A Catalogue of 20th and 21st Century Droughts for the upper Colorado River Basin

A Final Report to the Bureau of Reclamation, Lower Colorado Region

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Table of Contents

Drought Catalogue

1. Introduction
   1.1. Overview
   1.2. Analysis Approach and Data
   1.3. Definition of drought
2. Comparison of All Drought Periods
3. Catalogue of Droughts
   3.1. 1930s Dust Bowl Drought
   3.2. The 1950s drought: a La Niña drought
   3.3. The 1960s drought: the “sleeper” drought
   3.4. The 1970s drought: Short and Severe
   3.5. The 1980s-90s drought
   3.6. 2000s drought – a global warming drought?
4. Summary of Main Features of Droughts
5. Literature Cited
6. Figures and Tables

Appendix A: Correlation Maps for Circulation Indices with Sea Surface Temperatures, 500 mb Geopotential Heights, and Divisional Precipitation Data

Appendix B: References and Sources for Indices and Climate Data

Appendix C: North American Drought Dipole and its Influence on Colorado River Flow
(Annotated Presentation from AGU 2010; separate PowerPoint file: AppendixC.pptx)

Appendix D: Characterizing and visualizing drought onset for the Colorado River (Brewster Malevich)
1. Introduction

1.1. Overview

This study addresses the nature and potential causes of drought in the upper Colorado River basin (UCRB). Upper basin headwaters yield the majority of total Colorado River flow, and understanding drought and its causes in this region is of critical interest. Between 2000 and 2010, all but two years of annual streamflow at Lees Ferry have been below average, with the lowest value (25% of average) occurring in 2002. The flows have been above average in 2005 and 2008, but just barely so, at 113% and 108% of average, respectively (pers. comm. R. Callejo, 8/30/10). The 10-year period, 2000-2009 has been the driest in the natural flow record for Lees Ferry going back to 1906, which has brought drought to the forefront as a topic of concern. Since this analysis, 2011 has had above average flows, and 2012 is projected to be below average again.

Causes of drought in the UCRB have been linked to El Niño/Southern Oscillation (ENSO), but studies have failed to find a consistent relationship between runoff and ENSO events in the upper basin. There is some there is evidence for responses within the basis, with opposing responses to ENSO in the southern (San Juan River) and northern (upper Green River) portions of the basin (Cayan and Webb 1992, Hidalgo and Dracup 2003, Woodhouse et al. 2006). Overall, the upper basin appears to be transitional with respect to the impacts of ENSO, at least over the period of the gage record (e.g., Woodhouse et al. 2006, Wise 2010). A detailed analysis of how other ocean/atmospheric features impact the basin has not yet been performed, although continental-scale analysis indicates the basin is within a region in which cool season drought is associated with decadal and multidecadal-scale North Pacific/North Atlantic variability (e.g., Enfield et al. 2001, Cayan et al. 1998, McCabe et al. 2004, Moe et al. 2008).

This descriptive report documents the characteristics of upper Colorado River basin drought, the circulation patterns that accompany these droughts, and their possible causal mechanisms on an individual drought event basis. This catalogue of droughts provides evidence for a range of drought characteristics and accompanying atmosphere/ocean circulation features, and a potential baseline for evaluating future droughts.

1.2. Analysis Approach and Data

This report addresses drought and its causes by first identifying a set of six droughts in the UCRB, and examining sub-basin gage records to evaluate the spatial and temporal characteristics of each event. The sequence of flows by year, and the seasonal precipitation and temperature anomalies for the entire basin above Lees Ferry, as well as the sub-basins, are examined. To investigate possible causal mechanism, the circulation patterns accompanying drought conditions are assessed by examining global patterns of pressure (500mb geopotential heights) and sea surface temperatures (SSTs). In addition, a set of circulation indices that reflect tropical and extratropical conditions is compiled in order to get a sense for the state of global oceans and atmosphere during these droughts.
For streamflow, the 1906-2008 natural flow data were used, generated by Reclamation, for nine upper basin tributary gages including: Green R./Green River WY, Green R./Green River UT, Yampa R., Colorado R./Cisco, Gunnison R./Crystal, Gunnison R./Grand Junction, Dolores R., San Juan R./Navajo, and San Juan R./Bluff, as well as for the Colorado at Lees Ferry. For the Lees Ferry gage, we have added the years 2009-2010 as the natural flows became available.

Monthly climate data (total precipitation and average temperature, inches and degrees F) from the gridded PRISM data set (Daly et al. 2008) were downloaded for each sub-basin via the WestMap web site (http://www.cefa.dri.edu/Westmap/). Seasonal total precipitation and average temperatures were based on the water year climatology and the seasonality of moisture delivery. The standard four seasons were not used because they split the water year. Instead, a three-season year was used. Winter (October-February) represents the onset of the water year and the heart of the winter. A spring season, March-May, was differentiated from winter because the delivery of moisture may include upslope storms from east of the basin. The warm season (June-September) represents a period largely dominated by convective storms and warmer temperatures. To simplify circulation analyses, we focused on the winter season. While the months of highest precipitation tend to be March and/or April in most of the sub-basins (Figure 1), the link between seasonal precipitation totals and respective sub-basin water year flow are highest for winter in all sub-basins (Figure 2). The spring season can be very important in certain years, and when winter conditions do not appear to explain drought conditions for a given year, we have also examined the spring conditions.

