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Key Points:

- Temperature exacerbated the 2014 drought severity
- Greater than 86% chance of the drought being less severe in alternative temperature scenario
- Low-temperature forecast skill in California for winter and spring seasons

Supporting Information:

- Figure S1
- Readme

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Temperature impacts on the water year 2014 drought in California

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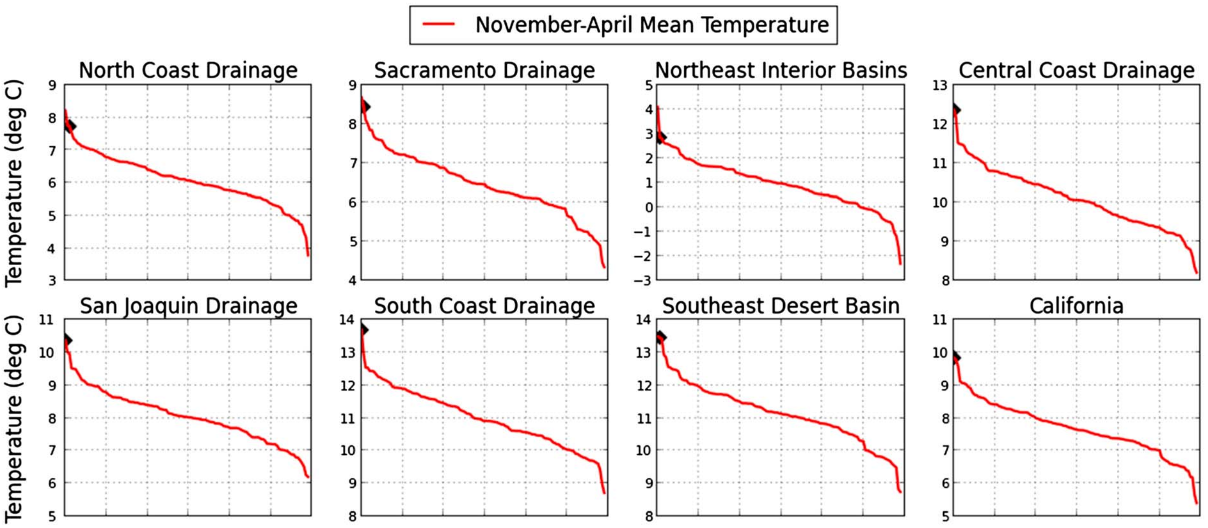
Abstract California is experiencing one of the worst droughts on record. We use a hydrological model and risk assessment framework to understand the influence of temperature on the water year (WY) 2014 drought in California and examine the probability that this drought would have been less severe if temperatures resembled the historical climatology. Our results indicate that temperature played an important role in exacerbating the WY 2014 drought severity. We found that if WY 2014 temperatures resembled the 1916–2012 climatology, there would have been at least an 86% chance that winter snow water equivalent and spring-summer soil moisture and runoff deficits would have been less severe than the observed conditions. We also report that the temperature forecast skill in California for the important seasons of winter and spring is negligible, beyond a lead time of 1 month, which we postulate might hinder skillful drought prediction in California.

1. Motivation

The water year (WY) 2014 (1 October 2013 to 30 September 2014) for California was marked by record low precipitation and record high temperature. Following droughts in WY 2012 and 2013, WY 2014 climatic conditions exacerbated dry conditions over most of the state. According to the United States Drought Monitor (USDM), about 11% of the state was experiencing “D3 (Extreme)” or “D4 (Exceptional)” drought at the start of WY 2014. By the end of WY 2014, it had increased to 82%. *Howitt et al.* [2014] estimated that the 2014 drought resulted in a 6.6 million acre-foot reduction in surface water available for agriculture, a shortfall which was mostly compensated for by increased groundwater pumping. The total statewide economic cost of the 2014 drought was estimated to be $2.2 billion, of which $1.5 billion alone was related to agriculture (including crop revenue losses, live stock value, and additional groundwater pumping costs) [*Howitt et al.*, 2014].

Extreme low precipitation in WY 2014 was the primary driver of the enhanced drought severity conditions [*Mao et al.*, 2015], and several recent studies have investigated the causes, attribution, and predictability of low precipitation during this event [*Funk et al.*, 2014; *Griffin and Anchukaitis*, 2014; *Seager and Hoerling*, 2014; *Seager et al.*, 2014; *Swain et al.*, 2014; *Wang and Schubert*, 2014; *Wang et al.*, 2014]. WY 2014 also experienced record high temperature which exacerbated the drought conditions even further [*AghaKouchak et al.*, 2014; *Griffin and Anchukaitis*, 2014]. November–April (NA) mean temperature over the state of California in WY 2014 was the hottest recorded since 1896 (Figure 1a, also shown by *AghaKouchak et al.* [2014]). At the climate division (CD) level, NA mean temperatures were the hottest on record for the Central Coast Drainage, San Joaquin Drainage, South Coast Drainage, and Southeast Desert Basin. For the rest of the CDs, NA mean temperature was within the warmest 10 seasons on record. A closer look at the ranks of monthly mean temperature reveals that, across all CDs, 9 WY 2014 months were among the top 20 hottest months on record when the temperature was averaged over the entire state (Figure 1b, see bottom right). Temperatures during the month of January were the hottest on the record for four out of seven CDs and for the state, and within the top three ranks for all CDs.

