The West Wide Drought Tracker

Drought Monitoring at Fine Spatial Scales

John T. Abatzoglou, Daniel J. Mcevoy, and Kelly T. Redmond

BACKGROUND. The western United States has seen increases in population and water use over the past century. Total water use has remained relatively unchanged over the past several decades due to water conservation efforts. However, water scarcity has become more acute across much of this semiarid region during recent decades due to long-term declines in water storage juxtaposed with the region's notable hydroclimatic variability. Observed declines in mountain snowpack and increases in atmospheric demands tied to long-term warming trends have further exacerbated water scarcity and increased the importance of monitoring efforts given the array of social, economic, and ecosystem sectors dependent upon the already stressed water supply. The recent severe drought in California and protracted drought across much of the southwestern United States over the past couple decades have prompted demand for accessible drought decision-making information at appropriate spatial scales across the western United States.

Drought monitoring is particularly important in the western United States due to the extensive coverage of arid and semiarid lands that are prone to water shortages. Stakeholders from a range of sectors across the region whose interests include energy, wildfire, agriculture, and water resource management have expressed the need for local-to-regional drought information as high-stakes decisions (e.g., drought declaration) may be made based on incomplete or insufficient data given the sparseness of long-term climate observations across the region. In addition, drought monitoring presents challenges across the western United States due to sharp geographic gradients in moisture availability, significant interannual-to-decadal climate variability, and the region's strong reliance on mountain snowpack for water supplies.

Numerous drought monitoring tools distribute crucial information to stakeholders. However, existing tools are typically limited by some combination of the following: a short period of record, coarse spatial resolution, or the inability to download and manipulate data. For example, the National Centers for Environmental Information (NCEI) Climate at a Glance tools provide drought and climate information at relatively coarse spatial scales (e.g., climate divisions) that are valuable for large-scale regional assessments, but may provide insufficient spatial detail for local decision-making. The PRISM Climate Group (PRISM is described in the next section) provides maps of hydroclimate anomalies from 1980 to the present, but does not present drought indices. A heavily used tool for drought declaration and decision-making is the U.S. Drought Monitor (USDM), which relies on a blend of quantitative metrics and local impact information to produce weekly maps of drought severity. However, the USDM is limited temporally with a period of record beginning in 2000. The West Wide Drought Tracker (WWDT) was developed to overcome some limitations of existing drought monitoring tools through a set of applied data and visualization platform to enhance access to data on climate and drought indices at finer spatial scales. Here we describe the WWDT web application and present a case study on the utility of the WWDT in examining the 2012–16 California drought.

AFFILIATIONS: Abatzoglou—University of Idaho, Moscow, Idaho; McEvoy And Redmond*—Desert Research Institute, and Western Regional Climate Center, Reno, Nevada
* Deceased
CORRESPONDING AUTHOR: John T. Abatzoglou, jabatzoglou@uidaho.edu

DOI:10.1175/BAMS-D-16-0193.1

DATA SOURCES. Two primary climate datasets are used to derive drought indices and climate summaries that are described in Table 1: i) gridded data from the Parameter-elevation Regression on Independent Slopes Model (PRISM), and ii) station data from the U.S. Historical Climatology Network (USHCN). PRISM serves as the foundational dataset for the WWDT and is used in both the spatial mapping and time series tools. PRISM uses station data, a digital elevation model, and additional spatial datasets to produce ≥4-km (2.5 arc min) resolution grids of monthly temperature and precipitation across the continental United States from 1895 to the present. PRISM uses high-elevation mountain stations and accounts for a number of physiographic factors, thereby making it an ideal dataset for resolving the climatic complexity across much of the mountainous western United States. Monthly station data from 1895 to the present for approximately 1,200 long-term USHCN stations are exclusively used in the time series tool. USHCN sites typically have long periods of record (100+ years), very few missing data gaps, and include adjustments to temperature data to account for historical changes in station location, instrumentation, and observing practice.