Seasonal composite maps for the six droughts were also generated from PRISM data using the Westmap mapping tool, with a baseline of 1906-2006 (the original study period at the onset of this project). Occasionally, to show US-wide patterns of precipitation for characterizing larger patterns of drought, US Divisional climate data were used, in the form of standardized precipitation anomalies based on 1895-2000. The slightly variable baselines were not intentional but a function of the flexibility of the mapping tools for the various datasets.

Sea surface temperatures (Smith et al. 2007) and 500mb geopotential height data and images (NCEP/NCAR Reanalysis Dataset, Kalnay 1996) were obtained from the NOAA/ESRL Physical Sciences Division (Boulder, Colorado) web site at http://www.esrl.noaa.gov/psd/. The 500mb data start in 1948, and in these analyses, anomalies are based on the 1981-2010 period. The extended SST data start in 1854, and the same baseline, 1981-2010, was used for consistency.

Circulation indices that describe conditions in the North Pacific (Aleutian Low Index, North Pacific Index, and Pacific North American Index), the equatorial Pacific/ENSO region (Nino 3.4, Pacific Decadal Oscillation –and N. Pacific also), and the northern hemisphere high latitudes (Arctic Oscillation and the Northern Atlantic Oscillation) were also used for this analysis (Table 1). The Atlantic Multidecadal Oscillation (AMO) was considered, but it since only represents three phases during the timespan of these UCRB droughts (with two droughts bridging phase changes), it is mostly included for comparison purposes. We examined indices for the same three seasons generated from the climate data, but focused on the index values for October-February, except for the case of the Aleutian Low Index, which was only available as an annual average). For ease of comparison, we smoothed all index time series, except AMO (which is in either positive or negative), with a three-year running average. Appendix A includes more detailed information on the relationships between most of these circulation indices, global patterns of SST and 500mb geopotential heights, and US precipitation patterns (Divisional data), by season.
It is important to note that correlation maps represent average conditions, and that associations between ENSO, for example, and US precipitation for a given year or set of years can vary from this average. The 30-year climatology normal period is used for these maps, but in two cases, maps for two different time periods are shown to illustrate range of variability in spatial patterns. The differences in correlation patterns may due to the decadal scale variability imbedded in some of these circulation features (e.g., Pacific Decadal Oscillation, precipitation patterns show for two phases, Figure A4) or may be due to other factors (including random variability, e.g., Figure A13). These maps, as well as the time series in Figure 5 also show that there are relationships between a number of these indices. In particular the, signature of ENSO in the equatorial Pacific sea surface temperatures is evident in the North Pacific and tropical Pacific indices, indicating the relationship between circulation in this region, primarily in winter and spring. The two North Pacific indices, the Aleutian Low (ALI) and the North Pacific Index (NPI), measure different features, but the time series are essentially mirror images of each other (Figure 5). Both the Artic Oscillation (AO) and the Northern Atlantic Oscillation (NAO) are shown. These are highly correlated with each other, but the correlation patterns indicate the AO is much more relevant for western North America. The AO is much shorter than the NAO; thus both are shown.

The objective of the discussion of the droughts in the context of circulation patterns and indices is not to provide a detailed analysis of the possible causal mechanism over the evolution of the drought but to summarize and highlight the main features that seem to characterize each drought. In all cases, there is no single driver of drought conditions, but I have attempted to describe some conditions that may have been important.

1.3. Definition of drought

Drought identification was based on the natural flow record for Lees Ferry, 1906-2010 (Russ Callejo, personal communication). A drought was defined as a period of consecutively below-average years broken by less than two above-average flow years at Lees Ferry (based on the 1906-2006 mean flow). Initial analyses were based on the years 1906-2006, but 2007-2010 were added as the natural flow estimates became available. Seven droughts were initially identified: 1931-40, 1943-46, 1950-56, 1959-69, 1972-77, 1988-96, and 2000-10. After evaluating these periods, we decide to drop the 1943-46 drought because of its mildness and lack of impact on the Colorado River system.

2. Comparison of All Drought Periods

Table 2 shows the time span of the six droughts, their duration, the number of single years with above-average flow within the drought, cumulative deficits, and average annual deficits. Plots showing the sequence of flows during these droughts are shown in Figure 3. The distribution of below-average flows over the years of each drought across the sub-basins is shown in Figure 4.

A comparison of the six droughts indicates a range of characteristics (Table 2, Figure 3). The longest drought occurred during the period 1959-1969, but as the current drought unfolds, as of 2010, it now matched the length of the 1960s drought. The 1960s drought was broken by two non-drought years, as has the current drought. The longest sequence of unbroken drought is five consecutive years, which occurred during the 1930s, 1980-90s, and current droughts. The largest cumulative deficit has occurred over the current drought (based on 2000-2010), at over 32 MAF.
or nearly 3 MAF annually. The second largest deficit occurred during the 1959-1969 period of
drought, with a total deficit of 26.4 MAF. The second largest average annual deficit of about 2.5
MAF occurred during the both the 1950s and 1930s droughts. The sequences of drought years
show a large range of variability, with some events displaying persistent drought at the onset,
like the 1980-90s and the current droughts, while others experience intermittently dry years
before plunging into more sustained drought conditions (e.g., 1930s, 1950s). In some cases,
severe drought is alleviated by several well-timed above-average flow years (e.g., 1960s, current
drought).

