Specification of United States Summer Season Precipitation

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ABSTRACT

The specification of summer season precipitation in the contiguous United States from summer season fields of 700 mb height, sea level pressure (SLP) and Pacific sea surface temperature (SST) was carried out using stepwise multiple linear regression. The specifier fields were characterized by their first five Empirical Orthogonal Functions (EOF's). The objectives were to assess the overall skill in specifying summer season precipitation, examine the differences among predictands with regard to both spatial averaging and type of statistic, compare the usefulness of the specifier fields, and to look at spatial variations in specification skill.

Overall, the strongest relationships between *actual* summer season precipitation and the predictors were found for 700 mb heights ($R^2 \sim 0.24$) followed by Pacific SST's ($R^2 \sim 0.21$) and SLP ($R^2 \sim 0.12$). The use of large area averages ($\sim 10^5$ km^2) for the predictand produced slightly greater R^2 values than for individual climatic division averages ($\sim 10^4$ km^2).

The use of transformed summer season precipitation statistics to account for precipitation skewness, did not improve upon the use of actual summer season precipitation as the predictand. However, frequency of precipitation greater than 0.1 inch resulted in an almost doubling of explained variances over actual precipitation (0.47 versus 0.24) when 700 mb heights were used as the specifier field.

The areas of weakest relationship (west of the Rockies and southern states) between predictor and summer precipitation statistic generally had R^2 values less than 0.3, even for the best models. Elsewhere, the R^2 values generally ranged from 0.5 to 0.7 for the best model (700 mb heights and precipitation frequency). After accounting for artificial predictability which results from imperfect estimates of the statistics, skill values (explained variances) east of the Rockies ranged from 0.01 to 0.44.

1. Introduction

As the initial part of a larger study, aimed at assessing the *predictability* of summer season precipitation in the United States using statistical methods, this study was conducted to investigate the *specification* of summer season precipitation from concurrent variables. The primary objective here was the formulation of a precipitation statistic which relates well, and hopefully optimally, to the concurrent circulation so that the chances of finding a useful lag relationship involving the antecedent atmospheric or oceanic state will be improved. The large degree of discontinuity of precipitation in both space and time makes the task of finding useful predictive relationships on a seasonal time scale especially difficult. It was necessary to do some experimentation with various forms of smoothing and filtering in order to limit the unpredictable portion of the raw station precipitation time series.

Skillful summer season prediction would obviously be of benefit to both the agricultural community and to water resource planners. The benefits of a specification study include: 1) the development of specification equations for summer season precipitation from summer circulation for use later in conjunction with predictive models of summer circulation; 2) the knowledge gained about the strength and nature of the relationship between summer precipitation and circulation as compared to other seasons and time scales; 3) the knowledge gained about geographical variations of summer season precipitation specification; and 4) determination of the relative usefulness of the various fields as predictors.

Investigations of the relationship between weather (especially surface air temperature and precipitation) and the tropospheric circulation are numerous. Wexler and Namias (1938) used monthly mean isentropic charts to infer tropospheric moisture transport and to explain precipitation regimes in the 1930's. Other early studies include Klein (1948, 1949), Martin and Hawkins (1950), and Martin and Leight (1949). In the Klein studies, five day winter precipitation was related to five day mean circulation. In Martin and Hawkins, the association between temperature/precipitation and the concurrent circulation was explained descriptively. In Martin and Leight, objective five day temperature prediction from concurrent circulation was addressed.

The use of correlation fields to explain the physical relationships between mean five-day or monthly precipitation with the concurrent sea level pressure (SLP)

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distribution was introduced by Stidd (1954). In a series of studies, Klein and colleagues derived or used various specification relationships, among which were five-day mean temperatures in winter (Klein *et al.*, 1959), monthly mean temperatures for all seasons (Klein, 1962), and five-day precipitation in winter (Klein, 1963). In Klein (1965) a summary of previous work involving specification or prediction of temperature, precipitation, thickness, sea level pressure (SLP) and 700 mb heights is given. With few exceptions, averages for five-day periods were used, although some work with 30-day periods was reported. The seasonal time scale has been neglected with regard to specification relationships. In particular, the combination of summer as the season chosen and precipitation as the weather element chosen has not been employed with the exception of Klein (1965), in which five-day mean data were used. Stidd (1954) studied summer precipitation in this context by using *monthly* precipitation during summer as part of his study; however, specification was not attempted; Walsh and Mostek (1980) correlated Empirical Orthogonal Functions (EOF's) of SLP and *monthly* precipitation during summer.

