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Key Points:
- California has experienced the worst drought in its historical record during 2012–2015
- Effects of this event have been relatively mild in some sectors but very severe others
- El Niño presents the simultaneous prospect of drought relief but also an increased risk of flooding

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A tale of two California droughts: Lessons amidst record warmth and dryness in a region of complex physical and human geography

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Abstract The state of California has experienced the worst drought in its historical record during 2012–2015. Adverse effects of this multiyear event have been far from uniformly distributed across the region, ranging from remarkably mild in most of California's densely populated coastal cities to very severe in more rural, agricultural, and wildfire-prone regions. This duality of impacts has created a tale of two very different California droughts—highlighting enhanced susceptibility to climate stresses at the environmental and socioeconomic margins of California. From a geophysical perspective, the persistence of related atmospheric anomalies has raised a number of questions regarding the drought's origins—including the role of anthropogenic climate change. Recent investigations underscore the importance of understanding the underlying physical causes of extremes in the climate system, and the present California drought represents an excellent case study for such endeavors. Meanwhile, a powerful El Niño event in the Pacific Ocean offers the simultaneous prospect of partial drought relief but also an increased risk of flooding during the 2015–2016 winter—a situation illustrative of the complex hydroclimatic risks California and other regions are likely to face in a warming world.

California's extraordinary and ongoing drought of 2012–2015 provides a fascinating example of complex interactions between the atmosphere, ocean, and land surface playing out in region of great geographic and socioeconomic diversity. From a meteorological perspective, the present California drought is unparalleled in the more than century-long instrumental record [*Griffin and Anchukaitis*, 2014; *Robeson*, 2015] (Figure 1a); the paleoclimate record suggests that the event is remarkable even in a millennial context [*Griffin and Anchukaitis*, 2014; *Robeson*, 2015]. At the same time, natural and human systems across California have experienced a wide range of drought impacts—ranging from the barely perceptible to the profound. The ongoing situation in California holds the potential to become an important case study both for scientists interested in understanding the causes of underlying temperature and precipitation anomalies and also for decision makers responsible for long-range planning and on-the-ground response to extreme climate events.

The California drought has garnered considerable attention in the scientific community: its complex evolution has highlighted gaps in the collective knowledge regarding processes governing extreme, persistent, and recurring atmospheric circulation patterns in the midlatitudes. The proximal cause of California's enormous multiyear precipitation deficit—a recurring northward shift in the Pacific storm track during California's rainy season associated with a prominent region of high pressure known as the "Ridiculously Resilient Ridge" (Figure 2)—has already been characterized extensively [*Swain et al.*, 2014; *Wang et al.*, 2014; *Seager et al.*, 2015]. Yet partitioning the relative contributions to this highly anomalous atmospheric feature by potential geographically remote influences—including tropical and midlatitude ocean warming [*Wang et al.*, 2014, 2015; *Hartmann*, 2015; *Seager et al.*, 2015; *Lee et al.*, 2015], declining Arctic sea ice [*Lee et al.*, 2015], internal atmospheric variability [*Seager et al.*, 2015], and anthropogenic radiative forcing [*Swain et al.*, 2014; *Wang et al.*, 2014, 2015; *Lee et al.*, 2015]—remains a considerable challenge. The hypothesized importance of complex interactions between various Earth systems across a wide range of spatial and temporal scales reinforces the notion that understanding the physical causes of extreme events like the current drought will require an integrated, cross-disciplinary approach. Given California's location near the climatological winter mean position of the Pacific storm track and its large interannual precipitation variability, such investigations are likely to yield substantial insights into the broader mechanisms underlying regional climate variability and change in the midlatitudes.