The distribution of drought conditions across the upper basin indicates a large degree of spatial
homogeneity (Figure 4). Drought years and breaks are often widespread throughout much of the
basin, but most remarkably so during the current drought. Regional differences are apparent in
the 1950s and 1970s droughts, when the Green River basin experienced a later onset of drought
conditions. More spatial variability of drought coverage is evident among basins during the
1930s and 1960s, perhaps because of their length. In both cases, the San Juan River basin (upper
in particular) had a relatively greater number of breaks during these periods of drought.

An examination of the circulation indices and their behavior during these six periods of drought
reveals a picture of variable ocean/atmosphere conditions (Figure 5). The three North Pacific
(Aleutian Low, North Pacific, and PNA) indices vary in a coherent way as expected, but indicate
a mixture of positive and negative conditions over any given drought. This is also the case for
the tropical Pacific (Nino 3.4 and PDO) and northern high latitude (NAO, AO) indices, as well
as the Atlantic multidecadal index.

In summary, this initial assessment indicates no clear picture of a condition or set of conditions
that are common to these droughts. Each drought appears to have different characteristics, and is
accompanied by a variety of ocean/atmosphere conditions. This necessitates a more detailed
look at each of the six droughts to see if it is possible to discern any commonalties among them
or among a subset of the droughts.

3. Catalogue of Droughts

3.1. 1930s Dust Bowl Drought

While the geographic heart of the Dust Bowl Drought was in the central Great Plains, the upper
Colorado River basin did feel the effects of this drought. The single year, 1934, stands out as the
year with the most widespread drought conditions across the entire US, back to at least 1700
(Cook et al. 1999). This drought extended from 1931-1940 in the upper Colorado River basin,
broken by two non-drought years, 1932 and 1938 (Figure 6). The most severe drought years
were 1931 and 1934, whereas flows in 1936 and 1937 were just below average at Lees Ferry.
Across the upper basin, flow conditions were fairly homogeneous, with most sub-basins also
experiencing a break in drought conditions in 1936, as well as in 1932 and 1938. The Dolores
and San Juan basins had a longer break, with non-drought conditions from 1935/36 to 1938
(Figure 4).

Seasonal precipitation deficits were most consistent, especially for winter, in the White/Yampa,
Colorado headwaters, and Gunnison basins (Figure 7). The precipitation deficits in the Green
River basin diminished after 1935 for at least some seasons (summer and to some extent, spring).
In the San Juan basin, winter precipitation was below average for all years except 1932 and 1937. Temperatures across the basin were mixed, but were above average for at least one season every year (again, except for 1932). In particular, 1934 and 1938 stand out for their warmth in all seasons and across all sub-basins. In contrast, 1933 is notable for cold temperatures in winter and spring across the UCRB. Spatially, the 1930s winter season had the most complete drought coverage (although absent in the upper Green River basin). Summers were relatively wet in the middle and southern part of the UCRB, while in spring, drought conditions were focused in the lower half of the headwaters basin and in the Gunnison and Dolores basins (Figure 8).

Composite maps of global patterns of seasonal sea surface temperatures (SSTs) suggest generally cool conditions in the equatorial Pacific and warm conditions in the North Atlantic for all seasons from 1931-1940 (Figure 9). In spite of cool equatorial Pacific SSTs, this pattern is not indicative of cool ENSO (see Appendix A). An inspection of winter precipitation anomalies across the US for strongest years of drought in the UCRB (1931, 1934, 1940) (Figure 10) and circulation indices (Figure 5), indicates El Niño conditions in 1931 with the UCRB acting like the Pacific Northwest (i.e., dry conditions), a weak La Niña in 1934 (UCRB coinciding with the typical Southwest US drought response to La Niña), and near neutral ENSO conditions in 1940, with a with a strong Aleutian Low in all these years. In 1940, much of the Great Basin and west was wet, and the UCRB reflected drought conditions in the central and eastern U.S. (Figure 10).

Over the course of this drought, ocean/atmosphere patterns were variable (except for the AMO) with Niño 3.4, N. Pacific, and N. Atlantic indices changing signs over the 10-year period (Figure 5). Hoerling et al. (2009) and Cook et al. (2009) suggest the 1930s cannot be explained by SST anomalies, but instead may have been due to random atmospheric variability exacerbated by dry soils, at least with respect to drought conditions in the northern Great Plains. These suggestions coincide with results shown here, which also indicates a mix of ocean/atmosphere conditions over the course of the drought. The variable UCRB response to ENSO during this period of drought is a demonstration of the transitional nature of the basin with respect to ENSO impacts.