This study was designed to carry out the objectives stated earlier. Unlike previous studies, specification relationships involving a variety of types of precipitation statistics were used; in addition, EOF analysis was used to reduce the number of potential predictors. SLP, 700 mb heights and SST fields were used in separate screening multiple linear regression models as predictors (specifiers). The effect of changing the form of the precipitation statistic used as well as differences among predictor types was assessed by comparing the explained variances and statistical significance levels. Similarly, geographic variations were examined.

2. Procedure

a. Predictands

Since time series of observed summer season precipitation for individual stations may include the effects of local and mesoscale terrain, water bodies, and urbanization, as well as that of changes in raingage exposure, it is expected that a substantial, but unknown portion of the record is unpredictable. Therefore, as a starting point, historical mean summer season precipitation by state climatic divisions (CD's) was derived using mean monthly precipitation for CD's (1931–77) available on magnetic tape from the National Climatic Center (NCC). The CD precipitation values on the tape were calculated as the arithmetic mean of all individual station totals available within the given CD. As such, the precipitation statistic represents the unweighted influence of many (usually ten or more) individual stations, so that *some* of the non-synoptic scale influences on the monthly precipitation values are already eliminated.

There are more than 400 CD's in the contiguous United States, with 1 to 10 in each state. In order to reduce the number of computations, 72 CD's were selected (not shown), evenly covering all areas of the 48 contiguous states. In addition to the 72 selected CD's, large area averages were used. Twenty "subareas" (Fig. 1) were formed by subdividing the ten climatologically homogeneous areas used by Namias (1978). Topography and climatology were considered

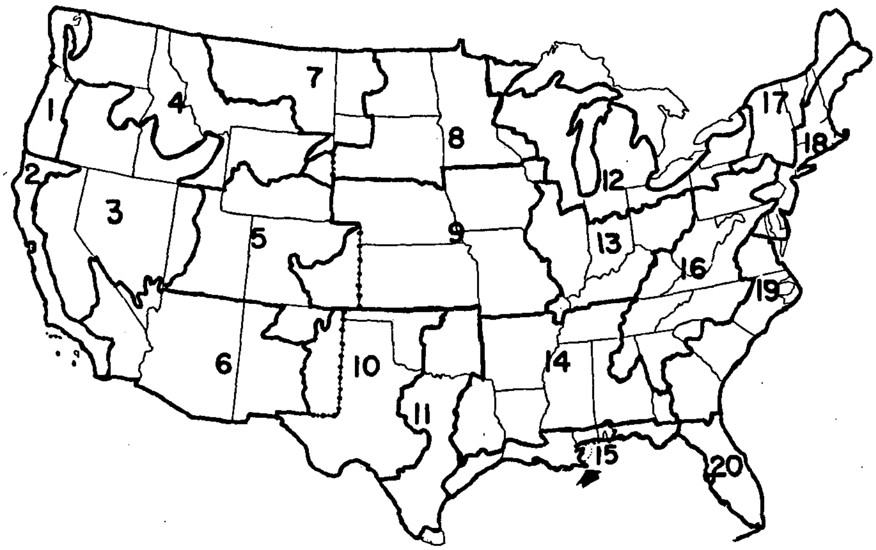

FIG. 1. Twenty sub-areas used for actual summer precipitation and 12 used for precipitation frequency (sub-areas 8–19). For precipitation frequency sub-areas 8, 9, 10, 15 boundaries (dotted) were redrawn slightly (because of lack of data).

when making the subdivisions. The sub-area boundaries were also drawn so as to follow CD boundaries. The precipitation value for each sub-area was arrived at by computing the weighted mean (weighting by area) of all CD's located within the given sub-area.

The summer precipitation time series for each of the 72 CD's and 20 sub-areas were used in original form (i.e., total summer precipitation) as well as in altered forms. These altered forms include the square root of actual precipitation as well as three-category form (i.e., below, near or above normal). Class limits for each CD or sub-area were determined by ranking the 1940–71 summer precipitation values, then dividing the series into thirds. In this way each precipitation class is equally likely from a climatological point of view. The purpose of using transformed precipitation is to try to determine the effect of limiting extreme values (or skewness).

