Secular Variations in Streamflow in the Western United States

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ABSTRACT

Long-term streamflow series in the western United States were examined for evidence of secular changes related to climate. Streamflow series contained appreciable low-frequency variation related to the combined influence of temperature and precipitation. Evidence of nonstationarity was found in selected records for the Pacific Northwest and the Upper Colorado Basins: mean annual streamflow increased significantly (0.05 level) from the first to last half of the 1914–80 period in the Pacific Northwest, and decreased significantly over the same period in the Upper Colorado region. Correlation analyses and examination of drought years revealed a strong tendency for anomalies of opposite sign in the Pacific Northwest and the Southwest. Drought in the Upper Colorado Basin was statistically independent of drought in the Pacific Northwest. Under exceptional meteorological conditions (e.g., water-year 1976–77), however, low flows occurred over a vast area from the Northwest coast to the mountains of central Arizona.

1. Introduction

A major concern about possible climatic warming due to anthropogenic increases in atmospheric CO_2 is that surface-water supplies in the arid and semiarid western United States may be substantially reduced. A recent assessment of results of climatic modeling arrived at $3 \pm 1.5°C$ as the equilibrium global surface warming expected from a doubling of CO_2 and concomitant increases in other greenhouse gases (Smagorinski, 1983). Using regression on divisional climatic data, Revelle and Waggoner (1983) estimated that a 2°C warming would reduce the mean annual flow of the Colorado River by $29 \pm 6\%$. The large magnitude of this reduction probably reflects covariation of air temperature with other atmospheric variables governing potential evapotranspiration. Further reduction would result from a decrease in precipitation, but the sign of expected precipitation change at the latitudes of the Colorado Basin (37–43°N) under doubling of CO_2 is a point of disagreement among various climate models (Schlesinger, 1983).

In evaluating the potential effects of climatic change on water supply in the West, it appears useful to examine some aspects of the natural variability of runoff as reflected in gaged streamflow records. Bartlein (1982) analyzed monthly streamflow over the United States and Canada for the period 1951–70, and found that much of the variation could be explained by a few basic spatial patterns most likely related to anomalies in the general large-scale circulation of the atmosphere. Streamflow might be expected to yield a different statistical picture of climatic fluctuations than would precipitation or temperature. Gaged streamflow in the mountainous West reflects rainfall in high mountain areas, in contrast with precipitation records which generally have a low-elevation bias (Bradley, 1976). Streamflow directly measures a precipitation-minus-evapotranspiration residual, and represents an areal sum, therefore smoothing out local noise inherent in station climatic records. These advantages, from a water-resources standpoint, are somewhat offset by the fact that most gaged streamflow records are distorted because appreciable amounts of water have been diverted for irrigation, or because flows have been regulated by dams and reservoirs. Only a small subset of gages is therefore suitable for the study of secular changes related to climate.

Investigations of large-scale aspects of streamflow variation in the western United States using a selected set of streamflow records are reported in this paper. Emphasis is placed on drought—its simultaneous occurrence in various water resources regions, inter-regional correlations and long-term trends.

2. Data

Streamflow series were grouped into regions and subregions according to boundaries designated by the United States Water Resources Council (1978). A set of 26 gages was selected based on the following criteria: geographical location, such that several major runoff-producing areas in the West were sampled; diversions for irrigation less than 7% of mean annual flow; total reservoir capacity less than 7% of mean annual flow; period of continuous record covering the years 1932–80; and a rating of "good" (measurement error $\leq 10\%$) or better in the "remarks" section of the United States Geological Survey (USGS) Water-Supply Papers. The criteria were relaxed somewhat for three of the gages in order to achieve desired geographical coverage for correlation analysis, but these gages were not used in

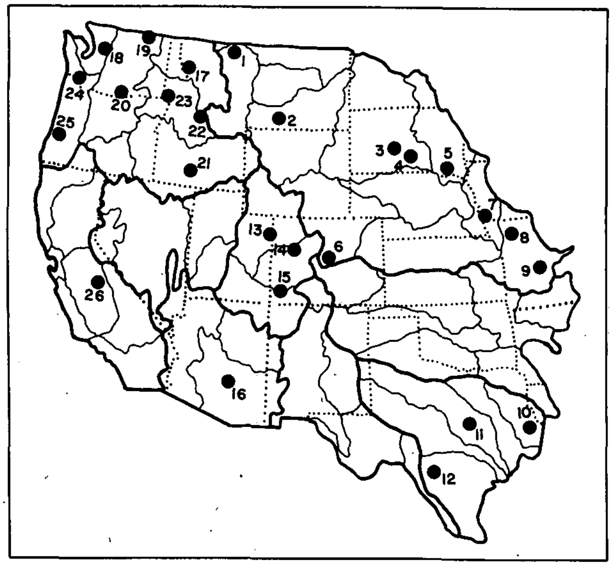

FIG. 1. Locations of selected streamflow gages and boundaries of water resources regions (thick lines) and subregions (thin lines). Numbering follows Table 1.

analyses of long-term secular variations. Sources of streamflow data were the USGS Water-Supply Papers (1914–76); data for recent years were obtained directly from various USGS regional offices.

