Climate change and California drought in the 21st century

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Climate science has advanced over decades from an initial focus on the development and use of numerical models of Earth's climate and compilation of rich networks of observational data, to now being in a position to "detect" and "attribute" specific impacts and events to anthropogenic climate change. Recent analyses have thus established the "fingerprint" of anthropogenic climate change in an increasingly diverse array of meteorological and hydrological phenomena around the world, from heat waves to coastal damages during extreme tides and storms, flooding from more intense precipitation events, and severe drought (1). In a new study published in PNAS, Diffenbaugh et al. now add weight to the accumulating evidence that anthropogenic climatic changes are already influencing the frequency, magnitude, and duration of drought in California (2). The authors show that the increasing co-occurrence of dry years with warm years raises the risk of drought despite limited evidence of a trend in precipitation itself, highlighting the critical role of elevated temperatures in altering water availability and increasing overall drought intensity and impact.

Golden State Goes Brown

California's nickname is the Golden State, a name that owes as much to the golden hue of its landscapes during the dry summer season as to the 19th century Gold Rush or the fields of golden poppies. The grasses green up again in late fall when the mid-latitude storms and rainfall return. What happens if those rains come late, come little, or in some cases don't come at all? Such has been the case in recent years.

California is experiencing extreme drought. Measured both by precipitation and by runoff in the Sacramento and San Joaquin river basins, 10 of the past 14 y have been below normal, and the past 3 y have been the driest and hottest in the full instrumental record. A plot of temperature and precipitation anomalies over the full instrumental record from 1895 through November 2014 shows that the 3-y period ending in 2014 was by far the hottest and driest on record (Fig. 1). As of the publication of this commentary, the state appears headed into a fourth consecutive year of water shortfall, leading to massive groundwater overdraft, cutbacks to farmers, reductions in hydroelectricity generation, and a range of voluntary and mandatory urban water restrictions.

As drought has taken hold, the Golden State is slowly becoming a more arid, brown state, where constraints on water availability threaten a large and growing population (up nearly 80% since the severe drought of 1976–77), unique ecological resources, a major source of agricultural produce, and one of the largest economies in the world. What a sadly ironic destiny that would be for the state currently led by one Governor Brown: The growing threat of climate change to California is one of the drivers for extensive efforts under the Brown (and prior Schwarzenegger) administration to understand the risks to the state and develop strategies to reduce greenhouse gas emissions and implement adaptation strategies (3). Of course, we're not just talking about whether or not the grass is green. There are growing concerns about whether California can continue to meet its tremendous demand for water for industrial use, growing food, sustaining ecosystems, and expanding cities in the face of drought (4).

As part of the effort to understand the influence of climate change on extreme regional events, there has been a robust scientific debate over the role of climate change on California's current drought. Some studies (5–7) have argued that we cannot yet discern a link between storm tracks (and the Pacific Ocean surface temperature patterns that influence their behavior) and drought in the western United States. Others (8) do, however, see a relationship in the form of observational data, physical analysis of possible

