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**Key Points:**
- When UCRB flow departs from precipitation, temperature is a major forcing
- Since 1988, flows have often been less than expected given winter precipitation
- Warm temperatures exacerbated modest precipitation deficits in the 2000s drought

**Supporting Information:**
- Texts S1 and S2, Figures S1–S8, Table S1, and Caption for Data Set S1
- Data Set S1

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# Increasing influence of air temperature on upper Colorado River streamflow

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**Abstract** This empirical study examines the influence of precipitation, temperature, and antecedent soil moisture on upper Colorado River basin (UCRB) water year streamflow over the past century. While cool season precipitation explains most of the variability in annual flows, temperature appears to be highly influential under certain conditions, with the role of antecedent fall soil moisture less clear. In both wet and dry years, when flow is substantially different than expected given precipitation, these factors can modulate the dominant precipitation influence on streamflow. Different combinations of temperature, precipitation, and soil moisture can result in flow deficits of similar magnitude, but recent droughts have been amplified by warmer temperatures that exacerbate the effects of relatively modest precipitation deficits. Since 1988, a marked increase in the frequency of warm years with lower flows than expected, given precipitation, suggests continued warming temperatures will be an increasingly important influence in reducing future UCRB water supplies.

## 1. Introduction

Understanding water resource responses to temperature, particularly in light of ongoing droughts and climate change, is critical for resource planning and management. Snow-fed rivers, a major water supply in the western United States (U.S.), are largely influenced by winter precipitation, but increasingly warmer temperatures are expected to play a role in water year runoff. In California, the recent and ongoing drought has mainly been attributed to precipitation deficits [*Mao et al*., 2015], although it is likely that temperatures have played an important role in exacerbating drought conditions [*Diffenbaugh et al*., 2015; *Shukla et al*., 2015; *Williams et al*., 2015]. In the Colorado River basin, warming temperatures have likely had a similar effect on drought conditions.

While modeling studies projecting the impacts of climate change on western water resources clearly foretell the critical role of warming temperatures in reducing Colorado River runoff [e.g., *Revelle and Waggoner* 1983; *Christensen et al*., 2004; *Christensen and Lettenmaier*, 2006; *Hoerling and Eischeid*, 2007; *McCabe and Wolock*, 2007; *Vano et al*., 2012], to date, observational studies present two perspectives: (1) that temperature is a minor component relative to precipitation and (2) that temperatures can impact the efficiency of runoff relative to precipitation, resulting in marked declines in streamflow. The dominance of precipitation variability as a driver of runoff relative to the effects of temperature variability across the coterminous U.S. and in western river basins has been well documented [*Wigley and Jones* 1985; *Gleick*, 1986, 1987; *Karl and Riebsame,* 1989; *Nash and Gleick*, 1991]. More recently, water balance modeling of hydrology with observed climate inputs confirmed this, indicating that virtually all annual runoff variability for the periods from 1900 and 1950 can be attributed to variations in precipitation, for all regions in the U.S., including regions that have warmed [*McCabe and Wolock*, 2011]. However, *Reynolds et al.* [2015] found that the frequency of intermittent stream drying in the upper Colorado River basin could only be explained by accounting for both temperature and precipitation. In addition, *Nowak et al.* [2012] found that the efficiency of runoff (annual flow relative to annual precipitation volume) in the upper basin may be impacted by underlying multidecadal temperature variability, independent from its relationship with precipitation [*Nowak et al*., 2012].

