# HISTORIC VARIATION OF WARM-SEASON RAINFALL, SOUTHERN COLORADO PLATEAU, SOUTHWESTERN U.S.A.

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**Abstract.** Rainfall during the warm season (June 15–October 15) is the most important of the year in terms of flood generation and erosion in rivers of the southern Colorado Plateau. Fluvial erosion of the plateau decreased substantially in the 1930s to early 1940s, although the cause of this change has not been linked to variation of warm-season rainfall. This study shows that a decrease of warm-season rainfall frequency was coincident with and probably caused the decreased erosion by reducing the probability of large floods. Warm-season rainfall results from isolated thunderstorms associated with the Southwestern monsoon and from dissipating tropical cyclones and (or) cutoff low-pressure systems that produce widespread, general rainfall. Warm-season rainfall is typically normal to above normal during warm El Niño-Southern Oscillation (ENSO) conditions. A network of 24 long-term precipitation gages was used to develop an index of standardized rainfall anomalies for the southern Colorado Plateau for the period 1900–85. The index shows that the occurrence of anomalously dry years increased and the occurrence of anomalously wet years decreased after the early 1930s, although 1939–41, 1972, and 1980–84 were anomalously wet. The decrease in warm-season rainfall after the early 1930s is related to a decrease in rainfall from dissipating tropical cyclones, shifts in the incidence of meridional circulation in the upper atmosphere, and variability of ENSO conditions.

## Introduction

Historic variation of warm-season rainfall is significant for understanding geomorphic and hydrologic changes of the past century in the southern Colorado Plateau (Figure 1). Rainfall during the warm season, defined here as June 15–October 15, produces 50 to 90% of the large floods of Colorado Plateau rivers (Webb, 1985), and the sediment load of the typical river is 10–100 times larger than those during winter or spring (Hereford, 1989). Warm-season rainfall, therefore, is probably the chief agent of fluvial erosion, sediment transport, and land-surface change in this region.

The sediment load of the Colorado River is an indicator of fluvial erosion on the Colorado Plateau (Howard, 1947; Iorns and others, 1965). Measurement of sediment and streamflow began in 1925 at Grand Canyon, and these measurements record the unregulated flow of the river until 1957 when several large reservoirs were constructed (Figure 1). During 1925–40, the sediment load of the river was

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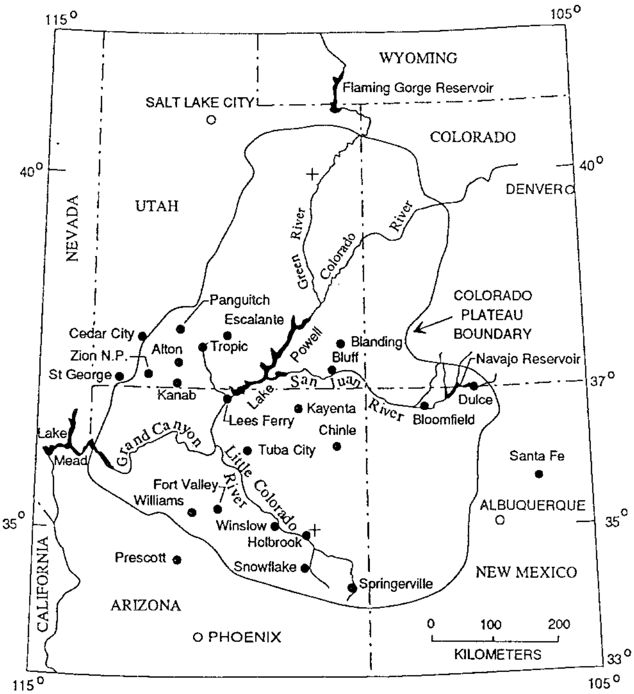


Fig. 1. The Colorado Plateau region of the Southwest United States showing the long-term weather stations used in this study (solid circles).

about 180 Tg $yr^{-1}$; during 1941–57, however, sediment load was only 80 Tg $yr^{-1}$ (Smith and others, 1960). The early period of high sediment load was associated with widespread erosion on the plateau. Although the causes are poorly understood, this erosion, termed ‘arroyo cutting’, probably began within one to three decades of 1880 and lasted until the early 1940s (Leopold, 1976). Arroyo cutting changed the land surface drastically by widening and deepening stream channels below the level of former floodplains. The decreased sediment load of the Colorado River since the early 1940s occurred at about the same time that tributary channels began to develop floodplains and partially fill with sediment (Hereford, 1987), which ended arroyo cutting (Leopold, 1976), at least temporarily. Floodplain reconstruction was evidently caused by a shift to less frequent large floods (Hereford, 1986; 1987; Webb and Baker, 1987; Graf and others, 1991). In this report, a shift in warm-season rainfall patterns during the 1930s to early 1940s is shown to be approximately coincident with this change of flood frequency.

The causes of this widespread erosion and subsequent channel filling are elusive, even though they have been studied by three generations of geologists, geomorphologists, and geographers (see reviews in Cooke and Reeves, 1976; and Graf, 1983). Recent explanations for arroyo cutting and filling typically emphasize either climate variation (Hereford, 1984; Graf, 1986; Balling and Wells, 1990) or the inherently unstable character of fluvial systems (Patton and Schumm, 1981). A single, all-encompassing explanation, however, is precluded by the complexity of the problem. How climate affects erosion and the magnitude of climate change since the late 19th century remain uncertain. Moreover, the influence of land use on erosion is equally uncertain. Increased erosion of the late 19th and early 20th centuries, for example, could result from settlement and overuse of resources, or from unusually high rainfall or frequent large storms. Likewise, less rainfall during the latter part of this century could reduce erosion, or the reduced erosion could result from improved land use and other conservation measures introduced in the mid- to late 1930s (Hadley, 1977).

