Anthropogenic warming has increased drought risk in California

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California is currently in the midst of a record-setting drought. The drought began in 2012 and now includes the lowest calendar-year and 12-mo precipitation, the highest annual temperature, and the most extreme drought indicators on record. The extremely warm and dry conditions have led to acute water shortages, groundwater overdraft, critically low streamflow, and enhanced wildfire risk. Analyzing historical climate observations from California, we find that precipitation deficits in California were more than twice as likely to yield drought years if they occurred when conditions were warm. We find that although there has not been a substantial change in the probability of either negative or moderately negative precipitation anomalies in recent decades, the occurrence of drought years has been greater in the past two decades than in the preceding century. In addition, the probability that precipitation deficits co-occur with warm conditions and the probability that precipitation deficits produce drought have both increased. Climate model experiments with and without anthropogenic forcings reveal that human activities have increased the probability that dry precipitation years are also warm. Further, a large ensemble of climate model realizations reveals that additional global warming over the next few decades is very likely to create ~100% probability that any annual-scale dry period is also extremely warm. We therefore conclude that anthropogenic warming is increasing the probability of co-occurring warm–dry conditions like those that have created the acute human and ecosystem impacts associated with the “exceptional” 2012–2014 drought in California.
Results

We analyze the “Palmer” drought metrics available from the US National Climatic Data Center (NCDC) (25). The NCDC Palmer metrics are based on the Palmer Drought Severity Index (PDSI), which uses monthly precipitation and temperature to calculate moisture balance using a simple “supply-and-demand” model (26) (Materials and Methods). We focus on the Palmer Modified Drought Index (PMDI), which moderates transitions between wet and dry periods (compared with the PDSI) (27). However, we note that the long-term time series of the PMDI is similar to that of other Palmer drought indicators, particularly at the annual scale (Figs. S1 and S2).

Because multiple drought indicators reached historic lows in July 2014 (Figs. S1–S3), we initially focus on statewide PMDI, temperature, and precipitation averaged over the August–July 12-mo period. We find that years with a negative PMDI anomaly exceeding −1.0 SDs (hereafter “1-SD drought”) have occurred approximately twice as often in the past two decades as in the preceding century (six events in 1995–2014 = 30% of years; 14 events in 1896–1994 = 14% of years) (Fig. 1A and Fig. S4). This increase in the occurrence of 1-SD drought years has taken place without a substantial change in the probability of negative precipitation anomalies (53% in 1896–2014 and 55% in 1995–2014) (Figs. 1A and 2A and B). Rather, the observed doubling of the occurrence of 1-SD drought years has coincided with a doubling of the frequency with which a negative precipitation year produces a 1-SD drought, with 55% of negative precipitation years in 1995–2014 co-occurring with a −1.0 SD PMDI anomaly, compared with 27% in 1896–1994 (Fig. 1A and B).

Most 1-SD drought years have occurred when conditions were both dry (precipitation anomaly < 0) and warm (temperature anomaly > 0), including 15 of 20 1-SD drought years during 1896–2014 (Fig. 2A and Fig. S4) and 6 of 6 during 1995–2014 (Fig. 2B and Fig. S4). Similarly, negative precipitation anomalies are much more likely to produce 1-SD drought if they co-occur with a positive temperature anomaly. For example, of the 63 negative precipitation years during 1896–2014, 15 of the 32 warm–dry years (47%) produced 1-SD drought, compared with only 5 of the 31 cool–dry years (16%) (Fig. 2A). (During 1896–1994, 41% of warm–dry years produced 1-SD droughts, compared with 17% of cool–dry years.) The probability that a negative precipitation anomaly co-occurs with a positive temperature anomaly has increased recently, with warm–dry years occurring more than twice as often in the past two decades (91%) as in the preceding century (42%) (Fig. 1B).

