Secular Fluctuations of Temperature in the Rocky Mountain States and a Comparison with Precipitation Fluctuations

RAYMOND S. BRADLEY

Department of Geology and Geography, University of Massachusetts, Amherst 01003

(Manuscript received 18 April 1979, in final form 25 February 1980)

ABSTRACT

Fluctuations of temperature in the Rocky Mountain states of Idaho, Montana, Wyoming, Colorado and Utah are analyzed for the period 1891–1978. Prior to 1891, data for this area are too sparse to make meaningful generalizations. After screening temperature data for homogeneity, selected records are used to map seasonal mean temperature departures from 1941–70 means. In all seasons, mean temperatures were higher by 1–1.5°C during the last 40 years compared to the previous 40–50 years. However, spring and fall temperatures have been declining since the period maximum in the late 1930's. Pentad mean winter and summer temperatures show a statistically significant temperature increase throughout the entire period, temperatures rising by 0.09 and 0.1°C per decade, respectively. In all seasons, except winter, the warmest decade was the 1930's. Winters were warmest in the period 1906–10 when summers were relatively cool. The coldest decade was centered around 1910–15, though for winters the period 1891–1900 was colder. An inverse relationship was found between decadal temperature and precipitation departures from 1941–70 averages; this may reflect a contrast between periods characterized by a high frequency of warm, dry anticyclonic conditions and periods with a higher frequency of cool, moist cyclonic activity. Growing season lengths were ~15% shorter around the beginning of this century compared to the 1930's as a result of both later spring and earlier fall killing frosts. Heating season degree day totals from the 1880's to the 1920's averaged ~140 degree days (°C) more than in 1941–70 over the whole area. This is estimated to be equivalent to an increase in the space heating load of ~1 barrel of oil per standard house per year.

1. Introduction

Instrumental measurements of the climate of North America began in Cambridge, Massachusetts in 1715. As European settlers migrated inland, from the Atlantic Coast and the Gulf of Mexico, the observational network increased accordingly, until by 1818 there were 67 temperature and 23 precipitation records of a year or more in duration east of the Mississippi River (Havens, 1958). At the same time, settlements on the west coast were being established and meteorological observations began in this area around 1826. In the Great Basin and Rocky Mountain states, settlement was greatly delayed and as a result the meteorological network was virtually non-existent before 1850. Thus our perspective on the climate of this region is restricted to the last 120 years and for large areas, hardly 100 years of data are available.

2. Previous work

Very few studies of instrumentally recorded data from the Rocky Mountain states[1] are available. This is particularly true of long-term temperature data. Wahl and Lawson (1970) produced maps of temperature and precipitation departures from 1931–60 means for the 1850's and 1860's, indicating that in all seasons the western states were "distinctly warmer and decisively wetter" in mid-nineteenth century (except for Pacific coastal regions). However, these maps are generalized for the western United States and do not show the distribution of stations for the period being considered. In fact, there are very few records at all during this interval, particularly for the Rocky Mountain states. Records were mainly kept in Arizona and New Mexico and the Columbia River Basin of Oregon and Washington (Bradley, 1976a). Only in the latter half of the 1860's [a period which was anomalously wet in at least parts of the Great Basin (Hardman and Venstrom, 1941; Whitaker, 1971)] were measurements made over a wider area. Consequently, Wahl and Lawson's conclusions regarding precipitation may be unduly weighted by this wet interval and may not be applicable to the Rocky Mountain states. A network of mid-nineteenth century temperature data is unavailable for Rocky Mountain states but data from other areas (the Pacific Northwest and the Southwest) suggest that temperatures were above 1951–60 averages in the mid-nineteenth century (Bradley, 1980). How-

---

[1] The Rocky Mountain states are defined here as Idaho, Montana, Wyoming, Colorado and Utah (cf. Fenneman, 1928).

0027-0644/80/070873-13$07.25

ever, the data are so sparse that any definitive *regional* assessment of temperature conditions prior to about 1870 is fraught with uncertainty.

Glacier mass balance studies in Glacier National Park, Montana indicate that mean annual temperature declined from the early 1900's to about 1920 and then rose markedly to about 1940 [an increase of ~2°F in a "weighted areal average for Montana" (Dightman and Beatty, 1952)]. Subsequently, temperature declined so that, by the mid-1950's, temperatures were similar to those around 1920 (Dightman, 1956). These changes were reflected in significant glacier mass loss in all 60–80 glaciers of Glacier National Park, Montana during the 1930's and 1940's and in a renewal of glacial activity in the 1950's (Dyson, 1948; Harrison, 1956). For example, the Sperry Glacier was 840 acres in extent in 1901 and only 330 acres by 1946; the Grinnell Glacier decreased in volume by 50% between 1850 and 1937 and by a further 25–30% between 1937–46. Marked changes in the extent of Front Range ice bodies in the early nineteenth century also have been noted (Ives, 1954). The Arapahoe Glacier lost 50% of its volume between 1938 and the early 1950's and other ice bodies (in "Ice Lake Valley, north of Arapahoe Glacier" and "at the head of Hauge Creek in Rocky Mountain National Park") melted out in the 1940's or early 1950's. This period of ablation in the Front Range continued through to the early 1960's, after which a change to more positive net balance years occurred.

Like fluctuations of temperature, precipitation variations in the western United States during the period of instrumental records have not been extensively studied. Recent work has attempted to remedy this situation with a detailed analysis of data from over 160 stations in the Rocky Mountain states (Bradley, 1976b). Nineteenth century data for all western states have also been analyzed (Bradley, 1976c). These studies concluded that in the Rocky Mountain states, the period 1941–70 was not "normal" when placed in perspective with data from the last 120 years. In particular, summer precipitation was unusually high during this period (especially during the 1960's) and winter precipitation was relatively low. Although generalizations are difficult due to limited data, on the whole the climate of the Rocky Mountain region 100 years ago was characterized by wetter winter and spring seasons, but much drier summer and (in some areas) fall seasons compared to the post-1940 climate of the region. Periods of greatest precipitation occurred in the 1890's, early 1910's, the 1940's and 1960's. The 1930's and 1950's were relatively dry, especially in the 1930's. The relationship of these variations in precipitation to fluctuations of temperature will be discussed later in the paper.

3. Sources of long-term temperature data

Unlike precipitation data, which were generally published in the first U.S. Weather Bureau Bulletin W (from the establishment of stations to 1930), early temperature data were not tabulated. In fact, the only published tabulations for all cooperative stations are for the period 1951–60. The lack of published tabulations has deterred studies of long-term temperature records from cooperative stations; data for pre-1951 can only be obtained by laboriously obtaining yearly summary statistics from *Climatological Data* (U.S. Weather Bureau) which only go back to 1914, making it difficult to assess which records are most complete. Some state climatological offices, prior to being phased out by NOAA, kept tabulations of temperature data for each station, but such records were frequently lost during reorganization of these agencies. Whenever possible, tabulations of data for the late nineteenth and early twentieth centuries were obtained from acting state climatological officers and from the "Washington Tabulations" (hand-written records pertaining only to the very early years of data collection, available at the National Climatic Center). Other sources included early issues of *Monthly Weather Review* and the annual Climate and Crop Service Reports of the U.S. Department of Agriculture. However, these sources are often not comprehensive and precise information on site, elevation, station moves, instrumentation used, etc., is generally not available. Considerable caution is therefore necessary when evaluating *individual* records; the best testimony to the veracity of a record is if it reflects a regional pattern of temperature variation. Hence, the analysis of a large number of climatic records and the preparation of regional anomaly maps is likely to indicate both the large-scale climatic variations and those records which do not conform to the regional pattern of climatic change because of inhomogeneities in the record. Careful selection of individual records can help to eliminate much of the noise due to data inhomogeneity.