To understand the role of climate in fluvial erosion, we examined the historic variation of the frequency and amount of warm-season rainfall on the southern Colorado Plateau. Rainfall frequency was analyzed because it along with seasonality and intensity are considered important factors in geomorphic studies of arroyo cutting (Leopold, 1951; Leopold and others, 1966; Cooke and Reeves, 1976, pp. 65–78; Webb, 1985; Graf, 1988, pp. 220–224; Balling and Wells, 1990). Generally, frequent storms are thought to weaken upland vegetative cover, increase the likelihood of floods, and enhance arroyo cutting. On the other hand, fewer storms presumably strengthen upland vegetative cover, decrease the frequency of large floods, and retard arroyo cutting.

Disregarding the condition of upland vegetation, a study of the Paria River basin shows that large floods typically result from unusual wet conditions during the warm season (Graf and others, 1991). In the present report, an index of seasonal rainfall is used to measure the spatial pattern of wetness on the southern Colorado Plateau, which is also an indirect measure of flood size and erosion across the region. The index was developed for two categories of daily rainfall; the occurrences of rain during a single day and the occurrences of rain on two consecutive days. Both categories are thought to be geomorphically relevant because a high occurrence of either type should enhance the possibility of large floods. The 2-day category, however, is possibly the most important in terms of flood generation, because of the increased antecedent moisture conditions associated with the multiple occurrences of rain on two consecutive days.

This analysis treats warm-season rainfall during only the 20th century, because weather data for the late 19th century are scarce to nonexistent. Thus, the linkage between climate and arroyo initiation cannot be addressed here; however, we can evaluate the climatic background for floodplain reconstruction, reduced frequency of large floods, and the decreased sediment load of the Colorado River. The results of this study indicate that the frequency and amount of rainfall were larger during the period of high sediment load than during the subsequent period of low sediment load and floodplain reconstruction. This change of rainfall was probably caused by three interrelated factors: a decrease in rainfall from dissipating tropical cyclones originating in the eastern North Pacific Ocean, from changes in the incidence of meridional flow in the upper atmosphere, and from shifts in the variability of El Niño-Southern Oscillation (ENSO) conditions in the equatorial Pacific Ocean.

*Setting and Statistical Methods*

The Colorado Plateau (Figure 1), covering about 333 000 km$^2$ in four Southwestern states, is an elevated area with general surface elevation greater than 1500 m (Hunt, 1967, p. 277–307). The region is semiarid and characterized by sparse vegetation and relatively few inhabitants. Climate of the plateau is controlled largely by its saucer-like shape. Consequently, precipitation is greater and evaporation rate is lower along the elevated rims than in the lower interior. The southern Colorado Plateau is characterized by broadly similar climate and physiography, and it lies within and southeast of the so-called 'summer monsoon air-mass boundary' (Mitchell, 1976), which is the average northern limit of monsoonal rainfall.

Records from 29 stations representing most of the operating weather stations were examined for completeness and record length (Hereford, 1989). Twenty-four stations with a reasonably complete record beginning before 1930 (Table I) were selected for this analysis. The data consist of daily rainfall measurements collected mainly at cooperative stations staffed by volunteers (NOAA, 1986). Most of the data were obtained on magnetic tape from the National Center for Atmospheric Research, Boulder, Colorado, or from the National Oceanic and Atmospheric Administration (NOAA), Asheville, North Carolina; data not included on magnetic tape were obtained from *Climatological Data* for Arizona, New Mexico, and Utah, which is available from NOAA on microfiche. Table I gives the elevation, period of record, and percent missing days of the 24 stations. The complete precipitation data set from which the warm-season data were extracted consists of about 683 000 observation days.

The effect of station relocation and urbanization were not rigorously evaluated because station histories are not readily available or published. The little information available in *Climatological Data* suggests that stations were commonly relocated within communities. For the most part, however, these are small, rural communities, and relocation would be over short vertical and horizontal distances. Urbanization is probably not a problem with the majority of stations, because population has not increased significantly and, in some cases, may have actually decreased since 1900 (see Gregory, 1945). Moreover, examination of individual time series did not reveal discontinuities or inhomogeneities. We suspect, therefore, that the data are reasonably free of systematic errors due to station relocation or urbanization.

Time series were developed to test for changes in the frequency and amount of rainfall in the warm season of June 15–October 15. Rainfall variability was analyzed using three time series composed of 1-day, 2-day, and combined 1- and 2-day frequency categories. On a seasonal basis, 1-day and 2-day frequency cate-