In addition to climate datasets, soil water holding capacity data at a ≥1-km resolution was acquired from The Pennsylvania State University State Soil Geographic (STATSGO) data and aggregated up to match the spatial scale of the PRISM data. Soil water holding capacity data are used in the soil water balance calculations of the Palmer Drought Severity Index (PDSI).

DROUGHT AND CLIMATE DATA VISUALIZATION. Despite the name, WWDT provides access to data for the contiguous United States, not just for the western states. The WWDT web application (www.wrcc.dri.edu/wwdt/) consists of two main tools: spatial mapping and time series. Data are updated monthly in the first couple days of each month. Table 1 provides a complete list of data and indices available on the WWDT.

The mapping tool provides the option to zoom into different regions including the western United States, Northwest, Southwest, and each of the 11 western

Table 1. Description of data sources for monthly climate and drought indices for the WWDT spatial mapping and time series tools; T_{mean} = mean temperature, Prcp = precipitation.

		Spatial mapping	Time series
Gridded data	PRISM	Yes	Yes
	• 4-km spatial resolution		
	• 1895–present period of record		
Station data	U.S. Historical Climatology Network	No	Yes
	• 1895–present period of record		
	• 1,218 stations		
Climate indices	• T_{mean} anomalies, 1–12-month time scales	Yes	Yes
	• T_{mean} percentiles, 1–12-month time scales		
	• Prcp anomalies, 1–12-month time scales		
	• Prcp percentiles, 1–12-month time scales		
Drought indices	• Standardized precipitation index (SPI), 1–12-, 15-, 18-, 24-, 30-, 36-, 48-, 60-, and 72-month time scales	Yes	Yes
	• Standardized precipitation evapotranspiration index (SPEI), 1–12-, 15-, 18-, 24-, 30-, 36-, 48-, 60-, and 72-month time scales		
	• Palmer drought severity index (PDSI)		
	• Self-calibrated palmer drought severity index (sc-PDSI)		
	• Palmer *Z*-index		

