Secular Changes of Precipitation in the Rocky Mountain States

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ABSTRACT

Long-term precipitation records from Montana, Idaho, Wyoming, Utah and western Colorado were obtained and carefully screened for missing data and station relocations. Each record was divided into five seasonal series and tested for homogeneity. Most of the unhomogeneous records were for the winter season, whereas there were fewest for summer and late summer seasons. Those seasonal records considered to be homogeneous were then used to examine the spatial variation of precipitation anomalies decade by decade (1891–1900, 1901–1910, etc.) from 1941–70 averages. Areas of statistically significant anomalies were identified. Generally, precipitation was high in the 1890's, 1910's and/or 1920's, 1940's and 1960's. Other decades were relatively dry, particularly the 1930's. Springs 1941–70 were wetter than the previous 30 years, but the period 1881–1910 was wetter than the 1941–70 averages. Considering summer precipitation, 1941–70 was probably the most anomalously wet period for at least 110 years and perhaps much longer. Over much of the Rockies the 1960's were extraordinarily wet. Fall precipitation was exceptionally low in the 1950's, but the 1941–60 average was still relatively high, though generally drier than the 1890's, 1910's and 1920's. Winter precipitation in recent decades has been considerably less than was characteristic of the late 19th and early 20th centuries, except in Idaho. Recurrent anomaly patterns, centered over southern Idaho, are characteristic of the winter record.

When the entire secular period is considered the recent "normal" is anomalous; in particular, summer precipitation has been unusually high and winter precipitation relatively low. One hundred years ago the climate of the Rockies was characterized by wetter winters and springs but much drier summers (and in some areas) drier falls compared to the post-1940 climate of the region.

1. Introduction

The Rocky Mountain region is one of the most rugged and diverse physiographic provinces in the United States. Perhaps because of this fact, the climatic characteristics of the area even today are not well-known (Bryson and Hare, 1974) though recent studies (e.g., Mitchell, 1969) have attempted to simplify the climate by removing the effects of topography. There has also been much recent work connected with short-term forecasting and this has indirectly shed light on the synoptic characteristics associated with particular precipitation and temperature patterns (see, for example, Korte *et al.*, 1969, 1972; Jorgenson *et al.*, 1967; Klein, 1965; Augulis, 1969, 1970a and b; Sullivan and Severson, 1966a,b). Nevertheless, compared with the rest of the United States the area has been relatively neglected in terms of climatological studies, particularly those concerned with climatic variations in the secular period. The work presented here has been directed towards this gap in our knowledge.

Bradley (1976a) has discussed previous studies of climatic fluctuations in the area and outlined late 19th century fluctuations in precipitation throughout most of the western United States. In this study the focus has been on *continuous data*, from stations which have operated in the area from 50 to approximately 100 years without any serious interruption in location. Precipitation was studied in detail because of its significance in terms of potential cloud seeding operations throughout the Rockies in the near future and because of its importance to tree growth in the area (Fritts, 1966) and hence to dendroclimatic reconstructions.

2. Initial data survey

The search for long-term records was confined to the states of Montana, Idaho, Wyoming, Utah, and western Colorado. In the initial data survey (using a criterion of at least 50 years of record to 1970) approximately 260 precipitation records were noted in the study area. These stations were then carefully screened 1) to assess the amount of missing data, and 2) to assess the number of times the recording station was moved during the period of record.

In the former case, monthly values were divided into seasonal units and the number of missing months in each season for the entire record length was assessed. Any station/season record with more than 5% of the monthly values absent was rejected. Any interpolated values already in the published record were assumed to be correct and were not recomputed or considered in calculating the 5% missing data limit.

On the question of station relocations, considerably more difficulty was encountered; station histories are poor in most cases. At nearly all stations, the original sites of observations are poorly known or not known at all, and station movements were seldom carefully noted. The U. S. Weather Bureau Publication, *Substation History*, for each state was an attempt to remedy this situation, but unfortunately many of the entries therein are ambiguous or uninformative. For example, the section "distance and direction from previous site" is absent on many of the earlier forms and a change in the elevation listed may be the only indication of an apparent move. Also, in some cases a "new location" entry is made each time there is a new observer, but the information given is frequently insufficient to tell whether this event was also associated with a new location of the observing station. In view of these problems, attempts to screen out those stations which may have experienced frequent moves were inevitably inadequate. Nevertheless, a procedure was followed which did result in the elimination of a considerable number of stations whose station histories indicated large and/or frequent moves which were likely to result in inhomogeneities in the record. The criteria for rejection were arbitrarily chosen; any move of greater than one mile was considered too large and more than an average of one move per fifteen years of record was considered too many. In either case the station was rejected. When doubt existed as to the character or authenticity of a station move, the record was assumed to be acceptable pending subsequent statistical investigations of homogeneity (see below).

As a result of these somewhat arbitrary data quality standards, the initial selection of 260 precipitation station records was reduced by about one third. The stations chosen are identified in Bradley (1976b, Figs. 37–40).

3. Missing data

Because only a few stations in the study area have no missing data, some monthly values had to be interpolated at most stations. As noted above, this ranged from one or two months to 5% of a seasonal record.

Interpolation is normally carried out using two records, one from the station (Q) which has missing data, the other from an adjacent station (A). In the case of precipitation, the ratio of the means for corresponding periods $(\bar{Q})/\bar{A}$ is first calculated. Then the missing monthly value at station Q is estimated to be the product of the corresponding monthly value at station A and the ratio of the means (Conrad and Pollack, 1950, p. 235).

In this study a slightly different procedure was followed which was found to give estimates generally as good as, or better than, the above method.[1] In choosing "adjacent stations," selection was limited to those long-term stations already isolated in the earlier data survey in order that the longest possible parallel records could be used. Shaded topographic relief maps were used to examine the location of stations nearest the key station. By assessing three factors—elevation, distance, and topographic situation (with respect to mountain ranges and divides in particular)—the most suitable record to be used for interpolation was chosen.

