AN OPERATIONAL SYSTEM FOR AUTOMATED PREDICTION OF PRECIPITATION PROBABILITY

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1. INTRODUCTION AND PROCEDURE

This investigation is an outgrowth of the authors' previous work on predicting daily precipitation (Klein, 1968) and temperature (Klein and Lewis, 1970) by application of the "perfect prog" method. In this technique 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. In this way stable forecasting relations can be derived for individual locations and seasons from a long period of record.

The predictand for the present study was the occurrence (1) or non-occurrence (0) of measurable precipitation during standard 12-hour periods at each of 108 stations of the National Weather Service (Figure 1). A binary variable of this sort yields the probability of precipitation (PoP) when treated by ordinary linear regression (Lund, 1955).

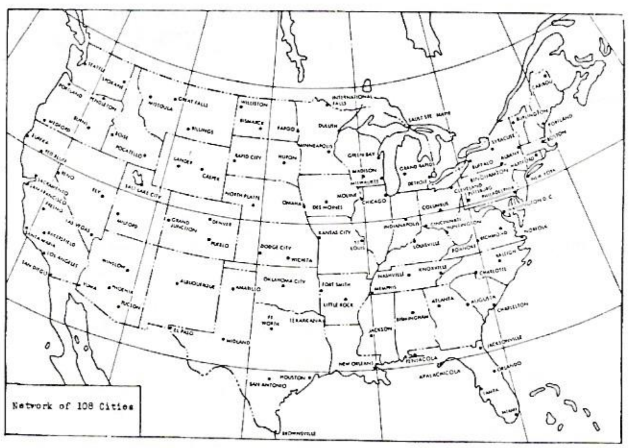

Figure 1. Names and locations of 108 weather stations for which prediction equations were derived.

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 dew-point spread at various levels,
c) a measure of surface weather given by reports of previous precipitation at selected cities.

The first two predictors were obtained from grid point values of objectively analyzed synoptic maps, the third from the same data used for the predictand. The period of record extended from May 1, 1964 through January 31, 1969, and the data were divided into the conventional four seasons.

By means of stepwise regression, a series of experiments was performed in which the precipitation at each city was screened as a function of the three basic sets of predictors. All predictors covered a large geographical area surrounding the predictand station, rather than being limited to local data as in other studies (Russo, 1968; Glahn and Lowry, 1969). For example, Figure 2 locates 48 predictand cities and 182 predictor grid points used for initial experiments in the western United States. All results 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 12-hour forecast period, as illustrated schematically in Figure 3. In order to take account of diurnal differences, two sets of PoP equations were derived, one valid for the daytime, defined as 12Z to 24Z, and the other for nighttime, from 00Z to 12Z.

2. PROPERTIES OF FORECAST EQUATIONS

The effectiveness of height at four

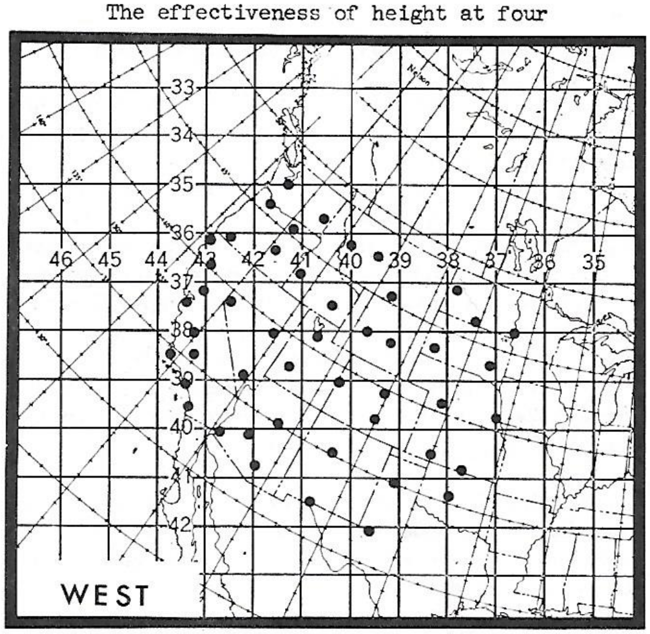

Figure 2. Location of 48 cities and 182 grid points used in initial screening experiments for the West. The rows and columns of the NMC grid points are numbered as shown.