All 20 August–July 12-mo periods that exhibited a −1.0 SD PMDI anomaly also exhibited a −0.5 SD precipitation anomaly (Fig. 1B and 2E), suggesting that moderately low precipitation is prerequisite for a 1-SD drought year. However, the occurrence of −0.5 SD precipitation anomalies has not increased in recent years (40% in 1896–2014 and 40% in 1995–2014) (Fig. 2A and B). Rather, these moderate precipitation deficits have been far more likely to produce 1-SD drought when they occur in a warm year. For example, during 1896–2014, 1-SD drought occurred in 15 of the 28 years (54%) that exhibited both a −0.5 SD precipitation anomaly and a positive temperature anomaly, but in only 5 of the 20 years (25%) that exhibited a −0.5 SD precipitation anomaly and a negative temperature anomaly (Fig. 2A). During 1995–2014, 6 of the 8 moderately dry years produced 1-SD drought (Fig. 1C), with all 6 occurring in years in which the precipitation anomaly exceeded −0.5 SD and the temperature anomaly exceeded 0.5 SD (Fig. 1C).

Taken together, the observed record from California suggests that (i) precipitation deficits are more likely to yield 1-SD PMDI droughts if they occur when conditions are warm and (ii) the occurrence of 1-SD PMDI droughts, the probability of precipitation deficits producing 1-SD PMDI droughts, and the probability of precipitation deficits co-occurring with warm conditions have all been greater in the past two decades than in the preceding century.

These increases in drought risk have occurred despite a lack of substantial change in the occurrence of low or moderately low precipitation years (Figs. 1B and 2A and B). In contrast, statewide warming (Fig. 1C) has led to a substantial increase in warm conditions, with 80% of years in 1995–2014 exhibiting a positive temperature anomaly (Fig. 2B), compared with 45% of years in 1896–2014 (Fig. 2A). As a result, whereas 58% of moderately dry years were warm during 1896–2014 (Fig. 2A) and 50% were warm during 1896–1994, 100% of the 8 moderately dry years in 1995–2014 co-occurred with a positive temperature anomaly (Fig. 2B). The observed statewide warming (Fig. 1C) has therefore substantially increased the probability that when moderate precipitation deficits occur, they occur during warm years.

The recent statewide warming clearly occurs in climate model simulations that include both natural and human forcings (“Historical” experiment), but not in simulations that include only natural forcings (“Natural” experiment) (Fig. 3B). In particular, the Historical and Natural temperatures are found to be different at the 0.001 significance level during the most recent 20-, 30-, and 40-y periods of the historical simulations (using the block bootstrap resampling applied in ref. 28). In contrast, although the Historical experiment exhibits a slightly higher mean annual precipitation (0.023 significance level), there is no statistically
A dry year is approximately twice the probability of a warm anomaly (Fig. 3A and C). However, the Historical experiment exhibits greater probability of a –0.5 SD precipitation anomaly co-occurring with a positive temperature anomaly (0.001 significance level) (Fig. 3D), suggesting that human forcing has caused the observed increase in probability that moderately dry precipitation years are also warm.

The fact that the occurrence of warm and moderately dry years approaches that of moderately dry years in the last decades of the Historical experiment (Fig. 3B and C) and that 91% of negative precipitation years in 1995–2014 co-occurred with warm anomalies (Fig. 1B) suggests possible emergence of a regime in which nearly all dry years co-occur with warm conditions. We assess this possibility using an ensemble of 30 realizations of a single global climate model [the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM1) Large Ensemble experiment (“LENS”)] (Materials and Methods). Before ~1980, the simulated probability of a warm–dry year is approximately half that of a dry year (Fig. 4B), similar to observations (Figs. 1B and 2). However, the simulated probability of a warm–dry year becomes equal to that of a dry year by ~2030 of RCP8.5. Likewise, the probabilities of co-occurring 0.5, 1.0, and 1.5 SD warm–dry anomalies become approximately equal to those of 0.5, 1.0, and 1.5 SD dry anomalies (respectively) by ~2030 (Fig. 4B).