It was felt that the interpolation method used was adequate for this study because:

1) the amount of missing data had been previously restricted to a maximum of 5% of any one season,

2) monthly values were being interpolated whereas in the statistical analyses which followed, seasonal totals were examined,

3) all seasonal series were to be tested for homogeneity after the interpolation of missing values (see next section).

4. The homogeneity of records

A fundamental prerequisite for studies of secular climatic change is that the station records are homogeneous. This implies that a given record is equally representative of climatic conditions in the vicinity of the station throughout the entire period of its operation. In practice, of course, stations are often moved, some observers may be less diligent than others, and exposures may not be ideal. Indeed, even if a station had an ideal exposure in 1900 and was never moved, its exposure may have deteriorated over time due to the construction of buildings nearby or simply the natural growth of trees (e.g., Lawrence, 1970). Furthermore, many of the longest records are associated with the growth of an urban center where the local climate has gradually been modified over time (Landsberg, 1970).

Conrad and Pollack (1950) distinguish two types of inhomogeneity: absolute and relative (see also, J. M. Mitchell, 1961). A precipitation series is said to be relatively homogeneous with respect to a synchronous series at another place if the "ratios of pairs of homologous averages constitute a series of random numbers that satisfies the law of errors" (Conrad and Pollack, 1950, p. 226). However, as pointed out by Mitchell *et al.* (W.M.O., 1966), the evaluation of relative homo-

[1] Suppose there are two series:

$$Q_1, Q_2, \ldots, Q_k, \ldots, Q_n; \quad A_1, A_2, \ldots, A_k, \ldots, A_n.$$

A new series of ratios is computed such that

$$Z_1=\frac{Q_1}{A_1}, \ldots, Z_k=\frac{Q_k}{A_k}, \ldots, Z_n=\frac{Q_n}{A_n}.$$

When the Q and A series are seasonal precipitation totals, the distribution of the Z series is highly positively skewed and the median ratio is selected to compute an estimate of the missing value ($Q_k=A_k\times Z$ [median]).

geneity is only a step towards ascertaining if a record is absolutely homogeneous, i.e., if, by itself, the record is representative of purely natural variations in the climate of the area immediately surrounding the recording site.

Unfortunately, the evaluation of absolute homogeneity is very difficult, if not impossible, in practice. Tests of absolute homogeneity usually require the construction of a "regional climatological series" (comprising the average of a number of adjacent records) with which the key station in question is tested. This generally involves computing a series of ratios of precipitation totals between the regional and key station records and testing the resulting series for non-randomness at a suitable significance level. However, in constructing a "regional climatological series" one is faced, inevitably, with assuming that some if not all of the station records to be used in constructing the regional series are homogeneous and of course this may not be so. There is, then, a danger of circular reasoning in the concept of absolutely homogeneous records, and in practice the best that can be achieved is a somewhat stronger evaluation of relative homogeneity than a simple test of relative homogeneity between one or more individual records.

In this study, further problems arise in using the classical tests of both relative and absolute homogeneity. Evaluation of homogeneity rests on the idea that the station record being evaluated is representative of its surrounding area, but in a mountainous region the problems of determining how large an area a particular station represents are formidable. Furthermore, when selecting the longest records in an area it is generally impossible to find stations in the immediate vicinity which have records as long as the record in question. Finally, in dealing with a large number of records, as this study does, the problems of acquiring long-period data from a dense network of stations close to each key station in question makes detailed studies of absolute homogeneity at each station an immense undertaking.

Because of all these problems the procedure used here to evaluate homogeneity was a compromise between computational costs, practical considerations of data availability, and the potential meaningfulness of exhaustive tests, given the extremely diverse topography of the study area. Nevertheless, it is felt that the careful application of the criteria outlined below were sufficiently stringent to preclude the incorporation of inhomogeneous records into subsequent statistical analyses. No attempts were made to adjust records which were thought to be inhomogeneous.

5. Testing for homogeneity

Tests of homogeneity generally involve the null hypothesis that series of ratios (or differences) between stations exhibit characteristics of a random series. This may be assessed by graphical techniques (Conrad and Pollack, 1950, p. 231; Kohler, 1949; W.M.O., 1966) or by statistical tests for alternatives to randomness. In this study, the latter were preferred as graphical analyses are often difficult to evaluate objectively. The following procedure was used: for each station in question (hereafter referred to as the key station), the nearest long-term stations which had records as long or longer than, the key stations were identified. Five seasons were then chosen (*spring:* April and May; *summer:* June, July and August; *late summer:* July, August and September; *fall:* September and October; *winter:* November, December [year 1], January, February and March [year 2]) and seasonal totals of precipitation were computed.[2]

Seasonal ratio series were constructed by dividing one of the series term by term, into the other. This new series was tested for non-randomness using the Mann-Kendall non-parametric statistic (Mann, 1945; Kendall, 1970). This is a general test of randomness against the alternative of trend (linear or otherwise) as trend is the form of non-randomness most likely to appear in the ratio series (W.M.O., 1966). A computed τ value exceeding the 95% probability point was taken to indicate that one of the two stations had an inhomogeneity in the seasonal record being examined. The problem was, which one? By comparing each seasonal record with two or more other seasonal records it was possible in many cases to isolate the inhomogeneous record in the following way. If a seasonal record was found to be inhomogeneous with respect to another record of comparable length *and* a second record of comparable length *or shorter*, the record was rejected. These criteria were generally adequate to isolate the most questionable records, and by removing these from the matrix of significant τ values generally only a few questionable pairs remained (see Bradley, 1976b, Table 6). These remaining pairs of records were noted as "suspect" and were rejected from many of the subsequent statistical analyses. Such precautions eliminated some records which might have been in reality acceptable, but it was felt that stringency was necessary in view of the problem of evaluating homogeneity in the area.

