Climatological Context for California's Ongoing Drought

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Back-to-back hot-dry years have left California parched. By late summer of 2021, half of California found itself in an exceptional drought. I review the climatic factors that led us into this deficit and provide its context relative to some of the state's most notorious droughts. Increasing atmospheric thirst, together with climate change, has arguably supercharged recent droughts, including California's ongoing drought.

The Sacramento basin had the lowest precipitation and highest evaporative demand in the past four decades for the 2021 water year.
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California's climate is defined by wild year-to-year variability in precipitation. An average water year in terms of accumulated precipitation is quite rare in California. Many of the state's ecosystems are adapted to such volatility. Further, state infrastructure—including reservoirs and water conveyance systems—has been designed to cope with historical droughts. Recent droughts, however, have tested many of these systems. In some cases, these droughts have catalyzed adaptation responses, as well as mitigation efforts, to provide a buffer against future droughts. Nonetheless, recent drought impacts have materialized in diverse sectors including widespread tree mortality in the Sierra Nevada, rapid groundwater depletion that has resulted in dry wells and agricultural challenges in the Central Valley, and combined low-flows and warm river temperatures decimating salmon populations in the rivers of Northern California. The ongoing drought presents another stress test for the state and likely will facilitate further adaptation plus mitigation efforts for future droughts.

The Ongoing Drought

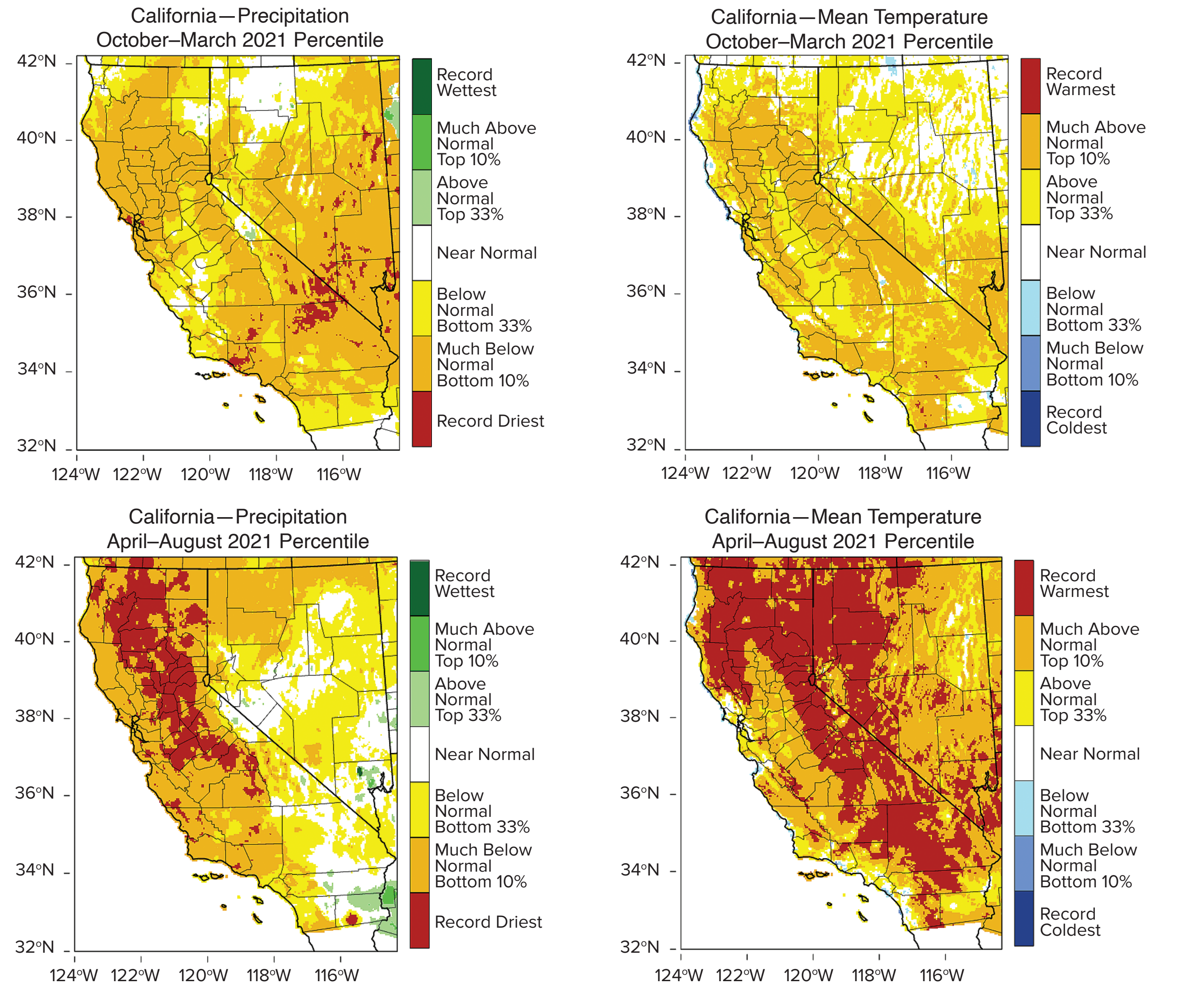
When did the ongoing drought start? A historic multi-year drought commenced during the 2012 water year (October 2011–September 2012). Several studies showed that the multi-year drought was not only the most extreme in the modern climate record but also the most extreme in at least the last 1,200 years based on tree-ring data. Although the state had a couple of very wet years in 2017 and 2019 that ameliorated drought impacts (e.g., reservoir levels), it is debatable as to whether a couple of wet years "ended" the drought based on other lagging indicators such as groundwater levels and vegetation mortality. For this writeup, I will focus on the ongoing drought beginning with the 2020 water year.

