2017

Droughts, floods, and hydrology

Michael Wehner
Lawrence Berkeley National Laboratory, MFWehner@lbl.gov

Jeff Arnold
U.S. Army Corps of Engineers, jeffrey.r.arnold@usace.army.mil

Thomas Knutson
NOAA Geophysical Fluid Dynamics Lab, Tom.Knutson@noaa.gov

Kenneth Kunkel
North Carolina State University, ken_kunkel@ncsu.edu

Allegra LeGrande
NASA Goddard Institute for Space Studies

Wehner, Michael; Arnold, Jeff; Knutson, Thomas; Kunkel, Kenneth; and LeGrande, Allegra, "Droughts, floods, and hydrology" (2017). *Publications, Agencies and Staff of the U.S. Department of Commerce*. 585.
https://digitalcommons.unl.edu/usdeptcommercepub/585

Droughts, floods, and hydrology

Michael Wehner, Lawrence Berkeley National Laboratory
Jeff Arnold, U.S. Army Corps of Engineers
Thomas Knutson, NOAA Geophysical Fluid Dynamics Lab
Kenneth Kunkel, North Carolina State University
Allegra LeGrande, NASA Goddard Institute for Space Studies

Citation: In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA (2017), pp. 336-374.

Abstract

1. Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

2. The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

3. Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)

4. Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

5. Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear. (*Medium confidence*)

6. The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms, with profound changes to certain ecosystems (*medium confidence*).

8. Droughts, Floods, and Wildfires

KEY FINDINGS

1. Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

2. The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

3. Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)

4. Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

5. Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear. (*Medium confidence*)

6. The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms, with profound changes to certain ecosystems (*medium confidence*).

8.1. Drought

The word “drought” brings to mind abnormally dry conditions. However, the meaning of “dry” can be ambiguous and lead to confusion in how drought is actually defined. Three different classes of droughts are defined by NOAA and describe a useful hierarchal set of water deficit characterization, each with different impacts. “Meteorological drought” describes conditions of precipitation deficit. “Agricultural drought” describes conditions of soil moisture deficit. “Hydrological drought” describes conditions of deficit in runoff (NOAA 2008). Clearly these three characterizations of drought are related but are also different descriptions of water shortages with different target audiences and different timescales. In particular, agricultural drought is of concern to producers of food while hydrological drought is of concern to water system managers. Soil moisture is a function of both precipitation and evapotranspiration. Because potential evapotranspiration increases with temperature, anthropogenic climate change generally results in drier soils and often less runoff in the long term. In fact, under the RCP8.5 scenario (see Ch. 4: Projections for a description of the RCP scenarios) at the end of the 21st century, no region of the planet is projected to experience significantly higher levels of annual average surface soil moisture due to the sensitivity of evapotranspiration to temperature, even though much higher precipitation is projected in some regions (Collins et al. 2013). Seasonal and annual total runoff, on the other hand, are projected to either increase or decrease, depending on location and season under the same conditions (Collins et al. 2013), illustrating the complex relationships between the various components of the hydrological system. Meteorological drought can occur on a range of timescales, in addition to seasonal or annual timescales. “Flash droughts” can result from just a few weeks of dry weather (Mo and Lettenmaier 2015), and the paleoclimate record contains droughts of several decades. Hence, it is vital to describe precisely the definition of drought in any public discussion to avoid confusion due to this complexity. As the climate changes, conditions currently considered “abnormally” dry may become relatively “normal” in those regions undergoing aridification, or extremely unlikely in those regions becoming wetter. Hence, the reference conditions defining drought may need to be modified from those currently used in practice.

8.1.1. Historical Context

The United States has experienced all three types of droughts in the past, always driven, at least in some part, by natural variations in seasonal and/or annual precipitation amounts. As the climate changes, we can expect that human activities will alter the effect of these natural variations. The “Dust Bowl” drought of the 1930s is still the most significant meteorological and agricultural drought experienced in the United States in terms of its geographic and temporal extent. However, even though it happened prior to most of the current global warming, human activities exacerbated the dryness of the soil by the farming practices of the time (Bennet et al. 1936). Tree ring archives reveal that such droughts (in the agricultural sense) have occurred occasionally over the last 1,000 years (Cook et al. 2004). Climate model simulations suggest that droughts lasting several years to decades occur naturally in the southwestern United States (Coats et al. 2015). The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; Bindoff et al. 2013) concluded "there is low confidence in detection and attribution of changes in (meteorological) drought over global land areas since the mid-20th century, owing to observational uncertainties and difficulties in distinguishing decadal-scale variability in drought from long-term trends." As they noted, this was a weaker attribution statement than in the Fourth Assessment Report (Hegerl et al. 2007), which had concluded "that an increased risk of drought was *more likely than not* due to anthropogenic forcing during the second half of the 20th century." The weaker statement in AR5 reflected additional studies with conflicting conclusions on global drought trends (e.g., Sheffield et al. 2012; Dai 2013). Western North America was noted as a region where determining if observed recent droughts were unusual compared to natural variability was particularly difficult. This was due to evidence from paleoclimate proxies of cases of central U.S. droughts during the past 1,000 years that were longer and more intense than historical U.S. droughts (Masson-Delmotte et al. 2013). Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined (Andreadis and Lettenmaier 2006; Mo and Lettenmaier 2015). Furthermore, there is no detectable change in meteorological drought at the global scale (Sheffield et al. 2012). However, a number of individual event attribution studies suggest that if a drought occurs, anthropogenic temperature increases can exacerbate soil moisture deficits (e.g., Seager et al. 2015; Trenberth et al. 2014). Future projections of the anthropogenic contribution to changes in drought risk and severity must be considered in the context of the significant role of natural variability.