4. Data analysis

Data from 130 selected long-term temperature stations, which have operated continuously for at least 60 years (to 1975) have been analyzed (Fig. 1). Substation histories indicated that these stations had fairly complete records and had not been moved significantly during the period of record. The general criteria of no more than one move per 15 years, no moves of more than a mile, and no more than 5% missing data in a season record were used as guidelines in selecting and rejecting stations, but due to poor documentation in some cases these criteria had to be loosely applied. The missing monthly data

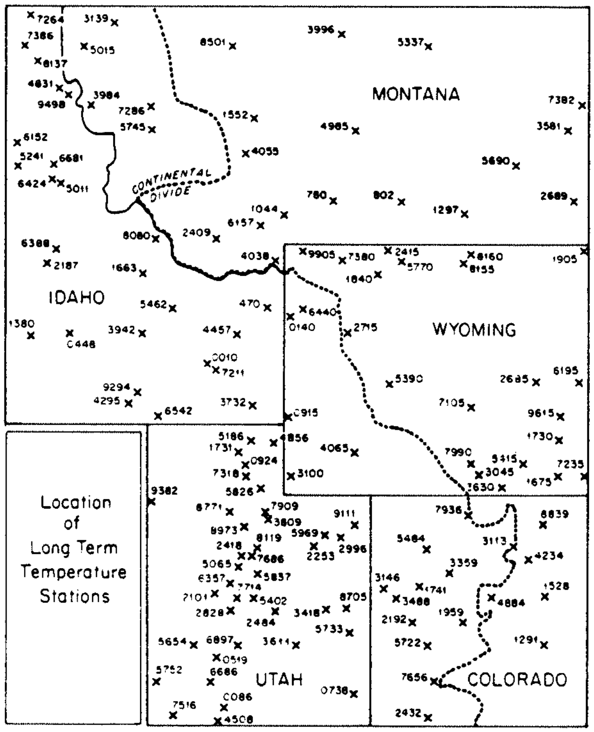

FIG. 1. Location of long-term temperature stations used in study. All records had a minimum of 60 years of data. Stations are identified by U.S. Weather Bureau index numbers. Dashed line is Continental Divide.

values were estimated by conventional methods (Conrad and Pollack, 1950, p. 241). Series of differences between the station in question and a number of other stations were computed; using the mean difference value at each station, estimates of the missing value were obtained and averaged to give a final estimate. As subsequent analyses involved seasonal mean values, it is unlikely that these monthly estimates, even if slightly in error, have a significant influence on the overall seasonal value, except perhaps, in a few cases where all seasonal values were missing. The resulting station network is fairly well distributed spatially and, like the precipitation data bank established in earlier work (Bradley, 1976b), is fairly representative of all but the highest elevations of the region (Table 1). Approximately 80% of the long-term temperature stations were also in the long-term precipitation data bank.

5. Data homogeneity

In order to fully evaluate the reality of measured climatic fluctuations it is necessary to be very selective over the choice of data used and to carefully evaluate the records for homogeneity. The initial screening procedure used in data selection has already been described; further evaluation involved tests of homogeneity computed for all seasonal records. The concept of homogeneity and the problems involved in deciding if a record is indeed representative of its surrounding area has been discussed elsewhere (Mitchell, 1961; Bradley, 1976a). In this study, year-by-year seasonal averages[2] for each station were first calculated. Series of differences were then computed between pairs of stations, selected whenever possible to be at similar elevations, in similar topographic situations with respect to major mountain barriers, and as close together as possible. The Mann-Kendall non-parametric test for randomness against trend was then applied to the new series of differences and the

TABLE 1. Summary of long-term temperature data bank, by elevation.[a]

Elevations (m)	Number of stations Colorado	Idaho	Montana	Utah	Wyoming	Sum	Percent
305–609		3	1			4	3
610–914		8	7	1		16	12
915–1219		5	8	1	4	18	14
1220–1524	2	5	4	14	5	30	23
1525–1829	5	5	1	20	4	35	27
1830–2134	5		1	2	9	17	13
2135–2439	1			1	2	4	3
2440–2744	2					2	2
2745–3049	1				1	2	2
>3049	1					1	1
Total	17	26	22	39	25	129	100
Average station elevation (m)	2039	1080	1062	1552	1733		
Overall average: 1472 m							

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

---

[2] Seasons were defined as follows: spring (April, May); summer (June, July and August); fall (September, October); winter (November, December [year 1], January, February, March [year 2]). Winters were identified by the year in which the December occurs (cf. Bradley, 1976b, p. 515).

TABLE 2. Percentage of records rejected (R) or suspected (S) of being nonhomogeneous.

	Spring		Summer		Fall		Winter	
	R	S	R	S	R	S	R	S
Colorado	18	6	24	0	18	12	12	30
Idaho	26	30	33	22	22	15	15	30
Montana	32	9	27	9	36	18	36	9
Utah	28	23	31	5	33	15	21	28
Wyoming	23	31	23	35	35	12	38	12
Averages	25	20	28	14	34	14	24	22

resulting statistic tested for significance at ≤5% level (WMO, 1966). The test was carried out on all 520 seasonal records, with each record being compared with at least two other records of comparable length. By using the procedure outlined in earlier work (Bradley, 1976a) an attempt was then made to isolate those seasonal records which were clearly not homogeneous (rejected) and those stations which appeared to be suspect. The results for all five Rocky Mountain states have been summarized in Table 2.

Twenty-six percent of all seasonal records examined were rejected; no spatially coherent regional or elevational pattern of inhomogeneity is apparent. By comparison, in a similar analysis of long-term seasonal precipitation records, only ~10% of records were rejected (Bradley, 1976b). Furthermore, there is virtually no correspondence between the precipitation and temperature records rejected, which, had there been one, might have indicated a change in station location or site characteristics as the cause of inhomogeneity. Another possible cause of inhomogeneity in the temperature records is the urban growth (heat island) factor. In order to investigate this effect, population records for each location were obtained from the U.S. decennial censuses (from 1900 to 1970). Population change provides a readily available statistic which reflects the changing physical size of the urban center.

Most stations have experienced rather minor changes in population size during this century. Only seven places increased in population by >5000 people from 1910 to 1940, and from 1940 to 1970 this figure increased to 16. Excluding these places, the average population change from 1910 to 1940 was +1000 and from 1940 to 1970 only +600. In fact, many places decreased in size from 1940 to 1970. Considering that most other stations (for which no population data are available) were "rural" throughout the period (e.g., ranger stations, reservoirs, etc.), the vast majority of stations are unlikely to have been affected by any significant cumulative heat island influence. It is worth noting, though, that the percentage of records rejected due to inhomogeneity is higher in the group of stations where large population changes have occurred than in the other more rural stations. However, in most cases, the cause of inhomogeneity in the record is unknown.