Those seasonal records which were rejected or designated suspect in this manner are to be found in Bradley, 1976b (Tables 7–11), and an example is given in Table 1. Only those stations which survived the initial screening for station movement and missing data (as outlined above) are included in the table. The stations are arranged by record length and it should be noted that the longest station record in each state was in-

[2] Seasons were selected to be comparable with other studies in the area. "Late summer" was added after an examination of intermonthly correlations showed a distinct break at some stations between the months of June and July. This reflects the July singularity noted previously by Bryson and Lahey (1958) and Bryson and Lowry (1955).

TABLE 1. Tests of homogeneity of precipitation records, Utah.

Station index number	Station name	Elevation (ft)	Year record begins	Season*† 1	2	3	4	5
2996	Fort Duchesne	4990	1887		S			
5065	Levan	5300	1889					
5186	Logan	4785	1891	S	S	S	S	R
2828	Fillmore	5160	1892				R	R
3809	Heber	5580	1893			S		S
5402	Manti	5585	1894	R			R	R
7714	Scipio	5306	1894					R
8771	Tooele	4820	1876					S
2101	Deseret	4585	1899					
4856	Laketown	5988	1900				R	
5752	Modena	5460	1901	S			S	R
2484	Emery	6200	1901					S
2418	Elberta	4690	1902	S				
5826	Morgan	5070	1903					R
8973	Utah Lake	4497	1904			S	S	R
0738	Blanding	6036	1905					S
6357	Oak City	5075	1905					S
2253	Duchesne	5510	1906					S
4527	Kanosh	5015	1907					
5837	Moroni	5525	1908	S				S
8119	Spanish Fork	4711	1910				S	
6534	Orderville	5460	1910					
3611	Hanksville	4308	1910				S	
0061	Alpine	4935	1910					
6658	Park Valley	5570	1911					
5610	Midvale	4342	1911			S		
7271	Richmond	4680	1911		S			S
9382	Wendover	4237	1911					S
6897**	Piute Dam	5900	1911					
7686	Santaquin	5100	1914	S		R		
7909	Snake Creek	5950	1914			S		
7318	Riverdale	4390	1914	S		S	S	
7846	Silver Lake Brighton	8740	1915					S
0086	Alton	7040	1915	S			S	
5969	Myton	5030	1915		S			S
3896	Hiawatha	7230	1916	S				S
1759	Cottonwood Weir	4950	1917					
8705	Thompson	5150	1918				S	

* 1 = spring (A, M); 2 = summer (J, J, A); 3 = late summer (J, A, S); 4 = fall (S, O); 5 = winter (N, D, J, F, M).
** Records end 1969.
† S = suspect; R = rejected.

evitably only partially tested. In all seasons there are no clear regional patterns of inhomogeneity.

Table 2 summarizes the results of the homogeneity tests. It is interesting to note that the number of station records rejected or suspected is considerably higher in winter than in summer months (an average of 44% of winter records compared with 18% of summer or late summer records). As most of the precipitation in the area falls as snow during the winter months, it is likely that problems of accurately recording snowfall (Leaf, 1962) are often responsible for inhomogeneities in the records. Snowfall recording problems may also be reflected in the number of records rejected or suspected for spring and fall seasons when precipitation falls in the form of both rain and snow. Of all the seasonal records examined, 26% were rejected or suspected of inhomogeneities.

Before the data are analyzed further, it is of interest to see if the long-term station network adequately

TABLE 2. Percentage of seasonal precipitation records rejected, or suspected of being inhomogeneous.

State	Spring	Summer	Late Summer	Fall	Winter
Colorado	26	32	26	11	47
Idaho	32	18	16	29	42
Montana	28	8	13	25	43
Utah	24	11	18	29	47
Wyoming	41	19	13	32	40
Average	30	18	17	25	44

represents the topographic and elevational diversity of the Rocky Mountain region. The average elevation of the stations selected is 4866 ft, ranging from 1260 ft at Kooskia, Idaho, to 9322 ft at Silverton, Colo. (Table 3). Clearly the stations chosen do not reflect in detail the diverse topography of the area; however, they can be considered to represent a topographic surface across the region as shown by the contours of station elevation in Fig. 1. Analyses of the data must be interpreted in terms of this "station-elevation" surface within the context of the "real" topography of the area. A comparison of station elevations with a hypsometric division of the study area indicates that the elevation zone below 5000 ft (38% of the area) is over-represented by the long-term station network (53% of stations selected). The higher elevation zones (>5000 ft) are under-represented (62% of area and 47% of stations). In particular, that part of the study area above 10 000 ft (6% of the region) is not represented at all, as there are no long-term stations at such elevations. In fact, there are very few high elevation stations with even 30 years of record (1941–70), as shown in Table 4. Only one station >10 000 ft in the entire study area has operated over a 30-year period and there are only eight such records for elevations >9000 ft (7 in Colorado, 1 in Wyoming). In the statistical analyses that follow, this problem of sampling

TABLE 3. Summary of elevation size categories* for long-term precipitation stations in the study area.

Elevations (ft)	Colorado	Idaho	Montana	Utah	Wyoming	Σ	Percent
1001–2000		2	1			3	2
2001–3000		12	10			22	13
3001–4000		7	14		4	25	15
4001–5000	2	8	8	14	8	40	23
5001–6000	4	8	5	19	6	42	25
6001–7000	4	1	1	2	10	18	11
7001–8000	1			2	4	7	4
8001–9000	4			1	1	6	4
9001–10 000	4				1	5	3
	19	38	39	38	33	168	100
Average elevation by state:	7211	3729	3715	5399	5790	4866	(overall average)

* Elevations from station indices in State *Annual Summaries of Climatological Data* for 1970 (U. S. Weather Bureau).