8.1.2. Recent Major U.S. Droughts

METEOROLOGICAL AND AGRICULTURAL DROUGHT

The United States has suffered a number of very significant droughts of all types since 2011. Each of these droughts was a result of different persistent, large-scale meteorological patterns of mostly natural origins, with varying degrees of attributable human influence. Table 8.1 summarizes available attribution statements for recent extreme U.S. droughts. Statements about meteorological drought are decidedly mixed, revealing the complexities in interpreting the low tail of the distribution of precipitation. Statements about agricultural drought consistently maintain a human influence if only surface soil moisture measures are considered. The single agricultural drought attribution study at root depth comes to the opposite conclusion (Cheng et al. 2016). In all cases, these attribution statements are examples of attribution without detection (see Appendix C). The absence of moisture during the 2011 Texas/Oklahoma drought and heat wave was found to be an event whose likelihood was enhanced by the La Niña state of the ocean, but the human interference in the climate system still doubled the chances of reaching such high temperatures (Hoerling et al. 2013). This study illustrates that the effect of human-induced climate change is combined with natural variations and can compound or inhibit the realized severity of any given extreme weather event.

[INSERT TABLE 8.1 HERE]

The Great Plains/Midwest drought of 2012 was the most severe summer meteorological drought in the observational record for that region (Hoerling et al. 2014). An unfortunate string of three different patterns of large-scale meteorology from May through August 2012 precluded the normal frequency of summer thunderstorms, and was not predicted by the NOAA seasonal forecasts (Hoerling et al. 2014). Little influence of the global sea surface temperature (SST) pattern on meteorological drought frequency has been found in model simulations (Hoerling et al. 2014). No evidence of a human contribution to the 2012 precipitation deficit in the Great Plains and Midwest is found in numerous studies (Rupp et al. 2013; Hoerling et al. 2014; Angélil et al. 2017). However, an alternative view is that the 2012 central U.S. drought can be classified as a "heat wave flash drought" (Mo and Lettenmaier 2016), a type of rapidly evolving drought that has decreased in frequency over the past century (Mo and Lettenmaier 2015). Also, an increase in the chances of the unusually high temperatures seen in the United States in 2012, partly associated with resultant dry summer soil moisture anomalies, was attributed to the human interference with the climate system (Diffenbaugh and Scherer 2013), indicating the strong feedback between lower soil moisture and higher surface air temperatures during periods of low precipitation. One study found that most, but not all, of the 2012 surface moisture deficit in the Great Plains was attributable to the precipitation deficit (Livneh and Hoerling 2016). That study also noted that Great Plains root depth and deeper soil moisture was higher than normal in 2012 despite the surface drying, due to wet conditions in prior years, indicating the long timescales relevant below the surface (Livneh and Hoerling 2016).

The recent California drought, which began in 2011, is unusual in different respects. In this case, the precipitation deficit from 2011 to 2014 was a result of the "ridiculously resilient ridge" of high pressure. This very stable high pressure system steered storms towards the north, away from the highly engineered California water resource system (Swain et al. 2014; Seager et al. 2014, 2015). The ridge itself was due to a slow-moving high sea surface temperature (SST) anomaly, referred to as "The Blob"—which was caused by a persistent ridge that weakened the normal cooling mechanisms for that region of the upper ocean (Bond et al. 2015). Atmospheric modeling studies showed that the ridge that caused the Blob was favored by a pattern of persistent tropical SST anomalies that were warm in the western equatorial Pacific and simultaneously cool in the far eastern equatorial Pacific (Hartman 2015; Seager et al. 2014). It was also favored by reduced arctic sea ice and from feedbacks with "The Blob" SST anomalies (Lee et al. 2015). These studies also suggest that internal variability likely played a prominent role in the persistence of the 2013–2014 ridge off the west coast of North America. A principal attribution question regarding the precipitation deficit concerns the causes of this SST anomaly.

Observational records are not long enough and the anomaly was unusual enough that similarly long-lived patterns have not been often seen before. Hence, attribution statements, such as that about an increasing anthropogenic influence on the frequency of geopotential height anomalies similar to 2012–2014 (e.g., Swain et al. 2014), are without associated detection (Ch. 3: Detection and Attribution). A secondary attribution question concerns the anthropogenic precipitation response in the presence of this SST anomaly. In attribution studies with a prescribed 2013 SST anomaly, a consistent increase in the human influence on the chances of very dry California conditions was found (Angélil et al. 2017).