PoP DERIVATION SCHEME

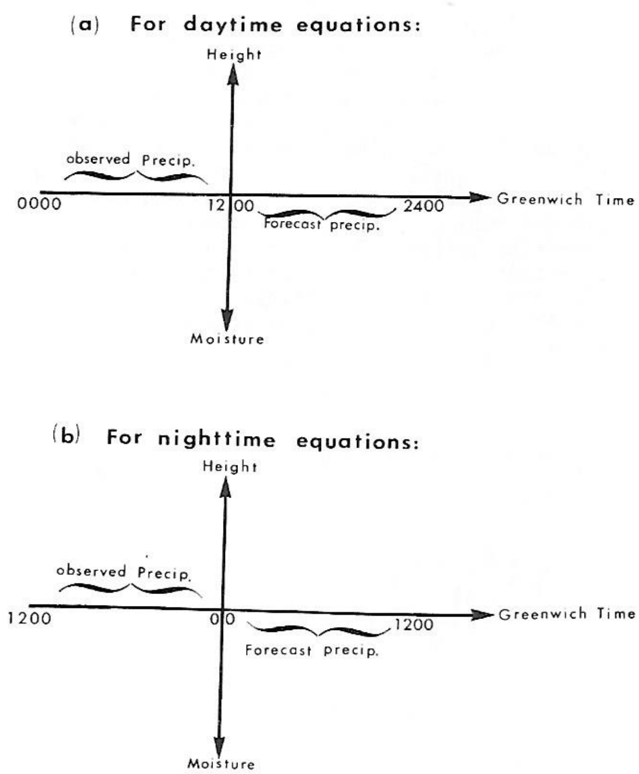

Figure 3. Schematic diagram showing how separate forecast equations were derived for 12-hour periods during day and night as a function of height and moisture at the beginning of the forecast period and precipitation observed during the previous 12 hours.

standard levels from 1000 mb to 500 mb was studied for the winter season. Results indicated that the best level was 850 mb and the worst was 500 mb. Screening of dew-point spread at various levels showed that the most effective level was 700 mb and the poorest was 500 mb. Better results were obtained by taking the mean spread at 850 and 700 mb, but such smoothing in the vertical produced no improvement in the case of height. In general, the results achieved by screening the moisture predictors were about equal to those achieved with the fields of height and almost as good as those obtained by considering prior 12-hour precipitation reports over the network of cities. The latter variable, which incorporates the effects of local persistence and upstream weather, was the best single predictor of PoP on an overall basis. Various combinations of the three predictor fields were also tested by screening, and it was concluded that the most useful combination consisted of 850-mb height, 850-700 mb mean dew-point spread, and prior 12-hour precipitation.

The above three predictors were combined to derive multiple regression equations for daytime and nighttime PoP at each of 108 cities for winter, spring, and fall seasons. On the average, the equations produced a standard error of estimate (SE) of about 30% and explained approximately 40% of the precipitation variance (RV) by means of about six variables, 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. Seasonal and diurnal variations in these characteristics were relatively small, as illustrated in Table 1.

Table 1.

Characteristics of multiple regression equations for predicting probability of precipitation from 850-mb height, 850-700 mb mean dew-point spread, and prior precipitation 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

The winter equation for Atlanta, Ga. is illustrated in Figure 4. The first predictor selected was the 850-700 mb mean dew-point spread just west of the station. By itself, it would explain 32.6% of the variance of PoP and produce a standard error of 35.0% in the probability forecasts. The second predictor was the 850-mb height at the same grid point. Taken jointly with the first, it increased the RV to 34.8% and lowered the SE to 34.5%. The third predictor was the 850-mb height in South Carolina. In conjunction with 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. The fourth and fifth predictors were precipitation during the previous 12 hours at New Orleans, La. and Memphis, Tenn., thereby demonstrating the importance of upstream weather. The screening process was stopped at this point, with an RV of 53.0% and an SE of 29.2%, since no other predictor could make a significant contribution to PoP.

