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An Operational Method For Objectively Forecasting Probability of Precipitation

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U.S. DEPARTMENT OF COMMERCE
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AN OPERATIONAL METHOD FOR OBJECTIVELY FORECASTING PROBABILITY OF PRECIPITATION

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ABSTRACT

An operational method for objectively producing forecasts of probability of precipitation (PoP) is discussed. The screening regression technique is used to relate precipitation observations to variables forecast by two existing numerical models, the TDL Subsynoptic Advection Model (SAM) and the NMC Primitive Equation (PE) Model. Verification figures for a 1-year period are presented for the eastern United States. These figures indicate that the objective forecasts were slightly more accurate than the official forecasts issued to the public by Weather Bureau local offices.

INTRODUCTION

A method has been developed that objectively produces forecasts of probability of precipitation (PoP). The method is based on a procedure called Model Output Statistics (MOS), which statistically relates precipitation observations to variables forecast by existing numerical models. Two numerical models have been used in this particular application--the Subsynoptic Advection Model (SAM) developed by the Techniques Development Laboratory (TDL) [10] and the Primitive Equation (PE) Model developed by the National Meteorological Center (NMC) [24].

The PoP forecasts are produced as an integral part of the twice-daily operational SAM computer program [11, 9, 10]. This program was developed to use the latest observations and numerical forecasts available in order to produce objective forecasts of PoP at the time they are needed by the local Weather Bureau offices for issuance to the public. The area covered and the SAM numerical grid are shown in figure 1. The evolution of the SAM project, from the testing of the model through the current operational program, is described in the Weather Bureau Technical Procedures Bulletin Series [3, 4, 5, 6, 7]. One of the unique features of SAM, in addition to the data time and grid length considerations, is the specification of initial layer moisture by using only surface observations [10, 15]. This feature allows the moisture field to be defined on a small scale (fig. 1) and at times other than 0000 and 1200 GMT. The latest surface data used in SAM are 0700 GMT for the "today" forecast and 1900 GMT for the "tonight" forecast.

Statistical relationships were derived by using the screening regression technique. A brief description of this procedure follows.

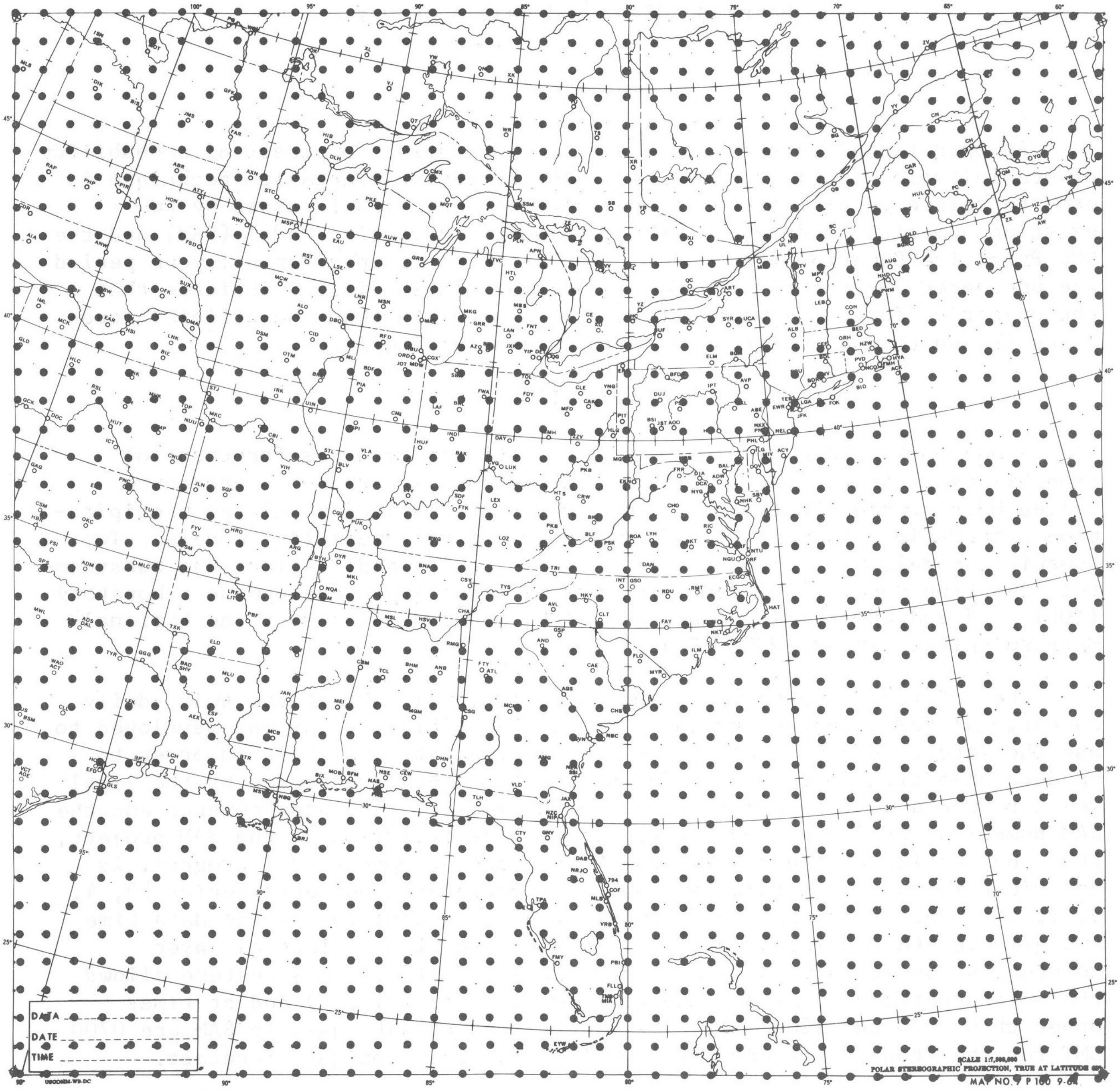

Figure 1.--The SAM 39 x 40 grid. The gridlength is exactly ¼ that used for the NMC synoptic scale products. This is approximately 50 miles and not much different from the average spacing of hourly reporting stations in the eastern and central United States.

THE SCREENING REGRESSION PROCEDURE

Multiple linear regression relates one variable Y, called the dependent variable or predictand, to k other variables X_i, called the independent variables or predictors. The result is an equation which can be used for estimating the predictand as a linear combination of the predictors:

$$\hat{Y} = a_o + a_1X_1 + a_2X_2 + \dots + a_kX_k.$$

The carat indicates an estimate, and the a_i's are the regression constant and coefficients. The a_i's are determined such that the sum of the squares of the estimation errors is a minimum on the developmental (or dependent) sample of size n, i.e.,

$$\sum_{j=1}^{n} \left(Y_j - \hat{Y}_j\right)^2 = \text{Minimum}$$

A measure of the goodness of the equation for estimating Y is the reduction of variance RV, where

$$RV = \frac{\frac{1}{n}\sum_{j=1}^{n}(Y_j - \bar{Y})^2 - \frac{1}{n}\sum_{j=1}^{n}(Y_j - \hat{Y}_j)^2}{\frac{1}{n}\sum_{j=1}^{n}(Y_j - \bar{Y})^2}$$

This is the fractional part of the variation of Y about its mean $\bar{Y}$, measured by the variance

$$\sigma_y^2 = \frac{1}{n}\sum_{j=1}^{n}(Y_j - \bar{Y})^2$$

that is "explained" by the regression equation. RV is the square of the multiple correlation coefficient, i.e.,

$$RV = R^2_{Y.X_1,X_2,\dots,X_k}$$

It is clear from the above equations that decreasing the sum of squares of the estimation errors is tantamount to increasing the reduction of variance RV and to decreasing the root mean square error (or standard error of estimate), where

$$RMSE = \left[\frac{1}{n}\sum_{j=1}^{n}(Y_j - \hat{Y}_j)^2\right]^{1/2}$$

Many times it is not known which or how many predictors to include in a regression equation. Even though the predictand may be correlated with hundreds of variables, a regression equation containing only a very few of them usually explains nearly as much of the variance as an equation containing many. This is due to the high intercorrelations among the variables. Also, if many predictors are included, the predictand may be estimated extremely well in the dependent data sample, but the equation may be showing not only the real physical relationships but also the chance relationships in the dependent data that will not be present in other samples. Therefore, the equation with many terms may perform more poorly on independent data than the one with fewer terms.

