Human water management intensifies hydrological drought in California

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Abstract. We analyze the contribution of human water management to the intensification and mitigation of hydrological drought over California using the PCR-GLOBWB hydrological model for the period 1979-2014. We demonstrate that considering water management results in more accurate discharge representation. During the severe 2014 drought, water management alleviated the drought deficit by ∼50% in Southern California through reservoir operation during low flow periods. However, human water consumption (mostly irrigation) in the Central Valley increased drought duration and deficit by 50% and 50-100%, respectively. Return level analysis indicates that there is more than 50% chance that the probability of occurrence of an extreme 2014-magnitude drought event was at least doubled under the influence of human activities compared to natural variability. This impact is most significant over the San Joaquin Drainage basin with a 50% and 75% likelihood that the return period is more than 3.5 and 1.5 times larger, respectively, because of human activities

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Keypoints:

- Human activities have increased the occurrence and intensity of hydrological drought in California, especially in the Central Valley
- This study underscores the need to take human water management into account for hydrological drought analysis
- Human activities have doubled the likelihood of the severe 2014 drought event in California

1. Introduction

California has endured severe drought since winter 2011 [*Seager et al.*, 2015]. This persistent drought has caused $2.2 billion in statewide losses in 2014 [*Howitt et al.*, 2014] and piqued wide public interest among the media, scientific communities, policy makers and stakeholders. This is not only due to the reduced productivity of agriculture (with crop revenue loss $810 million), but also due to the lack of water availability for irrigation and hydropower, and the depletion of groundwater storage (with additional pumping cost of $454 million), which has impacted food security [*Howitt et al.*, 2014] and caused land subsidence [*Amos et al.*, 2014; *Farr et al.*, 2015]. Furthermore, on-going urban water restrictions have been made either mandatory or voluntary [*Nagourney*, 2015; *Mann and Gleick*, 2015]. This long-lasting, multiyear drought has created extremely low soil moisture conditions, further increasing the risk of drought induced natural hazards, including landslides, flash floods and mid-winter wildfires [*Vardon*, 2015; *Yoon et al.*, 2015].

California has a typical Mediterranean climate with hot dry summers and mild wet winters. Most of its precipitation falls during the winter time (November to March). The long-term record indicates that 2014 is the third driest year in history and 2012-2014 is the driest consecutive three-year period [*Mann and Gleick*, 2015]. Associated with this dry condition are the extremely high temperatures, with 2014 being the hottest year and 2012-2014 being the hottest three years in history [*Diffenbaugh et al.*, 2015; *Mann and Gleick*, 2015]. Other significant droughts occurred during the periods 1929-1934, 1976-1977 and 1987-1992 [*Cooley et al.*, 2015].

Previous studies have primarily focused on meteorological drought (deficit in precipitation, *Diffenbaugh et al.* [2015]; *Mann and Gleick* [2015]; *Mao et al.* [2015]; *Kam and Sheffield* [2016]), agricultural drought (deficit in soil moisture, *Griffin and Anchukaitis* [2014]; *Williams et al.* [2015]; *Cook et al.* [2015]) and how the recent severe drought has impacted water resources such as snowpack conditions [*Belmecheri et al.*, 2016; *Margulis et al.*, 2016]. There has been a wide debate on the causes of the current California drought. Some studies demonstrate that there is no clear evidence to discern the link between the drought and storm tracks [*Funk et al.*, 2014; *Wang and Schubert*, 2014; *Seager et al.*, 2015]. Others hypothesize that climate change has strengthened and changed atmospheric circulation patterns and therefore will increase the frequency and severity of the future drought conditions [*Swain et al.*, 2014]. *Swain et al.* [2014] pointed out the unusual positive geopotential height (termed as "Ridiculously Resilient Ridge") over the northeastern Pacific Ocean shifted the position of the jet stream to the north and therefore reduced storm activity, which brought less precipitation to California and increased precipitation to the Pacific Northwest. *Diffenbaugh et al.* [2015] concluded that anthropogenic effects have already increased the risk of unprecedented drought in California through their analysis of the joint probability of temperature and precipitation anomalies. Other studies have focused on the teleconnection between precipitation and climate phases, including ENSO [*Cayan et al.*, 1999; *Haston and Michaelsen*, 1994; *Mo and Higgins*, 1998; *Woolhiser et al.*, 1993], PDO [*Cayan et al.*, 1998; *Fierro*, 2014; *McAfee*, 2014] and Madden-Julian oscillation [*Jones*, 2000].

However, no studies have investigated the direct influence of human water management on long-term changes in the frequency and intensity of hydrological drought (lack of water in the hydrologic system) in California. There is still much to understand about how human activities (e.g., water use, reservoir operations) intensify or mitigate hydrological drought in California [*AghaKouchak et al.*, 2015] and elsewhere. Therefore, the overarching scientific questions in this study are: (1) what are the effects of human water use on California drought?, (2) which regions within California are most heavily affected by human water use?, and (3) how does the human water management alter hydrological drought severity and duration in California?

This paper is organized as: Section 2 briefly introduces the study area, hydrological model and the experimental design. This section also presents a risk assessment framework to quantify the probability of occurrence for the 2014-magnitude drought event. Results are given in Section 3. Section 4 summarizes the main findings and points out limitations and further improvements. Methods used to define drought, and to calculate drought characteristics (duration and deficit) are presented as supporting information.