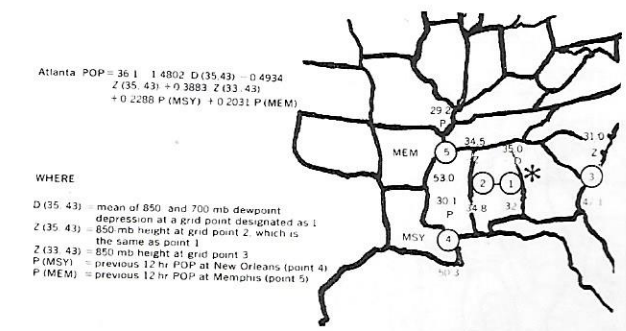

Figure 4. Operational equation for daytime PoP (in per cent) at Atlanta (asterisk) during winter. The numbers inside the circles denote the order of predictor selection, and the numbers above and below give the standard error and reduction of variance (both in per cent) at each step of the screening process.

Figure 5 shows the geographical variation of the standard error of the regression equations during winter. Values range from over 40% in parts of the Great Lakes and Pacific Northwest to less than 20% in the Southwest desert. The isopleths of SE in this figure can be relabeled

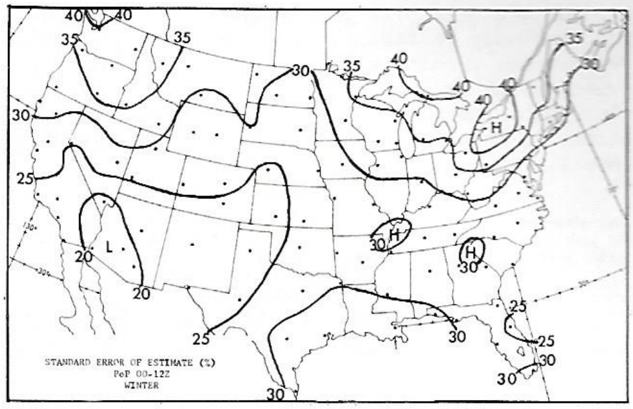

Figure 5. Standard error of estimate (in per cent) for operational equations for nighttime PoP during winter. Centers of high and low values are labelled H and L. Locations of 108 predictand cities are shown by dots, but individual values are not plotted.

in terms of the standard P-score (Brier, 1950) if they are converted to decimal form and squared (Klein, 1971). This conversion gives values of the P-score (hereafter called Brier score) which would be obtained if the regression equations were used to make forecasts of PoP on the dependent data from which the equations were derived. These Brier scores would range from less than .04 in the Southwest to more than .16 in the Great Lakes.

Figure 6 maps winter values of the reduction of variance. The RV 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. These isopleths of RV also indicate the percent improvement over climatology yielded by the regression equations on the developmental sample (Hughes, 1970; Klein, 1971). This improvement varies from less than 30% to more than 60% in different parts of the country.

3. OPERATIONAL SYSTEM

By means of the equations discussed in the preceding section, PoP forecasts are being prepared at the National Meteorological Center (NMC) twice a day on an experimental basis for periods 12 to 60 hours in advance. A sample computer output is illustrated in Figure 7. The forecast system, illustrated in Table 2, uses as input to the regression equations numerical forecasts of 850-mb height obtained from the NMC primitive equation (PE) model (Shuman and Hovermale, 1968), as well as 850-mb and 700-mb dew-point spreads obtained from a laminated moisture modification of this PE model. Precipitation input consists of observed 6-hour amounts transmitted over teletype and monitored by the NMC automatic data processing system. The same equations are used in 12-hour steps by means by means of an iterative process, so that the system uses its own forecasts of PoP made in one step as input to the next step.

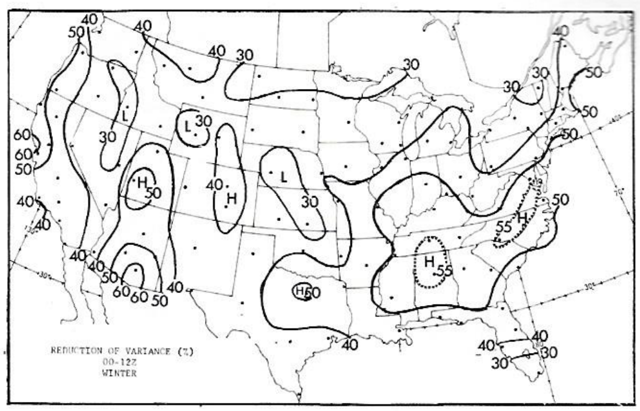

Figure 6. Reductions of variance (in per cent) of operational equations for nighttime PoP during winter. Centers of high and low values are labelled H and L. Locations of 108 predictand cities are shown by dots, but individual values are not plotted.