Along with temperature, antecedent moisture conditions may influence runoff. The role of soil moisture in upper Colorado River basin surface flows, particularly in the fall season prior to the snowpack accumulation season, has not been investigated although modeled soil moisture is used by the NOAA Colorado River Basin

Forecast Center in streamflow projections, particularly for fall base flow conditions, and research has suggested such a role elsewhere [*Merz et al*., 2006]. Modeling studies have used soil moisture as an indicator of drought [*Cayan et al*., 2010] as well as part of a suite of hydroclimatic variables with which to assess drought impacts from climate changes projected for the future in the Colorado River headwaters and elsewhere [e.g., *Cayan et al*., 2010; *Seager et al*., 2012; *Cook et al*., 2015]. Although soil moisture has been acknowledged as a potential source of runoff [*Seneviratne et al*., 2010], studies have not investigated an explicit role in streamflow generation.

Temperature, and perhaps antecedent moisture, may play a more critical role in situations where water supply closely matches or even exceeds demand, as is the case in the Colorado River basin [*McCabe and Wolock*, 2011]. In this basin, it may be possible to begin to detect what modeling studies project, linking observational study results with the changes projected for the future. Here we assess the contribution of temperature and antecedent soil moisture to water year (October–September) streamflow in the upper Colorado River basin (Figure S1 in the supporting information) over the period, 1906–2012. Specifically, we ask: What has been the contribution of temperature and prior fall soil moisture to total annual flow, during 20th to 21st century droughts? And over this period, are there indications that the contribution of temperature to total water year streamflow has been changing?

In this study, we take a straightforward approach using observation-based data for a perspective that encompassed the past 100 years. While there are a number of ways in which warming temperatures can directly or indirectly impact streamflow, including reduced accumulation and earlier melting of snowpack, earlier peak runoff, and less of the cool season's precipitation coming in the form of snow [e.g., *Mote et al*., 2005; *Kapnick and Hall*, 2011; *Knowles et al*., 2006; *Stewart et al*., 2005], we examine how the mean temperature averaged over the runoff period (March–July) and prior fall season (November) soil moisture modulate the influence of cool season precipitation (October–April) on annual streamflow. Our findings strongly suggest that warming is likely to be playing an increasingly important role in both dry and wet years. However, results for the role of soil moisture are less conclusive.

## 2. Data

Estimated natural flows for the Colorado River at Lees Ferry, representing streamflow for the upper Colorado River basin, were obtained from the Bureau of Reclamation, for the water years 1906 to 2012 (J. R. Prairie, personal communication, 2015). These data have had the effects of depletions, diversions, and reservoir operations removed. To represent basin-wide climate conditions, gridded total monthly precipitation and average monthly temperature ($4 \times 4$ km resolution) from the Precipitation-Elevation Regression on Independent Slopes Model [*Daly et al*., 2008] were averaged across the upper Colorado River basin. Targeted hydroclimatic variables for analyses were selected primarily on the basis of correlations of monthly data with Lees Ferry water year streamflow (Figure S2). October–April total precipitation was chosen as the season most closely associated with water year flow. For mean temperature, March, March–May, and March–July average temperature were selected as candidates. We also investigated the influence of antecedent (fall season prior to the winter snowpack accumulation season) moisture conditions, using October and November soil moisture storage from *McCabe and Wolock*'s [2011] monthly water balance model, as no long-term observations of soil moisture are available (Text S1).

The period of analysis was water year 1906–2012, constrained by the length of the estimated natural flow record. In most of the analyses, data were converted to percentiles to allow comparison between different metrics.

## 3. Quantifying Hydroclimatic Contributions to Water Year Flow

In order to assess the hydroclimatic contribution to water year streamflow, stepwise regression was used to estimate flows from cool season precipitation, runoff season temperature, and antecedent fall season soil moisture storage. The pool of candidate predictors included October–April total precipitation: March, March–May, and March–July average temperature and October and November soil moisture storage. The model was run on all years, 1906–2012, using an F-to-enter of 2.01 and an F-to-remove of 2.00. A model with three variables resulted, explaining 76% of the total variance in water year flow (Table 1a). The first predictor to enter was October–April precipitation, explaining 66% of the variance. March–July average temperature entered second, **e**xplaining 8% of the variance, and the third step was November soil moisture, explaining