2. Study Area, Model and Methods

2.1. Study Area

As the third largest state of the U.S., California has a variety of climate types and therefore can be further classified into seven climate divisions (CDs, Figure 1A). A strong precipitation gradient exists, with higher annual precipitation in Northern California (CD1, CD2 and CD3) and lower precipitation in Southern California (CD6 and CD7). Coastal and southern parts of California (CD1 and CD4) have a Mediterranean climate with dry summers and wet winters. Although CD5 (termed as San Joaquin Drainage) is classified as semi-arid desert, most of the state's agriculture still grows in this region making the Central Valley one of the most productive agricultural regions in the U.S., with benefits from statewide water transfer projects, including the Central Valley Project (CVP) and State Water Project (SWP). Large dams associated with these two projects also provide flood control during the spring snowmelt season and water supply during the dry summer and autumn. It is therefore necessary to investigate the different characteristics of these 7 CDs as they have very different climate types, and distinctive water resources management activities.

2.2. Model Description

The macro-scale hydrological and water resources model PCR-GLOBWB is utilized for the simulation of the terrestrial water cycle over the period 1979-2014. PCR-GLOBWB runs at a 0.5° spatial resolution at a daily temporal resolution [*van Beek et al.*, 2011; *Wada et al.*, 2014]. The model was forced with the WFDEI meteorological dataset [*Weedon et al.*, 2014]. Reference evapotranspiration is calculated based on the Penman-Monteith equation [*Allen et al.*, 1998]. In PCR-GLOBWB, runoff (direct runoff and interflow) and baseflow are routed using the kinematic wave approximation of the Saint-Venant equation [*Chow et al.*, 1988]. Reservoir operation is considered as four types (water supply, flood control, hydropower generation and others) based on the reservoir data from the GLWD (Global Lakes and Wetlands Database, *Lehner and Döll* [2004]). Reservoir release is dynamically linked with the routing scheme to meet the local and downstream water demand. Irrigation water demand is estimated based primarily on historical irrigated areas, crop calendar, meteorological conditions, and livestock water demand is based on livestock densities and their drinking water requirements (livestock feed has been included in irrigation if not rain-fed agriculture). To better account for the response of irrigation to model states/fluxes, irrigation water supply is dynamically updated at the daily time step based on the balance and deficit of surface water (for rice) and soil water (for non-rice). Groundwater abstraction is estimated based on the country reported data from the ICGRAC (International Groundwater Resources Assessment Centre) and downscaled with total water demand and surface water availability. Major water transfer projects in California have not been included in the model simulation due to the unavailable conveyance capacity data and the complex operational and regulatory rules. More details about the model structure and model configuration of human water use can be found in *Wada et al.* [2014] and *Wada et al.* [2016a].

2.3. Experiments Design

To investigate how human water use affects drought characteristics, two scenarios are simulated. The first scenario (natural experiment) is configured without any human water management, while the second scenario (human experiment) is conducted taking into account water resources management activities (except water transfers). Through the comparison of these two scenarios, we quantify the relative attribution of human water use in the drought assessment. We focus on hydrological drought, which is usually defined based on negative anomalies of surface and subsurface discharge [*Sheffield and Wood*, 2011; *Van Loon et al.*, 2016]. The commonly used variable threshold level (VTL) method [*Hisdal and Tallaksen*, 2003; *Fleig et al.*, 2006; *Wada et al.*, 2013; *Wanders et al.*, 2015; *Wanders and Wada*, 2015] is applied on the simulated daily discharge (Q) to derive drought duration (how long the drought lasts) and deficit volume (how severe the drought is) using Q_{90} (monthly 90-percentile flow) as the threshold. In order to quantify the relative contribution of human water use, Q_{90} calculated from the natural scenario over 1979-2014 is used to calculate drought characteristics (duration and deficit volume) for the human scenario. The methodology for calculation of these drought characteristics can be found in the supplementary material.

2.4. Return Level Analysis for Drought Risk Assessment

To quantify the probability of occurrence or return level for a 2014-magnitude drought event, Extreme Value Theory (EVT) is applied [*Swain et al.*, 2014; *Singh et al.*, 2014; *Mastrandrea et al.*, 2011]. The drought magnitude is characterized based on the mean January-December 2014 standardized drought deficit volume (StDef, see Equation (6) in the supporting information for details) for the entire state and for each individual CD. A parametric distribution is fitted to formulate the relationship between StDef and the return period (T_r) over the period 1979-2014 for the two scenarios (natural and human). Parameters of the distribution are estimated using the maximum log-likelihood estimator or L-moments [*Hosking*, 1990]. Given only 36 years of record and the rarity of the 2014 drought event, standard bootstrapping techniques are applied 1000 times to fit the distribution and estimate confidence intervals for the risk assessment.

3. Results

3.1. Comparison of Drought Severity between Observations and Model Simulation

Figure 1 compares the basin-averaged observed and simulated drought deficit volume under natural variability and influenced by human activities (see Figure S1-S5 for more validation results in the supporting information). Results from small river basins are variable compared to larger river basins and the addition of water management and consumption does not improve the simulation over these basins. Improvement is more apparent over larger river basins, where human activities and larger reservoirs play a more important role in intensifying/mitigating drought conditions (overestimating/underestimating drought deficit volume). Overall, the simulated drought deficit volumes considering human activities yields smaller deviations and higher R^2 value (0.68, p-value < 0.0001) compared to natural conditions ($R^2 = 0.58$, p-value < 0.0001), but the improvement of R^2 is not statistically significant at the basin scale according to the analysis of variance (ANOVA), which is probably due to the limited number of data points. We therefore repeated the analysis for each drought event (Figure S6) instead of the basin average (Figure 1) to increase the number of data samples. Tests of line coincidence (F-test=29.23, p-value < 0.0001) and parallelism (F-test=38.11, p-value < 0.0001) both indicate that the improvement of R^2 is statistically significant. This is consistent with earlier work by *Wada et al.* [2013], which compared the observed and simulated drought deficit volume based on a large number of drought events over 23 large river basins across the globe that are affected by human water consumption. They found that the improvement of R^2 is statistically significant in the human scenario, which demonstrates that for an accurate representation of the regional terrestrial water cycle, physical processes related to human activities should be included in hydrological models.

