An Operational System for Specifying Monthly Precipitation Amounts over the United States from the Field of Concurrent Mean 700-mb Heights

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ABSTRACT

This paper describes an operational system for specifying monthly precipitation amounts in the contiguous United States from the concurrent 700-mb monthly mean height field over North America and adjacent oceans. Multiple regression equations are derived for each month of the year at 60 climate divisions by applying a quasi-objective forward selection procedure to 30 yr of data for 1951–80. The resulting specification equations explain an average of 37% of the precipitation variance, but values range from 70% along the Pacific Coast in January to 10% in southern New England in July. When applied to prognostic 700-mb charts for 1987 and 1988, the equations have shown more skill than persistence but less skill than official monthly outlooks.

Four attempts to improve the specifications are discussed. Best results were obtained by screening the mean precipitation amounts within 10–12 coherent regions, selected by factor analysis, instead of 60 smaller climate divisions. This procedure raised the explained precipitation variance during each month of the year, with a mean increase of almost 11%. The average increases of explained variance produced by the other attempts were about 4% for precipitation frequency instead of amounts, 2% for seasonal instead of monthly means, and 1% for previous precipitation and variables derived from 700-mb heights as additional predictors. Consequently, average precipitation amounts within large coherent regions are now being specified routinely and used as additional guidance at the Climate Analysis Center.

1. Introduction

This paper describes the characteristics of multiple regression equations for specifying monthly precipitation amounts (PA) in the contiguous United States from the concurrent field of mean 700-mb heights over North America and adjacent bodies of water. A complete history of previous work on this subject has been given by Klein and Bloom (1987; hereafter referred to as KB) and will not be repeated here. Our main objective is to extend the work of KB from a series of statistical experiments to an operational system. This system is now applied routinely by the Climate Analysis Center (CAC) of the National Weather Service to help interpret its prognostic monthly 700-mb charts in terms of surface precipitation.

The basic data and methodology are explained in section 2. Properties of the specification equations are discussed in section 3, including their derivation, synoptic meaning, regional and seasonal differences, and month-to-month variations. Section 4 describes the performance of the specification equations by means of maps for observed heights and standard verification scores for prognostic heights. Possible methods of improving the specifications are discussed in section 5, with emphasis on spatial averaging in coherent regions. A summary and conclusions are presented in section 6.

2. Data and procedure

Because of the small scale and discontinuous nature of precipitation, we used a set of monthly data in a network of 60 high quality and quasi-homogeneous climate divisions (CDs) created by Englehart and Douglas (1985), each composed of approximately 15 surface stations. These CDs are of roughly equal area, with a near-uniform distribution across the United States (Fig. 1). The average monthly precipitation amount within each CD was transformed and tested in various ways, as previously described by KB. Since expressing PA as one of 21 percentiles (based upon the gamma distribution) gave good results and is used operationally by CAC (Ropelewski et al. 1985), we decided to utilize it (in anomaly form) as the predictand (dependent variable) for this study. For example, a percentile of 90 in a given CD for a particular month and year implies an observed amount that would be exceeded only 10% of the time over all years in that month and CD.

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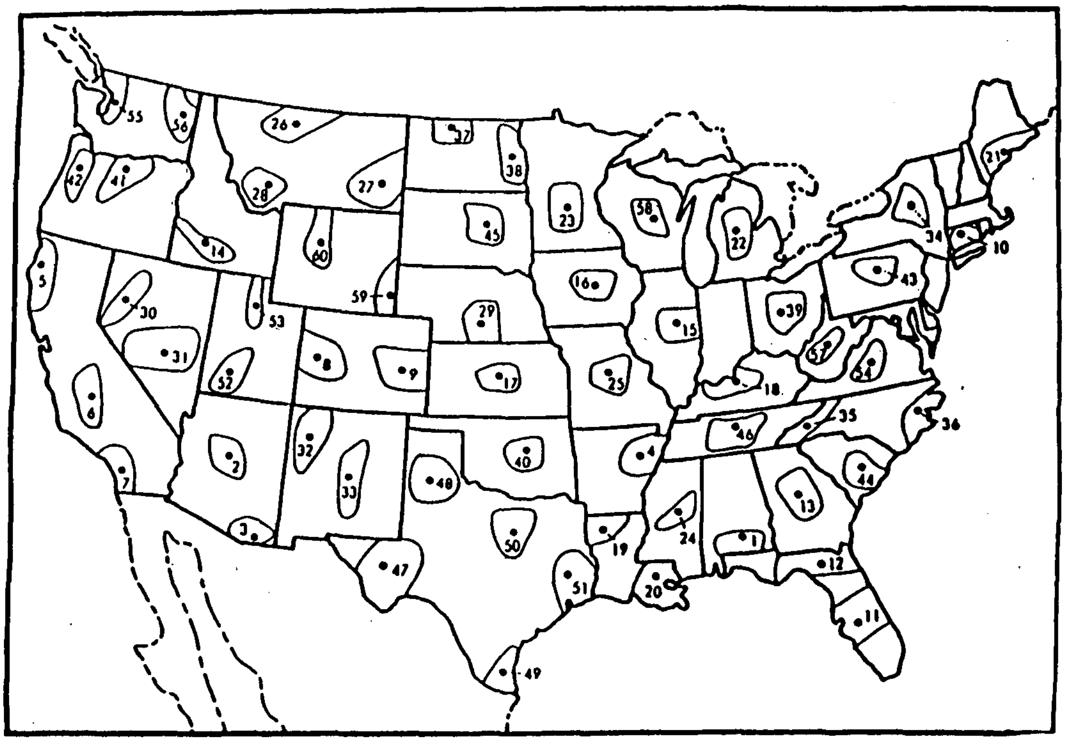

