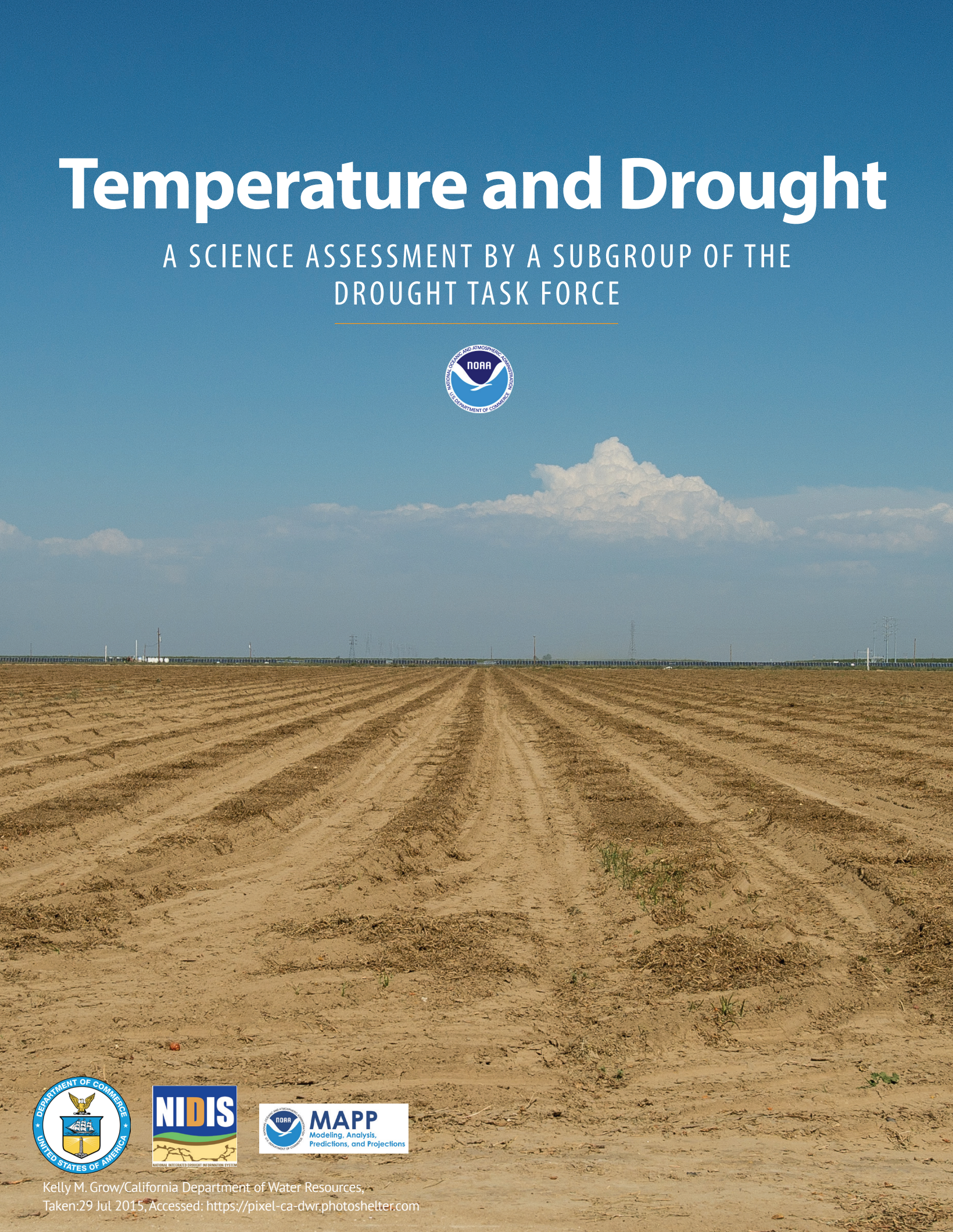
Temperature and Drought

A SCIENCE ASSESSMENT BY A SUBGROUP OF THE DROUGHT TASK FORCE



Kelly M. Grow/California Department of Water Resources,
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Drought research has historically focused on the analysis of how precipitation deficits cause drought. In contrast, temperature as a drought driver has only recently drawn attention.