6. Changes of seasonal mean temperature, 1891–1978

In order to investigate seasonal fluctuations of temperature based on a network of reliable long-term data, only those records not rejected in the homogeneity tests were analyzed. Data were divided into 5- and 10-year periods and maps of seasonal temperature departures from 1941–70 averages were produced. Decadal maps are shown in Fig. 2, based on a network of stations summarized in Table 3a. Although subregional-scale anomalies are seen in all decades, the broad-scale pattern of temperature change in each season is clear. These regional changes are shown graphically in Figs. 3 and 4 by means of 5-year mean departures from 1941–70 seasonal averages (calculated for each station and averaged for the entire region). Although it could be argued that the uneven distribution of station records shown in Fig. 1 makes a regional average overly weighted toward the area with most stations, subregional analysis indicates that the individual states have experienced very similar fluctuations of temperature. Averaging all records into a composite index does not, therefore, significantly bias the final regional estimate of temperature change.

The principal features of the Rocky Mountain temperature record are discussed below, decade by decade, followed by a summary of the entire period.

a. 1891–1900

This was one of the coldest decades in the 80-year period under consideration. Temperatures averaged ~0.9°C below 1941–70 means in fall, winter and spring months; in summers, temperatures averaged 0.4°C below 1941–70 averages. Temperatures were lowest in the first half of the decade and in general, the eastern and southern parts of the region were most anomalously cold.

b. 1901–10.

The 1900's were considerably warmer than the 1890's but still generally below 1941–70 means (average anomaly for spring, summer and fall was −0.6°C). However, this was the coldest decade of summer temperatures in the period. Again, eastern parts of the region had the largest negative temperature anomalies; a persistent positive anomaly existed in northern Idaho and parts of western Montana for spring and fall seasons.

The winter season in the 1900's was exceptional, being the warmest decade of winter temperatures for the period 1891–1978; winter temperatures were particularly high in the period 1906–10 (Fig. 3).

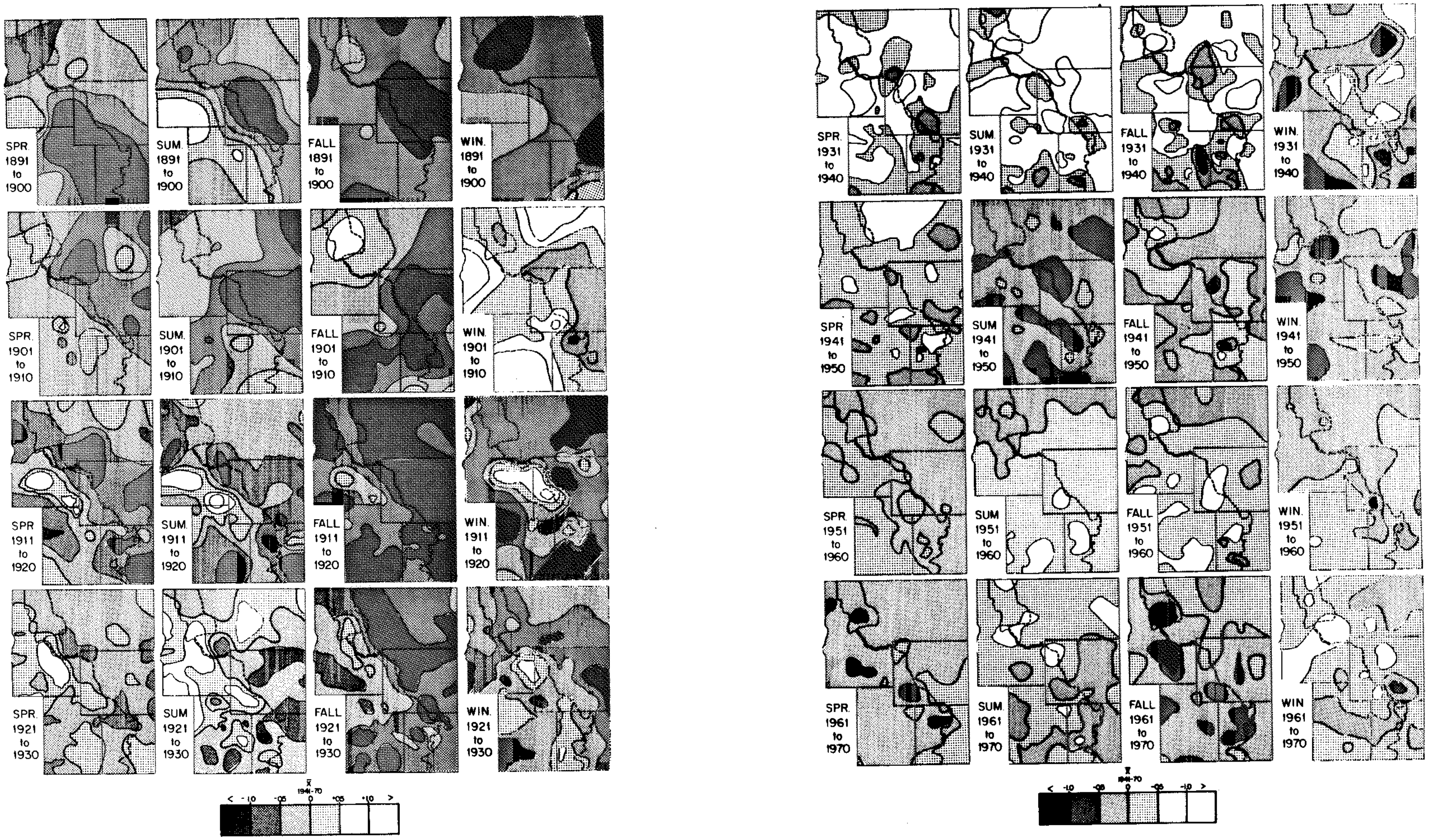

FIG. 2. Mean temperature departures, by decade, from 1941–70 averages at each station, 1891–1900 to 1961–70. Shading is in 0.5°C (0.9°F) intervals. State outlines are shown, clockwise from top left: Idaho, Montana, Wyoming, western Colorado, Utah. Dashed line is the Continental Divide.

