Water balance of the turn-of-the-century drought in the Southwestern United States

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Abstract

Analysis of the water balance of the southwestern United States (SWUS) during 1900 through 2018 was used to evaluate the magnitude of the turn-of-the-century (TOC) drought in the SWUS. Results indicate that the warm season (April through September) soil moisture and runoff during the TOC drought were among the lowest values of the 1900 through 2018 period. Additionally, increases in temperature were identified as a significant driver of low soil moisture and runoff conditions during the warm season. In contrast, during the cool seasons (October through March) and the water year (October 1 through September 30) during the TOC drought, soil moisture and runoff did not indicate extremely dry conditions even though temperatures were the highest of the 1900 through 2018 period.

1. Introduction

The southwestern United States (U.S.) is a water poor area that largely depends on snow melt runoff from a few river basins for water supply. During the past several years there has been research indicating that increases in temperatures (and associated increases in evapotranspiration) across the western U.S. have resulted in decreases in runoff from major river basins such as the Upper Colorado River Basin (UCRB) (Woodhouse et al 2016, McCabe et al 2017, Udall and Overpeck 2017, Milly and Dunne 2020).

Water supply shortages in the western U.S. associated with persistent multi-year drought are a substantial concern for water managers (Cook et al 2015). During persistent drought, water managers work to balance the water needs of both humans and aquatic ecosystems. In a study of the UCRB, one of the primary sources of water in the western U.S., Woodhouse et al (2016) found that cool season precipitation explained most of the variability in water year (the sum from October 1 of one year through September 30 of the following year) UCRB streamflow. Woodhouse et al (2016) also reported that spring/summer temperature and, to a lesser extent, antecedent fall soil moisture, had substantial effects on UCRB streamflow under certain conditions. For example, Woodhouse et al (2016) reported that recent droughts have been amplified by increased temperature, which exacerbated the effects of relatively modest precipitation deficits.

Udall and Overpeck (2017) found that recent increases in temperature have substantially reduced UCRB streamflow. They reported that during 2000 and 2014, annual UCRB streamflow was 19% below the 20th century (i.e. 1906 through 1999) mean and that this period was the worst 15-year drought on record in the UCRB. Additionally, they attributed at least one third of the decrease in UCRB streamflow to increases in temperature since 2000. Seager (2007) identified six North American droughts that have occurred since the mid-19th century and may have been the first to use the phrase ‘turn-of-the-century’ (TOC) drought.

Similarly, McCabe et al (2017) reported that since the late 1980s, increases in temperature have caused a significant reduction in UCRB runoff efficiency (the ratio of annual streamflow to annual precipitation). The magnitude of temperature-induced reductions in UCRB streamflow were shown to be the largest documented temperature-driven flow reductions since the early 20th century. McCabe et al (2017) also indicated...
that the increases in UCRB temperature since the late 1990s have resulted in a 7% decrease in mean UCRB streamflow. The decrease in flow attributed to an increase in temperature (i.e. 7%) is similar to the percentage decrease in UCRB streamflow (6% to 7%) ascribed to temperature increases by Udall and Overpeck (2017) during the TOC drought.

Most recently, Hoerling et al (2019) examined climatic factors driving a century-long decline in UCRB flow. Hoerling et al (2019) reported that about one-third of the long-term decreases in UCRB flow was attributable to increases in temperature and two-thirds resulted from decreases in precipitation. In a related analysis, Milly and Dunne (2020) examined the effects of increasing temperatures on UCRB streamflow and stated that annual UCRB streamflow has been decreasing by 9% per degree Celsius of warming. The negative effects of warming on UCRB streamflow were found to be related to increased evapotranspiration, primarily driven by snow loss and an associated reduction in surface albedo and increased temperatures. Milly and Dunne (2020) further reported that precipitation increases projected for the UCRB by climate models likely will not be sufficient to offset the projected increases in evapotranspiration due to warming and that there is an increasing risk of severe water shortages in the basin.