Recent interest in temperature as a driver likely stems from observational evidence of increased land surface temperatures, more frequent heat waves, and the increasing duration of hot spells, all of which are giving a heightened perception of the land surface being "parched". MAPP Drought Task Force research has explored the relation of temperature and drought, both as a driver of and responder to drought. In this drought information sheet, prior knowledge of drought is integrated with new insights on temperature-drought linkages. This information sheet is the state of the Drought Task Force's knowledge on this topic.

1. Broad concepts of drought

a. Definition

Drought is defined by an anomalous period of unmet moisture demand, either for purposes of meeting human consumption, sustaining ecosystem functioning, or meeting societal requirements overall. The term "drought" is generally reserved to indicate soil moisture and surface water supply deficits that curtail agricultural crop production and induce hydrologic imbalances occurring over an extensive area. Despite its large scale, drought is nonetheless understood to be a transient phenomenon; an event during which excursion into moisture scarcity, whether lasting only a few months or many years, is inevitably followed by full recovery. Droughts are one manifestation of the variability that defines a region's climate.

The experience of drought is vividly captured by the word "parched" – parched land, parched fields, parched laborers, and so on. Drought is indeed often characterized by unusual land surface dryness, below normal surface water supply, and curtailed access to water from remote sources. Hot temperatures can exacerbate the "parched" character of the surface through evapotranspiration.

b. Physical Causes

Atmospheric effects typically drive drought. Failed rains generally lead to drier soils, reduced streamflow, and depleted surface water storage. High evaporative demand due to hot temperatures, increased solar insolation, strong winds, or low relative humidity can also dry soils and deplete surface water storage. Both failed rains and high evaporative demand are usually a consequence of atmospheric circulation variability. Circulation anomalies can disrupt the normal flow of water vapor into a region for example by steering rain producing storms away from a region, thereby inhibiting cloud formation and precipitation. Circulation anomalies, via transport of warm air masses or subsidence-induced warming, can also

A dry and empty field on S. Merced Avenue off of Highway 33 in Coalinga, Calif. on July 29th, 2015.
Kelly M. Grow/ California Department of Water Resources