Record high temperatures during January and other winter months contributed to high atmospheric evaporative demand. High evaporative demands put greater stress on available moisture, exacerbating a drought’s severity [*Trenberth et al.*, 2013; *Seager and Hoerling*, 2014; *Seager et al.*, 2014]. Figure 2 shows


(a) Rank of November-April mean temperature

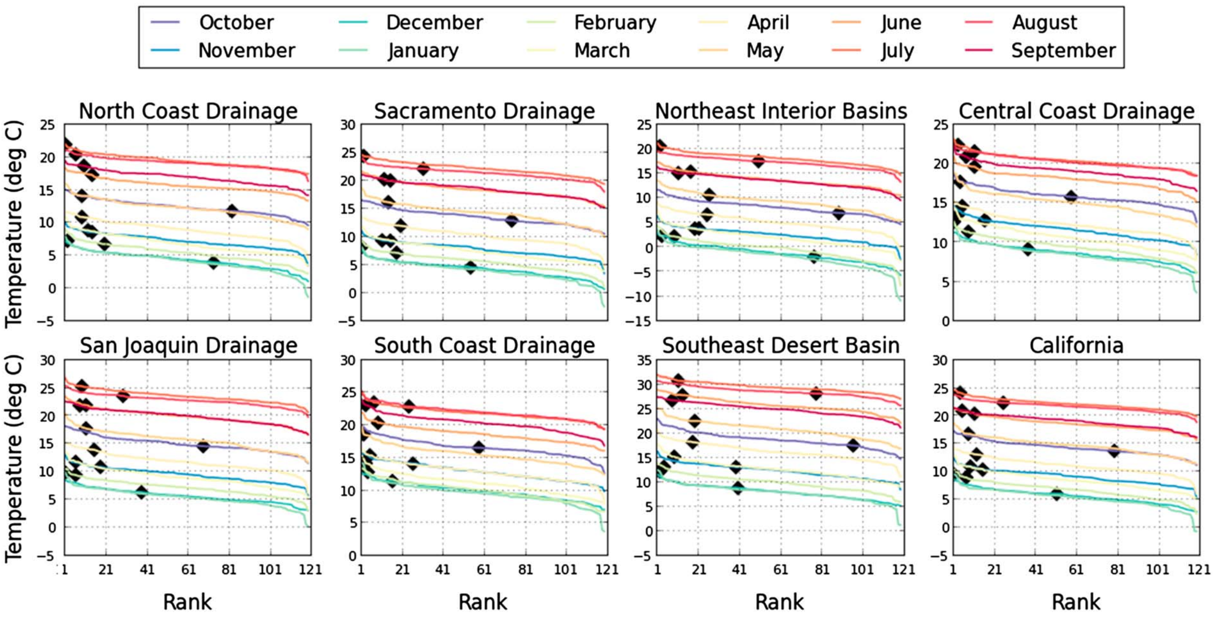

(b) Rank of monthly mean temperature

Figure 1. Temperature ranks for WY 2014 (a) November–April mean temperature and (b) monthly mean temperature during each month in comparison to the corresponding temperatures from each WY during 1896–2013. The black diamonds show the WY 2014 temperatures.

National Oceanic and Atmospheric Administration's (NOAA) physically based potential evapotranspiration (ETo) data [*Hobbins et al.*, 2012] for WY 2014 in terms of percentile relative to its 1979–2012 climatology. It indicates that ETo during December–June of WY 2014 was above the 90th percentile in most of the state. During January (June) of WY 2014, ETo values were exceptionally high, with much of the state (Northern California) falling above the 98th percentile. Furthermore, high temperatures (i.e., greater than freezing temperatures) lead to reduced snowfall and earlier and faster snowmelt, reducing the summer streamflow in snow-dominated runoff regions such as California [*Seager et al.*, 2014].

