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The twentieth-century pluvial in the western United States

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[1] Persistent, widespread wet conditions in the western United States in the early twentieth century have been noted in a number of studies. Here, we investigate the character of this pluvial, which covered a roughly 9-state region and lasted about 13 years. Paleoclimatic data used to evaluate the period in a long-term context indicate that the twentieth-century pluvial is an extremely rare event, as previous studies have suggested, even when assessed in the context of a 1186-year reconstruction of regional drought. An analysis of twentieth-century climate data, characterizing precipitation seasonality, intensity, and frequency, shows that the pluvial was primarily a result of winter season, heavy to moderately heavy precipitation events, during a handful of extremely wet winters. Temperatures were also anomalously cool. The combination of duration, intensity, and spatial extent make this an unusual event, not only in twentieth century, but in the past 12 centuries. **Citation:** Woodhouse, C. A., K. E. Kunkel, D. R. Easterling, and E. R. Cook (2005), The twentieth-century pluvial in the western United States, *Geophys. Res. Lett.*, *32*, L07701, doi:10.1029/2005GL022413.

1. Introduction

[2] A period of persistent and widespread wet conditions in the western U.S. in the first two decades of the twentieth century has been noted in a number of studies [e.g., *MacDonnell et al.*, 1995; *Fye et al.*, 2003; *Webb et al.*, 2004]. This period is of particular interest because it formed the basis for water resource allocations in the Colorado River basin in the 1920s, a baseline that is now acknowledged to be much higher than the twentieth-century average [*MacDonnell et al.*, 1995]. The goal of this paper is to assess the singularity of this early twentieth-century pluvial by 1) evaluating the event in the context of the past 12 centuries using paleoclimatic data, and 2) describing the characteristics of the precipitation related to the increased moisture, relative to the full twentieth-century. New data, which have recently become available, are used to analyze this event in the context of both paleoclimatic and twentieth-century time frames. A recent study [*Kunkel et al.*, 2003] found that the U.S national frequency of short duration extreme precipitation events was quite high in the early part of the twentieth century. One unanswered question to be addressed here is whether precipitation extremes made an important contribution to the pluvial.

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[3] We have adopted the spatial and temporal definition of the twentieth-century pluvial based on *Fye et al.* [2003], who defined essentially a nine-state area (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming) with anomalous moisture from 1905–1917, based on an analysis of gridded summer Palmer Drought Severity Index (PDSI). This pluvial region is further confirmed through our analysis of annual precipitation at 136 climate stations from the National Weather Service cooperative observer network with at least 50 years of data including at least 10 years during the pluvial period (Figure 1). Precipitation anomalies for 1905–1917 are positive for the great majority of stations throughout this region. The magnitude exceeds one standardized anomaly for many stations and is about two standardized anomalies at a few stations, very large values when considering that these are averages over a 13-yr period.

2. The Twentieth-Century Pluvial in a Paleoclimatic Context

[4] An examination of this early twentieth-century period of persistent and abundant moisture from a paleoclimatic perspective suggests that it is indeed an unusual occurrence in the context of past centuries. An analysis of a reconstruction of Colorado River flow at Lees Ferry indicated the period from 1907 to 1930 was the longest period of predominantly high flow in the 450-year record, with 13 years of consecutively above average flow from 1906–1918 [*Stockton and Jacoby*, 1976]. *Fye et al.* [2003] analyzed gridded reconstructed Palmer Drought Severity Index (PDSI) [*Cook et al.*, 1999] and found the period from 1905–1917 to be the most extreme wet period covering the nine-state region in the past 500 years (see *Fye et al.* [2003, Figures 4a and 4b] for maps of this region from instrumental and tree-ring data).

[5] A new tree-ring based set of drought reconstructions provides an even longer context with which to evaluate the twentieth-century pluvial. *Cook et al.* [2004] generated an updated and expanded set of gridded summer PDSI reconstructions for North America from a network of moisture-sensitive tree-ring chronologies. In this paper, the grid points that fell within the nine-state pluvial region (46 grid points, 2.5 by 2.5 degree spacing) were averaged together to create a regional drought index from AD 818 to 2003 (Figure 2). Gridded reconstructions were extended to 2003 by scaling the reconstructions to match instrumental records from 1979–2003 [*Cook et al.*, 2004]. Over most of the study area, the PDSI reconstructions explain 60% or more of the variance in instrumental data.