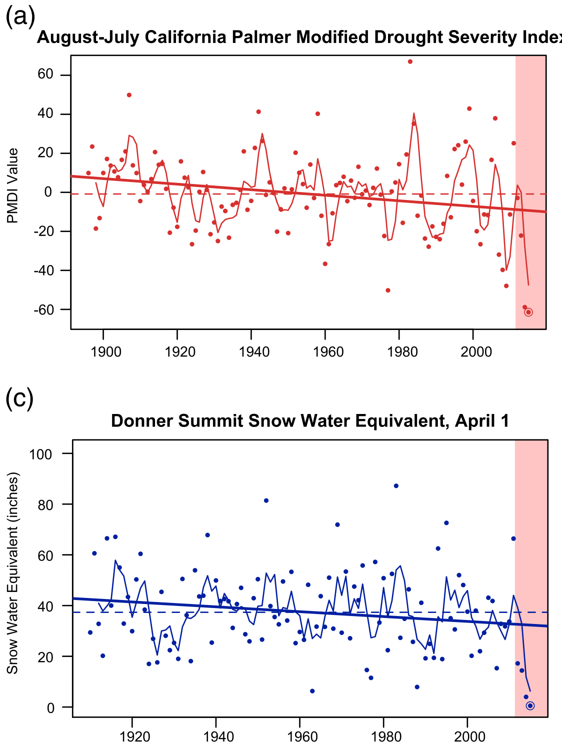

Figure 1. California's record-breaking 2012–2015 drought in historical context. Time series include (a) annually averaged (August–July) Palmer Modified Drought Severity Index, which integrates the net effect of precipitation and temperature, (b) annually averaged (August–July) mean temperature (Fahrenheit), and (d) annually averaged (August–July) precipitation (inches). (c) The time series depicts 1 April snow water equivalent (inches) for Donner Summit in the northern Sierra Nevada Mountains (2103 m above mean sea level). In each respective time series, annual data are plotted as points, the long-term mean value is represented by a horizontal dashed line, the 3 year right-sided moving average is represented by a thin solid curve, and the fitted least squares linear mean trend is represented by a heavy solid curve. The 2015 values are emphasized using concentric circles around each 2015 point, and the 4 year duration of the drought is highlighted with red light shading.

Indeed, the meteorological character of California's multiyear drought has already prompted new questions for physical scientists and policymakers alike. Precipitation, of course, has been far below the long-term mean—and the current drought has featured the driest consecutive 3 year period in California's history (Figure 1d). But even more impressive than these large accumulated precipitation deficits have been the astonishingly warm temperatures with which these dry years have cooccurred (Figure 1b). Record warmth has pervaded all corners of the state during both winter and summer, amplifying already severe drought impacts. The combination of well-above freezing temperatures and low precipitation in the Sierra Nevada Mountains—even in the heart of winter—resulted a snowpack during 2015 that was fully 95% below average [*California Department of Water Resources*, 2015] (Figure 1c). California, like the rest of the planet, has experienced a substantial long-term warming trend over the past century that can be attributed to the human emission of greenhouse gases into the atmosphere [*Diffenbaugh et al.*, 2015]—a trend that very likely contributed to the severity of California's worst drought on record [*Williams et al.*, 2015; *Shukla et al.*, 2015; *AghaKouchak et al.*, 2014] and to the observed overall increase in California drought [*Diffenbaugh et al.*, 2015; *Williams et al.*, 2015]. The increasing occurrence of "hot droughts" is a hallmark of global warming [*Overpeck*, 2013], and the current situation in California illustrates the sometimes dramatic effects of such events in a world with rising greenhouse gas concentrations.

It is a remarkable testament to the Golden State's resilience that for urban residents, the worst drought of California's statehood has been—for the most part—a modest inconvenience. Brown lawns abound, recreational opportunities on regional lakes and rivers have been curtailed, and short showers are now the norm. California's vast water conveyance system has kept thirsty cities quenched, transporting what relatively little water has been available away from the mountains where most of California's precipitation falls to the drier, more densely populated coastal areas. With the exception of occasional images of shrinking reservoir levels on

The Ridiculously Resilient Ridge, 2012-2015

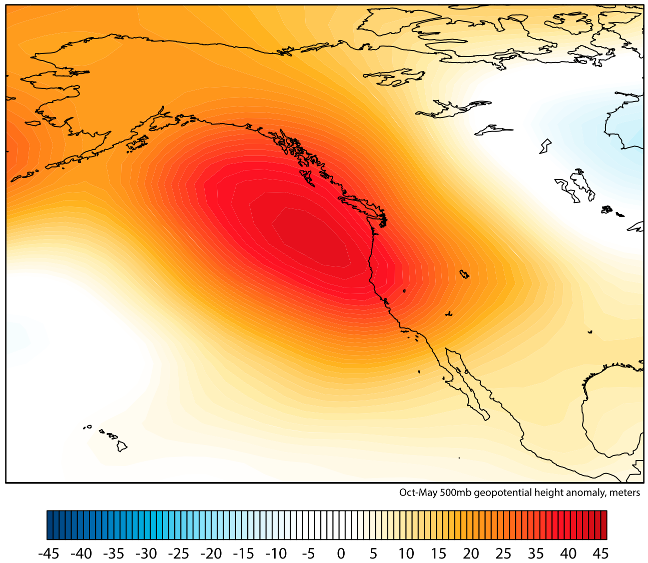

Figure 2. The proximal cause of California's multiyear drought is the remarkable persistence of a region of midtropospheric high pressure known as "The Ridiculously Resilient Ridge." The plotted quantity is the mean cool season 500 mbar geopotential height anomaly (meters) over four consecutive years (i.e., October–May 2012, 2013, 2014, and 2015).

the evening news, California's record-breaking drought has been largely out of sight—and out of mind—for a majority of the state's residents.

But the relatively mild effects in California's urban areas have masked much deeper and more troubling drought impacts elsewhere in the state. Hundreds of thousands of acres of the most productive farmland in North America has been fallowed due to the lack of water, resulting in multi-billion dollar losses [*U.S. Department of Agriculture* (*USDA*), 2014]. Those farms which have managed to stay afloat have done so by pumping tremendous quantities of groundwater out of the Central Valley at a rapid and highly unsustainable rate, leading to increasingly severe overdraft of critically stressed aquifers [*U.S. Geological Survey* (*USGS*), 2015]. This groundwater overdraft has not only led to infrastructure-threatening land subsidence but also caused taps to run dry in smaller, mostly low income agricultural communities dependent on local wells for domestic and drinking water supplies [*Howitt et al*., 2015; *Fresno Bee*, 2015].