3.2. Time Series of Area in Drought and Drought Deficit

The total area in drought (AID) and StDef have been calculated based on Q_{90} for both scenarios over the whole California (see supporting information for details). The temporal evolution of these two drought characteristics is given in Figure 2A and 2B and notable drought events can be detected. For example, two periods, 1987-1992 and 2011-2014, have large values of AID as well as high StDef, indicating severe multi-year droughts. Even though the 1987-1992 drought had a longer duration (5 years) compared to the 2011-2014 drought and the peak values of the drought characteristics (AID and StDef) are comparable to the recent drought, drought intensity quickly decreases after 1991. While in the 2011-2014 drought event, a long period of high StDef and AID values is found, indicating that the recent drought had a larger spatial extent and a prolonged high impact on the hydrological system. According to the simulation, more than 50% of the total area of California was under drought since late 2012. The temporal evolution of AID under natural conditions (climate variability only) and under human impacts demonstrates that reservoir regulation could reduce the drought area by about 10-20% for normal years, which helped to reduce the impact of short duration drought. Overall, a reduced drought impact is found as a result of reservoir buffering. In terms of StDef, there is no significant difference between these two scenarios for normal years. However, at the beginning of severe drought years (e.g., 1987-1992), human water consumption increases the relative drought intensity. On the other hand, we see a reduced impact as soon as drought recovery starts as a result of reservoir storage that can store excess water and store it for later use in a drier period. Similar findings are found for the recent drought, where the standardized drought deficit volume under human impacts is smaller than that under natural variability.

3.3. Relative Contribution of Human Water Management to Drought Duration and Intensity (During 2014 Drought)

Figure 3 shows the spatial pattern of the annual mean drought duration days and deficit for 2014 under the two scenarios, as well as the relative change in drought severity due to human impacts. For drought duration, the overall spatial distribution and the magnitude look very similar under natural variability and with human water consumption. Most parts of California had drought duration greater than 25 days (per month) during this severe drought year. However, the average duration in the eastern part of CD7 is less than 15 days. This is due to the fact that this region has a semi-arid climate and therefore the threshold (Q_{90}) calculated from the climatological streamflow to define drought events is also low. Although the spatial pattern looks similar between the two scenarios, there is clear evidence of human impacts on drought duration as indicated from the spatial distribution of the relative increase/decrease. With human impacts, drought duration increases by ∼50% for most parts of CD2 and CD3. This is primarily caused by irrigation water consumption, as these two regions have large irrigated areas. The lengthening of drought is also found in CD1, while its magnitude is much milder due to the reduced irrigation water demand.

Similar to the results for drought duration, the intensification of drought deficit (lower panel of Figure 3) due to human impacts is obvious in the Central Valley (CD2 and CD5), but the magnitude of the relative increase is much higher (50%-100%) compared to that for drought duration. Although the natural variability is the main driver of the recent drought in this region, human water consumption (water abstraction for irrigation) made the situation much worse by reducing local and downstream water availability. Over the regions where irrigation does not dominate water consumption (CD6 and CD7) and water demand is small, human impacts alleviated the hydrological drought by ∼50%. The decreased streamflow due to the lack of precipitation could be buffered by the release of reservoirs especially during low flow periods, which are supplies from snowpack.

3.4. Return Level Analysis

In this section, the EVT is applied for the annual averaged StDef to estimate the return level of the drought. The probability of a 2014 magnitude event and the associated uncertainty in the likelihood estimation are quantified. Five parametric distributions (LogNormal, GEV using L-moments, Pareto, Gamma and Weibull) are tested for the most suitable fit of the statistical distribution. Figure 4A and 4B (as well as Table S2) show that the LogNormal distribution best fits the data for both scenarios (only natural variability and with human impacts). In addition, the LogNormal distribution has the smallest root mean square error between the fitted and the empirical distributions among the five types (see Table S2). Therefore, this distribution is utilized for the return level analysis.

It is clear to find that 2014 has the largest return period for both scenarios followed by the drought events occurred in the 1990s (Figure 4A and 4B). The 95% confidence interval of the return period estimated from the bootstrapping method based on the LogNormal distribution indicates that the 2014 drought is between about a 1-in-3 year and 1-in-71 year event under the natural scenario. However, the human scenario has a relatively larger 95% confidence interval of 3-295 years. To better quantify how human activities change the drought risk, we further calculated the likelihood ratio for the return period ($T_{Natural}/T_{Human}$). As shown in Figure 4C, for the whole of California, there is a 50% likelihood that the probability of the 2014 drought event has at least doubled with human impacts. All the 7 CDs demonstrate that there is >50% likelihood that the 2014 drought event has higher probability under the influence of human water consumption. The most significant impact is found in CD5 (San Joaquin river basin), where there is a 50% chance that the return period is more than 3.5 times larger with human influence than that under natural variability alone. There is even higher confidence (>75%) that the return period becomes 1.5 times larger. This further demonstrates the role of irrigation in the alteration of the hydrological drought. Compared to CD5, which has the largest uncertainty in the estimation of the return period ratio, CD7 (Southeast Desert Basin) has the smallest uncertainty, with the least difference between the natural variability and anthropogenic impacts. These results are consistent with the spatial distribution of the relative increase of the drought characteristics as shown in Figure 3.