A technique for selecting predictors to include in an equation, called screening regression, was used in meteorology as early as 1944 by Bryan [1]. Since being popularized by Miller [18], it has had many applications in meteorology. (For instance, see Klein, Lewis, and Crockett [13] and Pore [21]; other applications are discussed by Glahn [8].) Actually, several variations of this general technique have been used. The one explained below, sometimes called the forward stepwise method, is perhaps the simplest.

The first step in the procedure is to select the variable which correlates most highly (in either a positive or negative sense) with the predictand. This is the variable which explains a greater fraction of the predictand variance than any other of those available. Then, the next variable selected is the one that together with the first increases the reduction of variance the most. Selection can continue in this way until some specified cutoff criterion is met. Usually the cutoff criterion is some function of the additional reduction of variance afforded by the next best predictor. A discussion of the screening technique and the necessary matrix operations is given by Efroymson [2].

Screening regression, as a mathematical technique, can be used no matter what the joint distribution of the predictand and predictors. (However, this distribution is important in the application of significance tests and the interpretation of results.) In fact, any or all of the variables involved can be binary (take on only one of two possible values, 0 and 1).

If a predictand can assume only one of two states, it can still be estimated by regression by giving it the value of zero for the first state and one for the second state. The estimate provided by the regression equation can then be considered as the probability of the second state for the particular combination of predictor values on which the estimate was calculated. (See Mook [19] and Lund [16] for early uses of this particular application.)

If a predictand can assume only one of several, say q, states, it can be transformed into q binary predictands and each treated as discussed above. Miller [17] used this technique for $q > 2$ when all predictors were binary and called it regression estimation of event probabilities (REEP).

Even though the individual estimates are not bounded by zero and one, their sum over all categories is always unity, provided exactly the same predictors are included in each of the q regression equations. Screening algorithms can also be specified for this application of regression.

The equations for estimating probabilities can include continuous as well as binary variables. It is also worthy of note that minimizing the RMSE is the same as minimizing the P-Score defined by Panofsky and Brier [20] and generally used today in PoP verification.

The assumptions underlying tests of significance are usually far from actuality when the screening procedure is used. Therefore, even though screening stopping rules may be based on some such test, no exact (or perhaps even approximate) level of significance can be attached to them. In practice, experience and subjective judgment are probably as good or better than objective rules in deciding which equation (how many predictors) to use in operation. For instance, if one is interested in explaining the variance of maximum temperature, then using several more predictors to reduce the RMSE from 5.00 degrees to 4.95 degrees is certainly questionable from a practical point of view. Other considerations may play a more important role than the slightly lower RMSE in deciding on the final equation.

DEVELOPMENT OF EQUATIONS

Our work in PoP forecasting to date has been restricted to a generalized operator approach. This amounts to a pooling of the developmental data for all stations and means that the same regression equation is used for all stations for a given period. An application of the generalized operator approach is contained in the work of Russo, Enger, and Merriman [23]. This approach can be used when the various station equations are almost identical or must be used when the dependent data sample is small. We consider the data sample still too small to derive dependable individual station equations. When it becomes possible to develop single station equations, a noticeable improvement in the accuracy of the forecasts for some stations should result.

Also, forecasts for nighttime have been produced by equations developed on daytime data. On October 1, 1969 we will have available both daytime and nighttime regression equations.

The variety of possible predictors used in the screening regression technique includes not only PE and SAM forecasts, but also initial observed data (0700 or 1900 GMT) and climatology. Initial data include weather, clouds, ceiling, visibility, temperature, dew point, sea-level pressure, and wind components at the surface. The initial saturation deficit (the moisture parameter in SAM) was also considered.

The saturation deficit is a term defined by Younkin, La Rue, and Sanders [25] as

$$S_d = h_5 - S_T$$

where h_5 is the 1000-500 mb thickness and S_T the saturation thickness. The saturation thickness, for our purposes, is that thickness between 1000 mb and 500 mb for which precipitation will occur for a given amount of moisture between those levels. The saturation deficit is the moisture parameter used in the SLYH precipitation model [25] that was operational for several years at NMC. The SLYH method was later adapted for on-station use by Kulawiec [14].

Climatology variables consisted of the relative frequency of precipitation during 6- and 12-hour periods for each month [12]. Another variable, the location of the observation point, could be considered to be in this category also.

Variables from the PE model output included forecast fields of the following at 6-hour intervals: mean relative humidity in the column from the surface to between 500 mb and 400 mb; quantitative precipitation; vertical velocities at 1000 mb, 850 mb and 500 mb; temperatures at 1000 mb and 500 mb; and wind components at 500 mb.

Forecasts from SAM were hourly and 3-hourly saturation deficits (see pp 8 and 16 of reference [10] for explanations of these terms), sea-level pressures, 1000 mb geostrophic wind components, and indicators of terrain induced vertical velocities for selected hours during the forecast period.

The screening procedure outlined above correlated the predictors with the observed 6- and 12-hour precipitation (an indicator that precipitation had occurred) during the season of interest (October-March for winter and April-September for summer). If precipitation was observed during the period, the predictand was given the value of one; otherwise it was given the value of zero.

The screening technique usually chooses a number of significant parameters for each regression equation. Those selected were the 3-hourly saturation deficits and sea-level pressure forecasts during the forecast period from SAM, and the 6-hourly mean relative humidity and quantitative precipitation forecasts from the PE model. Invariably, one of the SAM saturation deficit forecasts was chosen first. This variable was available in a continuous form and in a binary form. Interestingly enough, the binary form was always the one selected for any period in any season. This indicates that non-linear relationships exist that can be explained by the binary form that can not be explained by the continuous form. Use of initial data and climatology resulted in very little increase in the multiple correlation coefficient over that for the forecast variables alone.

SEASONAL REGRESSION EQUATIONS

One year of operations is covered by this article, July 1, 1968, to June 30, 1969. Portions of three seasons are involved--summer 1968, winter 1968-69, and summer 1969. Each season has its own set of regression equations. A set consists of three equations, one each for: the first 6-hour period, 1200-1800 GMT (0000-0600 GMT); the second 6-hour period, 1800-2400 GMT (0600-1200 GMT); and the 12-hour period, 1200-2400 GMT (0000-1200 GMT).