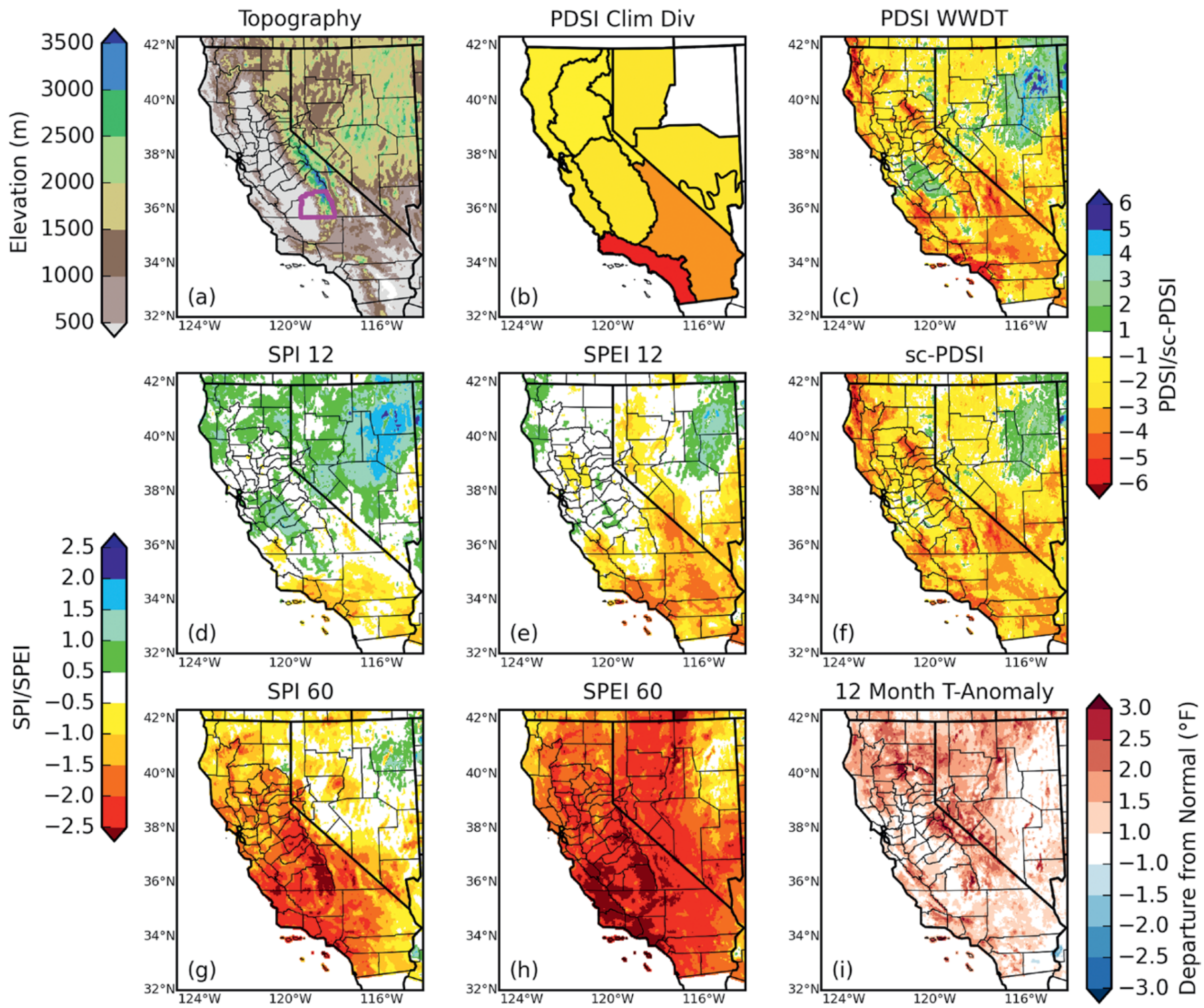

Fig. 1. California–Nevada drought and climate indicators ending September 2016. (a) Terrain elevation in meters at 4-km spatial resolution. (b) PDSI based on climate division data and (c) PRISM data. Short-term California drought shown by 12-month (d) SPI and (e) SPEI, and (f) sc-PDSI. Long-term California drought shown by 60-month (g) SPI and (h) SPEI. (i) The 12-month temperature anomaly created using 1981–2010 normal period. Maps can be generated by using the WWDT "Archived Maps" tab. Magenta outline in (a) shows Tulare County, which is used as a spatial averaging domain in Fig. 2. Links to WWDT maps: SPI 12: http://bit.ly/2hCXzoM, SPEI 12: http://bit.ly/2im7hJf, 12-month T-anomaly: http://bit.ly/2hUCxxR, SPI 60: http://bit.ly/2iNslYh, SPEI 60: http://bit.ly/2igKMHQ, and sc-PDSI: http://bit.ly/2iNsOK3. Links to netCDF files generated by WWDT used to make this figure: SPI 12: http://bit.ly/2hUMPy0, SPEI 12: http://bit.ly/2imchxK, 12-month T-anomaly: http://bit.ly/2iqpB6E, SPI 60: http://bit.ly/2hD0spK, SPEI 60: http://bit.ly/2iNA0Wt, and sc-PDSI: http://bit.ly/2igDdAF.

states for both the current month as well as previous months back to 1895. Temperature and precipitation can be visualized two ways: anomalies (percent of normal for precipitation) using the 1981–2010 baseline climatology or percentile rankings for the entire period of record. Accumulation (for precipitation) and mean (for temperature) can be viewed at time scales aggregated over the previous 1–12 months. Drought indices include the Palmer *Z*-index, Palmer drought severity index (PDSI), self-calibrated PDSI (sc-PDSI), standardized precipitation index (SPI), and standardized precipitation evapotranspiration index (SPEI). To account for the multiscalar nature of drought, SPI and SPEI are calculated at time scales from 1 to 12 months, as well as 15, 18, 24, 30, 36, 48, 60, and 72 months. Longer time scales are particularly important in the western United States (see California drought example below), where large reservoirs that are a common water supply can take several years to respond to drought. SPEI uses the same statistical methodology as SPI but also accounts for changes in temperature through evaporative demand using a simple water budget (precipitation minus evaporative demand). The entire archive of WWDT maps is available to view on the website and download as digital data in netCDF and GeoTIFF formats.