TABLE I: Elevation, period of record, and percent missing days for period of record of the 24-weather stations used in this study

| Station | Elevation (m) | Period of record | Percent missing days |
|---|---|---|---|
| | Arizona | | |
| Chinle | 1688 | 1909–1970 | 14.9 |
| Fort Valley | 2239 | 1909–1985 | 0.9 |
| Holbrook | 1539 | 1900–1985 | 6.7 |
| Kayenta | 1579 | 1915–1977 | 14.1 |
| Lees Ferry | 957 | 1916–1985 | 11.5 |
| Prescott | 1652 | 1898–1987 | 2.1 |
| Snowflake | 1720 | 1900–1985 | 9.0 |
| Springerville | 2123 | 1911–1985 | 0.7 |
| Tuba City | 1504 | 1900–1975 | 8.3 |
| Williams | 2057 | 1897–1987 | 3.5 |
| Winslow | 1487 | 1900–1985 | 12.1 |
| | New Mexico | | |
| Bloomfield | 1658 | 1904–1985 | 8.3 |
| Dulce | 2103 | 1906–1985 | 8.8 |
| Sante Fe | 2130 | 1900–1970 | 1.4 |
| | Utah | | |
| Alton | 2145 | 1915–1985 | 0.3 |
| Blanding | 1861 | 1905–1985 | 2.9 |
| Bluff | 1317 | 1928–1985 | 1.2 |
| Cedar City | 1778 | 1909–1986 | 1.3 |
| Escalante | 1676 | 1901–1985 | 11.3 |
| Kanab | 1496 | 1914–1985 | 0.1 |
| Panguitch | 2134 | 1914–1986 | 7.7 |
| St. George | 839 | 1898–1986 | 3.2 |
| Tropic | 1935 | 1898–1986 | 15.6 |
| Zion N.P. | 1219 | 1907–1986 | 5.9 |

gories refer to the number of occurrences of rain in a single day or in two consecutive days. The combined 1- and 2-day frequency is the total number of days of the 1- and 2-day categories.

The number of days with more than 5 mm of rainfall occurring in 1- and 2-days was counted and the daily rainfall was accumulated for each of the 24 stations and 86 seasons between 1900–85. Rainfall up to 15 consecutive days was counted, but rain occurring on more than three consecutive days is rare. Considering all 24 stations, the accumulated seasonal rain occurring in 1- and 2-days ranges from 84–97% (average and standard deviation are 92 and 2.4%, respectively) of 1-, 2-, and 3-day rain. Seasonal rainfall of 1- and 2-day categories, therefore, is close to the seasonal total of all rainfall categories.

A minimum value of 5 mm was chosen to reduce measurement error of small rainfall amounts and to eliminate observational bias regarding traces of rainfall. Moreover, such small amounts of rain have little hydrologic effect in this region of relatively high evaporation rate. A missing value was assigned to a season if more than 5% of daily entries of a particular station were missing. The number of stations reporting varies annually, because of missing entries and an increase in the number of active stations through time (Figure 2). The number of stations increased rapidly from 1900 until about 1915–20, with 50% established by 1909, and all of the stations reported intermittently from 1951–69 (Figure 2).

Frequency of days with rainfall and total rainfall of each station were standardized, and the standardized values were averaged to form the 'standardized-anomaly index' (SAI) developed by Katz and Glantz (1986), who discussed its theoretical properties. The SAI is defined as a random variable $I_t$ whose value for the $t$th season is given by

$$I_t = \frac{1}{N_t} \sum_{i=1}^{N_t} (\mathrm{R}_{it} - \mu_i)/\sigma_i \qquad (1)$$

where $N_t$ = the number of stations reporting, $R_{it}$ = the rainfall total or frequency of the $i$th station, $\mu_i$ = the population mean, and $\sigma_i$ = the population standard deviation. In short, the observed total rainfall and frequency of days with rainfall of each station were standardized and then averaged to obtain the SAI for a particular season. Generally, the index encapsulates the spatial pattern of rainfall with a single number. A large positive value suggests above normal total rainfall or frequency, conversely, a large negative value suggests below normal conditions.

In addition, rainfall for days when dissipating tropical cyclones are known to have affected the Southwest United States (Smith, 1986) was obtained from the daily rainfall record for the 24 stations (Table I). Also, an SAI was developed for precipitation from tropical cyclones using (1).

## Warm-Season Rainfall

### *Definition of Rainy Season*

The annual precipitation cycle at four stations representative of the region is shown in Figure 3. These stations are widely spaced (Figure 1) and have an elevation

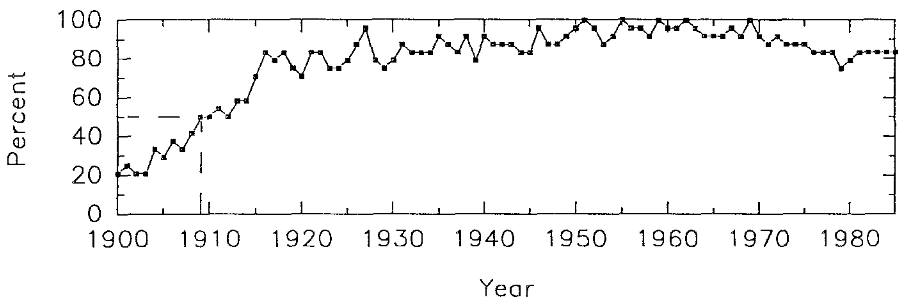


Fig. 2. Time series showing percent of active and reporting stations, 1900–85. Number of stations is 24. Fifty percent or more of the stations were active by 1909 (dashed line).