Anthropogenic climate change did increase the risk of the high temperatures in California in the winters of 2013–2014 and 2014–2015, especially the latter (Seager et al. 2015; Diffenbaugh et al. 2015; Wang and Schubert 2014), further exacerbating the soil moisture deficit and the associated stress on irrigation systems. This raises the question, as yet unanswered, of whether droughts in the western United States are shifting from precipitation control (Mao et al. 2015) to temperature control. There is some evidence to support a relationship between mild winter and/or warm spring temperatures and drought occurrence (Mote et al. 2016), but long-term warming trends in the tropical and North Pacific do not appear to have led to trends toward less precipitation over California (Funk et al. 2014). An anthropogenic contribution to commonly used measures of agricultural drought, including the Palmer Drought Severity Index (PDSI), was found in California (Diffenbaugh et al. 2015; Williams et al. 2015) and is consistent with previous projections of changes in PDSI (Dai 2013; Wehner et al. 2011; Walsh et al. 2014) and with an attribution study (Brown et al. 2008). Due to its simplicity, the PDSI has been criticized as being overly sensitive to higher temperatures and thus may exaggerate the human contribution to soil dryness (Milly and Dunne 2016). In fact, this study also finds that formulations of potential evaporation used in more complicated hydrologic models are similarly biased, undermining confidence in the magnitude but not the sign of projected surface soil moisture changes in a warmer climate. Seager et al. (2015) analyzed climate model output directly, finding that precipitation minus evaporation in the southwestern United States is projected to experience significant decreases in surface water availability, leading to surface runoff decreases in California, Nevada, Texas, and the Colorado River headwaters even in the near term. However, the criticisms of PDSI also apply to most of the CMIP5 land surface model evapotranspiration formulations. Analysis of soil moisture in the CMIP5 models at deeper levels is complicated by the wide variety in sophistication of their component land models. A pair of studies reveals less sensitivity at depth to surface air temperature increases than at near surface levels (Cook et al. 2015; Cheng et al. 2016). Berg et al. (2017) adjust for the differences in land component model vertical treatments, finding projected change in vertically integrated soil moisture down to 3 meters depth is mixed, with projected decreases in the Southwest and in the south central United States, but increases over the northern plains. Nonetheless, the warming trend has led to declines in a number of indicators, including Sierra snow water equivalent, that are relevant to hydrological drought (Mao et al. 2015). Attribution of the California drought and heat wave remains an interesting and controversial research topic.

In summary, there has not yet been a formal identification of a human influence on past changes in United States meteorological drought through the analysis of precipitation trends. Some, but not all, U.S. meteorological drought event attribution studies, largely in the "without detection" class, exhibit a human influence. Attribution of a human influence on past changes in U.S. agricultural drought are limited both by availability of soil moisture observations and a lack of sub-surface modeling studies. While a human influence on surface soil moisture trends has been identified with *medium confidence*, its relevance to agriculture may be exaggerated.

RUNOFF AND HYDROLOGICAL DROUGHT

Several studies focused on the Colorado River basin in the United States that used more sophisticated runoff models driven by the CMIP3 models (Christensen and Lettenmaier 2007; McCabe and Wolock 2007; Barnett and Pierce 2009; Barnett et al. 2008; Hoerling et al. 2009) showed that annual runoff reductions in a warmer western Unites States climate occur through a combination of evapotranspiration increases and precipitation decreases, with the overall reduction in river flow exacerbated by human water demands on the basin's supply. Reduced U.S. snowfall accumulations in much warmer future climates are virtually certain as frozen precipitation is replaced by rain regardless of the projected changes in total precipitation amounts discussed in Chapter 7: Precipitation Change (Figure 7.6). The profound change in the hydrology of snowmelt-driven flows in the western United States is well documented. Earlier spring runoff (Stewart et al. 2005) reduced the fraction of precipitation falling as snow (Knowles et al. 2006) and the snowpack water content at the end of winter (Mote 2003; Mote et al. 2005), consistent with warmer temperatures. Formal detection and attribution (Ch. 3: Detection and Attribution) of the observed shift towards earlier snowmelt driven flows in the western United States reveals that the shift is detectably different from natural variability and attributable to anthropogenic climate change (Hidalgo et al 2009). Similarly, observed declines in the snow water equivalent in the region have been formally attributed to anthropogenic climate change (Pierce et al. 2008) as have temperature, river flow, and snow pack (Barnett et al. 2008; Bonfils et al. 2008). As a harbinger of things to come, the unusually low western U.S. snowpack of 2015 may become the norm (Mote et al. 2016).

In the northwestern United States, long-term trends in streamflow have seen declines, with the strongest trends in drought years (Luce and Holden 2009) that are attributed to a decline in winter precipitation (Luce et al. 2013). These reductions in precipitation are linked to decreased westerly wind speeds in winter over the region. Furthermore, the trends in westerlies are consistent with CMIP5-projected wind speed changes due to a decreasing meridional temperature and pressure gradients rather than low-frequency climate variability modes. Such precipitation changes have been a primary source of change in hydrological drought in the Northwest over the last 60 years (Kormos et al. 2016) and are in addition to changes in snowpack properties.