FIG. 1. Locations of the 60 climate divisions defined by Englehart and Douglas (1985) for which monthly precipitation amounts were studied. The divisions are numbered alphabetically by state. Their centers of gravity are given by the heavy dots.

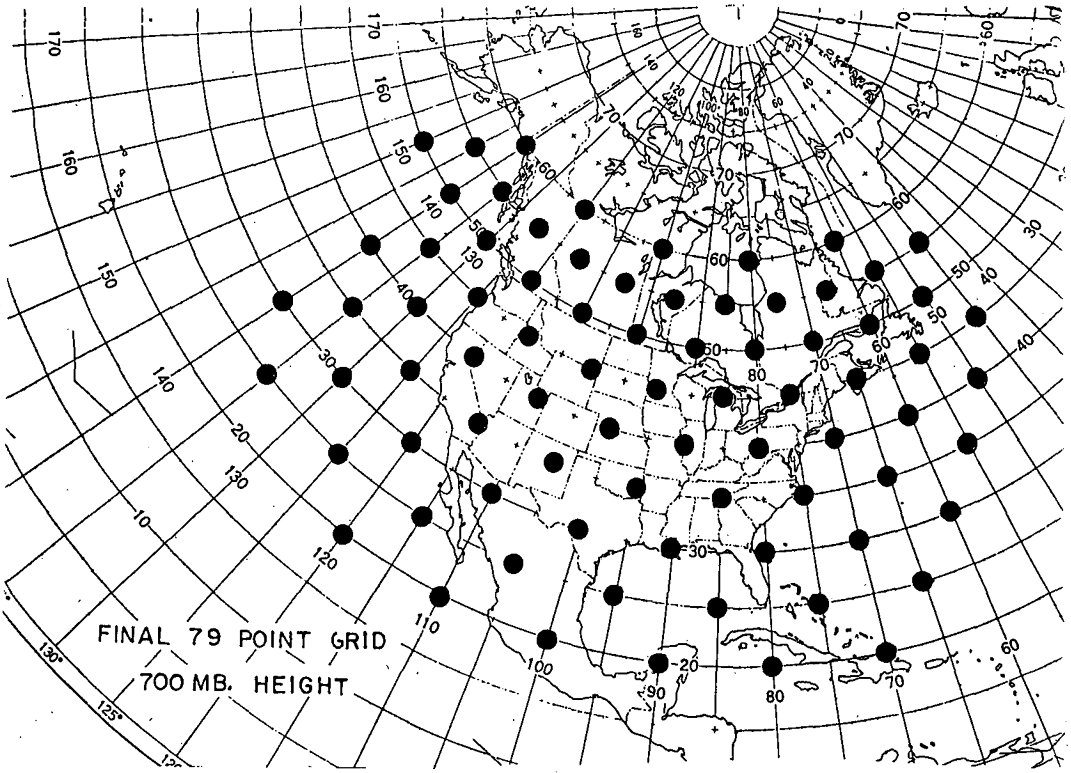

FIG. 2. Final network of 79 grid points used to delineate the field of 700-mb height at intersections of latitude and longitude ending in 0 or 5.

TABLE 1. Summary of the stepwise regression statistics obtained for northern California (41°N, 123°W) in January. The final equation selected for use in the specification is starred.

Step no.	Predictor selected	Regression coefficient upon entry	*F* value	Critical *F*	Probability (%)	Added RV (%)	Cumulative RV (%)
1	45°N, 125°W	−0.54	162.8	11.3	100.0	64.9	64.9
2	30°N, 120°W	+0.63	46.1	6.7	100.0	12.2	77.1
3*	40°N, 140°W	−0.07	6.1	5.7	98.4	1.5	78.6
4	20°N, 70°W	+0.22	2.4	5.0	87.8	0.6	79.2
5	35°N, 125°W	+0.28	2.1	4.8	85.2	0.5	79.7

The principal data used as predictors (independent variables) were anomalies of monthly mean 700-mb heights obtained from CAC at a network of 79 standard intersections of latitude and longitude illustrated in Fig. 2. This network was determined by KB to be more or less optimum after considerable experimentation with alternate grids. The period of record for both heights and precipitation extended from January 1951 to December 1980, giving 30 yr of monthly data. This coincides with the latest period used by the World Meteorological Organization in defining new "normals." Equations were developed separately for each month of the year by combining the target month with its adjacent month on either side, thus increasing the (apparent) sample size to 90. Anomalies were computed, however, as departures from the 30-yr mean computed individually for each of the 12 months of the year.