The gage network and boundaries of regions and subregions are shown in Fig. 1. Six of the Water Resources Council regions and 21 subregions are represented with widely varying degrees of coverage (Table 1). The present analysis was restricted to annual water-year (1 October–30 September) totals. Flows of selected streams within a region or subregion were summed to form what are termed here "regional" and "subregional" series. These series represent only a fraction of total streamflow within a region or subregion.

Although relatively detailed spatial analysis was limited to the 1932–80 period, longer term variations in parts of the mountainous West were studied using a subset of the 26 gages in addition to a time series of total annual flow of the Colorado River (1906–78) at Lee Ferry, Arizona. This series had been adjusted for numerous diversions and regulations, and represents an estimation of "natural" flow of the Colorado River.

TABLE 1. Streamflow gages by number and location with drainage areas and mean annual flow.

Map number	Identification number[a]	Region and subregion[b]		Drainage area (km^2)	Mean annual flow[c] (10^6 m^3)
1	06099550	Missouri	1002	8397	841
2	06207550		1004	2989	841
3	06441500		1005	8047	133
4	06452000		1005	26418	470
5	06478500		1006	55814	344
6	06707000		1007	1241	147[d]
7	06810000		1009	7267	947
8	06902000		1010	17819	3313
9	06933500		1010	7356	2142
10	08033500	Texas Gulf	1201	9420	2044
11	08095000		1203	2517	184
12	08167500		1205	3320	290
13	09306500	Upper Colorado	1401	10412	593
14	09085000		1402	3758	1076[d]
15	09166500		1402	1440	370
16	09498500	Lower Colorado	1503	11152	730
17	12354500	Pacific Northwest	1701	27736	6729
18	12134500		1706	1386	3604
19	12401500		1702	5750	1391
20	14113000		1702	3359	1454
21	13185000		1703	2150	1092
22	13302500		1704	9738	1784
23	13342500		1704	24786	13900
24	14243000		1705	5796	8344
25	14321000		1705	9539	6806
26	11213500	California	1803	2719	1295

[a] As in U.S. Geological Survey Water-Supply Papers.
[b] Numbers follow U.S. Water Resources Council (1978).
[c] For period 1932–80.
[d] Adjusted for intermountain diversions.

3. Inter-regional correlations

Correlation coefficients between the Upper Colorado regional series and subregional series from other regions for 1932–80 are mapped in Fig. 2. The wide band of positive values oriented southwest–northeast probably reflects the preferred orientation of winter storm tracks. Correlation drops off rapidly to the northwest, such that coefficients with all except the nearest of the subregions of the Pacific Northwest are essentially zero or negative. The correlation between regional series for the Upper Colorado and Pacific Northwest is −0.02. The pattern of correlation indicates that distances involved are sufficiently great compared to the size of weather systems for shifts in the storm tracks to produce compensating anomalies in the extreme reaches of the two regions. Northwest–southeast contrast is more obvious when the Pacific Northwest is used as the key region (Fig. 3). A broad band of zero correlations is flanked on the south by significant (0.05 level) negative correlations in Texas and Arizona. The only subregions positively correlated with the Pacific Northwest are those in the upper reaches of the Missouri region, draining the adjacent eastern side of the continental divide.

In addition to the limited size of synoptic-scale weather systems, another factor contributing to the decrease of correlation of annual streamflow with distance is spatial variation in seasonal distribution of precipitation and runoff. The season of primary maximum in precipitation varies from late fall in the Pacific Northwest, to winter in California, to late spring over much of the Missouri and Upper Colorado regions to summer in the Lower Colorado and Texas Gulf regions (Pike, 1972). Cool-season precipitation and snowmelt are dominant components of annual streamflow in the mountainous West, but not in the Texas Gulf and lower reaches of the Missouri region.

4. Large-scale drought

The experience of the drought year 1977, in which very low streamflow was recorded in the Pacific Northwest, California and the Central Rockies (Buchanan and Gilbert, 1977), suggests that the statistical picture given by the foregoing spatial correlations can be misleading. To study the simultaneous occurrence of drought in various regions in detail, an empirical definition of drought was adopted: a drought year was defined as any year among the driest 10 years (driest 20%) in a given regional series from 1932 to 1980. The analysis was restricted to regions whose streamflow was determined mainly by cool-season precipitation. A time series plot of regions in drought is shown in