The probability of co-occurring extremely warm and extremely dry conditions (1.5 SD anomaly) remains greatly elevated throughout the 21st century (Fig. 4B). In addition, the number of multidecadal periods in which a –0.5 SD precipitation anomaly co-occurs with a 0.5 SD temperature anomaly more than doubles between the Historical and RCP8.5 experiments (Fig. 4A). We find similar results using a 12-mo moving average (Fig. 4C). As with the August–July 12-mo mean (Fig. 4B), the probability of a dry year is approximately twice the probability of a warm–dry year for all 12-mo periods before ~1980 (Fig. 4C). However, the occurrence of warm years (including 1.5 SD temperature anomalies) increases after ~1980, reaching 1.0 by ~2030. This increase implies a transition to a permanent condition of ~100% risk that any negative—or extremely negative—12-mo precipitation anomaly is also extremely warm.

The overall occurrence of dry years declines after ~2040 (Fig. 4C). However, the occurrence of extreme 12-mo precipitation deficits (~1.5 SD) is greater in 2006–2080 than in 1920–2005 (~0.03 significance level). This detectable increase in extremely low-precipitation years adds to the effect of rising temperatures and contributes to the increasing occurrence of extremely warm–dry 12-mo periods during the 21st century.

All four 3-mo seasons likewise show higher probability of co-occurring 1.5 SD warm–dry anomalies after ~1980, with the probability of an extremely warm–dry season equaling that of an extremely dry season by ~2030 for spring, summer, and autumn, and by ~2060 for winter (Fig. 4D). In addition, the probability of a –1.5 SD precipitation anomaly increases in spring (P < 0.001) and autumn (P = 0.01) in 2006–2080 relative to 1920–2005, with spring occurrence increasing by ~75% and autumn occurrence increasing by ~44%—which represents a substantial and statistically significant increase in the risk of extremely low-precipitation events at both margins of California’s wet season. In contrast, there is no statistically significant difference in the probability of a –1.5 SD precipitation anomaly for winter.

Discussion
A recent report by Seager et al. (30) found no significant long-term trend in cool-season precipitation in California during the 20th and early 21st centuries, which is consistent with our

![August-July 12-month Mean](image)

Fig. 2. Historical occurrence of drought, precipitation, and temperature in California. Standardized anomalies are shown for each August–July 12-mo period in the historical record (calculated as in Fig. 1). Anomalies are shown for the full historical record (A) and for the most recent two decades (B). Percentage values show the percentage of years meeting different precipitation and drought criteria that fall in each quadrant of the temperature-precipitation space. The respective criteria are identified by different colors of text.
findings. Further, under a scenario of strongly elevated greenhouse forcing, Neelin et al. (31) found a modest increase in California mean December–January–February (DJF) precipitation associated with a local eastward extension of the mean subtropical jet stream west of California. However, considerable evidence (8–11, 31–33) simultaneously suggests that the response of northeastern Pacific atmospheric circulation to anthropogenic warming is likely to be complex and spatiotemporally inhomogeneous, and that changes in the atmospheric mean state may not be reflective of changes in the risk of extreme events (including atmospheric configurations conducive to precipitation extremes). Although there is clearly value in understanding possible changes in precipitation, our results highlight the fact that efforts to understand drought without examining the role of temperature miss a critical component. 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.

We note that the interplay between the existence of a well-defined summer dry period and the historical prevalence of a substantial high-elevation snowpack may create particular susceptibility to temperature-driven increases in drought duration and/or intensity in California. In regions where precipitation exhibits a distinct seasonal cycle, recovery from preexisting drought conditions is unlikely during the characteristic yearly dry spell (34). Because California’s dry season occurs during the warm summer months, soil moisture loss through evapotranspiration (ET) is typically high—meaning that soil moisture deficits that exist at the beginning of the dry season are exacerbated by the warm conditions that develop during the dry season, as occurred during the summers of 2013 and 2014 (7).