[6] The regional drought reconstruction indicates a period of seven consecutive years of wet conditions from 1911–1917. This is not the longest period of consecutive years of positive PDSI, as there are two nine-year runs

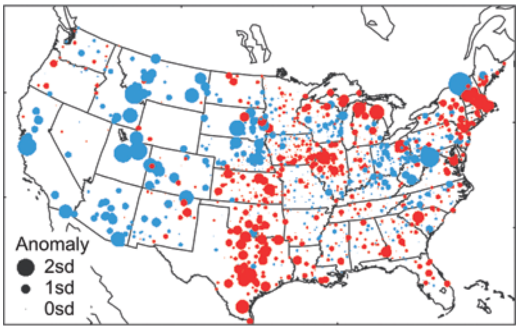

Figure 1. Annual standardized precipitation anomalies averaged for the period 1905–1917 for stations with at least 50 years of precipitation data and at least 10 years during 1905–1917. This includes 1284 U.S stations with 136 stations in the nine-state pluvial region. Blue (red) circles indicate positive (negative) anomalies.

Table 1. Periods With Consecutive Years of Reconstructed Positive PDSI, and Their PSDI Sums and Average Annual Values

Number of Years	Period	Cumulative Sum	Average Annual Value
9	1076–1084	8.99	1.000
9	1112–1120	12.86	1.429
8	1424–1431	6.46	0.807
7	1615–1621	11.52	1.645
7	1911–1917	12.22	1.746

(1112–1120, 1076–1084), one eight-year run (1424–1431), and one other seven-year run (1615–1621). However, when the cumulative sums of PDSI for the years in these periods and the average annual values are assessed, the twentieth-century period has the 2nd largest cumulative sum and largest average annual value (Table 1), indicating the intensity of this wet period relative to other longer periods. Running sums of ten-year periods, ranked, show that the four highest ten-year sums in this 1186-year record ended in 1915, 1916, 1914, 1917. The three highest running 20-year sums are also included in the twentieth-century pluvial, ending in 1924, 1923, and 1922.

3. Climatic Analysis of the Twentieth-Century Pluvial

[7] The modern climatic analysis of the twentieth-century pluvial was based on instrumental data from a set of 91 climate stations (representing 40 of the 65 climate divisions in the 9-state region) from the National Weather Service cooperative observer network with less than 10% missing daily precipitation data for the period 1895–2002. This includes a new data set (described by *Kunkel et al.* [2003]) from the National Climatic Data Center that increases the density of stations over what had previously been available. All analyses followed a similar procedure designed to produce a regional average not over-weighted toward areas with a higher density of stations. First, individual station data were analyzed. Next, climate division values were obtained as simple averages of the analysis products for the individual stations in a climate division. Third, state values were obtained by averaging the climate division values weighted by the climate division area. Finally, regional averages were obtained by averaging the state values weighted by the state area. Two of the station analysis products were seasonal and annual time series of total precipitation. A third analysis examined the distribution of precipitation for 5-day periods. For this latter product, the precipitation total was calculated for each 5-day period for 1895–2002. For each season and year, the precipitation was accumulated in one of four bins defined as follows: 0–12 mm, 12–25 mm, 25–50 mm, and >50 mm. The long-term average precipitation in each of these categories is roughly equal, each representing about 25% of the total precipitation.

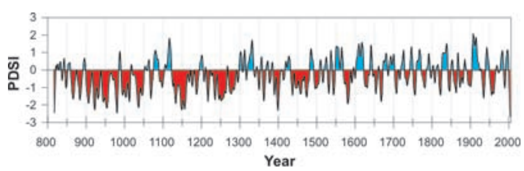

Figure 2. Regional reconstruction of the PDSI, AD 818–2003, smoothed with a 10-year spline. Red shading indicates negative values and dry years, and blue indicates positive values and wet years.

