Evidence of Climatic Change in United States Seasonal Precipitation Data, 1948–76

MARIE R. KLUGMAN

Department of Geography, The University of Iowa, Iowa City 52242

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ABSTRACT

A method for determining climatic change in precipitation data is applied to seasonal data for the United States. This method is an analysis of variance procedure with a Markov chain model used to estimate the within-groups variance. A comparison of the within-groups variance computed with an allowance for dependence to the estimate of the variance computed under the assumption of independence shows that the model with dependence is superior. The statistic which is calculated in the test for climatic change may be significantly inflated if dependence in the data is not modeled. A consequence of this is that climatic change may be inferred when, in fact, it has not occurred. The greatest possibility of this error is in the fall season, and at West Coast stations in all seasons, for the period studied.

1. Introduction

The climatic statistics of a particular location are usually calculated as the finite time averages of meteorological variables and are, therefore, subject to statistical sampling variations referred to as climatic noise or natural variability. This noise is present even in an unchanging climate and knowledge of its magnitude is necessary for the detection of climatic changes. Following the discussions of Leith (1975), Madden (1976) and Madden and Shea (1978), it is assumed that the climate is controlled by external conditions such as solar radiation, ice cover and sea surface temperatures. The external conditions are not external in the sense that they are independent of the atmosphere, but because the time scales over which they vary are long relative to daily weather fluctuations. The climatic statistics for one time period such as a season or a month can be thought of as one statistical observation of many which are all possible under certain set external conditions. The seasonal or monthly observations exhibit variability but each observation is associated with a process of constant statistical properties. If the external conditions remain constant through time it is assumed that the climate does not change. For the above statements to be valid, it is assumed that the climate is not intransitive since the intransitive hypothesis assumes that atmospheric processes allow for more than one set of long-term statistics (Lorenz, 1968).

Noise may obscure the actual response of the atmosphere to external influences. It reflects fluctuations in daily weather which have a memory on the order of days or at most one or two weeks (Lorenz, 1973; Leith, 1973). In most climatic change studies, time averages are statistically manipulated to determine whether or not climate has changed. When observations are averaged over several years, the amount of noise in the data is reduced. The longer the time interval over which the averaging is done, the more noise is filtered out. As long as the interval over which the averaging is done is finite, the average values will contain an unpredictable component which results from the time averaging of the noise (Leith, 1973). The magnitude of this effect must be known before climatic change can be determined. Climatic variability over and above the noise potentially may be explainable by variations in the external conditions.

Jones (1975) suggested an analysis of variance design to test for climatic change over time. If the between-groups variance estimate (based on time-averaged climatic data) is significantly greater than the noise or within-groups variance estimate (based on daily data), it is concluded that the climate has changed. Jones noted that autocorrelation in climatic variables may complicate this analysis. If dependence is not taken into account, the within-groups sum of squares may underestimate the group-to-group variability under the null hypothesis of equal group means. The resulting *F*-ratio could therefore be inflated causing a higher probability of incorrectly concluding that the climate has changed. Madden (1976) and Madden and Shea (1978) have applied Jones' suggestions to sea level pressure data and temperature data, respectively.

To determine a better estimate of the noise in precipitation data, a model which allows for dependence must first be fitted to the daily data. A first-order autoregressive [AR(1)] model has been fitted to climatic data (see Jenkinson, 1957; Leith, 1973) but does not in general describe the dependence in precipitation data. An AR(1) model fitted to precipitation data assumes that the amount of precipitation on day n is a function of the amount on day $n - 1$, plus a random component. It does not provide for the large number of zeros found in daily precipitation data. A better description of the dependence is found in a generalized Markov chain model proposed by Katz (1977). This model assumes that the probability of rain and the amount of precipitation on a particular day depend only on whether the previous k days were wet or dry. However, the amount of rain does not depend on the probability of rain. From this model an estimate of the group-to-group variability under the null hypothesis which allows for dependence can be obtained. Klugman and Klugman (1981) developed a methodology to be used in tests for climatic change in precipitation data using Katz's model. The purposes of this paper are to report the findings using the just-mentioned methodology on precipitation data to determine whether one aspect of the climate changed during the period 1948–76 over the United States and then to compare the results with results calculated under the assumption of independence in daily data.