3.2. The 1950s drought: a La Niña drought

The 1950s drought is well-known for its impacts in the southwestern US and the southern Great Plains. It is considered the worst 20th century drought in the US Southwest (Fye et al. 2003). The 1950s drought has been used by some Colorado water providers as the worst-case drought for planning. This drought, defined here as 1950-1956, was most severe (lowest flow) from 1954-1956, and broken by just one non-drought year, 1952 (Figure 11). Sub-basin flows were almost uniformly below average except for the Green River basin, which experienced above average flows in the first two years, and in the last year (Green River near Green River WY only) (Figure 4).

Precipitation deficits were also quite consistent across the sub-basins, with most basins experiencing below-average precipitation across most seasons, again, excepting 1952 (Figure 12). Seasons with above-average precipitation tended to be only slightly above average, again except for 1952 when the winter was quite wet in several sub-basins. As in the 1930s, temperatures were mixed. One of the driest years, 1954, was also remarkably warm in all seasons. In general, winter temperatures tended to be above average during the drought years, while the spring seasons tended to be cooler in at least some basins. Spatially, winter drought
impacted the southern part of the UCRB most strongly, while impacts were more uniform over spring and summer (Figure 13).

This drought is perhaps the most “straightforward” drought in the UCRB, in terms of likely causal mechanisms. Composite SST and 500 mb patterns and circulation indices indicate two La Niña events, in 1950-51 and 1955-56 (Figure 14, left). The PDO phase was negative, which has been shown to enhance the impact of La Niña events (Gershunov and Barnett 1998) (Figure 5). The intervening drought years, 1953-1954, were accompanied by high pressure over western North America, a condition which is conducive to widespread drought (Figure 14, lower right). The AMO remained positive through this period of drought.

### 3.3. The 1960s drought: the “sleeper” drought

Although the severity of the 1950s drought is widely acknowledged (e.g., Fye et al. 2003) and has often been used as a worst-case drought for planning, a drought that followed in the 1960s is rarely mentioned. This 11-year drought spanned 1959-1969, but was broken by two well-placed wet years, which is likely the reason its impact was not more significant (Figure 15). Without those two breaks, an extended run of below-average flows would have followed the 1950s drought, broken by wet conditions in just two years, 1957 and 1958.

Over this interval of drought, the lowest flow years were 1959-1961 and 1963-1964. The years 1962 and 1965 brought relief to these intervals of drought, but relatively moderate drought conditions returned in 1966 and lasted for three more years. In the final year (1969), flow was nearly average (Figure 15). Drought conditions were fairly uniform in the flows across the UCRB, but more consistently dry at the Dolores and lower San Juan (Bluff) basin gages, and somewhat less so at the upper Green River and upper San Juan gages (Figure 4).

Precipitation conditions during the 1960s were seasonally variable across the basin. Spring was most consistently dry throughout the period, while winter precipitation was more often in deficit during the first half of this drought (Figure 16). Of the two wet years, only the winter precipitation was above average (in most cases) in 1962, while all seasons were wet in 1965. Temperatures were most notably above or near average in all seasons from 1959-61 and in 1963. After this, springs and summers were much cooler than average across the basin in 1964-1965 and 1968, alleviating drought conditions somewhat, with modestly above-average temperatures in the intervening years. These patterns, when averaged for the years of the drought, indicate that the most widespread drought conditions occurred in spring (Figure 17). Winters were also dry, although conditions were less severe, and the San Juan basin actually showed positive precipitation anomalies for this drought period. Summers had above-average precipitation, except in the San Juan basin.

During the first part of this drought (1959-1964), circulation was characterized by a ridge of high pressure centered over the northwest US coast (Figure 18, left), promoting dry winter conditions across much of the region. The PNA was strongly positive, with enhanced meridional flow. Low pressure over the Aleutian Islands, coincided with a negative North Pacific Index to help set up this strong PNA flow. This pattern broke down in spring 1964-65. There was a brief El Niño event in 1966 (Figure 18, right), during which the UCRB behaved like the Pacific Northwest in the winter (e.g. experienced drought), although drought conditions became west-wide in spring 1966. Circulation indices indicate a switch in conditions after 1966 (Figure 5), with North
Pacific indices and the PNA reversing signs (as does the AMO), which is reflected in the 500 mb geopotential height pattern for 1967-1968 (Figure 19, left; compare with Figure 18, left). ENSO conditions remained relatively neutral. While the western US experienced variable conditions over these two years, the central US and southern Plains are quite dry, along with much of the UCRB in spring (Figure 19, right). High pressure over the central and southeastern states in spring may be partially responsible for these conditions, possibly causing a ridge that pushed the southwesterly jetstream over the UCRB and east.

In summary, winter drought during the beginning of this period of drought was influenced by high pressure imbedded in meridional flow. The second half of the drought seems to have been influenced by a different set of circulation patterns than the first part. Neither ENSO nor AMO appears to be a consistent feature influencing drought.