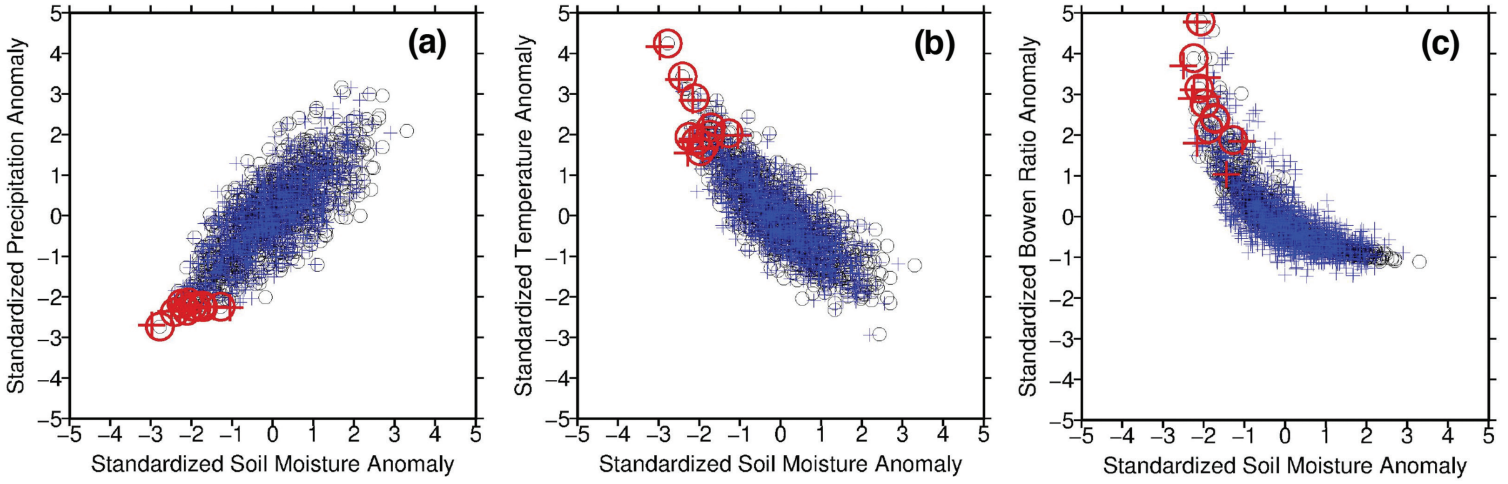

FIGURE 1.
Comparison of May-August 2012 standardized anomalies of soil moisture on the horizontal axis versus (a) precipitation, (b) surface air temperature, and (c) Bowen ratio on the ordinate. The results are for a Central Great Plains domain (36°N - 43°N, 90°W-105°W). Data are from atmospheric climate model simulations (circles) and land surface model simulations (crosses). The 1% lowest May-August precipitation simulations are highlighted in red. From Figure 10 of B. Livneh and M. Hoerling, 2016: The physics of drought in the U.S. Central Great Plains.

increase atmospheric demand for moisture from the land surface. Increasing surface air temperatures associated with radiative forcing associated with long term climate change can also increase evaporative demand and thus dry soils, though it is possible that this drying could be offset by a simultaneous increase in precipitation.

2. Some basic physics of temperature-drought linkages

a. Temperature as the responder

Drought and heat waves often co-exist. Land surface dryness, perhaps caused by precipitation deficits induced by atmospheric circulation patterns, leads to an increase in the ratio of sensible to latent heating, known as the Bowen ratio. As drought develops, incoming solar radiation contributes more toward raising surface temperature than to evaporating surface moisture, and this warmth is passed on to the overlying air. The ensuing surface warming is above and beyond what might have resulted from the horizontal advection of air masses alone. Through this local thermodynamic mechanism, warm temperature anomalies are basically a "passive" response to dry anomalies.

A positive correlation between surface temperature and drought severity is especially high during summer over mid-continental regions. The 2011 Texas, 2012 Great Plains, and 2012-2016 California droughts are recent examples. The physics of the relationship is intimately tied to anomalous surface energy exchange during drought. The atmosphere responds to the land surface as it dries via increased upward heat transfer consistent with a larger Bowen ratio (Figure 1). The land surface also responds to atmospheric conditions during drought; droughts are associated with clear-sky conditions that favor more incoming solar radiation, leading to higher daytime temperatures.

b. Temperature as the driver

Temperature anomalies are not always passive responses to dry anomalies; they can also drive moisture depletion. Droughts that rapidly develop in a matter of weeks (referred to as flash droughts) can be initiated when the land surface suddenly dries due to high evaporative demand produced by unusually high air temperatures. It is not unusual that both temperature and precipitation drivers act in tandem to produce rapid drought onset. A weather regime that is typified by high temperature is also often accompanied by increased surface radiation, gusty surface winds, and low relative humidity, which together drive drought by increasing evapotranspiration. Temperature driving is most important during the warm season when both the evaporative demand and vegetation water requirements are high. Passive responses of temperature to land surface dryness and active temperature driving of land surface dryness often co-exist during drought events; separating their individual effects remains a challenge.

3. Recent DTF science on temperature-drought linkages

• Within Seasons:

Empirical evidence using atmospheric moisture demand indices suggests that temperature was a significant driver of the rapid onset of the 2011 Southern Plains and 2012 Great Plains drought, which created flash drought conditions with agricultural impacts[1,2]. An index of evaporative stress has been found to reveal emergent drought development as diagnosed over eastern Oklahoma and western Arkansas during late spring 2011 (Fig. 2)[3]. Overall, heat waves originating from atmospheric drivers can initiate drought conditions, such as is evident in the onset of the 2011 Southern Plains drought. However, precipitation flash droughts are found to be more common than heat wave flash droughts over the United States[4,5].

Atmospheric circulation patterns that lead to drought onset and demise during the warm season were identified from historical data[6,7,8]. The dynamics of these patterns are linked to anomalous Rossby waves guided by the jet stream. Prediction skill of central US summertime drought onset and decay on sub-seasonal time scales is limited, despite our better understanding of such atmospheric drivers of drought. This is in part because of an inability to predict both the factors triggering such Rossby waves and the wave dynamics themselves, beyond about week-2[9]. Some recent work has shown that sub-seasonal forecasting skill can be achieved via empirical methods that consider current soil moisture, ET, and precipitation anomalies alone[10,11]. Projections of future climate over the Great Plains indicate an increase of sub-seasonal temperature variability that appears to be associated with enhanced land-atmosphere feedbacks as the region warms and dries, though amplification of future heat waves does not appear to be induced by changes in planetary wave variability[12].