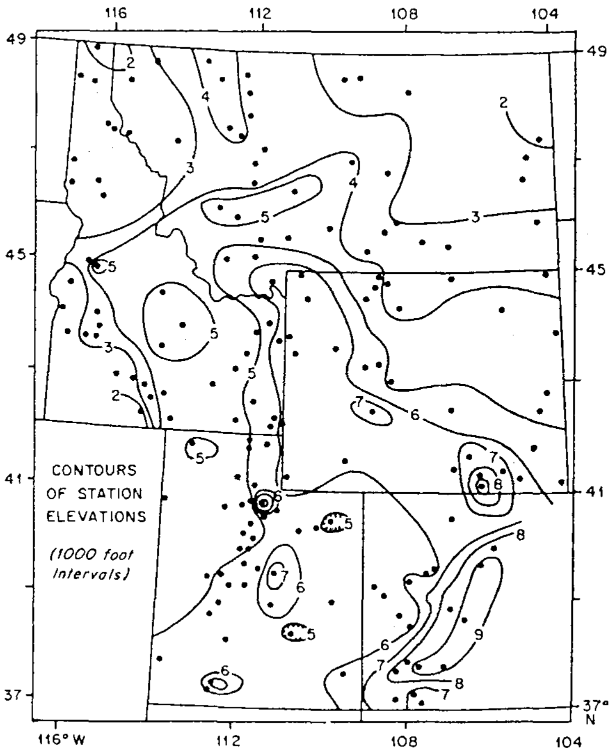

FIG. 1. Generalized contours of station elevation (thousands of feet).

the "real" topographic and climatological diversity of the region must be considered; for example, conclusions reached may not apply to the very high elevation parts of the region. Nevertheless, the author is

TABLE 4. Highest elevation Weather Bureau stations with precipitation normals for 1941–70.

State	Index no.	Station	Latitude	Longitude	Elevation (ft)
Colorado	4884	Leadville	39°15′	106°18′	10 158*
Idaho	4598	Island Park Dam	44°25′	111°24′	6 300
Montana	1995	Cooke City	45°36′	107°27′	7 553**
Utah	7846	Silver Lake	40°36′	111°35′	8 740†
Wyoming	3630	Foxpark	41°05′	106°09′	9 045†

* Only station normal at an elevation > 10 000 ft.
** Only station normal in the state at an elevation > 7000 ft
† Only station normal in the state at an elevation > 8000 ft.

confident that the stations chosen represent the optimum long-term station network for the area both geographically and with elevation.

6. Decadal seasonal precipitation maps (1891–1970)

In order to investigate the spatial distribution of precipitation change over time in the study area, maps of decadal seasonal precipitation from 1891–90 to 1961–70 were prepared (Figs. 2 to 5). The seasonal average precipitation at each station for each decade was compared with the average for 1941–70 and expressed as a deviation from the 1941–70 mean, in terms of the standard deviation for 1941–70 at each station. The value plotted at each station ($\hat{x}$) is thus a standardized or Z-score; thus,

$$\hat{x}_1 = \frac{\bar{x}_1 - \bar{x}}{s}$$

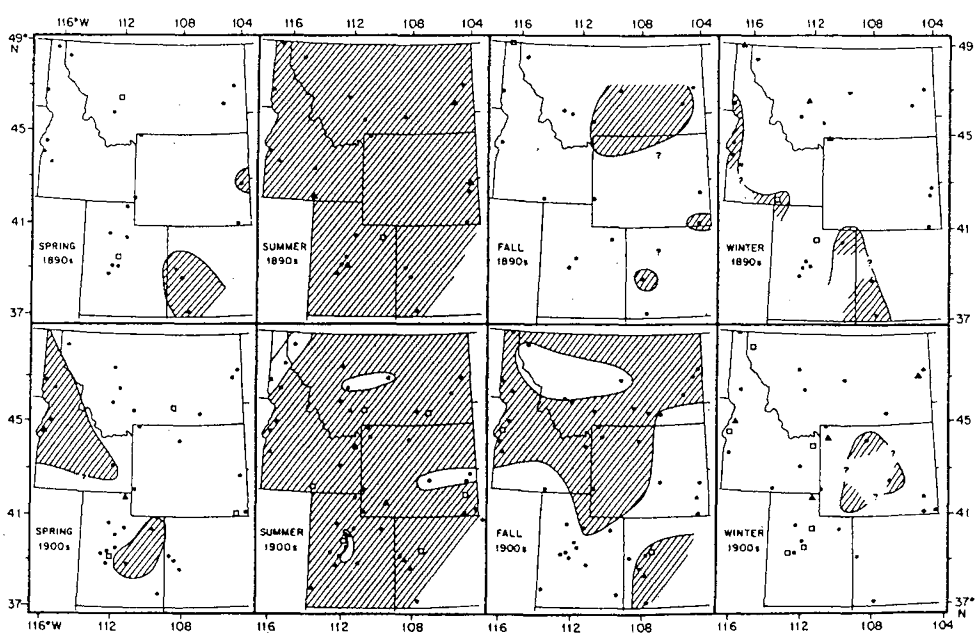

FIG. 2. Deviations of seasonal precipitation averages for 1891–1900 (above) and 1901–1910 (below) from the 1941–70 averages. Below average areas are shaded. Statistically significant departures from the means (+ or −) are indicated by a square (<5% level) or a triangle (<1% level).