3.4. The 1970s drought: Short and Severe

By our definition of drought, the 1970s drought extended from 1972-1977 (Figure 20). However, below-average flows in 1972 and 1974 were separated with above-average flows in 1973 and 1975, and even these two dry years were only slightly below average. This sequence of moderately wet and dry years probably helped buffer the system from the impacts of the severe drought years of 1976 and 1977. The single water year, 1977, was the driest value on record for many gages in the UCRB, including the value for 2002. It remains the worst-case scenario for a single year, but because it was preceded by moderate years and the severity was short-lived, its impact on the Colorado River system was more limited than it might have been. Flows across the basin were fairly coherent for the entire drought event, except at the Green River gages, which did not reflect drought conditions until 1976 (upper Green River) or even 1977 (lower Green River) (Figure 4), and the Yampa, to a lesser degree.

Precipitation was near average or moderately below average in spring and summer in the lower Green, Gunnison, and Colorado headwaters basins through 1976 (Figure 21). Winter conditions were average or slightly below over this period of drought, except in 1973, which was wet to very wet in all sub-basins. Across the entire region, spring and especially winter precipitation was quite low in 1977, although all sub-basins experienced nearly average to slightly above-average summer precipitation. Temperatures over this period of drought were most remarkable for their cool anomalies, particularly in 1973-1975. Moderately warm springs occurred across the basin in 1972 and 1974. In the extremely dry year of 1977, summers were warm in all basins, while winter temperatures ranged from near average to moderately warm everywhere except the San Juan basin. Spring temperatures were very close to average almost everywhere in 1977. Taken as a six-year average, the spatial pattern of precipitation shows the springs and summers were drier than average in most sub-basins, but particularly in the central and southern parts of the UCRB. In contrast, winter precipitation over this period was wetter than average in the southern part of the basin (Figure 22). Clearly, with this degree of averaging, the dry winter of 1977 is not evident.

With respect to circulation, most of the drought period (1973 to 1976) was characterized by coherence in the North Pacific indices and the PNA, which suggested a weakened Aleutian low and a reverse PNA pattern (Figure 5). Composite SST and 500 mb geopotential height maps for winter 1972-1976 show a high pressure anomaly slightly south of the Aleutian Islands, low pressure centered over western North America, and a distinctly cool tropical Pacific (especially
in 1976, but beginning to break down by spring), spreading poleward along the west coasts of North and South America (Figure 23, left). This is in sharp contrast with the SST and 500 mb patterns for winter 1977, which show a warm tropical Pacific, strengthened Aleutian low, and high pressure over western North America (Figure 23, right). Along with the tropical Pacific indices, the PDO also switches sign between 1976 and 1977, from a mode that enhances La Niña impacts (negative phase) to one that enhances El Niño (positive phase). The La Niña-enhanced conditions prior to 1977 coincide with low flows in 1972, 1974, 1976, when the UCRB was behaving like the US Southwest (Figure 24, left). This pattern broke down in 1977, when an area of intense drought becomes centered over the Pacific Northwest, as would be associated with El Niño events, but also it extended throughout the western and central US (Figure 24, top right). The widespread drought conditions of the 1977 water year are not characteristic of El Niño, and indeed, SSTs are only weakly warm in the tropical Pacific (Figure 23, right). Instead, drought in 1977 is more likely attributable to a strong Aleutian Low directing the storm track over a high pressure anomaly that extends from northwestern Canada to southern California (Figure 23, right). The PNA index value for the winter of 1977 is the highest on record, an indication of the extreme meridional flow pattern. Throughout the 1970s, the AMO was in its cool phase, and AO was positive over the middle years of this drought period, suggesting a jetstream contraction northward.

3.5. The 1980s-90s drought

The drought of the late 1980s and early 1990s was one of the worst on record for a large portion of California. Although it was one of the longer droughts in the UCRB (1988-1996), it was relatively moderate in terms of cumulative deficits (Table 2). The nine-year drought was broken by two above-average flow years and ended with nearly average conditions in 1996, all of which helped temper conditions in the second half of the drought. The core of the drought consisted of five consecutive years of below-average flows (1988-1992), which is tied with the 1930s and 2000s drought for the longest run of consecutive drought years (Figure 25). This drought was one of the most spatially consistent, with all sub-basins sharing below- and above-average years until 1996, when all but the Dolores and San Juan gages show above-average flows (Figure 4).

The precipitation patterns by season and basin confirmed that the heart of the drought was the first five years, except for the San Juan basin, which showed a more mixed pattern (Figure 26). Seasonally, winter precipitation was most consistently below average. Spring also shows fairly consistent deficits over the first five years, especially in the lower Green, Yampa/White, and Colorado headwaters basins. The non-drought years of 1993 and 1995 are marked by wet springs. Temperatures are very mixed seasonally and spatially for most basins, but warm anomalies are notably more extreme than cool anomalies (except for 1993) (Figure 26). Spring and summer have the greatest positive anomalies, while winter anomalies of either sign tend to be more moderate. The upper Green River basin, in particular, showed consistently above-average temperatures over this period of drought (except for 1993).