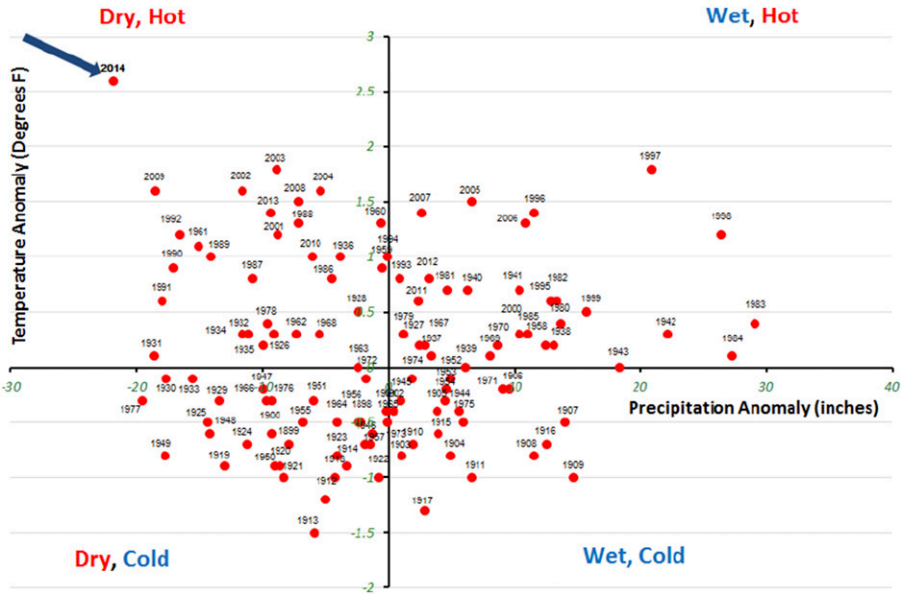

Fig. 1. California temperature (°F) and precipitation (inches) anomalies from January 1895 to November 2014, plotted as 3-y anomalies relative to 1901–2000 mean. Data from the National Climatic Data Center nClimDiv dataset.

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mechanisms, and model results that human-caused climate change is strengthening atmospheric circulation patterns in a way that "implies that the periodic and inevitable droughts California will experience will exhibit more severity." Seeming to weigh in favor of a climate change connection is the fact that by several measures the current drought appears to be unprecedented in at least 1,200 y (9).

Don't Blame It on the Rain

Part of the challenge is that the term "drought" can be defined in different ways: for example, meteorological, hydrological, agricultural, and socioeconomic drought (10). Drought, most simply defined, is the mismatch between the amounts of water nature provides and the amounts of water that humans and the environment demand. The National Drought Mitigation Center notes (11):

> In the most general sense, drought originates from a deficiency of precipitation over an extended period of time—usually a season or more—resulting in a water shortage for some activity, group, or environmental sector. Its impacts result from the interplay between the natural event (less precipitation than expected) and the demand people place on water supply, and human activities can exacerbate the impacts of drought. Because drought cannot be viewed solely as a physical phenomenon, it is usually defined both conceptually and operationally.

Commonly used indicators (such as the Palmer Drought Severity Index and the Standard Precipitation Index) evaluate the balance between incoming (through precipitation + snow/ice melt runoff) and outgoing (through evaporation, transpiration, and groundwater recharge) moisture (12, 13). Previous studies dismissing any link between anthropogenic climate change and the current California drought (5–7) have focused exclusively on only one part of this balance, the "incoming" part. These studies argue that climate change cannot be tied to the low levels of precipitation that have accompanied the drought. Another study (8) argues instead that the unusually strong atmospheric ridge in the west that has been associated with the drought (what has been termed the "ridiculously resilient ridge") was made more likely by global warming.

How can one reconcile these divergent findings? Diffenbaugh et al. (2) seem to solve that mystery in their latest assessment. As noted earlier in Fig. 1, recent years haven't just been hot and they haven't just been dry: they've been very hot and very dry at the same time. Climate change appears to be increasing the likelihood of a large-scale atmospheric pattern that yields warm, dry weather in California. That's a double whammy when it comes to the hydrological balance that governs drought: less precipitation and more evaporation and transpiration, at the same time. Combined with the role that temperature plays in increasing the loss of water from agriculture, soils, surface water bodies, and snowpack, the authors note that 100% of the moderately dry years between 1995 and 2014 co-occurred with a positive temperature anomaly. Diffenbaugh et al. (2) note:

Diffenbaugh et al. now add weight to the accumulating evidence that anthropogenic climatic changes are already influencing the frequency, magnitude, and duration of drought in California.

> efforts to understand drought without examining the role of temperature miss a critical contributor to drought risk. Indeed, our results show that even in the absence of trends in mean precipitation—or trends in the occurrence of extremely low-precipitation events—the risk of severe drought in California has already increased due to extremely warm conditions induced by anthropogenic global warming.

In addition, Diffenbaugh et al. (2) highlight model results that suggest the emergence of a climatic regime in which all future dry years coincide with warmer conditions. As they note, the region is moving toward "a transition to a permanent condition of ∼100% risk that any negative—or extremely negative—12-mo precipitation anomaly is also extremely warm" (2).

The conclusions of Diffenbaugh et al. (2) do not stand in isolation. Indeed, they reinforce the results of another new study analyzing future climate model projections (14). That study similarly concludes that there is growing risk of unprecedented drought in the western United States driven primarily by rising temperatures, regardless of whether or not there is a clear trend in precipitation.

That might sound like bad news, and certainly the trends are moving rapidly in the wrong direction. The good news, however, is that this is only one possible future. If society works to limit global warming to under 2 °C, which is still possible (1), then we can likely avoid committing to a brown California. California still has a chance to remain the Golden State.

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