**Table 1.** Stepwise Regression Results, 1906–2012, and Stepwise Regression Results, 1906–2012, but for the 30 Years in Which the Difference Between Water Year Flow and Cool Season Precipitation Is Greater Than 1 Standard Deviation

| Variable | Step | *R* | $R^2$ | $R^2$ Change | *F* | *p* Level |
|---|---|---|---|---|---|---|
| | | | *Stepwise Regression Results, 1906–2012* | | | |
| Oct–Apr *P* | 1 | 0.813 | 0.661 | 0.661 | 205.170 | 0.000 |
| Mar–Jul *T* | 2 | 0.859 | 0.738 | 0.077 | 30.472 | 0.000 |
| pNov soil | 3 | 0.871 | 0.758 | 0.020 | 8.442 | 0.004 |
| | | | *Stepwise Regression Results, 1906–2012, but for the 30 Years* | | | |
| Mar–Jul *T* | 1 | 0.647 | 0.419 | 0.419 | 20.190 | 0.000 |
| Oct–Apr *P* | 2 | 0.781 | 0.611 | 0.192 | 13.281 | 0.001 |
| Oct Soil | 3 | 0.831 | 0.691 | 0.081 | 6.802 | 0.015 |

just 2% of the variance. An additional model was generated, using the period 1960–2012, with very similar results (same predictors in the same order, but slightly more variance explained by cool season precipitation and soil moisture, with slightly less from temperature) (Table S1).

These results are in close agreement with *Nowak et al.* [2012] who reported that 70% of the total water year streamflow at Lees Ferry could be explained by temperature and precipitation. *Nowak et al.* [2012] used water year precipitation and residual temperatures (dependence on precipitation removed), and we obtained comparable results in an analysis using residual March–July temperatures and cool season precipitation. Results also are consistent with the findings of *Karl and Riebsame* [1989], *McCabe and Wolock* [2011], and others that precipitation is the dominant influence on streamflow over both the full instrumental period and the more recent decades.

## 4. Warm and Cool Droughts

While precipitation plays the dominant role in year-to-year streamflow variability, the effect of temperature on total water year flows may become more important during multiyear droughts. To investigate this, we examined droughts in the upper Colorado River basin and the associated values of October–April precipitation, March–July temperature, and prior November soil moisture. Drought was defined on the basis of water year flows at Lees Ferry and included spans of consecutive years below the long-term average broken by no more than 1 year with above average flow. Six periods were identified: 1931–1940, 1950–1956, 1959–1969, 1972–1977, 1988–1996, and 2000–2012. Percentile values for the hydroclimate variables were averaged over the years in these periods.

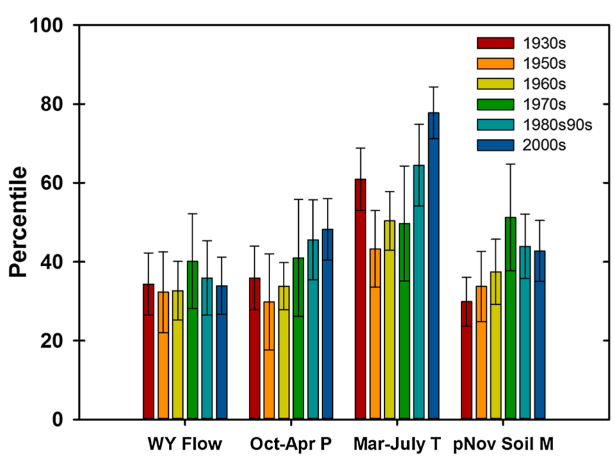


**Figure 1.** Comparison of hydroclimatic variables (Colorado River at Lees Ferry water year streamflow, October–April total precipitation, March–July average temperature, and prior November soil moisture) averaged for the years in each of six droughts in the upper Colorado River basin, percentile values with standard errors.