When composite maps for seasonal precipitation are examined, winter precipitation anomalies are mixed across the basin. Summer is more consistently dry, while spring shows mostly above-average precipitation for all but the upper San Juan basin (Figure 27). This pattern is likely attributed to the wet springs of 1993 and 1995.
Over the course of the core years of this drought, 1988-1992, tropical Pacific SSTs swing from conditions reflecting El Niño to La Niña and back to El Niño between 1988 and 1992 (Figure 28, left). Precipitation patterns in 1988 and 1992 show dry conditions in the upper part of the UCRB, and a larger pattern of drought indicative of the Pacific Northwest response to El Niño (Figure 29; conditions similar for spring). In two these winters, significant drought extends from central California to the northern Great Plains, dipping into the Great Basin and the northern portions and headwaters of UCRB. In 1989-1991, an extended period of relatively cool SSTs in the tropical Pacific may have helped promote drought (Figure 28). However, widespread winter drought across much of the western US in these years may be more attributable to the 500 mb pattern of pressure, in which an elongate pattern of high pressure from Asia to the Atlantic forced the jet stream north across northern North America. This pattern is supported by a negative PNA pattern and a weakened Aleutian Low, conditions similar to those in the first part of the 1970s drought. Also similar to the 1970s, the AO is positive, with zonal flow tracking in a more poleward direction. The AMO is negative during most of this drought, though it switches phase near end.

3.6. 2000s drought – a global warming drought?

The 2000s drought began in the fall of 1999 (Pielke et al. 2005), extended through 2010 (water year flows in 2011 were on the order of 120% of average, but 2012 will be below average again). The first five years of the drought were the most severe (2000-2004), characterized by one of the lowest flow years on record, 2002 (2nd only to 1977), and one of longest runs of consecutive drought years (shared with 1933-37 and 1988-1992) (Figure 30). After this run of low flow years, the remainder of the drought was broken by two years of slightly above-average flows (2005, 2008). Flows at Lees Ferry from 2006-2010 varied from moderately above to moderately below average. The pattern resembles the 1980s-90s drought to some extent, although the second half of this drought has been more prolonged. In addition, the magnitudes of the flows differ, with cumulative deficits over the 5-yr low flow period being more severe during the 2000s drought (46.8 MAF in 1988-92 versus 54.4 MAF in 2000-05), and the above-average year flows were not as high as the 1980-90s wet years. Flows across the basin were uniformly below average in 2000-2004 (Figure 4). Above-average flows brought some relief in 2005, especially in the Dolores and San Juan gages, and in all but one of the Gunnison gages. Drought returned to all sub-basins except the White/Yampa basin in 2006, but was again below average in all basins in 2007. In 2008, all but the Green River sub-basins, had above average flows.

Precipitation deficits over the first five years of this drought were most consistent in the Gunnison, White/Yampa, and upper Green River watersheds, especially in winter and spring (Figure 31). The lower Green and San Juan watersheds experienced slightly above-average conditions in the winter of 2001. While the winter-spring of 2002 was uniformly the driest year in all basins, the spring of 2003 showed a slight recovery in the Colorado headwaters, likely the result of one upslope storm in March of that year. Precipitation in the second half of this drought period was mixed. The watersheds in the central part of the basin (White/Yampa, Colorado headwaters, Gunnison, and the lower Green to some extent) experienced mostly above-average winter (and sometimes summer) precipitation from 2006-2009, while spring precipitation was mostly below average. The upper Green River basin tended to be drier or near average over this period, and the San Juan was quite mixed.
In general, the precipitation deficits do not stand out compared to those of other periods of drought, but what are anomalous are the temperature departures (Figure 31). Temperatures across nearly all seasons and all basins were consistently above average from 2000-2007. In 2008 and 2010, springs were cool and winters cool or near average. Summer temperatures stand out as being the most consistently above average in all basins throughout the 11-year period.

Spatial patterns of drought over the full drought period show a mix of conditions in winter, with fairly widespread drought in spring and summer (Figure 32). In contrast, the pattern of drought in winter for the first five year shows markedly drier conditions.

The first five years of this drought were initially characterized by cool tropical Pacific SSTs (2000-2002), which then switched to weak El Niño/warm tropical Pacific conditions in 2003-2004 (Figure 33), with indices of North Pacific circulation indicated a strong Aleutian low and meridional flow during this time. The switch in tropical Pacific conditions was accompanied by a corresponding switch in the sign the PDO (negative to positive) (Figure 5). Although cool SSTs characterized the winters of 2000-2002, the western North American pattern of precipitation did not reflect this in 2001, which was relatively wet in the Southwest and dry in the Pacific Northwest (a small center of low pressure on the coast of southern California appears to be responsible for this anomaly). The impact of El Niño conditions in 2003-2004 appear to have been weakened by a jet stream tracking far north (Figure 33, bottom right), agreeing with positive AO values (Figure 5). From 2006 to 2008, circulation indices fluctuated around zero, and composite SST and 500 mb maps for the dry years, 2006-2007 show no distinct patterns, except for a tongue of moderate high pressure extending across the North Pacific and into western North America (Figure 34). Conditions switched again between 2009 and 2010 from a weak to strong Aleutian Low, and from weak La Niña to weak El Niño conditions.

4. Summary of Main Features of Droughts

It is clear that the droughts of the UCRB are widely varied in terms of temporal and spatial characteristics. It is also obvious that a large number of circulation patterns and mechanism, and different sequences of these combine to produce multi-year droughts. In order to seek some clarity regarding common conditions that appear to accompany drought, composite maps of 500 mb and SSTs were generated for eight lowest flow years, that is, those years with flows < 10 MAF at Lees Ferry.