Effects upon California's natural environment, too, have steadily worsened with each passing warm and dry year. Low or nonexistent streamflows and unusually warm waters have threatened local extirpation of fish species [*San Francisco Chronicle*, 2015; *Sacramento Bee*, 2015]. Widespread forest mortality—potentially as high as 20% of all trees in the state [*Los Angeles Times*, 2015]—has occurred even among California's native and relatively drought resistant species, helped along by opportunistic bark beetle infestations encouraged by extreme drought stress [*USDA*, 2014]. Drought-killed or weakened trees, coupled with consecutive years of relentlessly warm temperatures, have led to explosive wildfire risk across most of California's millions of forested acres. This dangerous potential has unfortunately been realized during the 2015 fire season: multiple deadly and destructive wildfires have burned hundreds of thousands of acres and destroyed thousands of homes as they raced across the northern part of the state with "unprecedented" speed and intensity [*CAL FIRE*, 2015; *Capital Public Radio*, 2015]. And the fire-scorched, newly hydrophobic soils in these regions hold the potential to cause even more misery once the rains finally do return to California by preventing the absorption of heavy precipitation, increasing runoff and the subsequent risk of flash floods and debris flows.

Federal, state, and local actions have been successful in making California's drought a largely "invisible" disaster for those living in major cities. This relatively optimistic picture, though, does not hold for the residents of Porterville who have gone without running water for over a year; or for the (former) residents of fire-ravaged Middletown, whose entire community was devastated by the Valley Fire; or for San Joaquin Valley farmworkers, who have endured growing hunger and homelessness as their livelihoods turn to dust. Theirs is a very different drought reality than the one facing urban dwellers, but is representative of the challenges faced by tens of thousands of Californians living in smaller, poorer, or more rural communities throughout the state [*Fresno Foundation*, 2015]. This, combined with the essentially unmitigated adverse effects of the drought upon the region's forest and riverine ecosystems, suggests that systems at the socioeconomic and environmental margins of California remain vulnerable—even in a part of the world that is exceptionally wealthy by global standards. The disproportionate burden of extreme climate events borne by those with the least capacity and fewest resources to cope with them represents a key challenge in adapting to a changing climate [*Intergovernmental Panel on Climate Change*, 2012], both in California and across the globe.

California's precipitation predicament in late 2015 is further complicated by the emergence in the tropical Pacific Ocean of one of the most powerful El Niño events of the modern observational era. While El Niño does not always bring increased precipitation to Pacific Southwest—particularly in inland and mountainous parts of northern California, which are critically important regions for snowmelt-fed reservoir storage—top-tier El Niño events are more reliably associated with above-average winter precipitation throughout the state. Adding further uncertainty to the overall climatological picture is the presence of record oceanic warmth well to the north of the canonical El Niño region in the tropics, extending across a vast expanse of the eastern North Pacific. This observationally unprecedented combination of very warm tropical and extratropical conditions suggests that California may be facing an increased risk of extreme precipitation—and associated geophysical hazards, such as flooding and mudslides—despite the likely long-term persistence of its deeply entrenched multiyear drought

Recent evidence suggests that California's undoubtedly warmer future may also be characterized by an increased frequency of extremely dry and extremely wet years [*Berg and Hall*, 2015; *Yoon et al*., 2015]—despite relatively modest changes in mean precipitation [*Neelin et al*., 2013; *Seager et al*., 2015]. An increased risk of both drought and flood will require very different climate adaptation measures than those needed in a warming and gradually wetting California, underscoring the critical importance of clearly communicating these climatological nuances to decision makers. Ultimately, the successes (and failures) of California's response to the current drought—and its management of potentially competing flood risks associated with the evolving El Niño event—may offer a preview of challenges the state will face in decades to come.

Collectively, the body of research already published on the ongoing California drought points to an urgent need to better understand extreme events in the climate system. Studies motivated by the California drought have yielded more broadly generalizable findings regarding the physical processes responsible for changing regional climate extremes [*Swain et al*., 2014; *Wang et al*., 2014, 2015; *Lee et al*., 2015; *Berg and Hall*, 2015; *Yoon et al*., 2015]. Case studies focused on California have demonstrated that causes of trends in meteorological extremes are not necessarily inferable from those underlying regional mean trends, reiterating the importance of using quantitative metrics capable of accounting for nonstationary variability in observational and model-based analyses in a global context [*Xie et al*., 2015]. Ultimately, actions taken in response to lessons learned in the science, policy, and management realms during the present drought have to the potential to improve resilience—both by increasing our understanding of the relevant geophysical risks and by optimizing our adaptation strategies to future climate extremes.

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