The 2020 water year was dry and hot. Statewide precipitation was 68% of 20th century averages, with higher deficits in the Sacramento basin (60% of average). The state had its warmest April–September since 1895, with temperatures nearly 3.5ºF above the 20th century average. Record-setting warmth, combined with dry conditions, allowed for an extra 3–4 inches of evaporative demand (the amount of potential moisture pulled by the atmosphere from a well-watered land surface, sometimes referred to as potential evapotranspiration) relative to average levels for the late 20th century.

These conditions set the stage for moisture-starved soils and vegetation with the commencement of the 2021 water year. The storm track door remained sealed through early November, as the jet stream that is a highway system for storms remained well north of the state. A few meager storms visited the state throughout the winter. Davis, California saw only 16 days with meaningful precipitation (daily totals of at least a tenth of an inch)—tying a water-year record for futility with the infamous 1977 water year. Notably absent were strong atmospheric rivers. The presence or absence of atmospheric rivers can make or break a water year, as such events contribute up to 50% of the annual precipitation in parts of the state. A moderate atmospheric river in late January brought solid precipitation totals along the central California coast and into the central Sierra Nevada. This system brought significant lower-elevation snowfall accumulations, with locations like Calaveras Big Tree State Park receiving a record 76.5 inches of snowfall in a three-day period. This event softened the mounting precipitation deficits in the San Joaquin basin.

A persistent ridge of high pressure in the northeastern Pacific kept the storm track well north of the state, and continued through the remainder of the winter. By the end of March,

Figure 1. Temperature and Precipitation Rankings for Water Year 2021



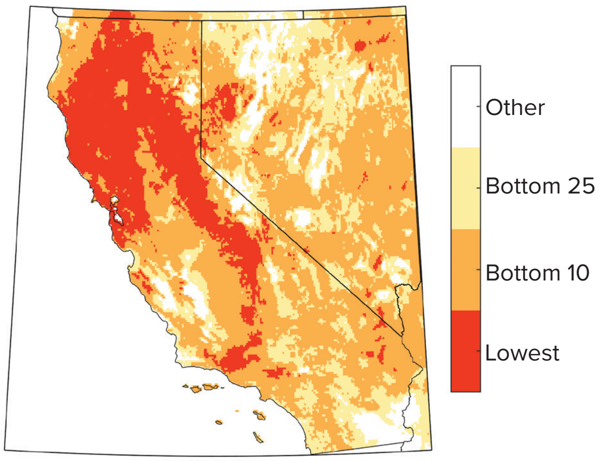
Note: (Top row) Rankings of October 2020–March 2021 cumulative precipitation and mean temperature relative to the 1895–2021 period. (Bottom row) Rankings of April 2021–August 2021 cumulative precipitation and mean temperature relative to the 1895–2021 period.