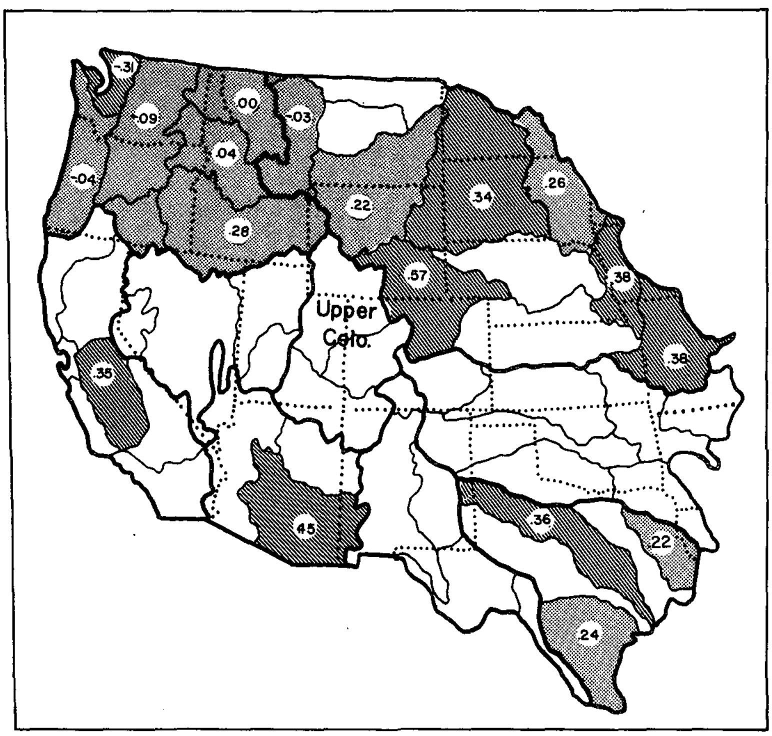

FIG. 2. Correlation coefficients for 1932–80 of various subregional streamflow series with the regional series for the Upper Colorado region. Hatching represents significance at 0.05 level, and stippling nonsignificance at 0.05 level. Subregions outside the key region for which no data were analyzed are blank.

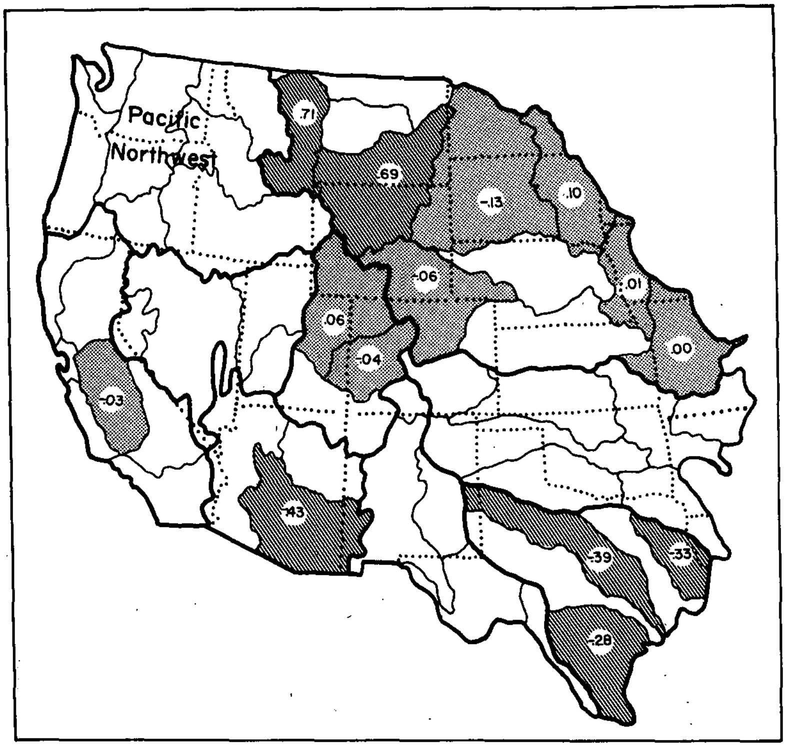

FIG. 3. As in Fig. 2, but correlation coefficients for 1932–80 of various subregional streamflow series with regional series for the Pacific Northwest.

Fig. 4. Regional streamflow as a percentage of the 1932–80 normal corresponding to the 10th-ranking dry year was as follows:

Upper Colorado	80
Lower Colorado	41
Pacific Northwest	79
California	59

In only one year, 1977, were all four regions simultaneously in drought. The meteorological conditions of the 1977 drought have been well-documented and studied elsewhere (Namias, 1978). A strong ridge dominated the upper-level winter circulation over the western United States. The mean position of the ridge line at the northwest coast and the exceptional strength of the ridge as measured by height anomalies at 700 mb were favorable for a maximum effect on water basins throughout the West. Examination of upper-air maps (Namias, 1979) revealed that the 700 mb height patterns for other severe drought years over the western basins were moderated versions of the 1977 pattern. For example, during the winter of 1961 an anomalous (but weaker) ridge dominated the West and the position of the ridge line was inland from the Pacific Northwest coast at about 120°W; streamflow in 1961 was extremely low in the Upper and Lower Colorado regions but normal in the Pacific Northwest.