We conclude with *high confidence* that these observed in changes temperature controlled aspects of western U.S. hydrology are *likely* a consequence of human changes to the climate system.

8.1.3. Projections of Future Droughts

The future changes in seasonal precipitation shown in Chapter 7: Precipitation Change (Figure 7.6) indicate that the southwestern United States may experience chronic future precipitation deficits, particularly in the spring. In much warmer climates, expansion of the tropics and subtropics, traceable to changes in the Hadley circulation, cause shifts in seasonal precipitation that are particularly evident in such arid and semi-arid regions and increase the risk of meteorological drought. However, uncertainty in the magnitude and timing of future southwestern drying is high. We note that the weighted and downscaled projections of Figure 7.6 exhibit significantly less drying and are assessed to be less significant in comparison to natural variations than the original unweighted CMIP5 projections (Walsh et al. 2014).

Western U.S. hydrological drought is currently controlled by the frequency and intensity of extreme precipitation events, particularly atmospheric rivers, as these events represent the source of nearly half of the annual water supply and snowpack for the western coastal states (Dettinger 2011; Guan et al. 2013). Climate projections indicate greater frequency of atmospheric rivers in the future (e.g., Dettinger 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch. 9: Extreme Storms). Sequences of these extreme storms have played a critical role in ending recent hydrological droughts along the U.S. West Coast (Dettinger 2013). However, as winter temperatures increase, the fraction of precipitation falling as snow will decrease, potentially disrupting western U.S. water management practices.

Significant U.S. seasonal precipitation deficits are not confidently projected outside of the Southwest. However, future higher temperatures will *likely* lead to greater frequencies and magnitudes of agricultural droughts throughout the continental United States as the resulting increases in evapotranspiration outpace projected precipitation increases (Collins et al. 2013). Figure 8.1 shows the weighted multimodel projection of the percent change in near-surface soil moisture at the end of the 21st century under the RCP8.5 scenario, indicating widespread drying over the entire continental United States. Previous National Climate Assessments (Karl et al. 2009; Walsh et al. 2014) have discussed the implication of these future drier conditions in the context of the Palmer Drought Severity Index (PDSI), finding that the future normal condition would be considered drought at the present time, and that the incidence of “extreme drought” (PDSI < -4) would be significantly increased. However, as described below, the PDSI may overestimate future soil moisture drying.

This projection is made “without attribution” (Ch. 4: Projections), but confidence that future soils will generally be drier at the surface is *medium*, as the mechanisms leading to increased evapotranspiration in a warmer climate are elementary scientific facts. However, the land surface component models in the CMIP5 climate models vary greatly in their sophistication, causing the projected magnitude of both the average soil moisture decrease and the increased risk for agricultural drought to be less certain. The weighted projected seasonal decreases in surface soil moisture are generally towards drier conditions, even in regions and seasons where precipitation is projected to experience large increases (Figure 7.6) due to increases in the evapotranspiration associated with higher temperature. Drying is assessed to be large relative to natural variations in much of the CONUS region in the summer. Significant spring and fall drying is also projected in the mountainous western states, with potential implications for forest and wildfire risk. Also, the combination of significant summer and fall drying in the midwestern states has potential agricultural implications. The largest percent changes are projected in the southwestern United States and are consistent in magnitude with an earlier study of the Colorado River Basin using more sophisticated macroscale hydrological models (Christensen and Lettenmaier 2007).

In this assessment, we limit the direct CMIP5 weighted multimodel projection of soil moisture shown in Figure 8.1 to the surface (defined as the top 10 cm of the soil), as the land surface component sub-models vary greatly in their representation of the total depth of the soil. A more relevant projection to agricultural drought would be the soil moisture at the root depth of typical U.S. crops. Cook et al. (2015) find that future drying at a depth of 30 cm will be less than at 2 cm, but still significant and comparable to a modified PDSI formulation. Few of the CMIP5 land models have detailed ecological representations of evapotranspiration processes, causing the simulation of the soil moisture budget to be less constrained than reality (Williams and Torn 2015). Over the western United States, unrealistically low elevations in the CMIP5 models due to resolution constraints present a further challenge in interpreting evapotranspiration changes. Nonetheless, Figure 8.1 shows a projected drying of surface soil moisture across nearly all of the coterminous United States in all seasons, even in regions and seasons where precipitation is projected to increase, consistent with increased evapotranspiration due to elevated temperatures (Cook et al. 2015).