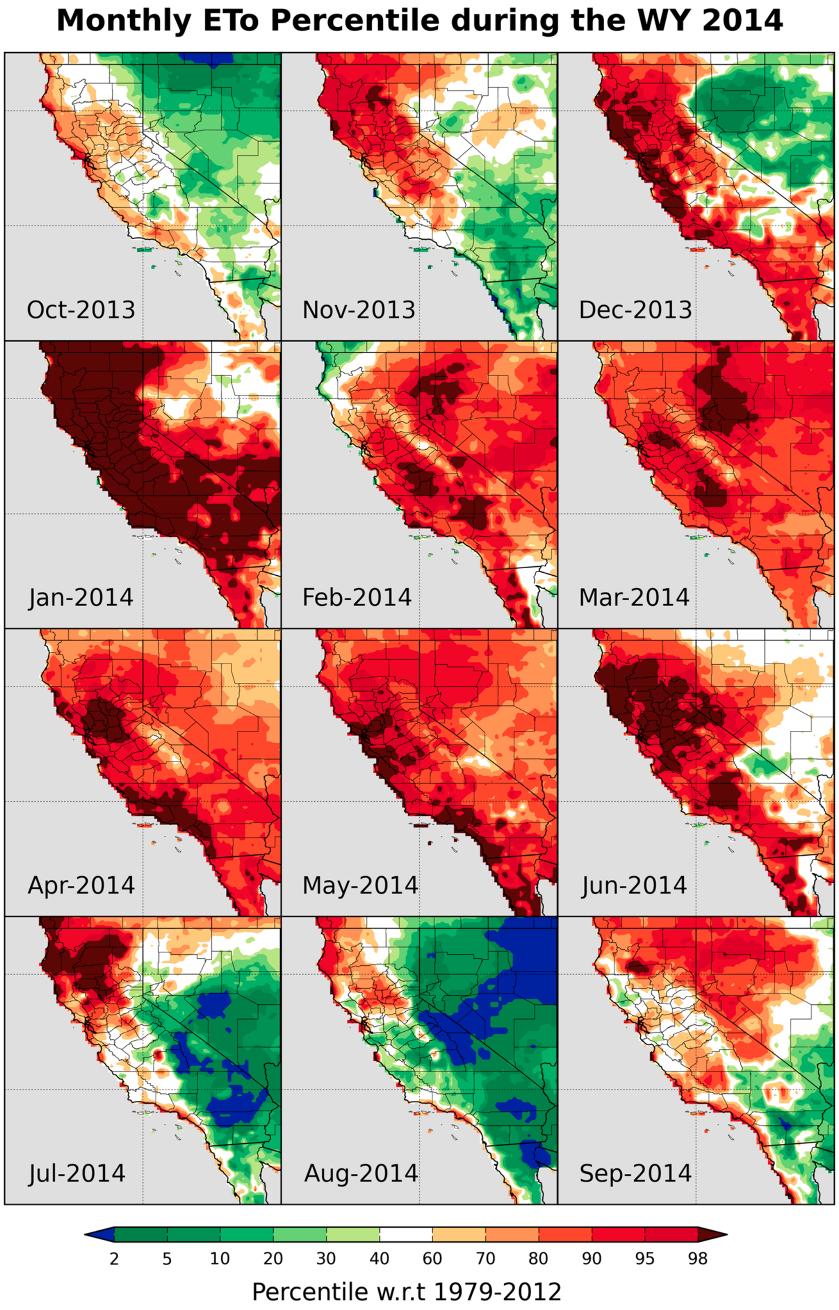


Figure 2. Percentiles of potential evapotranspiration (ETo) during WY 2014 with respect to 1979 to 2012 climatology.

The contribution of record high temperatures in the WY 2014 California drought is acknowledged by recent studies [*AghaKouchak et al.*, 2014; *California Nevada Applications Program*, 2014; *Griffin and Anchukaitis*, 2014; *Mao et al.*, 2015], but its relative role in exacerbating the WY 2014 drought severity as compared to precipitation remains poorly understood. *AghaKouchak et al.* [2014] showed that the traditional univariate risk (i.e., severity and likelihood of occurrence of an event) assessment methods based solely on precipitation might substantially underestimate the risk of events such as the WY 2014 California drought. *Griffin and Anchukaitis* [2014] conducted a simple experiment by replacing the WY 2014 temperature with climatological mean temperature to estimate the Palmer Drought Severity Index which suggested that temperature could have exacerbated the 2014 drought by approximately 36%. In this study, we use a hydrologic model and risk assessment framework to perform a more comprehensive analysis to investigate how temperature influenced the snow water equivalent (SWE), soil moisture (SM), and runoff deficits that contributed to the WY 2014 drought. For the purposes of this study, we define the WY 2014 drought based on simulated SWE, SM, evapotranspiration (ET), and runoff percentiles for that WY (see section 2.1 for further details). We examine the probability that the WY 2014 drought would have been less severe if temperatures resembled the 1916–2012 climatology. Understanding how record high temperatures may have contributed to the WY 2014 drought will be helpful for ongoing efforts to improve drought predictions skill in the region, especially in a future climate when temperatures are projected to be hotter than what have been observed in the past and are likely to increase the drought risk [*Cook et al.,* 2015].

2. Experimental Setup

We utilized a hydrologic modeling based approach to disentangle the relative role of precipitation and temperature on the WY 2014 California drought. We conducted model experiments to first reconstruct 2014 drought conditions (see Reference Simulation, section 2.1) and then generate scenarios of the WY 2014 drought conditions based on (1) temperature scenarios (see Constant Precipitation, section 2.2) and (2) precipitation scenarios (see Constant Temperature, section 2.3), sampled from 1916 to 2012 historical climatology. These modeling experiments were similar to those used by *McCabe and Wolock* [2011] to examine the relative role of precipitation and temperature on modeled runoff in the conterminous United States. However, unlike that study, we used temperature (Constant Precipitation) and precipitation (Constant Temperature) scenarios from each year from 1916 to 2012 to generate the scenarios in the place of using climatological mean of precipitation and temperature.

The Variable Infiltration Capacity (VIC) [*Liang et al.,* 1994, 1996] hydrologic model was used to simulate daily SWE, SM, ET, and runoff under each aforementioned model experiments. The VIC model has been widely used for simulating the water budgets of many major and small river basins in the US, including California, and to accurately reconstruct drought conditions [*Sheffield et al.,* 2004; *Andreadis et al.,* 2005; *Wood*, 2008; *Wang et al.,* 2009; *Shukla et al.,* 2011; *Mao et al.,* 2015]. For this study, the model was implemented at a 0.5° by 0.5° spatial resolution and daily time step. Model parameters (soil, vegetation, and elevation bands) and atmospheric forcings (daily precipitation, maximum and minimum temperatures, and climatological mean wind speed) were obtained from the University of Washington's Surface Water Monitor [*Wood*, 2008; *Xiao et al.,* 2015], which is a near real-time experimental hydrologic monitoring system We decided to use this data set and perform the analysis at 0.5° spatial resolution (versus 0.125° resolution as in *Vano et al.* [2014]) because of this data set's availability through the end of WY 2014 and its use in past studies that focused on reconstructing drought events in the U.S. [*Andreadis et al.,* 2005; *Wang et al.,* 2009].