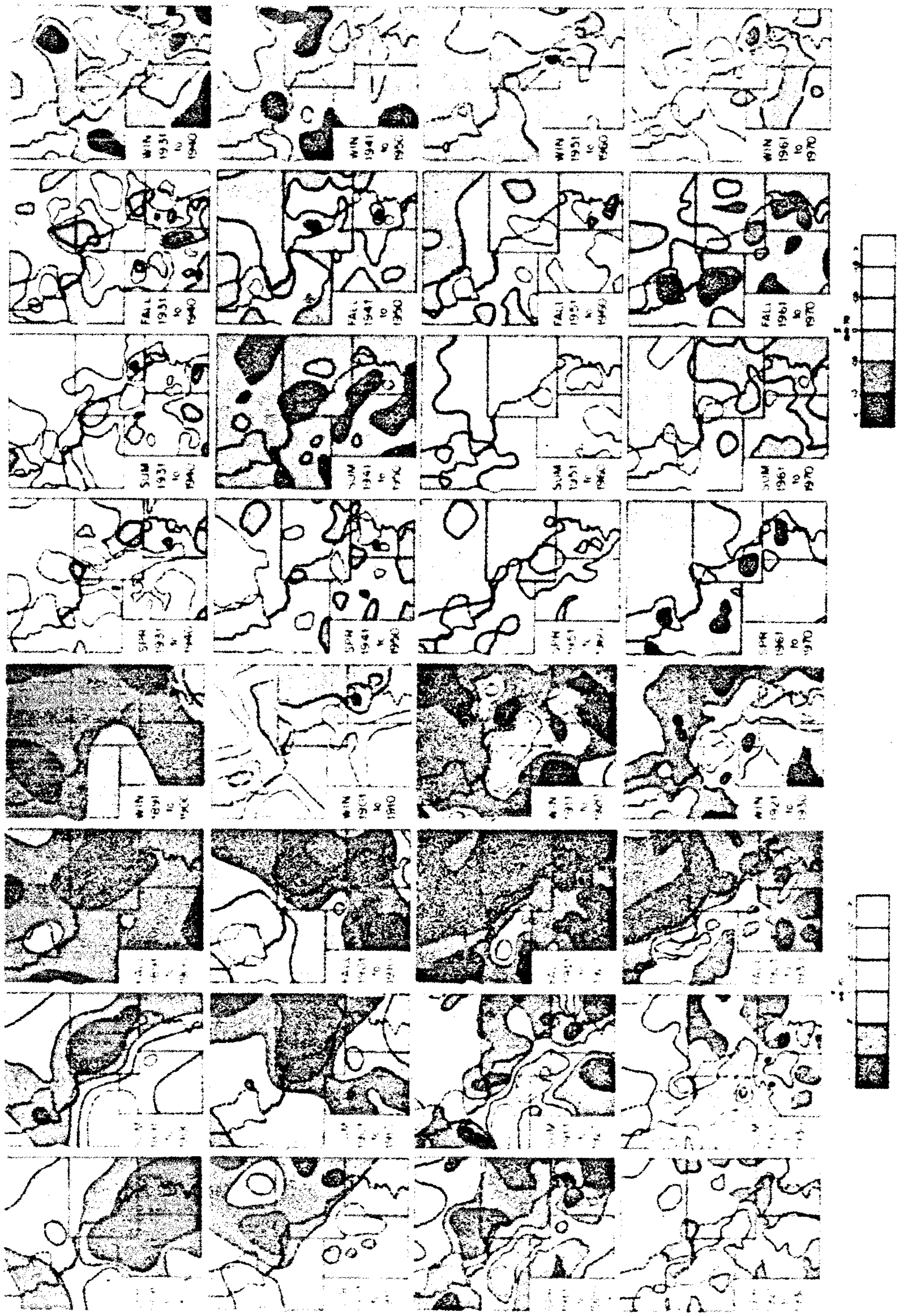

FIG. 2. Mean temperature departures, by decade, from 1941–70 averages at each station, 1891–1900 to 1961–70. Shading is in 0.5°C (0.9°F) intervals. State outlines are shown, clockwise from top left: Idaho, Montana, Wyoming, western Colorado, Utah. Dashed line is the Continental Divide.

TABLE 3. Number of records used to produce maps of temperature deviations from 1941–70 averages.

	1890's	1900's	1910's	1920's	1930's	1940's	1950's	1960's
			a. Non-rejected records only					
Spring	13	24	68	96	96	96	96	96
Summer	12	21	65	93	93	93	93	93
Fall	11	22	66	91	91	91	91	91
Winter	13	28	86	96	96	96	96	96
			b. All data, all seasons					
	17	35	91	130	130	130	130	130

c. 1911–20

Temperatures were again low in the 1910's, this being the coldest decade of the series in many areas. Falls were particularly cold with temperature anomalies in those months averaging −1.2°C. The other three seasons averaged 0.6°C below 1941–70 values.

d. 1921–30

The 1920's were warmer than the 1910's in all seasons. Falls and winters were still anomalously cool, however, with averages 0.5°C below 1941–70 values. It is interesting to note that maximum negative anomalies occur immediately to the east of the Continental Divide in Wyoming and Montana. This pattern is also seen in some other earlier decades (e.g., summer 1891–1900, spring and fall 1911–20) but the data network in those periods is more sparse.

e. 1931–40

This was the warmest decade in the period in all seasons except winter. Spring, summer and fall seasons averaged 0.6°C above the subsequent 30-year means; the pentad 1936–40 was particularly warm (Figs. 3 and 4). In general, the northern two-thirds of the region had the most positive temperature anomalies, particularly eastern Montana, eastern Wyoming and southern Idaho. In contrast to the other seasons, winter months were not outstandingly warm, averaging approximately the same as for the next 30 years.

f. 1941–50

Spring temperatures remained above average in this decade but other seasons were cooler, particularly summers. Average summer temperatures were 1.1°C cooler than in the 1930's. Winter tempera-

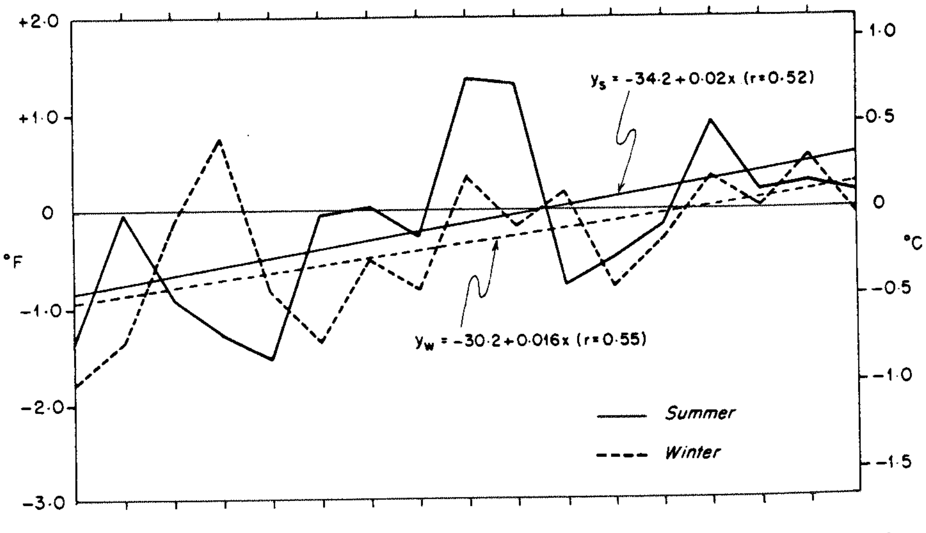

FIG. 3. Five year, mean temperature departures from 1941–70 means, averaged for all long-term Rocky Mountain stations not rejected in the homogeneity analysis: summer (Jun, July, Aug) and winter (Nov, Dec, Jan, Feb, Mar) seasons.