2. Data

The data examined in this study are daily precipitation records for the 29-year period, December 1947 through November 1976 for 104 weather stations in the conterminous United States (Fig. 1). The data for January 1948 through December 1963 and for July 1969 through September 1976 were from the National Center for Atmospheric Research (Jenne, 1975); the remaining data were taken from monthly publications of *Climatological Data for the United States* by Sections (U.S. Department of Commerce, 1947, 1964, 1965, 1966, 1967, 1968, 1969, 1976). The data were partitioned into four seasons: winter (1 December–28 February); spring (1 March–31 May); summer (1 June–31 August); and fall (1 September–30 November). Precipitation amounts for February 29 were deleted from the data for ease of computation.

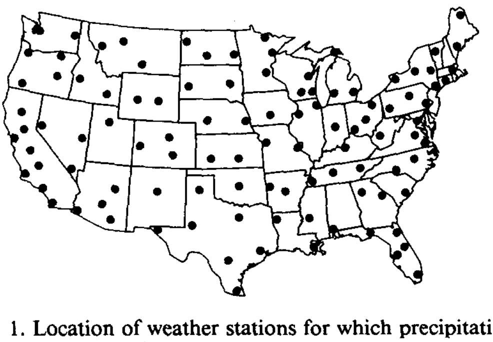

FIG. 1. Location of weather stations for which precipitation data were collected for the period 1948–76.

3. Methodology for determining change in precipitation data

To investigate whether there was change in seasonal precipitation data, it is necessary to know how much of the variation in seasonal amounts from year to year is due to day-to-day variability. This can be expressed by the variance components model (Graybill, 1961) as $X_{st} = \mu + a_s + b_{st}$, where X_{st} is the amount of rain in year s on day t, $s = 1, \ldots, n$ and $t = 1, \ldots, m$. The a_s and b_{st} are random variables with zero mean and variances σ_a^2 and σ_b^2. The hypothesis to be tested is that there is no change in the seasonal precipitation amounts from year to year, that is, $\sigma_a^2 = 0$. To test this hypothesis under the assumption of independence in daily data, the variance of the seasonal averages estimated from the seasonal data, $\hat{\sigma}_a^2$, is compared to an estimate of the variance of the seasonal averages estimated from the daily data, $\hat{\sigma}_b^2/m$. The ratio $m(\hat{\sigma}_a^2)/\hat{\sigma}_b^2$ has an F distribution with $n - 1$ and $n(m - 1)$ degrees of freedom. Allowing for Markov chain dependence in daily precipitation data as described by Katz (1977), $\hat{\sigma}_b^2/m$ must be replaced by a new estimate which takes the dependence into account. The new estimate, γ^2/m, is derived in Klugman and Klugman (1981) in which the formulas for $\hat{\sigma}_a^2$, $\hat{\sigma}_b^2$ and γ^2 are all included. Under the new model, the appropriate test statistic is $m(\hat{\sigma}_a^2)/\gamma^2$; it has a χ^2 distribution with $n - 1$ degrees of freedom. The large samples used make it reasonable to assume that γ^2 is estimated with negligible error.

4. Results

a. *Order of Markov chain dependence*

The Schwarz Bayesian criterion (Schwarz, 1978; Katz, 1981) was used to estimate the order of Markov chain dependence in daily precipitation data. This criterion selects the order k for which SBC(k) is smallest:

$$\mathrm{SBC}(k) = \eta_k - (s^m - s^k)(s - 1)\ln(n),$$

where η_k is $-2(\ln\lambda_k)$, and λ_k is the likelihood ratio test statistic for order k versus order m. The maximum possible order of the Markov chain is assumed to be less than m. In this study m was chosen to be 4. The s is the number of states in the Markov chain process (2 in this study) and n is the number of observations. For the winter season this formula becomes $\mathrm{SBC}(k) = \eta_k - (16 - s^k)\ln(2494)$. Table 1 contains two examples from the winter season to demonstrate how the order k is chosen. Little Rock, Arkansas is an example of first-order dependence in

TABLE 1. Estimating the order of dependence.

Order (k)	SBC (k) Little Rock	SBC (k) Boston
0	34.22	−19.90
1	−91.25*	−41.34
2	−87.59	−72.36*
3	−59.35	−47.78

* SBC chosen order of dependence.

daily precipitation data and Boston, Massachusetts is included as an example of second-order dependence. None of the stations exhibited zero- or third-order dependence in any of the seasons. In Table 2 the number of first- and second-order chains derived by the SBC for each season are presented. First-order dependence dominates in all seasons, but especially in summer when convective precipitation accounts for many of the precipitation days in the United States.

