the following predictors: initial 850-mb height, initial 850-700 mb mean dew-point spread, and previous 12-hour precipitation at the network of surface stations. Each of the three predictor fields contributes about equally toward explaining the variance of the observed precipitation, but considerable geographical variation is exhibited by the equations. The forecast system is applied in an iterative fashion in 12-hour time steps by using as input numerical predictions of height and moisture at standard grid points as well as prior values of precipitation. The resulting computerized forecasts of precipitation probability, when applied on an operational basis in real time, should offer valuable guidance to the local weather forecaster.

INTRODUCTION

The most widely used technique for combining numerical (dynamical) and statistical weather prediction has been called the "perfect prog" method (Veigas, 1966). In this technique observed historical data are used to derive statistical relations between a desired weather element and concurrent values of relevant circulation parameters. These relations are then applied to numerical prognostic charts which simulate the observed circulation in order to yield automated weather forecasts. Although errors in the numerical prognosis inevitably produce corresponding errors in the statistical forecast, the latter improves each time the former improves. Another advantage of this method is that stable forecasting relations can be derived for individual locations and seasons from a long period of record.

Initial attempts to apply the perfect prog method were limited to use of geopotential height in the mid troposphere, the element forecast best by numerical (barotropic) models (Cressman, 1960). This method was successfully employed to derive forecasting relations for both 5-day temperature (Klein et al., 1959) and precipitation (Klein, 1963). As multilevel, baroclinic models increased in accuracy (Cressman, 1963), it became feasible to include 1000-700 mb thickness as an additional predictor for daily maximum and minimum surface temperature (Klein et al., 1967). Later the field of 1000-mb height was added to the 700-mb height field as a statistical predictor of quantitative precipitation (Klein, 1968). The recent development of primitive equation, "moist" numerical models (Shuman and Hovermale, 1968) has made it feasible for the first time to include some measure of humidity as a potential predictor of precipitation. The importance of moisture in preparing statistical forecasts of precipitation was demonstrated by Russo (1968), using observed data, and by Glahn and Lowry (1969), using prognostic data.

The present investigation is an outgrowth of the author's previous work on predicting daily precipitation occurrence by combining statistical and numerical methods (Klein et al., 1965). However, the predictors now include fields of moisture and previous precipitation, in addition to the upper level heights used previously. Furthermore, the 850- and 500-mb levels are considered, as well as the 1000- and 700-mb levels studied earlier. In addition, equations are derived for 12-hour periods at 108 cities during each of three seasons, whereas previously they were derived for 24-hour periods in 40 circular areas during winter only. Finally, this paper is aimed at producing forecasts of probability of precipitation, in contrast to the categorical forecasts of rain or no rain derived previously.

BASIC DATA

The network of 108 Weather Service stations used in this investigation is illustrated in figure 1. These are the same cities used in earlier studies of temperature (Klein et al., 1967) and precipitation (Jorgensen, 1967) and were selected to give a good geographical coverage of large population centers. Synoptic reports at each of these stations were obtained from the NOAA National Climatic Center in Asheville, N. C., and then computer processed for the occurrence of measurable precipitation during standard 12-hour periods; i.e., from 0000Z to 1200Z and from 1200Z to 2400Z. Precipitation was considered measurable and recorded as one if it amounted to .01 inches or more; trace and no precipitation were recorded as zero. This simple precipitation code was used as the predictand in this study. Since it is expressed in binary (0, 1) form, it yields the probability of precipitation (hereafter called PoP) when treated by ordinary linear regression (Lund, 1955).

The following three basic types of predictors were used:

a) a measure of the circulation pattern given by the geopotential height at various levels,

b) a measure of atmospheric moisture expressed by the dew-point spread or depression (temperature minus dew point) at various levels, and

c) a measure of surface weather given by reports of previous precipitation at selected cities.

The third predictor was processed from the same observations and in the same manner described above for the predictand; i.e., in 0,1 form for 12-hour periods at 108 stations. The first two predictors were obtained from Northern Hemisphere maps prepared twice-daily by the Fleet Numerical Weather Facility in Monterey, Calif. (Stevenson and Woodworth, 1968; Woodworth, 1969). These maps are objectively analyzed at synoptic times (00Z and 12Z) on a square grid

Figure 1.--Names and locations of 108 Weather Service stations for which prediction equations were derived.

(with mesh length 381 km. at 60°N) which includes the 1977 grid points used in the National Meteorological Center (NMC).

The nature of the grid point data is illustrated in figure 2. The data consist of height and temperature at five standard levels from 1000 to 300 mb and dew-point spread at three intermediate levels (850, 700, and 500 mb). The period of record begins November 1, 1961, for the first two parameters (except June 1, 1962, for 1000-mb height and temperature) and May 1, 1964, for the third. All data extend through January 31, 1969. Thus only 7-8 years of height data and 4-5 years of moisture are available. For this reason, the data were stratified into four conventional seasons rather than the bimonthly periods used in a previous study (Klein et al., 1967). Winter was defined as the months of December, January, and February; spring as March, April, and May; and fall as September, October, and November. Summer was reserved for later investigation.

PROCEDURE

All results in this study were obtained by applying the stepwise screening regression technique (Miller, 1962) in a modified form on the Control Data Corporation 6600 computer in Suitland, Maryland. In this modified program (developed by Frank Lewis), every possible pair of predictors is examined, and the pair explaining most of the variability of the predictand is selected. The better predictor of this pair is retained in the regression equation, and the other one is temporarily dropped. Every remaining pair is then examined for its effect in conjunction with the first predictor already retained, and the pair explaining more of the remaining variance of the predictand than any other pair is identified. Again only the better single predictor of this pair is retained for inclusion in the multiple regression equation, and all remaining pairs are examined. The entire process is repeated until ten multiple regression equations are printed out for each predictand.

By means of this program, a series of experiments was performed in which the precipitation code at each city was screened as a function of the three basic sets of predictors. The predictors were not limited to those in the immediate locality of the predictand city; i.e., the local approach frequently used in meteorology (e.g., Russo, 1968; Glahn and Lowry, 1969). Instead the correlation field concept (Stidd, 1954) was employed to select potential predictors from a large geographical area surrounding the predictand since previous studies have demonstrated that distant points may have an important effect on local weather (Klein et al., 1959; Klein, 1963).

Two sets of screening runs were made initially; one for the western cities illustrated in figure 3, and the other for the eastern cities illustrated in figure 4. In these diagrams the cities are located by heavy black dots and the NMC grid points by intersections of the perpendicular lines. In the first set of runs, precipitation at 48 western cities was screened as a function of 182 grid point values on and inside the heavy black rectangle; for the second set, 50 eastern cities and 208 grid points were used. Ten cities in the center of the country were not included in these preliminary experiments.

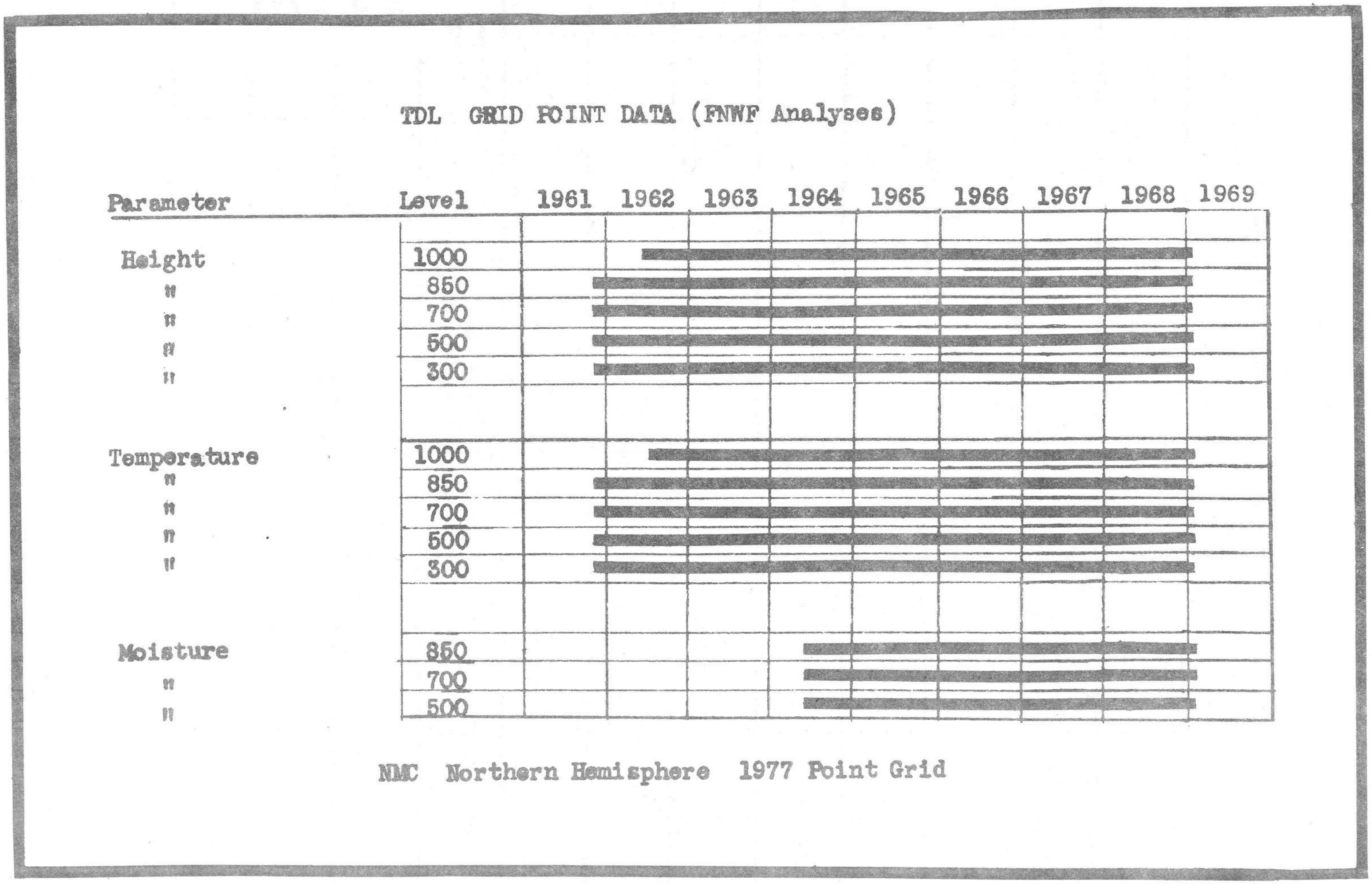


Figure 2.--Schematic diagram showing period of record, by element and level, of predictor data at NMC grid points available in the Techniques Development Laboratory.