These previous studies have focused on the UCRB because it is a major source of water for the western U.S. and specifically for the southwestern U.S. (SWUS). The changes in UCRB streamflow described in these previous studies reflect many of the changes occurring across the SWUS. In a recent study of the TOC drought across southwestern North America (30 degrees (c) North to 45 degrees North, 105 degrees West to 125 degrees West), Williams et al (2020) used a hydrologic model and tree ring reconstructions of summer (June through August) soil moisture to examine the TOC drought in southwestern North America, defined by Williams et al (2020) as the period 2000 through 2018. Rather than examine the TOC drought as did Williams et al (2020), we define the TOC drought as the period 2000 through 2018. Rather than examine the TOC drought across southwestern North America as did Williams et al (2020), we focus on the TOC drought in the SWUS. The objectives of this paper are to examine the TOC drought in the SWUS from a water balance perspective with the goal of answering the following questions: (1) how has the water balance during the TOC drought changed for the entire year—not just during the summer, (2) which water balance components (i.e. precipitation, temperature, actual evapotranspiration, soil moisture, and runoff) have changed the most during the TOC drought, (3) how do the changes in water balance components during the TOC drought compare to changes during previous periods in the instrumental record, and (4) what are the relative contributions of changes in precipitation and temperature to changes in water balance components during the TOC drought?

2. Data and methods

For this analysis the SWUS is defined as the region from the western U.S. coast to 100 degrees West longitude and from the southern U.S. border to 40 degrees North latitude (figures 1(c) and (d)). Analyses are performed within this region using hydro-climatic data aggregated to 433 U.S. Geological Survey 8-digit hydrologic units (HUs) located in the SWUS (figures 1(c) and (d)).

2.1. Monthly temperature and precipitation data

Monthly temperature and precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, Oregon State University, http://www.prism.oregonstate.edu, created November 19, 2019) for the period 1895 through 2018. These data are provided on a 4 km resolution for grid cells across the conterminous U.S. (CONUS) and were aggregated to the 433 HUs in the SWUS. The monthly temperature and precipitation data were used as inputs to a monthly water balance model to estimate monthly time series of water balance components (i.e. actual evapotranspiration, soil moisture, and runoff). Simulated water balance model output is used for this study rather than measured data because (1) complete records of measured water balance components for the SWUS are limited in both time and space, and (2) the water balance model...
provides estimates of natural runoff, whereas measured values may be substantially altered by human influences (e.g. dams, diversions, consumptive water use).

2.2. The water balance model
The water balance model partitions precipitation into evapotranspiration, changes in soil moisture, snow accumulation and melt, and runoff. The water balance model has been successfully used to simulate water balances for several regions of the U.S. and the world with a range of climatic and physiographic characteristics (McCabe and Wolock 2011).

Monthly temperature and precipitation data for 433 HUs in the SWUS were used as inputs to the water balance model and monthly water balance components (e.g. actual evapotranspiration, soil moisture, and runoff) were computed for each HU. Although the PRISM temperature and precipitation data record begins in 1895, the first few years (i.e. 1895 through 1899) of the water balance model simulations are not analyzed so that the effects of prescribed initial model conditions are minimized in the analyses. Thus, for the analyses presented in this study, water balance model simulations for the period 1900 through 2018 are used. Time series of monthly water balance components for the PRISM 4 km grid cells for the CONUS are available in a U.S. Geological Survey data release (Wolock and McCabe 2018).

The water balance model has been tested and applied in many previous studies (McCabe and Wolock 2008, 2011, Huntington et al 2018). Although the water balance model has been extensively evaluated, we did a separate verification of the model for the SWUS. For this verification, we compared monthly runoff estimated by the water balance model for the SWUS with measured monthly runoff aggregated to the 433 HUs in the SWUS. The measured monthly runoff estimates were generated from measured streamflow data collected at streamgages within the HUs in the SWUS (see Brakebill et al 2011 for details). Owing to limited runoff observations prior to the early 1950s, this verification was carried out for the years 1951–2018.

The water-balance estimated runoff represents natural runoff resulting only from climatic variability, whereas the measured runoff includes climatic variability as well as anthropogenic effects on runoff such as the effects of dams, reservoir operations, irrigation, and consumptive water use. Figures 1(a) and (b) illustrate a comparison of monthly mean measured and water balance estimated runoff for the SWUS for the period 1951 through 2018. The Pearson correlation is 0.91 ($p < 0.01$) and the bias (mean water balance runoff minus mean measured runoff) is 2 mm; this is about 33% (%) of mean monthly SWUS measured runoff. The high positive correlation between the water balance and measured runoff indicates that the water balance model reliably simulates the temporal variability of monthly runoff in the SWUS. The positive bias indicates that the water balance estimates of runoff are generally higher than are the measured values of runoff. This positive bias likely is due to the many anthropogenic effects (e.g. dams and diversions) on measured runoff in the basin.