• Across Seasons:

Land surface model experiments for the May-August 2012 Great Plains drought indicate that precipitation deficits were the main cause for low soil moisture conditions, with the associated heat wave primarily a response to the drought rather than a significant contributor to the soil dryness[13]. Temperature as a driver of the drought was found to contribute roughly 20% to the 2012 summertime Great Plains soil moisture deficit, while precipitation deficits accounted for about 80% of the soil depletion.

Empirical results of surface energy exchange indicate that low soil moisture can serve as a skillful predictor for summer heat waves at 1-2 months lead time (e.g. the southern Plains in 2012). Analysis of the 2011 and 2012 Great Plains drought reveals a strong coupling between dry states of the land surface, reduced evapotranspiration and high surface temperature that in part resulted from an increased Bowen ratio and enhanced air temperature warming above the dry soil region (Figure 3)[14]. The near surface heating associated with depleted soil moisture also affects weather patterns and can cause drought to expand into other locations, according to model sensitivity experiments[14].

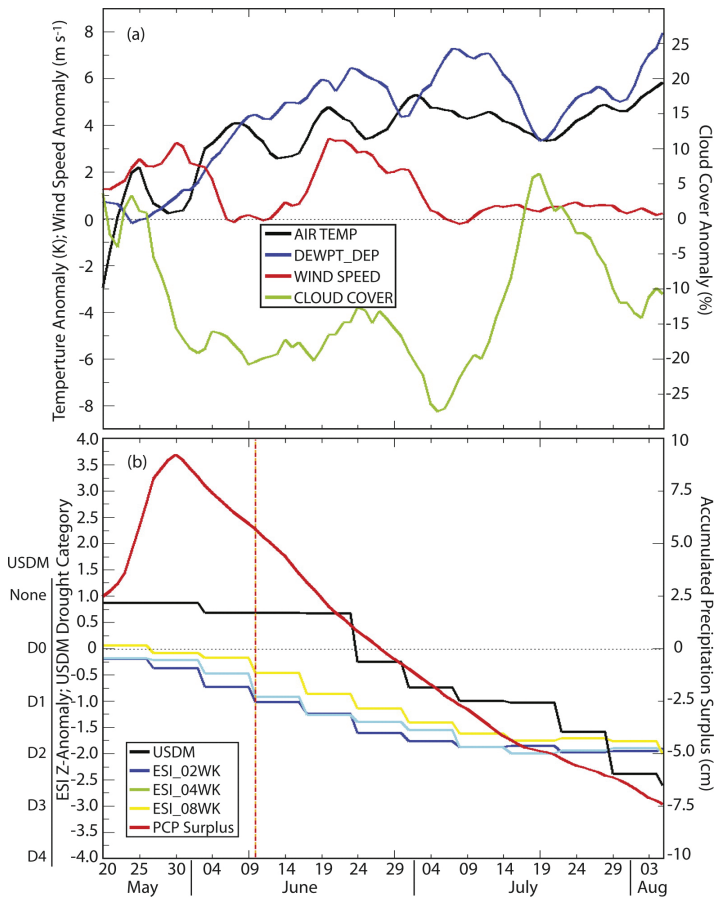

FIGURE 2.
(a) Time series of daily-averaged 2-m air temperature (K), dew point depression (K), surface wind speed (ms-1), and cloud cover (%) anomalies for eastern Oklahoma and western Arkansas during 2011. (b) Time series of US Drought Monitor drought category, Evaporative Stress Index (ESI)_02week, ESI_04week, and ESI_08week composites and accumulated precipitation surplus (cm). The precipitation surplus is computed starting from 29 April 2011. The vertical orange (red) dashed lines correspond to the first week in which at least one (four) of the twelve ESI anomalies was below -1. (Otkin et al., 2013)

• Across Multiple Years:

Land surface model experiments for the multi-year 2012-2015 California drought demonstrate that low precipitation was the main driver of the drought conditions, as measured by soil moisture deficits. Temperature helped to exacerbate the drought—especially by reducing the snow water equivalent accumulated in the Sierra snowpack, effectively changing the timing of runoff production and thereby water availability[15, 16].