Summer 1968

The generalized equations are based on developmental data from 100 stations for 72 days from April through October 1967. A total of 81 predictors were tested. None of these were PE model forecasts. Those chosen by the screening regression program are shown in table 1. The binary predictors enter into the equations in the form of a series of yes-no questions. A "yes" answer results in that term being included as a contribution while a "no" answer results in the term being dropped. The "contribution" due to a particular binary predictor X_i being one is the regression coefficient a_i, and the constant, which is always included as a contribution, is a_o.

Table 1. Summer 1968 regression equations for PoP forecasting. S_d is 3-hourly saturation deficit in meters and SLP is sea-level pressure in mb.

a. 6-hour PoP, 1200-1800 GMT (0000-0600 GMT)

	Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1)	Constant	1.02	
2)	SAM $S_d \leq 30$ at 18Z (06Z)	14.06	.2243
3)	SAM $S_d \leq -7.5$ at 15Z (03Z)	18.62	.2609
4)	SAM $S_d \leq 105$ at 21Z (09Z)	8.95	.2805
5)	SAM $S_d \leq 45$ at 15Z (03Z)	9.74	.2864
6)	SAM $S_d \leq -15$ at 15Z (03Z)	12.67	.2920
7)	SAM SLP $\leq$ 1010 at 15Z (03Z)	12.32	.3001

(Probability Range is 1% to 77%)

b. 6-hour PoP, 1800-2400 GMT (0600-1200 GMT)

	Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1)	Constant	1.01	
2)	SAM $S_d \leq 60$ at 21Z (09Z)	9.34	.1856
3)	SAM $S_d \leq -7.5$ at 21Z (09Z)	16.29	.2305
4)	SAM $S_d \leq -22.5$ at 21Z (09Z)	26.19	.2417
5)	SAM $S_d \leq 90$ at 24Z (12Z)	10.59	.2528
6)	SAM $S_d \leq 30$ at 21Z (09Z)	8.22	.2564
7)	SAM SLP $\leq$ 1015 at 21Z (09Z)	7.63	.2657

(Probability Range is 1% to 79%)

c. 12-hour PoP, 1200-2400 GMT (0000-1200 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	0.40	
2) SAM $S_d \leq 45$ at 18Z (06Z)	20.90	.2877
3) SAM $S_d \leq -7.5$ at 18Z (06Z)	11.44	.3211
4) SAM $S_d \leq 90$ at 24Z (12Z)	14.05	.3460
5) SAM $S_d \leq -15$ at 15Z (03Z)	17.19	.3526
6) SAM $S_d \leq 15$ at 21Z (09Z)	11.72	.3572
7) SAM $S_d \leq 210$ at 24Z (12Z)	4.87	.3596
8) SAM SLP ≤ 1010 at 21Z (09Z)	17.75	.3744

(Probability Range is 0% to 98%)

Winter 1968-69

The generalized equations are based on developmental data for 80 stations for 139 days from October 1967 through March 1968. A total of 99 predictors were examined in the final regression screening. These include various forecasts produced by both SAM and the PE model. Those chosen by the program are shown in table 2. Again, the binary predictors enter into the equations in the form of a series of yes-no questions.

Table 2. Winter 1968-69 regression equations for PoP forecasting. S_d is 3-hourly saturation deficit in meters, SLP is sea-level pressure, and PE precipitation amounts are in inches.

a. 6-hour PoP, 1200-1800 GMT (0000-0600 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	34.68	
2) SAM $S_d \leq 0$ at 15Z (03Z)	15.85	.3388
3) PE 12-hr precipitation $\leq .10$ at 24Z (12Z)	-13.71	.3999
4) SAM $S_d \leq -7$ at 15Z (03Z)	13.54	.4155
5) SAM $S_d \leq 60$ at 18Z (06Z)	6.65	.4254
6) SAM SLP ≤ 1010 at 18Z (06Z)	6.06	.4305
7) PE 6-hr precipitation $\leq .20$ at 18Z (06Z)	-12.12	.4343
8) PE mean relative humidity $\leq 70\%$ at 18Z (06Z)	- 3.48	.4377
9) SAM $S_d \leq -15$ at 15Z (03Z)	8.74	.4390
10) PE 12-hr precipitation = 0 at 24Z (12Z)	- 5.02	.4402
11) SAM $S_d \leq 105$ at 15Z (03Z)	3.85	.4414

(Probability Range is 0% to 89%)

b. 6-hour PoP, 1800-2400 GMT (0600-1200 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	41.25	
2) SAM $S_d \leq 15$ at 21Z (09Z)	8.83	.2750
3) PE 12-hr precipitation $\leq .10$ at 24Z (12Z)	- 5.55	.3312
4) SAM $S_d \leq -15$ at 21Z (09Z)	18.45	.3495
5) PE mean relative humidity $\leq 80\%$ at 24Z (12Z)	- 4.13	.3655
6) SAM $S_d \leq 75$ at 21Z (09Z)	9.30	.3720
7) PE 12-hr precipitation $\leq .40$ at 24Z (12Z)	-10.20	.3778
8) PE mean relative humidity $\leq 90\%$ at 24Z (12Z)	- 7.60	.3801
9) SAM $S_d \leq -7$ at 15Z (03Z)	7.32	.3823
10) PE mean relative humidity $\leq 70\%$ at 24Z (12Z)	- 4.78	.3835
11) PE 12-hr precipitation $\leq .20$ at 24Z (12Z)	- 7.44	.3845

(Probability Range is 2% to 85%)

c. 12-hour PoP, 1200-2400 GMT (0000-1200 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	42.67	
2) SAM $S_d \leq 0$ at 18Z (06Z)	10.73	.3606
3) PE 12-hr precipitation $\leq .05$ at 24Z (12Z)	- 7.68	.4334
4) SAM $S_d \leq 75$ at 21Z (09Z)	10.19	.4529
5) SAM $S_d \leq -5$ at 15Z (03Z)	12.68	.4669
6) PE mean relative humidity $\leq 70\%$ at 18Z (06Z)	- 6.33	.4761
7) PE 12-hr precipitation $\leq .20$ at 24Z (12Z)	-12.97	.4817
8) SAM SLP ≤ 1015 at 18Z (06Z)	6.44	.4863
9) SAM $S_d \leq 45$ at 15Z (03Z)	8.63	.4889
10) PE mean relative humidity $\leq 90\%$ at 24Z (12Z)	- 7.36	.4912
11) SAM $S_d \leq -15$ at 15Z (03Z)	8.62	.4925
12) PE 12-hr precipitation = 0 at 24Z (12Z)	- 6.42	.4937

(Probability Range is 2% to 100%)

Summer 1969

The generalized equations are based on developmental data for 99 stations for 129 days from July through September 1967 and April through September 1968. A total of 99 predictors were examined in the final regression screening. These include various forecasts produced by both SAM and the PE model. Those chosen by the program are shown in table 3. As in tables 1 and 2, the binary predictors enter into the equations in the form of a series of yes-no questions.