2.1. Reference Simulation

This simulation was conducted for the period 1916–2014 to obtain a long-term climatology of SWE, SM, ET, and runoff for California and reconstruct the WY 2014 drought conditions. The simulated SWE, SM, ET, and runoff for WY 2014 were used to reconstruct the WY 2014 "observed" drought conditions. The simulated SWE, SM, ET, and runoff for 1916–2012 provided a climatological distribution to convert actual WY 2014 values into percentiles. Figure S1 in the supporting information depicts the precipitation, average temperature, SWE, SM, ET, and runoff conditions for WY 2014 as estimated by the reference simulation. It shows that the majority of the state was under drought conditions (generally below 10 percentile) with west-central part of the state experiencing the most severe drought conditions ($<$2 percentile). USDM (http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx) also showed similar spatial pattern of the WY 2014 drought severity during April and May 2014 (not shown here).

2.2. Constant Precipitation (*P*) Experiment

This experiment was conducted to examine the influence of changes in temperatures on WY 2014 drought conditions. We did so by forcing the VIC model with 97 different atmospheric forcing scenarios in which the seasonal precipitation totals were forced to match the observed WY 2014 conditions, while the temperatures varied in each scenario according to the prior 97 WYs. We generated constant precipitation scenarios by rescaling the daily precipitation of each month during WY 1916 through 2012 (resulting in a total of 97 scenarios) so that monthly total precipitation of each month matched the precipitation total as recorded in the corresponding month of WY 2014. We then kept the daily minimum and maximum temperature forcings to the original values of the previous 97 WYs. This method of altering the precipitation forcings

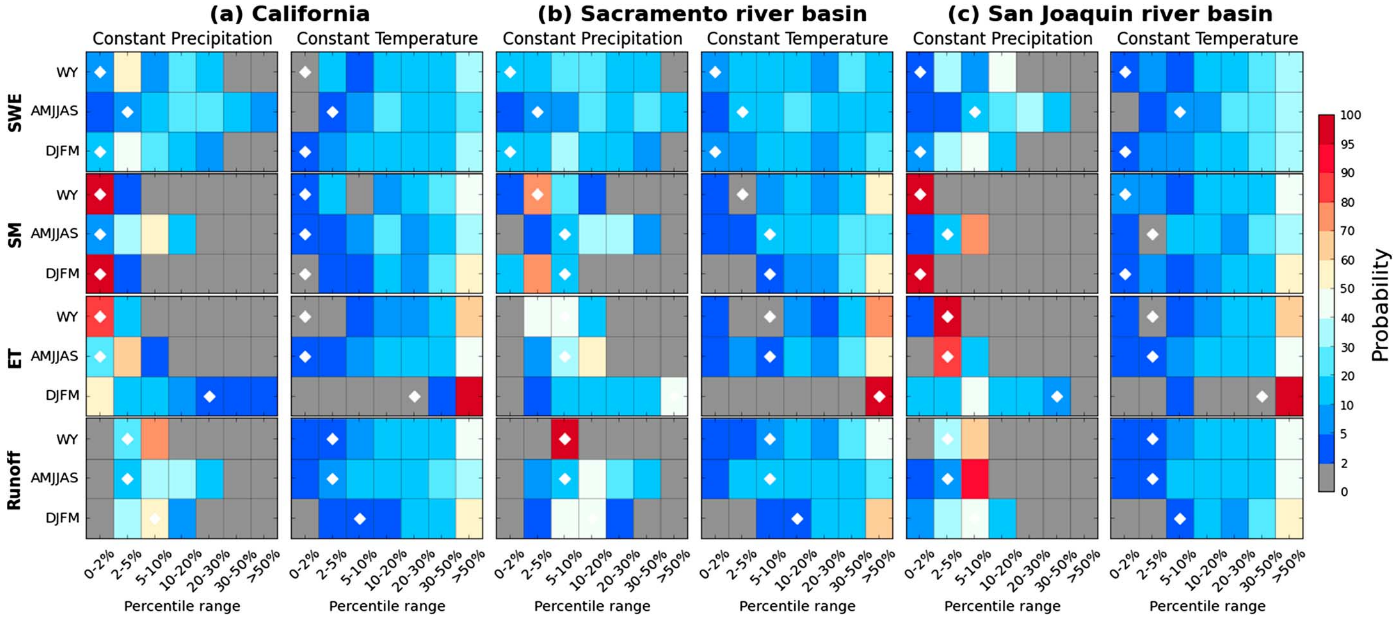


Figure 3. The probabilities of mean winter (DJFM), spring-summer (AMJJAS), and WY snow water equivalent (SWE), soil moisture (SM), evapotranspiration (ET), and runoff scenarios of the Constant Precipitation and Constant Temperature experiment being in given drought classes for (a) California, (b) Sacramento River basin, and (c) San Joaquin River basin. White diamonds indicate the observed drought for WY 2014, as estimated using the reference simulation.

insured that (a) the monthly precipitation totals in each scenario were the same as in WY 2014 but (b) the temperature in each scenario varied in such a way that the temperature ensemble represented historical climatology, and (c) the daily covariability of precipitation and temperature did not change.

We then forced the VIC model with these 97 scenarios to simulate scenarios of the WY 2014 drought. Each model simulation was initialized with the same hydrologic conditions as of 30 September 2013 (obtained from the Reference simulation). Hereafter, we refer to this experiment as the *Constant P* experiment.