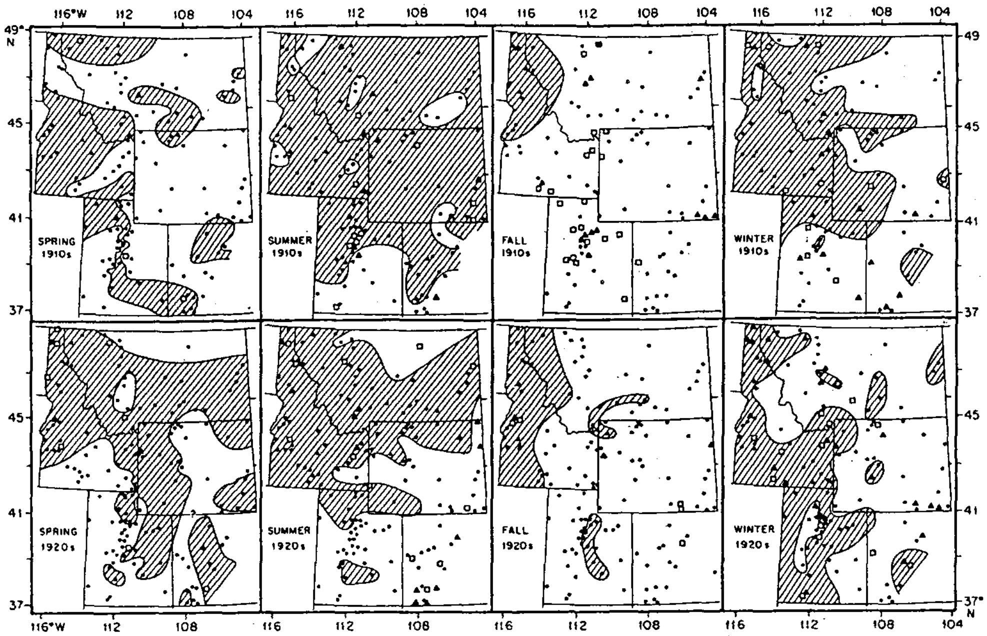

FIG. 3. Deviations of seasonal precipitation averages for 1911–1920 (above) and 1921–30 (below) from the 1941–70 averages. Below average areas are shaded. Statistically significant departures from the means (+ or −) are indicated by a square (<5% level) or a triangle (<1% level).

where $\bar{x}_1$ is the decadal seasonal average precipitation for decade 1, $\bar{x}$ is the seasonal average for 1941–70, and s is the standard deviation for 1941–70.

This procedure was carried out in order to take into account differences in variability from one part of the area to another. The period 1941–70 was chosen, as this is the most recent "normal" period (according to W.M.O. definition; W.M.O., 1966). Isopleths separating areas of above and below normal precipitation have been drawn without oversimplifying the patterns. Care was taken to take all data points into account; however, generally at least two adjacent stations were

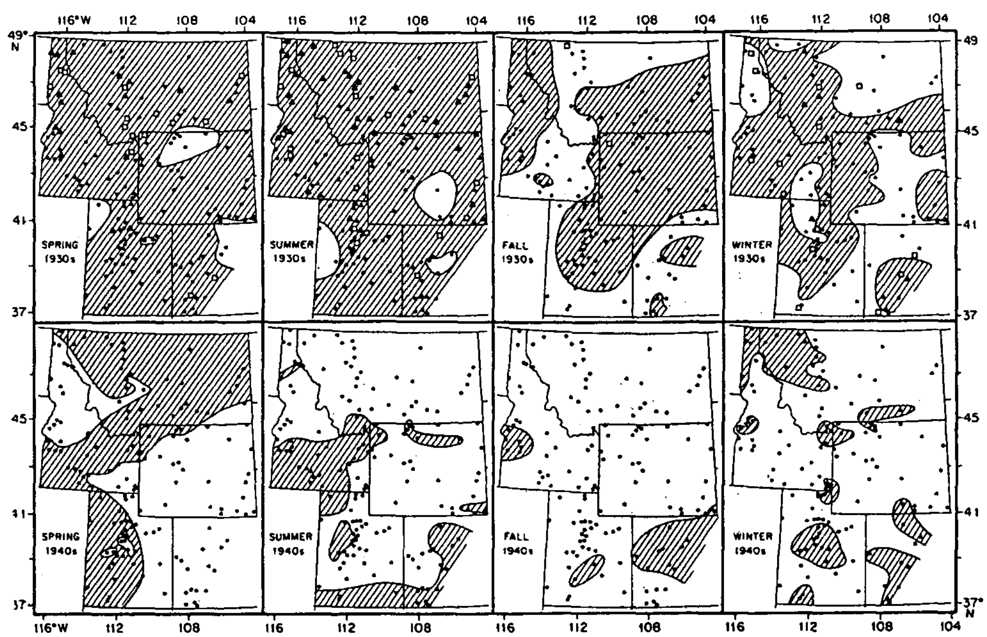

FIG. 4. Deviations of seasonal precipitation averages for 1931–1940 (above) and 1941–60 (below) from the 1941–70 averages. Below average areas are shaded. Statistically significant departures from the means (+ or −) are indicated by a square (<5% level) or a triangle (<1% level).