From all indications the winter and spring of 1977 was an extreme outlier in producing low streamflow from the Pacific Northwest to the mountains of central Arizona. In fact, in agreement with correlation analyses discussed previously, large anomalies in the Pacific Northwest and the Southwest were often of opposite sign. Of the ten driest years in the Lower Colorado region, five were among the ten *wettest* in the Pacific

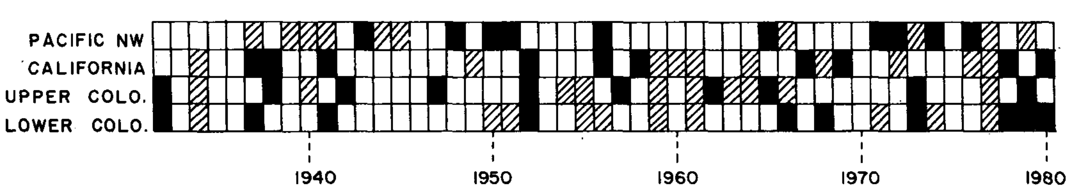

FIG. 4. Drought years (hatched) and wet years (solid) in four regions for 1932–80. Drought (wet) years are defined as those with the ten lowest (highest) mean annual flows out of 49 years in the regional series.

Northwest; and of the ten driest in the Pacific Northwest, five were among the ten wettest in the Lower Colorado region. The probability of this occurring by chance was tested with a simple binomial model. A "success" was defined as occurrence of a wet (among the wettest ten) year in the Lower Colorado regional series; the sample was the ten driest years in the Pacific Northwest in 1932–80.

The probability of m successes in n trials is

$$P_m = \frac{n!}{m!(n-m)!} p^m(1-p)^{n-m},$$

where p is the probability of a "success" in any given year, n is the sample size, and m is the number of successes out of n trials.

Substituting the values $p = 10/49 = 0.204$, $n = 10$ and $m = 5$, and assuming the ten driest years in the Pacific Northwest are a random sample with respect to conditions in the Lower Colorado, the probability $P_m < 0.03$ that the observed opposition of anomalies is by chance.

Similar analyses keyed on each of the four westernmost regions indicate that drought in the Pacific Northwest is generally not associated with simultaneous drought over any other region, including the California Region. This result is based on analysis of regional streamflow sums, and does not necessarily imply lack of correlation for adjacent subregions across regional boundaries. Note in particular that the California "region" is represented here by the Kings River, which drains only the central part of the Sierra Nevada. Closer linkage with Pacific Northwest drought might be expected from watersheds in the northern Sierras. As for the Upper Colorado region, severe droughts there were positively linked (0.05 significance level) with droughts in both the Lower Colorado and California regions.

5. Secular trends

Identification of climatically-induced trends in streamflow series is complicated by the interdependence of surface water and ground water. Although the surface-flow component of streamflow may reflect annual fluctuations in net precipitation (precipitation minus evapotranspiration), the base-flow component, that due to groundwater, may require years to respond in some basins (McDonald and Langbein, 1948). An additional distortion is introduced in some basins by groundwater pumping for irrigation and other uses. The following four gages were selected to minimize nonclimatic influences in evaluating long-term climatic trends:

River	Map number	Period of record
Umpqua, OR	25	1906–80
Clark Fork, MT	17	1911–80
Roaring Fork, CO	14	1911–80
Salt, AZ	16	1914–80

The Umpqua drains from the Pacific slopes of the Cascade Mountains; the Clark Fork, a tributary of the Columbia River, drains from the central part of the northern Rockies; the Roaring Fork, a tributary of the Colorado, drains from the Front Range of the Colorado Rockies; and the Salt, a tributary of the Colorado, drains from the central mountains of Arizona. These series, though certainly insufficient for the fine detail of geographic variations in runoff, serve to sample runoff in widely spaced mountainous areas where cool-season precipitation and snow melt are dominant components of streamflow. In view of the possible distortion of annual fluctuations by groundwater storage, a low-pass filter was applied to emphasize low-frequency variation. Filter specifications and filtered plots are shown in Fig. 5.

A prominent feature in the plots of low-pass filtered series is the divergence in trends between the northernmost rivers and the Salt River in the 1940s and 1950s. This behavior is in contrast to the parallel decrease for all four rivers in earlier segments, especially from the wetness of the 1910s to drought in the 1930s. The 1930s were drier than normal (1915–80 mean) in all four series. The early 1950s showed a spatial contrast, being extremely dry in the Southwest and extremely wet on the Northwest coast as reflected in the Umpqua series. After a widespread drought centered about 1961, flow in all four rivers gradually increased through the early 1970s.