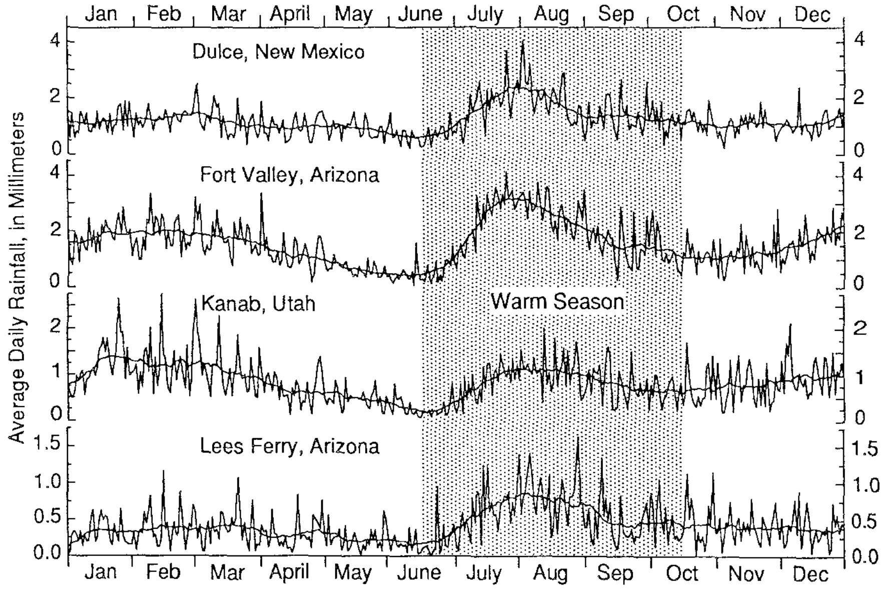


Fig. 3. Average daily rainfall of four weather stations having large elevation range (Table I) and geographic extent (Figure 1) showing warm-season rainfall singularity (pattern). Average computed from full station record and daily rain > 0.25 mm. Heavy line is 21-day moving average.

range of about 1200 m (Table I). Precipitation typically has a winter and summer maxima, although the winter maximum is not well developed at all stations. Warm-season rainfall begins in mid-June, reaching a maximum during late July to early August. Rainfall then declines steeply from late August until early September. Thereafter, rain declines gradually to the end of the season in late September to middle to late November. In short, the rainy season is not strictly limited to summer, rather it typically begins in early summer and lasts until mid-fall.

Warm-season rainfall on the Colorado Plateau is a climatic singularity (Bryson and Lowry, 1955; Carleton and others, 1990) because it recurs at the same time each year. Although the rainy season recurs each year, the beginning and ending date vary by several weeks from station to station. For regional comparison, therefore, the season was defined as June 15–October 15, a definition that includes most of the rainy season of each station (Hereford, 1989).

The length of the rainy season has evidently changed since the early 1940s. Before this time the rainy season was 5–40% longer than since the early 1940s (Hereford, 1989). Although the beginning of the rainy season was unchanged, the average ending date before the early 1940s was October 10–October 26, whereas after the early 1940s the ending date was September 16–October 5. This apparent shortening of the rainy season would decrease average daily rainfall during the warm season.

*Synoptic Climatology of Warm-Season Rainfall*

Moisture for warm-season rainfall on the Colorado Plateau originates in both the Gulf of Mexico and eastern North Pacific Ocean. Rainfall is associated with the 'Southwest monsoon', low-pressure troughs that produce widespread flash flooding (Maddox and others, 1980), tropical cyclones, and cut-off low-pressure systems. Monsoonal rainfall results from moisture-laden air masses associated with large subtropical high-pressure cells (Reyes and Cadet, 1988). Surges in monsoonal rainfall are associated with several weak circulation features; Carleton (1986) identified six diverse circulation patterns that produce 'bursts' of rainfall. In contrast, circulation associated with southerly displacement of either the Bermuda High or the North Pacific subtropical anticyclone cause 'breaks', or a suppression of rainfall (Carleton, 1985, 1986).

Tropical cyclones originating in the eastern North Pacific Ocean have the potential to produce rainfall throughout the warm season. Moisture from tropical cyclones is steered over the Southwest United States by a weak westerly circulation field or by a low-pressure trough or cut off low-pressure system (Smith, 1986). Only rarely do tropical cyclones recurve sharply enough to make landfall, although at least 80 tropical cyclones, averaging 1 $yr^{-1}$, have affected Colorado Plateau climate between 1900–85 (see Smith, 1986). Since 1965 and the advent of satellite coverage, the occurrence of tropical cyclones is known completely, and their occurrence is reasonably well known since 1945. Before 1945, however, the number of tropical cyclones is underestimated (Smith, 1986). For the 24 stations, rainfall from tropical cyclones is about 19% of August through October rainfall and 7% of annual precipitation. Also, tropical cyclones cause rainfall approximately 1 day $yr^{-1}$ and, therefore, account for approximately 14% of rainfall $yr^{-1}$.

Extreme precipitation in the Southwest United States is possible from cut off low-pressure systems, either alone or in conjunction with tropical cyclones (Douglas, 1974; Hansen and Shwarz, 1981). These systems form during breakdown of low-pressure troughs and may meander across the Southwest United States for several days. The peak months for cutoff lows are April and October, with minimal occurrences in July and August (Webb and Betancourt, 1990). The co-occurrence of cut-off lows and tropical cyclones is the prototype for probable maximum precipitation during the warm season for the Colorado Plateau (Hansen and others, 1981).