Historical precipitation and temperature observations show that the frequency of concurrent droughts and heatwaves have increased substantially over most parts of the United States[17]. The empirical cumulative distribution function (CDF) of the concurrent droughts and heatwaves

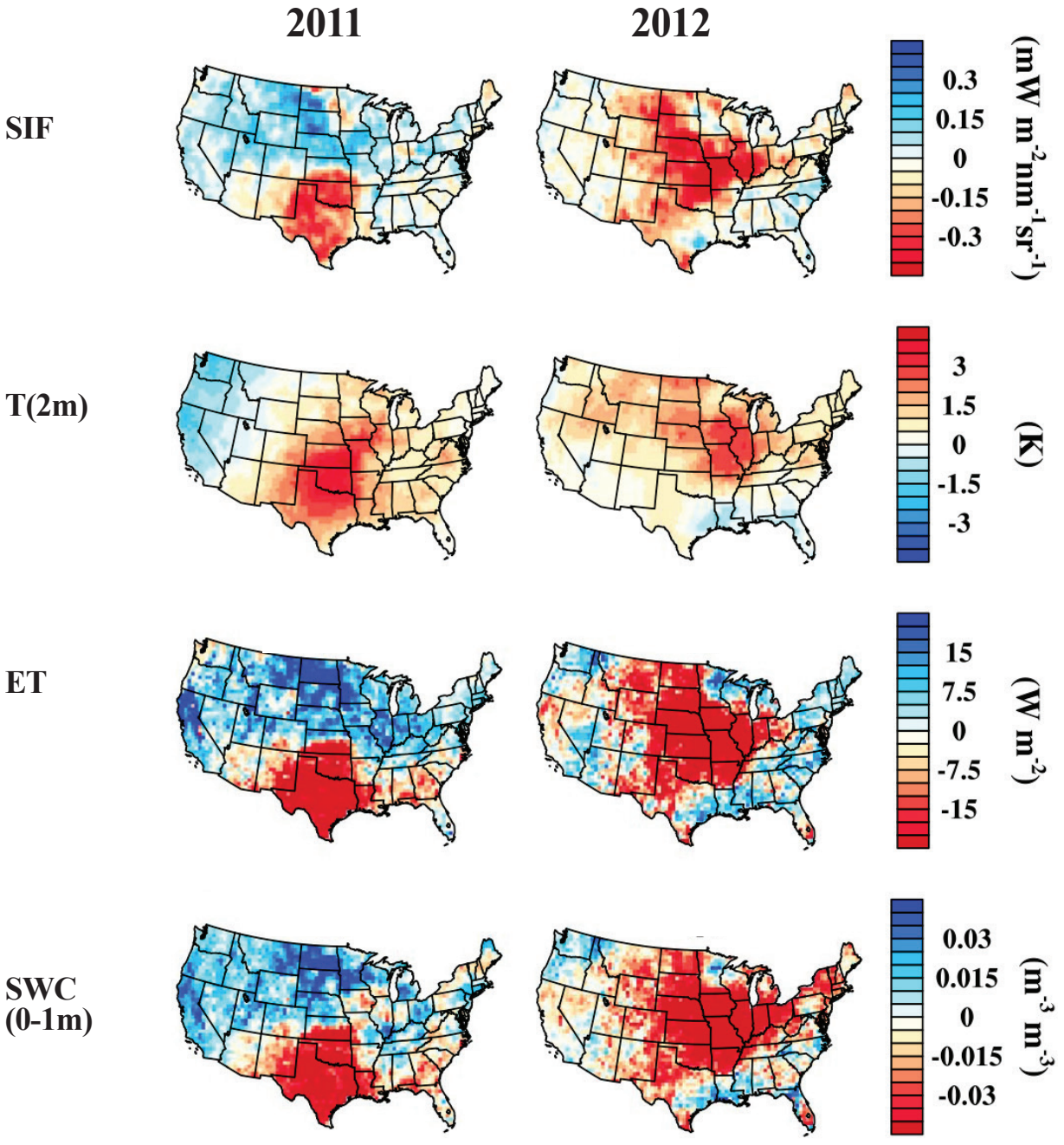

FIGURE 3.
The spatial distributions of the anomalies of solar-induced chlorophyll fluorescence (SIF, satellite measurements representing photosynthesis), T2m, ET, and root-zone SWC (soil water content) for the US during the 2011 Texas drought (left column) and the 2012 central Great Plains drought (right column) during summer (June, July and August), demonstrating the dynamic development of two drought events (Modified from Sun et al. 2015 (JGR-A))

reveals a shift toward more extreme concurrences in the recent decades[17]. This highlights that a concurrent extreme value analysis viewpoint may be essential for assessing risk of droughts in a warming climate[18, 21].