6. Climatological factors

The time-series trends evident in Fig. 5 can be explained in terms of trends in precipitation and temperature. The streamflow trends for the Clark Fork and Roaring Fork Rivers, which drain from the Rockies at latitudes 47 and 39°N, respectively, parallel secular trends in Rocky Mountain precipitation and temperature (Bradley *et al.,* 1982). The low-frequency variation in precipitation reaches peaks (wet) in the 1910s, 1940s and 1970s; and troughs (dry) in the 1930s, and late 1950s to early 1960s. The time-series plots for Montana and Colorado (Bradley *et al.,* 1982) also show that, particularly for spring and summer, major wet anomalies tended to be cool, and dry anomalies warm. Variations in evapotranspiration therefore likely acted in concert with variations in precipitation in producing the observed low-frequency streamflow anomalies.

The strong opposition of streamflow anomalies between the two Pacific Northwest rivers and the Salt River (Arizona) from the mid 1940s to the late 1950s (Fig. 5) appears to reflect climatic influences in different seasons. The summer rainfall contribution to the annual flow of the Salt River probably cannot be ignored, and summer rainfall in Arizona declined steadily from the 1910s to the mid 1940s (Bradley *et al.,* 1982). Over the same period, Blasing and Lofgren (1980) show a marked decrease in frequency of a summer surface

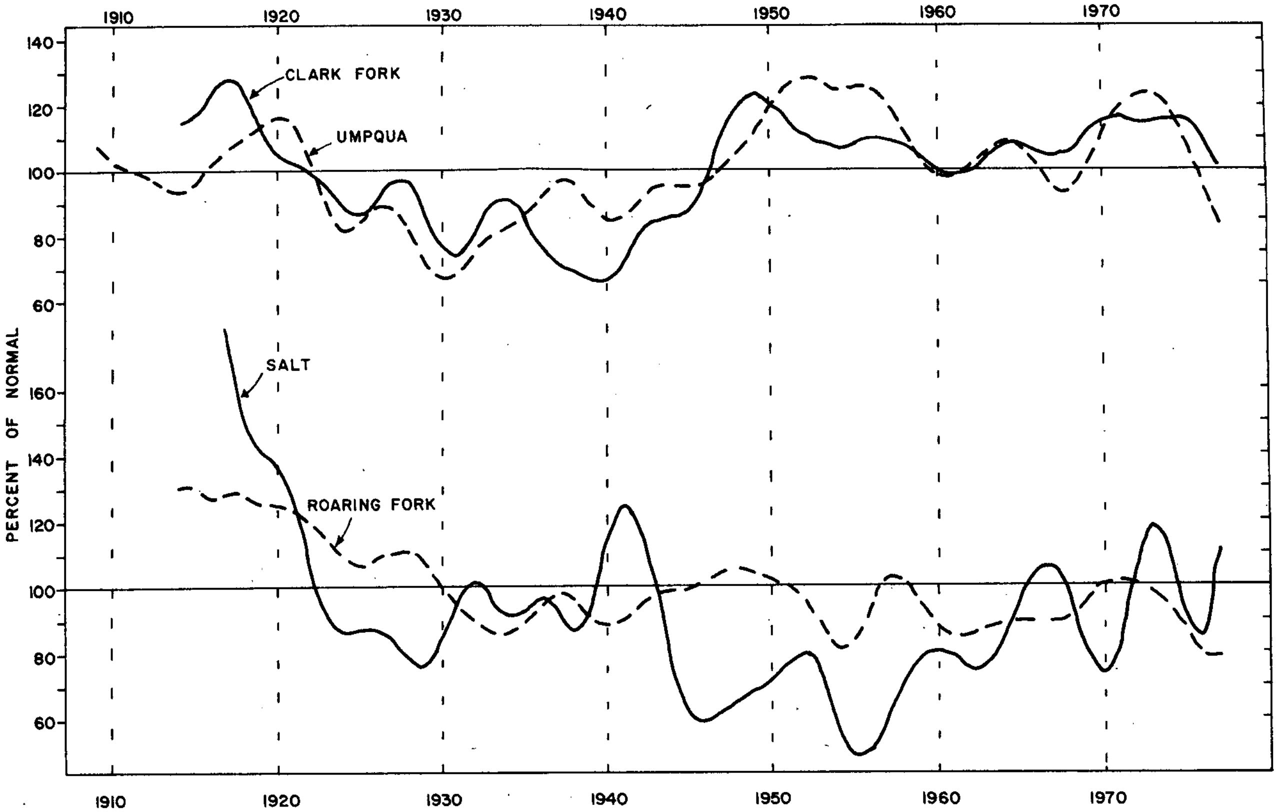

FIG. 5. Low-pass filtered plots of mean annual flow of four long streamflow series. Vertical axis is percent of 1915–80 normal. A raised-cosine filter (Hamming, 1983) with weights 0.2646, 0.2187, 0.1158 and 0.0332 on lags zero through ±3 was used. Frequency response falls below 0.01 at wavelength 4.6 years.

pressure pattern associated with northward and westward displacement of the Bermuda High. Winter precipitation also declined steadily in Arizona from the 1910s to the mid-1950s, with the steepest decline after 1940 (Bradley *et al.*, 1982; Sellers, 1960). Interestingly, streamflow in the northern Rockies and the Cascades increased dramatically at this time.