2.3. Constant Temperature (*T*) Experiment

This experiment was conducted to examine the influence of changes in precipitation on WY 2014 drought conditions. This experiment was similar in implementation to the Constant *P* experiment (section 2.2), except we adjusted (by subtracting or adding the difference) daily minimum and maximum temperatures of each of the 97 scenarios so that monthly temperature means for each month matched the monthly mean temperature as recorded in the corresponding month in WY 2014. The precipitation scenarios in these simulations were drawn from the previous 97 WYs. Thus, this experiment represented the 1916–2012 precipitation climatology combined with fixed WY 2014 temperatures. Hereafter, we refer to this experiment as the *Constant T* experiment.

3. Scenarios of the WY 2014 Drought

Here we examine how WY 2014 drought conditions would have been under different temperature (Constant *P*) and different precipitation (Constant *T*) scenarios. Figure 3 displays the probability of the winter (December-January-February-March, DJFM) and spring-summer (April-May-June-July-August-September, AMJJAS) and WY mean of SWE, SM, ET, and runoff (aggregated over (a) California, (b) Sacramento River basin, and (c) San Joaquin River basin, respectively) being in a given drought class (as shown on the abscissa) in the Constant *P* (left) and Constant *T* (right) experiments. The white diamond shape shows the drought class of the observed conditions during WY 2014. As mentioned in section 2.1, we consider the WY 2014 values from the reference simulation as observed values for this analysis.

3.1. Constant Precipitation (*P*) Scenarios

Constant *P* results (Figure 3) show that although WY 2014 drought conditions would have likely been in the "severe drought" category (5th to 10th percentiles) or worse given the climatological temperature range, the record high 2014 WY temperatures did exacerbate the drought severity. We find that in general over California (Figure 3a), in 86% or more of the WY 2014 drought scenarios generated using Constant *P* scenarios, the drought severity was less than the observed conditions. In other words, the sum of the probabilities to the right of the observations (diamonds) in Figures 3a–3c (left) is greater than 86%. More specifically, SWE percentiles during winter, and SM and runoff percentiles during spring-summer season, would likely have been greater than the observed conditions if the temperatures resembled the historical climatology. The observed DJFM SWE percentile of WY 2014 was below 2 percentile (indicated by the white diamond); however, if the temperatures were like any other year in the past, the probability of the SWE being in the 5th to 10th percentiles would have been about 41% and the probability of SWE being above the 2nd percentile would have been 90% (Figure 3a). Likewise, during AMJJAS, the probability of mean SWE being greater than it was during WY 2014 would have been 90%.

Figure 3a also indicates that higher SWE during the DJFM season would have resulted in higher AMJJAS SM (probability of 94%) and runoff percentile (probability of 86%). California-averaged DJFM ET (Figure 3a) would most likely have been below 2 percentile, which is smaller than the 2014 value (20th to 30th percentiles), and ET during AMJJAS would have been higher (probability of 70%) during 2014 (likely due to higher-moisture availability).

We also find that the above-mentioned differences in the WY 2014 drought scenarios with the observed conditions were more pronounced over basins that receive their runoff at least partly through snow melt, such as the Sacramento River basin (Sac) and San Joaquin River basin (SanJ) (Figures 3b and 3c). (Of the two basins, SanJ receives a larger fraction of its runoff from snow melt). For example, the probability of DJFM SWE being in the 5th to 10th percentiles would have been 34% in the case of the Sac (Figure 3b) and 50% in the case of the SanJ (Figure 3c). Likewise, the AMJJAS runoff in the Sac (Figure 3b) would have likely (43% probability) been in the 10th to 20th percentiles category (as opposed to the 5th to 10th percentiles), and in the SanJ (Figure 3c) it would have been (92% probability) in the 5th to 10th percentiles category (as opposed to 2nd to 5th percentiles).

Figure 3a also indicates that in 10% of the scenarios the DJFM SWE, and in 6% (14%) of the scenarios the AMJJAS SM (runoff), would have been in the same drought category as in conditions observed in WY 2014. This likely happened in scenarios where one or more winter months were warmer than the corresponding months in WY 2014 as shown in Figure 1b.

3.2. Constant Temperature (*T*) Scenarios

The influence of record high temperature can also be seen in the distribution of the Constant *T* scenarios, as the probability of DJFM SWE being above the 50th percentile was only 38% for California (Figure 3 a). For the Sac, the probability of SWE being above the 50th percentile was less than 29% (Figure 3b). The influence of this shift can be seen in seasonal runoff. In the case of the Sac, the probability of DJFM runoff being above the 50th percentile was 63%, whereas the probability of AMJJAS runoff being above the 50th percentile was 23% (Figure 3b). The probability of DJFM ET being above the 50th percentile is above 95% in all cases due to the high temperatures (Figures 3a–3c).

The influence of temperature on the probability of winter SWE and spring-summer SM and runoff deficits can be estimated in terms of the odds ratio $P_{\text{Constant-}T}/P_{\text{clim}}$, where $P_{\text{Constant-}T}$ is the probability of SWE, SM, and runoff being below a certain percentile level (5th percentile in this case) in the Constant *T* simulations, and P_{clim} is the probability of the same happening given the climatological distributions. We find that the chances of winter SWE and spring-summer SM, and runoff being below the 5th percentile ($P_{\text{clim}} = 5\%$) in Constant *T* simulations ($P_{\text{Constant-}T}$) was 8.16%, 7.14%, and 7.14%, respectively. Hence, the odds ratio ($P_{\text{Constant-}T}/P_{\text{clim}}$) for getting below 5th percentile winter SWE and spring-summer SM and runoff was at least 1.4. Although this indicates the role of temperature in increasing drought risk, we acknowledge that further research using a larger sample size (generated through dynamical and/or statistical methods) is warranted to confirm this change in the likelihood of occurrence of severe drought events.