Table 3. Summer 1969 regression equations for PoP forecasting. S_d is 3-hourly saturation deficit in meters, SLP is sea-level pressure, and PE precipitation amounts are in inches.

a. 6-hour PoP, 1200-1800 GMT (0000-0600 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	24.87	
2) SAM $S_d \leq 30$ at 18Z (06Z)	7.89	.2173
3) PE 6-hr precipitation $\leq .05$ at 18Z (06Z)	- 8.64	.2537
4) SAM $S_d \leq -7$ at 15Z (03Z)	15.80	.2751
5) PE mean relative humidity $\leq 75\%$ at 18Z (06Z)	- 6.99	.2886
6) PE mean relative humidity $\leq 95\%$ at 24Z (12Z)	- 8.10	.2927
7) SAM $S_d \leq 45$ at 21Z (09Z)	8.39	.2959
8) SAM $S_d \leq 15$ at 15Z (03Z)	9.54	.2990
9) SAM $S_d \leq -15$ at 15Z (03Z)	12.49	.3012
10) SAM SLP ≤ 1010 at 18Z (06Z)	4.84	.3027

(Probability Range is 1% to 84%)

b. 6-hour PoP, 1800-2400 GMT (0600-1200 GMT)

Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1) Constant	26.73	
2) SAM $S_d \leq 60$ at 24Z (12Z)	11.51	.1449
3) PE mean relative humidity $\leq 85\%$ at 24Z (12Z)	-10.54	.1855
4) SAM $S_d \leq -15$ at 24Z (12Z)	22.12	.1993
5) SAM $S_d \leq 120$ at 24Z (12Z)	6.52	.2081
6) SAM SLP ≤ 1015 at 18Z (06Z)	5.20	.2135
7) PE 12-hr precipitation $\leq .20$ at 24Z (12Z)	- 9.03	.2169
8) PE mean relative humidity ≤ 70 at 24Z (12Z)	- 6.49	.2203

(Probability Range is 1% to 72%)

c. 12-hour PoP, 1200-2400 GMT (0000-1200 GMT)

	Predictor	Contribution to PoP (%)	Cumulative Reduction of Variance
1)	Constant	31.09	
2)	SAM $S_d \leq 45$ at 21Z (09Z)	10.76	.2233
3)	PE mean relative humidity $\leq 75\%$ at 24Z (12Z)	- 5.02	.2780
4)	PE 6-hr precipitation $\leq .05$ at 18Z (06Z)	- 7.66	.2954
5)	SAM SLP ≤ 1015 at 18Z (06Z)	4.81	.3051
6)	SAM $S_d \leq -5$ at 18Z (06Z)	12.55	.3133
7)	SAM $S_d \leq 105$ at 18Z (06Z)	7.38	.3203
8)	PE mean relative humidity $\leq 90\%$ at 24Z (12Z)	-10.60	.3252
9)	PE mean relative humidity $\leq 70\%$ at 24Z (12Z)	- 8.11	.3271
10)	SAM $S_d \leq 45$ at 18Z (06Z)	9.09	.3290
11)	SAM SLP ≤ 1010 at 18Z (06Z)	6.87	.3305
12)	SAM $S_d \leq -15$ at 24Z (12Z)	10.43	.3319
13)	SAM SLP ≤ 1020 at 18Z (06Z)	3.80	.3332

(Probability Range is 0% to 97%)

The multiple correlation coefficient with each added predictor is given by the square root of the corresponding cumulative reduction of variance.

Since a separate equation is used for each of the three forecast periods, the 12-hour PoP may not be consistent with the two 6-hour PoPs covering the same 12-hour period. When these inconsistencies occur in the set of probabilities forecast at a grid point, the following adjustments are made:

a. If either or both of the 6-hour PoPs exceed the 12-hour PoP, either or both are reduced to the value of the 12-hour PoP.

b. If the 12-hour PoP is larger than the sum of the two 6-hour PoPs, the 12-hour PoP is reduced by one-half the difference and each of the 6-hour PoPs is increased by one-quarter of the difference.

The ranges shown in tables 1, 2, and 3 are unadjusted. Therefore, it is possible for the final forecast to fall outside the range shown.

When only SAM predictors were available in summer 1968 (see table 1), the saturation deficits were far more important than the sea-level pressures. In the later months, when the various forecast fields from the PE model were also available, several of these fields were chosen but none as a first predictor. It was found that for the winter 1968-69 equations, the SAM predictors alone gave about 3 percent greater reduction of variance than the PE predictors alone. Also, it was found that by allowing both SAM and PE predictors to be available, about 3 percent greater reduction of variance was shown than for the

SAM alone. These figures were obtained on dependent data but quite likely independent data would indicate about the same thing. Thus the decision was made to include the PE forecast information along with the SAM predictions.

Both the mean relative humidities and the precipitation amounts from the PE model were chosen frequently. It is interesting that several PE vertical velocity fields were screened but not once was any of them chosen. This indicates that the vertical velocity predictions, in their present form, offer no help in forecasting PoP after the other fields are known.

In general, the screening regression program had available as possible predictors fields valid before, during, and after the predictand verification period. It is encouraging that most of the fields chosen were forecasts for the period of interest rather than before or after the period. This indicates certain favorable features concerning the timing of forecasts produced by the numerical models.

Seasonal variations are apparent from tables 1, 2, and 3. The reduction of variance figures are higher (better) in winter than in summer. This is to be expected because of the convective nature of the summer precipitation.

OPERATIONAL TRANSMISSIONS

At the present time, two scheduled SAM runs are made each day, one to cover the "today" period and one to cover the "tonight" period. Information from the most recent PE operational run is available on a history tape during each SAM run.

Two methods of transmitting the SAM/PE PoP forecasts from NMC to the users are being used. These are the Service "C" teletypewriter service and the FOFAX facsimile circuit. Service "C" has a fairly large user coverage while FOFAX is rather limited.

A portion of a typical "today" period teletypewriter bulletin is shown in figure 2. Transmission times for the 79-station SAM bulletin are 0839 and 2039 GMT daily. A station list with call letters is given by Glahn, Lowry, and Hollenbaugh [10]. PoP forecasts contained in the bulletin (last three groups for each station) include a 12-hour prediction (three digits), the first 6-hour prediction (two digits), and the last 6-hour prediction (two digits). The values shown are the adjusted regression estimates rounded to the nearest percent. As an example (see fig. 2), the PoP forecast for Caribou, Maine, is 21 percent for the 12-hour "today" period. The PoP prediction for the first 6 hours (1200-1800 GMT) of the same period is 5 percent and the forecast is 18 percent for the second 6 hours (1800-2400 GMT).

The bulletins also contain predictions of saturation deficit and 1000-mb geostrophic winds. These are direct output from SAM and are explained in detail in another Technical Memorandum [10].

```
ZCZC
FOUS KWBC 030800
SAM FORECASTS
         15Z            18Z            21Z            00Z        POP 12 6 6
CAR 049 0204    058 0506    068 0508    080 0509    021 05 13
BTV 060 3105    057 3604    059 0405    066 0507    018 08 13
PWM 113 3207    116 3205    117 3503    117 0304    010 02 09
BOS 116 0106    124 0204    127 0303    130 0503    007 01 06
PVD 102 0406    109 0406    116 0405    121 0504    008 01 07
BDL 105 0304    107 0203    107 0203    107 0403    005 01 04
LGA 084 0512    096 0409    108 0406    115 0405    010 02 08
ALB 101 3003    092 3303    085 0204    082 0406    010 02 08
BGM 064 2705    050 3103    041 0203    043 0505    021 09 13
SYR 056 2703    046 3402    046 0304    055 0505    017 04 14
BUF 010 3002    014 0302    027 0704    044 0807    031 26 19
CLE 031 1806    019 1706    015 1306    017 1108    030 15 19
DTW 009 1408    017 1109    028 1010    041 1010    032 26 20
BTL 013 1010    027 0910    043 1009    057 1208    034 25 23
FWA 010 2103    014 1002    023 0905    031 1106    036 27 24
IND 030 2507    025 2404    020 1903    -02 1606    036 17 24
CVG 048 2511    033 2411    020 2409    -02 2207    033 15 22
SDF 063 2411    045 2312    -00 2212    -06 2111    027 10 19
```

Figure 2.--A portion of a typical SAM teletypewriter bulletin showing PoP forecasts as derived from Model Output Statistics (MOS). Saturation deficit and 1000-mb geostrophic wind forecasts direct from SAM are also shown. This example is for the same case as shown in figures 3 and 4.