## Rainfall Variability

*Spatial Variability*

Rainfall frequency and amount vary spatially across the southern Colorado Plateau. Average warm-season rainfall of combined 1- and 2-day categories ranges from 50 mm in the low-lying country surrounding Lake Powell to more than 150 mm in the elevated country in the southwest portion of the plateau (Figure 4a). Rainfall frequency follows a similar pattern. The average number of days with rain of the combined category ranges from about 4 $yr^{-1}$ in the Lake Powell area to more than 10 $yr^{-1}$ in the southwest corner of the area (Figure 4b). This variation is close-

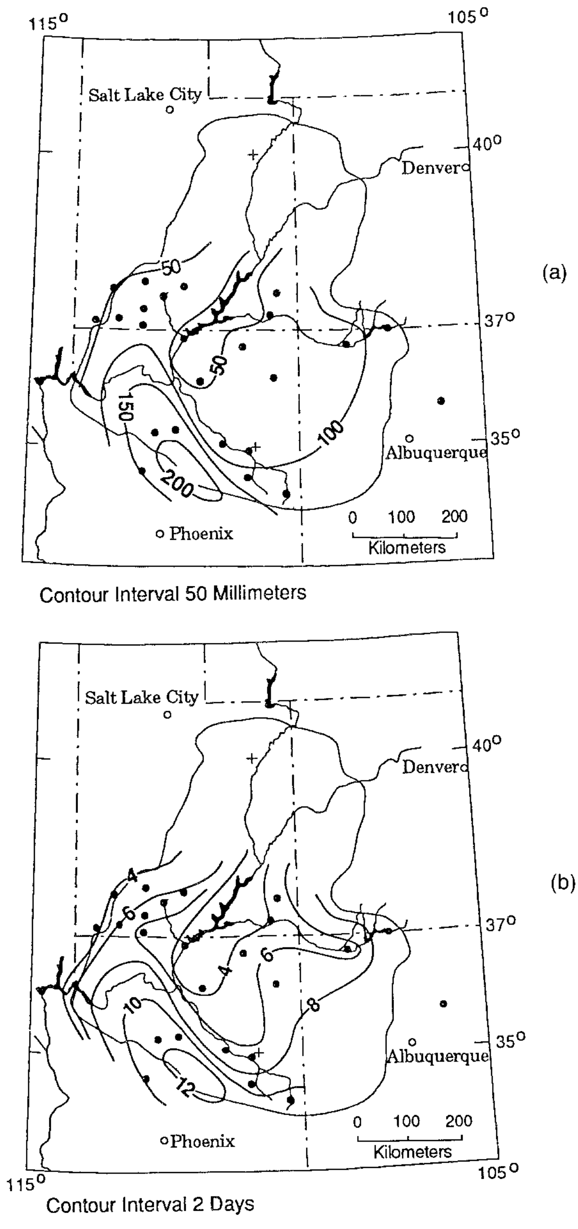


Fig. 4. Maps showing average annual warm-season rainfall total and frequency for the combined 1- and 2-day category. (a) Isohyets and (b) Isopleths of days with rain. Solid circles are long-term weather stations used in analysis.

ly related to elevation, which decreases from the southern rim of the plateau to the valleys of the Colorado, Little Colorado, and San Juan Rivers. Moreover, the variation ranges over a factor of 2–3, requiring the use of the SAI for regional comparison.

*Relation of Total Rain to Frequency of Rain*

Rainfall frequency is well correlated with total seasonal rainfall at the 24 stations (Table II). On average, frequency of rain accounts for about 85, 94, and 86% of the variation of total rain for the 1-, 2-, and 1- and 2-day categories. Figure 5a–c shows the SAI of total rainfall as a function of SAI of rainfall frequency. Figure 5d shows 2-day rain as a function of 1-day rain. These indices (Figure 5d) are not well correlated; one-day rainfall accounts for only 37% of the 2-day rainfall variation, in part due to a trend in decreasing frequency of 2-day rain through time.

TABLE II: Squared Spearman correlation coefficient of 1-, 2-, and combined 1- and 2-day frequency of rain with corresponding rain total

| Station | 1-Day | 2-Day | 1 & 2-Day |
|---|---|---|---|
| | Arizona | | |
| Chinle | 0.91 | 0.98 | 0.89 |
| Fort Valley | 0.85 | 0.91 | 0.92 |
| Holbrook | 0.90 | 0.95 | 0.92 |
| Kayenta | 0.90 | 0.97 | 0.92 |
| Lees Ferry | 0.87 | 0.97 | 0.85 |
| Prescott | 0.78 | 0.94 | 0.84 |
| Snowflake | 0.80 | 0.90 | 0.79 |
| Springerville | 0.86 | 0.86 | 0.86 |
| Tuba City | 0.87 | 0.99 | 0.79 |
| Williams | 0.81 | 0.80 | 0.82 |
| Winslow | 0.85 | 0.98 | 0.88 |
| | New Mexico | | |
| Bloomfield | 0.89 | 0.94 | 0.92 |
| Dulce | 0.81 | 0.95 | 0.88 |
| Santa Fe | 0.73 | 0.92 | 0.83 |
| | Utah | | |
| Alton | 0.80 | 0.88 | 0.73 |
| Blanding | 0.87 | 0.93 | 0.87 |
| Bluff | 0.83 | 0.98 | 0.84 |
| Cedar City | 0.88 | 0.96 | 0.86 |
| Escalante | 0.86 | 0.96 | 0.88 |
| Kanab | 0.90 | 0.98 | 0.90 |
| Panguitch | 0.88 | 0.94 | 0.90 |
| St. George | 0.88 | 0.98 | 0.88 |
| Tropic | 0.90 | 0.96 | 0.87 |
| Zion N.P. | 0.87 | 0.97 | 0.89 |
| **Average** | **0.85** | **0.94** | **0.86** |
| **Standard deviation** | **0.05** | **0.05** | **0.05** |

Rainfall frequency of the composite data is well correlated with total rainfall (Figure 5a–c). The relatively small unexplained variation of total rainfall at the individual stations (Table II) as well as the unexplained variation of the composite data (Figure 5a–c) probably results from random errors and variation of rainfall intensity. Nonetheless, total rainfall is closely related to the number of days with rain, which average 7 $yr^{-1}$. Englehart and Douglas (1985) also found high correlation between frequency of rain and total rainfall, although their data suggest that total rainfall is a power function of frequency. These results suggest that warm-season rainfall of the southern Colorado Plateau is related to the persistence of synoptic conditions that enhance the frequency of rain.