Average water year flows for all six drought periods fell between the 32nd and 40th percentiles, with the 1970s drought being the least severe (Figure 1). Values for cool season precipitation show greater differences between droughts. The 1950s drought was the most severe in terms of precipitation deficits (30th percentile), while the 2000s drought was the least severe (48th percentile). In contrast, March–July temperatures for these periods indicate that the 1950s was the coolest period, with average values just below the median, while the 2000s drought was the warmest at almost the 80th percentile. Since average flows were similar for these two droughts, it is likely that cooler temperatures in the 1950s help offset the greater precipitation deficits, and vice versa during the 2000s drought. The late 1980s through early 1990s drought also follows the pattern of the 2000s drought with modest precipitation deficits and higher temperatures. The 1930s drought is severe both in terms of precipitation deficits and warmth, though not as dry as the 1950s or as warm as the most recent two periods of drought. Soil moisture values were lowest during the 1930s drought, followed by the 1950s. These values were somewhat higher during the 1980s–1990s and 2000s droughts but still below the median. Only the 1970s drought period shows above median soil moisture, and with nearly median temperature and moderately low precipitation, together these may be responsible for the highest average flows of all the drought periods.

## 5. Temperature Moderates Relationships Between Cool Season Precipitation and Streamflow

Temperature can exacerbate or ameliorate drought conditions, but may also play a role in moderating streamflow during times other than droughts. In general, when the cool season is wet, runoff is high and when it is dry, runoff is low (Figure 2a). However, in some years, the two variables do not track each other as closely, and in these years (henceforth referred to as "anomalous flow years"), temperature and soil moisture may be factors. In order to identify anomalous flow years, we took the differences between the percentile values for cool season precipitation and water year flow and examined the years when the difference exceeded 1 standard deviation from the mean (Figure 2b).

These years, when the flow anomaly was greater or less than might be expected given the cool season precipitation (30 years in total), fell into four categories. The first two categories are years when flow was greater than expected given that year's cool season precipitation in (1) above median flow years ("high-flow +" hereafter, 10 years) and (2) below median flow years, ("low-flow +" hereafter, 4 years). The second two categories are composed of years when flow was less than expected given that year's cool season precipitation in (3) above median flow years ("high-flow −" hereafter, 7 years) and (4) below median flow years, ("low-flow −" hereafter, 9 years). The four categories of anomalous flow years are shown with colored shading in Figure 2b and are summarized in the headings above the associated bar graphs in Figure 2c.

The distribution of these four categories of anomalous flow years, along with the time series of Colorado River at Lees Ferry water year flows minus October–April total precipitation, is displayed in Figure 2b. In general, there is clustering of flow anomaly years in the early part of the record (1910s and 1920s), followed by an interval with fewer flow anomalies (1930s to 1970s) before anomalous events increase in frequency again from the late 1970s through the end of the record. More specifically, most of the years with high-flow + anomalies (i.e., above median flows that are greater than expected based on precipitation) fall between 1918 and 1930, with a few occurrences later in the century. It is possible that this result is due, at least in part, to data scarcity (Text S2). In contrast, all but two of the low-flow − years (i.e., below median flows that are less than expected given precipitation) occur after 1987. The other two types of anomaly years occur less frequently. Above median years with less flow than might be expected (high-flow −), occur in 7 years, but three of these are consecutive, 1978–1980. The least common type of year is that with below median flows that are still greater than might be expected from precipitation (low-flow +). Two of the four cases occur during the relatively cool 1950s drought.

For each category of anomalous flow years, the importance of temperature or soil moisture as a conditioning factor becomes apparent in the averaged percentile values of each hydroclimatic variable (Figure 2c). In the two categories with flows higher than expected given precipitation (high-flow+ and low-flow+ anomaly years), temperatures fall below the 40th percentile. Soil moisture values in these years are high relative to cool season precipitation, suggesting soil moisture in the prior fall may have helped increase water year flows. As might be expected, in low flow years, with less flow than expected (low-flow − anomaly years), March–July temperatures are quite high (>80th percentile), but here the role of soil moisture, if any, is not obvious.