The upper two panels of the SAM facsimile transmission are shown in figure 3. These transmissions are sent on FOFAX at 0849 and 2045 GMT daily. Only the solid isolines on the left panel are PoP predictions. These are 12-hour forecasts and should agree with those values transmitted for cities on the SAM teletypewriter bulletin (see fig. 2). In case of an apparent inconsistency, it is better to accept the teletypewriter report unless there has been an obvious transmission error. The specific isolines depicted on PoP charts are 5, 15, 25, ..., 75, 85, 95 percent. Details concerning other forecast fields shown in figure 3 are given elsewhere [10].

The lower two panels of the SAM facsimile transmission are shown in figure 4. Again, only the solid isolines are PoP predictions. The left panel shows forecasts for the first 6-hour period (1200-1800 GMT), while the right panel includes the predictions for the second 6-hour period (1800-2400 GMT). Dashed isolines, when they appear, represent forecasts of conditional probability of frozen precipitation [6] and are not discussed here.

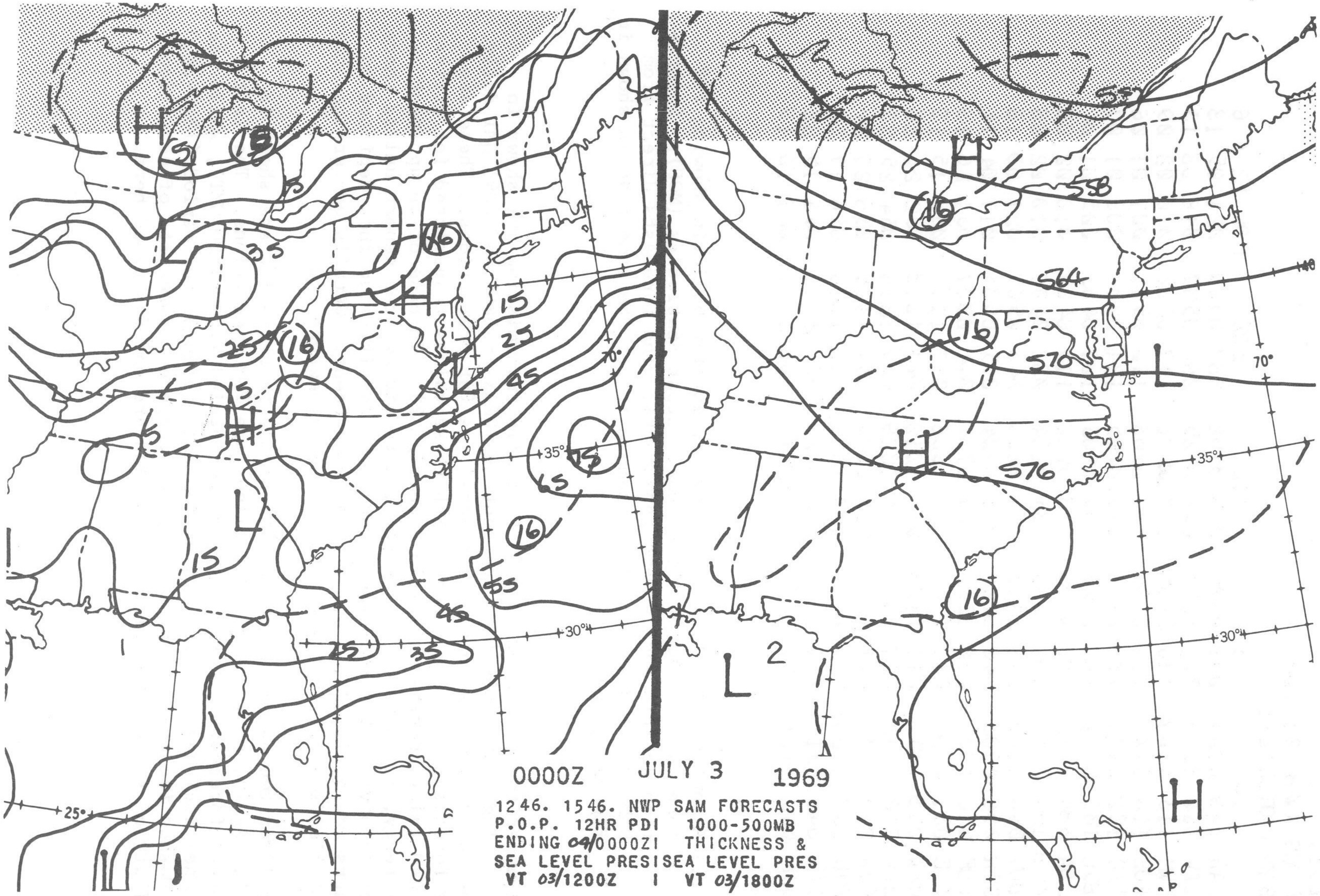

Figure 3.--The upper two panels of a typical SAM facsimile transmission showing a 12-hour PoP forecast on the left panel (solid isolines). Other forecasts direct from SAM are sea-level pressure and 1000-500-mb thickness. This example, from July 3, 1969, is referred to as a 0000 GMT run because that was the time of the initial upper-air input data.