In addition to transforming actual precipitation totals, a completely different type of statistic was employed, namely frequency of precipitation. Because of the skewness of precipitation, the total summer precipitation might poorly characterize the season. For instance, a few heavy rains might result in near or above normal precipitation totals during a summer which had very infrequent precipitation. This approach seems particularly well suited for the summer season during which time convection is of greater importance; thus, the number of "rain events" during a season (as measured by the number of days having precipitation greater than some critical value) might relate better to the tropospheric circulation than the total amount of precipitation received during that season. Because of availability, precipitation frequency data for three different critical values (0.1, 0.5 and 1.00 inches) were used and will be referred to as P1, P2 and P3, hereafter.

The precipitation frequency data used in this study (1947–77) was obtained from the NCC in the form of station data. In the same manner as for actual precipitation, averages for each CD and sub-area were formed. However, data for states west of the Rocky Mountains were not obtained in order to reduce the cost of processing the data. This particular region was excluded for two reasons: 1) interannual variability in precipitation has less impact in the western states since it is dry there and since agriculture is less widespread than in the East, and 2) preliminary results of this study indicated that skill in specifying precipitation is quite low in the western states.

In addition to the western states, *precipitation frequency* data for Florida were not obtained due to an error in filling the data request. Because of this, only 12 of the original 20 sub-areas could be used (sub-areas 8–19) where precipitation frequency was employed; also, sub-areas 8, 9, 10 and 15 were made slightly smaller than before (as shown by the dotted lines in Fig. 1). The number of selected CD's used for precipitation frequency was reduced from 72 to 45.

b. Predictors

Three fields: 700 mb heights, SLP and Pacific SST's were used to specify the various precipitation statistics described above. Each field has its own advantages

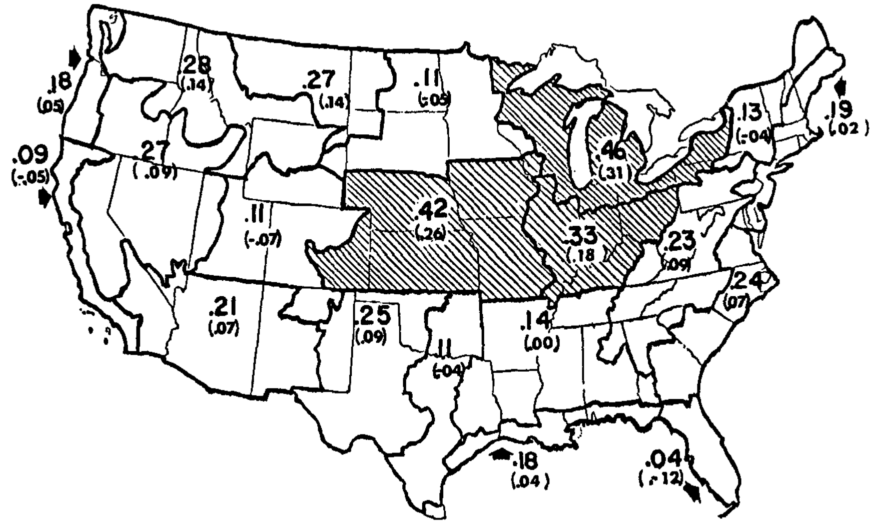

FIG. 2. Explained variances (R^2) and estimated true skill S (in parentheses) for the prediction of 20 sub-area actual summer precipitation from summer 700 mb heights. The hatched areas were deemed significant at the 5% level using a Monte Carlo simulation. The area-weighted average R^2 and S values are 0.24 and 0.08, respectively, while the percentage of the total area tested deemed significant at the 5% level (A) is 20.6. The $\bar{R}^2$, $\bar{S}$ and A values for the 12 sub-areas east of the Rockies are 0.26, 0.10 and 34.0, respectively.

TABLE 1. Explained variances (percent) of Empirical Orthogonal Functions for summer 700 mb heights, sea level pressure, and Pacific sea surface temperature used in this study.