In order to specify the monthly precipitation from the concurrent 700-mb circulation, we used a forward selection method of multiple regression (Miller 1962; Draper and Smith 1981) to screen PA anomalies at each CD of Fig. 1 as a function of the simultaneous height anomalies at each grid point of Fig. 2. An objective criterion for adding terms to the multiple regression equations was determined by a Monte Carlo simulation (Walsh 1984) applied to each of the 12 months separately. We randomly shuffled the year of our predictand 100 times at each of 12 CDs while leaving the predictors intact, screened each shuffled time series, computed classical *F*-values each time a variable was added to the regression equation, and ranked the resulting *F*'s to obtain the critical *F* (i.e., the value exceeded 5% of the time by screening the random predictands). These critical *F*'s must be exceeded for a new term to be truly significant at the 95% level. Additional criteria were also considered in determining the cutoff point for each equation including the reduction of unexplained precipitation variance (RV or square of the multiple correlation coefficient), synoptic and physical reasoning, additional variance explained (at least 2%), probability of an added term making a significant contribution if all the assumptions of the classical *F*-test are met (at least 97%), total number of terms (no more than 6), and continuity in sign of a variable's initial regression coefficient (not accepted if sign changed). Thus our quasi-objective selection procedure emphasized simple equations that were statistically significant, physically meaningful, easy to understand, and likely to prove stable on future samples.

3. Properties of specification equations

The statistics and synoptic interpretation involved in selecting an unusually good specification equation are illustrated in Table 1 for January at the CD in northern California, centered at 41°N, 123°W. The grid point whose heights explain most of the precipitation variance is 45°N, 125°W, about 500 km northwest of the reference CD, with an RV of almost 65%. Its negative regression coefficient indicates that below normal heights at this point favor above normal precipitation in northern California. Since we are using linear regression, and since KB showed that the assumption of a linear relation between monthly precipitation and the large scale circulation pattern is a fairly good one, then the first line of Table 1 also indicates that above normal heights at 45°N, 125°W accompany below normal precipitation in northern California.

TABLE 2. Summary of the stepwise regression statistics obtained for western North Carolina (36°N, 83°W) in July. The final equation selected for specification is starred.

Step no.	Predictor selected	Regression coefficient upon entry	*F* value	Critical *F*	Probability (%)	Added RV (%)	Cumulative RV (%)
1	35°N, 95°W	−1.25	33.7	12.0	100.0	27.7	27.7
2*	35°N, 65°W	+0.60	12.1	8.0	99.9	8.8	36.5
3	50°N, 150°W	+0.15	5.0	6.6	97.1	3.5	40.0
4	55°N, 45°W	+0.17	2.5	5.8	87.9	1.7	41.7
5	25°N, 115°W	−0.40	2.0	5.6	83.5	1.3	43.0

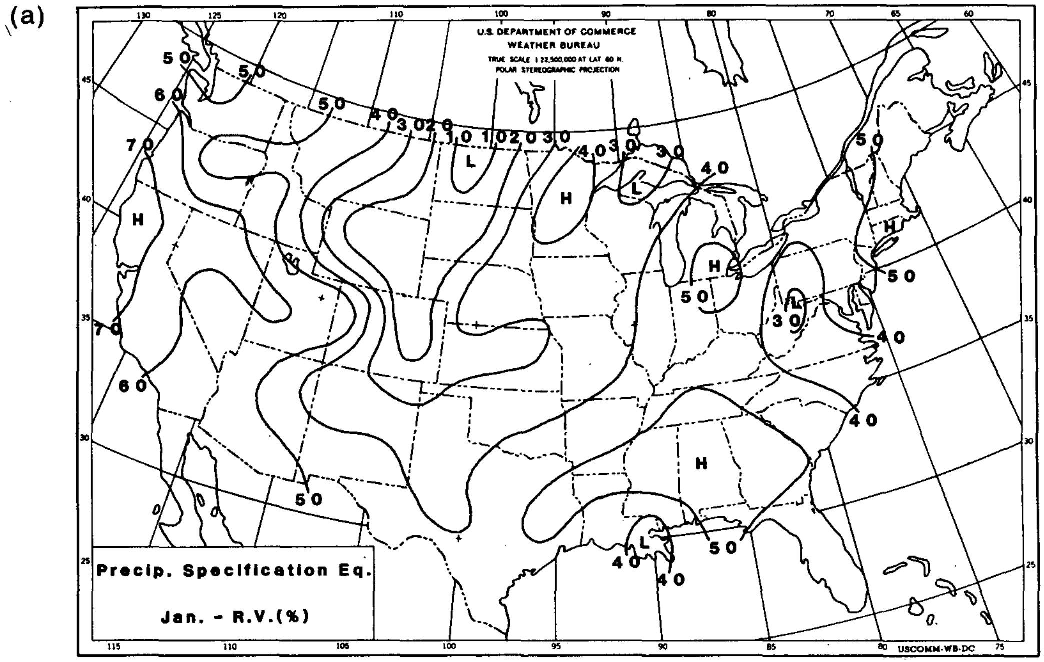

FIG. 3. Reduction of variance of final specification equations for percentiles of monthly precipitation amounts at 60 climate divisions of Fig. 1 as a function of 700-mb height anomalies at 79 grid points of Fig. 2 during (a) January and (b) July.