The proximal causes of the above median flow years with less flow than expected (high-flow − anomaly years), however, are less clear-cut than the other three categories. These are exceedingly wet winters, above the 80th percentile, but both temperature and soil moisture values are close to the median. A closer look at these years in comparison with the seven wettest winters with correspondingly high flows reveals more subtle differences that relate to the timing of delivery and spatial distribution of cool season precipitation. In the wettest winters, relatively more of the precipitation is delivered in October, December, and April, while the years with lower flows than would be expected from the wet winters experience more precipitation in

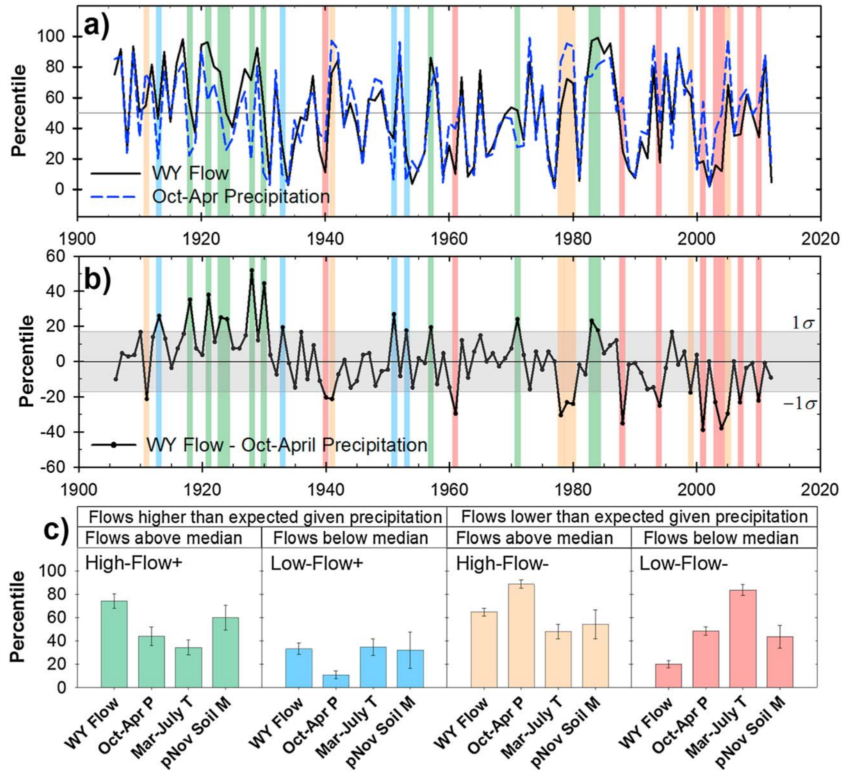


**Figure 2.** (a) Colorado River at Lees Ferry natural flows (black line) with October–April total precipitation for the UCRB (blue dashed line), 1906–2012. Anomalous years (years with differences greater than 1 standard deviation) in vertical colored bars. Years with flows higher than precipitation are in green (above median flow years) and blue (below median flows). Years with flows lower than precipitation are in orange (above median flow years) and pink (below median flow years). (b) Time series of water year flow in percentile minus October–April total precipitation in percentile (black line), with +/− one standard deviation range (horizontal gray bar) and anomalous years (years with differences greater than 1 standard deviation) in vertical colored bars as in Figure 2a. (c) Percentile hydroclimatic values averaged for water year flow anomalies in each of the four categories as in Figure 2b and described above the bar graphs, with standard error bars. Colors indicate the same year types as in Figure 2b.