3.1. Characterizing Pluvial Period Rainfall and Temperature

[8] Figure 3 shows a time series of total annual precipitation for the 9-state western U.S. region, smoothed by a 13-yr moving average filter, the window length of 13 years corresponding to the length of the anomaly identified in the *Fye et al.* [2003] PDSI analysis. The early part of the time series is characterized by the highest values of the period, around 440 mm yr^{-1} or about 10% above the long-term mean of about 400 mm yr^{-1}. This period is followed by a substantial decrease of about 80 mm to a minimum in the 1930s. The 1940s were somewhat wetter and were followed

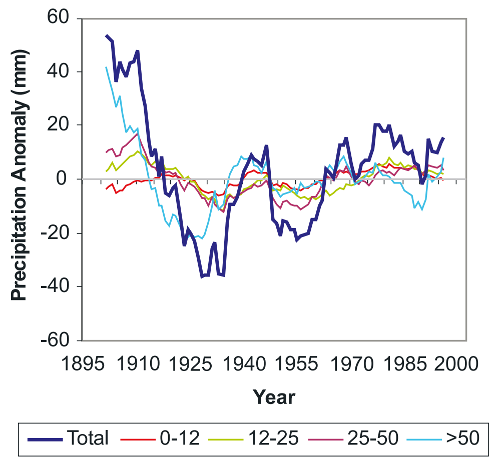

Figure 3. Time series of 13-yr moving average annual precipitation for 9-state western U.S. region. The 13-yr moving average values are plotted at the mid-point of the window. Time series are plotted for total annual precipitation and precipitation for 5-day periods occurring in one of 4 different categories: 0–12 mm, 12–25 mm, 25–50 mm, and >50 mm. Precipitation values are expressed as departures from normal.

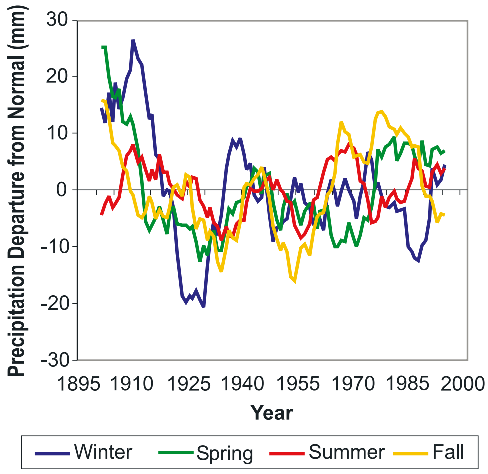

Figure 4. Time series of 13-yr moving average precipitation for the four seasons in the 9-state western region, expressed as a departure from normal.

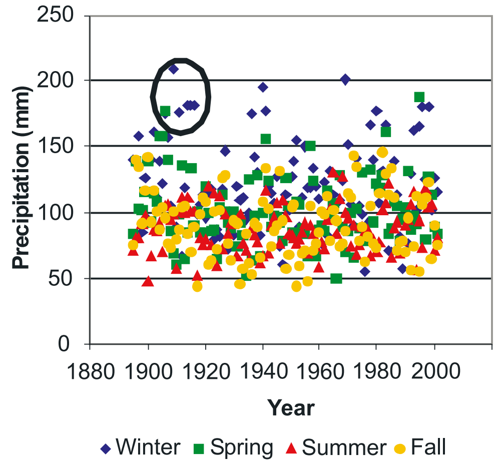

Figure 5. Seasonal precipitation (mm) averaged for the 9-state western U.S. region. Black oval highlights cluster of high values during the pluvial.

by a drier period in the 1950s. Since the 1960s, long-term fluctuations have been relatively small.

[9] The contribution of light, moderate, heavy, and very heavy precipitation to the total anomalies differs with a greater contribution from heavier events (Figure 3). In particular, 5-day periods with >50 mm contribute about 75% to the total anomaly early in the pluvial. Averaged over the entire pluvial, events of 25–50 mm and >50 mm each contribute about 40% while events in the 12–25 mm category account for the remaining 20% with no contribution from the 0–12 mm category. The very heavy (>50 mm) events are both more frequent and larger in magnitude during the pluvial. Throughout the early period, accumulated precipitation in the light event category of 0–12 mm is near the long-term average. The seasonal contribution to the anomalies (Figure 4) indicates that this was primarily a cold season phenomenon. Early in the pluvial, the contribution of spring to the anomalies is greatest, but there are substantial contributions from winter and fall. Averaged over the entire pluvial, the greatest contribution occurs during the winter, representing about 60% of the total anomaly. Smaller positive anomalies also occurred in the spring (early in the pluvial) and summer, but not in the fall.