The second point selected is at 30°N, 120°W where heights, taken in conjunction with those at the first point, increase the RV by 12%. The positive sign of this regression coefficient and the negative coefficient of the first height selected suggest that heavy (light) precipitation in northern California is favored by moist (dry), cyclonic (anticyclonic), southwesterly (northeasterly), anomalous geostrophic flow around a strong low (high) off the coast of Oregon. Selection of the third height, at 40°N, 140°W, is more questionable since it raises the RV by only 1.5%, but it was included because it reinforces the first point, makes good meteorological sense, and has an *F* value of 6.1, slightly greater than the critical (Monte Carlo) value of 5.7 for three variables. The selection process was stopped at step 3, with almost 79% of the PA variance explained, since no additional variable exceeded the critical *F* value or raised the RV by more than 2%.

A much poorer specification equation (typical of summer) is illustrated in Table 2 for the CD in western North Carolina, centered at 36°N, 83°W, during July. The first point selected is located at 35°N, 95°W, about 1100 km west of the target CD, with an RV of 27.7%. Its negative regression coefficient indicates that below (above) normal heights at this point favor above (below) normal PA in western North Carolina. The second point selected is at 35°N, 65°W, near the well-known Bermuda high, where heights increase the RV by 8.8%. The positive sign of this regression coefficient and the negative sign of the first coefficient indicate that heavy (light) precipitation is favored by southerly (northerly) flow of moist (dry) air from the Gulf of Mexico (Canada) between a strong trough (ridge) to the west and ridge (trough) to the east. The selection process was stopped at this point with 36.5% of the variance of PA explained by only two heights since no additional variable exceeded the critical *F*-value given by the Monte Carlo procedure.

Similar specification equations were derived for each CD and each month. The geographical distribution of the RV for January (Fig. 3a) ranges from maxima of 70% along the West Coast and 50% in parts of the Northeast and Southeast (where sources of warm moist air are readily available), to values below 20% in the northern plains (where the moisture source is indeterminate and light snowfall is difficult to measure accurately). During July, on the other hand, the RV increases to about 40% in the Great Plains (where moisture from the Gulf of Mexico can produce heavy showers) but decreases in most of the remainder of the country (Fig. 3b). Similar charts during the other 10 months of the year have been analyzed and turned over to CAC for guidance in interpreting the specification equations.

The annual cycle of RV is shown in Fig. 4 (solid), where mean values for all 60 CDs have been plotted by month. The curve is approximately sinusoidal in shape, with maximum RV of 44% in early winter,

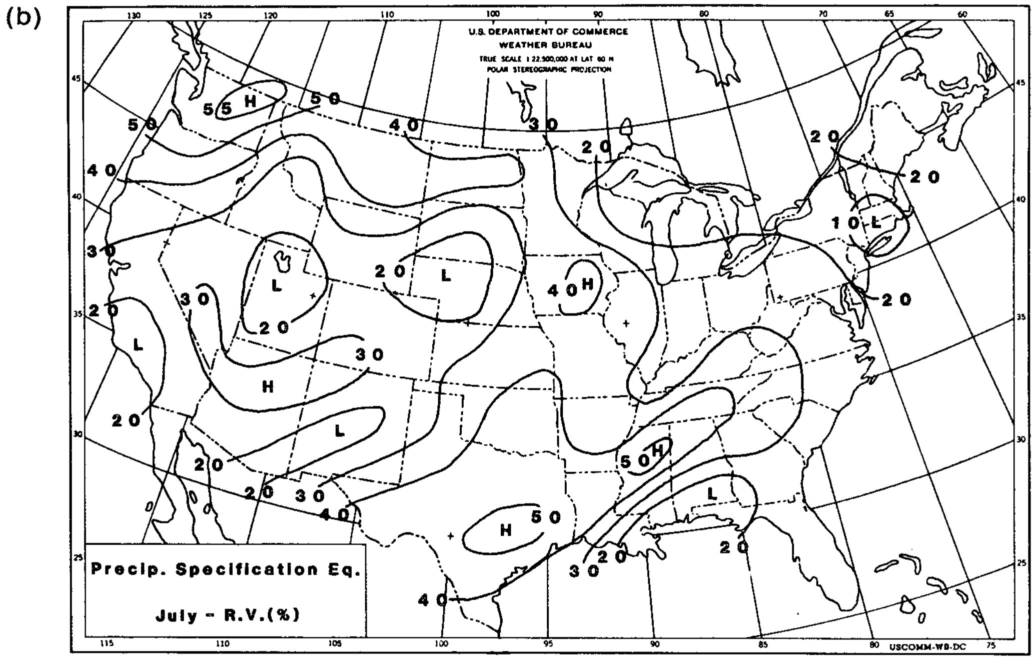

FIG. 3. (*Continued*)