4. Discussion and Conclusions

Few studies have tried to quantify the direct impact of human activities on the recent California drought, and hydrological drought in general. Most studies have focused on quantifying the likelihood that climate change has impacted meteorological droughts, either through changes in large-scale circulation and teleconnections [e.g., *Shukla et al.*, 2015a; *Hoell et al.*, 2016; *Kam and Sheffield*, 2016], or local scale thermodynamic forcing and feedbacks via temperature [e.g., *Seager et al.*, 2015]. A few studies have looked at the full hydrological cycle based on long-term hydrological simulations [e.g., *Mao et al.*, 2015; *Shukla et al.*, 2015b] but have not examined how human water management has contributed to enhancing or mitigating drought, mainly due to the lack of human representation in modeling frameworks. We show that human activities play an increasingly important role in hydrological drought in California, altering the natural occurrence of hydrological drought as driven by precipitation anomalies, through local scale water use and management that influences the propagation of drought through the hydrological cycle and into changes in streamflow.

Uncertainties in this study are caused by the relatively short period of the model simulation for the risk analysis, but also suffer from the uncertainty in representing human management effects [*Wada et al.*, 2016b]. For instance, some human water management modules in the current modeling framework are still configured in a simplistic form or not explicitly considered, such as regulation rules for water use policy, energy production and information on aqueducts or water diversions. This may affect the results in the Central Valley in particular, where large uncertainties may exist in the simulated water availability. Improved estimates of the human impacts could be obtained by a higher resolution representation of reservoir operation, groundwater pumping, irrigation activities as well as more detailed river networks, and particularly specific accounting for water transfers through artificial diversion networks, which in reality can contribute to the supply of irrigation water requirement and may alleviate drought conditions to some extent, especially in the Central Valley. However, we believe that this work provides an appropriate first estimate of the human impact on the 2014 drought. Future research should focus on extending the simulation to 2015/2016 to examine the impact of the 2016 strong El Niño winter [*Wanders et al.*, 2016]. Future work could also focus on a more detailed study of the relative attribution of different types of human activities (groundwater pumping, reservoir operation and irrigation) on changes in drought risk.

This study demonstrates that without considering human water use, the impact of hydrological droughts in California is underestimated. This is especially the case in regions like the Central Valley (Sacramento Drainage and San Joaquin Drainage), where irrigation is the main driver of water consumption. We find that elsewhere in the state water resources management through reservoir operation reduces drought duration and severity.

Our extreme value analysis implies that there is high confidence that human water management significantly increases hydrological drought risk over the Central Valley or other areas with a high irrigation water demand. Although this study focuses on the historical perspective, our findings have important policy implications for drought mitigation and management in the context of future climate change. Given that human activities have already worsened the recent drought (as discussed above) and the uncertainty of drought recovery in the near term, water infrastructure in California may face a greater challenge for drought adaptation due to increased water demand [*Wada et al.*, 2013], reduced groundwater storage [*Famiglietti*, 2014] and declining snowpack [*Belmecheri et al.*, 2016; *Margulis et al.*, 2016].

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References

AghaKouchak, A., D. Feldman, M. Hoerling, T. Huxman, and J. Lund (2015), Water and climate: Recognize anthropogenic drought, *Nature*, *524*, 409–411.

Allen, R. G., L. S. Pereira, D. Raes, M. Smith, et al. (1998), Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, *FAO, Rome*, *300*(9), D05,109.

Amos, C. B., P. Audet, W. C. Hammond, R. Bürgmann, I. A. Johanson, and G. Blewitt (2014), Uplift and seismicity driven by groundwater depletion in central California, *Nature*, *509*(7501), 483–486.

Belmecheri, S., F. Babst, E. R. Wahl, D. W. Stahle, and V. Trouet (2016), Multi-century evaluation of Sierra Nevada snowpack, *Nature Climate Change*, *6*(1), 2–3.

Cayan, D. R., M. D. Dettinger, H. F. Diaz, and N. E. Graham (1998), Decadal variability of precipitation over western North America, *Journal of Climate*, *11*(12), 3148–3166.

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *Journal of Climate*, *12*(9), 2881–2893.

Chow, V. T., D. R. Maidment, L. W. Mays, et al. (1988), *Applied hydrology*, New York: McGraw-Hill.

Cook, B. I., T. R. Ault, and J. E. Smerdon (2015), Unprecedented 21st century drought risk in the American Southwest and Central Plains, *Science Advances*, *1*(1), e1400,082.

Cooley, H., K. Donnelly, R. Phurisamban, and M. Subramanian (2015), Impacts of California's ongoing drought: Agriculture, *Pacific Institute: Oakland, CA, USA*.

Diffenbaugh, N. S., D. L. Swain, and D. Touma (2015), Anthropogenic warming has increased drought risk in California, *Proceedings of the National Academy of Sciences*, *112*(13), 3931–3936.

Famiglietti, J. (2014), The global groundwater crisis, *Nature Climate Change*, *4*(11), 945–948.