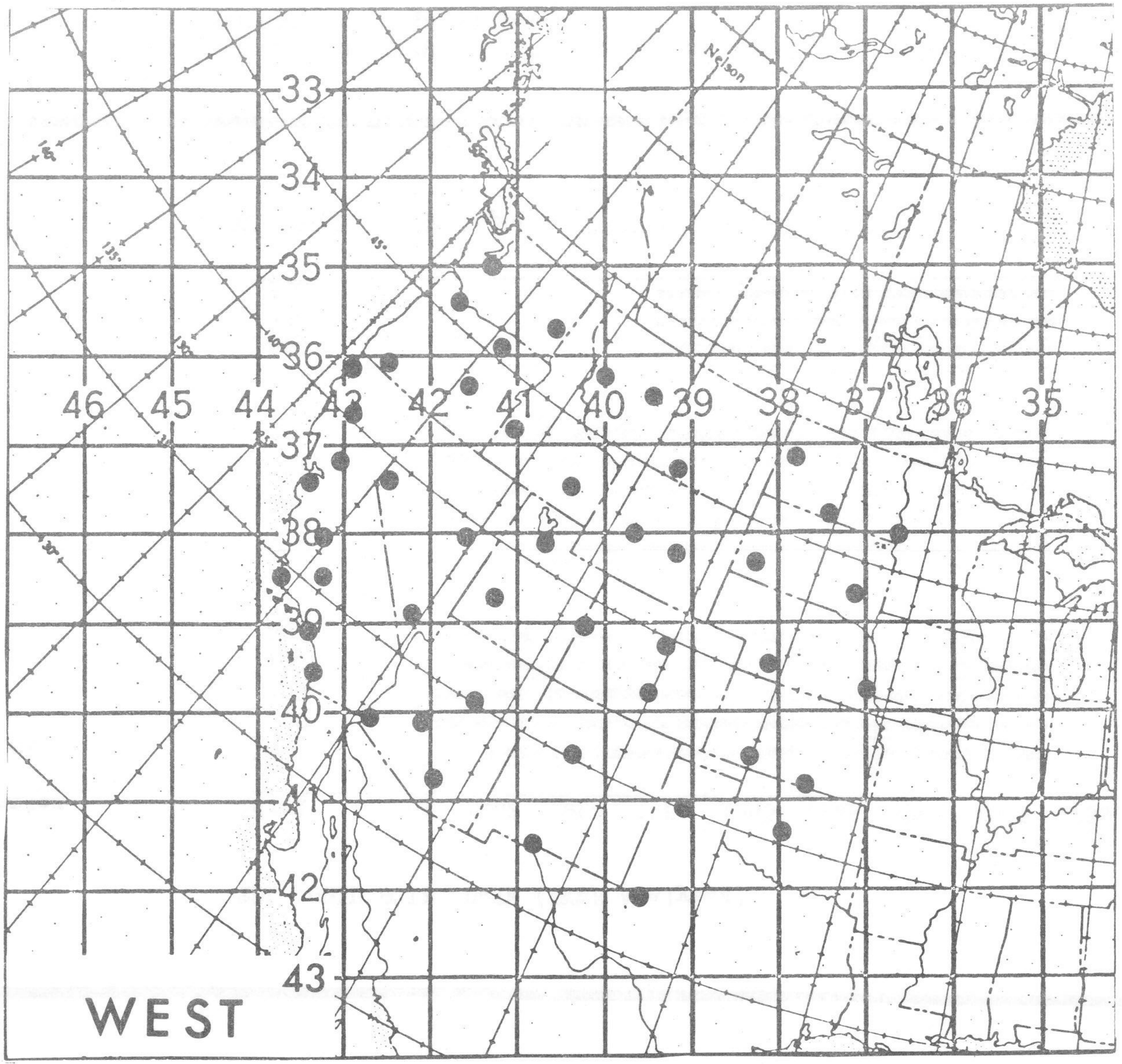


Figure 3.--Locations of 48 cities and 182 grid points used in initial screening experiments for the West. The rows and columns of the NMC grid points are numbered as shown.

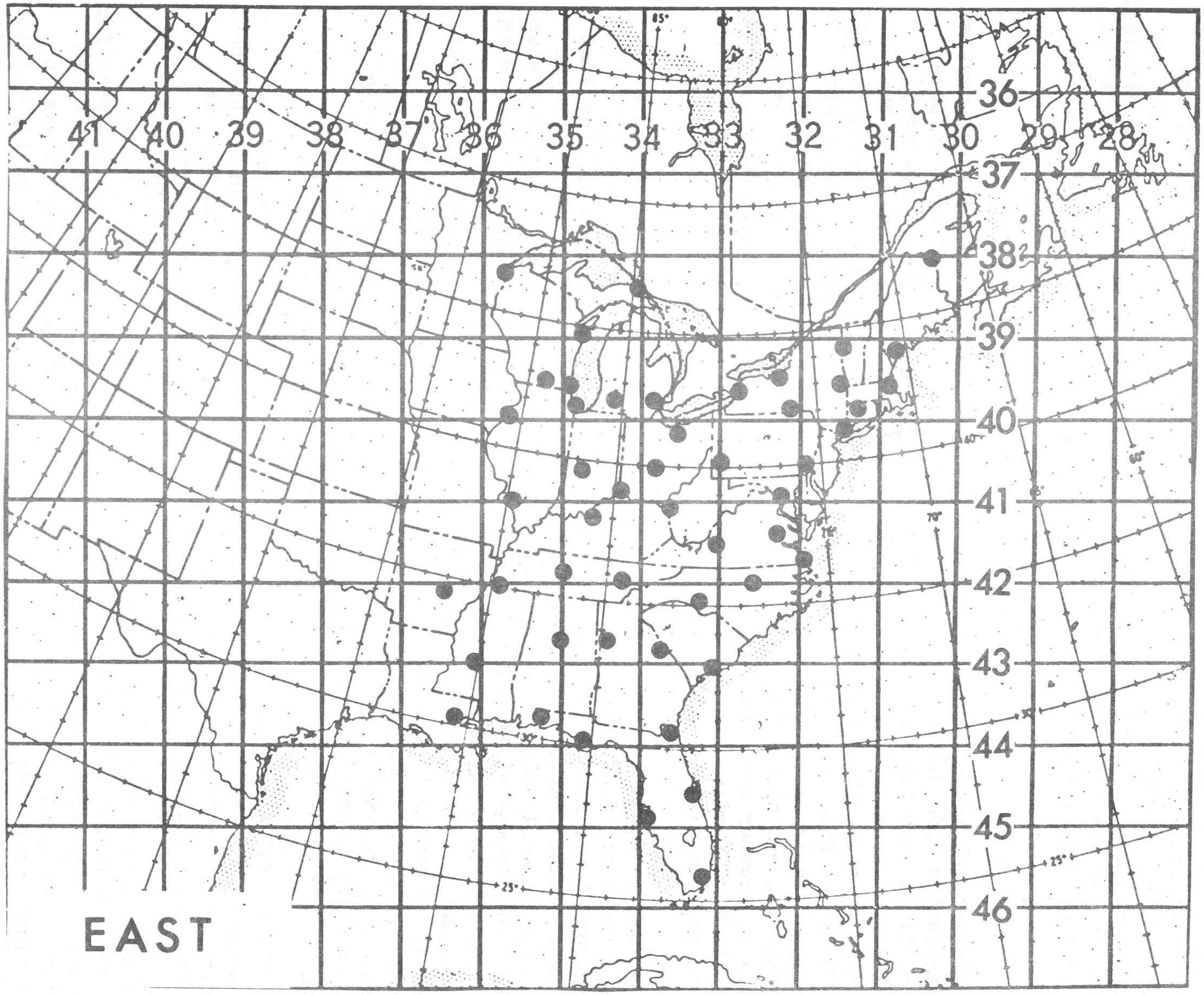


Figure 4.--Locations of 50 cities and 208 grid points used in initial screening experiments for the East. The rows and columns of the NMC grid points are numbered as shown.

In order to take account of normal diurnal differences in the probability of precipitation (Jorgensen, 1967), two sets of PoP equations were derived, one valid for the daytime hours, defined as 12Z to 24Z, and the other for nighttime, from 00Z to 12Z. As illustrated in figure 5, both sets were based on precipitation reports during the 12 hours just prior to the forecast period and on height and moisture values at the beginning of the forecast period. Thus PoP for the daytime hours was screened as a function of precipitation from 00Z to 12Z and of height and moisture at 12Z. Likewise, nighttime PoP was screened as a function of precipitation from 12Z to 24Z on the previous day and of height and moisture at 00Z on forecast day.

INITIAL RESULTS

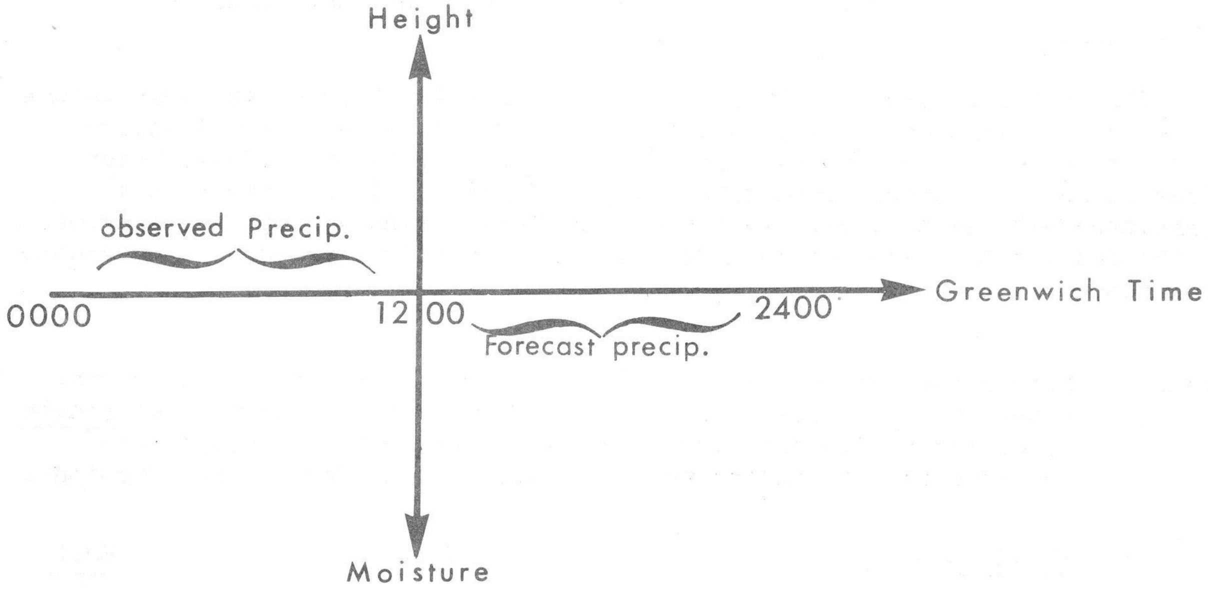
Tables 1-3 present preliminary results obtained by screening the daytime precipitation code during the winter season as a function of various predictor fields observed at 12Z in accordance with the scheme of figure 5. Results are given in terms of RV -- reduction of variance (square of the multiple correlation coefficient), averaged for 48 cities in the West (fig. 3) and 50 in the East (fig. 4). Because of uncertainties about appropriate levels and tests of significance, all data in these tables are based on multiple regression equations containing exactly five variables, approximately the number selected in previous screening studies (Klein et al., 1959, 1965, 1967). Similar results were obtained by using other cutoff criteria, but these data will not be shown here.

Table 1 shows results obtained using only one basic parameter at a time. The first four lines compare the effectiveness of the field of geopotential height at four standard levels. In both the West and the East the best height predictor of PoP was 850 mb. The importance of the 850-mb level has recently been stressed by Klein et al. (1968), Spiegler and Fisher (1970), and Browne and Younkin (1970). The second best height was 700 mb in the West and 1000 mb in the East, while 500 mb was the worst height on an overall basis. As expected, 1000-mb height was relatively poor in the West, where it is partly fictitious due to high elevation. These results, together with the increased accuracy of baroclinic compared to barotropic models, suggest that the 850-mb level should receive more emphasis in the Weather Service forecast system, while the 500-mb level might well be weighted less heavily than it is now in precipitation forecasting.

The second four lines in table 1 show the results of screening the dew-point spread at various levels. In both portions of the country the best single level for this moisture predictor was 700 mb, the second best was 850 mb, and the worst by a wide margin was 500 mb, which is evidently too high a level to exert much influence on PoP. Since it is difficult to predict moisture at a fixed level, mean values of dew-point spread at various levels were also screened. Best results were yielded by the mean for 850 and 700 mb, and this mean increased the RV over the 700-mb level alone by more than 1% in the West and more than 3% in the East, where it was the best single predictor. In general the RVs achieved by screening the moisture parameters were about equal to those achieved with the fields of geopotential height.