[10] An inspection of individual seasonal values (Figure 5) indicated that a few extreme events were very important. During the pluvial, a cluster of very high primarily winter values stands out. In fact, seven of the 15 wettest seasons (Table 2) occurred during 1905–1916, including the wettest (the winter of 1908–09). The accumulated anomaly during these seven seasons was about 450 mm, accounting for almost all of the accumulated anomaly of 470 mm during 1905–1916. In order to determine whether the analysis was sensitive to the relatively small number of stations used, the missing data criterion was relaxed to include all stations with at least 20 years of data. This increased the number of stations available during the pluvial to 370. Although the rankings of individual years shifted somewhat and the rank of winter 1910–11 fell from 14th to 31st, the other six were ranked in the top 16 and the conclusions about the highly unusual nature of the period are the same.

[11] This was also an anomalously cool period. Temperature anomalies (compared to 1971–2000 normals) averaged −0.8°C during 1905–1917 for annual temperature. Seasonal anomalies were also all negative (−0.9°C in winter, −0.8°C in spring, −1.0°C in summer, and −0.4°C in fall).

3.2. Summary of Climatic Analysis Results

[12] These results show that the wet conditions during the pluvial were primarily a cold season phenomenon. There were several extremely wet winters, including the wettest season on record, and a very wet spring. Early in the pluvial, there was the consecutive occurrence of the 14th (winter 1905–06) and tenth (spring 1906) wettest seasons on record. Near the end of the pluvial, the 3 consecutive winters of 1913–14, 1914–15, and 1915–16 were the sixth, seventh, and fifth wettest seasons on record. This clustering of seasonal extremes is perhaps the most striking climate feature of the pluvial. Another noteworthy feature is the dominant contribution of moderately heavy and heavy 5-day periods to the precipitation anomaly. In fact, 5-day periods with light precipitation did not increase at all. Cooler temperatures likely promoted slower melting of accumulated snowpack and lower evaporation rates.

Table 2. Fifteen Wettest Seasons in the Western U.S., 1895–2002[a]

Season	Precipitation (mm)
winter 1908–09[a]	209
winter 1968–69	201
winter 1939–40	196
spring 1995	189
winter 1915–16[a]	182
winter 1913–14[a]	182
winter 1914–15[a]	182
winter 1997–98	181
winter 1995–96	180
spring 1906[a]	178
winter 1940–41	178
winter 1979–80	177
winter 1910–11[a]	176
winter 1905–06[a]	176
winter 1935–36	175

[a]Seasons occurring during the pluvial.

[13] The spatial extent of this pluvial also makes it a remarkable event. In one additional analysis, with instrumental PDSI grid point data for the 9-state area, a drought area index was generated for the years 1900–2003 [*Cook et al.*, 2004]. The index, reflecting the numbers of grid points with positive PDSI values for each year, shows that 80% of the grid points reflected above average moisture in nine of the 13 years of the pluvial. These sustained and widespread wet conditions do not occur at any other time in this record. This PDSI-based drought area index, reflecting moisture in primarily winter, spring, and summer, indicates the extensive nature of this event. The footprint of the pluvial is also somewhat unusual in that it encompasses a region that tends to have a dipole response to ENSO, a major driver of winter precipitation variability across much of this region.

4. Summary

[14] The results of this work, using newly available data sets, provide a longer and more detailed perspective on the rarity and characteristics of the twentieth-century pluvial. Paleoclimatic analyses indicate that this may have been the most extreme pluvial period, with regard to duration, extent, and intensity, that has occurred in nearly 12 centuries. The main contributing precipitation features appear to be winter season, moderately heavy to heavy events, as measured in 5-day periods. Although the pluvial spans more than a decade, the total precipitation anomaly was in large part due to a handful of extremely wet seasons during this time. Anomalously cool temperatures contributed to the effects by slowing snowmelt and reducing evaporation. The spatial extent is also unusual, given the duration of the event. A statistical recurrence interval could be calculated for this event, but an understanding of the causes of these anomalies during this period is needed to determine the conditions under which a similar event could occur again. Because of the important role the early twentieth-century pluvial has played in the allocation of water resources in the western U.S. [*MacDonnell et al.*, 1995], this information may be important for future decision making and effective water management.

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