Further, California’s seasonal snowpack (which resides almost entirely in the Sierra Nevada Mountains) provides a critical source of runoff during the low-precipitation spring and summer months. Trends toward earlier runoff in the Sierra Nevada have already been detected in observations (e.g., ref. 35), and continued global warming is likely to result in earlier snowmelt and increased rain-to-snow ratios (35, 36). As a result, the peaks in California’s snowmelt and surface runoff are likely to be more pronounced and to occur earlier in the calendar year (35, 36), increasing the duration of the warm-season low-runoff period (36) and potentially reducing montane surface soil moisture (37). Although these hydrological changes could potentially increase soil water availability in previously snow-covered regions during the cool low-ET season (34), this effect would likely be outweighed by the influence of warming temperatures (and decreased runoff) during the warm high-ET season (36, 38), as well as by the increasing occurrence of consecutive years with low precipitation and high temperature (Fig. 4.4).

The increasing risk of consecutive warm–dry years (Fig. 4.4) raises the possibility of extended drought periods such as those found in the paleoclimate record (14, 39, 40). Recent work suggests that record warmth could have made the current event the most severe annual-scale drought of the past millennium (12). However, numerous paleoclimate records also suggest that the region has experienced multidecadal periods in which most years were in a drought state (14, 39, 41, 42), albeit less acute than the current California event (12, 39, 41). Although multidecadal ocean variability was a primary cause of the megadroughts of the last millennium (41), the emergence of a condition in which there is ~100% probability of an extremely warm year (Fig. 4) substantially increases the risk of prolonged drought conditions in the region (14, 39, 40).

A number of caveats should be considered. For example, ours is an implicit approach that analyzes the temperature and precipitation conditions that have historically occurred with low PMDI years, but does not explicitly explore the physical processes that produce drought. The impact of increasing temperatures on the processes governing runoff, baseflow, groundwater, soil moisture, and land-atmosphere evaporative feedbacks over both the historical period and in response to further global warming remains a critical uncertainty (43). Likewise, our analyses of anthropogenic forcing rely on global climate models that do not resolve the topographic complexity that strongly influences California’s precipitation and temperature. Further investigation using high-resolution modeling approaches that better resolve the boundary conditions and fine-scale physical processes (44–46) and/or using analyses that focus on the underlying large-scale climate dynamics of individual extreme events (8) could help to overcome the limitations of simulated precipitation and temperature in the current generation of global climate models.

**Conclusions**

Our results suggest that anthropogenic warming has increased the probability of the co-occurring temperature and precipitation conditions that have historically led to drought in California. In addition, continued global warming is likely to cause a transition to a regime in which essentially every seasonal, annual, and multiannual precipitation deficit co-occurs with historically warm conditions. The current warm–dry event in California—as well as historical observations of previous seasonal, annual, and multiannual warm–dry events—suggests such a regime would substantially increase the risk of severe impacts on human and natural systems. For example, the projected increase in extremely
low precipitation and extremely high temperature during spring and autumn has substantial implications for snowpack water storage, wildfire risk, and terrestrial ecosystems (47). Likewise, the projected increase in annual and multiannual warm–dry periods implies increasing risk of the acute water shortages, critical groundwater overdraft, and species extinction potential that have been experienced during the 2012–2014 drought (5, 20).

California’s human population has increased by nearly 72% since the much-remembered 1976–1977 drought (1). Gains in urban and agricultural water use efficiency have offset this rapid increase in the number of water users to the extent that overall water demand is nearly the same in 2013 as it was in 1977 (5). As a result, California’s per capita water use has declined in recent decades, meaning that additional short-term water conservation in response to acute shortages during drought conditions has become increasingly challenging. Although a variety of opportunities exist to manage drought risk through long-term changes in water policy, management, and infrastructure (5), our results strongly suggest that global warming is already increasing the probability of conditions that have historically created high-impact drought in California.

