Science Advances:

Current Effects of Human-induced Climate Change on California Drought

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Summary: A human-induced warming and wetting of California State since preindustrial times is shown to increase the frequency of severe droughts whose metric incorporates shallow soil moisture, but to decrease the frequency of severe drought whose metric incorporates deep soil moisture.

Abstract

The 2011-2014 California drought (i.e., 3 years) has cast a heavy burden on statewide agriculture and water resources, further exacerbated by concurrent extreme high temperatures. Furthermore, industrial-era global climate warming brings into question the role of long-term climate change on the 2011-2014 CA drought. How has human-induced climate change affected California drought risk? Here we apply observations and model experimentation to characterize this drought employing metrics that synthesize drought duration, cumulative precipitation deficit, and soil moisture depletion. Our model simulations show that climate change since the late 19th Century induces both increased annual precipitation and increased surface temperature over California, consistent with prior studies. As a result, droughts defined using bivariate indicators of precipitation and 10-cm soil moisture become more frequent because shallow soil moisture responds most sensitively to increased evaporation driven by warming. However, when using 1-m soil moisture as co-variate, droughts become less frequent because deep soil moisture responds most sensitively to increased precipitation. The results illustrate different land surface responses to anthropogenic forcing at this time with return periods for severe droughts either increasing or decreasing about 10% depending on drought metric.

Introduction

The failure of three consecutive rainy seasons since 2011 has produced severe California moisture deficits reducing agricultural productivity and depleting ground water (*1,2*). Aggravated by record surface air temperatures (*3*), the concern is that this drought may be symptomatic of human-induced change, and that a new normal of dryness is emerging that will soon rival the worst droughts since 1000 AD (*4*). The question has been raised how human influences on climate have played a role in this drought event. Whereas some initial evidence indicates that human-induced climate change has unlikely caused the failed rains (*5,6*), questions nonetheless remain about the role of global warming. How, for instance, has the return period for such an extreme drought occurrence over California changed as a result of the change in climate since pre-industrial times?

Event return period is an essential characteristic of natural hazards that informs decision makers and management agencies seeking to mitigate societal impacts and ensure resilience (*7-9*). In the case of precipitation alone, the recurrence interval/frequency of deficits that contribute to drought is typically evaluated from single indicator/univariate approaches (e.g., deficit in precipitation, Standardized Precipitation Index, i.e., SPI) (*10,11*). Yet, as the 2011-2014 California drought (hereafter, CA drought) suggests, both dynamic and thermodynamic processes characterize dry conditions that thus dictates the use of multiple indicators for characterizing drought conditions. The traditional univariate analysis cannot account for the combined effects of multiple extremes (e.g., heat waves, soil moisture) on droughts (*12*); neither can they address the interdependence between drought characteristics (e.g., drought severity, duration) (*13*). A potential consequence is misinterpretation of drought risk, and how changes in some meteorological elements may bear upon a change in drought risk itself (*14*).

Over the last decade, copulas have emerged as an effective method to describe multivariate probability distributions and for addressing the interrelationship between variables (*15,16*). Here, we attempt to characterize CA drought from the multivariate viewpoint (e.g., drought duration and severity, rainfall and soil moisture), assess the return period of the current event, and quantify how the return period has changed as a consequence of human-induced climate change.

One way of accounting for the combined effects of rainfall and temperature on drought is to examine soil moisture. However, long-term soil moisture observations are not readily available. Here, we analyze the combined effects of precipitation and soil moisture on droughts using long-term historical simulations from the Community Climate System Model 4.0 (hereafter, CCSM4) with preindustrial (i.e., the year of 1850, hereafter, Y1850) and industrial/current (i.e., the year of 2000, hereafter, Y2000) climate forcings, respectively. We investigate the current role of anthropogenic climate change in CA drought, defined in a multivariate sense involving precipitation and soil moisture, by quantifying the changes in drought frequency for a range of severities between preindustrial and current climate.

Results

a. Characterizing CA drought from historical precipitation

Our analysis of the historical California water year (WY) precipitation time series (see Section *a* in Materials and Methods) identifies 30 drought events in the past 119 years, 10 of which have had three-year or longer duration (see Fig. 1). The 2011-14 three-year drought has been the most severe of all prior three-year events, having an accumulated precipitation deficit of 522 mm corresponding to almost a full WY loss.