*Temporal Variability*

Time series of the SAI for the three rainfall categories are shown in Figure 6. The SAI have considerable interannual variation that is caused primarily by local orographic factors and, to a lesser extent, by the variable number of reporting stations (Figure 2). The principal changes of warm-season rainfall occur mainly after the early-1930s to early-1940s. These changes are an increased occurrence of dry

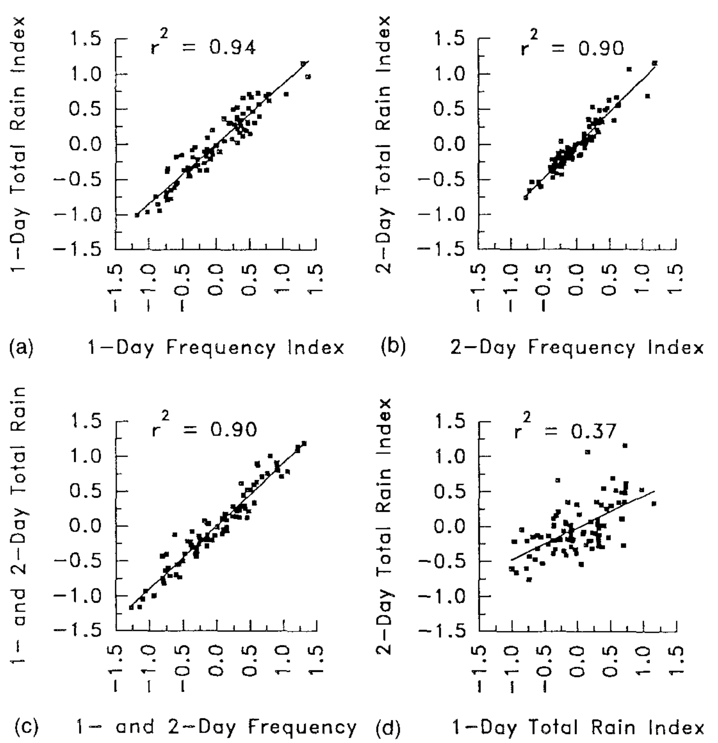


Fig. 5. (a–c) Relation of total-rain index to rainfall-frequency index. (d) Relation of 2-day total rain index to 1-day total rain index.

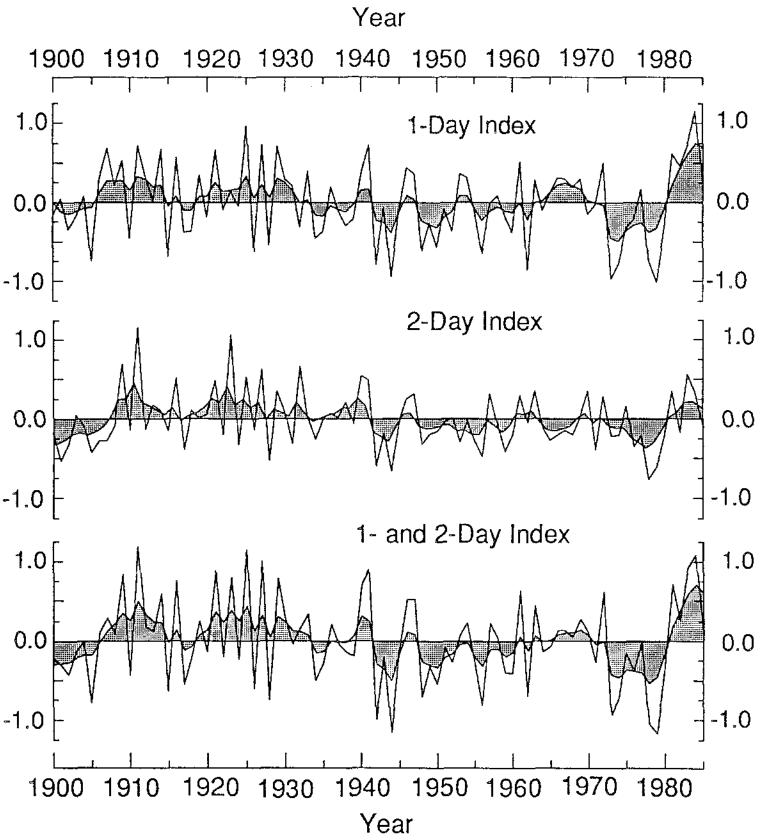


Fig. 6. Time series of total rain of three frequency categories expressed as a standardized anomaly index, 1900–85. Line with pattern is the series smoothed using locally weighted regression (Chambers and others, 1983).

years and a decreased occurrence of wet years, particularly of the 2-day rainfall category. The net effect is generally reduced warm-season rainfall beginning in the early 1930s to early 1940s that continued until 1980 (Figure 6).