PoP DERIVATION SCHEME

(a) For daytime equations:



(b) For nighttime equations:

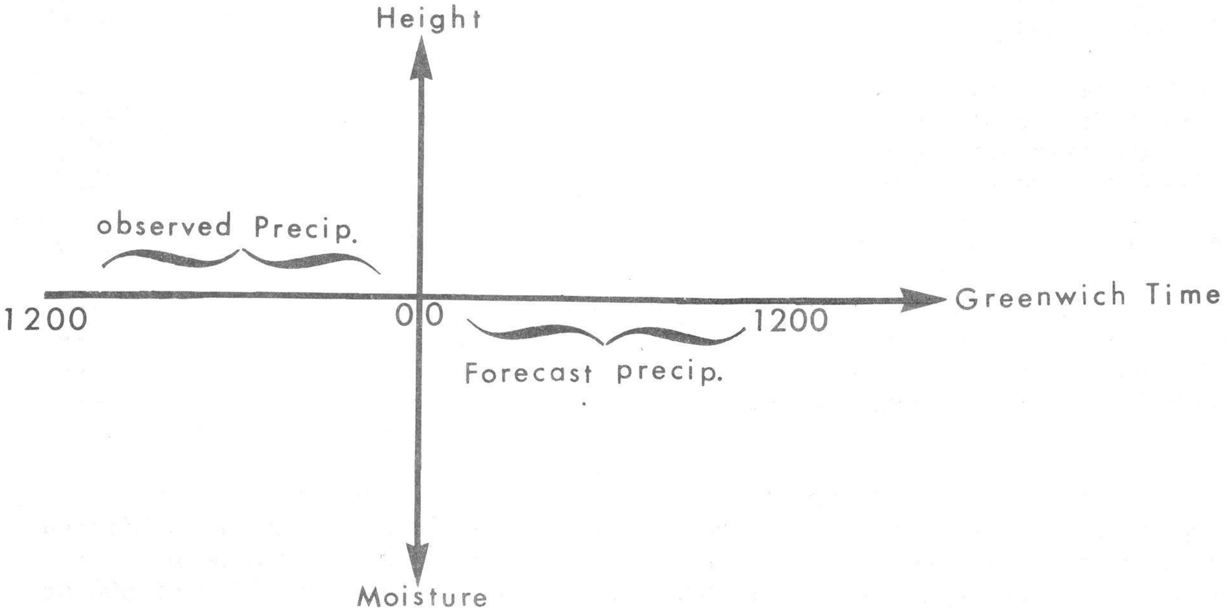


Figure 5.--Schematic diagram showing how separate forecast equations were derived for 12-hour periods during day and night as a function of height and moisture at the beginning of the forecast period and precipitation observed during the previous 12 hours.

The ninth line of table 1 gives the results of screening prior 12-hour precipitation reports over the network of 108 cities. This variable explained over 30% of the precipitation variance and was the best single predictor in the West and second best in the East. This result is not too surprising in view of the fact that use of the previous precipitation field combines the important effects of local persistence (Jorgensen and Klein, 1970) and "upstream" weather, both of which forecasters have long used subjectively.

The last four lines of table 1 show the results of screening mean values of height at different levels in the West. Although several combinations of 2, 3, and 4 levels were tried, none was able to improve over 850-mb height alone (line 2), probably because heights at different levels are highly correlated with each other. This result differs markedly from the behavior of the dew-point spread, where smoothing in the vertical produced appreciable improvement (line 8).

Table 1. Mean reductions of variance (%) obtained by screening winter precipitation occurrence between 1200 and 2400 GMT as function of single predictor fields observed at beginning of period. Results are averaged for 48 western and 50 eastern cities for 5-term equations.

Predictors	West	East
1000-mb height	23.6	29.5
850-mb height	28.8	31.1
700-mb height	26.3	24.5
500-mb height	23.9	20.5
850-mb dew-point spread	25.7	27.4
700-mb dew-point spread	25.9	30.3
500-mb dew-point spread	16.8	18.3
850-700 mb mean spread	27.1	33.7
Prior 12-hr precipitation	30.5	32.0
850-700 mb mean height	28.5	----
1000-850-700 mb mean height	28.3	----
850-700-500 mb mean height	26.7	----
1000-850-700-500 mb mean height	27.9	----

Table 2 summarizes screening runs made with two predictor fields in combination. In order to save computer time, these experiments were limited to western cities and to predictors located at every other grid point depicted in figure 3. The first two lines show that consideration of 500-or 700-mb height, in addition to 850-mb height, did not explain appreciably more of the precipitation variance than use of heights at 850 mb alone (table 1). The third line is similar but for dew-point spread. Here screening of both the 850-and 700-mb levels raised the RV by about 2% over that given by either level alone (table 1). However, the increase over the 850-700 mb mean spread was negligible.

The next five lines of table 2 present the results of screening various combinations of height and dew-point spread. Since these two parameters are relatively independent, their combination produced RVs about 5% higher than those listed for the better of the corresponding single predictors in table 1. As before, the most effective single level was 850 mb and the poorest was 500 mb. Overall, the best combination of height and moisture was 850-mb height and 850-700 mb mean spread, which together explained almost 35% of the precipitation variance.

The last three lines of table 2 summarize screening runs for various height fields in conjunction with the field of prior precipitation. RV increases over precipitation alone (table 1) ranged from 3 to 5%, with maximum improvement at 850 mb and minimum at 500 mb. Note that the RV of 35.6% for precipitation and 850-mb height is the highest listed in table 2.

Table 2. Mean reductions of variance obtained by screening winter precipitation occurrence between 1200 and 2400 GMT as function of two predictor fields in combination. Results are given for 5-term equations at 48 stations in western half of United States.

Predictors	RV (%)
850- and 500-mb heights	29.0
850- and 700-mb heights	28.9
850- and 700-mb dew-point spread	27.7
Height and dew-point spread at 850 mb	32.9
Height and dew-point spread at 700 mb	31.9
Height and dew-point spread at 500 mb	28.2
850-mb ht and 700-mb dew-point spread	33.0
850-mb ht and 850-700 mb mean spread	34.6
Prior precipitation and 850-mb height	35.6
Prior precipitation and 700-mb height	34.3
Prior precipitation and 500-mb height	33.5

Table 3 is similar to table 2 but for combinations of three or four predictor fields. The first line combines 850-mb height with dew-point spread at both 850 and 700 mb, but the RV was only slightly better than corresponding values in table 2. The next four lines consider fields of one height, one dew-point spread, and prior precipitation in conjunction. The resulting RVs were almost 4% greater than the highest values in table 2. This indicates that each of the three basic parameters (height, spread, and precipitation) makes a significant and independent contribution to PoP. The

RVs in this group generally confirm the results of tables 1 and 2 in showing that the 850-mb height was more effective than the 700-mb height, the 700-mb spread was better than the 850-mb spread, and the mean 850-700 mb spread gave better results than either level alone. The last line in table 3 shows that use of four different predictor fields produced no improvement over use of three.

Table 3. Mean reductions of variance obtained by screening winter precipitation occurrence between 1200 and 2400 GMT as function of <u>three or four</u> predictor fields in combinations. Results are given for 5-term equations at 48 stations in western half of United States.

Predictors	RV (%)
850-mb ht, 850-mb spread, and 700-mb spread	33.7
850-mb ht, 700-mb spread, and prior precip.	39.1
700-mb ht, 700-mb spread, and prior precip.	38.0
850-mb ht, 850-mb spread, and prior precip.	39.0
850-mb ht, 850-700 mb mean spread, and prior precip.	39.2
850-mb ht, 850-mb spread, 700-mb spread, and prior precip.	38.6

On the basis of the above results, it is concluded that the best combination of predictors for PoP consists of 850-mb height, 850-700 mb mean dew-point spread, and prior 12-hour precipitation.

OPERATIONAL EQUATIONS

In view of the preceding section, multiple regression equations were derived for operational use by screening fields of the three basic parameters. Screening runs were made separately for the western and eastern parts of the country, using the derivation scheme illustrated in figure 5 and the network of points plotted in figure 6 and figure 7. Since the total number of predictors for any run was limited to 210 by machine capacity, the grid points used for each part were carefully selected on the basis of physical reasoning, synoptic experience, and results of the preliminary screening runs described in the previous section. In the West equations were derived for 59 cities from predictors made up of 82 850-mb heights, 67 mean 850-700 mb dew-point spreads, and 59 precipitation stations. In the East the predictands were 49 cities and the predictors consisted of 76 heights, 63 spreads, and 69 surface stations. In addition, the day of the year was included as a simple predictor during spring and fall in order to represent the climatological trend of PoP during the transition seasons.

Since it is difficult to determine the statistical significance of improvements obtained by adding independent variables in screening regression, the following criteria were adopted in selecting the final multiple regression equations:

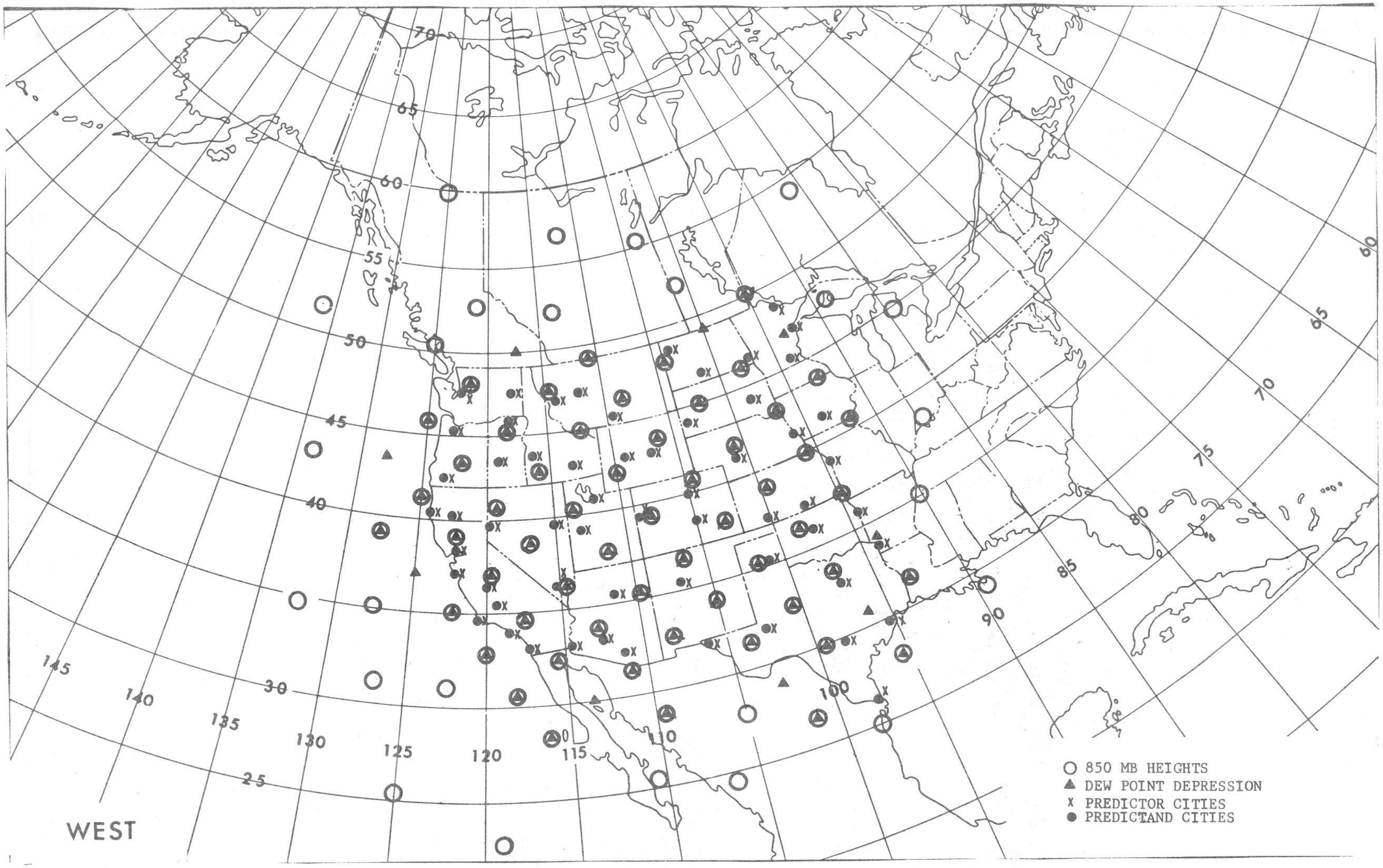


Figure 6.--Locations of variables used to derive operational equations for 59 cities in the West (dots) from 850-mb heights (circles), mean dew-point spreads (triangles), and surface reports (crosses). Triangle inside circle indicates that both height and spread were used at the same grid point.