To evaluate the ability of the water balance model to simulate the spatial variability in runoff across the SWUS, we compared mean water-year runoff estimated by the water balance model with mean water-year measured runoff for the 433 HUs in the SWUS for the period 1951 through 2018 (figures 1(c) and (d)). The Pearson correlation is 0.92 ($p < 0.01$) and the bias is 28 mm (this is about 27% of mean SWUS water-year measured runoff). The water balance estimates of water-year runoff indicate a positive bias, but the high correlation values across space indicates that the water balance model reliably simulates the spatial variability of runoff across the SWUS.

The positive bias may be due to the many anthropogenic effects (e.g. dams and diversions) on measured runoff in the basin. The high positive correlation between the water balance and measured runoff is somewhat surprising. One might expect the human-influenced measured runoff time series to be different
from the near–natural water-balance time series. Two possible explanations for the high degree of correlation are (1) anthropogenic factors cause both reductions and additions to streamflow and thereby offset each other, and (2) the anthropogenic effects are significantly smaller in magnitude than natural factors such as evapotranspiration, which result in high magnitude losses of streamflow in arid regions such as the SWUS. We conclude that the high degree of correlation between the near-natural and human-influenced runoff time series is due to the overwhelming effect of a natural process, i.e. evapotranspiration, which masks a much smaller effect from anthropogenic factors.

Although there is a positive bias in water balance estimates of SWUS runoff in both time and space, the water balance model adequately simulates the temporal and spatial variability in relative magnitudes of runoff. The ability of the water balance model to simulate the relative temporal and spatial changes in runoff across the SWUS indicates that the model provides runoff estimates that are suitable for this analysis.

To examine the relative effects of temperature and precipitation on the mean SWUS runoff during the TOC drought, we performed experiments using the water balance model. These experiments involved running the water balance model in three ways: (1) with measured monthly temperature and precipitation (complete model), (2) with measured monthly temperature but with monthly precipitation held constant to long-term mean monthly precipitation (Tvar model), and (3) with measured monthly precipitation but with monthly temperature held constant to mean monthly temperature (Pvar model). The complete model provides estimates of runoff based on the combined effects of variable monthly temperature and precipitation, whereas the Pvar and Tvar models provide estimates of runoff based on the variability of temperature and precipitation separately. Thus, comparing runoff estimates from the Tvar and Pvar models allows the individual effects of temperature and precipitation on SWUS runoff to be isolated.

3. Results

Before performing detailed analyses of the water balance for the TOC drought, we examined the mean hydro-climatic conditions during the TOC drought for the water year, cool season (October through March), and warm season (April through September). Departures from long-term (1900 through 2018) means of selected water balance components (i.e. precipitation, temperature, actual evapotranspiration, soil moisture storage, and runoff) for the TOC drought (i.e. 2000–2018) indicate negative precipitation, actual evapotranspiration, soil moisture, and runoff departures across most of the SWUS (figure 2).

Soil moisture departures were not as extreme as the departures of precipitation, actual evapotranspiration, and runoff because in the dry SWUS soil moisture levels are low and thus variability in soil moisture is small (figures 2(j)–(l)). In contrast, the temperature departures are positive for all of the SWUS with a median departure of 0.6 °C (figures 1(d)–(f)). This positive departure in temperature has been identified as a substantial factor contributing to the TOC drought (Williams et al 2020).

To examine the TOC drought in the context of century scale climatic variability, we analyzed monthly water balance components averaged for the SWUS for 19-year moving periods (figure 3). The length of the moving period (i.e. 19 years) was selected because the TOC drought is defined by a specific 19-year period (i.e. 2000–2018). Comparison of mean monthly time series of water balance components for each 19-year moving period during 1900 through 2018 provides a context for the TOC drought. Results show that TOC drought precipitation was in the bottom half of the distribution of values for all 19-year periods during January through June—the lowest percentile values were for May (8th percentile) and June (13th percentile)—but was near the middle or higher than the center of the distributions during most other months, except for November (figure 3(a)). In contrast, mean monthly values of temperature for the TOC drought were near the top of the distribution of values for all 19-year periods, was the highest for March, April, June and July, and was at the 95th percentile or higher for all months except for December (75th percentile) (figure 3(b)).

Mean monthly actual evapotranspiration values for the TOC drought were between the 25th and 75th percentile for 8 of the 12 months of all 19-year periods. For April and May mean actual evapotranspiration during the TOC drought was below the 25th percentile with the value for May being one of the lowest (3rd percentile). The low value of actual evapotranspiration for the TOC drought for May corresponds to a low value of precipitation for May during the TOC drought (figure 3(a)).