Results of eigenvector analysis of monthly precipitation (Sellers, 1968) and winter cyclone frequency (Diaz and Fulbright, 1981) indicate a pronounced northward shift in winter storm track in the late 1940s and 1950s. The observed low-frequency contrast from above normal streamflow in the Montana Rockies and Oregon Cascades to slightly below normal in the Colorado Rockies to much below normal in the mountains of central Arizona (Fig. 5) is compatible with such a shift.

Comparison of low-frequency streamflow variations of the Clark Fork River (Montana) and Salt River (Arizona) (Fig. 5) suggest two types of epochs: one with anomalies of the same sign in the northern and southern parts of the western United States (1910s to early 1920s) and another with anomalies of opposite sign (late 1940s to early 1950s). These epochs may be associated with preferred modes of variation in atmospheric circulation. Sellers (1968), in a study of monthly precipitation patterns in the West for 1931–66, concluded that two of the most important eigenvectors probably represented 1) east–west shifts in the midlatitude pressure systems and 2) north–south shifts in the storm track. The observed streamflow epochs may represent periods when one of these features dominated over the other. Some association with larger-scale atmospheric circulation characteristics is suggested by Dzerdzeevskii's (1962) plots of departure from normal of zonal and meridional components of the general circulation in the Northern Hemisphere. The plots for seasons most important to streamflow (those other than summer and autumn) indicate that meridional flow dominated in the 1910s and zonal flow in the late 1940s and early 1950s.

7. Magnitudes of anomalies

The large magnitude of low-frequency variations of streamflow (Fig. 5) points to an uncertainty in ascertaining mean annual supply from available record lengths. This difficulty is illustrated by a test of difference of means for 1914–46 versus 1947–80 for the seven records extending back to 1914 (Table 2). Gages in the northern Rockies and Pacific Northwest showed a 20% increase in mean between the two periods; gages

TABLE 2. Mean annual streamflow for subperiods.

Gages*	Region	Mean flow (10^6 m^3) 1914–46	1947–80	Ratio**
1	Missouri	763	926	1.21
10	Texas Gulf	2311	1845	0.80
14	Upper Colorado	1273	1125	0.88
16	Lower Colorado	856	719	0.84
18	Pacific Northwest	6023	7344	1.22
22		986	1150	1.17
25		6053	7131	1.18

* As numbered in Table 1.
** Ratio of 1947–80 mean to 1914–46 mean.

to the south showed a 15–20% decrease. A t-test (Panofsky, 1968) revealed that the means of the four northernmost gages increased significantly (0.05 level) while the mean of the Roaring Fork River in the Upper Colorado region decreased significantly. The decreases in mean in the remaining southern series, although even larger as a percentage of normal than on the Roaring Fork, were not significant at the 0.05 level due to the relatively large standard deviations of the flows.

Streamflow variations on the Colorado River are of particular importance because of the Upper Colorado Basin's strategic importance to water supply in the West. The flow of the Colorado River at Lee Ferry, Arizona, is a measure of outflow from the entire basin. The dominant component of this flow is snowmelt runoff from mountainous areas: 85% of the streamflow comes from 15% of the area of the basin (Stockton and Jacoby, 1976). Magnitudes of streamflow anomalies for 1924–78 were examined for the flow at Lee Ferry and for two subseries, the regional Upper Colorado series and the series for the Roaring Fork River (gage 14 in Fig. 1). Some statistics (1924–78) of these series are as follows:

River	Area (km^2)	Mean-annual flow (10^6 m^3)	Average runoff (cm)
Roaring Fork, Colorado	3758	1131	30.0
Upper Colorado regional	15 600	2128	13.6
Colorado River	279 460	17 219	6.2

The Roaring Fork is clearly a very small sample of the entire water supply of the Upper Colorado Basin, but it does sample the central part of the important runoff-producing higher elevations.

To facilitate comparison with frequently-used 30-year climatic normals, series were first converted to percentages of the 1924–78 normal, which differs only slightly (0.1%) from the 1941–70 normal for the Lee Ferry record. Time-series variations in decadal-average anomalies on the relatively small Roaring Fork River closely track variations in the total flow of the Colorado River (Fig. 6). This observation testifies to the representativeness of the Roaring Fork of the key runoff-producing areas of the Colorado watershed. Expressed as percentages of 1924–78 normals, extreme anomalies of various lengths were consistently more severe for the total flow of the Colorado River than for the relatively small tributary, the Roaring Fork (Fig. 7). Possible reasons for this unexpected result are that the flow at Lee Ferry includes contributions from many arid and semiarid watersheds whose flows are extremely sensitive to changes in precipitation, and that the precipitation anomalies associated with very low annual flows are large enough in spatial extent to simulta-