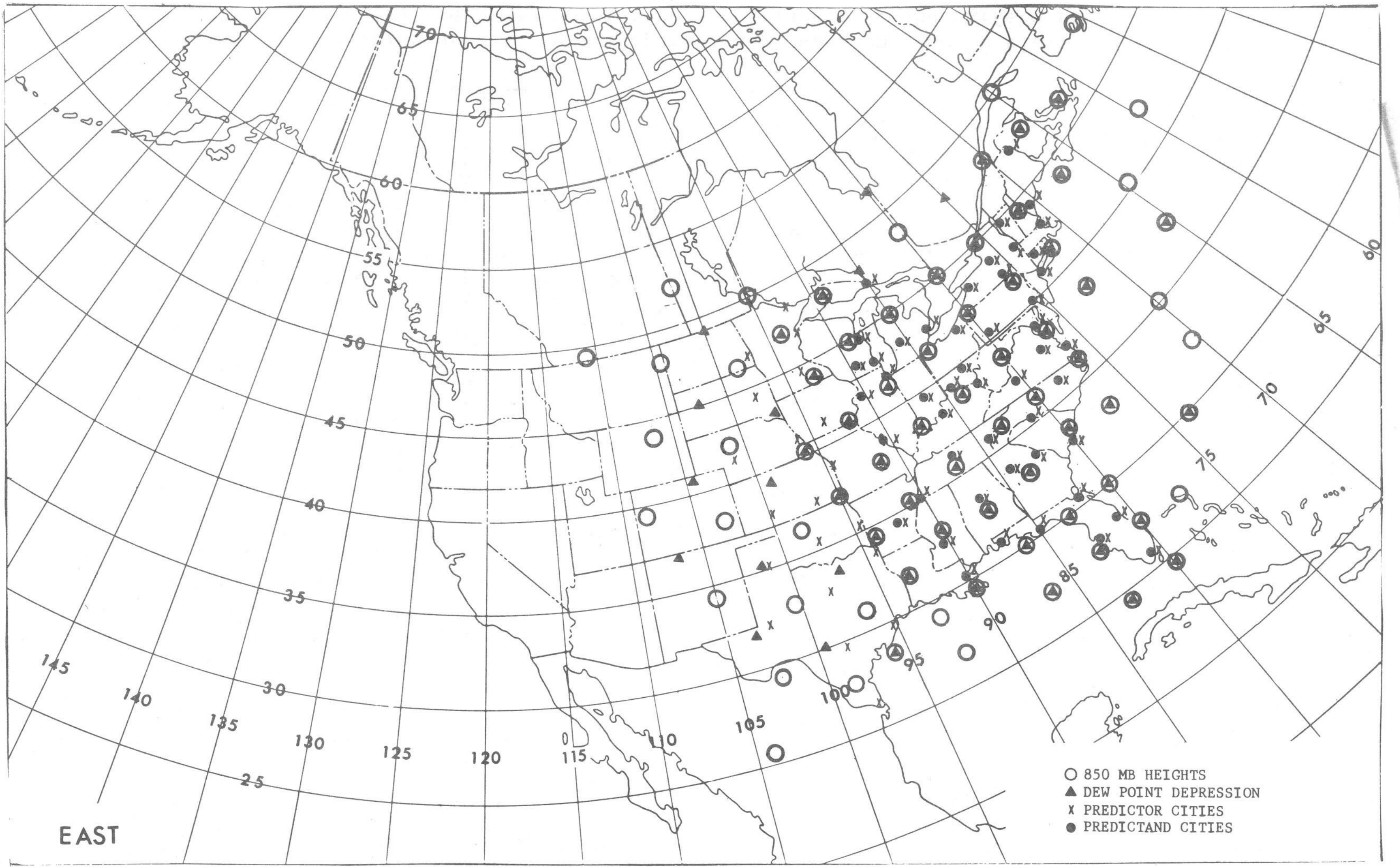


Figure 7.--Locations of variables used to derive operational equations for 49 cities in the East (dots) from 850-mb heights (circles), mean dew-point spreads (triangles), and surface reports (crosses). Triangle inside circle indicates that both height and spread were used at the same point.

a) Any pair of predictors which increased the RV by at least 4% was accepted.

b) No pair of predictors which failed to increase the RV by at least 2% was accepted.

c) Pairs of predictors which raised the RV between 2 and 4% and individual predictors which raised the RV between 1 and 2%, were examined subjectively and accepted if they appeared to be physically reasonable and to make good synoptic sense.

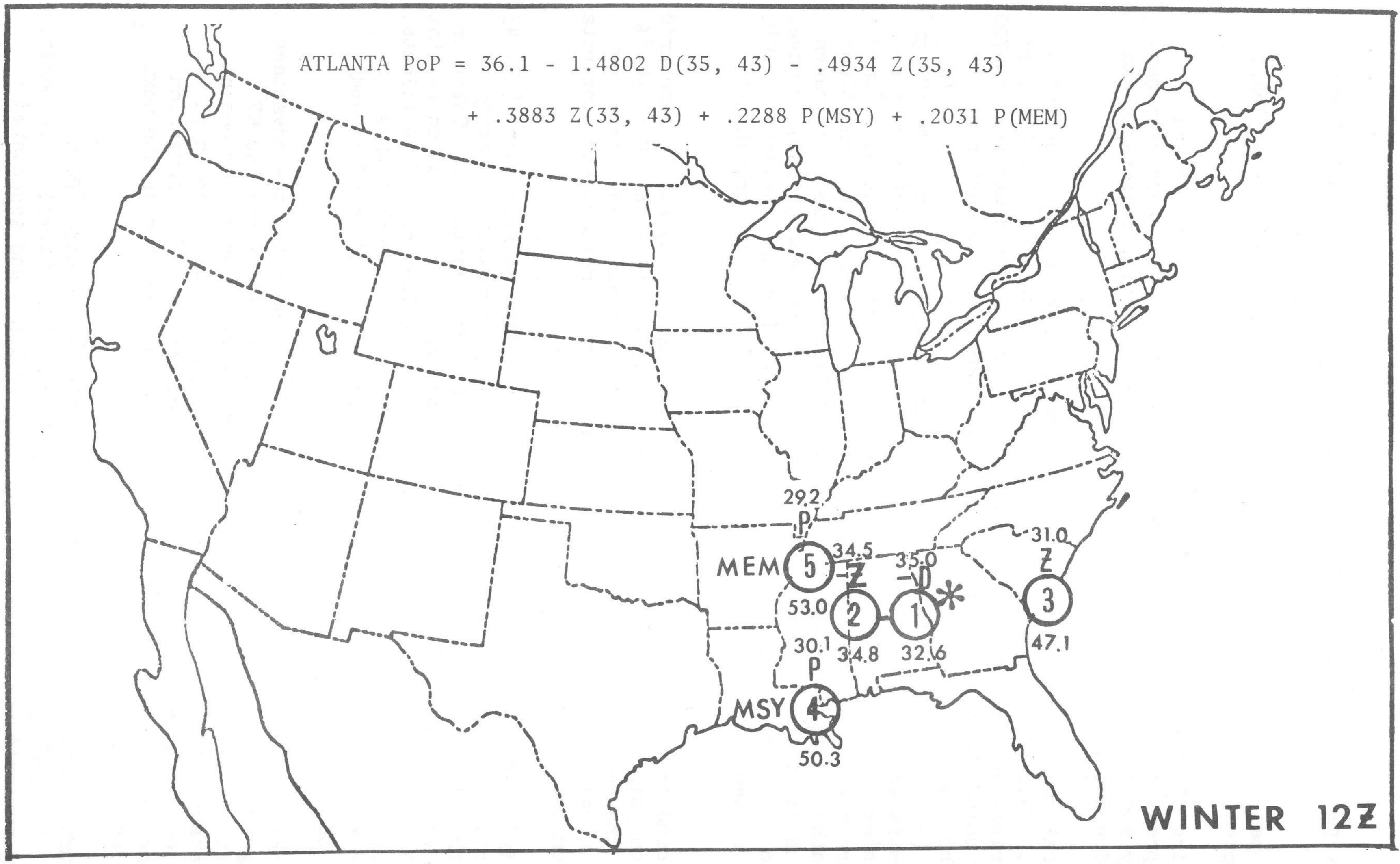
A typical equation derived by this screening procedure is illustrated in figure 8. This equation is for the daytime PoP at Atlanta, Ga. (located by the asterisk) during winter. The first predictor selected was the 850-700 mb mean dew-point spread (denoted by D) at 1200 GMT near the center of Alabama. The exact location of this predictor is given in parenthesis by coordinates (35, 43) which refer to the standard numbering scheme for NMC grid points illustrated in figures 3 and 4. Its sign in the forecast equation is negative, as expected, because low values of the spread indicate high humidity and therefore high values of PoP, while high values indicate dry conditions and fair weather. Its location is just west of Atlanta because it is taken at the beginning of the 12-hour forecast period and the weather usually moves from west to east. By itself, it would explain 32.6% of the variance of PoP and produce a standard error of estimate (SE) of 35.0% in the probability forecasts.

The second predictor selected was the 850-mb height (Z) at the same grid point. Taken jointly with the first predictor, it increased the RV to 34.8% and lowered the SE to 34.5%. Its sign is negative, as expected, since low pressure is usually associated with convergence, upward motion, and precipitation, and conversely for high pressure.

The third predictor selected was the 850-mb height at grid point (33, 43), on the Atlantic coast of South Carolina. Its sign is positive, thereby reflecting the direct effect of the "Bermuda High" on Atlanta PoP. Taken in conjunction with the negative sign of the second predictor, it indicates that southerly flow from the Gulf of Mexico favors large values of PoP in Atlanta, while northerly flow is associated with low values. Addition of this predictor to the multiple regression equation raised the RV to 47.1% and lowered the SE to 31.0%.

Selection of the second and third predictors illustrates the advantage of screening by pairs. Although the second predictor increased the RV produced in the first step by only 2.2%, it was selected by the screening procedure because it would add 14.5% when taken jointly with the third predictor. Once the second predictor was introduced into the regression equation, the way was paved for choice of the third predictor in the next step of the screening process.