Farr, T. G., C. Jones, and Z. Liu (2015), Progress Report: Subsidence in the Central Valley, California, *Retrieved from http://water.ca.gov/groundwater/docs/NASA_REPORT.pdf.*

Fierro, A. O. (2014), Relationships between California rainfall variability and large-scale climate drivers, *International Journal of Climatology*, *34*(13), 3626–3640.

Fleig, A. K., L. M. Tallaksen, H. Hisdal, and S. Demuth (2006), A global evaluation of streamflow drought characteristics, *Hydrology and Earth System Sciences*, *10*(4), 535–552.

Funk, C., A. Hoell, and D. Stone (2014), Examining the contribution of the observed global warming trend to the California droughts of 2012/13 and 2013/14, *Bulletin of the American Meteorological Society*, *95*(9), S11.

Griffin, D., and K. J. Anchukaitis (2014), How unusual is the 2012–2014 California drought?, *Geophysical Research Letters*, *41*(24), 9017–9023.

Haston, L., and J. Michaelsen (1994), Long-term central coastal California precipitation variability and relationships to El Niño-Southern Oscillation, *Journal of Climate*, *7*(9), 1373–1387.

Hisdal, H., and L. M. Tallaksen (2003), Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark, *Journal of Hydrology*, *281*(3), 230–247.

Hoell, A., M. Hoerling, J. Eischeid, K. Wolter, R. Dole, J. Perlwitz, T. Xu, and L. Cheng (2016), Does El Niño intensity matter for California precipitation?, *Geophysical Research Letters*, *43*(2), 819–825, doi:10.1002/2015GL067102, 2015GL067102.

Hosking, J. R. (1990), L-moments: analysis and estimation of distributions using linear combinations of order statistics, *Journal of the Royal Statistical Society. Series B (Methodological)*, pp. 105–124.

Howitt, R., J. Medellín-Azuara, D. MacEwan, J. Lund, and D. Sumner (2014), Economic analysis of the 2014 drought for California agriculture, *Center for Watershed Sciences, University of California, Davis.*

Jones, C. (2000), Occurrence of extreme precipitation events in California and relationships with the Madden-Julian oscillation, *Journal of Climate*, *13*(20), 3576–3587.

Kam, J., and J. Sheffield (2016), Increased drought and pluvial risk over California due to changing oceanic conditions, *Journal of Climate*, *29*(22), 8269–8279.

Lehner, B., and P. Döll (2004), Development and validation of a global database of lakes, reservoirs and wetlands, *Journal of Hydrology*, *296*(1), 1–22.

Mann, M. E., and P. H. Gleick (2015), Climate change and California drought in the 21st century, *Proceedings of the National Academy of Sciences*, *112*(13), 3858–3859.

Mao, Y., B. Nijssen, and D. P. Lettenmaier (2015), Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective, *Geophysical Research Letters*, *42*(8), 2805–2813.

Margulis, S. A., G. Cortés, M. Girotto, L. S. Huning, D. Li, and M. Durand (2016), Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery, *Geophysical Research Letters*, *43*(12), 6341–6349.

Mastrandrea, M. D., C. Tebaldi, C. W. Snyder, and S. H. Schneider (2011), Current and future impacts of extreme events in California, *Climatic Change*, *109*(1), 43–70.

McAfee, S. A. (2014), Consistency and the Lack Thereof in Pacific Decadal Oscillation Impacts on North American Winter Climate, *Journal of Climate*, *27*(19), 7410–7431.

Mo, K. C., and R. W. Higgins (1998), The Pacific-South American modes and tropical convection during the Southern Hemisphere winter, *Monthly Weather Review*, *126*(6), 1581–1596.

Nagourney, A. (2015), California imposes first mandatory water restrictions to deal with drought, *The New York Times*.

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson (2015), Causes of the 2011–14 California Drought, *Journal of Climate*, *28*(18), 6997–7024.

Sheffield, J., and E. F. Wood (2011), *Drought: Past problems and future scenarios*, Earthscan, London.

Shukla, S., A. Steinemann, S. F. Iacobellis, and D. R. Cayan (2015a), Annual Drought in California: Association with Monthly Precipitation and Climate Phases, *Journal of Applied Meteorology and Climatology*, *54*(11), 2273–2281.

Shukla, S., M. Safeeq, A. AghaKouchak, K. Guan, and C. Funk (2015b), Temperature impacts on the water year 2014 drought in California, *Geophysical Research Letters*, *42*(11), 4384–4393.

Singh, D., D. E. Horton, M. Tsiang, M. Haugen, M. Ashfaq, R. Mei, D. Rastogi, N. C. Johnson, A. Charland, B. Rajaratnam, et al. (2014), Severe precipitation in northern India in June 2013: Causes, historical context, and changes in probability, *Bull Am*

Meteorol Soc, *95*(9), S58–S61.

Swain, D. L., M. Tsiang, M. Haugen, D. Singh, A. Charland, B. Rajaratnam, and N. S. Diffenbaugh (2014), The extraordinary California drought of 2013-2014: Character, context, and the role of climate change, *Bull Am Meteorol Soc*, *95*(7), S3–S7.

van Beek, L. P. H., Y. Wada, and M. F. P. Bierkens (2011), Global monthly water stress: 1. Water balance and water availability, *Water Resources Research*, *47*(7), doi: 10.1029/2010WR009791.

Van Loon, A. F., T. Gleeson, J. Clark, A. I. Van Dijk, K. Stahl, J. Hannaford, G. Di Baldassarre, A. J. Teuling, L. M. Tallaksen, R. Uijlenhoet, et al. (2016), Drought in the Anthropocene, *Nature Geoscience*, *9*(2), 89–91.