Further consideration of Figure 6 shows that the period from 1900–85 has about five distinct episodes with different rainfall characteristics. (1) An early episode from 1900–1906 had normal to below normal rainfall. (2) From about 1907–33 the pattern was dominated by large amplitude, bi-seasonal variation with rainfall typically normal to above normal in all categories, except for 1910, 1915, 1917, 1926, and 1928. (3) A relatively short, episode from about 1934–41 was characterized by below normal to normal rainfall in the 1-day and 1- and 2-day categories, except for the unusually wet years during the ENSO conditions of 1940–41. This episode, which is contemporaneous with the 'Dust Bowl' era of the midwest (Bark, 1978), is considered a transition between the preceding relatively wet period and the following relatively dry period. (4) The recent episode from about 1942–80 was characterized by several periods of persistent below-normal rainfall particularly in the 2-day category, and the driest period of the century (up to 1985) was 1973–80. Rainfall varied only slightly below normal, however, from about 1964–71. (5) Finally, 1981–84 was unusually wet compared with the preceding 80 years.

**Relation of Historic Rainfall Variability to ENSO and Tropical Cyclones**

The historic variability of warm-season rainfall on the southern Colorado Plateau (Figure 6) is probably related to low-frequency changes in oceanic processes and general atmospheric circulation. In particular, warm-season rainfall is affected by ENSO conditions (see Enfield, 1989, for a review of the affects of ENSO on climate), dissipating tropical cyclones, and intensity of monsoonal moisture flow into the region. Moreover, these phenomena are interrelated (see Carleton and others, 1990). We were unable to evaluate variations in the intensity of monsoonal moisture flow during the period of interest, because upper-atmospheric data necessary to evaluate this moisture source is not available before 1945 (Carleton, 1987).

Other workers have found that ENSO conditions influence Colorado Plateau climate (Ropelewski and Halpert, 1986; Andrade and Sellers, 1988). Ropelewski and Halpert (1986) report that precipitation in the 'Great Basin', which on their maps includes the Colorado Plateau, is typically above normal from April-October during warm ENSO conditions. Andrade and Sellers (1988) found that ENSO affected rainfall in Arizona and New Mexico during fall and spring. According to Ropelewski and Halpert (1986), a physical explanation of this enhancement is difficult to develop, but the ENSO related signal is in phase with the bimodal precipitation cycle of the region (Figure 3). The increased precipitation during ENSO conditions is probably related to direct or short-term effects of the subtropical jet stream and above-average sea-surface temperatures in the eastern North Pacific Ocean.

Specifically, historic variation of the southern Colorado Plateau warm-season SAI is related to ENSO conditions. The ENSO chronology of Webb and Betancourt (1990), which is a composite of chronologies by Rasmussen (1984) and Quinn and others (1987), was used to compare the occurrence of ENSO conditions with warm-season rainfall anomalies of the Colorado Plateau. Of the 35 years with ENSO conditions, 29% were above normal, 54% were normal, and only 17% were below-normal. Using Quinn and others (1987) chronology, 47% of years with 'strong or very strong' ENSO conditions ($n = 15$) were above normal, 27% were normal, and 26% were below normal. Thus, the typical result of ENSO conditions is normal to above normal warm-season rainfall.

Finally, SAI is also weakly correlated with warm ENSO conditions, as measured by the index of Line Island precipitation (ILP). The ILP is expressed as a percentage of normal precipitation for a group of six islands in the equatorial Pacific Ocean (Wright, 1984). During warm ENSO conditions, the ILP is large and rainfall is high. Correlations between the SAI and ILP for 1-day rainfall for July, August, September, and October are $r = 0.269 (P < 0.014)$, $r = 0.217 (P < 0.050)$,

$r = 0.235 (P < 0.034)$, and $r = 0.301 (P < 0.006)$, respectively, where $P$ is the probability that no correlation exists. Similar results were obtained for 2-day and 1- and 2-day rainfall. A seasonal ILP was formed by averaging the July, August, September, and October values. Correlations between the seasonal SAI and ILP for 1-, 2-, and 1- and 2-day rainfall are $r = 0.271 (P < 0.014)$, $r = 0.232 (P < 0.036)$, and $r = 0.294$ ($P<0.007$), respectively. Thus, the null hypothesis that warm-season rainfall is unrelated to warm ENSO conditions as measured by the ILP cannot be rejected, although the relation is weak.

Changes in frequency of ENSO conditions before and after 1940 that might explain the historic rainfall variation are somewhat equivocal. The average recurrence interval between moderate to strong ENSO conditions is 3.2 and 3.9 years for 1900–42 and 1943–86, respectively, but addition of 2 years of ENSO conditions to 1943–86 yields an equal recurrence interval. Michaelsen (1989), however, found that 1917–41 was a high amplitude ENSO phase, a pattern recurring every 80–100 years that is dominated by strong to moderate ENSO events. This phase evidently decreased into a low amplitude phase dominated by weak ENSO events after the early 1940s. Thus, the relatively weak ENSO events of the post-1940 era are probably a factor in the decreased warm-season rainfall.

The historic variation of warm-season rainfall is partly related to changes in rainfall from dissipating tropical cyclones. Rainfall from tropical cyclones was generally average or above average between 1923–41 and below average between 1953–71, as illustrated in Figure 7, which is a tropical cyclone rainfall anomaly index. The largest anomalies – 1939, 1951, 1972, and 1983 – occur in years with ENSO conditions, suggesting that the number of tropical cyclones is related to ENSO conditions.