Fig. 2A summarizes the joint distribution (see Section *c* in Materials and Methods) of CA drought duration (abscissa) and severity (ordinate) for these 30 historical events. A red asterisk identifies the current CA drought. In terms of duration alone, 6 prior events were longer lasting. In terms of severity alone, only two prior events have had larger cumulative precipitation deficits (1987-1992 and 1928-1931). The result of a bivariate copula analysis based on these precipitation co-variates indicates that the 2011-14 CA drought has a roughly 30-year return period. This is to be contrasted with 19-year and 41-year return periods estimated from univariate analysis of drought duration and precipitation deficit, respectively (see Fig. S1). Clearly, the interdependence/combined effect of physical attributes of drought alters the perceived intensity of the current event and its expected recurrence. Nonetheless, whether using univariate or bivariate precipitation-based methods, the data indicate that the current CA drought is neither unprecedented nor rare within the 119-year instrumental record. This interpretation is consistent with inferences based on comparing the current event to univariate drought statistics derived from a 400-year paleo-reconstruction of CA precipitation (*17*). (We note, at the time of this writing, that the current event is ongoing with precipitation conditions during the first half of the 2015 rainy season suggesting a 4th year of drought is likely.)

Our results are largely insensitive to the use of other precipitation indices, which provide guidance in drought management. For example, Fig. 2B shows the result of a bivariate analysis for 18-month SPI (SPI18). While based on monthly statistics, such a time window is broadly consistent with WY averages used here. When applied to the current CA drought event, SPI18 yields a 29 month duration drought event that broadly matches the 3 consecutive dry years diagnosed from observed WY data. The result of the bivariate analysis of duration and severity is in good agreement with results using observed WY precipitation, with a return period estimated to be about 30 years.

b. CA drought in climate simulations

Climate simulations are based on two long runs of CCSM4 (see Section *b* in Materials and Methods). As a measure of CCSM4 suitability for addressing the role of human-induced climate change in CA drought, we first repeat a bivariate analysis (see Section *c* in Materials and Methods) for duration and severity of SPI18 using the 2133 years of model simulations. The results in Fig. 2C show the isolines of return periods for droughts occurring relative to the model's equilibrium climate of year 1850 (black) and year 2000 (magenta). The red asterisks and red circles denote drought events having similar duration and severity attributes as the 2011-14 CA drought. For such analogous conditions, the CCSM4-derived recurrence interval analyses yield return periods of 20-30 years, close to the estimated return period of the 2011-14 drought defined using the instrumental record.

The model-based analysis reveals numerous drought events having much longer duration and greater severity, akin to the impression gained from the short observational record. The model result thereby strengthens the evidence that a 30-year CA drought is not a rare event from the bivariate viewpoint using SPI. With the benefit of the much larger sample, it is now also evident that for particular drought duration (e.g. 40 months), drought severity can greatly vary. This yields a wide range in return periods, from as short as 20 years to as long as 150 years (see Fig. 2C). The results thus illustrate the importance of using multiple indicators for characterizing CA drought in order to accurately express the event and posit a meaningful return period.

The statistics of drought in the two equilibrium climates are not appreciably different from each other. Note the similarity in bivariate SPI-based return periods denoted by isolines for the cold/dry preindustrial CA climate compared to the warm/wet current CA climate of CCSM4. This result suggests that monthly and interannual statistics of CA precipitation (e.g. consecutive dry months or dry years) are not materially different within each of these two climate states, and as such drought characteristics are not materially altered. However, the assessment in Fig. 2 does not directly express climate change impacts, which requires calculating statistics of the Y2000 data relative to the Y1850 reference. And, by focusing solely on precipitation, it does not demonstrate how a warmed CA climate is currently affecting the intensity of CA drought.

c. The current role of climate change on CA drought

To assess the current effects of human-induced climate change on CA droughts, such as the 2011-14 event, we diagnose the long-term change in return periods for droughts characterized using two different covariates. One involves drought defined by the joint deficits of precipitation and 10-cm soil moisture, and the other by the joint deficits of precipitation and 1-m soil moisture. The analysis is applied to droughts having duration from 2 to 4 years (hereafter, 3-yr drought) in order to be representative of the 2011-2014 event's longevity. In order to evaluate the impact of climate change on 3-yr droughts, the statistics of precipitation and soil moisture in the Y2000 simulation are calculated relative to the climatology of the Y1850 simulation.