The time series tool (www.wrcc.dri.edu/wwdt/time/) allows users to visualize and extract annualized data (e.g., August PDSI for all years), monthly sequences (e.g., PDSI for the past 36 months), and the complete monthly data for the period of record. Time series data can be extracted for individual stations or user-selected ≥4-km pixels, as well as spatial averages for geographical regions including states, counties, NCEI climate divisions, level 4 subregion hydrologic units, and predictive service areas (subregions of Geographic Coordinating Areas used by wildfire management) across the contiguous United States. Time series data are available to download in comma-separated value (CSV) format.

CASE STUDY: THE 2012–16 CALIFORNIA DROUGHT. The most severe drought in the instrumental record across parts of California began in 2012 and continued through 2016 before being largely ameliorated by abundant precipitation (record-breaking in some cases) during the 2016–17 winter. The 2012–16 California drought was driven by a multiyear precipitation deficit and exceptionally warm temperatures. Here we highlight how the WWDT can be used to visualize the spatial and temporal complexity of the California drought and the importance of having multiple drought and hydroclimate indices across different time scales.

Figure 1 shows SPI and SPEI at 12- and 60-month time scales, PDSI, sc-PDSI, and 12-month temperature anomalies all ending September 2016. Maps were generated using the "Archived Maps" tab from the WWDT page. Each map shows different aspects of the drought. Figures 1b and 1c show PDSI from NCEI at the scale of climate divisions and from the WWDT at the scale of PRISM data. Features like more severe drought (PDSI < –3), as seen in WWDT PDSI (and sc-PDSI, Fig. 1f) over the higher elevations of the Sierra Nevada adjacent to neutral to slightly wet conditions (PDSI > 0) in the low-lying Central Valley, elucidate spatial features of drought monitoring not evident at coarser scales like NCEI climate divisions that typically have spatial extents much larger than individual counties. At short time scales spanning the water year (October 2015–September 2016) 12-month SPI and SPEI (Figs. 1d and 1e, respectively) show some drought relief in Northern California due to slightly above-average precipitation. By contrast, sc-PDSI (Fig. 1f) shows the persistence of severe drought over the Sierra Nevada. Nearly the entire state of California was in some form of longer-term drought in September 2016, as evident in the 60-month SPI and SPEI shown in Figs. 1g and 1h, respectively. Exacerbation of drought severity at both time scales due to anomalously warm temperatures (Fig. 1i) is evident in the SPEI, PDSI, and sc-PDSI.

Figure 2 shows an example application of the WWDT time series tool for data averaged over Tulare County, California (highlighted in Fig. 1a for reference), located in the drought-stricken southern Sierra Nevada. Water year percent of normal precipitation (Fig. 2a) shows that individual dry years (<60% of normal) occur throughout the entire record, but five dry years in a row with three consecutive water years below 60% (2013–15) is unprecedented in the instrumental record. Coinciding with the dry streak were five consecutive years (2012–16) of temperature anomalies more than 0.7°C (1.3°F) above normal, with 2014 and 2015 being the only two years in the observational record that were more than 1.7°C (3°F) above normal (Fig. 2b). While previous multiyear droughts are evident in the instrumental record, the compounding effect of warm and dry conditions from 2012 to 2016 can be seen in the 60-month SPEI, with 2016 being the lowest on record followed closely by 2015 (Fig. 2c).