Source: West Wide Drought Tracker. Available at http://www.wrcc.dri.edu/wwdt/.

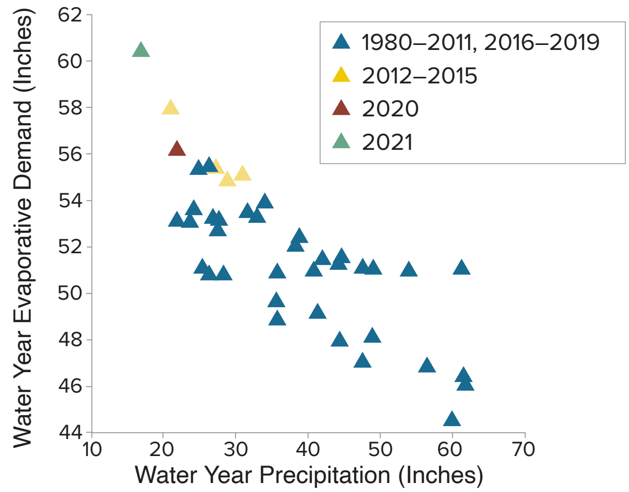
most of the state had well below-average water-year precipitation, with a few isolated locations in Ventura and Marin counties having their driest start to a water year since at least 1895 (Figure 1). Autumn and winter temperatures were warm, but not unusual in the context of the past couple decades for the state. Consequentially, late winter snowpack (60% of average) largely reflected precipitation deficits. The snow drought was not as acute as in recent winters, such as water year 2015 that saw below-normal mountain precipitation and extremely warm winter temperatures. By early April, nearly all of the state was in drought—per the U.S. Drought Monitor—with about 5% in exceptional drought. Snowpack decreased rapidly in April, with the onset of anomalously warm temperatures. Unfortunately, the decrease in spring snowpack was not well reflected in spring streamflow, leading to a sizable reduction in state water resource allocations. It is hypothesized that snowmelt infiltration into parched soils reduced the amount of water available for runoff. Spring continued the streak of months with below-normal precipitation. Record low April–August precipitation was seen for much of the western slopes of the Sierra Nevada northward into the Klamath basin (Figure 1). Just as the storm track door opened late in autumn, it closed early in the spring. Statewide, the 2021 water year was the third driest since 1895 and the driest since 1977—receiving about half of the 20th century average rainfall (47% of average in the Sacramento basin). Cumulative precipitation deficits since

Figure 2. Drought Rankings for Water Year 2021

a. Rankings of July 2021 PDSI Relative to the 1895–2021 Period of Record.*



b. Scatterplot of Water Year Precipitation and Evaporative Demand for the Sacramento Basin for 1980–2021.



Note: *Red denotes the lowest PDSI on record, with orange and yellow denoting PDSI values in the lowest 10 and 25 years on record, respectively.
Source: West Wide Drought Tracker, gridMET. Available at: http://www.wrcc.dri.edu/wwdt/.

October 2019 have left parts of the state missing more than a year's worth of precipitation. Such numbers have been reflected in low—and in some cases record-low (Oroville)—reservoir levels by late summer.

Some have viewed drought as being entirely driven by precipitation shortfalls. This view presumes little change in drought in California after April, given the nominal precipitation that falls from May–September. However, the data do not bear out that view. Between early May and late August, the percent of the state in exceptional drought rose from 5% to nearly 50%. Drought isn't defined solely by water supply. The demand side can be particularly important. Climate-based drought monitoring typically considers some type of demand in addition to precipitation.

Significant increases in evaporative demand have been observed across California and much of the western United States over the past several decades. Evaporative demand in 2021 for much of Northern California is the highest it has been in at least the last four decades—over 8 inches above the late 20th century average. A combination of dry conditions and low cloud cover in spring, and record-setting summer temperatures, were responsible for a very thirsty atmosphere. This exceptional atmospheric thirst has further taxed sparse soil and vegetative moisture, allowing for worsening drought conditions.