Materials and Methods

We use historical time series of observed California statewide temperature, precipitation, and drought data from the National Oceanic and Atmospheric Administration’s NCDC (7). The data are from the NCDC “nClimDiv” di- visional–precipitation–drought database, available at monthly time resolution from January 1895 to the present (7, 25). The NCDC nClimDiv database includes temperature, precipitation, and multiple Palmer drought indicators, aggregated at statewide and substate climate division levels for the United States. The available Palmer drought indicators include PDSI, the Palmer Hydrological Drought Index (PHDI), and PMDI. PMDI and PHDI are variants of PDSI (25–27, 48, 49). PDSI is an index that measures the severity of wet and dry anomalies (26). The NCDC nClimDiv PDSI calculation is reported at the monthly scale, based on monthly temperature and precipitation (49). Together, the monthly temperature and precipitation values are used to compute the net moisture balance, based on a simple supply-and-demand model that uses potential evapotranspiration (PET) calculated using the Thornthwaite method. Calculated PET values can be very different when using other methods (e.g., Penman–Monteith), with the Thornthwaite method’s dependence on surface temperature creating the potential for overestimation of PET (e.g., ref. 43). However, it has been found that the method of choice in the calculation of PET does not critically influence the calculation of historical PDSI estimates in the vicinity of Cali- fornia (15, 43, 50). In contrast, the sensitivity of the PET calculation to large increases in temperature could make the PDSI inappropriate for calculating the response of drought to high levels of greenhouse forcing (15). As a re- sult, we analyze the NCDC Palmer indicators in conjunction with observed temperature and precipitation data for the historical period, but we do not calculate the Palmer indicators for the future (for future projections of the PDSI, refer to refs. 15 and 40).

Because the PDSI is based on recent temperature and precipitation conditions (and does not include human demand for water), it is considered an indicator of “meteorological” drought (25). The PDSI calculates “wet,” “dry,” and “transition” indices, using the wet or dry index when the probability is 100% and the transition index when the probability is less than 100% (26). Because the PDSI always calculates a probability-weighted average of the wet and dry indices (27), the PDSI and PMDI will give equal values in periods that are clearly wet or dry, but the PMDI will yield smoother transitions between wet and dry periods (25). In this work, we use the PMDI as our primary drought indicator, although we note that the long-term time series of the PMDI is similar to that of the PDSI and PHDI, particularly at the annual scale considered here (Figs. S1 and S2).

We analyze global climate model simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) (51). We compare two of the CMIP5 multimodel historical experiments (which were run through 2005): (i) the Historical experiment, in which the climate models are prescribed both an- thrhogenic and nonanthropogenic historical climate forcings, and (ii) the Natural experiment, in which the climate models are prescribed only the nonanthropogenic historical climate forcings. We analyze those realizations for which both temperature and precipitation were available from both experiments at the time of data acquisition. We calculate the temperature and precipitation values over the state of California at each model’s native resolution using all grid points that overlap with the geographical boundaries of California, as defined by a high-resolution shapefile (vector digital data obtained from the US Geological Survey via the National Weather Service at www.nws.noaa.gov/geodata/catalog/national/html/us_state.htm). We also analyze NCAR’s large ensemble (“LENS”) climate model experiment (29). The LENS experiment includes 30 realizations of the NCAR CESM1. This large single-model experiment enables quantification of the uncertainty arising from internal climate system variability. Although the calculation of this “irreducible” uncertainty likely varies between climate models, it exists independent of uncertainty arising from model structure, model parameter values, and climate forcing path. For each realization, we calculate the PMDI. LENS results were available for 1920–2005 in the Historical ex- periment and 2006–2080 in the RCP8.5 (Representative Concentration Pathway) experiment. The four RCPs are mostly indistinguishable over the first half of the 21st century (52). RCP8.5 has the highest forcing in the second half of the 21st century and reaches ~4 °C of global warming by the year 2100 (52).

Given that the ongoing California drought encompasses the most extreme 12-mo precipitation deficit on record (8) and that both temperature and many drought indicators reached their most extreme historical values for California in July 2014 (7) (Fig. 1 and Figs. S1 and S2), we use the 12-mo August–July period as one period of analysis. However, because severe conditions can manifest at both multiannual and subannual timescales, we also analyze the probability of occurrence of co-occurring warm and dry conditions for multiannual periods for all possible 12-mo periods, and for the winter (DJF), spring (March–April–May), summer (June–July–August), and autumn (September–October–November) seasons.