Second-order dependence appears to be related to location near the East or West Coast (Fig. 2). In winter, except for the extreme northwest, southwest and southeast corners of the United States, second-order dependence dominated the East and West. In spring, most of the stations exhibiting second-order dependence were again located on or relatively near the oceans. Five of the seven second-order stations in the summer season are located in the Northwest. Finally, in the fall, there is a large group of stations in the Far West and several stations in the East with second-order dependence. This grouping may reflect the moderating effect of the oceans on weather systems.

A different criterion for selecting the correct order of Markov chain dependence was employed by Chin (1977) on January–February and July–August data for 1949–73. He used the Akaike Information Criterion (AIC) (Akaike, 1974; Tong, 1975) which selects the order k for which AIC(k) is smallest:

$$\mathrm{AIC}(k) = \eta_k - 2(s^m - s^k)(s - 1),$$

where η_k, s and m are as above. Katz (1981) has showed that this criterion tends to overestimate the correct order of Markov chain dependence.

The SBC results for winter and summer seasons were compared to the results of Chin. Over much of the United States the AIC-determined chain order was higher than the SBC-determined order. For January–February, Chin found that second- and third-order models dominated the United States with areas of first-order chains in the Midwest, Great Plains and Florida. For July–August, first-order cases dominated with areas of second-order dependence in the West, the southern Great Plains and near the Great Lakes. The SBC results, however, lead to the conclusion that in many, if not all, cases higher-order models may not need to be considered.

b. Stationary transition probabilities

One of the assumptions of Katz's model is that the Markov chain transition probabilities are stationary over time. This assumption is tested on the precipitation data for each station on both the day-to-day and year-to-year time scales at the $\alpha = 0.05$ level following the procedure of Anderson and Goodman (1957). The results of these analyses for the 104 stations are reported in Table 3.

The day-to-day case results are mapped in Fig. 3. In the winter season the transition probabilities of four stations in the north-central United States varied significantly through the season. Since this is less than 5% of the stations, it can be concluded that these probabilities varied due to random effects. In spring only three of the nine stations which had significant variations in transition probabilities are closely grouped; they are located in Florida. The stations are again a relatively small percentage of the total number of stations investigated and it is concluded that the transition probabilities are stationary. The summer and fall seasons had 21 and 29 stations, respectively, for which transition probabilities varied from day to day. The majority of these stations in summer are located in the western Great Plains and Rocky Mountains, areas which generally have little or no rainfall in the summer. In fall, small groups of stations with significant variations in transition probabilities are located in the Northwest, the central United States, the Great Lakes area and the Southeast. The climates of these areas differ substantially from one another so nonstationary transition probabilities cannot be related to specific climatic properties with ease.

The variability of transition probabilities from day to day has been discussed in the literature dealing with the application of Markov chains to daily precipitation data. Solutions to this problem which have been suggested include partitioning the data into shorter time periods such as seasons (Caskey, 1963), months (Longley, 1953) and 10-day intervals (Eichmeier and Baten, 1962). The shorter partitioning interval is a better solution if the transition probabilities vary gradually from the beginning to the end of the period. Another possibility of partitioning the data

TABLE 2. Number of first- and second-order Markov chains for each season.

Season	First-order	Second-order
Winter	73	31
Spring	86	18
Summer	97	7
Fall	79	25

FIG. 2. Markov chain order of daily precipitation occurrence data for (a) winter, (b) spring, (c) summer and (d) fall, 1948–76, determined by SBC.

into more stable groups was suggested by Smith and Schreiber (1973) who separated their data into time periods corresponding to the atmospheric processes which caused precipitation. A more involved procedure of allowing the transition probabilities to vary continuously with time through the use of Fourier series has been proposed (Woolhiser and Pegram, 1979; Coe and Stern, 1982).

The data for the 21 stations in summer and 29 stations in fall that had significant day-to-day variability in probabilities were partitioned into monthly data sets, the SBC order of Markov chain was determined and the new transition probabilities were tested for day-to-day and year-to-year stability. The new partitioning solved some of the problems with nonstationary probabilities in either the daily or yearly case for any of the months included in the respective season.

TABLE 3. Number of stations with nonstationary transition probabilities for each season.