minimum RV of 31% in early summer and intermediate values during the transition seasons. These differences are probably caused by the great (small) frequency of local, small scale, convective and noncoherent regions of precipitation in summer and late spring (winter and late fall).

4. Performance of specification equations

The performance of the specification equation is illustrated in Fig. 5. Panel (a) shows the precipitation classes (heavy, moderate or light) specified for January 1987. These classes are defined so that heavy and light normally occur 30% of the time each and moderate 40% (Epstein 1988). Because the conservative nature of regression would usually produce too many specifications of moderate precipitation, the specified percentiles of PA are routinely inflated (by dividing their anomalies by the appropriate multiple correlation coefficients) so that each class is specified on average about as often as it is observed (Klein et al. 1959). Figure 5a was analyzed by CAC on the basis of percentiles of PA at 60 CDs specified from the heights observed during January 1987, so that percentiles greater (less) than 69% (31%) are classified as heavy (light) and remaining percentiles as moderate. Figure 5b gives the CAC analysis of the precipitation classes actually observed that month at 100 stations across the United States. The two charts are similar in large-scale patterns, but the observed map contains more small-scale features. This typical difference between specified and observed charts probably arises from the smoothness of monthly mean 700-mb maps and averaging of the original precipitation data from which the specification equations were derived. In contrast, the map of observed precipitation is based on point data at single stations without any spatial averaging.

In actual forecast operations, the specification equations have to be applied to prognostic (not observed) 700-mb maps. Since the progs are imperfect, the equa-

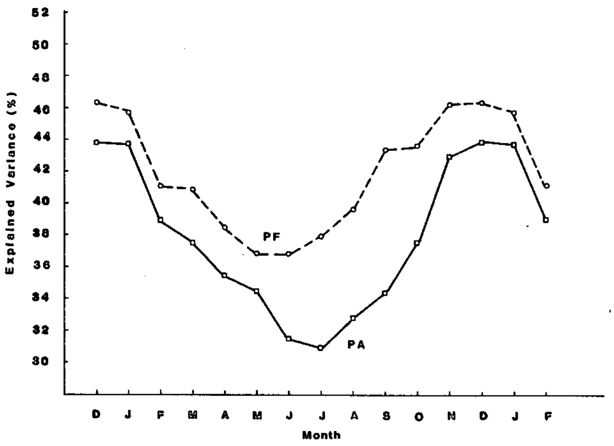

FIG. 4. Reduction of variance of precipitation specification equations at 60 climate divisions averaged by month for amounts (PA) and frequency (PF).

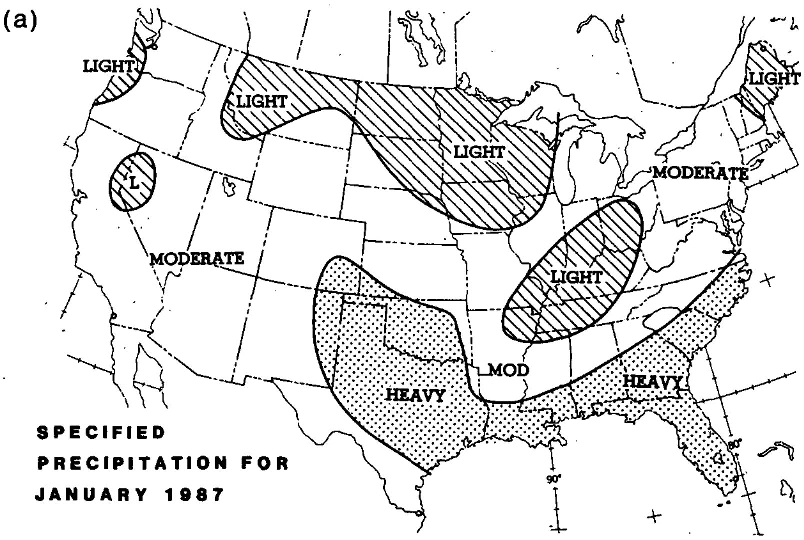

FIG. 5. Monthly precipitation amounts during January 1987 as specified at 60 climate divisions from (a) observed 700-mb heights and (b) as observed at 100 surface stations. The analysis is given in terms of three classes: heavy (stippled), moderate (blank) and light (hatched).

tions do not do as well as suggested in Fig. 5. Table 3 summarizes comparative verification figures for almost 2 yr since the equations became operational at CAC on 1 January 1987. The CAC analyses of 42 sets of specification maps for monthly periods starting on the first and sixteenth (ending on the last or fifteenth) of each month from 1 January 1987 through 15 October 1988 had 37.4% in the correct class for an average Heidke skill score[1] of 5.7. These scores were not as good as the official forecasts, with 38.5% correct and skill of 7.2. They were better, however, than random forecasts (skill of 0) or simple persistence of the previous month's precipitation class, which gave only 36.0% correct and a skill score of 3.6. All these scores would probably be higher if CAC were to verify precipitation forecasts in terms of spatial averages rather than single-station observations.