Widespread reductions in mean snowfall across North America are projected by the CMIP5 models (O'Gorman 2014). Together with earlier snowmelt at altitudes high enough for snow, disruptions in western U.S. water delivery systems are expected to lead to more frequent hydrological drought conditions (Barnett et al. 2008; Pierce et al. 2008; Barnett and Pierce 2009; Cayan et al. 2010; Das et al. 2011). Due to resolution constraints, the elevation of mountains as represented in the CMIP5 models is too low to adequately represent the effects of future temperature on snowpacks. However, increased model resolution has been demonstrated to have important impacts on future projections of snowpack water content in warmer climates and is enabled by recent advances in high performance computing (Kapnick and Delworth 2013). Figure 8.2 and Table 8.2 show a projection of changes in western U.S. mountain winter (December, January, and February) hydrology obtained from a different high-resolution atmospheric model at the middle and end of the 21st century under the RCP8.5 scenario. These projections indicate dramatic reductions in all aspects of snow (Rhoades et al. 2017) and are similar to previous statistically downscaled projections (Cayan et al. 2013; Klos et al. 2014).

Table 8.2 reveals that the reductions in snow water equivalent accelerate in the latter half of this century under this emissions scenario and with substantial variations across the western United States. Changes in snow residence time, an alternative measure of snowpack relevant to the timing of runoff, is also shown to be sensitive to elevation, with widespread reductions across this region (Luce et al. 2014). Given the larger projected increases in temperature at high altitudes compared to adjacent lower altitudes (Pierce and Cayan 2013) and the resulting changes in both snowpack depth and melt timing in very warm future scenarios such as RCP8.5, and assuming no change to water resource management practices, several important western U.S. snowpack reservoirs effectively disappear by 2100 in this dynamical projection, resulting in chronic, long-lasting hydrological drought. This dramatic statement is also supported by two climate model studies: a multimodel statistical downscaling of the CMIP5 RCP8.5 ensemble that finds large areal reductions in snow dominated regions of the western United States by mid-century and complete elimination of snow-dominated regions in certain watersheds (Klos et al. 2014), and a large ensemble simulation of a global climate model (Fyfe et al. 2017).

As earlier spring melt and reduced snow water equivalent has been formally attributed to human induced warming, substantial reductions in western U.S. winter and spring snowpack are projected (with attribution) to be *very likely* as the climate warms as the climate continues to warm (*very high confidence*). Under higher emissions scenarios and assuming no change to current water-resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

[INSERT FIGURES 8.1 AND 8.2 HERE]

8.2. Floods

Flooding damage in the United States can come from flash floods of smaller rivers and creeks, prolonged flooding along major rivers, urban flooding unassociated with proximity to a riverway, coastal flooding from storm surge which may be exacerbated by sea level rise, and the confluence of coastal storms and inland riverine flooding from the same precipitation event (Ch. 12: Sea Level Rise). Flash flooding is associated with extreme precipitation somewhere along the river which may occur upstream of the regions at risk. Flooding of major rivers in the United States with substantial winter snow accumulations usually occurs in the late winter or spring and can result from an unusually heavy seasonal snowfall followed by a “rain on snow” event or from a rapid onset of higher temperatures that leads to rapid snow melting within the river basin. In the western coastal states, most flooding occurs in conjunction with extreme precipitation events referred to as “atmospheric rivers” (see Ch. 9: Extreme Storms) (Ralph and Dettinger 2011; Neiman et al. 2011), with mountain snowpack being vulnerable to these typically warmer-than-normal storms and their potential for rain on existing snow cover (Guan et al. 2016). Hurricanes and tropical storms are an important driver of flooding events in the eastern United States. Changes in streamflow rates depend on many factors, both human and natural, in addition to climate change. Deforestation, urbanization, dams, floodwater management activities, and changes in agricultural practices can all play a role in past and future changes in flood statistics. Projection of future changes is thus a complex multivariate problem (Walsh et al. 2014).

The IPCC AR5 (Bindoff et al. 2013) did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration or frequency. Trends in extreme high values of streamflow are mixed across the United States (Walsh et al. 2014; Archfield et al. 2016; EPA 2016). Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude (Hirsch and Ryberg 2012) but does not provide robust evidence that these trends are attributable to human influences. Significant increases in flood frequency have been detected in about one-third of stream gauge stations examined for the central United States, with a much stronger signal of frequency change than is found for changes in flood magnitude in these gauges (Mallakpour and Villarini 2015). This apparent disparity with ubiquitous increases in observed extreme precipitation (Figure 7.2) can be partly explained by the seasonality of the two phenomena. Extreme precipitation events in the eastern half of the CONUS are larger in the summer and fall when soil moisture and seasonal streamflow levels are low and less favorable for flooding (Wehner 2013). By contrast, high streamflow events are often larger in the spring and winter when soil moisture is high and snowmelt and frozen ground can enhance runoff (Frei et al. 2015). Furthermore, floods may be poorly explained by daily precipitation characteristics alone; the relevant mechanisms are more complex, involving processes that are seasonally and geographically variable, including the seasonal cycles of soil moisture content and snowfall/snowmelt (Berghuijs et al. 2016).