Season	Day-to-day	Year-to-year
Winter	4	50
Spring	9	31
Summer	21	12
Fall	29	42

To determine the effect of this repartitioning on all the data, the data for all 104 stations were submitted to the new analyses. The results are reported in Table 4. On the average, the numbers of stations with probability problems are fewer per month than per season for both the day-to-day and year-to-year cases. In fact, the numbers of stations with nonstationary transition probabilities in the day-to-day case are small enough to conclude that this is due to chance variation. Therefore, it can be concluded that the monthly partitioning scheme is preferable to the seasonal scheme used in this study. However, because seasonal forecasts are made and therefore estimates on the noise in the data are necessary and also because one of the purposes of this study was to apply a new methodology, it was decided to report the findings of this study and to identify those stations for which results may be questionable.

FIG. 3. Stations for which day-to-day transition probabilities were unstable for (a) winter, (b) spring, (c) summer and (d) fall, 1948–76.

The results for the year-to-year situation using seasonal data are mapped in Fig. 4. In winter, most of the 50 stations with transition probabilities that were not stationary are grouped in the northeastern quarter of the United States and in the western United States. The 31 stations with nonstationary transition probabilities in spring are not clustered together as tightly, but most are located in the western half of the United States. In summer, only 12 stations were indicated to have transition probability problems and these are scattered over the United States. In fall, 42 stations, scattered over all but the eastern United States, had significant variations in year-to-year transition probabilities.

TABLE 4. Number of stations with nonstationary transition probabilities for each month.

Month	Day-to-day	Year-to-year
January	5	29
February	1	10
March	1	19
April	4	16
May	5	7
June	4	10
July	7	7
August	7	6
September	7	5
October	7	9
November	6	14
December	2	23

Climatic change in total precipitation can occur either through changes in the frequency of precipitation or through changes in the intensity of precipitation. Changes in frequency can be detected from the transition probabilities, changes in intensity can be detected from the actual amounts of precipitation. Therefore, the test for stationary year-to-year transition probabilities can be interpreted as a test for climatic change in the occurrence of precipitation over the 29-year period. Stations which experienced changes in actual precipitation amounts over time are presented later in this paper. It will then be seen that the results from these two tests are quite different.