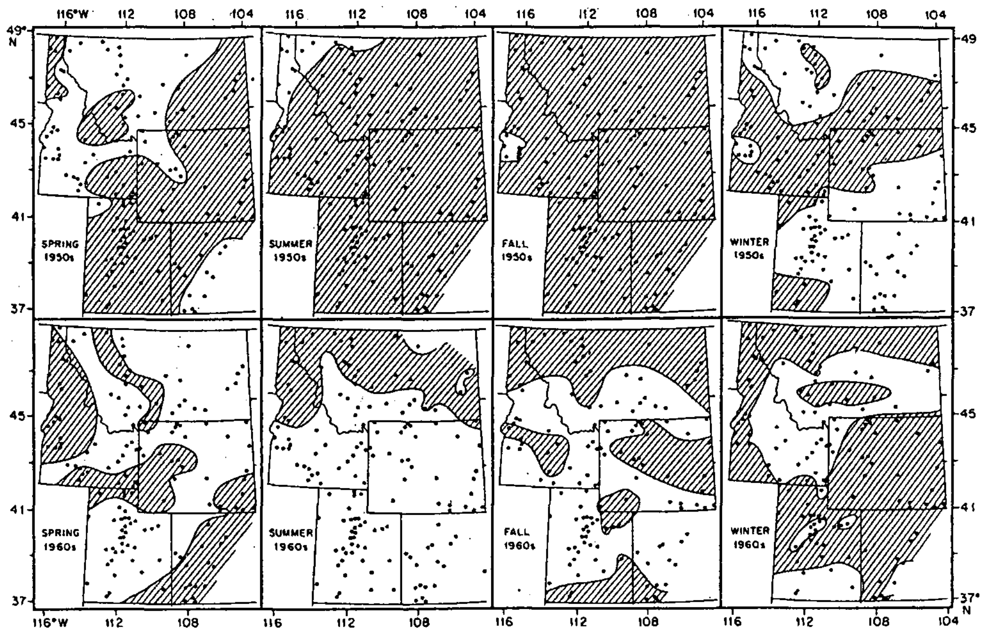

FIG. 5. Deviations of seasonal precipitation averages for 1951–60 (above) and 1960–70 (below) from the 1941–70 averages. Below average areas are shaded.

needed before "anomalous" points would be identified by isopleths. All rejected stations (see above) were omitted from the analysis; suspect stations were used to supplement the other data points but were not used to construct isopleths unless other "acceptable" stations in the area appeared to support the suspect stations. Statistical significance of the decadal averages from 1941–70 "normals" was assessed by means of Student's t statistic. Those decadal averages which were significantly different from 1941–70 averages at $<5\%$ level are identified on the maps, indicating those areas and periods in which the most important moisture surpluses and deficits have occurred.

In addition, seasonal precipitation records were examined for trend using the Mann-Kendall rank statistic (described above). Although the data bank contained records of varying length, all records span the 51-year period 1920–70, so trends during this period were examined. Only those stations which were not rejected or "suspect" were chosen for this part of the study. Those records which gave statistically significant τ values and maps of τ values for each season are given in Bradley (1976b). In general τ values were negative (precipitation values declining) over most of the region in spring, fall, and winter, whereas summer τ values were positive, particularly in southern Idaho.

a. Spring

In most areas precipitation totals in the period 1941–70 were higher than in the previous 30-year period (1911–40). Increases were most marked in Idaho, Montana, and northern Wyoming, whereas in Utah and Colorado about half of the stations showed increases and half decreases. Overall, more than 70% of stations with 60 years or more of record showed increases from 1911–40 to 1941–70.

The relatively high averages for 1941–70 are mainly the result of heavy spring precipitation in the 1940's and 1960's. In the 1940's (Fig. 6) precipitation was the maximum for 60 years (1911–1970) over most of western Colorado, southern Wyoming, southeastern Idaho, and the Idaho panhandle.[3] In the 1960's maximum precipitation was recorded at stations in central Utah, southern Montana, northern Wyoming and the upper Snake River valley of Idaho. In most areas, therefore, the period 1941–70 was anomalous in terms of spring precipitation amounts over the last 60 years. However, precipitation in the 1890's and 1900's was relatively high at most stations with records for this period, the main exceptions being Idaho stations in the 1900's. As a result, the few records for the 30-year period 1881–1910 indicate relatively high spring precipitation amounts compared to the subsequent 60 years.

Precipitation was well below average over much of the area in the 1930s and over Montana, Idaho and Utah no other decade in the entire period 1891–1970 was as

[3] Stations in these areas (apart from northern Idaho) are generally above 5000 ft, but whether this is a factor in causing the area to experience maximum precipitation in this period (e.g., due to a particularly strong orographic effect at this time) is debatable. This is a problem in all cases where strong differences occur between northern and southern parts of the region; all the very high elevation stations are in the southeast (Fig. 1), so it is frequently difficult to assign a given pattern to factors of geographical location or influences of elevation.

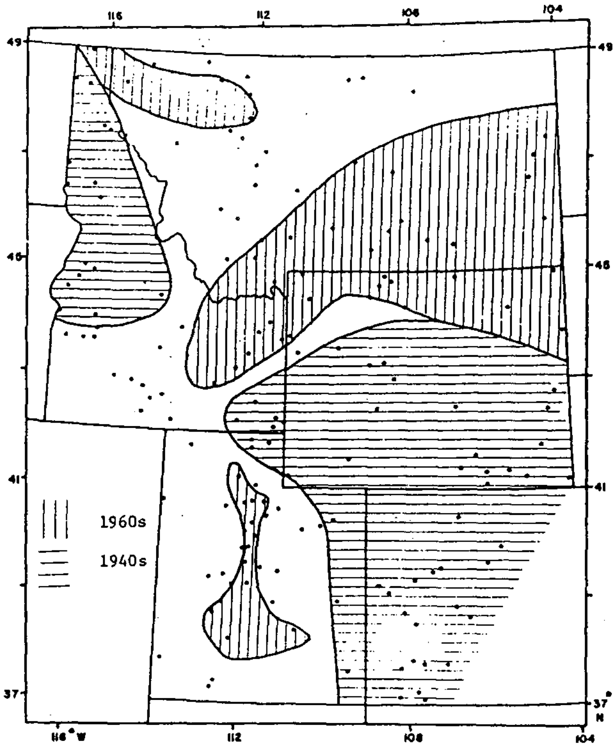

FIG. 6. Periods of decadal precipitation maxima (1911–70) in spring months.

dry. In fact, 70% of stations in these states recorded lowest spring precipitation in the 1930's. The most significant "anomalies" were in northern Idaho and western Montana. In Wyoming and Colorado, however, no single decade stands out as a clear minimum.