The fourth predictor selected was the precipitation code (P) at New Orleans, La. (MSY), during the previous 12 hours (nighttime). Its positive sign largely reflects the well-known fact that cyclones and associated



$$\text{ATLANTA PoP} = 36.1 - 1.4802\ D(35,\ 43) - .4934\ Z(35,\ 43) + .3883\ Z(33,\ 43) + .2288\ P(\text{MSY}) + .2031\ P(\text{MEM})$$

Figure 8.--Operational equation for daytime PoP (in %) at Atlanta (asterisk) during winter where D is the mean dew-point spread in °C, Z is the 850-mb height in meters, and P is the precipitation probability during the previous 12 hours in %. Location of the predictors is given by coordinate numbers or station symbols in parentheses in equation (above) and by circles on map (below). The numbers inside the circles denote the order of predictor selection, and the numbers above and below give the standard error and reduction of variance (both in %) at each step of the screening process.

precipitation tend to move from southwest to northeast, so that Atlanta is strongly influenced by the weather at New Orleans 12 hours earlier. Inclusion of this predictor in the forecast equation raised the RV to 50.3% and lowered the SE to 30.1%.

The fifth predictor selected was similar to the fourth, but for the precipitation code at Memphis, Tenn., where weather 12 hours earlier was also positively correlated with Atlanta PoP. The contribution of this predictor may reflect the tendency for both cold-frontal showers and fair high-pressure areas to approach Atlanta from the west-northwest during winter. Addition of Memphis to the multiple regression equation raised the RV to 53.0% and lowered the SE to 29.2%. The screening process was stopped at this point, where no pair of predictors could raise the RV by at least 4% and no individual predictor by at least 2%.

Similar equations were derived for each of the 108 cities of figure 1 for winter, spring, and fall. Their characteristics are summarized in table 4. On the average, they produced a standard error of estimate of about 30% and explained approximately 40% of the variance of precipitation occurrence by means of about 6 predictors, of which between 2 and 3 were prior precipitation, slightly more than 2 were 850-mb heights, and between 1 and 2 were dew-point spreads. Less than half of the cities selected their own prior precipitation as one of the predictors (next to last line). The day of the year was relatively unimportant, being selected only about 3% of the time on the average.. Seasonal and diurnal variation in these characteristics was relatively small. However, the RV was highest in winter (42%),

TABLE 4. Characteristics of multiple regression equations for predicting probability of precipitation from 850-mb height, 850-700 mb mean dew-point spread, prior precipitation, and day of year averaged for 108 cities in the United States.

	Winter		Spring		Fall		
	Day	Night	Day	Night	Day	Night	Mean
Mean PoP (%)	21.0	20.7	19.1	19.3	16.5	16.0	18.8
Standard deviation (%)	39.2	39.1	38.1	38.2	35.8	35.3	37.6
Reduction of variance (%)	42.0	41.7	36.9	35.8	39.7	38.3	39.1
Standard error (%)	30.0	29.7	30.2	30.4	27.7	27.6	29.3
No. of predictors	6.2	6.0	5.7	5.8	6.8	6.4	6.2
No. of 850-mb height	2.3	2.2	2.1	2.4	2.3	2.4	2.3
No. of dew-point spread	1.1	1.2	1.2	1.2	1.4	1.1	1.2
No. of prior precip.	2.9	2.5	2.4	2.2	3.2	2.8	2.7
% of local precip.	39.9	38.0	52.7	39.8	55.5	43.6	44.9
No. of day of year	----	----	.02	.05	.02	.03	.03

when large-scale effects predominate, and lowest in spring (36%), when local convection is important. The fall equations had somewhat lower standard errors (27-28%), both because they contained more predictors (6-7) and because fall is a dry season, as shown by its mean PoP of only 16% in line 1.

On the other hand, geographical variation in the properties of the operational equations was quite large, as illustrated by figures 9 and 10 for nighttime precipitation during winter. Figure 9 shows that the reductions of variance ranged from over 60% near Tucson, Ariz. and San Francisco, Calif. to under 30% in portions of southern Florida, the Canadian border, the western mountain states, and the Central Plains. Additional maxima were found in Utah, Colorado, Texas, and the Southeast.

Figure 10 shows the standard error of estimate in map form. Values range from over 40% in parts of the Great Lakes and Pacific Northwest to less than 20% in the Southwest desert. Except for portions of the Gulf States, the SE generally increases with latitude. Somewhat similar behavior is exhibited by climatological values of PoP (Jorgensen, 1967), as illustrated by figure 11 for the sample mean during the winter season. Apparently, the regression equations, like human forecasters, have more difficulty in predicting PoP in relatively wet areas than in relatively dry regions (Glahn and Jorgensen, 1970).

The reason for the above behavior is the fact that wet areas are normally more variable in precipitation occurrence than dry ones. In fact, for a binary variable like PoP, the standard deviation is equal to the square root of the product of the mean frequency of precipitation and the mean frequency of no precipitation. As a result, the isopleths of figure 11 can be relabeled as the standard deviation of PoP about its climatological mean such that a mean PoP of 50% corresponds to a standard deviation of 50%, a mean of 30% corresponds to a deviation of 46%, and a mean of 10% corresponds to a deviation of 30%. Interpreted in this sense, figure 11 indicates the standard error that would be obtained by forecasting PoP equal to its climatological mean, while figure 10 represents the reduced error obtained through use of the regression equations. (See Appendix.)

FORECAST SYSTEM

Table 5 illustrates the system used in preparing PoP forecasts for 12 to 60 hours in advance on an operational basis. The forecasts are prepared twice a day on the CDC 6600 in Suitland, and the same two sets of equations are used in alternate 12-hour steps by means of an iterative process.

For example, at 0000 GMT the first forecast is made by means of the nighttime equations and is valid for the 12 hours from 00Z to 12Z that night. It is based on grid point values of 850-mb height and mean dew-point spread analyzed at forecast time (00Z) and on station reports of precipitation for the previous 12 hours from 12Z to 24Z yesterday. The second forecast, made from the daytime equations, is for the period from 12Z to 24Z today and is based on 12-hour numerical prognoses of height and moisture (valid 12Z), as well as 12-hour forecasts of PoP generated by the system in the first step

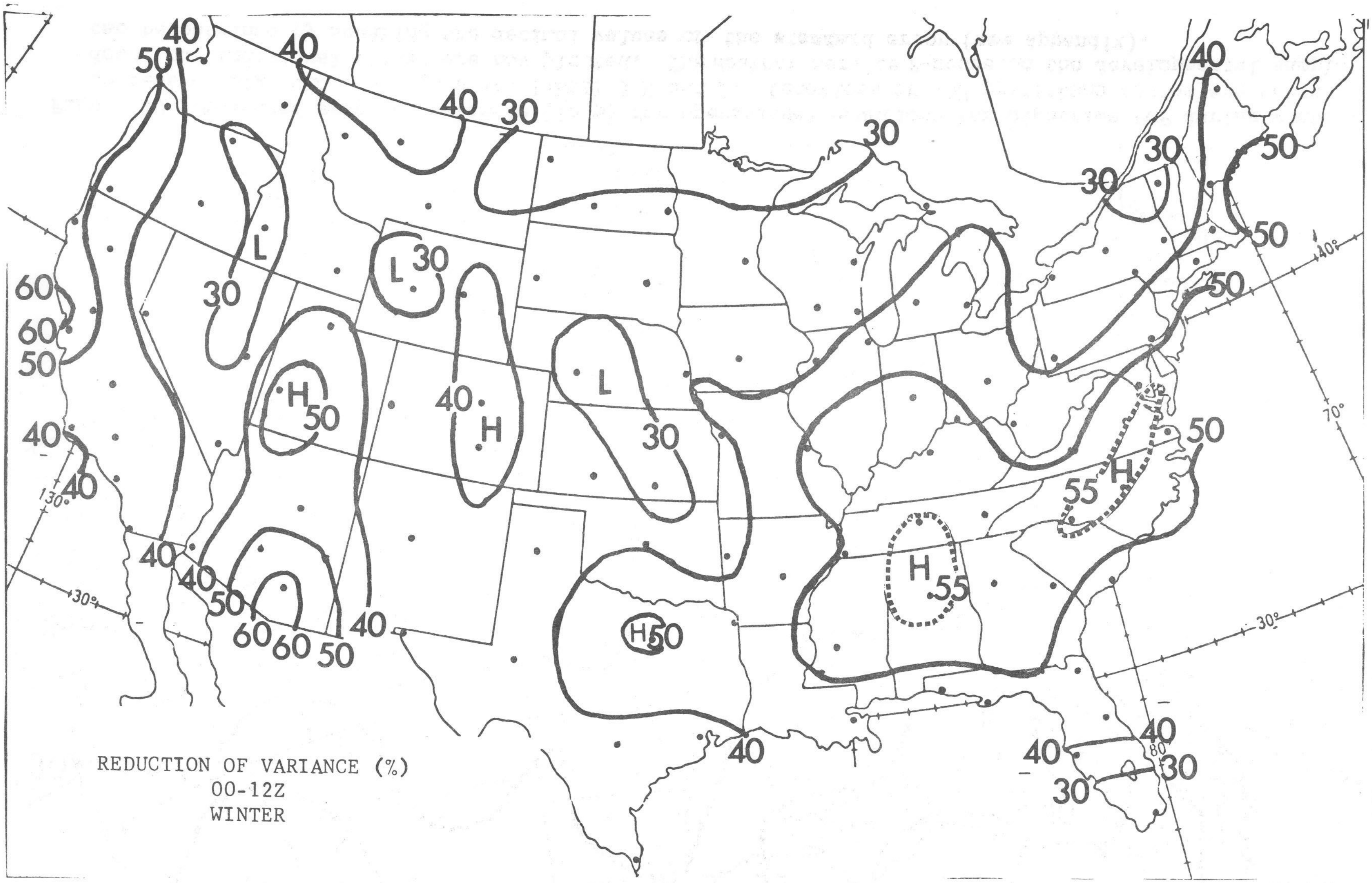


Figure 9.--Reductions of variance (in %) of operational equations for nighttime PoP during winter. Centers of high and low values are labelled H and L. Locations of 108 predictand cities are shown by dots, but individual values are not plotted. The isopleths can also be interpreted as the percent improvement of the regression forecasts over climatology (see Appendix).