Vardon, P. J. (2015), Climatic influence on geotechnical infrastructure: a review, *Environmental Geotechnics*, *2*(3), 166–174.

Wada, Y., L. P. H. van Beek, N. Wanders, and M. F. P. Bierkens (2013), Human water consumption intensifies hydrological drought worldwide, *Environmental Research Letters*, *8*(3), 034–036.

Wada, Y., D. Wisser, and M. F. P. Bierkens (2014), Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, *Earth System Dynamics*, *5*(1), 15–40, doi:10.5194/esd-5-15-2014.

Wada, Y., I. E. M. de Graaf, and L. P. H. van Beek (2016a), High-resolution modeling of human and climate impacts on global water resources, *Journal of Advances in Modeling Earth Systems*, *8*(2), 735–763, doi:10.1002/2015MS000618.

Wada, Y., M. Flörke, N. Hanasaki, S. Eisner, G. Fischer, S. Tramberend, Y. Satoh, M. Van Vliet, P. Yillia, C. Ringler, et al. (2016b), Modeling global water use for the

21st century: the Water Futures and Solutions (WFaS) initiative and its approaches, *Geoscientific model development*, *9*(1), 175–222.

Wanders, N., and Y. Wada (2015), Human and climate impacts on the 21st century hydrological drought, *Journal of Hydrology*, *526*, 208–220.

Wanders, N., Y. Wada, and H. Van Lanen (2015), Global hydrological droughts in the 21st century under a changing hydrological regime, *Earth System Dynamics*, *6*, 1–15.

Wanders, N., A. Bachas, X. He, H. Huang, A. Koppa, Z. Mekonnen, B. Pagán, L. Peng, N. Vergopolan, K. Wang, et al. (2016), Forecasting the hydroclimatic signature of the 2015-16 El Niño event on the western US, *Journal of Hydrometeorology*, doi: http://dx.doi.org/10.1175/JHM-D-16-0230.1.

Wang, H., and S. Schubert (2014), Causes of the extreme dry conditions over California during early 2013, *Bull Am Meteorol Soc*, *95*(7), S7–S11.

Weedon, G. P., G. Balsamo, N. Bellouin, S. Gomes, M. J. Best, and P. Viterbo (2014), The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, *Water Resources Research*, *50*(9), 7505–7514.

Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook (2015), Contribution of anthropogenic warming to California drought during 2012–2014, *Geophysical Research Letters*, *42*(16), 6819–6828.

Woolhiser, D., T. Keefer, and K. Redmond (1993), Southern oscillation effects on daily precipitation in the southwestern United States, *Water Resources Research*, *29*(4), 1287–1295.

Yoon, J.-H., B. Kravitz, P. J. Rasch, S.-Y. Simon Wang, R. R. Gillies, and L. Hipps (2015), Extreme Fire Season in California: A Glimpse Into the Future?, *Bulletin of the*

American Meteorological Society, *96*(12), S5–S9.

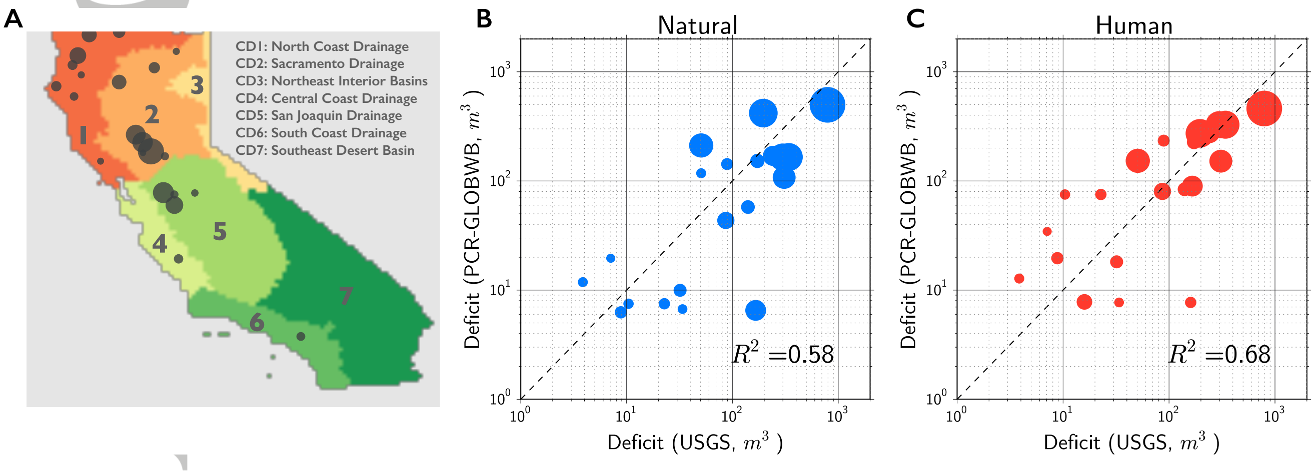

Figure 1. (A) Climatic divisions in California and the USGS stations used for validation and comparison. Size of the dots indicates the relative size of the observed drainage area. (B, C) Comparison between the observed and simulated basin-averaged drought event deficit volume (logarithmic scale) calculated respectively from 22 USGS stations located in major river basins and the collocated grid cells extracted from PCR-GLOBWB under (B) natural variability and (C) including human activities. The points are scaled based on the actual drainage area. See Figure S7 in the supporting information for the correction of the simulated drainage area.