Fig. 3A shows the occurrences of 3-yr drought events given by the joint conditions of averaged 10-cm soil moisture anomalies (abscissa) and accumulated precipitation deficit/severity (ordinate), both standardized with respect to the annual pre-industrial climatology. Fig. 3B shows the same analysis except using 1-m soil moisture as co-variate. The joint return periods, based on copula analysis for the Y1850 simulations, are indicated by the black contours (top). To quantify the changes in drought frequency, a box-whisker analysis of the count of drought events exceeding different quantiles/isolines (black contours) is shown in the lower panels. We summarize the change in the frequency of 3-yr drought events relative to their pre-industrial frequency.

Two very different impacts of human-induced climate change arise, a result mostly of depth-dependent soil moisture sensitivity to meteorological forcing. For drought metrics involving 10-cm soil moisture the results indicate a statistically significant **increase** (i.e., at 95% significance level) in the drought frequency across all categories of severity, with the most notable increase in the frequency of moderate (e.g., 10~30-yr) to severe (e.g., 50-yr) droughts. Recalling that the simulated long-term climate change is wetter and warmer for CA, this metric of drought ---incorporating a very shallow soil layer---indicates that increased evaporative demand trumps the increase in precipitation thereby yielding more frequent droughts. Soil moisture deficits in this shallow layer thus increase, and droughts would be intensified as a result of the warmer climate. Of course, a significant portion of the increased precipitation would infiltrate to deeper layers, and furthermore these deep layers would lose moisture primarily by transpiration rather than both transpiration and evaporation as in the 10-cm layer, leading to different sensitivities to the change in meteorological conditions. For drought metrics involving 1-m soil moisture and precipitation, the results (Figs. 3B and 3D) indicate a statistically significant **decrease** (i.e., at 95% significance level) in the drought frequency across all categories of severity, with the most notable decrease in the frequency of severe to extreme droughts. It is clear in this characterization of drought that the increase in CA precipitation in response to the human-induced climate change is dominating the drought statistics when the covariate is deep layer soil moisture. Unlike the surficial 10 cm of soil that is depleted by both transpiration and direct evaporation, water loss in the deep soil layer depends much more on transpiration, making it less susceptible to temperature effects.

How do these very different land surface responses to anthropogenic forcing change the occurrence frequency and return periods of severe California drought? From a perspective of *shallow land surface moisture balances* (i.e., 10 cm), we find the frequency of California drought having return periods of 30-50 years to increase from 30 events in pre-industrial climate to 34 events in the current climate. In other words, a drought event that would occur about every 30-50-years is now occurring every 26-44-years. From a perspective of *deep land surface moisture balances* (i.e., 1 m), we find the 30-50-year drought event of pre-industrial climate now occurs once every 35-58 years. Whereas the availability of over 4000 years of model simulations has permitted a statistically robust estimate of these modest changes, it is important to emphasize that detectability of either a 10% increase or a 10% decrease in the return periods of severe CA drought at this time in the observational record is exceedingly unlikely.

Discussion

Current understanding is that while human-induced climate change has unlikely caused the failed rains (*18-20*), questions nonetheless remain about the role of global warming (*21*). Here we have examined how the return period for such an extreme drought occurrence over California has changed since preindustrial times. Given the scientific detection for a regional warming in the western United States that is attributable to human influence (*22*), we explored how characteristics of the current drought, especially warming surface temperatures, carry a fingerprint of anthropogenic forcing.

By examining soil moisture and precipitation from the model simulations, we find droughts of all severities (i.e., the joint return periods of 10- to 200-year) in the preindustrial period become more frequent in the current climate when using a bivariate drought definition of 10-cm soil moisture and precipitation. The same analysis with the 1-m soil moisture and precipitation reveals that droughts of the 1850-vintage become less frequent in the current climate. The changes in return period are found to be small, making it very difficult to detect such human-induced change in severe drought events at this time.