ENHANCING DROUGHT MONITORING CAPABILITIES. Continued advancements in operational drought monitoring systems will make use of higher-spatial-resolution datasets such as those presented in WWDT. However, there is additional need for producers of drought monitoring tools to address structural uncertainty in such traditional drought products that result from using different climate forcing datasets and methods for estimating evaporative demand. One shortcoming of the WWDT is that it is limited to providing monthly updates. Consumers of drought information such as the USDM would benefit from having more timely

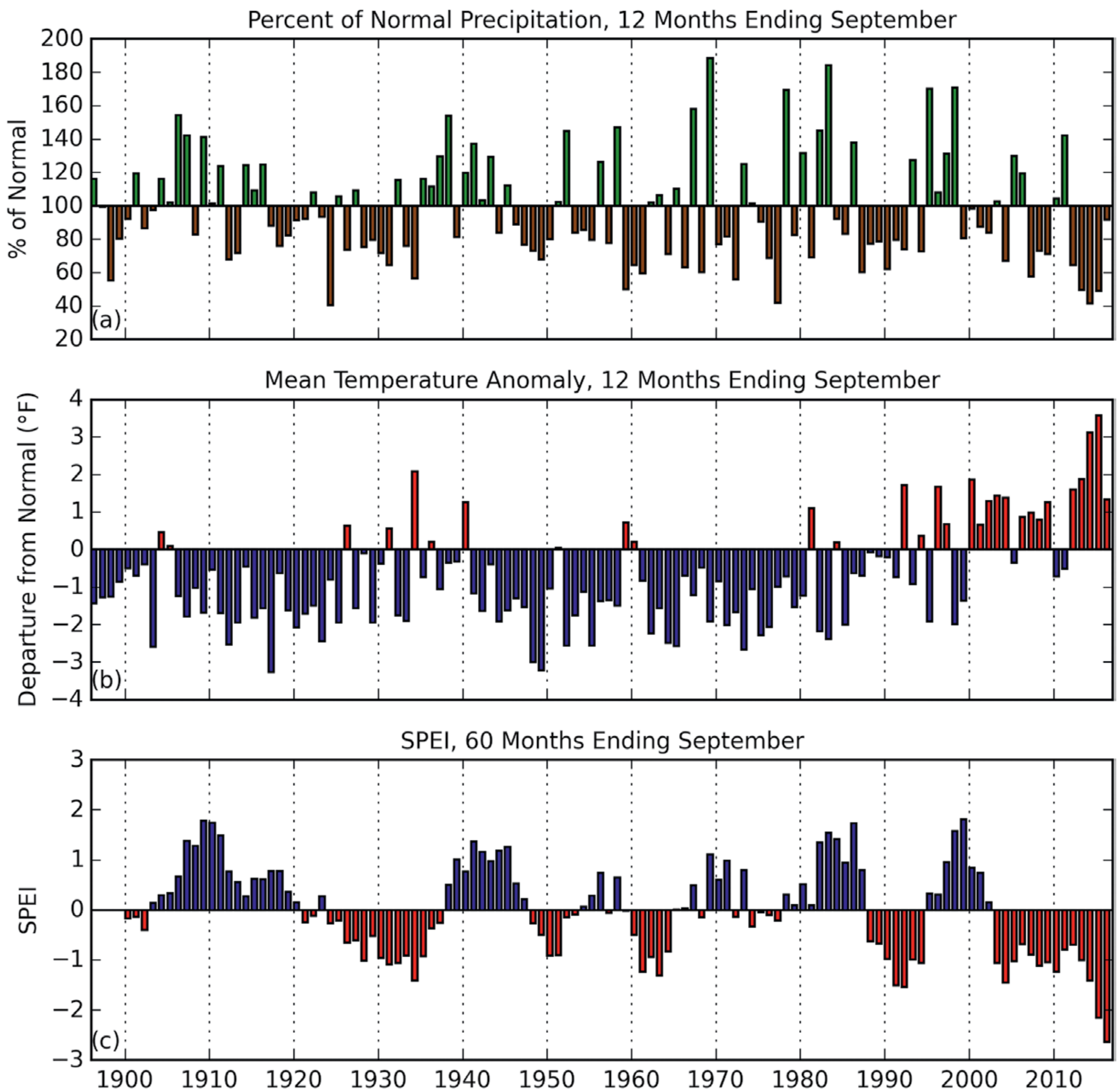

Fig. 2. Temperature, precipitation, and drought indices averaged over Tulare County, California (see Fig. 1a for geographic location). (a) Water year percent of normal precipitation, (b) water year mean temperature anomaly, and (c) 60-month SPEI ending in September. Anomalies in (a) and (b) are relative to the 1981–2010 period. Time series can be generated using the WWDT "Time Series" tab. Links to time series graphs: percent of normal precipitation (expressed as precipitation values on WWDT): http://bit.ly/2iqu891, temperature anomaly: http://bit.ly/2iOgflP, and SPEI 60: http://bit.ly/2hBcBJV.

updates that capture aspects of intramonthly drought evolution important to decision-making.

The WWDT has been operational since 2011 and has become a popular tool for applied climate research, public outreach communication, and data visualization. Drought information statements issued by many National Weather Service offices regularly provide links to WWDT maps. NCEI uses SPEI maps and time series from the WWDT in monthly State of the Climate updates (http://bit.ly/2iJut4q). In addition, many state climate offices and applied climatologists regularly use the WWDT for stakeholder and public outreach to communicate local/regional drought updates in webinars or workshop settings (e.g., National Integrated Drought Information System workshops: http://bit.ly/2iF6AND).