Recent analysis of annual maximum streamflow shows statistically significant trends in the upper Mississippi River valley (increasing) and in the Northwest (decreasing) (McCabe and Wolock 2014). In fact, across the midwestern United States, statistically significant increases in flooding are well documented (Groisman et al. 2001; Novotny and Stefan 2007; Tomer and Schilling 2009; Ryberg et al. 2014; Villarini and Strong 2014; Slater et al. 2015; Mallakpour and Villarini 2015, 2016). These increases in flood risk and severity are not attributed to 20th century changes in agricultural practices (Tomer and Schilling 2009; Frans et al. 2013) but instead are attributed mostly to the observed increases in precipitation shown in Figures 7.1 through 7.4 (Novotny and Stefan 2007; Wang and Hejazi 2011; Frans et al. 2013; Mallakpour and Villarini 2015). Trends in maximum streamflow in the northeastern United States are less dramatic and less spatially coherent (McCabe and Wolock 2014; Frei et al. 2015), although one study found mostly increasing trends (Armstrong et al. 2014) in that region, consistent with the increasing trends in observed extreme precipitation in the region (Ch. 6: Temperature Change; Walsh et al. 2014; Frei et al. 2015).

The nature of the proxy archives complicates the reconstruction of past flood events in a gridded fashion as has been done with droughts. However, reconstructions of past river outflows do exist. For instance, it has been suggested that the mid-20th century river allocations for the Colorado

River were made during one of the wettest periods of the past five centuries (Woodhouse et al. 2006). For the eastern United States, the Mississippi River has undergone century-scale variability in flood frequency—perhaps linked to the moisture availability in the central United States and the temperature structure of the Atlantic Ocean (Munoz et al. 2015).

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies (Merz et al. 2012). As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed (Mallakpour and Villarini 2015).

A projection study based on coupling an ensemble of regional climate model output to a hydrology model (Najafi and Moradkhani 2015) finds that the magnitude of future very extreme runoff (which can lead to flooding) is decreased in most of the summer months in Washington State, Oregon, Idaho, and western Montana but substantially increases in the other seasons. Projected weighted increases in extreme runoff from the coast to the Cascade Mountains are particularly large in that study during the fall and winter which are not evident in the weighted seasonal averaged CMIP5 runoff projections (Collins et al. 2013). For the West Coast of the United States, extremely heavy precipitation from intense atmospheric river storms is an important factor in flood frequency and severity (Dettinger 2011; Dettinger et al. 2011). Projections indicate greater frequency of heavy atmospheric rivers in the future (e.g., Dettinger et al. 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch. 9: Extreme Storms). Translating these increases in atmospheric river frequency to their impact on flood frequency requires a detailed representation of western states topography in the global projection models and/or via dynamic downscaling to regional models and is a rapidly developing science. In a report prepared for the Federal Insurance and Mitigation Administration of the Federal Emergency Management Agency, a regression-based approach of scaling river gauge data based on seven commonly used climate change indices from the CMIP3 database (Tebaldi et al. 2006) found that at the end of the 21st century the 1% annual chance floodplain area would increase in area by about 30%, with larger changes in the Northeast and Great Lakes regions and smaller changes in central part of the country and the Gulf Coast (AECOM 2013).

Urban flooding results from heavy precipitation events that overwhelm the existing sewer infrastructure's ability to convey the resulting stormwater. Future increases in daily and sub-daily extreme precipitation rates will require significant upgrades to many communities' storm sewer systems, as will sea level rise in coastal cities and towns (SFPUC 2016; Winters et al. 2015).

No studies have formally attributed (see Ch. 3: Detection and Attribution) long-term changes in observed flooding of major rivers in the United States to anthropogenic forcing. We conclude that there is *medium confidence* that detectable (though not attributable to anthropogenic forcing changes) increases in flood statistics have occurred in parts of the central United States. Key Finding 3 of Chapter 7: Precipitation Change states that the frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century with *high confidence*. Given the connection between extreme precipitation and flooding, and the complexities of other relevant factors, we concur with the IPCC Special Report on Extremes (SREX) assessment of "medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions" (IPCC 2012).

Existing studies of individual extreme flooding events are confined to changes in the locally responsible precipitation event and have not included detailed analyses of the events' hydrology. Gochis et al. (2015) describes the massive floods of 2013 along the Colorado front range, estimating that the streamflow amounts ranged from 50- to 500-year return values across the region. Hoerling et al. (2014) analyzed the 2013 northeastern Colorado heavy multiday precipitation event and resulting flood, finding little evidence of an anthropogenic influence on its occurrence. However, Pall et al. (2017) challenge their event attribution methodology with a more constrained study and find that the thermodynamic response of precipitation in this event due to anthropogenic forcing was substantially increased. The Pall et al. (2017) approach does not rule out that the likelihood of the extremely rare large-scale meteorological pattern responsible for the flood may have changed.

8.3 Wildfires

A global phenomenon with natural (lightning) and human-caused ignition sources, wildfire represents a critical ecosystem process. Recent decades have seen a profound increase in forest fire activity over the western United States and Alaska (Westerling et al. 2006; Running 2006; Higuera et al 2015; Abatzouglou and Williams 2016). The frequency of large wildfires is influenced by a complex combination of natural and human factors. Temperature, soil moisture, relative humidity, wind speed, and vegetation (fuel density) are important aspects of the relationship between fire frequency and ecosystems. Forest management and fire suppression practices can also alter this relationship from what it was in the preindustrial era. Changes in these control parameters can interact with each other in complex ways with the potential for tipping points—in both fire frequency and in ecosystem properties—that may be crossed as the climate warms.