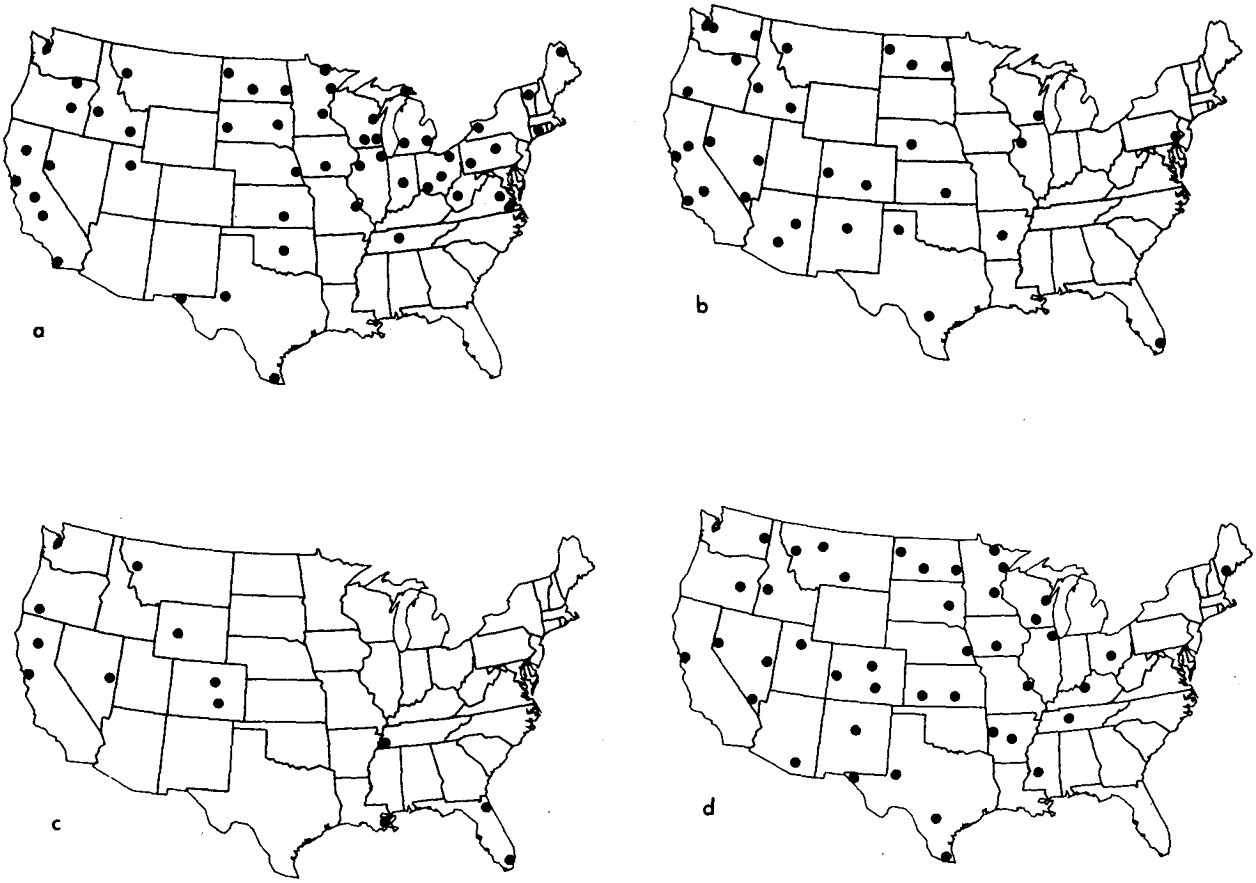

FIG. 4. Stations for which year-to-year transition probabilities were unstable for (a) winter, (b) spring, (c) summer and (d) fall, 1948–76.

c. Conditional independence of data

Another assumption of Katz's model is that the amounts of precipitation on consecutive wet days are independent. Following the procedure discussed in Katz (1977), the correlation coefficients of the natural logarithms of precipitation amounts were calculated for each season. Instead of testing whether the correlation coefficients were significantly different from zero as Katz did, correlation coefficients with absolute values greater than 0.3 were considered to be significant. The reason for this seemingly arbitrary decision is that even very small correlations may have a significant t-value associated with them if sample sizes are large. Sample sizes large enough to cause such a problem were encountered at most of the stations covered by this study. The value of 0.3 was chosen since even at that level of dependence, less than 10% of the variance in precipitation amounts can be explained by the amounts on the previous day or days. The order of Markov chain dependence determined earlier was considered in determining which pattern of dependence should be tested. In first-order cases, precipitation amounts on days n and $n + 1$ were tested for dependence. Three cases were tested when second-order dependence was estimated: 1) precipitation on days n, $n + 1$ and $n + 2$, 2) precipitation on days $n + 1$ and $n + 2$, and 3) precipitation on days n and $n + 2$. Under the above-stated restrictions it was found that only in a few cases could the assumptions of independence in precipitation amounts be rejected (Table 5).

d. Estimates of seasonal variance based on daily data

Estimates of seasonal variance based on daily data were computed first assuming independence of the

TABLE 5. Number of stations with significant correlation between amounts of precipitation.

Season	First-order	Second-order
Winter	5	3
Spring	2	0
Summer	3	0
Fall	1	2

daily data and then allowing for dependence as described in Katz's model. The dependence estimates in almost all cases are greater than the estimates computed under the assumption of independence. As already discussed, if variance estimates based on independence are used in an analysis of variance design to determine climatic change, then there may be an increased danger of concluding that the climate has changed even though it has not. Maps of the ratio of estimates of seasonal variance allowing for dependence to estimates under the independence assumption are presented in Fig. 5. Large ratios indicate those stations for which there is a greater chance that the independence assumption may lead to erroneous conclusions on climatic change.

The four seasonal maps are quite similar to each other with relatively low ratios in the East increasing to the highest ratios in the West. In addition to this trend, there are also pockets of higher ratios compared to surrounding areas in the South-Central states in all seasons. The fall season generally has the highest ratios of all the seasons. The dependence assumption is, therefore, most critical in tests for climatic change in the fall, and in the West in all seasons.

The pattern does not change if the first-order model is assumed to be the correct model for all stations. Only small absolute differences were found between the variance estimates under the assumption of first- or second-order dependence when second-order dependence had been chosen as correct by SBC. Whether the small differences result in different conclusions on climatic change will be addressed in the next section.

e. Test for change in precipitation amounts

Change in seasonal precipitation amounts was earlier defined to have occurred if the variance of the seasonal climatic averages was significantly greater than an estimate of that variance computed from daily data. Results of this test, outlined in Section 2, under the assumption of independence and also allowing for dependence in daily data, are presented in Fig. 6 and Table 6.