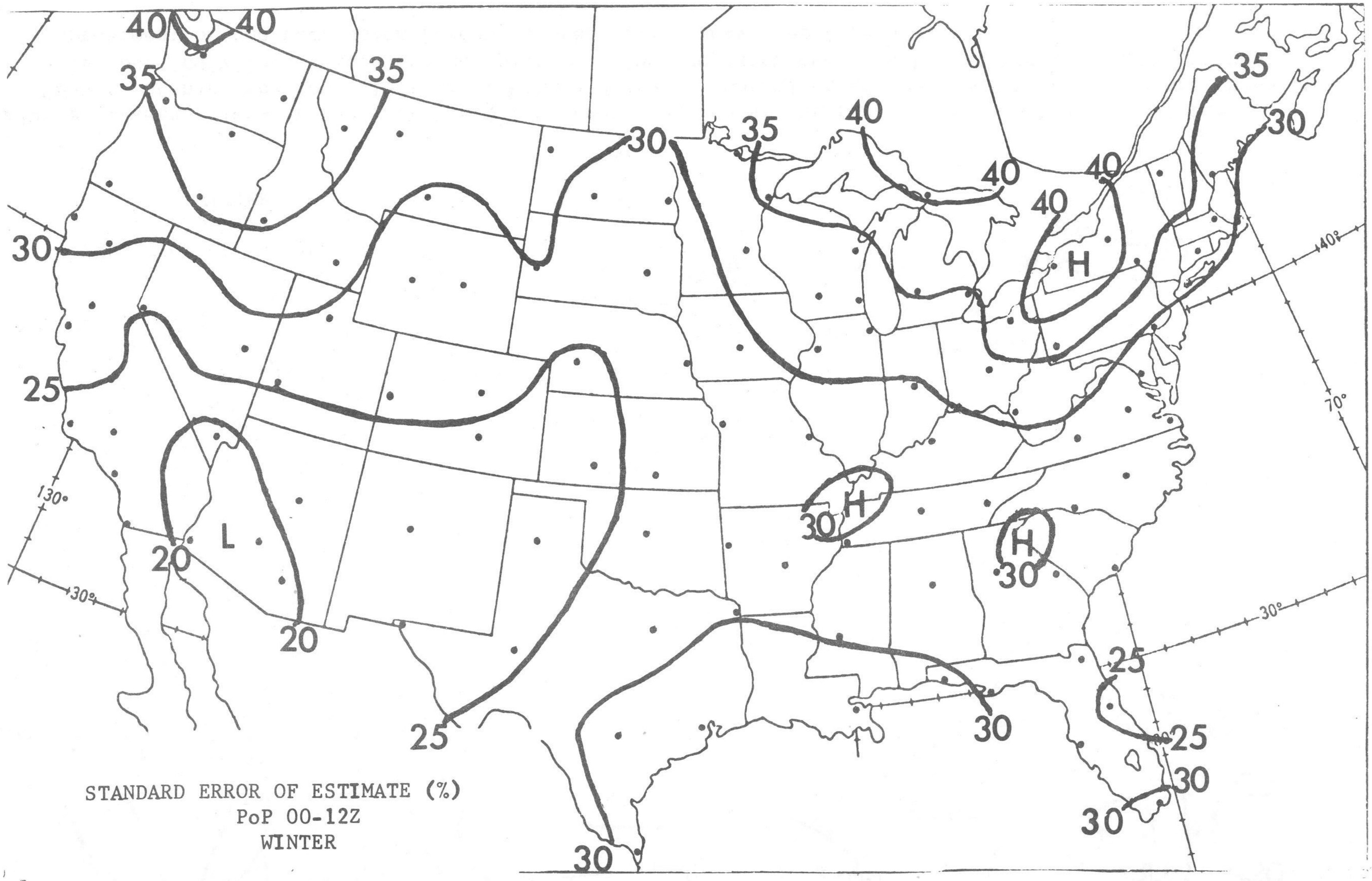


Figure 10.--Standard error of estimate (in %) for operational equations for nighttime PoP during winter. Centers of high and low values are labelled H and L. Locations of 108 predictand cities are shown by dots, but individual values are not plotted. The Weather Service P-score on the developmental sample can be obtained by squaring the decimal values of the standard error (see Appendix).

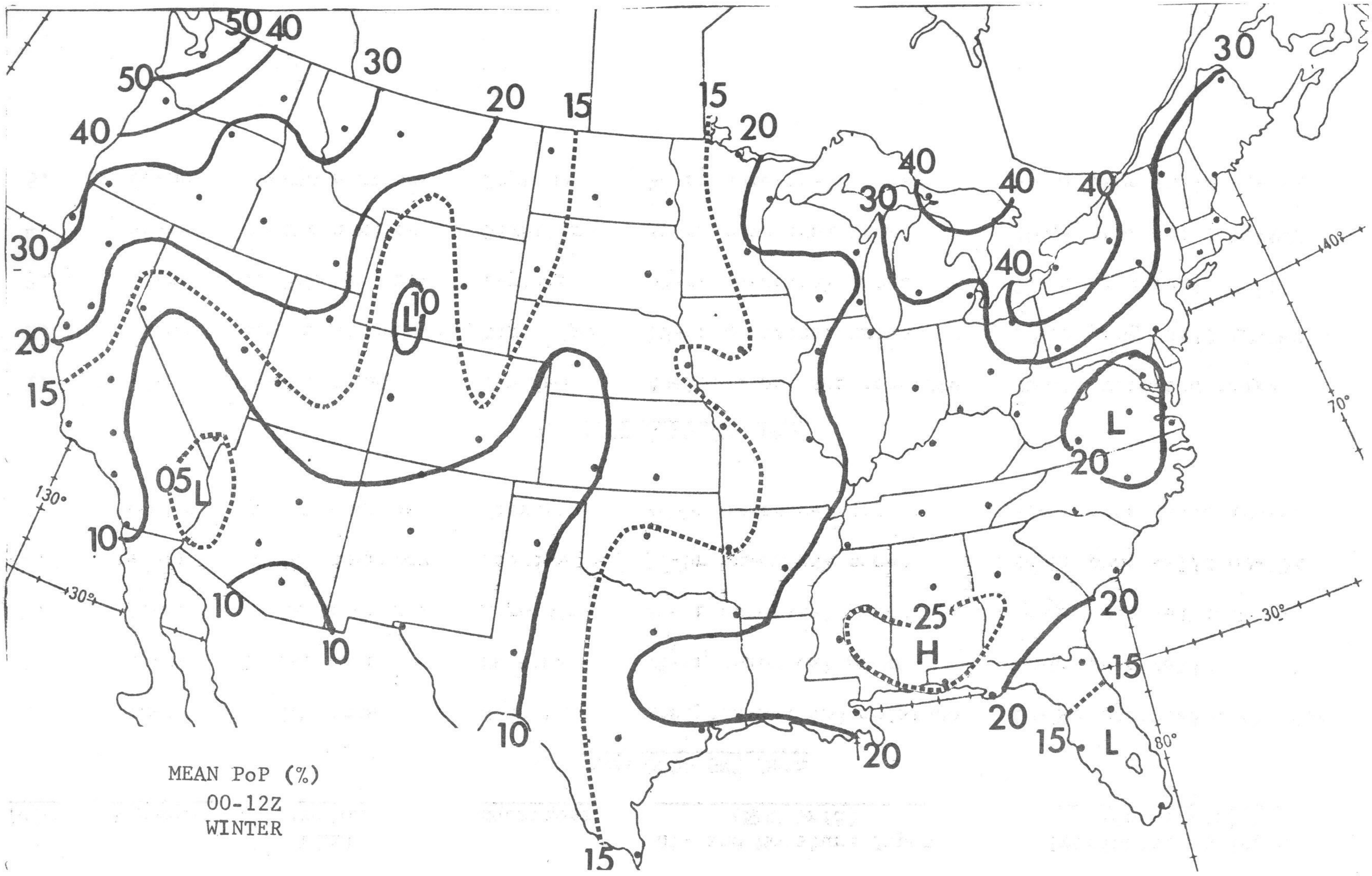


Figure 11.--Mean values of nighttime PoP during winter (in %). Centers of high and low values are labeled H and L. Locations of 108 predictand cities are shown by dots, but individual values are not plotted.

Table 5. System for preparation of operational PoP forecasts for 12 to 60 hours in advance.

Step	Forecast	Valid Period	Equations	Ht. and Moisture Input (NMC Grid)	Precipitation Input (108 Cities)
			a) From 0000 GMT Data		
1.	12-hr	00-12Z today	Nighttime	Analyzed ht. and moisture	12-24Z reported yesterday
2.	24-hr	12-24Z today	Daytime	12-hr numerical progs	12-hr prog valid 00-12Z
3.	36-hr	00-12Z tomorrow	Nighttime	24-hr numerical progs	24-hr prog valid 12-24Z
4.	48-hr	12-24Z tomorrow	Daytime	36-hr numerical progs	36-hr prog valid 00-12Z
5.	60-hr	00-12Z next day	Nighttime	48-hr numerical progs	48-hr prog valid 12-24Z
			b) From 1200 GMT Data		
1.	12-hr	12-24Z today	Daytime	Analyzed ht. and moisture	00-12Z reported today
2.	24-hr	00-12Z tomorrow	Nighttime	12-hr numerical progs	12-hr prog valid 12-24Z
3.	36-hr	12-24Z tomorrow	Daytime	24-hr numerical progs	24-hr prog valid 00-12Z
4.	48-hr	00-12Z next day	Nighttime	36-hr numerical progs	36-hr prog valid 12-24Z
5.	60-hr	12-24Z next day	Daytime	48-hr numerical progs	48-hr prog valid 00-12Z

for the period 00-12Z today.* The third forecast is based on the nighttime equations, covers the period from 00Z to 12Z tomorrow, and utilizes as upper air input 24-hour numerical prognoses of height and moisture and as surface input 24-hour PoP forecasts generated in step 2. The fourth forecast, for the period 12Z to 24Z tomorrow, is based on daytime equations which utilizes as input 36-hour numerical prognoses of upper air condition and the system's 36-hour PoP forecast made in step 3. The fifth forecast, for the period from 00Z to 12Z the day after tomorrow, uses as input to the nighttime equations 48-hour numerical prognoses and automated PoP forecasts generated in step 4. The system is stopped at this point because numerical forecasts are not routinely available twice a day beyond 48 hours.

It should be noted that the system described above uses forecasts of PoP made in one step as input to prediction equations for the next step. Precipitation is expressed as a fraction between 0 and 1 when used as input in steps 2-5, even though it was always observed as either 0 or 1 in the development sample. This has the effect of modifying the PoP forecasts with time, so that they tend to approach climatological means with increased forecast projection. Such inherent conservatism is probably desirable as forecast skill diminishes with time.

Since the multiple regression equations used in the forecast system are linear, they may produce occasional values of PoP which either exceed 100% or are less than 0% (negative probabilities). When this happens, the computer truncates the extreme values to either 100% or 0% for PoP.

The numerical forecasts used as input to the prediction equations are 850-mb heights obtained from the NMC primitive equation model (Shuman and Hovermale, 1968), as well as 850-mb and 700-mb dew-point spreads obtained from the laminated moisture version of the PE model put into operation during the winter of 1969-70 (Stackpole and Bedient, 1970). Since the numerical forecasts are not ready until 5-6 hours after observation time (00Z and 12Z), it is feasible to add synoptic reports of precipitation transmitted at 06Z and 18Z to the forecast system. This is done by changing the 12-hour forecast probability (step 1 of table 5) to 100% whenever measurable precipitation is reported during the six hours which have already elapsed at the time the forecast is made. Of course the forecast for this period is prepared too late to be of practical use to forecasters and the public, but it is important for the internal mechanics of the forecast system

Precipitation input to the prediction equations consists of observed 6-hour amounts transmitted in the synoptic code at 00, 06, 12, and 18Z. These teletype reports (Service C) are monitored by the NMC automatic data processing system. If a measurable amount is reported in one of the two

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*For convenience, the PoP forecast for the period from 0 to 12 hours after initial time will be called a 12-hour forecast; for the 12-24 hour period, a 24-hour forecast; for the 24-36 hour period, a 36-hour forecast; for the 36-48 hour period, a 48-hour forecast; and for the 48-60 hour period, a 60-hour forecast.

6-hour periods making up the desired 12-hour period, then the precipitation predictor is 1; if no precipitation is reported during both 6-hour periods, it is 0.

Unfortunately, on the average, about a dozen stations are missing, garbled, or incomplete each day. Of these missing stations, about two-thirds report only one of their two 6-hour precipitation periods. If this report shows no precipitation, then the report for the 6-hour period immediately adjacent to the missing one (before or after the desired 12-hour period) is examined. If the adjacent report also shows no precipitation, it is assumed that no precipitation has occurred during the missing 6 hours and the desired 12 hours. A different procedure is followed if the adjacent report indicates a measurable amount of precipitation. In this case, one half the objective forecast of PoP made by the system 12 hours previously is used in place of the desired 12-hour report.