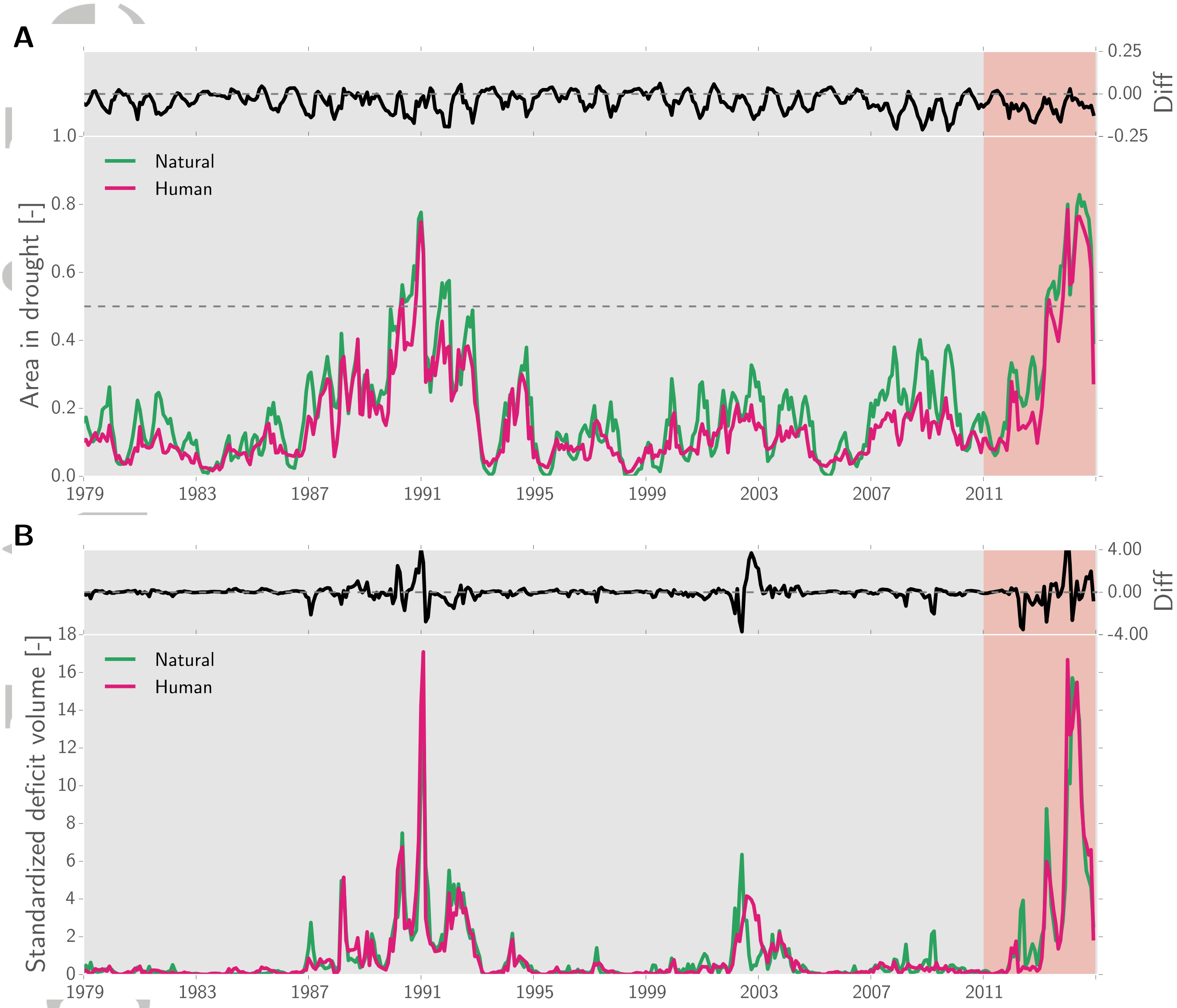

Figure 2. Time series of (A) AID and (B) StDef over California from 1979 to 2014 under natural variability (green line), with human activities (red line) and their difference (black line, Human minus Natural). The horizontal dashed line in (A) indicates that 50% of total area in California is under drought.