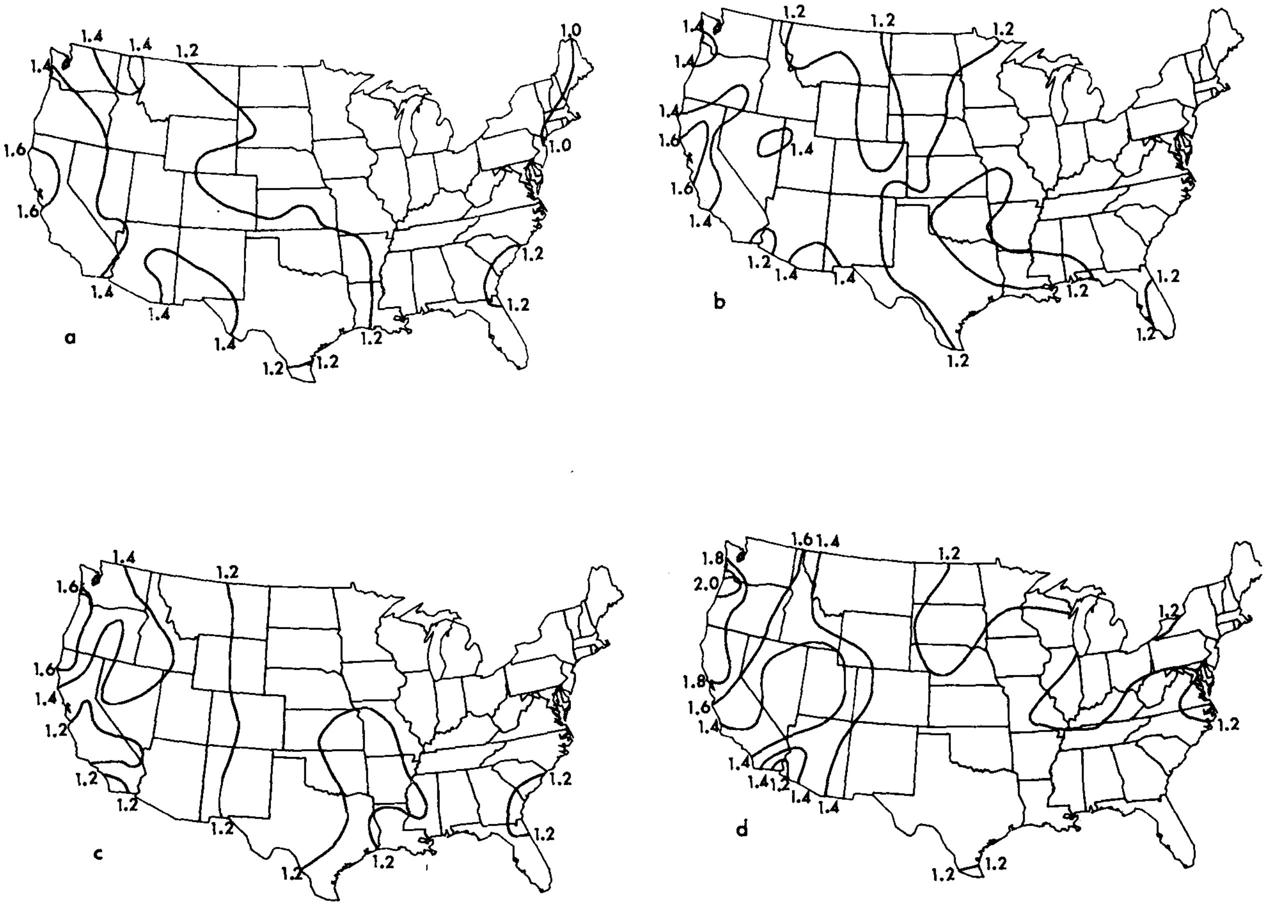

FIG. 5. Ratios of an estimate of the seasonal variance allowing for dependence in daily data to an estimate of the seasonal variance assuming independence in daily data for (a) winter, (b) spring, (c) summer and (d) fall, 1948–76.