In cases where both 6-hour periods (of the desired 12 hours) are missing, the entire PoP forecast made 12 hours previously is used as the precipitation predictor. If no forecast was available 12 hours earlier, the forecast made 24 hours previously is used as a first guess. If both reports and forecasts are missing for three successive 12-hour periods, the appropriate climatological normal (Jorgensen, 1967) is used. Thus the prediction system is fully automated, but its accuracy suffers when precipitation reports are not available.

FORECAST EXAMPLE

The forecast system described above has been applied on an experimental basis since May 1970. A sample forecast made by applying the spring equations at 12Z, May 8 is illustrated in figures 12-13. In these figures the shading delineates areas with measurable precipitation observed during each successive 12-hour period, the dots locate the 108 cities for which predictions are made, and the lines depict hand analyses of the spot forecasts for every 20% of PoP from 5% to 85% with intermediate lines dashed. Of course, local topographical effects, which are particularly important in the West, have been neglected in these analyses.

Figure 12 is for the first period corresponding to step 1 in table 5. Here the individual station forecasts have been plotted to show that it is possible to draw a fairly smooth pattern without violating any of the numbers. Precipitation (shaded) was reported in the Northwest, Northern Plains, and Northeast during this 12-hour period. Some stations in these areas have values of 100% because rain fell during the first 6 hours of the period, before the forecast was prepared. In the majority of the country no precipitation occurred and forecast probabilities were quite low.

Figure 13 covers the last four periods from 24 to 60 hours in advance. Comparison with figure 12 shows that precipitation generally persisted in the Northwest, diminished in the Northeast, and moved northeastward in the Northern Plains. Of particular interest is the development of a large band of precipitation in the Upper Mississippi Valley in 36 hours and its

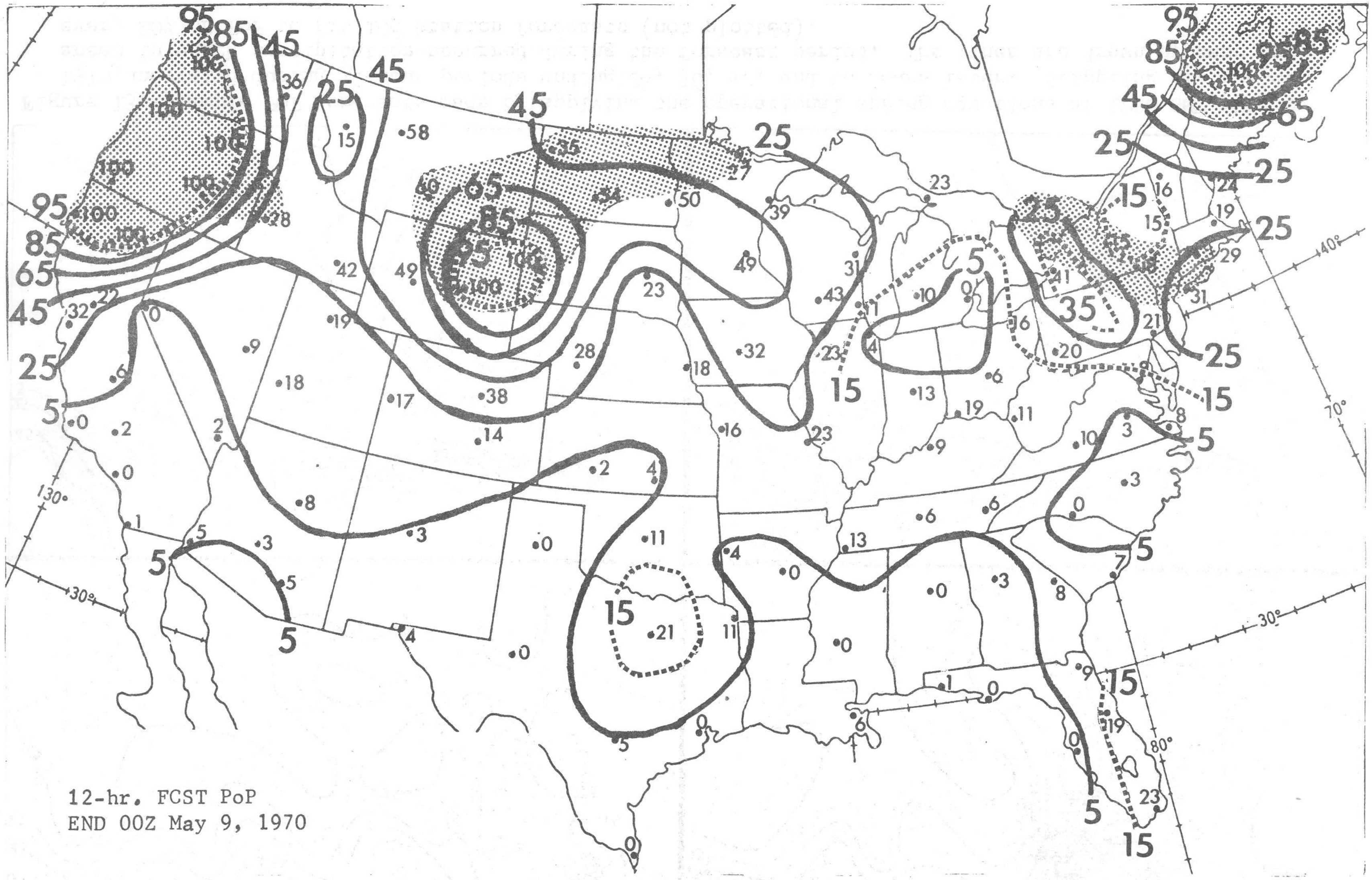

Figure 12.--Sample PoP forecast made by applying the daytime spring equations at 1200 GMT, May 8, 1970, and valid during the next 12 hours. Stippling delineates areas in which precipitation occurred during the forecast period. The lines are drawn by hand for every 20% of PoP to fit the individual forecasts plotted at 108 cities.

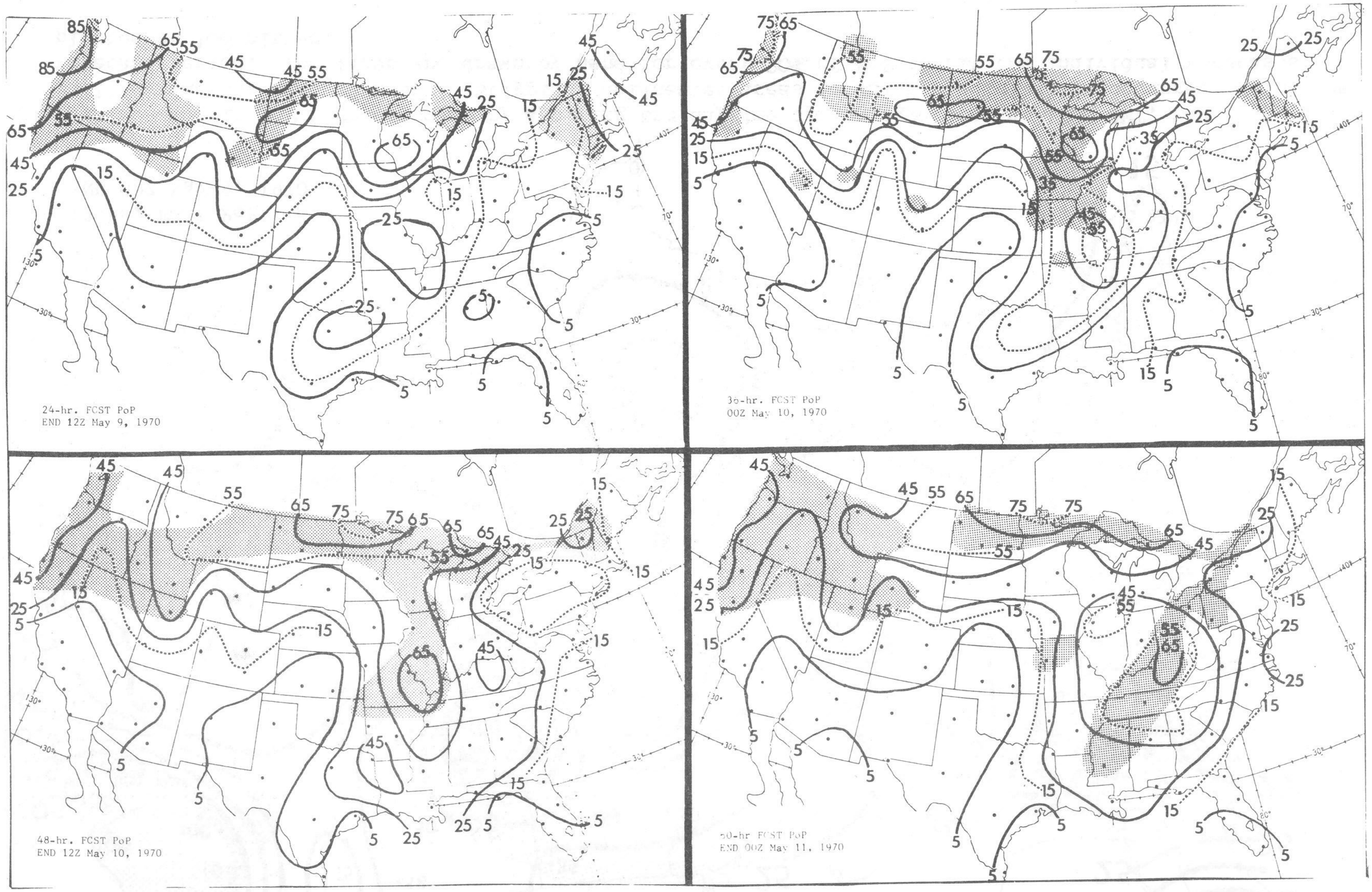

Figure 13.--Sample PoP forecasts made by applying the operational spring equations at 1200 GMT, May 8, 1970, and valid during 12-hour periods ending 24, 36, 48, and 60 hours later. Stippling delineates areas in which precipitation occurred during the forecast period. The lines are drawn by hand for every 20% of PoP to fit 108 station forecasts (not plotted).

subsequent southeastward motion to the Ohio and Tennessee Valleys in 60 hours. This development was forecast quite well, with PoP values of 65% in parts of the rain area 48 and 60 hours in advance. PoP forecasts over 65% were also verified by precipitation on all maps in northern border states of the Mid-West. However, observed precipitation in parts of the Northwest and Northeast was underforecast. The majority of the country remained dry during all periods, and this was generally well indicated by low forecast probabilities.

Similar forecasts have been prepared for other periods during May and June. Although quantitative verification figures are not yet available, most of the forecast maps resemble subjective forecasts and appear to be synoptically reasonable. A real-time operational test and verification was therefore initiated on September 1, 1970; evaluation of the results will be presented at a later date.

ACKNOWLEDGMENTS

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REFERENCES

Browne, R. F. and Younkin, R. J., "Some Relationships Between 850-Millibar Lows and Heavy Snow Occurrences Over the Central and Eastern United States," Monthly Weather Review, Vol. 98, No. 5, May 1970, pp. 399-401.

Cressman, G. P., "Improved Terrain Effects in Barotropic Forecasts," Monthly Weather Review, Vol. 88, Nos. 9-12, Sept.-Dec. 1960, pp. 327-342.

Cressman, G. P., "A Three-Level Model Suitable for Daily Numerical Forecasting," NMC Technical Memorandum No. 22, 1963, 27 pp.

Glahn, H. R., and Lowry, D. A., "An Operational Method for Objectively Forecasting Probability of Precipitation," ESSA Technical Memorandum WBTM TDL 27, Oct. 1969, 24 pp.

Glahn, H. R., and Jorgensen, D. L., "Climatological Aspects of the Brier P-Score," Monthly Weather Review, Vol. 98, No. 2, Feb. 1970, pp. 136-141.