	EOF number					
	1	2	3	4	5	Total
Heights	18.4	11.3	9.8	7.8	7.5	54.9
SLP	14.0	10.9	8.5	6.9	6.0	46.2
SST	24.3	18.0	11.3	10.3	7.3	71.2

distinct from the others. Ideally, the 700 mb height field, which has been used preferentially in long-range forecasting, should relate best to the circulation of the lower troposphere and hopefully to precipitation. However, 700 mb heights are available only since 1947. The precipitation data, which starts in 1931, can be fully utilized (increasing the sample size by more than 50% from 31 to 47) if SLP is used to characterize the state of the atmosphere. Unfortunately, SLP does a poorer job in characterizing the circulation of the troposphere, for the purpose of long range forecasting, than does the 700 mb height field.

Application of specification equations involving atmospheric parameters in making long range forecasts depends upon the skill of predicting the atmospheric state one season in advance. Currently, the skill at making seasonal circulation forecasts is marginal at best. However, unlike 700 mb heights or SLP, Pacific SST's, which have been shown to relate concurrently to SLP (Davis, 1976) (grouping all seasons together) and to 700 mb circulation during winter and summer (Harnack and Broccoli, 1979), do exhibit a considerable amount of persistence on the monthly and seasonal time scale. Thus skillful, concurrent relationships between Pacific SST's and precipitation might prove useful for making long range forecasts by using a prior SST field and assuming persistence through summer.

Data for the three predictor fields were obtained on magnetic tape in the form of monthly mean gridded values and were averaged to form seasonal means. The data sources are: 1) 700 mb heights (1947–77), Climate Analysis Center; 2) SLP (1931–77), National Center for Atmospheric Research; and 3) Pacific SST's (1947–77), Scripps Institution of Oceanography. The spatial domain used for both 700 mb heights and SLP consisted of 105 grid point locations from 20 to 80°N, 120°E eastward to 40°E with 10° latitude × 20° longitude resolution. For Pacific SST's, 50 grid points between 25–55°N and 160°E–125°W (on a staggered 5 × 5° grid) were used as shown in Fig. 2 of Harnack and Landsberg (1978).

In order to reduce the number of variables and to extract only the major portion of the climatic signal, EOF analysis was used. The EOF's were derived from the correlation matrix for each data set. The first five eigenvectors of each field were retained for use in the specification models. The explained variances for these eigenvectors or EOF's are shown in Table 1.

c. Methodology

The approach adopted here was the use of screening multiple linear regression to specify each of the types of precipitation statistics cited previously from each of the three predictor fields in turn. A separate equation was derived for each location (either a CD or sub-area). The STEPWISE procedure of the Statistical Analysis System (SAS) with the maximum explained variance improvement (MAXR) technique was used to perform the regression analyses (Helwig and Council, 1979). This technique finds the one variable model producing the highest R^2 and adds each predictor, one at a time, to produce the greatest increase in R^2. As each variable is added, the variables not in the model are re-checked to see if they could replace any in the model and increase the R^2.

Since five predictors (in the form of EOF's) were available for use from each of the three predictor fields, it was possible to produce five different models (one through five predictors) for each precipitation statistic/predictor field combination. The average R^2 value and number of CD's or sub-areas significant at the 5% level were computed separately for each of the five models and precipitation statistic/predictor field combinations. Generally, the R^2 value increased considerably when adding the second predictor, and moderately when adding the third, while little increase in R^2 value was seen when adding the fourth or fifth predictors. The number of significant models decreased as predictors were added. The sharpest drop generally occurred going from three to four predictors; however, in a few cases this occurred going from two to three predictors. Based on these observations it was decided that the best three-variable model would be used for the remainder of this study.

In assessing the statistical significance of screening regression models, it is important to account for the

TABLE 2. Area weighted average R^2 value for various model types. CD = climatic divisions, SA = sub-areas, HTS = 700 mb heights, SLP = sea level pressure and SST = sea surface temperature.