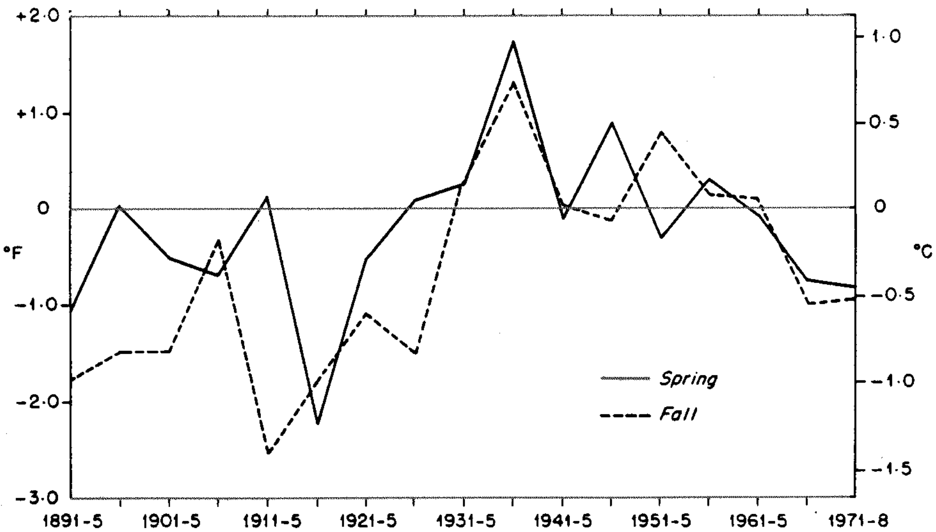

FIG. 4. As in Fig. 3 except for spring (Apr, May) and fall (Sep, Oct) seasons.

tures also were below average over almost the entire area.

g. 1951–60

The 1950's show only small deviations from 1941–70 averages. The spring season shows a marked northwest-southeast boundary between lower temperatures to the east and higher temperatures to the west. As in other decades, this boundary approximates the Continental Divide (except in Colorado where stations west of the divide are at high elevations.) The mean departure from 1941–70 averaged at all stations for all seasons is only +0.1°C, making this a suitable period for comparison with earlier 19th century temperature data (cf. Bradley, 1976c, 1980).

h. 1961–70

Springs and falls in the 1960's were considerably cooler than in the 1950's. Spring temperatures continued their post-1930's decline reaching lowest mean values since the 1910's. Fall temperatures were the lowest since the 1920's (0.6°C below averages in the 1950's). Fall temperatures were particularly low in the southern and western parts of the region. Summer and winter temperature deviations were generally the inverse of the 1950's.

i. 1971–78 (maps not shown)

In all seasons, the 1970's have witnessed a continuing decline in mean temperature compared to the 1960's. In spring and fall seasons this continues the trend toward lower temperatures which began after the late 1930's. In summer and winter months, however, temperatures in the 1970's can be interpreted as a minor departure from the general upward trend in temperature which characterizes both seasons for the period of record (Fig. 3).

j. Mean temperature fluctuations, 1891–1978

In general, all seasons show a fall in temperature from the 1880's to around 1915 (±5 years). Scant records from adjacent regions suggest this fall in temperature may have started earlier, after the relatively warm mid-19th century (Bradley, 1979). Spring and fall seasons experienced an increase in mean temperature from the 1910's to the late 1930's, followed by a fall in temperature through to the present. Temperatures in the 1970's were similar to those recorded in the early part of this century (~1°C cooler than in the 1930's). Winter and summer season data do not show as large a fall in temperature since the 1930's (Fig. 3); in fact, in both these seasons, a linear trend (statistically significant at $<5\%$ level) is apparent, with temperatures increasing an average of 0.1°C per decade in summer and 0.09°C per decade in winter (based on pentad mean values). There is some indication in Fig. 2 that the gradient of temperature departure is often aligned with the position of the Continental Divide; more negative anomalies are relatively common east of the Divide (particularly in spring and fall months). It is possible that during periods with frequent outbreaks of cool, continental air from central Canada, the mountain barrier restricts the cooler air to the region east of the Divide so that locations west of the Divide experience relatively higher temperatures.

7. Removal of inhomogeneous records

All of the temperature maps and graphs discussed above were based on a sample of the initial data

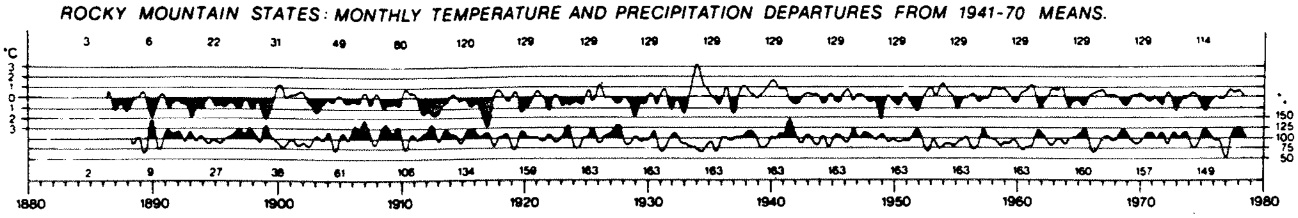

FIG. 5. Temperature departure of each month from its corresponding monthly mean temperature for 1941–70 (upper curve, scale to left) and monthly precipitation amounts as a percentage of the corresponding monthly mean for 1941–70 (lower curve, scale to right). Departure and percentage data were calculated for each station separately, then averaged to produce this composite graph for the five-state region. Number of stations used for composite varies from a minimum of 3 to 163, as shown above upper curve (for temperature records) and below lower curve (for precipitation records). Data smoothed by low-pass filter [Gaussian ordinate method with $\sigma_G = 2.5$; (see WMO, 1966, p. 47)] to remove high-frequency variations with a period < 15 months.

bank, the rejected records having been omitted. In order to evaluate the impact of incorporating inhomogeneous records into the analysis a second set of maps was produced utilizing all the available data. Thus the network density was increased to that shown in Table 3b, and the two sets of maps were compared. It is interesting that both sets of maps are extremely similar; the maps from which rejected stations have been omitted are somewhat more coherent spatially but in general there are no significant changes in the basic patterns of temperature anomaly. This is particularly true in the 1920's to 1960's period when the two sets of maps are almost identical. In earlier decades, when fewer stations are available anyway, somewhat larger differences are apparent but in no case does the basic pattern change.

TABLE 4. Correlation coefficients (r) and statistical significance (s) of long-term precipitation and temperature records,* east and west of the Continental Divide, Rocky Mountain states.

	East precipitation and temperature		West precipitation and temperature	
	r	s	r	s
Jan	−0.46	0.001	0.05	0.33
Feb	−0.48	0.001	−0.09	0.20
Mar	−0.44	0.001	−0.13	0.11
Apr	−0.30	0.002	−0.39	0.001
May	−0.45	0.001	−0.46	0.001
Jun	−0.45	0.001	−0.44	0.001
Jul	−0.45	0.001	−0.32	0.001
Aug	−0.40	0.001	−0.29	0.003
Sept	−0.44	0.001	−0.30	0.002
Oct	−0.49	0.001	−0.45	0.001
Nov	−0.59	0.001	−0.09	0.21
Dec	−0.40	0.001	−0.04	0.34
Years	1889–1978		1891–1978	
N	90		88	

* Each record is a composite of all stations in data bank averaged by year as a departure from 1941–70 means at each station (temperature) or as a percentage of 1941–70 means at each station (precipitation). Each year comprises an average of at least three station records (start of period) reaching a maximum of 103 toward the end of the record.