A strength of our assessment on how land surface moisture responds to long term climate change is its use of physically-based multivariate drought definitions that explicitly incorporate different meteorological variables and land surface properties. Using a global climate model coupled to a sophisticated land surface model (CCSM4), we calculate soil moisture deficits and their projection on drought severity directly, rather than relying on inferences of land moisture drawn indirectly from precipitation alone or from a Palmer Drought Severity Index (PDSI). In this sense, the soil moisture studied herein is physically consistent with precipitation and temperature variations through the model coupled interactions, leading to consistent drought indications. Furthermore, the availability of long climate simulations permits a statistically robust estimate of changes in tail events, such as extreme drought intensity, which is otherwise difficult from the short instrumental record. Despite these strengths, we note that the generality of our results needs to be assessed for their consistency across different climate models. There are limitations in the global land model, including uncertainties in representing physical processes of moisture exchange through soil depth which may result in biases in the sensitivities to meteorological forcing. The lack of adequate soil moisture observations creates additional difficulties in evaluating the realism of the simulated soil moisture and thus also the drought sensitivity.

Finally, we note that the presented results are for a particular response to the human-induced warming (+1.6 °C) and wetting (+55 mm; +7%). This may differ from the climate change occurring in other models, and also will differ from the trajectory of future temperature and precipitation.

Projected average temperatures in California are expected to rise dramatically in future decades, greatly exceeding the warming that has occurred to date since the late 19th Century (*23*). By comparison, annual precipitation is not projected to increase at a commensurate rate, and winter increases may become compensated by spring declines (*24*). While recognizing the considerable uncertainty in projections of annual California precipitation (*5*), it is plausible that thermal impacts on drought frequency are likely to dominate precipitation changes, increasing drought frequency across a range of drought metrics by the late 21st Century (*25*).

Materials and Methods

a. Observational data

Contiguous U.S. precipitation for 1895-2014 is derived from National Oceanic and Atmospheric Administration (NOAA) monthly U.S. Climate Division data (*26*). Analyses of California averaged conditions are constructed by averaging the 7 individual climate divisions available for the state. Water year (October-September, hereafter WY) precipitation departures for the state averages are calculated relative to the 1895-2014 reference.

b. Model data

Climate simulations are based on the fourth version of NCAR's Community Climate System Model (CCSM4) (*27*). Two 2133-year long runs of CCSM4 were conducted, one using year-

1850 (Y1850) external radiative forcing, and a second using year-2000 (Y2000) external radiative forcing. The specified external forcings consist of greenhouse gases (e.g. CO_2, CH_4, NO_2, O_3, CFCs), natural and human-induced aerosols. Analysis is conducted for the monthly temperature, precipitation, 10-cm soil moisture, and 1-m soil moisture. The model data are interpolated to US Climate Divisions, and California water year averages are calculated. For the Y1850 experiment, the climatological means for California WY temperature, precipitation, 10-cm and 1-m soil moisture are 14.6 °C, 762.3 mm, 22.31 mm and 218.87 mm, respectively. For the Y2000 experiment, the corresponding climatological means are 16.2 °C, 817.0 mm, 22.33 mm and 220.39 mm, respectively. The simulated California warming (+1.6 °C) and wetting (+55 mm; +7%) in the CCSM4 equilibrium experiments is qualitatively consistent with the transient response from the late 19th Century to the early 21st Century occurring in CMIP5 experiments (see IPCC (2013) Figs. AI.16 and AI18). We note that the small magnitude of simulated increase is unlikely detectable in the observed time series, and neither observed nor simulated WY precipitation shows significant increase/decrease trend in the data overall (e.g., at 95% significance level).

c. *Methods*

Drought Definition. We define drought duration ($\mathbf{d_i}$) as the number of consecutive intervals (j years) during which anomalies remain below the climatology mean, and we define drought severity ($\mathbf{S_i}$) as the total precipitation deficit accumulated during a drought's duration (i.e., $\mathrm{S_i} = -\sum_{\mathrm{j=1}}^{\mathrm{d_i}} \mathrm{Anomalies_j}$) (*16*). Fig. 1 illustrates these characteristics of drought using the 119-year time series of observed California WY precipitation anomalies. The same definitions can be applied using SPI values (*28*).