Predictor	Spatial area	Predictand (Precipitation)	$\overline{R^2}$
HTS	72 CD	Actual	0.21
	20 SA	Actual	0.24
	20 SA	Square root	0.24
	20 SA	Category	0.22
	12 SA	Frequency (>0.10″)	0.47
	12 SA	Frequency (>0.50″)	0.31
	12 SA	Frequency (>1.0″)	0.26
SLP	20 SA	Actual	0.12
SST	20 SA	Actual	0.21

fact that the predictors are not selected *a priori*. Instead, the "best" predictors are selected from a pool of potential predictors, thus invalidating the classical F test. In order to account for this *a posteriori* selection process, a Monte Carlo simulation was performed (Neumann *et al.*, 1977). In application, the 5% tail value from the distribution of R^2 values generated using 300 random trials was used as a critical value in assessing model significance. For each trial, the 31 observations of the predictand were "shuffled" randomly prior to entering the screening regression. In the next section, the major concern is a comparison of the different model types rather than significance. The question of model significance and skill will be addressed more fully (for selected models) in Section 4.

3. Results of regression analyses

a. 700 mb height field as a predictor

The first predictor/predictand type to be discussed is for 700 mb heights and actual summer precipitation. The first question to be addressed is the effect of the spatial averaging used. The area-weighted, average R^2 values are given in Table 2. The average R^2 values for the selected 72 CD's and the 20 sub-areas do not differ much. Careful examination of the spatial distribution of R^2 (not shown) leads one to the conclusion that the use of the sub-area averages results in an R^2 distribution which appears to be a smoothed version of the 72 CD R^2 field. However, in the three sub-areas deemed significant (i.e., central Plains, Great Lakes and Ohio Valley), the R^2 values are comparable to or higher than the R^2 values for the selected CD's located in these sub-areas. Overall, the sub-area averaging produces slightly better results; in the regions with the best relationships, a moderate improvement is seen. These conclusions are supported by comparisons (not shown) between 72 CD and 20 sub-area averaging, which was done for most of the models presented subsequently in this paper. The use of large area averages is more practical since less computations are needed and since one cannot hope to skillfully predict the details on a smaller (CD) scale anyway. In addition, the use of large area averages increases the area covered by a model deemed significant. For these reasons, the 20 sub-areas were used throughout the remainder of this study.

Transformed actual precipitation is presented next as a predictand. The results for the square root of actual precipitation and (three) category precipitation are shown in Table 2. For the square root precipitation statistic, the average R^2 value is almost identical to that for actual precipitation; for category precipitation, R^2 values are slightly less overall, than for actual precipitation.

Results using precipitation frequency as a predictand are indicated in Table 2 for the three critical values available (0.1, 0.5 and 1.0 inches, respectively). As explained earlier, only models for 12 of the 20 sub-areas (8–19), which cover the area east of the Rockies, excluding Florida, were computed. The effectiveness of the models clearly deteriorates as the critical value is increased. This finding is not surprising since a higher critical value represents a more extreme event and an attendant smaller number of realizations. It is expected that the predictor field (*mean* circulation for summer) would relate more poorly to the occurrence of an *extreme* event, especially during summer when sub-synoptic scale factors

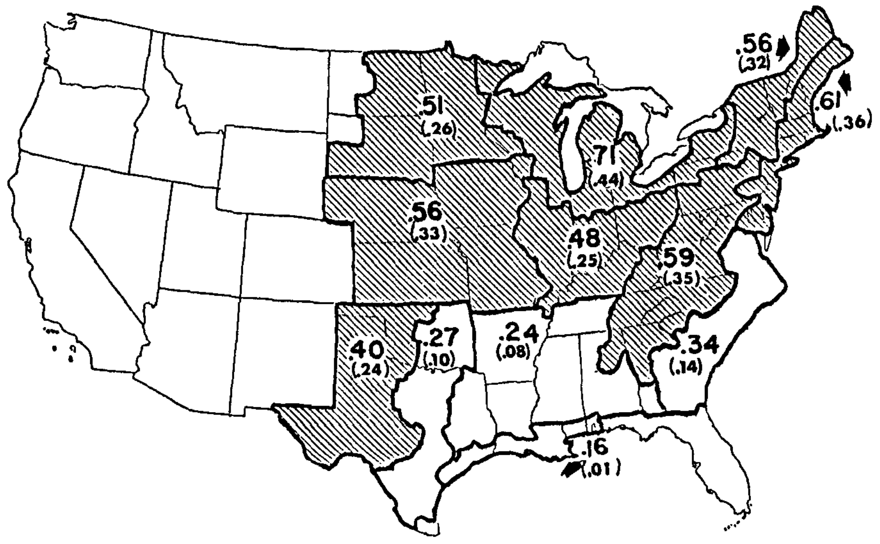

FIG. 3. As in Fig. 2, except for 12 sub-area frequency of precipitation (P1) from 700 mb heights. The $\bar{R}^2$, $\bar{S}$ and A values are 0.47, 0.25 and 72.8, respectively.

are quite important in enhancing or suppressing convection.