midwinter, January, February, and March (Figure S3). Spatial patterns of the difference between these two sets of years indicate more precipitation falling in the headwaters regions in the years with wet winters and correspondingly high flows (Figure 3a). There are some differences in the temperatures over the months of March–July, which may be contributing factors as well. The wet winters with high flows are cooler in March

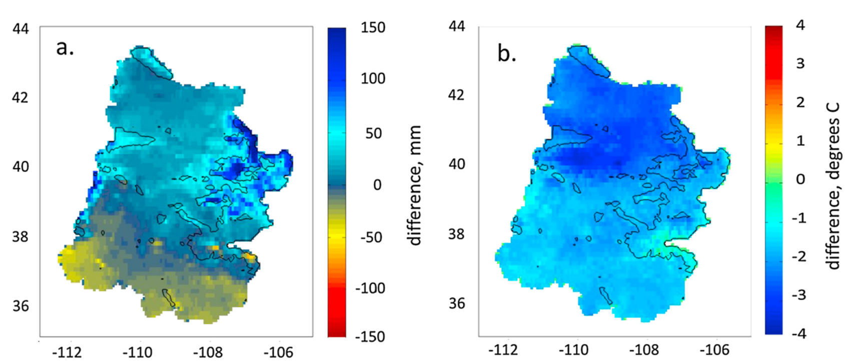


**Figure 3.** Climate differences between the seven wettest winters with correspondingly high flows and the seven high-flow − anomaly winters when streamflow was above the median but less than expected given winter precipitation. (a) October–April total precipitation. (b) March mean temperature. Dark blue indicates locations that are wetter or cooler in the wettest winters, compared to the high-flow − anomaly years. The black contour lines indicate 2500 m.

and July, relative to the other set of years, with March temperature values averaged for those years at the 31st percentile, compared to slightly above median temperatures for the set of lower than expected flow years. The differences are similar for July, though not quite as marked (29th versus 49th percentiles) (Figure S4). Spatial patterns suggest differences in March may be most important with cooler temperature throughout the entire basin in the wettest winters, but with the largest differences in the northern half of the basin. More northerly latitudes are cooler in general, making these regions more efficient in terms of moisture demand. But during the high-flow − winters, this advantage is discounted. (Figures 3b and S5). This suggests that high-flow − anomaly years are defined by winters with lower early season precipitation and snowpack in the highest-elevation regions and 2–3°C warmer average March temperatures in the northern half of the basin, relative to the wettest winters with correspondingly high flows.

In one final test to determine the importance of temperature in anomalous flow years, we repeated the stepwise regression analysis done previously but only used the 30 years classified as anomalous (that is, years with the difference between water year flow and October–April precipitation greater than 1 standard deviation from the mean difference). The same predictor pool yielded a model in which the first variable to enter was March–July temperature, explaining 42% of the total variance in flow for these years (Table 1b). October–April precipitation contributed an additional 19% variance explained, and October soil moisture added 8%. This result helps confirm the importance of temperature, and to a lesser degree soil moisture, as a moderating or exacerbating influence on the more dominant control of cool season precipitation during anomalous flow years. In addition, the regression was rerun with the addition of May and June precipitation in the predictor pool to assess the possible importance of spring precipitation to water year flows in these anomalous years. Although March–July temperature and October–April precipitation still explain the same amount of variance, both May and June are significant predictors, together explaining an additional 13% of the variance (Table S1b). We also assessed the average values for precipitation in these 2 months for the four categories of anomalous years (Figure S6), and it does appear that wet springs may also contribute to the differences between flow and cool season precipitation. In particular, in the years when flows are higher than would be expected, given cool season precipitation, May and June are much wetter relative to the cool season (Figures S6a and S6b). So along with cooler March–July temperatures, these wet springs may contribute to the higher flows. Although not as marked, in years with less flow than would be expected given cool season precipitation when flows are below the median (Figure S6d), drier May and June conditions could be contributing, along with very warm March–July temperatures.