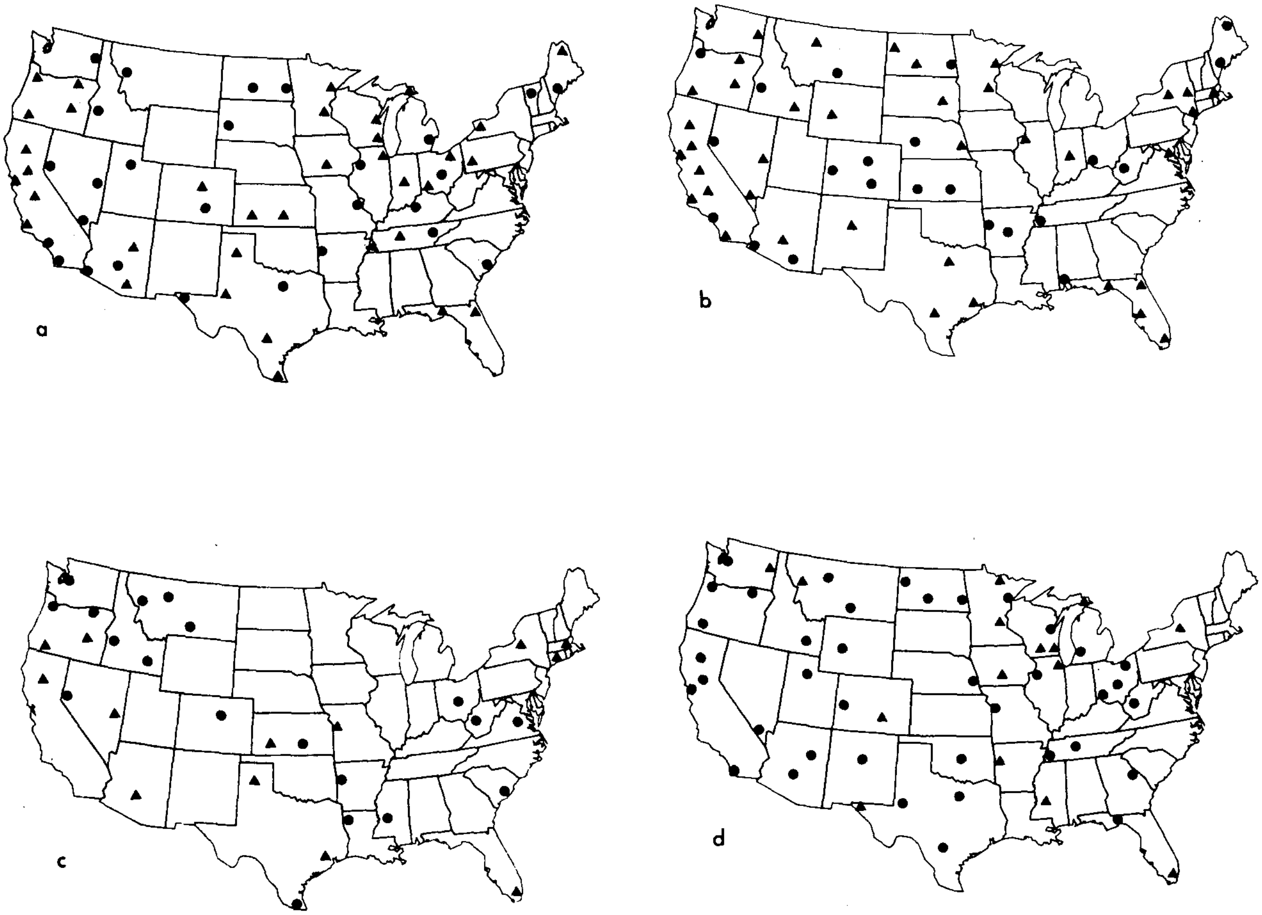

FIG. 6. Stations which exhibited change in seasonal precipitation amounts for (a) winter, (b) spring, (c) summer and (d) fall, 1948–76. Stations which exhibited change only under the assumption of independence are indicated by dots, stations which exhibited change also when dependence in daily data was allowed are indicated by triangles.

Under the independence assumption, 62 of the 104 stations exhibited change in precipitation amounts during the winter season. These stations tend to be located together, many of them in the western quarter of the United States and another large group in the central third of the country. Precipitation regimes of only 35 of those 62 stations changed when dependence was incorporated in the model. These 35 stations are found along the West Coast, in the South-Central states and in the area around the Great Lakes.

In spring the precipitation amounts of 60 stations changed under the assumption of independence. These stations are located west of the Mississippi River, in the Northeast and in Florida. When dependence is allowed, only 38 of these stations still exhibited change. The West Coast, northern United States, southern United States and Northeast each contain a group of these stations.

TABLE 6. Number of stations which exhibited change in precipitation amounts, 1948–76.

	Data assumption	
Season	Independence	Dependence
Winter	62	35
Spring	60	38
Summer	32	13
Fall	54	15

Of the four seasons, summer had the fewest stations which experienced change under the assumption of independence and also when dependence was allowed. For the independence case, the 32 stations that underwent change are located in the Northwest and in the South-Central and Atlantic Coast states. The precipitation regimes of only 13 of these stations changed when dependence was allowed. Most of these 13 are in three clusters located in the western, central and northeastern United States.