Return Period Calculation. We calculate the multivariate return period using the concept of copulas (*29*). Assuming two variables X (e.g., drought duration) and Y (e.g., drought severity) with cumulative distribution functions (hereafter, CDF): $F_X(x) = \Pr(X \leq x)$ and $F_Y(y) = \Pr(Y \leq y)$, the copula (C) is defined as:

$$F(x, y) = C\big(F_X(x), F_Y(y)\big) \tag{1}$$

where $F(x, y)$ is the joint distribution function of X and Y (*30*):

$$F(x, y) = \Pr(X \leq x, Y \leq y) \tag{2}$$

Using the survival copula concept, the joint survival distribution $\overline{F}(x, y) = \Pr(X > x, Y > y)$ is defined as (*31*):

$$\overline{F}(x, y) = \hat{C}(\overline{F}_X(x), \overline{F}_Y(y)) \tag{3}$$

where $\overline{F}_X$ and $\overline{F}_Y$ (i.e., $\overline{F}_X = 1 - F_X$, $\overline{F}_Y = 1 - F_Y$) are the marginal survival functions of X and Y, and $\hat{C}$ is the survival copula.

A unique survival critical layer (or isoline) on which the set of realizations of X and Y share the same probability $t \in (0,1)$ is derived as (*32*): $\mathcal{L}_t^{\overline{F}} = \{x, y \in R^d : \overline{F}(x, y) = t\}$, where $\mathcal{L}_t^{\overline{F}}$ is the survival critical layer associated with the probability t.

The survival return period of concurrent X and Y is defined as:

$$\overline{\kappa}_{XY} = \frac{\mu}{1 - \overline{K}(t)} \tag{4}$$

where $\overline{\kappa}_{XY}$ is the survival Kendall's return period; $\mu > 0$ is the average interarrival time of the concurrent X and Y; and $\overline{K}$ is the Kendall's survival function associated with $\overline{F}$ defined as:

$$\overline{K}(t) = \Pr(\overline{F}(X, Y) \geq t) = \Pr(\hat{C}(\overline{F}_X(x), \overline{F}_Y(y)) \geq t) \tag{5}$$

By inverting the Kendall's survival function $\overline{K}(t)$ at the probability level $p = 1 - \frac{\mu}{T}$, the survival critical layer $\mathcal{L}_t^{\overline{F}}$ can be estimated and corresponds to the return period T:

$$\bar{\mathrm{q}} = \bar{\mathrm{q}}(\mathrm{p}) = \bar{\mathrm{K}}^{\mathbf{-1}}(\mathrm{p}) \quad (6)$$

where $\bar{\mathrm{q}}$ is the survival Kendall's quantile of order p.

The survival critical layer $\mathcal{L}_{\mathrm{t}}^{\bar{\mathrm{F}}}$ corresponding to the survival Kendall's quantile $\bar{\mathrm{q}}$ describes that the combined X and Y have a joint return period T (*33*). Different copulas are available for the joint return period analysis. We use a Gaussian-copula for combined drought duration and severity (see Fig. 2); Frank and Gaussian copulas for concurrent precipitation and 10-cm soil moisture (see Fig. 3A), and precipitation and 1-m soil moisture (see Fig. 3B), respectively. The goodness-of-fit of copula is tested using the log-maximum likelihood, empirical validation, and p-value significance test (*34*).