12-HOUR PRECIPITATION PROBABILITY FORECASTS FOR PERIOD ENDING IN:

NAME OF CITY	12 HRS	24 HRS	36 HRS	48 HRS	60 HRS
MIAMI	67	20	33	19	0
ORLNDO	1	9	40	28	27
JCKSNV	100	47	52	0	45
CHRLST	100	48	60	46	53
TAMPA	0	0	36	0	21
AUGSTA	100	56	28	53	50
ATLNTA	77	0	41	48	60
BRMGHM	39	6	37	37	56
NORLNS	36	49	41	77	60
JACKSN	10	7	37	46	68
HOUSTN	10	27	44	37	62
TXARKN	11	18	33	40	57
BRNSVL	5	0	7	18	30
SNANTO	17	29	14	45	31
FTWRTH	8	37	39	53	53
MIDLND	0	0	0	4	4
ELPASO	5	3	9	12	8
TUCSON	3	7	13	18	26
PHENIX	0	0	1	15	27
YUMA	0	0	0	14	13
SANDGO	0	2	0	20	28
LSANGL	9	14	20	13	7
RALEGH	67	36	20	57	52
NRFOLK	69	61	13	64	41
CHARLT	76	52	11	68	41
KNXVIL	81	36	35	66	51
NSHVIL	66	23	46	54	66
MEMPHS	55	40	49	58	55
LTLRCK	22	20	52	57	66
FTSMTH	7	23	39	39	61
OKLACY	0	17	14	51	36
AMRILO	41	0	35	11	40
ALBQUE	8	5	11	11	18
WNSLOW	0	6	23	19	22
BKSFLD	6	14	10	13	8
LSVGAS	2	0	13	12	10
FRESNO	6	23	14	10	16
STMRIA	4	4	24	10	14
RCHMND	87	50	23	27	38
WASHDC	100	30	0	34	51
PHILIE	100	42	0	47	39
ROANKE	100	0	30	37	55
CINCIN	65	42	29	61	45
LOUVIL	88	33	66	50	46
HNTGN	85	0	45	56	61
COLMBS	100	0	21	43	52
STLOUS	20	25	39	8	36
INDPLS	76	42	46	59	47
KANCTY	21	24	13	11	50
WCHITA	0	18	35	24	44
DODGCY	19	46	30	30	35
PUEBLO	3	56	38	42	36
DENVER	100	65	43	56	32
MLFORD	18	15	28	35	10

NAME OF CITY	12 HRS	24 HRS	36 HRS	48 HRS	60 HRS
GRJNCN	16	17	23	25	23
SCMNTO	27	32	38	16	22
ELY	14	18	33	12	0
RENO	100	29	24	14	19
SFRSCO	40	41	44	25	22
NYCNY	100	'77	5	39	60
HRTFRD	100	83	0	27	36
BOSTON	100	100	21	0	21
ALBANY	100	32	0	26	37
SYRCSE	100	17	29	47	49
PTSBRG	100	0	25	54	79
CLVLND	100	57	77	75	70
BUFFLO	92	85	45	52	87
CHICGO	44	28	0	0	7
DTROIT	79	47	44	56	36
MOLINE	49	24	21	0	31
DESMNS	12	5	18	21	22
OMAHA	0	26	15	23	41
NOPLAT	34	17	28	34	25
CASPER	52	44	40	37	15
SLCITY	18	32	35	30	26
LANDER	42	0	37	18	8
PCTLLO	11	13	26	24	26
RDBLUF	39	24	20	13	23
EUREKA	100	44	30	41	17
MFDFRD	100	54	25	22	11
PORTME	100	100	29	0	23
BRLNGT	92	74	3	17	17
GRRPDS	100	80	36	66	0
MILWKE	100	5	0	0	13
MADISN	38	13	0	0	0
GRNBAY	100	71	7	0	0
HURON	15	13	9	16	10
MINPLS	46	17	0	5	24
RAPCTY	61	35	43	35	23
BILNGS	100	48	57	15	24
BOISE	18	30	43	51	33
BURNS	26	42	33	12	6
PNDLTN	43	50	27	29	0
PORTOR	24	13	0	0	0
CARBOU	78	100	89	8	18
STSTEM	100	100	100	51	47
DULUTH	100	24	22	0	41
INTFLS	4	28	10	15	23
FARGO	22	4	21	3	11
BISMRK	100	59	10	28	0
WLSTON	27	39	26	28	0
MSOULA	64	42	28	22	26
GRTFLS	77	49	42	12	12
SPKANE	4	9	25	17	28
SEATLE	19	10	2	0	0
APALCH	42	48	29	47	41
PNSCLA	69	37	35	44	26
BNGHTN	98	51	4	16	65

Figure 7. Computer printout of PoP forecasts prepared at 1200 GMT on February 5, 1971. The forecasts apply to the periods and stations shown.