## Discussion and Conclusions

The frequency of days with rain and the amount of warm-season rainfall was persistently less after the early 1930s on the southern Colorado Plateau, except for a

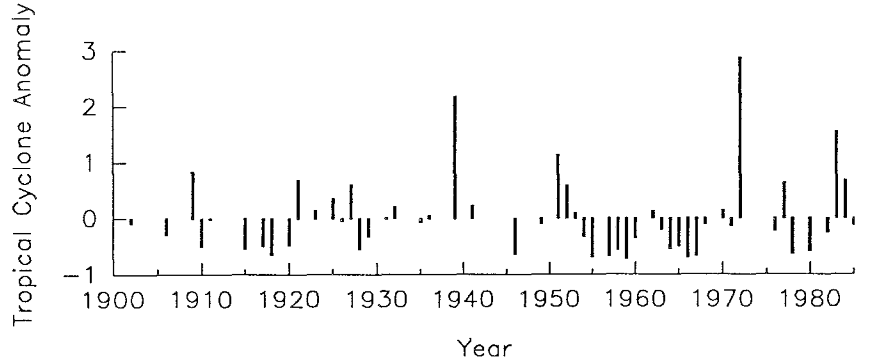


Fig. 7. Time series of tropical cyclone rainfall anomaly index, 1900–85.

resurgence of rainfall caused by the moderate to strong ENSO conditions of 1939–41 that delayed the hydrologic and geomorphic results until the early 1940s. The principal longterm change is the lack of anomalous rainfall of the 2-day category after about 1940, although 1-day and combined 1- and 2-day rainfall categories were also affected. Generally, the occurrence of anomalously dry seasons increased, and the occurrence of anomalously wet seasons decreased after the early 1940s.

These findings are broadly consistent with other studies of total annual precipitation and of seasonal rainfall frequency. In an analysis of rainfall intensity of a small basin on the southern plateau, Balling and Wells (1990) found that the frequency of intense storms decreased after the early 1930s. The 'Dust Bowl era' of the 1930s, particularly 1934–40, has become the standard for defining drought (Bark, 1978). This drought was widespread in the western United States (Felch, 1978), and it also affected southern Colorado Plateau warm-season rainfall between about 1934–39 (Figure 6). A second drought affected the Southwest at various times between 1942–56, reaching its greatest areal extent in 1950 and 1952–54 (Thomas, 1962, p. A-15). During this drought, water resources of the Colorado Plateau were reduced such that annual runoff was less than average for all except two years between 1943–56 (Thomas and others, 1963). Warm-season rainfall during this time was typically below normal except for 1946–47 and possibly 1953–54. This drought, however, evidently did not affect southern Arizona where monsoonal rainfall increased (Carleton and others, 1990). Finally, a recent drought affected most of the western United States from 1976–77 (Matthai, 1979). During these two years, warm-season rainfall was below normal (1976) to normal (1977), but as previously discussed 1973–80 was the driest period of the century.

The decreased frequency of rain after the 1930s to early 1940s probably resulted from four interrelated factors. These are decreased rainfall from tropical cyclones, decreased intensity of monsoonal flow, an increase in incidence of meridional circulation, and changes in the intensity of ENSO conditions. Changes in monsoonal flow are difficult to evaluate because of the lack of upper-atmosphere pressure data before 1945. However, long-term, possibly interrelated changes of ENSO conditions, atmospheric circulation, and tropical cyclones are reasonably well known and would produce the documented changes of southern Colorado Plateau rainfall.

Advection of moisture from dissipating tropical cyclones is facilitated by cut off low-pressure systems and low-pressure troughs in the upper atmosphere (Smith, 1986). Therefore, long-term changes in the frequency of meridional circulation might alter warm-season rainfall on the southern Colorado Plateau. Dzerdzeevskii (1970) reported an increase of meridional flow between 1930 and 1960 over the Northern Hemisphere. This general increase in meridional circulation, coupled with a decreased variability of ENSO conditions after 1930, could have contributed to decreased rainfall frequency on the Colorado Plateau in the middle part of the 20th century, as shown in Figure 6.

Warm ENSO phases influence southern Colorado Plateau weather. During these events, the frequency of rain is generally normal to above normal. Several studies have shown that the occurrence and (or) intensity of ENSO conditions were higher in the early part of this century (Enfield, 1989; Michaelsen, 1989; Webb and Betancourt, 1990). Webb and Betancourt (1990) found that variability of ENSO conditions from 1900–32 and 1960–86 was significantly greater than variability from 1930–60. The increased variability of ENSO conditions would cause high inter-annual variability and generally higher rainfall on the Colorado Plateau in the early part of the century. The shift to higher variability of ENSO in the late 1950s to early 1960s (Webb and Betancourt, 1990) apparently did not significantly increase rainfall on the Colorado Plateau, although the very strong ENSO conditions of 1982–83 (Philander, 1990, pp. 38–42) form a spike in the SAI comparable in magnitude with 1939–41 (Figures 6, 7).

Finally, the hydrology and geomorphology of Colorado Plateau rivers were quite likely changed by the warm-season rainfall variations described here. The high runoff, sediment load, and erosion of the early part of this century were probably related to the frequent rainfall of that era, although poor land use was probably a contributing factor. During the latter part of the century, less frequent rain and conservation efforts reduced runoff, sediment loads, and erosion. If the influence of human activity was minor relative to that of rainfall variation, then it is reasonable to conclude, at least for a 50–100 year time scale, that increased warm-season rainfall is associated with frequent large floods and increased erosion. In contrast, reduced warm-season rainfall is associated with less frequent large floods and reduced erosion.

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