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Figures

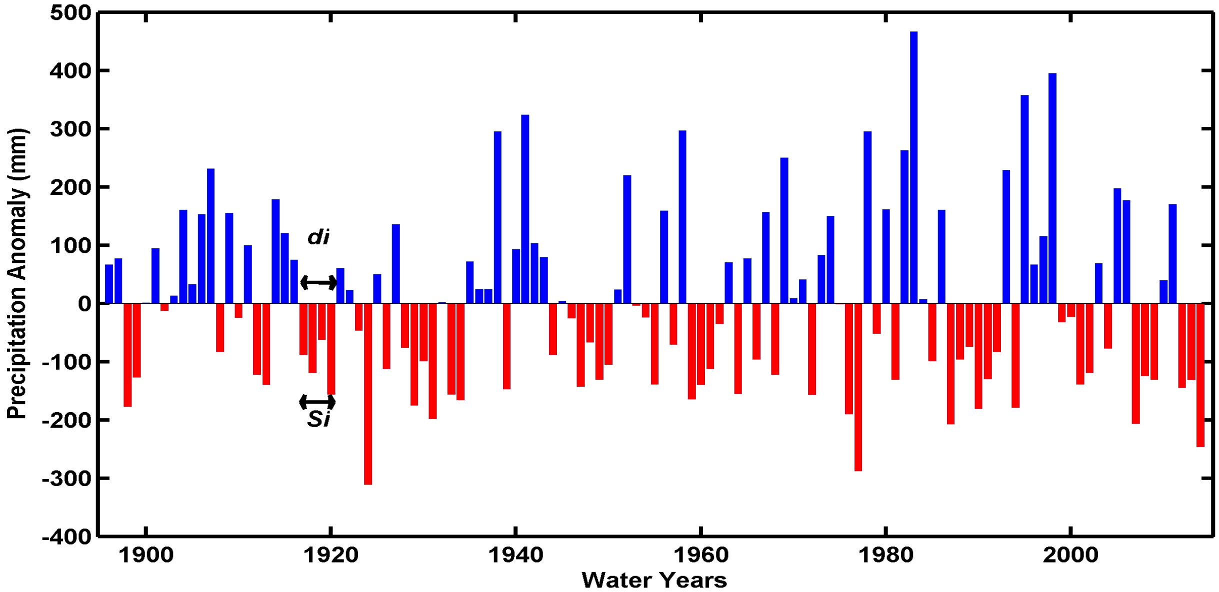

Fig. 1 119-year WY precipitation anomalies, in which d_i is the drought duration and S_i is the drought severity.