ACKNOWLEDGMENTS. This work was funded by NOAA Transition of Research Applications to Climate Services grant NA08OAR4310661; the NOAA Regional Integrated Sciences and Assessment (RISA) Program from NOAA's Climate Program Office under cooperative agreement NA15OAR4310145; University of California—San Diego California Nevada Climate Application Program grant number NA11OAR4310150; and NOAA WRCC grant AB-133E-16-CQ-022. We would like acknowledge Andrew Joros and Donovan VanSant for their contributions to the web development of the WWDT and Laura Edwards for her help conceptualizing the WWDT.

FOR FURTHER READING

Daly, C., R. P. Neilson, and D. L. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor.,* **33,** 140–158, doi:10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2.

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.

McEvoy, D. J., J. L. Huntington, J. T. Abatzoglou, and L. M. Edwards, 2012: An evaluation of multiscalar drought indices in Nevada and Eastern California. *Earth Interact.,* **16,** 1–18, doi:10.1175/2012EI000447.1.

McKee, T. B., N. J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration to time scales. *Proc. 8th Conf. Appl. Climatol.,* Boston, MA, Amer. Meteor. Soc., 179–183.

Redmond, K. T., 2002: The depiction of drought: A commentary. *Bull. Amer. Meteor. Soc.,* **83,** 1143–1147, doi:10.1175/1520-0477(2002)083<1143:TDODAC>2.3.CO;2.

Shukla, S., M. Safeeq, A. AghaKouchak, K. Guan, and C. Funk, 2015: Temperature impacts on the water year 2014 drought in California. *Geophys. Res. Lett.,* **42,** 4384–4393, doi:10.1002/2015GL063666.

Svoboda, M., and Coauthors, 2002: The Drought Monitor. *Bull. Amer. Meteor. Soc.,* **83,** 1181–1190, doi:10.1175/1520-0477(2002)083<1181:TDM>2.3.CO;2.

Vicente-Serrano, S. M., S. Beguería, and J. I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Climate,* **23,** 1696–1718, doi:10.1175/2009JCLI2909.1.

Wells, N., S. Goddard, and M. J. Hayes, 2004: A self-calibrating Palmer drought severity index. *J. Climate,* **17,** 2335–2351, doi:10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.

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. *Geophys. Res. Lett.,* **42,** 6819–6828, doi:10.1002/2015GL064924.