• Over Decades:

Diagnosis of coupled climate model simulations from the CMIP5 experiments indicate that the warm (positive) phase of multi-decadal Atlantic SST variability increases the likelihood of US drought, via a response of US soil moisture to both high temperatures and low precipitation signals. The inference from coupled models is supported by controlled experiments with AGCMs[19].

For the recent California drought, anthropogenic forcing is estimated to have accounted for 8–27% of the observed drought anomaly (Penman-Monteith based PDSI) during 2012–2014, and 5–18% in 2014[20]. Anthropogenic forcing

driving an associated surface warming is thus a factor increasing the overall likelihood of extreme California droughts. This change in the surface energy balance must be weighed against changes in precipitation that are also expected to be part of global warming but that are less conclusively defined[21].

4. A look forward toward future DTF science

Accounting for the relative effects of precipitation, temperature, and other variables in producing drought will require more accurate monitoring of evolving drought severity. Progress is expected from improved knowledge of the patterns and timing of soil moisture depletion during agricultural drought. Advances in understanding how local and remote land surfaces generate runoff and groundwater will be key for improved understanding of hydrologic drought. Land surface modeling will be an important diagnostic tool in such efforts, though more complete representation of land-atmosphere coupling in models used to diagnose drought will be required. Off-line moisture-balance modeling is widely used yet limited by treating meteorology as having a one-way interaction with soil moisture.

Such methods will nonetheless continue to be useful tools for assessing meteorological forcing of land surfaces. Work is underway within the DTF community to improve the accuracy of these models by accounting for land-atmosphere coupling. Analyses of observations, off-line land surface models, ocean-forced atmosphere models and fully coupled models will become increasingly integrated and be conducted in parallel with tools used for prediction. DTF research findings indicate atmospheric variability occurring within seasons can control the transition toward or away from drought, raising prospects for better prediction of rapid drought onset and decay. Current models used in prediction science appear to simulate such sub-seasonal variability poorly however. As such, improving simulation of the propagation of waves along the north Pacific mid-latitude waveguide constitutes an opportunity for improving sub-seasonal drought prediction. Identifying the variety of factors controlling drought will focus future research efforts.

DTF science clearly shows North American drought variability to result from a mix of the aforementioned internal atmospheric behavior, land-atmosphere interaction, and longer-lived remote SST forcing. With careful attention to the feedbacks between the system components, approaches that integrate land-atmosphere and ocean systems more realistically offer the best way forward to improve understanding of the roles of precipitation, temperature and other drivers in causing drought and improving capabilities to predict drought life cycles.

An empty field having the last remains of an orchard removed on Twissleman Road, just west of Shellco Road, in Lost Hills, Calif. Kelly M. Grow/California Department of Water Resources, Taken:29 Jul 2015, Accessed: https://pixel-ca-dwr.photoshelter.com

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WHAT IS MAPP?

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WHAT IS THE DROUGHT TASK FORCE?

The overall goals of the MAPP Drought Task Force are to achieve significant advances in understanding and in the ability to monitor and predict drought over North America. The Task Force is an initiative of NOAA's MAPP program. The research results are expected to help advance basic understanding of drought mechanisms, official national drought products, the development of early warning systems by the National Integrated Drought Information System (NIDIS), and experimental drought monitoring and prediction activities and tools for operational and service purposes as part of the National Centers for Environmental Prediction's (NCEP) Climate Test Bed. The Task Force will coordinate with other relevant national and international efforts including the emerging National Multi-Model Ensemble (NMME) capabilities, and the international effort to develop a Global Drought Information System (GDIS).

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A view looking north from the California Aqueduct Vista Point
Florence Low/California Department of Water Resources,
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