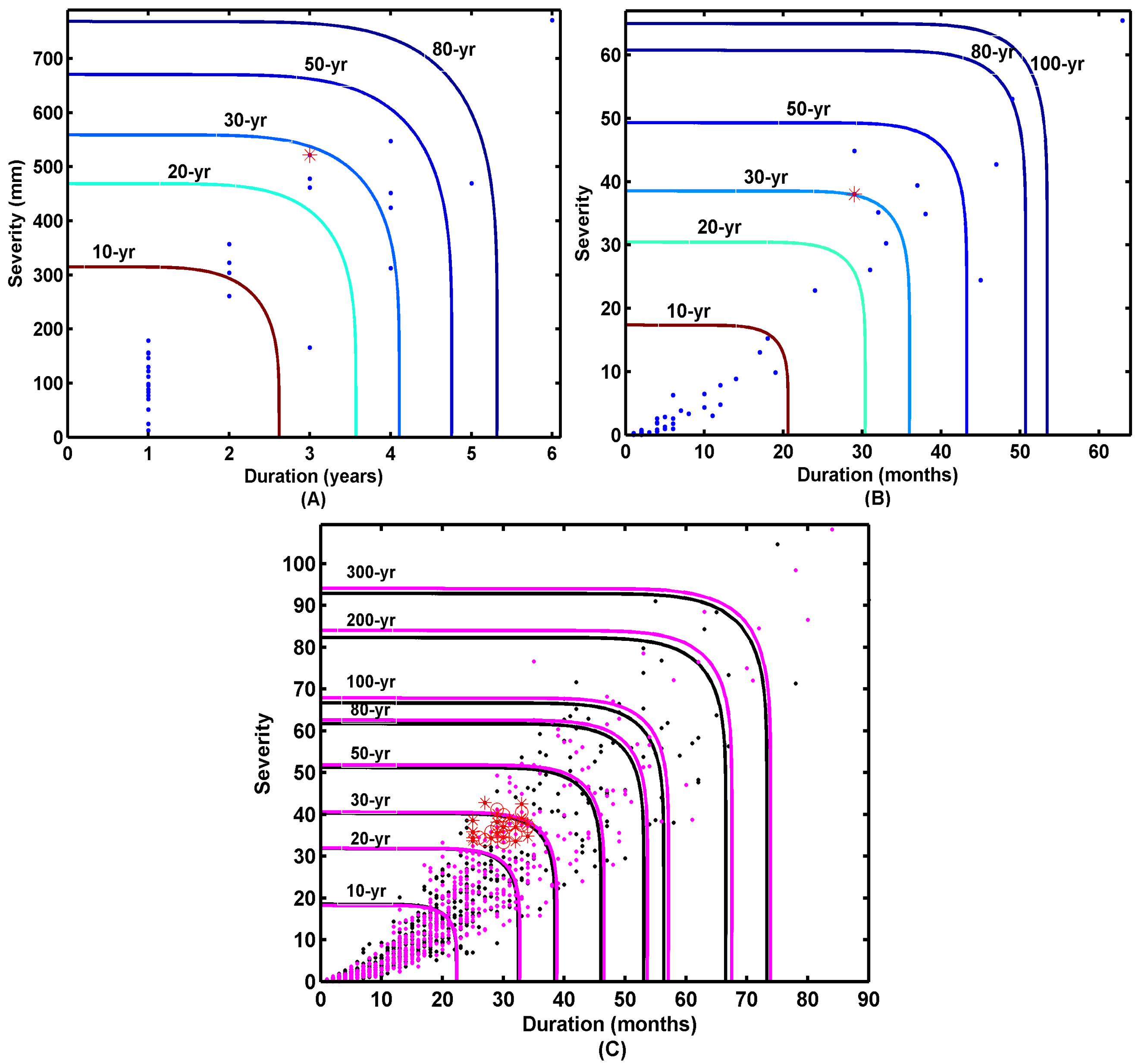

Fig. 2 Joint return period of drought duration (years) and accumulated precipitation deficit (mm)/severity using observed precipitation (**A**); using SPI18 (**B**); and using modeled SPI18 (**C**). The red star in (**A**) and (**B**) is the 2011-2014 CA drought; in (**C**), black contour lines and dots are derived based on Y1850; magenta contours and dots are based on Y2000; red circles are droughts analogous to the 2011-2014 CA drought.