Figure 8.3 shows that the number of large fires has increased over the period 1984–2011, with high statistical significance in 7 out of 10 western U.S. regions across a large variety of vegetation, elevation, and climatic types (Dennison et al. 2014). State-level fire data over the 20th century (Littell et al. 2009) indicates that area burned in the western United States decreased from 1916 to about 1940, was at low levels until the 1970s, then increased into the more recent period. Modeled increases in temperatures and vapor pressure deficits due to anthropogenic climate change has increased forest fire activity in the western United States by increasing the aridity of forest fuels during the fire season (Abatzouglou and Williams 2016). Increases in these relevant climatic drivers were found to be responsible for over half the observed increase in western U.S. forest fuel aridity from 1979 to 2015 and doubled the forest fire area over the period 1984–2015 (Abatzouglou and Williams 2016). Littell et al. (2009, 2010, 2016) find that two climatic mechanisms affect fire in the western United States: increased fuel flammability driven by warmer, drier conditions and increased fuel availability driven by antecedent moisture. Littell et al. (2016) find a clear link between increased drought and increased fire risk. Yoon et al. (2015) assessed the 2014 fire season, finding an increased risk of fire in California. While fire suppression practices can also lead to a significant increase in fire risk in lower-elevation and drier forest types, this is less important in higher-elevation and moister forests (Harvey 2016; Stephens et al. 2013; Schoennagel et al. 2004). Increases in future forest fire extent, frequency, and intensity depend strongly on local ecosystem properties and will vary greatly across the United States. Westerling et al. (2011) project substantial increases in forest fire frequency in the Greater Yellowstone ecosystem by mid-century under the older SRES A2 emissions scenario, and further state that years without large fires in the region will become extremely rare. Stavros et al. (2014) project increases in very large fires (greater than 50,000 acres) across the western United States by mid-century under both the RCP4.5 and RCP8.5 emissions scenarios. Likewise, Prestemon et al. (2016) project significant increases in lightning-ignited wildfire in the Southeast by mid-century but with substantial differences between ecoregions. However, other factors, related to climate change such as water scarcity or insect infestations may act to stifle future forest fire activity by reducing growth or otherwise killing trees leading to fuel reduction (Littell et al. 2010).

[INSERT FIGURE 8.3 HERE]

Historically, wildfires have been less frequent and of smaller extent in Alaska compared to the rest of the globe (Flannigan et al. 2009; Hu et al. 2015). Shortened land snow cover seasons and higher temperatures have made the Arctic more vulnerable to wildfire (Flannigan et al. 2009; Hu et al. 2015; Young et al. 2016). Total area burned and the number of large fires (those with area greater than 1,000 square km or 386 square miles) in Alaska exhibits significant interannual and decadal scale variability from influences of atmospheric circulation patterns and controlled burns, but have *likely* increased since 1959 (Kasischke and Turetsky 2006). The most recent decade has seen an unusually large number of severe wildfire years in Alaska, for which the risk of severe fires has *likely* increased by 33%–50% as a result of anthropogenic climate change (Partain et al. 2016) and is projected to increase by up to a factor of four by the end of the century under the moderate RCP6.0 scenario (Young et al. 2016). Historically less flammable tundra and cooler boreal forest regions could shift into historically unprecedented fire risk regimes as a consequence of temperatures increasing above the minimum thresholds required for burning. Alaska's fire season is also *likely* lengthening—a trend expected to continue (Flannigan et al. 2009; Sanford et al. 2015). Thresholds in temperature and precipitation shape Arctic fire regimes, and projected increases in future lightning activity imply increased vulnerability to future climate change (Flannigan et al. 2009; Young et al. 2016). Alaskan tundra and forest wildfires will *likely* increase under warmer and drier conditions (Sanford et al. 2015; French et al. 2015) and potentially result in a transition into a fire regime unprecedented in the last 10,000 years (Kelly et al. 2013). Total area burned is projected to increase between 25% and 53% by the end of the century (Joly et al. 2012).

Boreal forests and tundra contain large stores of carbon, approximately 50% of the total global soil carbon (McGuire et al. 2009). Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric CO_2 and alter the carbon cycle if ecosystems change from higher to lower carbon densities (McGuire et al. 2009; Kelly et al. 2013). Additionally, increased fires in Alaska may also enhance the degradation of Alaska's permafrost, blackening the ground, reducing surface albedo, and removing protective vegetation.