5. Improved specification

Section 4 demonstrates that the specification equations have shown modest skill on an operational basis, but their accuracy leaves much to be desired. This section therefore discusses four research attempts to improve the specification system discussed thus far.

First, six additional predictors were screened, including local values of the previous month's precipitation and of simultaneous monthly mean geostrophic 700-mb zonal and meridional wind components, relative vorticity, vorticity advection, and horizontal divergence. Table 4 shows the results of adding these potential predictors successively to the field of 700-mb heights and terminating the selection at the 97% (classical) probability level. No individual predictor added more than 0.5% to the RV obtained by simple specification of PA from the height field. The lack of appreciable precipitation persistence agrees with earlier papers by Namias (1953), Walsh et al. (1982) and van den Dool (1985), while the nonutility of the predictors derived from the height field is consistent with earlier results of Klein (1965). Thus, although the derived predictors taken by themselves may correlate better than heights with the precipitation in some areas (Walsh et al. 1982; Weare and Hoeschele 1983; Cayan and Roads 1984), they add little additional information on a nationwide basis to the height field alone.

In a second experiment limited to four watersheds in California and Arizona, the length of the averaging period was increased from 1 month to 1 season (3 months) for both predictors and predictand; i.e., seasonal, as well as monthly values of PA were screened as a function of concurrent anomalies of height for each month from October through March with the same procedure described in section 2. The resulting specification equations for the seasonal equations explained, on the average, 2% more of the PA variance than the corresponding monthly equations (63% vs 61%) and did so by means of 0.5 fewer variables (2.2 vs 2.7). Additional details are given by Klein and Bloom (1988). Although these results are encouraging, they suggest that time averaging for periods longer than

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[1] The skill score is defined as 100 times the number of correct forecasts minus the number expected correct by chance, divided by the total number of forecasts minus the expected number correct.

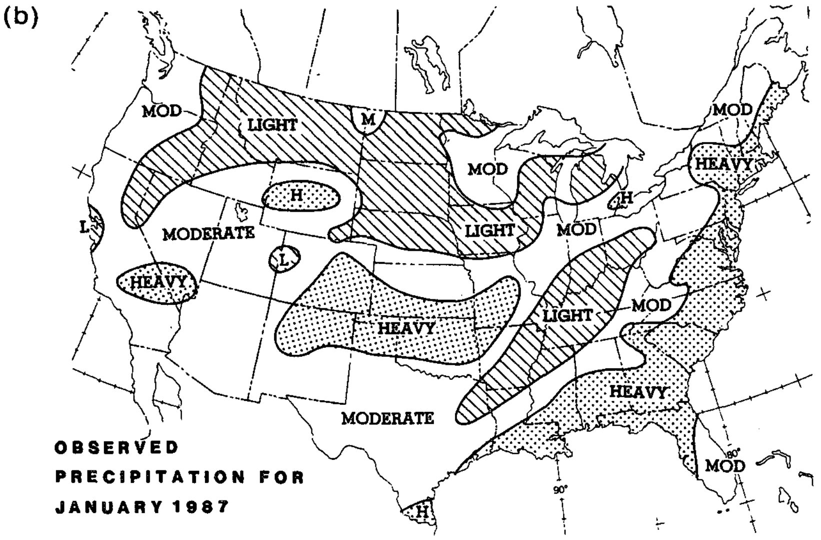

FIG. 5. (*Continued*)

1 month will produce only small improvement in the specification equations.

A more sizeable improvement can be obtained by expressing the predictand as precipitation frequency (PF) instead of amount. Klein and Bloom (1987) found that screening PF, defined as the number of days per month with precipitation at least 2.54 mm (0.10 in.), instead of PA, raised the nationwide RV by about 3% in January and 7% in July. Recent results of Klein and Whistler (1988), reproduced as the dashed curve in Fig. 4, indicate that PF outperformed PA during each of the 12 months of the year, with annual average RV's of 41% for PF and 37% for PA. This difference may be attributed to marked, small-scale gradients of PA and its undue sensitivity to only 1 or 2 days of heavy amounts in an otherwise dry month.