However, it is noticeable that while the general pattern and direction of temperature anomalies is consistent, the overall magnitudes of deviations do vary very slightly. For the complete data network, seasonal deviations averaged for all stations are consistently warmer from the 1890's to the 1930's than averages based on non-rejected records only. However, these differences are generally less than 0.1°C and are only significant in one or two seasons. It is suggested that in future work in which the focus of interest is *regional* variations of climate, not changes at specific stations, the tests of homogeneity are unnecessary provided a dense station network is utilized and reasonable precautions are taken in the initial data selection procedure.

8. Relation to precipitation fluctuations

A comparison of decadal mean temperature departures with decadal precipitation amounts as a percentage of 1941–70 averages (Bradley, 1978b) for all Rocky Mountain states, indicates some interesting broad-scale relationships. In general, periods of high precipitation correspond to periods of low temperature (negative anomalies) and vice versa. Thus, for example, fall months in the period 1911–20 were relatively wet (over all stations, precipitation averaged 128% of 1941–70 values); during the same decade, mean fall temperature averaged 1.2°C below 1941–70 means. Conversely, the relatively warm 1950's were extremely dry in fall months during the same period. This inverse relationship was found in nearly all months (Fig. 5) reflecting the predominance of relatively warm and dry anticyclonic conditions during certain periods (particularly the 1930's and 1950's) and more frequent depressions and northerly air flow during the cooler, wetter periods (particularly from the 1890's to the 1920's). The relationship is seen best at stations east of the Continental Divide (Table 4). West of the Divide, the correlation is still negative, though generally less

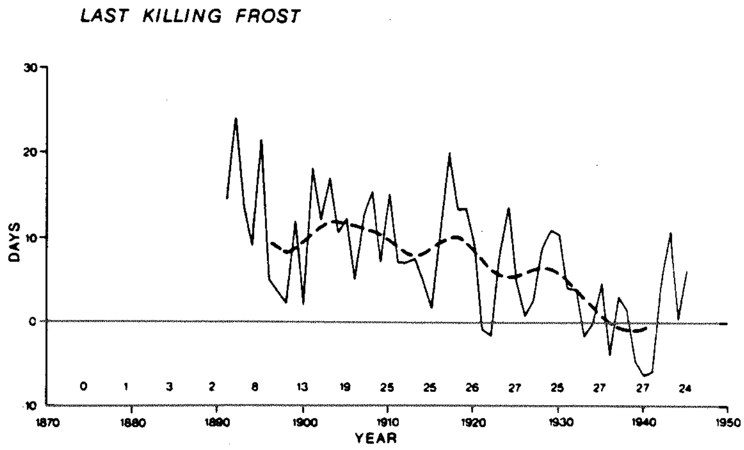

FIG. 6. Date of occurrence of the last killing frost in the spring in eastern Montana, expressed as a departure from the 1931–40 average at each station. Individual station data averaged into the composite graph shown, with the number of stations used varying as indicated above *x* axis. Dashed line is record smoothed by low-pass filter (see caption to Fig. 5).

significant, particularly in winter months (November–March).

Regional indices of temperature and precipitation also reveal important trends in seasonal climatic conditions in the Rockies. In fall and winter months (September–March) total precipitation amounts from the 1890's to the 1970's have declined, particularly in winter months (November–March). During the same period, temperatures generally increased. In summer months, however, both mean temperature and precipitation totals have risen since the 1890's, so that on the whole summers have been both warmer and wetter in recent years than at the turn of the century. The change in circulation leading to both warmer and wetter conditions in the long-term but with individual decades being alternately "warm and dry" and "cool and wet" warrants further investigation from a synoptic climatological viewpoint.

It should be emphasized that these regional indices of temperature and precipitation, discussed above, may mask subregional/temporal patterns. For example, relatively low elevation sites east of the Continental Divide receive most of their annual precipitation in summer months (3–7 inches) whereas winter precipitation at these stations is less than 5 inches. West of the Divide, winter precipitation may average up to 18 inches. One might thus

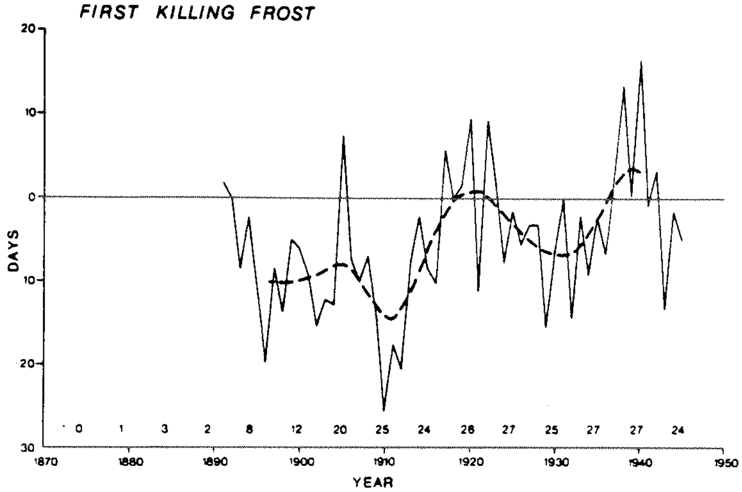

FIG. 7. Date of occurrence of the first killing frost in the fall in eastern Montana, expressed as a departure from the 1931–40 average at each station. Constructed as for Fig. 6 (see Fig. 6 caption).

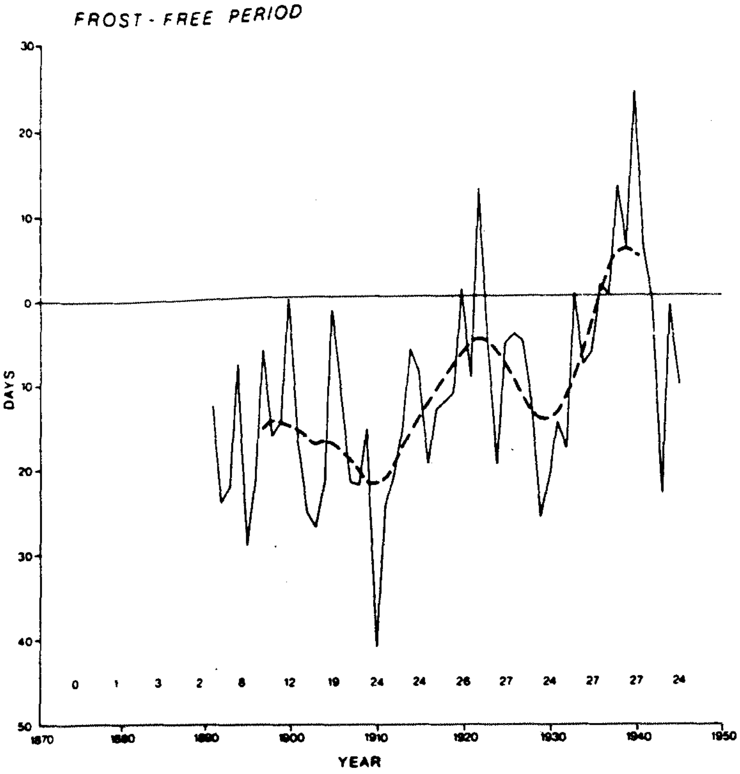

FIG. 8. Length of the killing frost-free period in eastern Montana expressed as a departure from 1931–40 averages, as explained in text and in Figs. 6 and 7.

expect the eastern section of the region to be affected differently by the opposing seasonal trends of increasing summer rainfall and lower winter precipitation than areas west of the Divide. However, the regional indices discussed may not be typical of all parts of the five-state region so the indices should be used with caution, recognizing the spatial and temporal variability of temperature and precipitation change.