Benchmarking the Ongoing Drought

Where does this drought rank relative to many of the state's infamous droughts? The answer depends on how we define drought. Based on the Palmer Drought Severity Index (PDSI)—a widely used drought index that tracks normalized soil moisture anomalies based on precipitation and evaporative demand—July 2021 values set records for much of Northern California (Figure 2a). Most of the rest of the state had PDSI values in the ten driest years; conditions in 2014 were more acute in the San Joaquin and Tulare basins. PDSI values for the Sacramento basin during July 2021 were the lowest since at least 1895—topping individual values during the 2012–2015 period. By comparison, water-year precipitation for the Sacramento basin was the third lowest since 1895—highlighting the important role of extreme evaporative demand in 21st century droughts.

Another way to benchmark the ongoing drought is to contextualize water-year precipitation and annual evaporative demand, given their combined influence on drought. Constraining the period of analysis to water years 1980–2021, and focusing on the Sacramento basin, we see a moderate negative correlation suggesting that high-demand years tend to co-occur with low-precipitation cool seasons (Figure 2b). Water year 2021 was unique: it was both the driest water year and had the highest demand for the Sacramento basin of any year in the past four decades. Water year 2020 was close behind—it was the third driest water year and had the third highest demand. Both years were drier and had higher demand than any two consecutive years in the 2012–2015 drought.

Furthermore, while the 1976 and 1977 water years had similar cumulative precipitation deficits to the 2020 and 2021 water years, evaporative demand during the current, ongoing drought is at least 4 inches higher. A hallmark

of recent droughts is the acute atmospheric thirst tied to the shifting baselines of temperature and evaporative demand. Increased atmospheric thirst not only depletes soil and vegetated moisture in natural lands, but can also translate into increased irrigation demands for agricultural lands.

Influence of Human-Caused Climate Change

Can we blame this drought on climate change? Not exactly. The predominant driver of droughts in California is shortfalls in precipitation—something inherent to the state's climate. Yet, there is mounting evidence to suggest that climate change has increased evaporative demand and supercharged droughts. The state has warmed nearly 3ºF over the past five decades, consistent with changes simulated by climate models forced by known human activity (i.e., human-caused greenhouse gas emissions).

Changes in precipitation are less clear. There is a non-significant decline in annual precipitation over the past century, yet this decline is entirely due to the past decade that has been punctuated by severe drought. We observe declines in autumn precipitation and a delayed onset of seasonal precipitation that result in a seasonal compression of the wet season. Several generations of climate models agree on one thing regarding changes in precipitation for the state: they agree to disagree. While climate models do not suggest any robust changes in annual precipitation, they show a tendency for less precipitation in the shoulder seasons of spring and autumn and more precipitation in mid-winter.

A few studies have quantified the influence of human-caused climate change on recent extreme droughts in California and the broader southwestern United States. Warming exerts direct control on the mountain snowpack storage efficiency and evaporative demand. The former results in reduced spring snowpack, hastened seasonal drying of soils and vegetation in montane environments, and an advancement in the timing of runoff that further decouples water supply and demand in California's Mediterranean climate. The latter acts as a tax on the surface water balance—like adding a couple of extra straws to a drink. Whereas in wet years, an extra couple of straws sucking surface water may have negligible impacts, the extra straws pulling from the half-empty glasses we experience in dry years intensifies impacts.

Studies estimate that human-caused warming made the 2012–2015 drought in California approximately 8–27% worse. Furthermore, studies show that human-caused climate change has effectively doubled the severity of the "megadrought" that the broader southwestern United States has been in since the turn of the century—turning a significant long-term drought into potentially the worst in at least 1,200 years. Given the elevated evaporative demand in the two most recent years, it is likely that human-caused climate change has its fingerprints on the ongoing drought.

Conclusion

As we end the 2021 water year, the question that we all want to know is when this drought will end. The state may play host to a conga line of drought-busting atmospheric rivers this upcoming winter or may be left high and dry. Improvements in subseasonal-to-seasonal forecasting may help aid in seasonal water-resource decision making. The long-term prospects suggest further increases in evaporative demand with a warming climate that will tilt the odds for acute drought conditions similar to the ongoing drought. This aridification will not be without wet and very wet years. The optimist in me hopes the upcoming water year will be one of these wet years and bring some reprieve to the ongoing drought. The pessimist in me says we should prepare for lean years ahead.

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For additional information, the author recommends:

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