3.3. Comparison of Climatological Distribution With Constant Precipitation (*P*) and Constant Temperature (*T*) Scenarios

Figure 4 shows a comparison of the climatological distribution of SWE, SM, ET, and runoff depth (in millimeter) with the ensemble spread of Constant *P* and Constant *T* scenarios, aggregated over (a) California, (b) Sac, and (c)

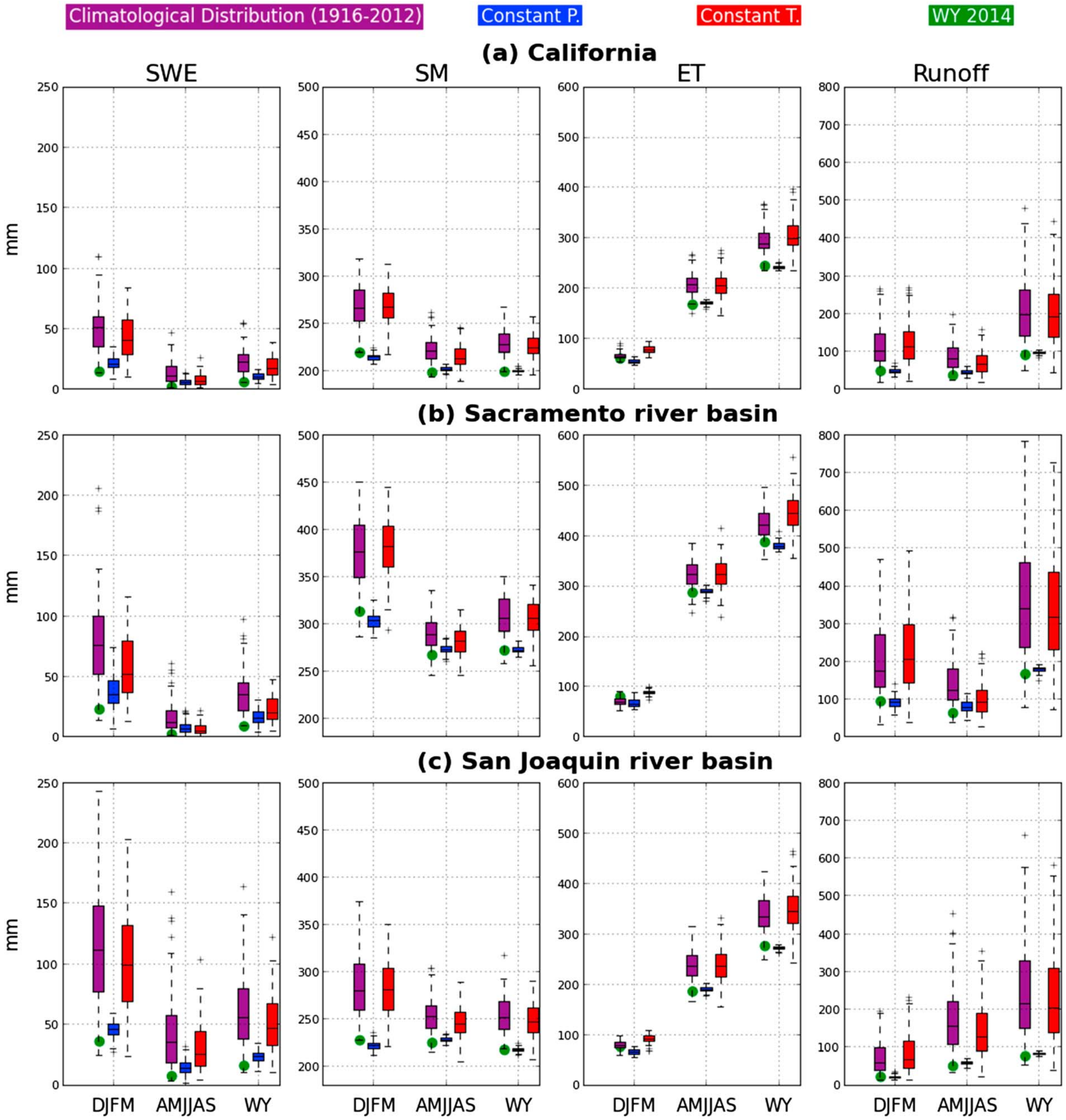


Figure 4. Ensemble spread of DJFM, AMJJAS, WY mean SWE, SM, ET, and runoff scenarios of Constant *P* and Constant *T* experiments as well as climatological distribution for (a) California State, (b) Sacramento River basin, and (c) San Joaquin River basin. Green circles show the values of those variables as observed in the WY 2014.

SanJ, respectively, for DJFM, AMJJAS, and WY. The ensemble of the Constant *P* scenario is below the median and often below the 25th percentile (indicated by the bottom line of the box in Figure 4) of the climatological distribution, indicating drought conditions in SWE and SM. The ensemble spread (median) of Constant *T* DJFM SWE was lower than the ensemble spread (median) of the climatological distribution.