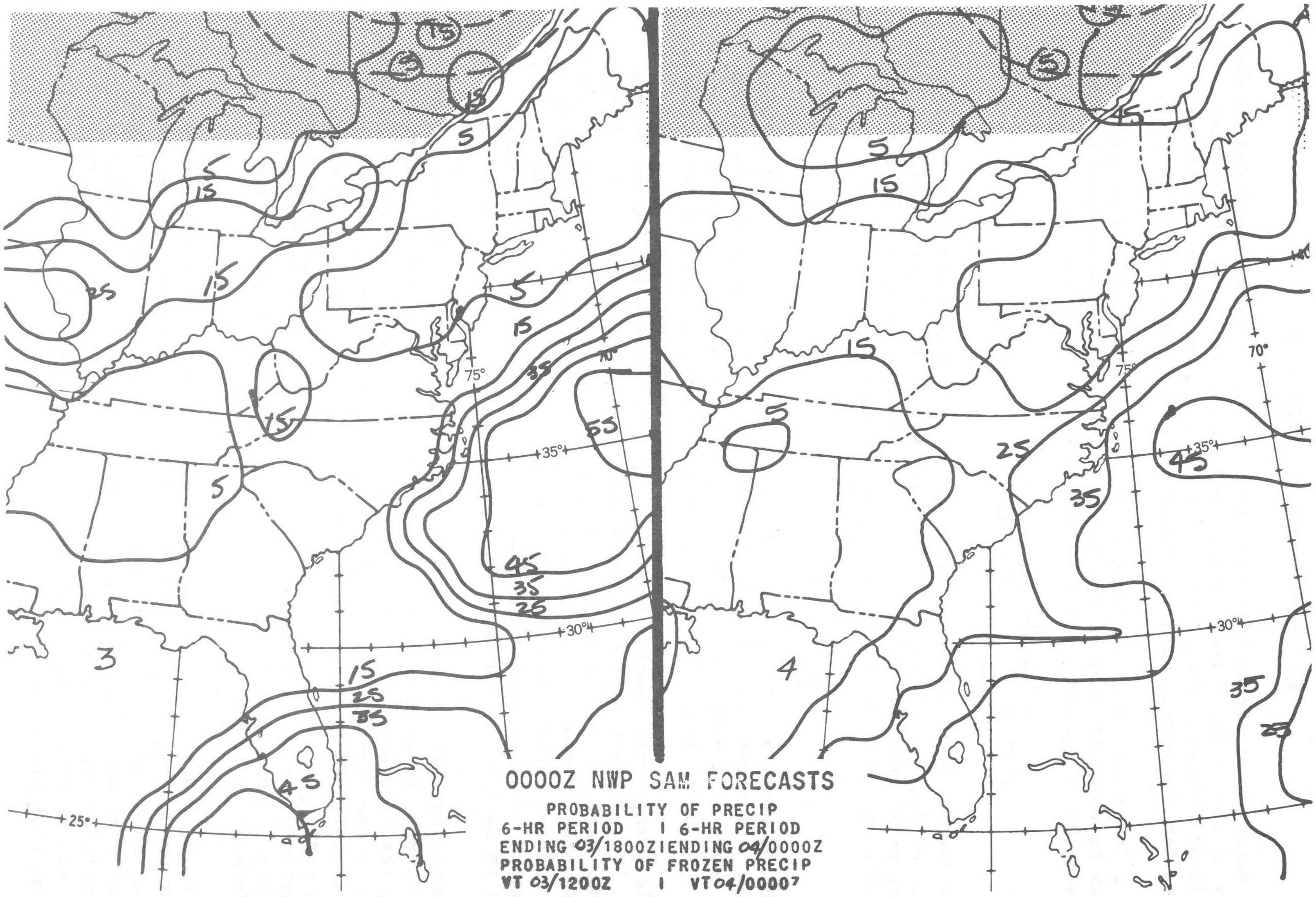

Figure 4.--The lower two panels of a typical SAM facsimile transmission showing two 6-hour PoP forecasts (each panel, solid isolines). Dashed isolines, when they appear, indicate conditional probability of frozen precipitation. This example is for the same case as shown in figures 2 and 3.

ACCURACY OF THE POP FORECASTS

The accuracy of the machine produced PoP forecasts was compared to the accuracy of the official forecasts issued to the public by the Weather Bureau local offices. Verification figures covering a 1-year span are presented for the eastern United States for the 12-hour "today" period.

The Brier score is in common use throughout the Weather Bureau as the yardstick by which to measure the goodness of probability forecasts. This score is ½ the "P" score defined by Panofsky and Brier [20] as

$$P = \frac{1}{N} \sum_{j=1}^{r} \sum_{i=1}^{N} (f_{ij} - E_{ij})^2$$

where on each of N occasions an event can occur in only one of r possible classes, and f_{i1}, f_{i2}, ..., f_{ir} represent the forecast probabilities that the event will occur in classes 1, 2, ..., r, respectively. If the r classes are chosen to be mutually exclusive and exhaustive,

$$\sum_{j=1}^{r} f_{ij} = 1$$

for each and every i = 1, 2, ..., N. E_{ij} takes the value 1 or 0 according to whether the event occurred in class j or not. For perfect forecasting the "P" score will have a value of zero and for the worst possible forecasting a value of two. The Brier score, then, has a range of zero to one.

Table 4 shows the monthly breakdown of Brier scores by Weather Bureau Region. Five Eastern Region stations were used (Washington, D. C., Boston, Mass., New York, N. Y., Raleigh, N. C., and Cleveland, Ohio); four Southern Region stations (Miami, Fla., Atlanta, Ga., New Orleans, La., and Memphis, Tenn.); and two Central Region stations (St. Louis, Mo., and Chicago, Ill.). The 12-month averages showed the SAM/PE forecasts to be slightly more accurate in each of the three regions than the local forecasts.

Seasonal variations are apparent from table 4 but can be seen better in figure 5 where the monthly scores for all regions combined are shown. In general, the forecasts are shown to be more accurate in the winter and less accurate in the summer. This is due to the relative difficulty of forecasting convective precipitation which occurs predominately in summer. For the most part, the local and the SAM/PE scores are in phase (i.e. rise and fall together). Exceptions were the months of December 1968 and March 1969. Again, this in-phase relationship is tied to the difficulty factor which varies from month to month.

The Brier score alone does not show the reliability of the forecasts in different probability ranges. Table 5 shows the number of SAM/PE forecasts in a given range and the number of times precipitation occurred. Eight additional stations were added to the previously listed 11 for this portion of the verification. The cities are Norfolk, Va., Jacksonville, Fla., Jackson, Miss., Albany, N. Y., Charleston, S. C., Buffalo, N. Y., Nashville, Tenn., and Louisville, Ky.

Table 4. Brier scores for one year of PoP forecasts for the 12-hour "today" period (1200-2400 GMT). Objective forecasts for July, August, and September used only SAM predictors. Later forecasts were based on SAM and PE predictors. Five Eastern Region, four Southern Region, and two Central Region stations were used. The total number of forecasts was 3682.

		EASTERN REGION		CENTRAL REGION		SOUTHERN REGION		ALL REGIONS	
		LOCAL	SAM/PE	LOCAL	SAM/PE	LOCAL	SAM/PE	LOCAL	SAM/PE
1968	July	.1258	.1248	.1157	.1429	.1749	.1942	.1419	.1534
	August	.1216	.1073	.1090	.1007	.1574	.1608	.1323	.1256
	September	.0817	.0878	.1026	.1114	.1208	.1140	.0997	.1016
	October	.0831	.0784	.0487	.0615	.1062	.0890	.0852	.0792
	November	.0912	.1004	.1279	.0910	.1084	.0793	.1041	.0910
	December	.1101	.1221	.0945	.1099	.0679	.0553	.0919	.0956
1969	January	.0963	.0776	.1243	.0916	.1055	.1016	.1047	.0889
	February	.0820	.0913	.0878	.0694	.0921	.0685	.0867	.0790
	March	.0770	.0939	.0504	.0673	.0731	.0779	.0707	.0832
	April	.0937	.0687	.0959	.0632	.0903	.0915	.0928	.0760
	May	.0941	.0811	.1419	.1279	.1263	.0941	.1145	.0944
	June	.1428	.1346	.1583	.1499	.1256	.1405	.1394	.1395
	Average	.1000	.0973	.1048	.0989	.1124	.1056	.1053	.1006