b. Summer

The summer precipitation record is quite different from other seasons being characterized by three periods of high precipitation which affected different parts of the study area to different extents. These three periods are, in order of increasing importance, the 1920's, 1940's, and 1960's. Considering the entire period 1891 to 1970, precipitation was at a maximum in the 1960's over a wide area including the Snake River basin, northwestern Utah and the Colorado River basin, northwestern Wyoming, and southern Montana (Fig. 7). In northern Idaho and most of Montana, precipitation was heaviest in the 1940's, whereas maximum precipitation was reached in the 1920's in the Colorado mountains and in eastern Wyoming. It should be noted, however, that precipitation was well below "normal" at many stations in the northwestern half of the region in the 1920's, particularly western Idaho and western Montana. These patterns may reflect the dominant influence of storms from the Pacific across northern parts of the region in the 1940's, whereas in the 1960's storms may have entered the region more from the Great Basin area and the southwest, to be channeled along the Snake River and Colorado River basins. The 1920's maxima over eastern parts of the region may be related to the predominant influence of storms from the Gulf of Mexico during this period.

Because of the relatively high precipitation totals over much of the area in the 1940's and 1960's, other decadal maps show a pattern of predominantly below 1941–70 average values. All stations in the 1890's and over 75% of stations in the 1900s were below "normal." In the 1910's, precipitation was also generally below average except for the Colorado River basin in Utah and parts of the southwestern Colorado mountains. In the 1930's and 1950's precipitation was well below average over virtually the entire area. In particular, the 1930's were extremely anomalous in the northwestern part of the region; 70% of stations in Montana and almost all stations in the Idaho panhandle showed highly statistically significant differences from 1941–70 averages. This is similar to the spring pattern of the 1930's, but even more anomalous.

In view of these facts, it is clear that the 30-year "normal" for 1941–70 is probably the most anomalously wet period in this area for at least the past 80 years. If the historical data for 1866–1890 are considered (Bradley, 1976a) it is clear that most stations were below or only slightly above 1951–60 averages during this period (virtually no Rocky Mountain data are available for the period 1851–65). As the 1950's were

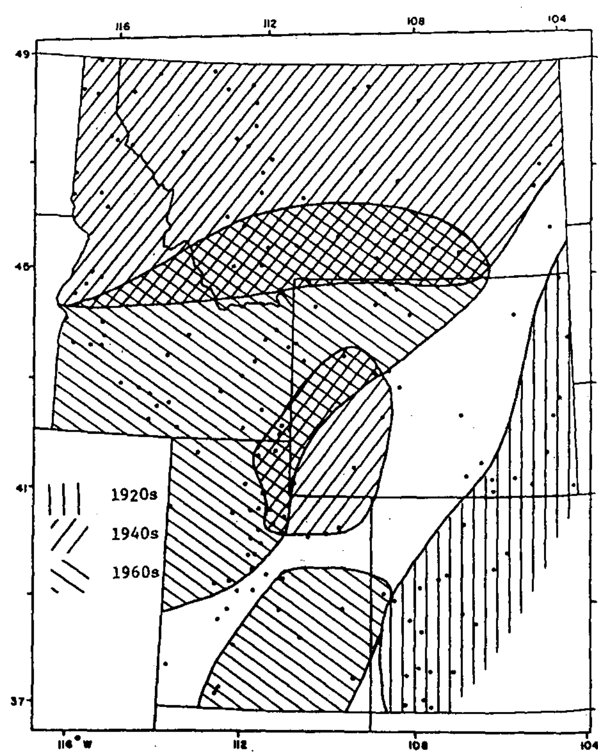

FIG. 7. Periods of decadal precipitation maxima in summer months (1891–1970). Areas of overlap indicate regions where decadal maxima are found in one decade at approximately half the stations and in another decade at the remaining stations.

markedly below the 1941–70 average in all areas except the extreme northern parts of Idaho and northwestern Montana, it is very probable that summers in the period 1941–70 were, on average, wetter than for any comparable period in at least the last 110 years.

c. Fall

As in other seasons already discussed, fall precipitation was relatively heavy in the 1910's and 1920's (in all areas except northern and western Idaho) and the 1940's (except in northwestern Colorado). The 1960's were also relatively wet over much of the region, the principal exceptions being northern Idaho, northern Montana, and central Wyoming. The 1950's, on the other hand, were extremely low in fall precipitation in all areas except the Idaho panhandle (where the 1920's were lowest) and part of the Colorado River basin in Utah (where the 1930's were lowest) (Fig. 8). Excluding these two areas, over 85% of stations recorded in the 1950's their lowest decadal totals for at least 60 years (the 1900's were even drier in some cases). Data for the 1890's are scarce, particularly in the eastern half of the region, but it appears that Idaho, Utah, and western Montana, at least, were above average. In short, the 1890's(?) 1910's, 1920's, 1940's and in some areas the 1960's were relatively wet (particularly the 1910's), and the 1900's, 1930's, and 1950's were mostly dry (particularly the 1950's).

d. Winter[4]

Over much of the western region—Idaho, western Montana, western and central Utah, and western Wyoming—precipitation in the period 1941–69 was considerably above the average for the previous 30 years. This is mainly due to relatively high precipitation receipts over Utah, western Montana, and western Wyoming in the 1940's and 1950's, and over Idaho in the 1940's and 1960's. The pattern of anomalously high precipitation in the 1950's is almost the inverse of that in the 1960's when precipitation was below average in almost all areas except eastern Idaho, central and southern Montana, and southern Utah. However, it is of interest that about 24 stations received their highest decadal average of winter precipitation for 50 years in the 1960's. Further examination of these stations indicates they are at relatively high elevations in each state. The four stations in Wyoming and Colorado, for example, are among the eight highest-elevation stations in these states. A similar pattern, though with more low-elevation stations included, is

[4] Although "decadal" averages are referred to above, winter seasons were examined in nine-year intervals so that data for the "1890's" extends from November 1891–March 1892 to November 1899–March 1900, etc. It is felt that this is representative of each decade, so the term decadal has been retained for convenience. The normal period for comparison extended from November 1941–March 1942 to November 1969–March 1970 (i.e., 29 years).