The composite maps indicate a distinctive 500 mb pressure pattern, but a much more variable pattern of SSTs (Figure 35). The 500 mb composite features a relatively strong Aleutian Low, a high pressure anomaly centered just east of the US west coast, and low pressure over northeastern North America. The pattern is reminiscent of the PNA pattern with a slight, but critical shift in the high pressure anomaly over western North America (Figure 36). In the PNA correlation field map, the high is centered over western Canada, a position north and east of that in the drought composite map. In the PNA, low pressure is centered in the southeastern US, while the in drought composite, this low is over northeastern North America. Thus, the Aleutian Low appears to be a common feature, but the position of the high pressure over the western US seems to be the critical feature for drought, and the pressure pattern is more of a wave train centered between 45º - 50ºN than a classic PNA pattern. The position of the Aleutian Low and the high pressure over the coast of western North America would result in a jetstream that is directed north above most of the western US. In addition, the position of the wave train suggests
the jetstream is contract toward the pole, leaving much of the western and central US below its track. Not surprisingly, these extreme low flow years are also severe drought years in other areas (Figure 37). A composite map of standardized precipitation anomalies for US Climate Divisions for these eight years shows widespread and severe drought from California, across the Great Basin, the northern and central Great Plains and most of the eastern US. Areas with above average precipitation are limited to the far Pacific Northwest and the Gulf Coast area from southern Texas to Florida.

The composite map of SSTs features a bulge of cool water off the coast of South American and just south of the equator, with little similarity to the classic ENSO pattern (Figure 35, right). The strongest anomalies are in the far northeastern Pacific with a small areas of cool SSTs south of the Aleutian Islands (perhaps a reflection of the low pressure), and in the southeast Pacific Ocean. The pattern in the North Pacific again, is just slightly reminiscent of the PNA SST pattern (Appendix A). The far northern and northeastern North Atlantic is warm, and the pattern is not similar to any of those of circulation indices.

These results suggest more dynamic atmospheric conditions that influence the polar jetsteam may be more likely to influence drought than the equatorial Pacific SST-driven conditions of ENSO. In addition, this also suggests that a variety of circulation influences could result in drought if they influence the jetstream in such a way as to set up the Aleutian Low and high over western North American in just the right way.

5. Literature Cited


Figures and Tables

Table 1. Circulation indices cited in this study, with climate variable measured, main region measured, and reference or source of data. Full references and links to data are listed in the Sources for Indices and Climate Data (Appendix B).

<table>
<thead>
<tr>
<th>Index</th>
<th>Climate variable measured</th>
<th>Region</th>
<th>References/source*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nino 3.4</td>
<td>Sea surface temperatures</td>
<td>Eastern Equatorial Pacific Ocean, 5°N-5°S, 170-120°W</td>
<td>Climate Prediction Center</td>
</tr>
<tr>
<td>Pacific Decadal Oscillation (PDO)</td>
<td>Sea surface temperatures</td>
<td>North Pacific Ocean, poleward of 20°N</td>
<td>Mantua et al. 1997</td>
</tr>
<tr>
<td>Aleutian Low</td>
<td>Sea level pressure (area)</td>
<td>North Pacific; Aleutian Low region</td>
<td>Beamish and Bouillon 1993</td>
</tr>
<tr>
<td>North Pacific Index</td>
<td>Sea level pressure</td>
<td>North Pacific, 30°N-65°N, 160°E-140°W</td>
<td>Trenberth and Hurrell 1994</td>
</tr>
<tr>
<td>Pacific North American pattern (PNA)</td>
<td>500 mb geopotential heights</td>
<td>North Pacific-North America</td>
<td>Wallace and Gutzler 1981</td>
</tr>
<tr>
<td>Northern Atlantic Oscillation (NAO)</td>
<td>Sea level pressure</td>
<td>North Atlantic; Iceland/Azores</td>
<td>Wallace and Gutzler 1981</td>
</tr>
<tr>
<td>Arctic Oscillation (AO)</td>
<td>Sea level pressure</td>
<td>Northern hemisphere poleward of 20°N</td>
<td>Thompson and Wallace 1998</td>
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<tr>
<td>Atlantic Multidecadal Oscillation (AMO)</td>
<td>Sea surface temperatures</td>
<td>North Atlantic, poleward of the equator</td>
<td>Enfield et al. 2001</td>
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Table 2. Droughts identified based on Lees Ferry WY flow, 1906-2010.

<table>
<thead>
<tr>
<th>Years</th>
<th>Longest period of consecutive drought</th>
<th>Duration</th>
<th>Wet yrs within drought</th>
<th>Cumulative deficit*</th>
<th>Avg. annual deficit*</th>
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<tbody>
<tr>
<td>1931-1940</td>
<td>1933-1937</td>
<td>10</td>
<td>2</td>
<td>-25,468,660</td>
<td>-2,546,866</td>
</tr>
<tr>
<td>1943-1946</td>
<td>1945-1946</td>
<td>4</td>
<td>1</td>
<td>-6,027,184</td>
<td>-1,506,796</td>
</tr>
<tr>
<td>1950-1956</td>
<td>1953-1956</td>
<td>7</td>
<td>1</td>
<td>-17,667,811</td>
<td>-2,523,973</td>
</tr>
<tr>
<td>1972-1977</td>
<td>1976-1977</td>
<td>6</td>
<td>2</td>
<td>-10,489,992</td>
<td>-1,748,332</td>
</tr>
</tbody>
</table>

*Units in acre feet
Figure 1. Average total monthly precipitation by sub-basin, based on 1906-2007. Data from PRISM.