Jorgensen, D. L., "Climatological Probabilities of Precipitation for the Conterminous United States," ESSA Technical Report WB-5, Dec. 1967, 60 pp.

Jorgensen, D. L., and Klein, W. H., "Persistence of Precipitation at 108 Cities in the Conterminous United States," ESSA Technical Memorandum WBTM TDL 31, May 1970, 84 pp.

Klein, W. H., "Specification of Precipitation from the 700-Millibar Circulation," Monthly Weather Review, Vol. 91, Nos. 10-12, Oct.-Dec. 1963, pp. 527-536.

Klein, W. H., "An Objective Method of Predicting Quantitative Precipitation in the Tennessee and Cumberland Valleys," Proceedings of the First National Conference on Statistical Meteorology, Hartford, Conn., May 27-29, 1968, American Meteorological Society, Boston, Mass., 1968, pp. 20-28.

Klein, W. H., Lewis, B. M., and Enger, I., "Objective Prediction of Five-Day Mean Temperature During Winter," Journal of Meteorology, Vol. 16, No. 6, Dec. 1959, pp. 672-682.

Klein, W. H., Crockett, C. W., and Andrews, J. F., "Objective Prediction of Daily Precipitation and Cloudiness," Journal of Geophysical Research, Vol. 70, No. 4, Feb. 1965, pp. 801-813.

Klein, W. H., Lewis, F., and Casely, G. P., "Automated Nationwide Forecasts of Maximum and Minimum Temperature," Journal of Applied Meteorology, Vol. 6, No. 2, April 1967, pp. 214-228.

Klein, W. H., Jorgensen, D. L., and Korte, A. F., "Relation Between Upper Air Lows and Winter Precipitation in the Western Plateau States," Monthly Weather Review, Vol. 96, No. 3, March 1968, pp. 162-168.

Lund, I. A., "Estimating the Probability of a Future Event from Dichotomously Classified Predictor," Bulletin of the American Meteorological Society, Vol. 36, No. 7, Sept. 1955, pp. 325-328.

Miller, R. G., "Statistical Prediction by Discriminant Analysis," Meteorological Monographs, Vol. 4, No. 25, Oct. 1962, 54 pp.

Russo, J. A., Jr., "Physical-Statistical Prediction of Precipitation Probability for the Summer Season," Proceedings of the First National Conference on Statistical Meteorology, Hartford, Conn., May 27-29, 1968, American Meteorological Society, Boston, Mass., 1968, pp. 29-38.

Shuman, F. G., and Hovermale, J. B., "An Operational Six-Layer Primitive Equation Model," Journal of Applied Meteorology, Vol. 7, No. 4, Aug. 1968, pp. 525-547.

Spiegler, D. B., and Fisher, G. E., "Prediction of Snowfall Distribution About 850-MB Cyclones Along the Atlantic Seaboard," Final Report, Contract No. E-269-68(N), The Travelers Research Corporation, Hartford, Conn., Jan. 1970, 70 pp.

Stackpole, J. D., and Bedient, H. A., "PEP Computation of Dew Point Temperature at Mandatory Levels," NMC Office Note 36, Jan. 1970, 2 pp.

Stevenson, N. M., and Woodworth, W. C., "Extracting Digital Historical Weather Fields from U. S. Fleet Numerical Weather Facility Files," Final Report, ESSA Contract No. E-166-67(N), Litton Systems, Inc., Monterey, Calif., March 1968, 4 pp. Appendix A-H.

Stidd, C. K., "The Use of Correlation Fields in Relating Precipitation to Circulation," Journal of Meteorology, Vol. 11, No. 3, June 1954, pp. 202-213.

Veigas, K. W., "The Development of a Statistical-Physical Hurricane Prediction Model," Final Report, Contract Cwb-10966, The Travelers Research Corporation, Hartford, Conn., July 1966, 19 pp.

Woodworth, W. C., "Extracting Digital Historical Upper Air Fields from U. S. Fleet Numerical Weather Facility Files, Final Report, ESSA Contract No. E-237-68, Litton Systems, Inc., Monterey, Calif., May 1969, 3 pp.

APPENDIX

A. Relation Between Mean and Variability of Precipitation

The sample variance s^2 of a binary variable such as precipitation occurrence can be expressed as a function of its mean in the form:

$$s^2 = f(1 - f) \qquad (1)$$

where f is the relative frequency (or probability) of precipitation in the developmental sample (illustrated by fig. 11), and 1 - f is the relative frequency of no precipitation. The standard deviation s is given by:

$$s = \sqrt{f(1 - f)} \qquad (2)$$

Thus the standard deviation of the binary precipitation variable is equal to the square root of the product of the relative frequencies of precipitation and no precipitation. Sample values obtained from the above relations are given in table 6.

Table 6. Sample values of mean and variability of precipitation occurrence obtained from equations (1) and (2).

f	1-f	s^2	s
.05	.95	.05	.22
.10	.90	.09	.30
.15	.85	.13	.37
.20	.80	.16	.40
.25	.75	.19	.43
.30	.70	.21	.46
.40	.60	.24	.49
.50	.50	.25	.50

By means of this table, the lines of figure 11 can be interpreted in terms of either the mean or the variability of the binary precipitation variable, as noted on page 18 of the text.

B. Relation Between Brier P-Score and Standard Error of Estimate

Forecasts of probability of precipitation are usually verified in terms of the P-score, which can be expressed as:

$$P = f(1 - f)\ (1 - r^2) \qquad (3)$$

where f is the relative frequency of precipitation as before, and r^2 is the reduction of variance of the regression equation used to forecast PoP (or the square of the multiple correlation coefficient). P as defined above is exactly half the verification score originally suggested by Brier in 1950.*

Introducing the expression for the variance of a binary variable from equation (1) into equation (3) gives:

$$P = s^2(1 - r^2) \tag{4}$$

But the standard error of estimate S can be expressed in the form:

$$S^2 = s^2(1 - r^2) \tag{5}$$

Therefore:

$$P = S^2 \tag{6}$$

Thus the isopleths of standard error of estimate given in figure 10 can be relabeled in terms of the standard P-score if they are converted to decimal form and squared. Sample values yielded by equation (6) are given in table 7. This table gives values of the P-score which would be obtained during the winter season if the multiple regression equations were used to make forecasts of PoP on the dependent data from which the equations were derived. These P-scores would range from less than .04 in the desert Southwest to more than .16 in parts of the Great Lakes (see fig. 10).

Table 7. Sample values of standard error of estimate and P-score obtained from equation (6).

Standard error	P-score
20%	.0400
25%	.0625
30%	.0900
35%	.1225
40%	.1600

The P-scores resulting from implementation of the automated forecast system would be worse (higher) than those obtained on the developmental sample because of imperfect NMC prognostic charts, missing precipitation data, and possible instabilities in the regression equations. On the other

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*Brier, G. W., "Verification of Forecasts Expressed in Terms of Probability," Monthly Weather Review, Vol. 78, No. 1, Jan. 1950, pp. 1-3.

hand, the scores would be lowered slightly by the procedure of truncating forecast values of PoP less than 0 or greater than 100 (see page 23). Exact values of the final P-score can only be determined by an operational test of the type now underway.

C. Relation Between S-Score and Reduction of Variance

If the climatological probability of precipitation (computed on the sample) is used as a constant forecast of PoP for each case, the reduction of variance is zero. Then equations (1) and (3) show that the resulting P-score is given by the expression:

$$P_c = f(1 - f) = s^2 \tag{7}$$

Thus the climatological P-score P_c is the sample variance of the binary variable s^2 or the mean square error of climatological forecasts.

Combination of equations (4) and (7) yields an alternate expression for the P-score in the form:

$$P = P_c(1 - r^2) \tag{8}$$

Therefore the P-score can be expressed as a function of the climatological P-score and the reduction of variance.

The fractional amount by which forecasts improve over climatological forecasts has been called the S-score by Hughes* and labeled K by Glahn and Jorgensen (1970). This quantity can be defined as:

$$K = \frac{P_c - P}{P_c} \tag{9}$$

It can also be interpreted as the reduction of variance (Hughes, 1970), so that

$$K = r^2 \tag{10}$$

In view of equation (10), the isopleths of reduction of variance given in figure 9 can be relabeled in terms of the S-score. They can then be used to indicate the percent improvement over climatology yielded by the regression equations on the developmental sample. This improvement varies from less than 30% to more than 60% in different parts of the country.

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*Hughes, L. A., "A Note on the Comparability of the "S-Score" and the Reduction of Variance," Central Region News and Views, Technical Attachment 70-14, August 1970.

(Continued from inside front cover)

WBTM TDL 16 Objective Visibility Forecasting Techniques Based on Surface and Tower Observations. Donald M. Gales, October 1968. (PB-180 479)

WBTM TDL 17 Second Interim Report on Sea and Swell Forecasting. N. A. Pore and Lt. W. S. Richardson, USESSA, January 1969. (PB-182 273)

WBTM TDL 18 Conditional Probabilities of Precipitation Amounts in the Conterminous United States. Donald L. Jorgensen, William H. Klein, and Charles F. Roberts, March 1969. (PB-183 144)

WBTM TDL 19 An Operationally Oriented Small-Scale 500-Millibar Height Analysis. Harry R. Glahn and George W. Hollenbaugh, March 1969. (PB-184 111)

WBTM TDL 20 A Comparison of Two Methods of Reducing Truncation Error. Robert J. Bermowitz, May 1969. (PB-184 741)

WBTM TDL 21 Automatic Decoding of Hourly Weather Reports. George W. Hollenbaugh, Harry R. Glahn, and Dale A. Lowry, July 1969. (PB-185 806)

WBTM TDL 22 An Operationally Oriented Objective Analysis Program. Harry R. Glahn, George W. Hollenbaugh, and Dale A. Lowry, July 1969. (PB-186 129)

WBTM TDL 23 An Operational Subsynoptic Advection Model. Harry R. Glahn, Dale A. Lowry, and George W. Hollenbaugh, July 1969. (PB-186 389)

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WBTM TDL 25 Charts Giving Station Precipitation in the Plateau States From 850- and 500-Millibar Lows During Winter. August F. Korte, Donald L. Jorgensen, and William H. Klein, September 1969. (PB-187 476)

WBTM TDL 26 Computer Forecasts of Maximum and Minimum Surface Temperatures. William H. Klein, Frank Lewis, and George P. Casely, October 1969. (PB-189 105)

WBTM TDL 27 An Operational Method for Objectively Forecasting Probability of Precipitation. Harry R. Glahn and Dale A. Lowry, October 1969. (PB-188 660)

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WBTM TDL 31 Persistence of Precipitation at 108 Cities in the Conterminous United States. Donald L. Jorgensen and William H. Klein, May 1970. (PB-193 599)

WBTM TDL 32 Computer-Produced Worded Forecasts. Harry R. Glahn, June 1970. (PB-194 262)

WBTM TDL 33 Calculation of Precipitable Water. L. P. Harrison, June 1970. (PB-193 600)

WBTM TDL 34 An Objective Method for Forecasting Winds Over Lake Erie and Lake Ontario. Celso S. Barrientos, August 1970. (PB-194 586)

WBTM TDL 35 A Probabilistic Prediction in Meteorology: A Bibliography. A. H. Murphy and R. A. Allen, June 1970. (PB-194 415)

WBTM TDL 36 Current High Altitude Observations--Investigation and Possible Improvement. M. A. Alaka and R. C. Elvander, July 1970. (Com-71-00003)

NWS TDL 37 Prediction of Surface Dew Point Temperatures. R. C. Elvander, January 1971.

NWS TDL 38 Objectively Computed Surface Diagnostic Fields. Robert J. Bermowitz, February 1971.