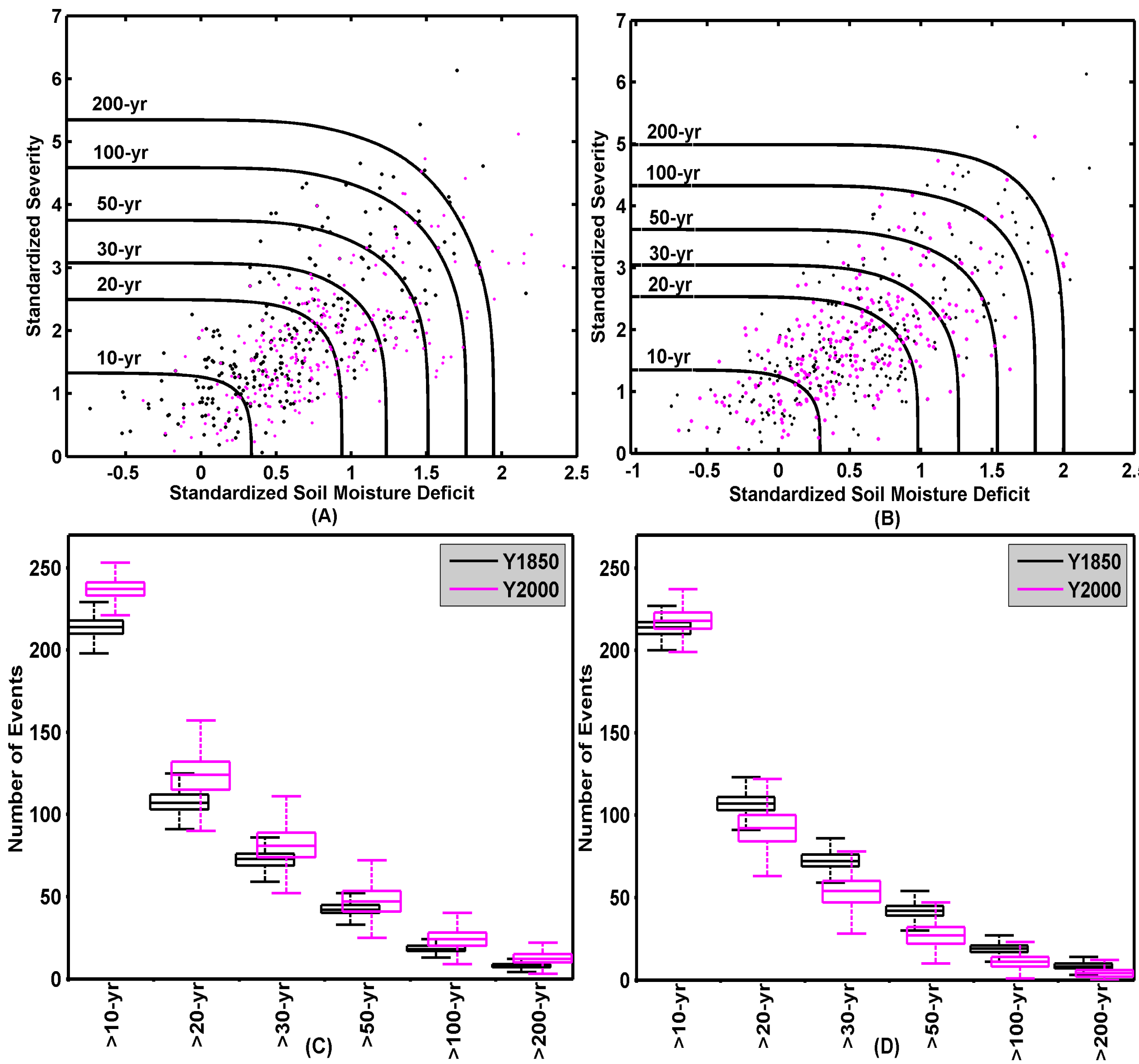

Fig. 3 Joint return period of accumulated precipitation deficit/severity and averaged soil moisture deficit standardized relative to the climatology of Y1850 at 10-cm (**A**) and at 1-m soil layer (**B**) simulated in Y1850 (black) and in Y2000 (magenta); events exceeding joint return periods of 10- to 200-years at 10-cm (**C**); at 1-m soil layer (**D**) simulated in Y1850 (black) and in Y2000 (magenta); the boxplots showing the median (center mark), and the 25th (lower edge) and 75th (upper edge) percentiles; the analyses in (**C**) and (**D**) using bootstrap resampling of 1000 times the population sample of drought events, which informs whether the changes are statistically significant. All changes in empirical distributions of drought frequency, for all return periods, is found to be statistically significant at 95% based on a K-S test.

Supplementary Materials

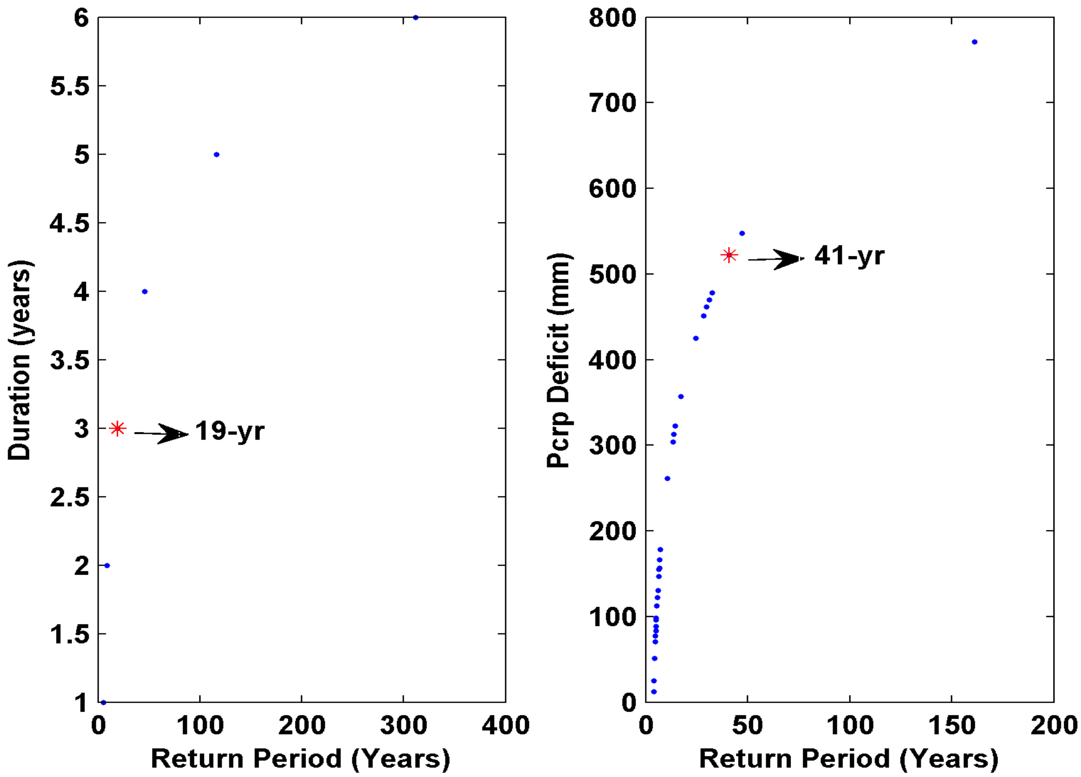

Fig. S1 Return period of drought duration (years) (left) and accumulated precipitation deficit (mm) (right), respectively for 2011-2014 (i.e., 3-year) California drought. The red star is the 2011-2014 CA drought.