Mean monthly soil moisture values during the TOC drought were near the middle or higher than the middle values of soil moisture of all 19-year periods for the months of October through March but were near the bottom of all 19-year periods for April through September, and lower than the 2nd percentile of all 19-year periods for June through August (figure 3(d)). The low values of soil moisture during the TOC drought for the months of June through August are consistent with the results of Williams et al (2020) who suggest that the summer soil moisture during the TOC drought is the second lowest since 800 CE and is indicative of a persistent megadrought.

Mean monthly runoff during the TOC drought was near the middle of the distributions for all 19-year
moving periods during December through March, but was among the lowest values of all 19-year periods (lower than the 5th percentile) for the months of May through August (figure 3(e)).

The low values of soil moisture and runoff during April through September, and especially during June through August indicate extremely dry conditions for these months during 2000 through 2018 (the TOC drought), which corresponds with the results reported by Williams et al. (2020). However, the values of soil moisture and runoff for October through March during 2000 through 2018 are near the middle or higher than the middle values for all other 19-year periods. This suggests that for October
through March the 2000 through 2018 period was not among the driest periods.

To further examine the relative magnitudes of water balance components for the TOC drought compared to other 19-year periods, we computed (1) mean SWUS water-year, cool season (October through March) and warm season (April through September) totals for precipitation, actual evapotranspiration, and runoff, and (2) mean SWUS water-year temperature and soil moisture for all 19-year moving periods during 1900 through 2018 (figure 4). For the water-year time series, mean SWUS water-year precipitation, actual evapotranspiration, soil moisture, and runoff during the TOC drought were below the long-term mean of all 19-year periods, but were not the lowest values (figures 4(a), (g), (j) and (m)). In contrast, mean SWUS water-year temperature for the TOC drought was the highest of all 19-year periods (figure 4(d)).

Cool season precipitation, soil moisture, and runoff during the TOC drought were below the long-term mean of all 19-year moving periods, but these cool season values were not the lowest of all 19-year periods (figures 4(b), (k) and (n)). The cool season value of actual evapotranspiration for the TOC drought was close to the long-term mean of all 19-year periods (figure 4(h)), and the cool season mean SWUS temperature for the TOC drought was the highest of all 19-year periods (figure 4(e)). Even though mean SWUS time series of water balance components for the water year and cool season indicate the 2000 through 2018 period included the warmest conditions of the 1901 through 2018 period, they do not indicate that this period included the driest water years and/or cool seasons.

Warm season precipitation, actual evapotranspiration, soil moisture, and runoff during the TOC drought are below the mean of all 19-year periods, with the TOC drought warm season soil moisture value being the 12th lowest of all 19-year periods and the TOC drought warm season runoff value being the fifth lowest of all 19-year periods (figures 4(c), (i), (l), and (o)). Similar to the water-year and cool season analyses, the mean SWUS warm season temperature was the highest of all 19-year periods (figure 4(f)). The values of warm season soil moisture and runoff for the TOC drought indicate some of the driest warm season conditions during 1901 through 2018. These results support the concept that during the TOC drought extremely warm temperatures in conjunction with moderately low precipitation resulted in low warm season soil moisture conditions consistent with the findings of Williams et al (2020).

3.1. Climatic drivers of the 2000–2018 departures
To examine the relative effects of temperature and precipitation on the mean SWUS soil moisture and runoff during the TOC drought, we performed experiments using the three versions of the water balance model (i.e. the complete model, the Pvar model, and the Tvar model). Time series of 19-year moving averages of mean SWUS soil moisture computed using the complete, Pvar, and Tvar models indicate that estimates of soil moisture computed using the Pvar model closely match those computed using the complete model (figures 5(a)–(c)). Thus, precipitation accounts for most of the inter-annual variability in soil moisture. The time series of 19-year moving average soil moisture computed using the Tvar model (figures 5(a)–5(c)) indicates departures of soil moisture that are much smaller than those computed using the complete and Pvar models, which suggests that temperature accounts for a much smaller amount of the inter-annual variability in soil moisture than does precipitation. The temporal pattern of soil moisture departures computed using the Tvar model indicates a general decrease in soil moisture during 1900 through 2018, with larger negative departures after about 1980. This suggests that as temperature in the SWUS has warmed, the effects of temperature on SWUS soil moisture have become increasingly negative. The correlations of the time series of 19-year moving average soil moisture computed using the Tvar model (figures 5(a)–c)) with the time series of 19-year moving average temperature (figures 4(d)–(f)) for the water year, cool season, and warm season are −0.99, −0.90, and −0.96, respectively.