4. Evaluating the Skill of Temperature Forecast in California

Temperature played an important role in exacerbating the WY 2014 drought. Therefore, skillful temperature forecasts are necessary to accurately forecast the severity of drought conditions in an

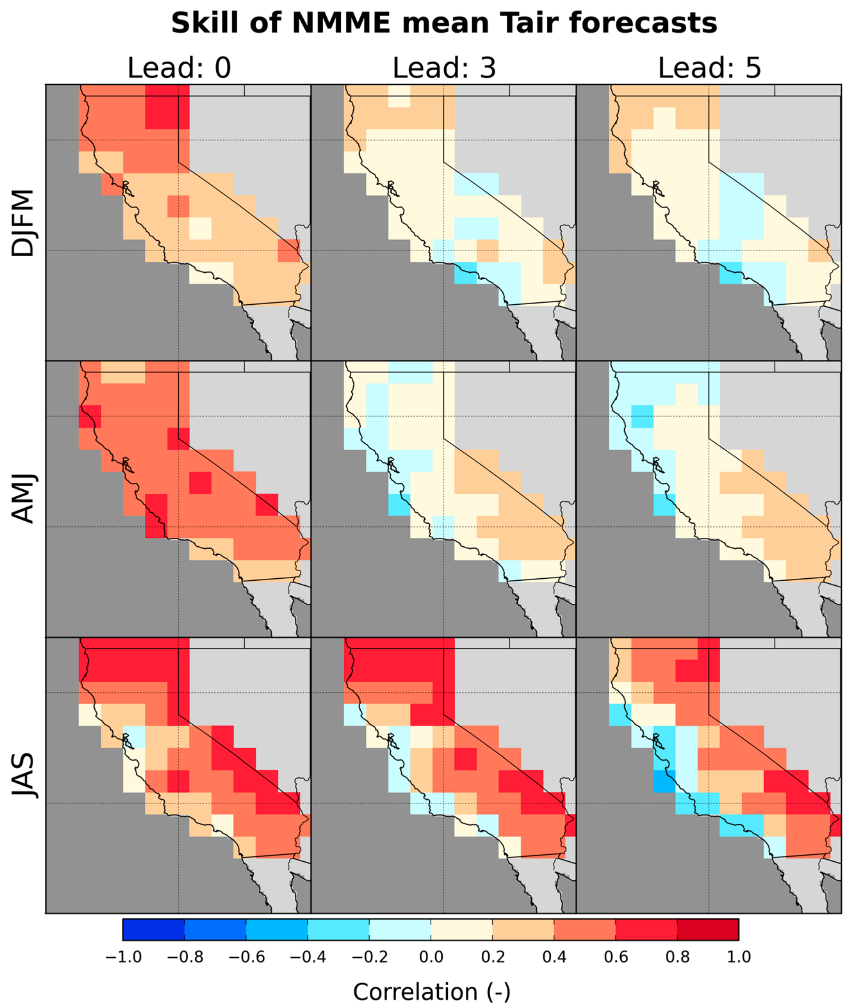


Figure 5. The skill of NMME mean temperature forecasts for December-January-February-March (DJFM), April-May-June (AMJ), and July-August-September(JAS) seasons at lead 0 (start of the season) through lead 5 (5 months before the start of the season).

event like WY 2014. In this section, we examine the level of temperature forecast skill in California. We use the air temperature reforecasts (forecasts generated for a long-term retrospective period) from the North American Multimodel Ensemble (NMME) [*Kirtman et al.,* 2014]. The NMME is a state-of-the-art seasonal to intraseasonal climate forecast system. We estimate the correlation between the ensemble mean NMME temperature forecasts and the gridded temperature observations used for the reference simulation (section 2.1), over 1982–2010 for each grid cell in California (at the native spatial resolution of $1° \times 1°$). For this analysis, we use six of the NMME models (CFSv2, CCSM3, GFDL-CM2p1-aer04, CMC1-CanCM3, CMC2-CanCM4, and NASA-GMAO), resulting in a total of 70 ensemble members.

We find that the skill of temperature forecasts in California (Figure 5) is very low for the important seasons of DJFM and April-May-June (AMJ), when snow accumulation and melt occurs. At lead 0 (i.e., when the forecast is made at the beginning of a given season), some skill exists; however, for both the DJFM and AMJ seasons, the skill is generally below 0.2 (correlation) if the forecasts were made 3 to 5 months (lead 3 and lead 5 respectively) before the start of the season. For the July-August-September season, we find that the forecast skill is higher (correlation >0.4) mainly for the interior parts of the state that could be useful for estimating evaporative demand during a season of peak evaporative demand.

5. Concluding Remarks

This study shows that although low precipitation was the main driver of the WY 2014 drought conditions in California, temperature played an important role in exacerbating the drought. Our results demonstrate that if temperatures during that WY resembled the 1916–2012 climatological distribution, there was a greater than 86% probability that winter SWE and spring-summer SM and runoff percentiles would have been less severe than the observed conditions of WY 2014.

This study also finds that although November–April 2014 mean temperature was the warmest on record, with the exception of January (which was the hottest month on record for four out of seven CDs), there have been months in the past that were hotter than the same months in WY 2014. As a result, we find that the probability of the drought conditions being similar to WY 2014 conditions, given the observed rainfall and climatological temperature conditions, was generally only between 5 and 15%. It is worth mentioning here that WY 2014 was the third year of a multiyear drought event; and hence, WY 2014 started with drier than normal initial hydrologic conditions (IHCs). If the IHCs were different at the start of the WY, the results of this analysis could have been different. However, exploring the influence of the change in IHCs along with Constant *P* and Constant *T* scenarios is beyond the scope of this study.