As compared to actual precipitation (Fig. 2), precipitation frequency P1 (Fig. 3) shows a much stronger relationship with the summer mean circulation at the 700 mb level. The R^2 values are higher in all 12 sub-areas used. In addition, for the 12 sub-areas in common, P1 had an average R^2 value almost twice as great as for actual precipitation (0.47 versus 0.26). As for actual precipitation, R^2 values are greatest in the Great Lakes and central Plains. However, with precipitation frequency, all areas east of the Rockies have significant relationships except for a region in the deep south, extending inland from the Gulf Coast, encompassing four sub-areas.

b. *SLP field as a predictor*

The results of regression analyses using the SLP field as a predictor were poor for all geographical areas and for all predictand (precipitation) types as well as for the two precipitation averaging schemes (72 CD's versus 20 sub-areas). The average R^2 value for 20 subarea averaged actual summer precipitation is quite low (0.12). It is obvious that the SLP field, as used here, does a much poorer job of specifying summer season precipitation than does the 700 mb height field.

c. *Pacific SST as a predictor*

As mentioned earlier, midlatitude Pacific SST was examined as a predictor because of its proposed connection with the lower tropospheric circulation and because of its conservative nature. Even in specification, it is more of an indirect indicator than a primary parameter. The average R^2 values using the Pacific SST field as a predictor are somewhat lower than 700 mb heights as a predictor. The best model with 20 sub-area actual precipitation as a predictand achieved an average R^2 value of 0.21. Unlike the 700 mb heights models, the use of precipitation frequency did not produce an improvement over actual precipitation as a predictand.

4. Model skill and significance

In the preceding section, average R^2 values were used for comparisons among the different predictor and predictand types. In this section, model hindcast skill was estimated, accounting for the autoregressive nature of predictors and predictands and imperfect estimates of the statistics (i.e., sampling errors), as well as the screening process. The best (in terms of average R^2 and percentage of the area deemed significant) model overall (700 mb heights and precipitation frequency, P1) was verified. In addition, skill for the 700 mb heights, actual summer precipitation model was included for comparative purposes, because of the basic nature of the predictand.

a. *Model skill for individual sub-areas*

The approach used here is to assess skill through dependent sample verification as done by Davis (1976, 1977, 1978). Davis computed the true skill S using

$$S = S_H - S_A, \qquad (1)$$

where S_H is the R^2 value for the model and S_A is the artificial skill resulting from imperfect estimates of the statistics. Davis (1976) estimated S_A using

$$S_A = \sum_{p=1}^{M} \tau_p/N\Delta t, \qquad (2)$$

where M is the number of predictors (5, the number of predictors in the pool), N is the sample size (31), Δt is the time increment used in the model (one month), and τ_p is the integral time scale for predictor p with respect to the predictand. The use of 5 as the value for M is conservative because only three predictors were used in the models. Hence, the S_A values were multiplied by 0.93 in accordance with Fig. 1 of Davis (1977) with $M_s/M = 3/5$. Monte Carlo simulations in which the predictand was "shuffled" randomly using a pool of five predictors confirmed the value of 0.93. The integral time scale τ was estimated using the formula presented by Sciremammano (1979):

$$\tau = \sum_{i=-\infty}^{+\infty} C_{xx}(i\Delta t)C_{yy}(i\Delta t)\Delta t, \qquad (3)$$

where C_{xx} and C_{yy} are the autocorrelation functions of the two time-series used (i.e., predictor and predictand). In practice, the summation is carried out for values $i = \pm L$, where L is large compared to the lag at which the autocorrelation functions become statistically indistinguishable from zero. The estimates of C_{xx} and C_{yy} were damped (multiplied by $[1 - (i/31)]$) to account for error growth as $|i|$ increases. Hence, the weighting of each C value decreases as the lag (i) increases since the smaller sample size leads to greater uncertainty in the estimate of the C's.