Figure 2. Correlations between Lees Ferry WY flow and sub-basin precipitation, by season, 1906-2007. Data from PRISM.
 Runs of below-average flows broken by less than 2 yrs above-average flows

Figure 3. Upper Colorado River Basin Droughts; Lees Ferry WY in MAF, 1906-2010. Red line indicates period of drought.
Figure 4. Above and below average flows indicated by blue (above) or red (below) by basin and sub-basin, and for years of the six identified droughts. Data from Reclamation, estimated natural flows.
Figure 5. Ocean/atmosphere circulation indices derived from sea surface temperatures (SSTs) and atmospheric pressure, for the winter season, Oct-Feb (except annual for Aleutian Low Index), plotted as 3-year running averages. The general regions in which they primarily operate are shown on the right. Indices The Atlantic Multidecadal Oscillation is plotted by phase (yellow = negative, red = positive)
Figure 6. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Figure 7. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches. Temperatures in the White/Yampa and the Colorado Headwaters in 1934 are slightly off the scale in the graph.
Figure 8. Composite precipitation maps, by season, over the years of the drought (1931-1940). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.

Figure 9. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C for the years of the drought, by season (shown as departures from climate normal period, 1981-2010).
Figure 10. Precipitation anomalies for US Climate Division and SST maps, Oct-Feb for 1931, 1934, 1940.
Upper Colorado River Basin Droughts
1950-1956

Figure 11. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Figure 12. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches.
Figure 13. Composite precipitation maps, by season, over the years of the drought (1950-1956). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.

Figure 14. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter season (Oct-Feb), and years specified (shown as departures from climate normal period, 1981-2010).
Figure 15. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Figure 16. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches.
Figure 17. Composite precipitation maps, by season, over the years of the drought (1959-1969). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.

Figure 18. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter and spring, and years specified (shown as departures from climate normal period, 1981-2010).
Figure 19. Composite maps of 500 mb geopotential height maps and precipitation anomalies for US Climate Division for winter and spring, 1967-1968.
Figure 20. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Figure 21. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches.
Figure 22. Composite precipitation maps, by season, over the years of the drought (1972-1977). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.

Figure 23. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter season (Oct-Feb), and years specified (shown as departures from climate normal period, 1981-2010).
Figure 24. Standardized precipitation anomalies, US Climate Division data for selected seasons and years.
Figure 25. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Figure 26. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches.
Figure 27. Composite precipitation maps, by season, over the years of the drought (1988-1996). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.

Figure 28. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter season (Oct-Feb), and years specified (shown as departures from climate normal period, 1981-2010).
Figure 29. Composite precipitation maps, by season, over the 1988-1992. Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin.
Upper Colorado River Basin Droughts

2000-2010

Figure 30. Colorado River at Lees Ferry flow in MAF. Red line indicates period of drought.

Temperature and Precipitation 2000-2010

Figure 31. Seasonal temperature and precipitation anomalies (based on 1906-2006) by basin for the years of the drought period. UGR = upper Green River, WY = White/Yampa, LGR = lower Green River, CH = Colorado headwaters, GN = Gunnison, SJ = San Juan (data from PRISM data by HUC). Units are in Fahrenheit and inches.
Figure 32. Composite precipitation maps, by season, over the years of the drought (2000-2010). Shown as percent of average, based on 1906-2006. Data from PRISM. Circle indicates upper Colorado River basin. Subset composite for 2000-2004, winter is also shown.
Figure 33. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter season (Oct-Feb), and years specified (shown as departures from climate normal period, 1981-2010).

Figure 34. Composite maps of global patterns of seasonal sea surface temperatures (SSTs) in degrees C and 500 mb geopotential heights in meters, for the winter season (Oct-Feb), and years specified (shown as departures from climate normal period, 1981-2010).
Figure 35. Top: composite maps for the Lees Ferry WY flows < 10 MAF (8 years) for 500 mb geopotential heights (meters) and SSTs (degrees C) (Oct-Feb, departures based on 1981-2010 climate normals). Bottom: for comparison, correlation fields for Oct-Feb Nino 3.4 showing characteristic patterns in 500 mb geopotential heights and SSTs.
Figure 36. Top: composite maps for the Lees Ferry WY flows < 10 MAF, 500 mb geopotential heights (Oct-Feb, departures based on 1981-2010 climate normals). Bottom: for comparison, correlation fields for Oct-Feb PNA showing characteristic patterns in 500 mb geopotential heights and SSTs.
Figure 37. Composite map of standardized precipitation anomalies for US Climate Divisions for the 8 years with Lees Ferry WY flows < 10 MAF. Standardized values are based on 1895-2000.