We use the monthly-mean time series from NCDC to calculate observed time series of statewide 12-mo values of temperature, precipitation, and PMDI. Likewise, we use the monthly-mean time series from CMIPS and LENS to calculate simulated time series of statewide 12-mo and seasonal values of PMDI and PHDI. For the multiannual analysis, we calculate consecutive occurrences of August–July 12-mo values. For the analysis of all possible 12-mo periods, we calculate the annual anomaly from the baseline measured over the period of record (1971–2005) for each observed or simulated realization, where the baseline is defined as the mean value over the length of the record, (ii) the annual anomaly from the baseline mean value, (iii) the SD of the detrended baseline annual anomaly time se- ries, and (iv) the ratio of each individual annual anomaly value to the SD of the detrended baseline annual anomaly time series. (For the 21st-century simulations, we use the Historical simulation as the baseline.) Our time series of standardized values are thereby derived from the time series of 12-mo annual (or 3-mo seasonal) mean anomaly values that occur in each year.

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We quantify the statistical significance of differences in the populations of drought during the periods using the bootstrap resampling approach (53). To perform the bootstrap resampling, we randomly sample (with replacement) 28. For the CMIPS Historical and Natural ensembles, we compare the pop- ulations of the August–July values in the two experiments for the 1986– 2005, 1976–2005, and 1966–2005 periods. For the LENS seasonal analysis, we compare the respective populations of DJF, March–April–May, June–July–August, and September–October–November values in the 1920–2005 and 2006–2080 periods. For the LENS 12-mo analysis, we compare the pop- ulations of 12-mo values in the 1920–2005 and 2006–2080 periods, testing block lengths up to 16 to account for temporal autocorrelation out to 16 mo for the 12-mo running mean data. (Autocorrelations beyond 16 mo are found to be negligible.)

Throughout the text, we consider drought to be those years in which negative 12-mo PMDI anomalies exceed ~1.0 SDs of the historical interannual PMDI variability. We stress that this value is indicative of the variability of the annual (12-mo) PMDI, rather than of the monthly values (compare Fig. 1 and Figs. S1 and S2). We consider “moderate” temperature and precipitation anomalies to be those that exceed 0.5 SDs (“0.5 SD”) and “extreme” tem- perature and precipitation anomalies to be those that exceed 1.5 SDs (“1.5 SD”).

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**Fig. S1.** Time series of monthly values of the PDSI (A), PMDI (B), and PHDI (C), for the 1895–2014 observed record.
Fig. S2. Time series of August–July annual values of the PDSI (A), PMDI (B), and PHDI (C), for the 1895–2014 observed record. Annual values are calculated as the 12-mo mean from August of the starting year to July of the following year.
Fig. S3. Histograms of August–July annual values of California statewide PMDI, precipitation, and temperature for the 1895–2014 observed record. Histograms show the distribution of values from the time series shown in Fig. 1. As in Fig. 1, values are calculated for the August–July 12-mo mean in each year of the observed record, beginning in August 1895. In each year, the standardized anomaly is expressed as the magnitude of the anomaly from the long-term annual mean divided by the SD of the detrended historical annual anomaly time series. The respective standardized values for the August 2013–July 2014 period are shown in pink.
The joint probability distribution function (PDF) of historically observed temperature and precipitation anomalies for the full historical record (**Left column**) and the most recent two decades (**Right column**). The **Top row** (**A** and **B**) shows the joint PDF for all years in the period. The **Bottom row** (**C** and **D**) shows the joint PDF for those years in which the standardized anomaly of the PMDI is less than $-1.0$ SDs. Percentage values show the percentage of years meeting different precipitation criteria that fall in each quadrant of temperature–precipitation space. The respective criteria are identified by different colors of text.

**Fig. S4.** The joint probability distribution function (PDF) of historically observed temperature and precipitation anomalies for the full historical record (**Left column**) and the most recent two decades (**Right column**). The **Top row** (**A** and **B**) shows the joint PDF for all years in the period. The **Bottom row** (**C** and **D**) shows the joint PDF for those years in which the standardized anomaly of the PMDI is less than $-1.0$ SDs. Percentage values show the percentage of years meeting different precipitation criteria that fall in each quadrant of temperature–precipitation space. The respective criteria are identified by different colors of text.