The estimated true skill (S) for the 20 sub-areas is plotted in Figs. 2–3 (in parentheses) for the two models selected. The spatial patterns of S are, as one would expect, rather similar to those of R^2 (S_H). Overall, the skill is moderate for even the best area (Fig. 3), with an average value of 0.25 for the 12 sub-areas. It should be kept in mind that application of similar models in real time forecasting would be expected to result in lower skill levels than shown in these figures, because 1) forecast skill is likely to be somewhat less than hindcast skill (i.e., independent versus dependent sample verification), and 2) the summer predictor fields must be estimated from prior values assuming persistence or using a numerical model prediction.

b. *Field significance*

The final question addressed in this paper is that of the significance of the entire R^2 field as a whole. Investigators frequently claim field significance at the 5% level, if more than 5% of the field is significant at the 5% level. In fact, a certain amount in excess of 5% of the total area is needed in order to make this statement of field significance. This is due to both the finiteness of the sample as well as the spatial interdependence of the variables.

A Monte Carlo simulation and interpretation by application of the binomial distribution (Livezy and Chen, 1981) can be used to estimate just how much of the area must be deemed significant in order to claim field significance. A Monte Carlo approach is used to determine the percentage area of significance needed to claim field significance.

The first step was to perform a simulation in which a normally distributed series of 31 (original sample size) random numbers was correlated with the predictand field (i.e., either 12 or 20 sub-area actual precipitation or P1), noting the percentage of the total area of the predictand field having a correlation coefficient significant at the 5% level (hereafter referred to as A_*). This procedure was repeated for 10 000 trials and a frequency distribution of the A_* values was constructed. Next, the value of A_* which is greater than 95% of all A_* values was determined (hereafter referred to as A'_*). A field must have more than this percentage (A'_*) of its field deemed significant in order for field significance to be claimed. This simulation is a slight variation on that suggested by Livezy and Chen, since correlation rather than regression analysis was used in the Monte Carlo tests.

For the three *predictand fields* displayed in Figs. 2 and 3, the A'_* values are: 20 sub-area actual precipitation, 15.9%; 12 sub-area actual precipitation, 19.8%; and 12 sub-area P1, 33.8%. The relatively large magnitude of the third value is indicative of a high degree of intercorrelation among the 12 sub-area P1 variables. It is important to keep in mind that the A'_* values are properties of the *predictand* field and have nothing to do with the predictors. As can be seen by comparing the A'_* values to the percentages of area (A) significant, given in Figs. 2 and 3, the model used in Fig. 3 has field significance for 12 subareas, while that in Fig. 2 has field significance for both 12 and 20 sub-areas.

5. Conclusions

This study has sought to examine the predictability of summer season precipitation in the contiguous United States through the use of screening multiple linear regression analysis. All of the models discussed here were of a specification type (i.e., the "predictors" were summer season variables). This study has also sought to examine the effect of spatial averaging of the predictand fields, relative strength of different predictor and predictand fields, and geographical variations in skill. The major findings are:

1) The 700 mb height field ($R^2 \sim 0.24$) is a better specifier of actual summer season precipitation than either the midlatitude eastern Pacific SST field ($R^2 \sim 0.21$) or the SLP field ($R^2 \sim 0.12$).

2) The use of large sub-area averages (area $\sim 10^5$ km^2) for the predictand produces slightly larger R^2 values (especially where the relationship is strongest) than for the use of individual CD data (area $\sim 10^4$ km^2).

3) The various transformations of actual summer precipitation did no better, and usually poorer, than actual summer precipitation in its raw state.

4) Frequency of precipitation as a predictand produced higher R^2 values than actual summer precipitation. The critical value of 0.1 inches ($R^2 \sim 0.47$) was best and produced R^2 values about twice as large as for actual precipitation ($R^2 \sim 0.24$) (when 700 mb heights were used).

5) The weakest relationships were found west of the Rockies and near the Gulf Coast ($R^2 \sim 0.10$–0.30). Elsewhere, the R^2 values (for 700 mb heights and precipitation frequency) generally ranged from 0.5 to 0.7. After accounting for artificial predictability, skill values (explained variances) ranged from 0.01 to 0.44.

It is concluded, based on the results of this study, that future prediction studies of summer season precipitation should employ frequency of precipitation instead of actual precipitation. It can be argued that precipitation frequency information is as useful, if not more useful, for some interests, especially those in the agricultural sector, than is precipitation amount information.

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