Finally, given the important role played by temperature during the WY 2014 drought, we also examined the level of temperature forecast skill in California. We report that the temperature forecast skill in California is very low (correlation with observations was generally below 0.2), especially for the important DJFM and AMJ seasons, if the forecasts were made a few months ($>$1 month) in advance. We postulate that the lack in temperature forecast skill might hinder accurate seasonal drought prediction in California.

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References

AghaKouchak, A., L. Cheng, O. Mazdiyasni, and A. Farahmand (2014), Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought, *Geophys. Res. Lett.*, *41*, 8847–8852, doi:10.1002/2014GL062308.

Andreadis, K. M., E. A. Clark, A. W. Wood, A. F. Hamlet, and D. P. Lettenmaier (2005), Twentieth-century drought in the conterminous United States, *J. Hydrometeorol.*, *6*(6), 985–1001, doi:10.1175/JHM450.1.

California Nevada Applications Program (2014), *The California Drought of 2014: Record Hot, Record Dry*, California-Nevada Climate Applications Program, San Diego, Calif.

Cook, B. I., T. R. Ault, and J. E. Smerdon (2015), Unprecedented 21st century drought risk in the American Southwest and Central Plains, *Sci. Adv.*, *1*(1), e1400082, doi:10.1126/sciadv.1400082.

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, *Bull. Am. Meteorol. Soc.*, *95*(9), S11–S15.

Griffin, D., and K. J. Anchukaitis (2014), How unusual is the 2012–2014 California drought?, *Geophys. Res. Lett.*, *41*, 9017–9023, doi:10.1002/2014GL062433.

Hobbins, M., A. Wood, D. Streubel, and K. Werner (2012), What drives the variability of evaporative demand across the conterminous United States?, *J. Hydrometeorol.*, *13*, 1195–1214, doi:10.1175/JHM-D-11-0101.1.

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, Univ. of California, Davis, Calif.

Kirtman, B. P., D. Min, J. M. Infanti, J. L. Kinter III, D. A. Paolino, Q. Zhang, H. van den Dool, S. Saha, M. P. Mendez, and E. Becker (2014), The North American Multi-Model Ensemble (NMME): Phase-1 seasonal to interannual prediction; Phase-2 toward developing intra-seasonal prediction, *Bull. Am. Meteorol. Soc.*, *95*(4), 585–601, doi:10.1175/BAMS-D-12-00050.1.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *J. Geophys. Res.*, *99*(D7), 14,415–14,428, doi:10.1029/94JD00483.

Liang, X., E. F. Wood, and D. P. Lettenmaier (1996), Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification, *Global Planet. Change*, *13*(1), 195–206.

Mao, Y., B. Nijssen, and D. P. Lettenmaier (2015), Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL063456.

McCabe, G. J., and D. M. Wolock (2011), Independent effects of temperature and precipitation on modeled runoff in the conterminous United States, *Water Resour. Res.*, *47*(11), W11522, doi:10.1029/2011WR010630.

Seager, R., and M. Hoerling (2014), Atmosphere and ocean origins of North American droughts, *J. Clim.*, *27*(12), 4581–4606, doi:10.1175/JCLI-D-13-00329.1.

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson (2014), Causes and predictability of the 2011–14 California drought, NOAA Drought Task Force/National Integrated Drought Information System.

Sheffield, J., G. Goteti, F. Wen, and E. F. Wood (2004), A simulated soil moisture based drought analysis for the United States, *J. Geophys. Res.*, *109*, D24108, doi:10.1029/2004JD005182.

Shukla, S., A. C. Steinemann, and D. P. Lettenmaier (2011), Drought monitoring for Washington State: Indicators and applications, *J. Hydrometeorol.*, *12*(1), 66–83.

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*, S3–S7.

Trenberth, K. E., A. Dai, G. van der Schrier, P. D. Jones, J. Barichivich, K. R. Briffa, and J. Sheffield (2013), Global warming and changes in drought, *Nat. Clim. Change*, *4*(1), 17–22, doi:10.1038/nclimate2067.

Vano, J. A., et al. (2014), Understanding uncertainties in future Colorado River streamflow, *Bull. Am. Meteorol. Soc.*, *95*(1), 59–78, doi:10.1175/BAMS-D-12-00228.1.

Wang, A., T. J. Bohn, S. P. Mahanama, R. D. Koster, and D. P. Lettenmaier (2009), Multimodel ensemble reconstruction of drought over the continental United States, *J. Clim.*, *22*(10), 2694–2712, doi:10.1175/2008JCLI2586.1.

Wang, H., and S. Schubert (2014), Causes of the extreme dry conditions over California during early 2013, *Bull. Am. Meteorol. Soc.*, *95*(9), S7–S11.

Wang, S.-Y., L. Hipps, R. R. Gillies, and J.-H. Yoon (2014), Probable causes of the abnormal ridge accompanying the 2013–2014 California drought: ENSO precursor and anthropogenic warming footprint, *Geophys. Res. Lett.*, *41*, 3220–3226, doi:10.1002/2014GL059748.

Wood, A. (2008), The University of Washington Surface Water Monitor: An experimental platform for national hydrologic assessment and prediction, in American Meteorological Society Union Meeting: 2nd conference on hydrology, pp. 1–13, New Orleans, La.

Xiao, M., Y. Mao, D. P. Lettenmaier, and B. Nijssen (2015), UW surface water monitor. [Available at http://www.hydro.washington.edu/forecast/monitor/, Accessed date 10 Jan 2015.]