Although we elected to focus on the upper Colorado River basin (UCRB), regression models and anomalous flow year analyses were performed for the three main subbasins (Green/Yampa, Main Stem/Gunnison, and San Juan/Dolores River basins) with results similar to those for the full UCRB, suggesting that our results are robust to differences due to gradients in temperature and precipitation across the UCRB (Table S1c and Figures S7a and S7b).

## 6. Conclusions

This historical perspective on hydroclimatic factors controlling UCRB streamflow suggests that while temperature has been a minor influence on streamflow overall, under certain conditions, runoff season temperatures exert an important moderating or exacerbating influence on streamflow relative to the role of cool season precipitation. Specifically, in years when flow is greater or less than might be expected given cool season precipitation, temperatures explain over 40% of the variability in streamflow. Our results indicate that precipitation is the leading control on water year streamflow in the upper Colorado River basin when all years are assessed, both for the full period of record and for the most recent half century, in concurrence with previous work by *Karl and Riebsame* [1989], *McCabe and Wolock* [2011], and others. However, as suggested by work that examines the impact of warming temperatures on runoff [e.g., *Vano et al.*, 2014], these results also strongly indicate that temperature, and to a lesser degree soil moisture, may be an important influence on streamflow. In contrast to studies that assess the impact of warming, we show that both cooler and warmer temperatures can result in flows greater or less than expected from cool season precipitation, respectively, with the latter conditions becoming much more prevalent over the past decades.

This importance of temperature, and to some extent, soil moisture, is evident in the examination of droughts on the Colorado River. A comparison of the 1950s and 2000s droughts shows how differences in precipitation deficits, runoff season temperatures, and soil moisture resulted in similar runoff conditions. The 1950s drought was characterized by low precipitation, drier antecedent soil moisture, and relatively cool temperatures compared to the moderate precipitation, relatively wetter antecedent soils, and very warm conditions during the 2000s drought (Figure 1). The fact that the drought prior to the 2000s drought (the 1980s–90s drought) also displayed these characteristics hints at the beginning of a possible temperature-driven trend, given warming runoff season temperatures in the basin (Figure S8).

The potential role of antecedent soil moisture conditions in anomalous flow years appears minor to uncertain. Results suggest that it is a more important contributor in years when flows are greater than might be expected from cool season precipitation totals alone. However, a number of other factors could contribute to antecedent and persistent moisture conditions, including base flow variability, basin size, and groundwater storage [e.g., *Wang et al*., 2015]. More work is needed to characterize accurately the antecedent soil moisture and groundwater conditions that are likely to make a substantive difference in water year flows.

An important finding revealed by this work is the clustering over the last two decades of anomalous years in which already low flows are lower than might be anticipated given cool season precipitation totals. Drought conditions have persisted over the past 15 years in the upper Colorado River basin, negating any substantive positive effect of a handful of wet years (2005, 2008, and 2011) within this interval of time. In most recent drought years, low flows have been further exacerbated by warm temperatures. As severe as the most recent drought has been, however, multicentury to multimillennial length paleoclimatic records indicate that droughts of this length are not unprecedented for this region [*Woodhouse et al*., 2006; *Meko et al*., 2007; *Pederson et al*., 2011; *Routson et al*., 2011; *Ault et al*., 2013]. A growing number of recent studies suggest warming temperature superimposed on natural drought variability will exacerbate the impacts of these droughts, not only on water supplies but also on the demand for water by both human and natural systems [e.g., *Seager et al*., 2012; *Cook et al*., 2015]. Our work suggests warming temperatures are playing an increasingly important role in causing runoff declines even in nondrought years. This finding has important implications for water resource management. Cool season precipitation has been a robust predictor of water year streamflow, but streamflow forecasts run the risk of overprediction if warming spring and early summer temperatures are not adequately considered. Given the current and projected trends in spring temperatures, we suggest the influence of temperature in driving further reductions of UCRB water supplies will continue.

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