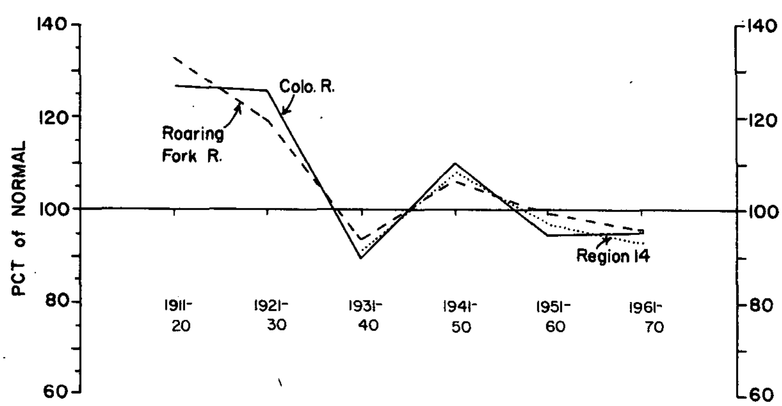

FIG. 6. Decadal-average anomalies (as percent of 1924–78 mean) for three streamflow series from the Upper Colorado region. The Colorado River at Lee Ferry, Arizona, is the outflow series for the entire Upper Colorado Basin. The Roaring Fork drains from the Front Range of the Colorado Rockies. The Region-14 series includes flow of the Roaring Fork plus the White River, Utah, plus the Dolores River, Colorado.

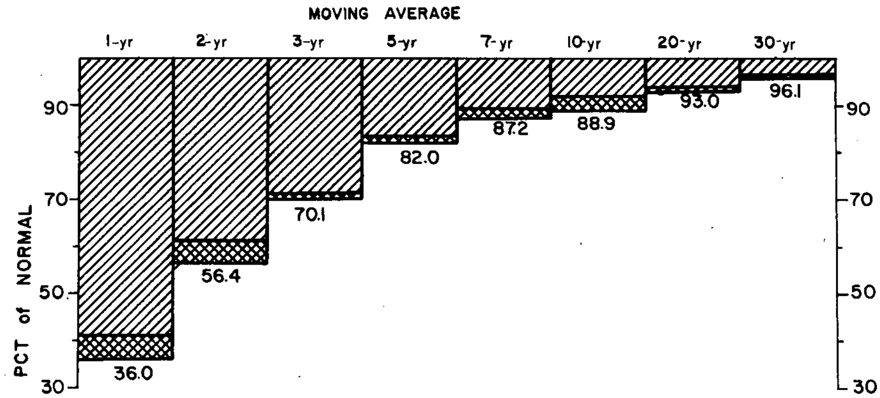

FIG. 7. Extreme anomalies (as percent of 1924–78 mean) of streamflow for moving averages of various lengths on Roaring Fork River (hatched) and the Colorado River at Lee Ferry, Arizona (crosshatched). The period for analysis was 1914–78, but the same values apply for the longer 1906–78 period in the Lee Ferry flow.

neously affect widely separate watersheds within the Colorado Basin.

Although the projected effects of increasing CO_2 on temperature and precipitation over the Colorado Basin are uncertain, some perspective on a reasonable scenario can be gained by comparing the anomalies shown in Fig. 7 with the 29% reduction that Revelle and Waggoner (1983) estimate would take place in the flow of the Colorado River if climate over the basin were to warm by 2°C. The 29% value corresponds approximately to the level of the driest three-year period since 1906 on the Colorado River. In the driest single year (1977), flow was 64% below normal. The critical distinction between an anomaly and a CO_2-induced reduction is that the effect of the latter would likely be a lowering of the mean rather than a fluctuation. The large surface-storage capacity of the Colorado system (USGS, 1970), while mitigating the effects of transient anomalies in flow, would only delay inevitable water shortage under a reduced mean flow. Note, however, that changes in 30- or 40-year "means" on the order of 20% have been characteristic of series of annual streamflow over much of the western United States in this century (Table 2).

8. Conclusions

Carefully selected streamflow records can provide useful information on climatic variations, especially in mountainous areas where high-elevation weather stations are sparse. Examination of annual streamflow series in the West indicates that significant hydrologic changes related to climate have taken place in the past century. In general, major low-frequency variations in streamflow have tracked variations in precipitation and temperature; minima in the low-frequency $[<1\ (5\ \mathrm{yr})^{-1}]$ component of streamflow have generally been associated with periods of both low precipitation and high temperature.

Secular trends in streamflow in various parts of the West have sometimes paralleled one another and at other times have diverged. This behavior appears to be related to major shifts in regimes of the general circulation. A pronounced northward shift in the storm track appears to have resulted in exceptional north–south contrast in streamflow anomalies in the late 1940s and early 1950s. This period was also characterized by dominance of the zonal over the meridional component in the atmospheric circulation in winter and spring. The 1910s appear to represent the opposite extreme, with high streamflow along a north–south transect of the mountainous West from Montana to Arizona. This pattern possibly reflects the dominance at that time of the meridional component in atmospheric circulation.