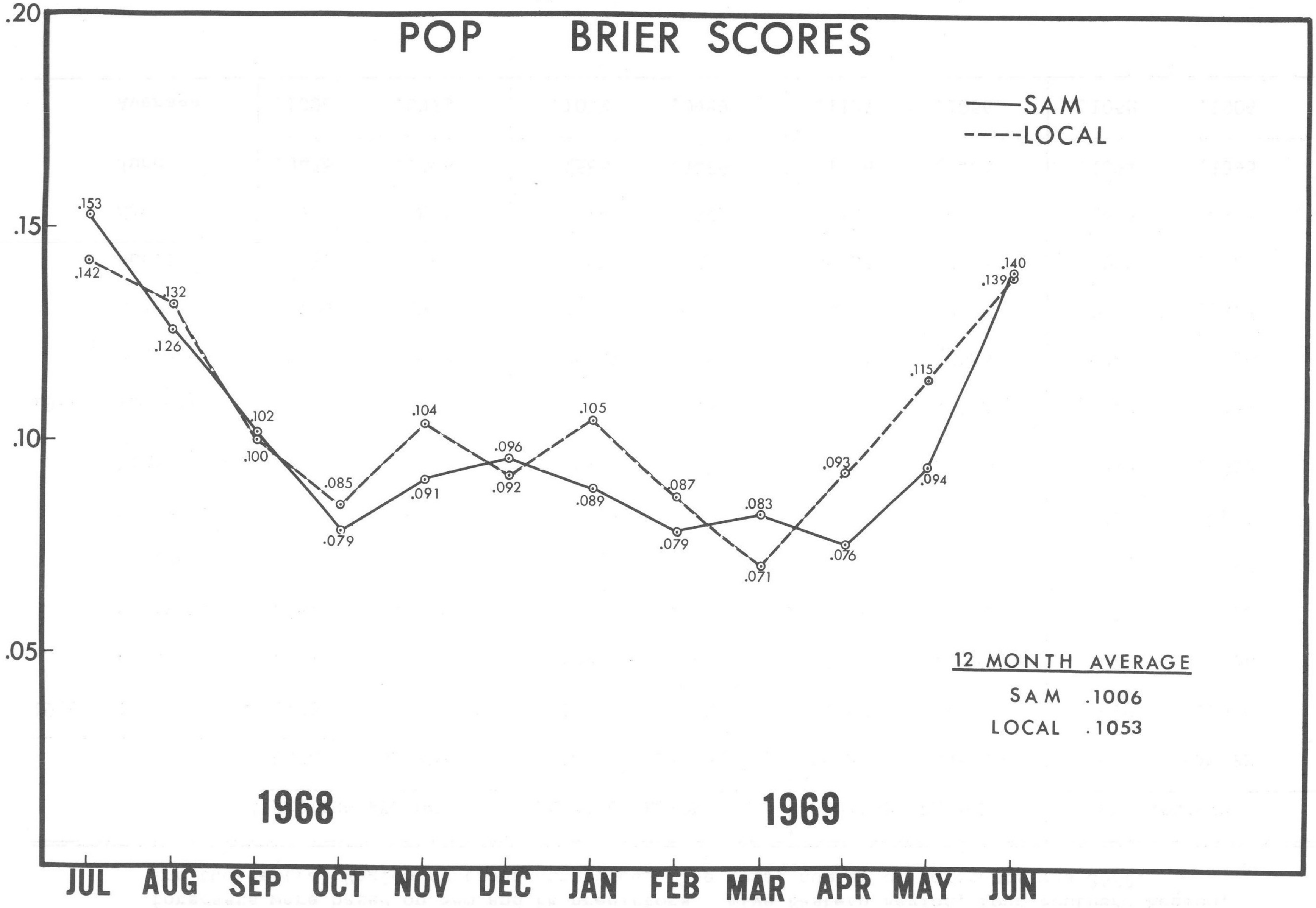

Figure 5.--Comparative verification of SAM/PE and local forecasts for 12-hour "today" period. The number of forecasts was 3682, representing 11 stations.

Table 5. Distribution of SAM/PE PoP forecasts covering the 12-hour "today" period (1200-2400 GMT). "A" is the number of forecasts in a given range; "B" is the number of times precipitation occurred. The total number of forecasts was 6361 from 19 stations for a 1-year period (July 1968-June 1969).

	$.00 \le P \le .04$		$.05 \le P \le .09$		$.10 \le P \le .19$		$.20 \le P \le .29$		$.30 \le P \le .39$		$.40 \le P \le .49$		$.50 \le P \le .59$		$.60 \le P \le .69$		$.70 \le P \le .79$		$.80 \le P \le .89$		$.90 \le P \le 1.00$	
MONTH	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
July	38	0	251	29	183	55	4	0	3	2	57	29	27	18	3	2	2	1	0	-	0	-
Aug.	30	0	177	16	171	32	2	0	3	0	61	26	26	9	3	1	2	2	0	-	0	-
Sept.	58	0	220	8	91	19	6	2	1	0	28	15	32	22	7	6	6	5	4	4	3	2
Oct.	263	6	88	7	49	15	37	8	16	6	14	8	16	14	14	11	13	10	4	4	18	17
Nov.	242	7	76	9	40	8	27	8	26	12	19	9	25	16	9	6	26	19	5	4	37	36
Dec.	269	13	47	5	36	8	25	12	20	8	18	7	29	17	9	4	22	16	11	10	46	41
Jan.	234	2	54	2	39	7	28	5	21	8	24	7	24	6	16	10	20	13	20	16	33	29
Feb.	255	5	65	5	32	4	34	9	21	7	20	3	20	9	15	10	19	16	17	12	34	32
Mar.	288	7	83	9	49	8	26	11	25	13	21	9	15	8	8	4	13	11	9	7	32	31
Apr.	230	2	68	3	57	11	28	9	19	7	16	6	19	16	15	14	18	16	26	22	16	15
May	265	7	60	5	86	12	56	21	26	11	21	12	16	9	18	15	18	16	4	4	0	-
June	103	5	111	8	131	18	69	20	39	13	44	18	29	13	24	14	12	9	5	3	3	2
TOTAL	2275	54	1300	106	964	197	342	105	220	87	343	149	278	157	141	97	171	134	105	86	222	205

A close inspection of table 5 reveals that some ranges were rarely forecast in a certain season. For example, during the summer of 1968 there were relatively few forecasts in the .00 to .04, the .20 to .39, and the .60 to 1.00 ranges. Correspondingly, there were relatively many forecasts in the .05 to .19 and .40 to .59 ranges. This is probably due to the binary nature of the predictors and the inclusion of a fairly small number of them in the equation. Other equations do not exhibit this same pattern of favoring certain forecast ranges. Table 5 shows clearly the large number of forecasts being made in the very low ranges.

The values from table 5 were used to compute the observed relative frequencies shown in table 6. These figures give an indication as to the reliability of the forecasts. Good reliability is indicated if the figure being examined falls within the range shown at the top of the table. Considerable variation exists from month to month and from range to range. However, the totals show rather good reliability.

Table 6. Observed relative frequency (RF) in percent for given ranges of the SAM/PE PoP forecasts. Values shown are computed using the figures from table 5 where RF = B/A.