9. Consequences of temperature fluctuations

It is of interest to consider how the climate of the Rocky Mountain states in the late 19th century differed from that in recent decades to determine, first, if settlement of this region was made even more difficult by a more extreme climate and, second, what the consequences would be for present society if climatic conditions today were like those of the late 19th century.

Two items of vital concern to early settlers were food and fuel. Agricultural practices were certainly affected by the cooler temperatures of the late 19th and early 20th centuries discussed above. Summers were cooler and drier and the cooler spring and fall months probably resulted in shorter growing seasons. Some evidence for this is shown in Figs. 6–8 in which the dates of first and last killing frosts[3] in eastern Montana are plotted from the late 19th century through the early 1940's. No comparable, more recent data have been located. The graphs are composed of a composite index of the longest continuous records available. For each location, the mean first frost, last frost and killing frost-free period was calculated for 1931–40. Data for each year were expressed as a departure from the 1931–40 mean. Departure values at each station were then averaged by year for all available stations to produce the resulting composite diagrams shown. In Figs. 6 and 7 points above the zero line indicate "later" killing frosts, points below the zero line "earlier" frosts. In Fig. 6, mean dates of the last spring frost in Montana indicate that from the late 1880's to the 1930's spring killing frosts commonly occurred 10–15 days later than in the 1930's. Fig. 7 indicates that in the same period the first fall killing frost occurred 10–15 days earlier in the year compared to the 1930's. The net result of these trends is shown in Fig. 8 which shows the interannual variation of the killing frost-free period from the late 1880's to the

---

[3] Killing frost is defined non-numerically as the freezing condition which kills cultivated vegetation in the vicinity of the observing station.

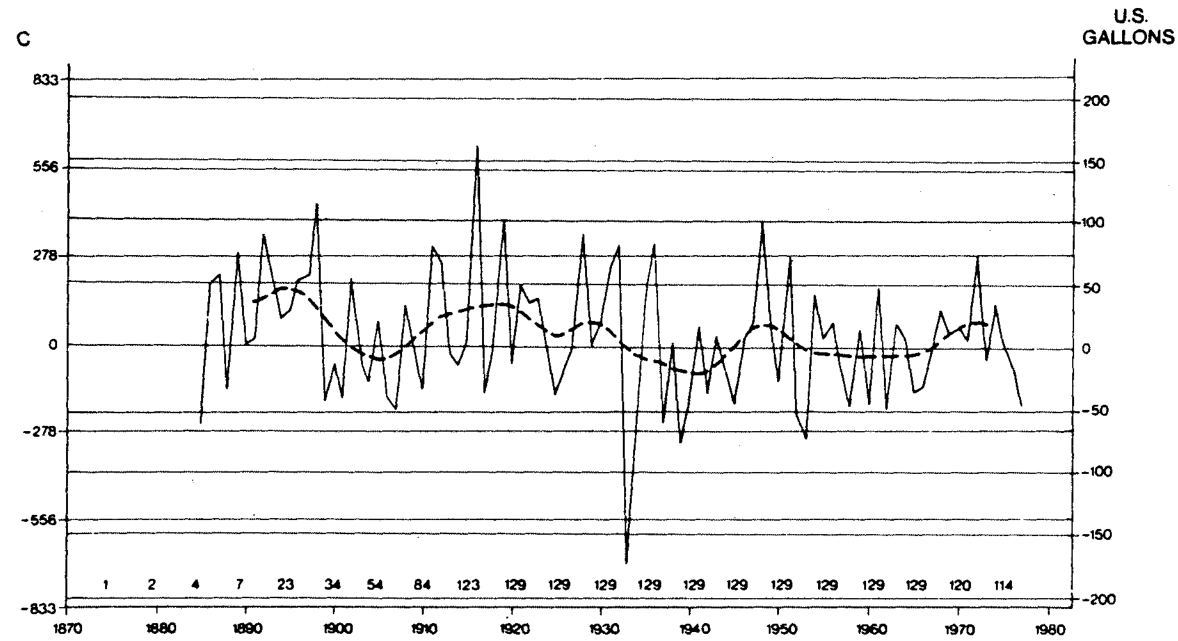

FIG. 9. Composite heating degree day (°C) totals for Rocky Mountain states expressed as a departure from 1941–70 means. Number of stations are shown above x axis. Positive departures indicate colder heating season temperatures. Scale of y axis to right indicates theoretical change in demand for heating oil to maintain standard house at 18.3°C (see text). Dashed line is record smoothed by low-pass filter, as in Fig. 6.

early 1940's. Around the turn of the century, this period was about 20 days shorter (less than the mean) than in the 1930's. This represents a reduction in the overall killing frost-free period in the region of ~15% (mean for all stations, 1931–40, is about 136 days), with an equivalent change in spring and fall temperatures of 1–1.5°C. In addition, growing season temperatures were cooler by 0.5–1.0°C. Similar results were reported by Barry and Bradley (1966) in a small-scale study of southwestern Colorado. At Durango (2000 m) the frost-free period (minimum temperature $\leqslant$ 0°C) began 10 days later and ended 4 days earlier in the period 1895–1941 compared to the period 1942–70 (i.e., the frost-free season was 12–13% shorter in the cooler period). Early settlers thus faced not only cooler summer temperatures but a shorter frost-free period in which to grow their yearly supplies. At higher elevations these changes may have been particularly critical; alpine areas may have experienced longer periods of snowcover and very brief growing seasons which may have had severe ecological consequences. Certainly, the mass balance of alpine glaciers was much more positive earlier this century than in recent decades when most glaciers have been drastically reduced in size, and many have disappeared entirely.