The fall season has the greatest discrepancy in the number of stations with change under the two assumptions. The 54 stations exhibiting change under the assumption of independence are scattered across the country. Only 15 of these stations also exhibited change under the allowance for dependence, seven of this second group are located in the upper Midwest and the others are scattered over the United States.

Very similar results were obtained when only first-order model variance estimates were used in the test for change in precipitation amounts over time. Four or fewer stations were affected by this difference in each season; however, the small number of decision changes must be compared to the number of stations with second-order dependence. It is then seen that the proportion of stations affected by the assumption of first-order dependence is relatively high in all seasons but summer (Table 7). It is suggested, therefore, that higher-order models should not be ignored in this analysis.

There were several surprising results in the number and the location of stations affected by climatic change in precipitation amounts when there was an allowance for dependence in daily data. Of the 104 stations investigated in this study, the precipitation regimes of 68 of them were affected by change in at least one season. Of the 68, 41 exhibited evidence of change for only one season, 21 stations for two seasons and only six stations for three seasons. No station's precipitation records gave evidence of change in all four seasons. The majority of the 27 stations with precipitation data which changed in two or three seasons are located in two regions: the West Coast and the upper Midwest. Conspicuously absent from this group are many of the Great Plains stations with precipitation records that were considered to have varied during much of this time period (Borchert, 1971). On the other hand, precipitation regimes during winter and spring for most California stations, which also underwent severe drought during 1948–76, did exhibit change. These results suggest that years of severe drought may contribute significantly to the variance statistic, but are not necessarily indicative of climatic change as it is defined in this paper.

The results of this test for change in precipitation amounts can be compared to the results for change in precipitation occurrence over the 29-year period. From Table 8 and from a comparison of Figs. 4 and 6 it can be seen that the two tests do not lead to the same results. It is obvious from these results that, as stated earlier, the precipitation climate of a station can change in two distinct ways and that a change in one component is not necessarily related to a change in the other component.

TABLE 7. Number of stations at which the climatic change decision was affected by allowing only first-order dependence in precipitation data.

Season	Decision switch: From change to no change	Decision switch: From no change to change	Proportion of stations affected
Winter	2	1	0.097
Spring	2	0	0.111
Summer	0	0	0.000
Fall	0	4	0.160

TABLE 8. Number of stations that exhibited change in precipitation occurrence and precipitation amounts, 1948–76.

Season	Precipitation occurrence	Precipitation amounts	Precipitation amounts and occurrence
Winter	50	35	22
Spring	31	38	17
Summer	12	13	4
Fall	42	15	11

5. Summary and conclusions

Climatic change was defined as change in climatic means due to changes in external conditions rather than to noise in daily data. A variance components model was used to test whether there is evidence of climatic change in seasonal precipitation amounts for 104 stations in the United States during the period 1948–76. Climatic change was defined to have occurred at those stations for which the variance estimate computed for seasonal averages was significantly larger than the variance estimate computed from daily data. A generalization of the Markov chain model was fitted to daily precipitation amounts, the data were tested to see whether the assumptions of the model were upheld, and a new estimate of the seasonal variance was then estimated. Precipitation amounts on consecutive rainy days were found to be independent. Transition probabilities, however, varied from day to day or from year to year at quite a few of the stations studied. Partitioning the data into monthly data sets would lessen the problem of day-to-day unstable transition probabilities.

Estimates of the seasonal variance were computed from daily data under the assumption of independence and also allowing for dependence. The dependence estimates were larger than the independence estimates, especially in the fall and in the western United States in all seasons. The results of the test of climatic change in precipitation data showed a marked drop in the number of stations with change from the assumption of independence to allowing for dependence in all seasons. A large group of stations in the western United States were represented in all seasons, but especially in the fall.

A majority of the stations in the Great Plains, an area which had experienced droughts during the period, did not exhibit change in more than one season. The precipitation records of most California stations, another area affected by droughts, did contain evidence of climatic change for two or three of the seasons. It was concluded that severe droughts may contribute significantly to the variance statistic, but are not necessarily indicative of climatic change. More generally, short-term variations in precipitation patterns and amounts may not be the result of changes in external conditions but rather may be explainable by noise in the data. Above all, it must be concluded that external causes of climatic change should only be searched for after it has been determined that climatic change has occurred.

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