Correlation analysis for 1932–80 indicates that in terms of regional sums of annual streamflow, water supply of the Pacific Northwest is uncorrelated ($r = -0.02$) with water supply of the Upper Colorado region, and significantly (0.05 level) negatively correlated with streamflow in Arizona and Texas. In selected long series, t-tests indicate considerable uncertainty in mean annual streamflow over the West. From the first to second half of the 1914–80 period, the mean increased significantly (0.05 level) in the Pacific Northwest, and decreased significantly (0.05 level) in the Upper Colorado region. These changes in mean were on the order of 15–20%.

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REFERENCES

Bartlein, P. J., 1982: Streamflow anomaly patterns in the U.S.A. and southern Canada—1951–1970. *J. Hydrol.*, **57**, 49–63.

Blasing, T. J., and G. R. Lofgren, 1980: Seasonal climatic anomaly types for the North Pacific sector and western North America. *Mon. Wea. Rev.*, **108**, 700–719.

Bradley, R. S., 1976: *Precipitation History of the Rocky Mountain States.* Westview Press, 334 pp.

——, R. G. Barry and G. Kiladis, 1982: Climatic fluctuations of the western United States during the period of instrumented records. Contrib. No. 42, Dept. of Geol. Geogr., University of Massachusetts, Amherst, 169 pp.

Buchanan, T. J., and B. K. Gilbert, 1977: The drought. *Water Spectrum,* **9,** 6.

Diaz, H. F., and D. C. Fulbright, 1981: Eigenvector analysis of seasonal temperature, precipitation, and synoptic-scale system frequency over the contiguous United States. *Mon. Wea. Rev.,* **109,** 1267–1284.

Dzerdzeevskii, B., 1962: Fluctuations of climate and of general circulation of the atmosphere in extra-tropical latitudes of the Northern Hemisphere and some problems of dynamic climatology. *Tellus,* **14,** 329–336.

Hamming, R. W., 1983: *Digital Filters.* Prentice-Hall, 257 pp.

McDonald, C. C., and W. B. Langbein, 1948: Trends in runoff in the Pacific Northwest. *Trans. Amer. Geophys. Union,* **29,** 387–397.

Namias, J., 1978: Multiple causes of the North American abnormal winter 1976–77. *Mon. Wea. Rev.,* **106,** 279–295.

——, 1979: Northern Hemisphere seasonal 700-mb height and anomaly charts, 1947–1978, and associated North Pacific sea surface temperature anomalies. Atlas No. 27, California Cooperative Oceanic Fisheries Investigations (CALCOFI), Marine Life Research Group, Scripps Institution of Oceanography 275 pp.

Panofsky, H. A., and G. W. Brier, 1968: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University Press, 224 pp.

Pike, C. B., 1972: Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California. Contrib. No. 139, University of California Water Resources Center, 205 pp.

Revelle, R. R., and P. E. Waggoner, 1983: Effects of carbon dioxide-induced climatic change on water supplies in the western United States. *Changing Climate: Report of the Carbon Dioxide Assessment Committee,* National Academy of Science Press, 419–432.

Schlesinger, M. E., 1983: Simulating CO_2-induced climate change with mathematical climate models: Capabilities, limitations and prospects. *Proc. Carbon Dioxide Research Conf.: Carbon Dioxide, Science, and Consensus,* Coolfont, VA, U.S. Dept. Energy, Washington, DC, III.3.

Sellers, W. D., 1960: Precipitation trends in Arizona and western New Mexico. *Proc. 28th Annual Western Snow Conf.,* Santa Fe, U.S. Soil Conservation Service 81–94.

——, 1968: Climatology of monthly precipitation patterns in the western United States, 1931–1966. *Mon. Wea. Rev.,* **96,** 585–595.

Smagorinski, J., 1983: Effects of carbon dioxide. *Changing Climate: Report of the Carbon Dioxide Assessment Committee,* National Academy of Science Press, 266–284.

Stockton, C. W., and G. C. Jacoby, 1976: Long-term surface-water supply and streamflow trends in the upper Colorado River Basin. *Lake Powell Res. Proj. Bull.,* No. 18, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 69 pp.

United States Geological Survey, 1914–1976: *Surface Water Supply of the United States.* Various issues published as part of the series of Water-Supply Papers, U.S. Govt. Printing Off., Washington, DC.

——, 1970: *Surface Water Supply of the United States 1961–65.* Geol. Surv. Water-Supply Papers No. 1924, 1925, U.S. Govt. Printing Off., Washington, DC.

United States Water Resources Council, 1978: *The Nation's Water Resources 1975–2000,* Vol. 1, *Summary.* Water Resources Council, U.S. Govt. Printing Off., Washington, DC, 52 pp.