Lower temperatures in the late 19th and early 20th centuries also must have had an impact on fuel consumption for space heating. Fig. 9 shows the estimated interannual heating degree day load [18.3°C (65°F) base], calculated for the Rocky Mountain states as a whole, from the mid-1880's through the 1970's. For each station in Fig. 1, mean temperatures for October–April were calculated. These were converted to (°C) heating degree days (HDD) by the formula $N(18.3 - \bar{x})$, where N is the number of days in the months October–April (212) and $\bar{x}$ the mean October–April temperature (°C). This conversion was found to closely approximate the actual heating degree day values calculated from daily records simply because mean daily temperatures during this period rarely exceed 18.3°C. Generally, the October–April period accounts for 85–95% of the total annual heating load so this conversion is considered to be a good approximation of space heating demand. For each station, yearly totals were expressed as departures from 1941–70 means at the station in question. Yearly departure values were then averaged for all stations to give the composite Rocky Mountain states index shown in Fig. 9. Points above the mean (zero) line indicate a heating load above the 1941–70 mean; points below the line indicate a relatively warm season. Considering the low-frequency aspects of the data (dotted line) it is clear that in the period from 1890 to 1930 heating degree day totals over the entire five-state area averaged 110–170 (°C) degree days more than in the 1941–70 period. Early settlers were thus routinely faced with greater energy demands to keep themselves and their families warm through the winter months.

In view of the record of declining temperatures since the 1930's it is of interest to assess the impact such a change in temperature would have on energy consumption for space heating in a modern "standard" house.[4] Heating degree day data can be converted into energy consumption per standard house as shown on the y axis to the right of Fig. 9 (Hittman Associates, 1973). It can be seen that energy consumption in the late 19th century would, in modern terms, have been greater than in recent times (1941–70) by approximately 45 U.S. gallons of oil (one barrel of oil) *per house* per year. In fact, energy usage for space heating in the Rockies is predominantly by natural gas, not oil; this change in HDD totals is estimated to be 3000 ft^3 of gas *per household*.[5] With a present Rocky Mountain population of $\sim 1.26 \times 10^6$ households currently using gas for space heating, this difference of ~140 (°C) HDD is equivalent to 3.9×10^9 ft^3 gas year^{-1} for the five-state region. If heating season temperatures returned to early 19th century levels, the increase cost to Rocky Mountain gas customers would (at present prices) average over $6 million per year. If consumption was primarily of electricity or oil, this figure would be more than $35 million.

9. Concluding remarks

Since the mid-19th century, the Rocky Mountain states have experienced climatic fluctuations of a sufficient magnitude to have had significant effects on human activities in the area. Seasonal mean temperatures averaged by decade for the entire region, have differed by up to 1.6°C from one decade to another, and seasonal precipitation totals have been up to 50% higher in some decades than in others. For smaller areas within the five-state region, even larger interdecadal variations have occurred.

Over the past 40 years, fall, winter and spring months have been warmer and drier than in the previous 40–80 years. Early settlers would have experienced colder winters and considerably more snowfall, resulting in difficult winter travel conditions and the need for larger winter heating supplies and livestock food requirements. Spring runoff would have been greater than in recent years, though lower spring temperatures may have delayed the peak discharge. Cooler and drier summers, coupled with a shorter growing season, may have been a constraint on certain crops.

Climatic fluctuations of the Rocky Mountain states may thus have had a wide variety of effects on both human and natural systems. These effects have received little attention and warrant further study to determine explicitly the consequences of fluctuations in seasonal mean temperatures and precipitation totals, in a mountainous area. With the increasing pressure on natural resources in the Rockies, particularly water and fuel, such studies are of increasing importance.

Acknowledgments. This work was supported by Grant GA-40256 of the Division of Atmospheric Sciences, National Science Foundation and Grant ATM77-15189 of the Climate Dynamics Program, Climate Dynamics Research Section, Division of Atmospheric Sciences, National Science Foundation. I am grateful to Professor R. G. Barry for his collaboration on this project. I also acknowledge, with thanks, the invaluable assistance of R. Housel and M. Richards.

REFERENCES

Barry, R. G., and R. S. Bradley, 1976: Historical climatology, *Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado*, H. W. Steinhoff and J. D. Ives, Eds., Colorado State University Press, 43–67.

Bradley, R. S., 1976a: *The Precipitation History of the Rocky Mountain States*. Westview Press, Boulder, 334 p.

——, 1976b: Secular changes of precipitation in the Rocky Mountain states. *Mon. Wea. Rev.* **104,** 513–523.

——, 1976c: Seasonal precipitation fluctuations in the western United States during the late nineteenth century. *Mon. Wea. Rev.* **104,** 501–512.

——, 1980: Late nineteenth century seasonal temperatures in parts of the western U.S. compared to contemporary values (submitted).

Conrad, V., and L. W. Pollack, 1950: *Methods in Climatology*. Harvard University Press.

Dightman, R. A., 1956: Grinnell glacier studies: A progress report as related to climate. U.S. Weather Bureau, State Climatologist's Office, Helena, Montana. (Unpublished manuscript).

——, and M. A. Beatty, 1952: Recent Montana glacier and climate trends. *Mon. Wea. Rev.*, **80,** 77–81.

Dyson, J. L., 1948: Shrinkage of Sperry and Grinnell glaciers, Glacier National Park, Montana. *Geogr. Rev.*, **38,** 96–103.

Fenneman, C. F., 1928: Physiographic divisions of the United States. *Ann. Assoc. Amer. Geogr.*, **18,** 261–353.

Hardman, G., and C. Venstrom, 1941: A 100 year record of Truckee River runoff estimated from changes in the levels and volumes of Pyramid and Winnemucca Lakes. *Trans. Amer. Geophys. Union*, **22,** 71–90.

Harrison, A. E., 1956: Glacial activity in the western United States. *J. Glaciol.*, **2,** 666–668.

Havens, J. M., 1958: An annotated bibliography of meteoro-

---

[4] A "standard house" is here defined as a single-family detached dwelling of 1695 ft^2, wood construction with R7 insulation in the walls and 5 inches of loose fill in the ceiling. Further structural details and energy analysis are given in Hittman Associates (1973).

[5] Consumption per household (i.e., per domestic consuming or sales unit) is an average across all consumers occupying single-family detached, or semi-detached houses, apartments, condominiums, etc. These figures are first attempts to estimate gas consumption and are based on per household consumption per degree day for the area of Nashua, New Hampshire, provided by the Gas Company of Nashua. Different housing constructions, mix of housing types, consumption patterns and living styles in the Rockies will affect the estimate for that area but the figures given are likely to be of the right magnitude.

logical observations in the United States, 1715–1818. Key to Meteorological Records Documentation, No. 5–11, U.S. Weather Bureau, Dept. of Commerce, Washington, DC.

Hittman Associates, 1973: Residential Energy consumption, single family housing. Final Report to U.S. Dept. of Housing and Urban Development, Office of Assistant Secretary for Policy Development and Research, [Govt. Printing Office Publ. No. HUD-PDR-29-2].

Ives, R. L., 1954: Climatic studies in western North America. *Proceedings of the Toronto Meteorological Conference*, Roy. Meteor. Soc., 218–222.

Mitchell, J. M., Jr., 1961: The measurement of secular temperature change in the eastern United States. Res. Pap. No. 43, U.S. Weather Bureau.

Wahl. E. W., and T. L. Lawson, 1970: The climate of the mid-nineteenth century United States compared to the current normals. *Mon. Wea. Rev.*, **98**, 259–265.

Whitaker, G. L., 1971: Changes in the elevation of Great Salt Lake caused by man's activities in the drainage basin, U.S. Geological Survey Prof. Pap. 750-D, D187–D189.

World Meteorological Organization, 1966: Climatic change. Tech. Note No. 195, Geneva, 79 pp.