The best way to improve the specification is to average the precipitation over larger coherent regions determined by factor analysis with a varimax rotation, as demonstrated by KB using loadings ≥ 0.6 derived by Englehart and Douglas (1985) and ≥0.5 supplied by P. J. Englehart (personal communication). The former criterion resulted in regions covering only half the United States, however, while the latter produced regions that were too large and heterogeneous for the forecasters in CAC to use. We therefore produced a new set of reasonably coherent regions by subjectively combining areas delineated by loading factors approximately ≥0.55 with regions previously derived by Walsh et al. (1982), Karl and Koscielny (1982), and Richman and Lamb (1985). Figure 6 illustrates 10 such regions in winter and 12 in summer; similar regions for spring and fall months are not shown.

The results of screening the average PA within these coherent regions are summarized on a nationwide and month-to-month basis in Fig. 7. During each season

TABLE 3. Verification of monthly precipitation forecasts at 100 stations in the contiguous United States for 42 consecutive predictions made every 15 days for monthly and midmonthly periods beginning 1 January 1987 and ending 15 October 1988.

Type of forecast	In correct class (%)	Skill score
Official CAC outlook	38.5	7.2
Objective specification	37.4	5.7
Persistence of last month's precipitation	36.0	3.6

TABLE 4. Reduction of variance and number of variables selected at the 97% probability level, averaged over 60 Climate Divisions across the contiguous United States, in screening monthly precipitation amounts (expressed in 21 percentiles) as a function of concurrent anomalies of 700-mb height at 79 points (H) and geostrophic values of zonal and meridional wind components (u, v), relative vorticity (ξ), vorticity advection (VA), and horizontal divergence (D). The previous month's observed precipitation percentile (PP) was also screened. All results were obtained by pooling 90 winter (D, J, F) cases from January 1951 to December 1980.

Potential predictors		Reduction of variance (%)	Number of variables
Type	Number		
H	79	41.6	2.6
H, PP	80	41.7	2.6
H, PP, u, v	82	42.0	2.8
H, PP, u, v, ξ	83	42.2	2.9
H, PP, u, v, ξ, VA	84	42.4	2.9
H, PP, u, v, ξ, VA, D	85	42.8	3.0

(a)

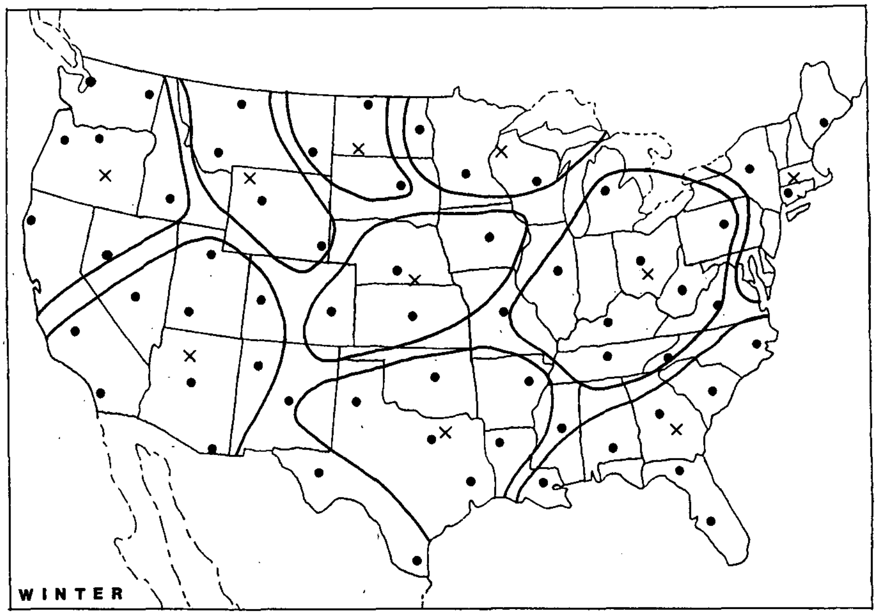

FIG. 6. Coherent regions of monthly precipitation during (a) winter and (b) summer months. Centers of regions are given by crosses; centers of climate divisions by dots.

and month, the average RV for the coherent regions is greater than the mean RV of the individual CDs, with an average difference for the year of 10.8%. Thus, spatial smoothing significantly improves the relations between precipitation and the large-scale circulation, probably by minimizing small-scale effects and observational or communication errors. As a result, CAC is now routinely specifying PA within each coherent region of Fig. 6 as additional guidance in preparing its monthly precipitation outlooks.

6. Conclusion

In this paper we have described the development of an operational system for specifying average monthly precipitation amounts in the contiguous United States from the concurrent field of monthly mean 700-mb heights over North America and adjacent bodies of water. For each month of the year at 60 climate divisions across the country, we derived multiple regression equations that give the precipitation as a function of heights at a few grid points selected quasi-objectively by a forward screening procedure. These equations explain about 37% of the precipitation variance by means of 2.7 heights on the average, but with marked temporal and spatial variations. The reduction of variance is greatest in winter (average of 44%), when it decreases from 70% along the Pacific Coast to less than 20% in the northern plains, and least in summer (average 31%), when it increases to about 40% in the Great Plains but decreases in the remainder of the country. Since becoming operational at the Climate Analysis Center in January 1987, the specification equations have shown modest positive skill when applied to prognostic 700-mb heights, with average accuracy better than persistence but not as good as the official monthly outlooks.