	.00 ≤ P ≤ .04	.05 ≤ P ≤ .09	.10 ≤ P ≤ .19	.20 ≤ P ≤ .29	.30 ≤ P ≤ .39	.40 ≤ P ≤ .49	.50 ≤ P ≤ .59	.60 ≤ P ≤ .69	.70 ≤ P ≤ .79	.80 ≤ P ≤ .89	.90 ≤ P ≤ 1.00
MONTH	RF	RF	RF	RF	RF	RF	RF	RF	RF	RF	RF
July	.00	.12	.30	.00	.67	.51	.67	.67	.50	-	-
August	.00	.09	.19	.00	.00	.43	.35	.33	1.00	-	-
September	.00	.04	.21	.33	.00	.54	.69	.86	.83	1.00	.67
October	.02	.08	.31	.22	.38	.57	.88	.79	.77	1.00	.94
November	.03	.12	.20	.30	.46	.47	.64	.67	.73	.80	.97
December	.05	.11	.22	.48	.40	.39	.59	.44	.73	.91	.89
January	.01	.04	.18	.18	.38	.29	.25	.63	.65	.80	.88
February	.02	.08	.13	.26	.33	.15	.45	.67	.84	.70	.94
March	.02	.11	.16	.42	.52	.43	.53	.50	.85	.78	.97
April	.01	.04	.19	.32	.37	.38	.84	.93	.89	.85	.94
May	.03	.08	.14	.38	.42	.57	.56	.83	.89	1.00	-
June	.05	.07	.14	.29	.33	.41	.45	.58	.75	.60	.67
TOTAL	.02	.08	.20	.31	.40	.43	.56	.69	.78	.82	.92

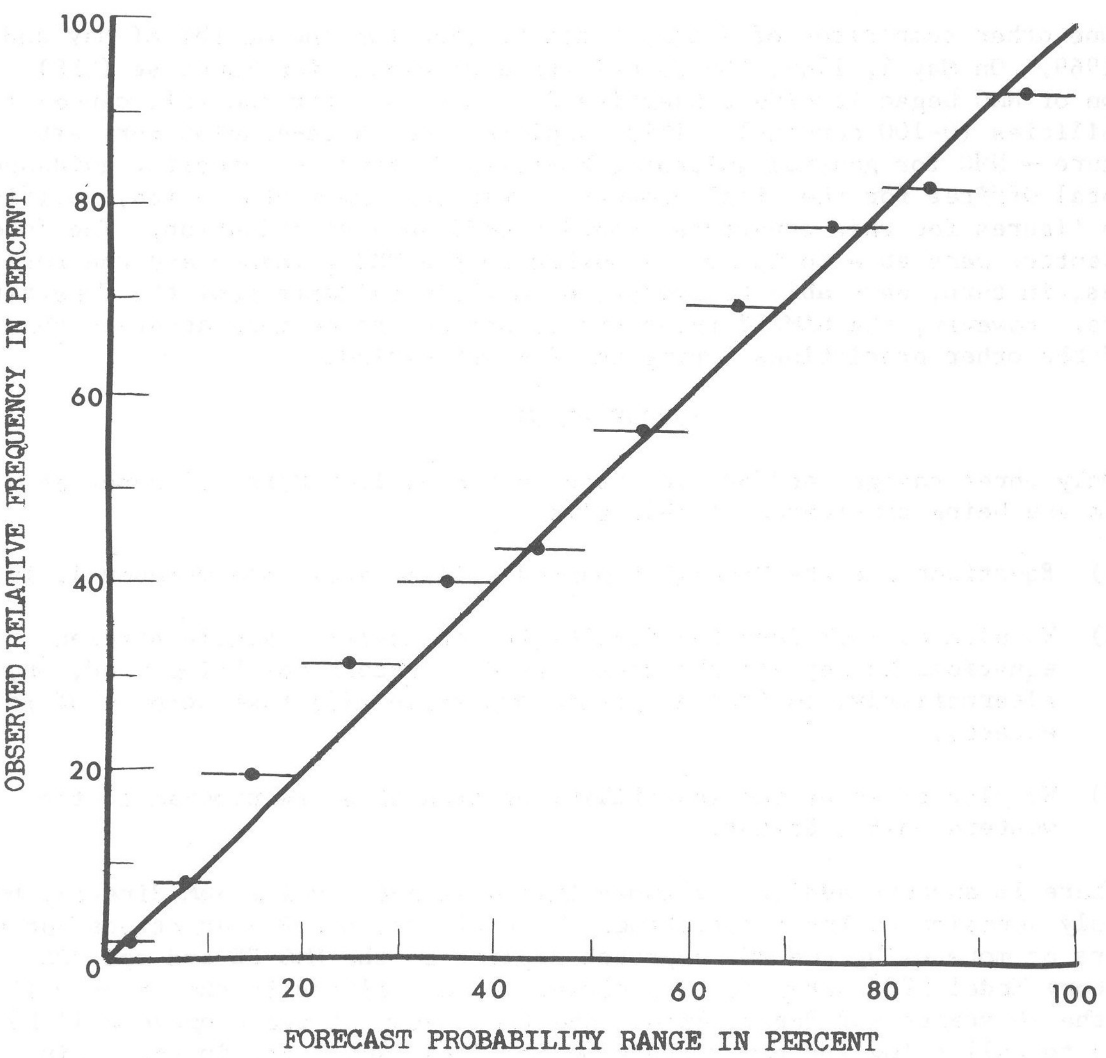

Figure 6.--Reliability of SAM/PE forecasts of PoP for 12-hour "today" period. The number of forecasts was 6361, representing 19 stations over a 1-year span. Each horizontal line represents the forecast interval over which the corresponding observed relative frequency was calculated.

Figure 6 gives a graphical presentation of the totals. The diagonal represents perfect reliability. If the short horizontal lines (which, together, represent the full forecast probability range) intersect or touch the diagonal, this indicates favorable reliability. If the forecasts within a given range are assumed to be centered about the mid-point (shown as dots on fig. 6) and if the ranges are weighted according to the number of forecasts they contain, the forecasts were, on the average, 1.6 percent too high. This is considered to be insignificant, especially in view of the fact that Weather Bureau offices normally round probability forecasts to the nearest 10 percent. SAM/PE probability forecasts are made to the nearest percent and there is no indication that this is hurting the forecasts. The slight overforecasting may not hold true for future seasons since new equations will be derived from different samples.

One other comparison of interest can be made for the months of May and June 1969. On May 1, 1969, the Quantitative Precipitation Forecast (QPF) Section of NMC began issuing subjective PoP forecasts for the full range of probabilities (0-100 percent). This completed the three-echelon forecast structure — NMC for general guidance, Forecast Centers for specific guidance, and Local Offices for the final product. Over the two month period, verification figures for this structure showed a desirable distribution. The Forecast Centers were able to improve somewhat on the NMC guidance and the Local Offices, in turn, were able to improve upon their guidance from the Forecast Centers. However, the SAM/PE forecasts turned out to be more accurate than any of the other predictions during the 2-month period.

FUTURE PLANS

Only three changes and/or additions in the basic SAM/PE PoP forecast program are being considered at this time.

1) Equations for the "tonight" period will be available October 1, 1969.

2) We plan to look into the feasibility of deriving single station equations to replace the generalized operators now being used, or, alternatively, to include predictors which will take account of local effects.

3) We plan to study the feasibility of extending the program to the western United States.

There is another addition planned that does not involve SAM directly but certainly pertains to PoP forecasting. We will extend PoP predictions out to 48 hours or more using the MOS approach applied to the NMC PE and the TDL Trajectory Model [22] outputs. The cities to be included in the study will cover the 50 states and Puerto Rico. The first year of the program will be devoted to collecting and error checking the data sample and in developing a number of computer programs necessary for processing it.

CONCLUSIONS

An operational program for objectively forecasting probability of precipitation with computers has been discussed and examined in some detail. The comparative verification figures for July 1968 - June 1969 indicate that the machine produced forecasts were slightly more accurate than the official forecasts issued to the public by Weather Bureau local offices.

ACKNOWLEDGMENTS

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