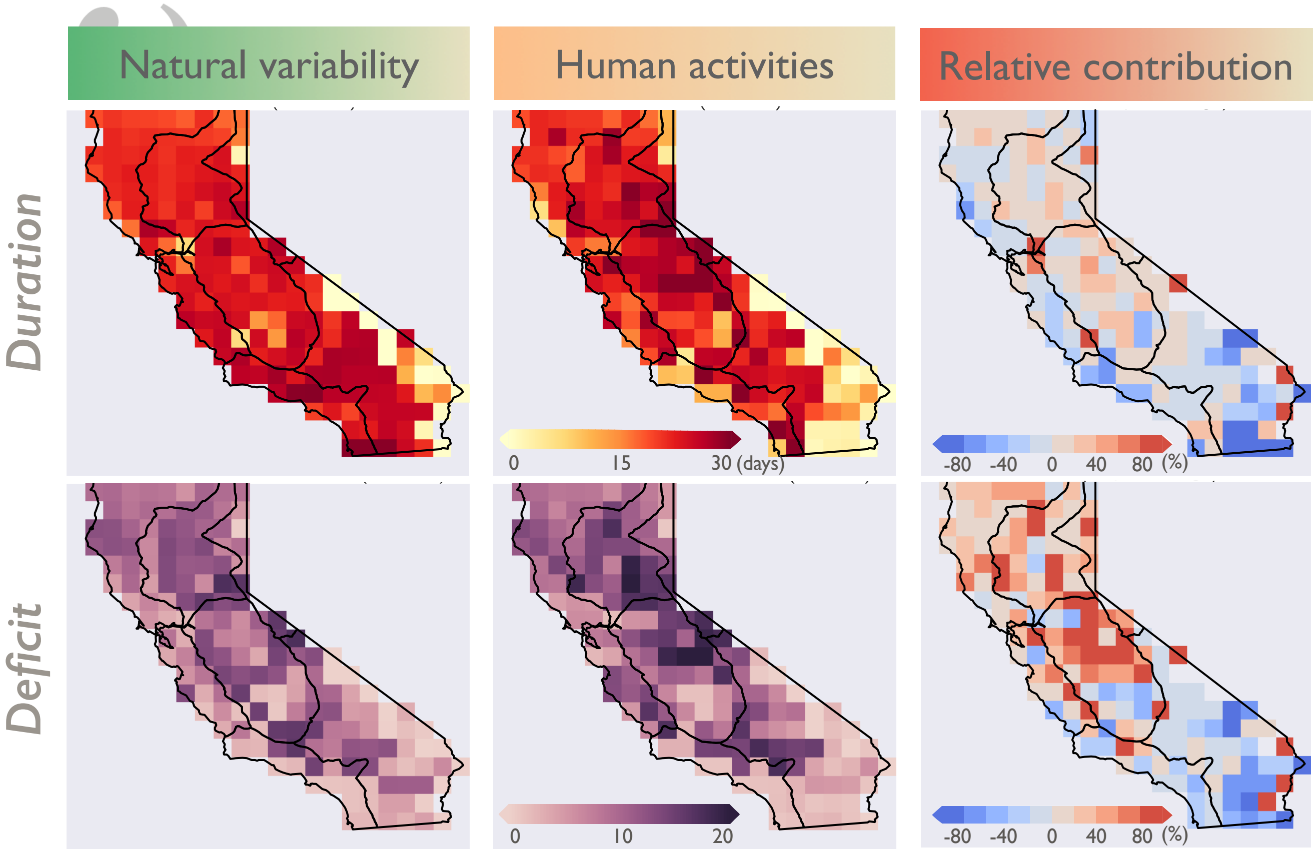

Figure 3. Comparison of drought duration (upper panel, unit: days) and standardized drought deficit volume (lower panel) over California in 2014 under natural variability (left) and with human activities (middle) and the relative contribution (right) due to human activities.

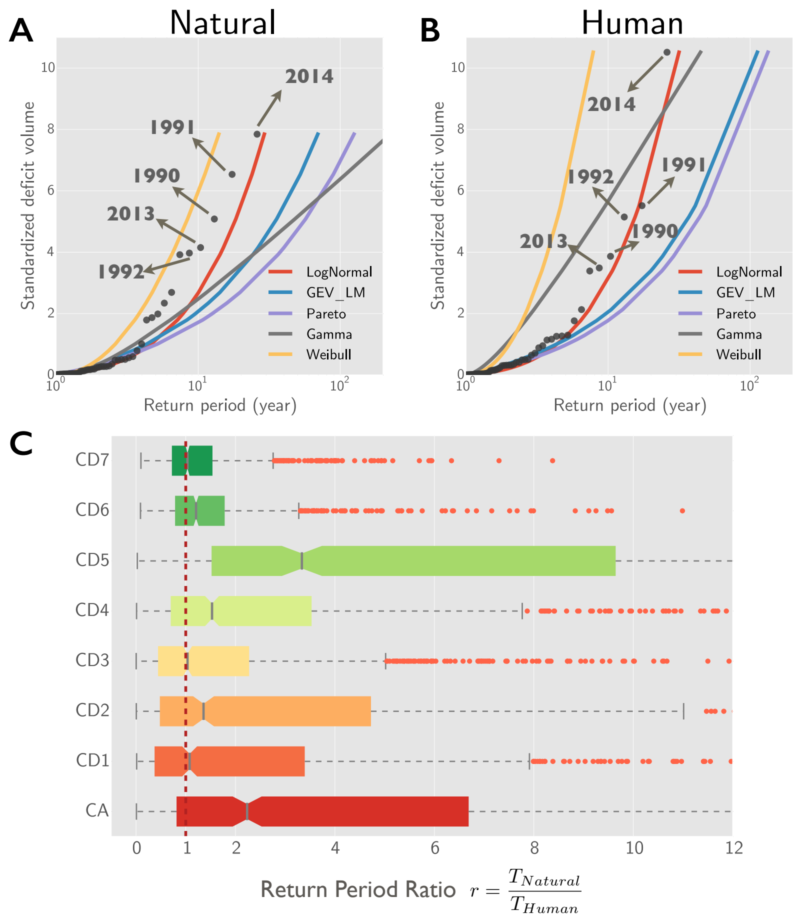

Figure 4. Return level curves fitted by five parametric distributions under (A) natural variability and (B) with human impacts for the entire state over the period of 1979-2014. (C) Box plot showing the distribution of the return period ratio ($T_{Natural}/T_{Human}$) using the bootstrapping method for the entire state and each individual CD. The rectangle spans the 25th and 75th percentile and the vertical segment inside the rectangle shows the median. Values larger than 1.5×interquartile above the 75th percentile are considered as outliers. Colors of the box plot are corresponding to the seven climatic divisions as shown in Figure 1A. Return period for the 2014 magnitude drought event is calculated based on the LogNormal distribution.