Table 2.

SYSTEM FOR PREPARATION OF OPERATIONAL PoP FORECASTS FOR 12 TO 60 HOURS IN ADVANCE

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

A sample forecast prepared May 8, 1970 is illustrated in Figures 8 and 9. In these figures the shading delineates areas where precipitation actually occurred during the verifying period, the dots locate the 108 cities for which predictions are made, and the lines depict hand analyses of the spot forecasts. Figure 8 is for the first 12-hour period, corresponding to line 1, part b), Table 2. 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. Figure 9 is for the fourth period, corresponding to line 4, part b), Table 2. Of particular interest is the development of a large band of precipitation in the Upper Mississippi Valley. This development was forecast quite well, with PoP values of 65% in parts of the rain area from 36 to 48 hours in advance. The majority of the country remained dry during all periods, and this was generally well indicated by low forecast probabilities.

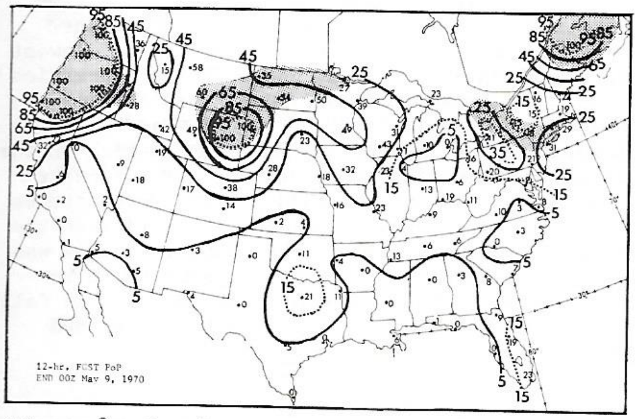

Figure 8. Sample PoP forecast made by applying the daytime spring equations at 1200 GMT, May 8, 1970 and valid during the next 12 hours. Stippling delineates areas in which precipitation occurred during the forecast period.

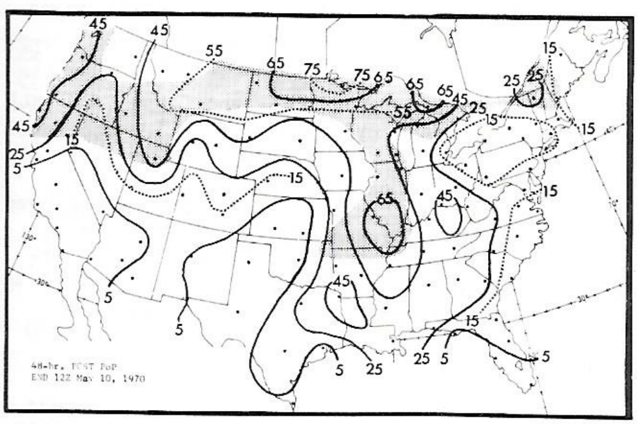

Figure 9. Sample PoP forecast made by applying the operational spring equations at 1200 GMT, May 8, 1970 and valid during 12-hour period ending 48 hours later. Stippling delineates areas in which precipitation occurred during the forecast period.

4. SUMMER SCREENING EXPERIMENTS

Thus far the contents of this paper have been limited to winter, spring, and fall. Recently an additional series of computer experiments was performed for the summer season. Precipitation occurrence during 12-hour periods at the 108 stations of Figure 1 was screened as a function of various predictor fields observed at the beginning of the period. The results are averaged in Table 3 for 59 western and 49 eastern cities in terms of the reduction of variance for multiple regression equations containing three variables.

Table 3.

Mean reductions of variance (%) obtained by screening summer precipitation occurrence during 12-hour periods as function of single predictor fields observed at beginning of period (time in parenthesis). Results are averaged for 59 western and 49 eastern cities for 3-term equations.