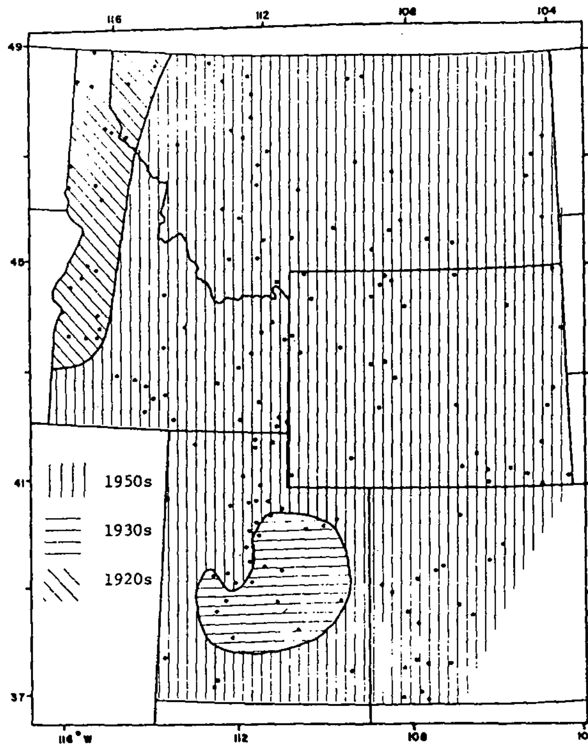

FIG. 8. Periods of decadal precipitation minima in fall months (1911–70).

also seen in Idaho and Utah and to some extent in Montana. Further study of high-elevation precipitation receipts in the 1960's would be of interest, particularly in view of suggestions that the climate of the 1960's in the Northern Hemisphere may have resembled that of the Little Ice Age (Sanchez and Kutzbach, 1974; Lamb, 1969).

For the period 1891–1910, although data are scarce, it appears that precipitation was relatively heavy (above 1941–70 averages) in both decades for most of the area. At a number of stations, in fact, maximum decadal precipitation for the 70 (or 80) year period was recorded in these decades.

Over the last 70 years, one pattern of precipitation deficit has frequently recurred. This is the pattern seen in the 1910's, 1920's, 1930's and 1950's with low precipitation amounts centered over southern Idaho and extending to different extents northward over northern Idaho and western Montana, eastward over western Wyoming, and southward over northern and central Utah. It is interesting that a pattern similar to this is shown by Sellers (1968) as the dominant December eigenvector of precipitation anomaly over the western United States (actually the inverse of Sellers' example). A similar pattern is shown by the second eigenvectors for November and March, and certain features of the pattern can be seen in eigenvectors for other winter months. As Seller's analysis covered only the period 1931–1966, it appears that this anomaly pattern has been common for at least the past 60 years and perhaps longer (c.f. LaMarche and Fritts, 1971). It is also of interest that the low precipitation receipts centered in the area of Idaho were lowest in the 1920's and 1930's, and that, although the pattern has recurred, the magnitude of the deficit has been less in recent decades. Over 70% of Idaho stations not suspect or rejected, for example, recorded lowest winter precipitation (1921–1969) in the 1920's (55%) or 1930's (18%).

In the rest of the region, winter precipitation at most stations generally decreased during this century. Furthermore, heavy precipitation over most of the area in the 1890's and 1900's (and over much of the area in the 1910's) suggests that a general decrease has affected the region for the last 80 years. Consideration of nineteenth century precipitation records for this area (Bradley, 1976a) indicates that precipitation was generally above 1951–1960 averages in the 1870's and 1880's (at least) and, therefore, it seems likely that winter precipitation over much of the region (except Idaho) has been considerably less in recent decades than was characteristic of the late 19th and early 20th centuries.

7. Concluding remarks

A consideration of the data presented here and in Bradley (1976a) indicates that seasonal precipitation totals over the Rocky Mountains and adjacent western states have undergone very significant changes over the last 120 years. In particular the most recent "normal" period is very anomalous; precipitation totals in summer months have been unusually high and in winter months unusually low. One hundred years ago the climate of the Rockies was characterized by wetter winters and springs but much drier summers and (in some areas) much drier falls compared to the post-1940 climate of the region.

Secular changes in precipitation throughout the world have received little attention in the literature, mainly due to a general skepticism regarding the quality and accuracy of precipitation recording procedures. Such skepticism is even more prevalent regarding 19th century data. However, this study has demonstrated that such an attitude is unwarranted. Early records were well kept, enabling broad-scale regional patterns to be discerned even in this topographically diverse region. Furthermore, even though recording precipitation (particularly snow) in mountainous regions is a problem and topoclimatic variations may be great, it is clear that by the judicious use of carefully screened long-term data, coherent and meaningful *regional* changes can be identified without resorting to techniques which artificially remove the effects of topography. Topography is clearly important to the total amount of precipitation received at any point (and indeed to the steering of some small-scale systems along broad basins such as those of the Snake and Upper Colorado rivers) but in terms of secular *changes* in precipitation, it appears to be of much less importance than the regional synoptic controls which determine the broad-scale changes observed. This author thus concurs with Lamb's (1966) remark (made after studying precipitation changes in different parts of the world) that,

> It is gratifying to find that there are such simple trends of rainfall, changing nearly uniformly over wide areas and intelligibly related to the large-scale atmospheric circulation. This might not have been expected in view of the characteristically complex patterns that local rainfall amounts present, varying with all the intricate details of topography.

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