The last data point in the time series of 19-year moving average soil moisture (figures 5(a)–(c)) represents values for the TOC drought (2000 through 2018). For the water year (figure 5(a)) the departure of soil moisture is −2 mm, which is largely accounted for by the soil moisture departure estimated by the Tvar model (also −2 mm). The soil moisture departure estimated by the Pvar model is approximately zero. For the cool season (figure 5(b)) the soil moisture departure computed using the complete model is −1 mm, which also is largely accounted for by the soil moisture departure computed using the Tvar model (i.e. −1 mm). The soil moisture departure computed by the Pvar model is positive and does not account for the negative soil moisture departure computed using the complete model. For the warm season (figure 5(c)) the soil moisture departure computed using the complete model is −3 mm, which is largely due to the soil moisture departure computed using the Tvar model. The warm season soil moisture departure for the TOC drought computed using the Pvar model is close to zero.

Although precipitation accounts for the majority of the inter-annual variability in soil moisture, as indicated by the close association of the time series of soil moisture computed using the complete and Pvar models (figures 5(a)–(c)), temperature appears to have had a substantial effect on soil moisture departures during the TOC drought. Additionally, for the water year, cool season, and warm season, the soil
moisture departures driven by temperature (the Tvar model) are the most negative of any 19-year period during 1900 through 2018. These results are consistent with those of Williams et al (2020) who reported that temperature has been an important driver of the TOC drought in southwestern North America.

Similar to soil moisture, time series of 19-year moving averages of water year, cool season, and warm season runoff computed using the complete model also correspond closely with runoff computed using the Pvar model (figures 5(d)–(f)). Additionally, for the water year and warm season, runoff

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**Figure 4.** Mean water year, cool season (October through March), and warm season (April through September) water balance components for the southwestern U.S. for 19-year moving periods during 1900 through 2018. (a)–(c) precipitation (P in mm), (d)–(f) temperature in °C, (g)–(i) actual evapotranspiration (AET in mm), (j)–(l) soil moisture (SM in mm), (m)–(o) runoff (R in mm). The solid line is the long-term value for each variable and the dashed line is the value for 2000 through 2018 for reference.

**Figure 5.** 19-year moving averages of mean southwest U.S. departures (in mm) of water-year, cool season (October through March), and warm season (April through September) soil moisture storage (a)–(c) and runoff (d)–(f) computed using the complete, precipitation variable (Pvar), and temperature variable (Tvar) models for 1900 through 2018. The horizontal solid black line indicates a departure of zero and the horizontal dashed line indicates the value for 2000 through 2018.

4. Conclusions

A water balance model was used to estimate time series of monthly water balance components (i.e. actual evapotranspiration, soil moisture, and runoff) for the SWUS for the period 1900 through 2018. Analyses of these time series of water balance components and of monthly temperature and precipitation were used to evaluate the water balance of the TOC drought. Results indicate that the warm season soil moisture and runoff during the TOC drought were among the lowest values of the 1900 through 2018 period. In comparison, Williams et al (2020) reported that soil moisture in the SWUS during the summer months of the TOC drought were the second lowest since 800 CE. Additionally, we found that increases in temperature have been a significant driver of low runoff conditions during the TOC drought, particularly during the warm season. The departures in TOC drought warm season runoff are explained equally by increases in temperature and decreases in precipitation. This result agrees with the results of Williams et al (2020) who reported that increases in temperature were a primary cause of low soil moisture in the SWUS during the TOC drought.

In contrast to the results for the warm season, an evaluation of precipitation, actual evapotranspiration, soil moisture, and runoff for the TOC drought for the cool season and water-year do not indicate that this period was the driest period during 1900–2018. Although the decreases in warm season runoff during the TOC drought across the SWUS are small in magnitude, when multiplied by the area of the SWUS to compute the volume of water, the amount of water represented by the departures in runoff represents a substantial decrease in water supply in the SWUS. Continued warming likely will result in drier warm seasons in the SWUS and may result in drying of the spring and fall seasons that border the warm season.

Data availability statement

Monthly data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) are available from the PRISM Climate Group, Oregon State University at https://prism.oregonstate.edu and the monthly runoff data for the U.S. Geological Survey 8-digit hydrologic units are available at https://waterwatch.usgs.gov/index.php?id=romap3- &sid=w_download. Additionally, monthly water balance estimates of potential evapotranspiration, actual evapotranspiration, and runoff for the PRISM 4-km grid cells for the conterminous U.S. are available in a U.S. Geological Survey data release (Wolock and McCabe 2018).
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