Predictors	West (12Z)	East (00Z)
Prior 12-hr precipitation	16.7	18.0
1000-mb height	9.8	13.9
850-mb height	10.7	15.6
700-mb height	10.6	11.9
500-mb height	9.7	8.8
1000-mb temperature	9.5	7.4
850-mb temperature	11.8	7.8
700-mb temperature	11.8	7.3
500-mb temperature	6.3	5.7
850-mb dewpoint	11.2	10.1
700-mb dewpoint	11.1	13.7
500-mb dewpoint	7.3	9.9
Precipitable water	11.9	14.8
850-mb dewpoint spread	10.8	10.2
700-mb dewpoint spread	12.0	12.5
500-mb dewpoint spread	8.4	9.3
850-700 mb mean dewpoint spread	13.0	14.4
Mean relative humidity	16.6	18.2
1000-700 mb temperature	9.6	6.3
850-700 mb temperature	8.5	9.3
850-500 mb temperature	9.7	6.1
K-index	12.7	13.4
Total index	11.5	9.5
Total totals index	10.0	9.7

In both parts of the country the highest values of RV were yielded by prior precipitation and mean relative humidity (surface to 500 mb). The former variable was obtained from surface reports at the 108 stations of Figure 1, the latter from upper air soundings at 69 RAOB stations plotted in Figure 10. All other variables listed in Table 3 (except precipitable water) were obtained from data at grid points of the type illustrated in Figure 2.

The field of height was screened at four levels from 1000 to 500 mb, with highest values of RV obtained at 850 mb and lowest at 500 mb. Temperature at all four levels was less effective than height in specifying precipitation in the

Figure 10. Network of 69 RAOB stations where values of precipitable water and mean relative humidity were tested as potential predictors of PoP.

East but slightly better at 850 and 700 mb in the West. Of the measures of absolute humidity, dew point at the upper three levels was about as good as height but not as effective as precipitable water from the surface to 500 mb. The best level for dew-point spread was 700 mb, but the mean spread at 850 and 700 mb was better than either level alone. The last six lines list various measures of static stability including three temperature lapse rates, the K-index of George (1960), and two indices used by the Air Weather Service. Of the six, best results were yielded by the K-index, which combines the effects of lapse rate (850-500 mb temperature), moisture (850-mb dew point), and humidity (700-mb spread).

The results of Table 3 for summer are generally similar to those obtained previously for winter (Klein, 1971). The best single predictor of PoP was the field of prior precipitation, the best level for height was 850 mb, and the best measure of dew-point spread was the mean of values at 850 and 700 mb. The latter variable was better than mean relative humidity during winter but not as effective in summer. A special screening run was therefore made for the spring season, but the results were inconclusive. The mean dew-point spread produced higher values of RV than the mean relative humidity in the West, but opposite results were obtained in the East. Results of a similar test for the fall season are not yet available.

Additional screening experiments will be conducted for the summer season in order to determine how much improvement can be obtained by using several different predictor fields in combination. The optimum combination will then be used to derive a final set of multiple regression equations for operational implementation on June 1, 1971.

5. IMPROVEMENT OF PoP FORECASTS

The PoP forecast system described in Section 3 has been run on a real time basis at NMC twice daily since September 1, 1970. Most of the forecast maps resemble subjective predictions and appear to be synoptically reasonable. However, quantitative verification indicates that these perfect prog forecasts were not quite as good as either subjective or MOS objective forecasts during the fall of 1970 (Glahn et al., 1971), even though they were consistently superior to climatology.

One reason for this rather disappointing result is the large bias of the perfect prog forecasts; according to the statistics of Glahn et al. (1971), their forecast probability was about 6 percent too high on the average. Some such bias is probably inherent in any perfect prog system which applies regression equations to numerical prognostic charts as if they were observed maps, without taking account of the uncertainties in the numerical prognoses. In order to remove this bias and calibrate the forecast system, simple regression equations were computed between predicted PoP and observed precipitation occurrence at 86 stations for the fall season of 1970. Separate adjustment equations were derived for each of the four regions in the National Weather Service (Figure 11) and for each valid period (today, tonight, and tomorrow). As expected,