Four attempts to improve the specification have been discussed. Best results were yielded by screening the average precipitation amount within 10–12 coherent regions selected by a modified factor analysis and covering most of the country. This procedure explained more of the variance than screening the precipitation within 60 climate divisions during each month of the year, with a mean annual increase of almost 11%. The second largest improvement in the specification equations was obtained by expressing the monthly precipitation as frequency (number of rainy days per month) instead of amount. On a nationwide basis, screening the frequencies consistently explained more of the precipitation variance than screening the amounts, with an annual average improvement of approximately 4%. The third largest improvement was obtained by using seasonal, instead of monthly, mean values, but the increase in RV was only about 2%. Finally, an increased RV of only 1% resulted from adding previous precipitation or derived local geostrophic predictors (winds, vorticity, advection and divergence) to the field of 700-mb height.

In order to improve precipitation specification in future research, heights at other levels of the atmosphere should be used as predictors, in addition to 700

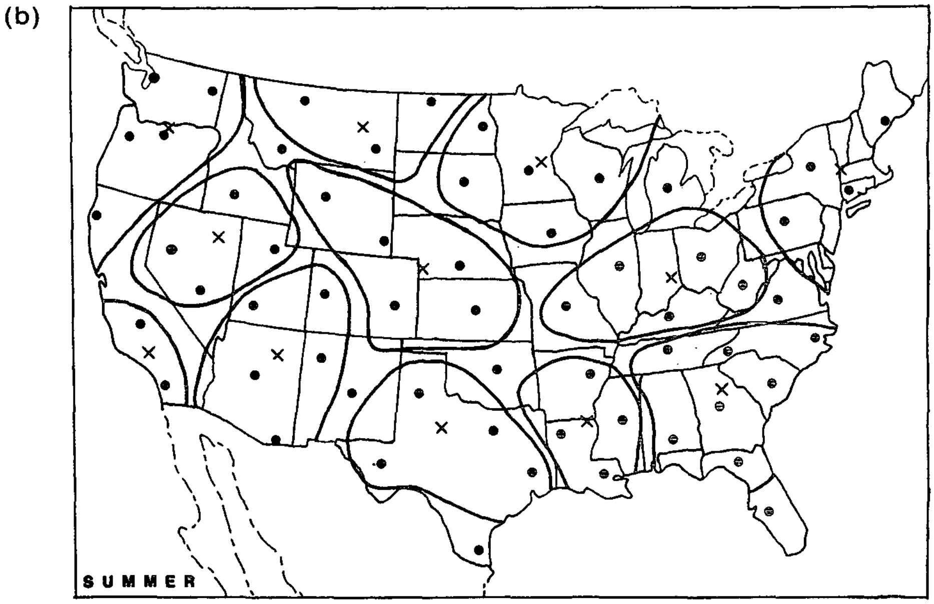

FIG. 6. (*Continued*)

mb. For example, Klein (1971) found that 850-mb heights were more highly correlated with daily precipitation than 1000-, 700- or 500-mb heights. In addition, use of more than one level would allow thickness advection to supplement vorticity advection as proxies for mean vertical motion. It is also probable that some measure of monthly moisture, vertical velocity, and static stability would improve the specification of precipitation (van den Dool 1987; Peppler and Lamb 1989). Finally, the impact of transient eddies should be considered (van den Dool 1988). All of these additional predictors should be available in the future on an operational basis as medium range numerical models of the general circulation type become more accurate and are routinely integrated out to 30 days.

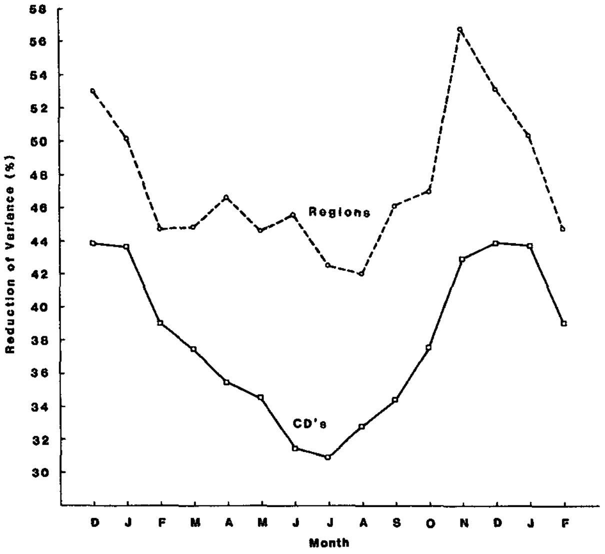

FIG. 7. Reduction of variance of precipitation specification equations, averaged by month, at 60 climate divisions (solid) and 10–12 coherent regions (dashed).

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