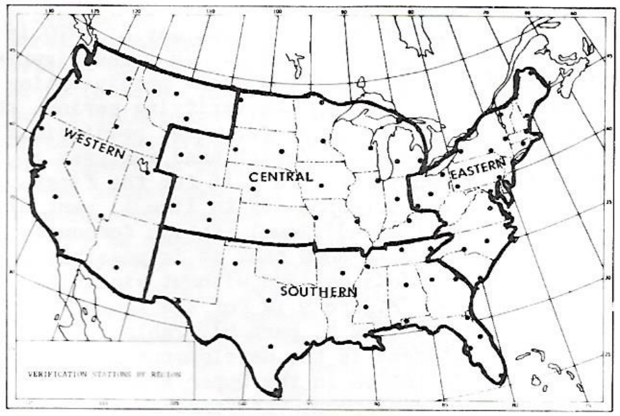

Figure 11. Network of 86 stations used for verification and calibration of operational PoP forecasts. Heavy lines delineate the boundaries of four regions of the National Weather Service.

forecast accuracy diminished steadily with time (Table 4). Best results were obtained in the Western Region, with highest values of RV, lowest values of SE and greatest slope of the regression line (b). Poorest results were found in the Southern Region in terms of b and RV and in the Eastern Region in terms of SE. Application of the adjustment equations to objective PoP forecasts made during the fall of 1970 yielded Brier scores which averaged about .004 lower (better) than the original (operational) scores. However, this was a test on dependent data, and it remains to be seen how much improvement will occur when the fall adjustment equations are applied to winter and spring.

Table 4.

Properties of simple linear regression equations between observed precipitation at 86 cities and PoP forecast by the perfect prog method during the fall months of 1970. Results are stratified by Eastern, Southern, Central, and Western Regions and by forecast projection.

	12-24 hours			24-36 hours			36-48 hours		
	RV	b	SE	RV	b	SE	RV	b	SE
E	.188	.853	.387	.159	.806	.388	.142	.810	.397
S	.210	.786	.335	.135	.650	.309	.123	.616	.344
C	.179	.737	.364	.167	.785	.374	.126	.681	.376
W	.348	.949	.292	.294	.930	.310	.276	.916	.313

Another possible advantage of the MOS over the perfect prog forecast system is that the former uses as input the relative humidity averaged over most of the troposphere (from surface to about 420 mb), whereas the latter utilizes the dew-point spread at only two levels (850 and 700 mb) since no moisture data below 850 mb were available in the original derivation. The mean relative humidity from the surface to 500 mb was therefore computed twice daily at the 69 RAOB stations of Figure 10 for 23 winter months from December 1, 1961 through January 31, 1969. By utilizing these data as predictors of PoP, in conjunction with values of 850-mb height and prior precipitation previously screened, a new set of multiple regression equations was derived. Their RV and SE were no better than the original set derived by using dew-point spread instead of relative humidity (Section 2). Nevertheless the new equations were tested on prognostic data, since the PE model may have more difficulty forecasting the spread at fixed levels than the humidity for an entire column. The new equations were therefore applied to make PoP forecasts for the same fall months of 1970 for which verification statistics were already available for the original equations. However, the new Brier scores were slightly worse than those obtained originally, and it was decided to discontinue further work along these lines.

Since precipitation and moisture patterns sometimes occur on a smaller scale than ordinary synoptic features, a Limited-Area Fine Mesh Model recently developed by Howcroft (1971) has been tested as input to the regression equations in place of the standard PE model run operationally at NMC. Only five cases have been run with this LFM model to date, and thus far the resulting Brier scores are not significantly different from those obtained operationally. A large number of additional cases will be tested in the next few months.

Several other efforts to improve the operational PoP forecasts are planned. Since George's K-index was found to be an effective measure of stability during the summer season (Section 4), it will also be tested during the other seasons. Hopefully it will contribute additional, useful information to the PoP forecasts. An experiment will also be conducted on space smoothing the numerical moisture forecasts before using them as input to the regression equations. This should remove an undesirable tendency of the PE model to intensify predicted moisture gradients with time. Finally, an attempt will be made to combine the perfect prog forecasts with the MOS forecasts by means of multiple regression equations computed separately for each of the four regions of Figure 11. Since the two forecast systems are skillful and somewhat independent of each other, it is hoped that the combined forecasts will prove to be more accurate than either set alone. The results of these and other experiments will be presented at the International Symposium on Probability and Statistics in Honolulu, June 1-4, 1971.

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