Both anthropogenic climate change and the legacy of land use/management have an influence on U.S. wildfires and are subtly and inextricably intertwined. Forest management practices have resulted in higher fuel densities in most of U.S. forests, except in the Alaskan bush and the higher mountainous regions of the western United States. Nonetheless, there is *medium confidence* for a human-caused climate change contribution to increased forest fire activity in Alaska in recent decades with a *likely* further increase as the climate continues to warm, and *low to medium confidence* for a detectable human climate change contribution in the western United States based on existing studies. Recent literature does not contain a complete robust detection and attribution analysis of forest fires including estimates of natural decadal and multidecadal variability, as described in Chapter 3: Detection and Attribution, nor separate the contributions to observed trends from climate change and forest management. These assessment statements about attribution to human-induced climate change are instead multistep attribution statements (Ch. 3: Detection and Attribution) based on plausible model-based estimates of anthropogenic contributions to observed trends. The modeled contributions, in turn, are based on climate variables that are closely linked to fire risk and that, in most cases, have a detectable human influence, such as surface air temperature and snow melt timing.

TRACEABLE ACCOUNTS

Key Message 1

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*Very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

Description of evidence base

Recent droughts are well characterized and described in the literature. The Dust Bowl is not as well documented, but available observational records support the key finding. The last sentence is an "absence of evidence" statement and does not imply "evidence of absence" of future anthropogenic changes. The inferred decreases in some measures of U.S. drought or types of drought (heat wave/flash droughts) are described in Andreadis and Lettenmaier (2006) and Mo and Lettenmaier (2015).

Major uncertainties

Record breaking temperatures are well documented with low uncertainty (Meehl et al 2009). The magnitude of the Dust Bowl relative to present times varies with location. Uncertainty in the key finding is affected by the quality of pre-World War II observations but is relatively low.

Assessment of confidence based on evidence and agreement

Precipitation is well observed in the United States, leading to *very high confidence*.

Summary sentence or paragraph that integrates the above information

The key finding is a statement that recent U.S. droughts, while sometimes long and severe, are not unprecedented in the historical record.

Key Message 2

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)

Description of evidence base

Observational records of meteorological drought are not long enough to detect statistically significant trends. Additionally, paleoclimatic evidence suggests that major droughts have occurred throughout the distant past. Surface soil moisture is not well observed throughout the CONUS, but numerous event attribution studies attribute enhanced reduction of surface soil moisture during dry periods to anthropogenic warming and enhanced evapotranspiration. Sophisticated land surface models have been demonstrated to reproduce the available observations and have allowed for century scale reconstructions.

Major uncertainties

Uncertainties stem from the length of precipitation observations and the lack of surface moisture observations.

Assessment of confidence based on evidence and agreement

Confidence is *high* for widespread future surface soil moisture deficits, as little change is projected for future summer and fall average precipitation. In the absence of increased precipitation (and in some cases with it), evapotranspiration increases due to increased temperatures will lead to less soil moisture overall, especially near the surface.

Summary sentence or paragraph that integrates the above information

The precipitation deficit portion of the key finding is a conservative statement reflecting the conflicting and limited event attribution literature on meteorological drought. The soil moisture portion of the key finding is limited to the surface and not the more relevant root depth and is supported by the studies cited in this chapter.

Key Message 3

Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)

Description of evidence base

First principles establish that evaporation is at least linearly dependent on temperatures and accounts for much of the surface moisture decrease as temperature increases. Plant transpiration for many non-desert species controls plant temperature and responds to increased temperature by opening stomata to release more water vapor. This water comes from the soil at root depth as the plant exhausts its stored water supply (*very high confidence*). Furthermore, nearly all CMIP5 models exhibit U.S. surface soil moisture drying at the end of the century under RCP8.5, and the multimodel average exhibits no significant annual soil moisture increases anywhere on the planet (Collins et al 2013).

Major uncertainties

While both evaporation and transpiration changes are of the same sign as temperature increases, the relative importance of each as a function of depth is less well quantified. The amount of transpiration varies considerably among plant species, and these are treated with widely varying of sophistication in the land surface components of contemporary climate models. Uncertainty in the sign of the anthropogenic change of root depth soil moisture is low in regions and seasons of projected precipitation decreases (Ch. 7: Precipitation Changes). There is moderate to high uncertainty in the magnitude of the change in soil moisture at all depths and all regions and seasons. This key finding is a “projection without attribution” statement as such a drying is not part of the observed record. Projections of summertime mean CONUS precipitation exhibit no significant change. However, recent summertime precipitation trends are positive, leading to reduced agricultural drought conditions overall (Andreadis and Lettenmaier 2006). While statistically significant increases in precipitation have been identified over parts of the United States, these trends have not been clearly attributed to anthropogenic forcing (Ch. 7: Precipitation Change). Furthermore, North American summer temperature increases under RCP8.5 at the end of the century are projected to be substantially more than the current observed (and modeled) temperature increase. Because of the response of evapotranspiration to temperature increases, the CMIP5 multimodel average projection is for drier surface soils even in those high latitude regions (Alaska and Canada) that are confidently projected to experience increases in precipitation. Hence, in the CONUS region, with little or no projected summertime changes in precipitation, we conclude that surface soil moisture will likely decrease.

Assessment of confidence based on evidence and agreement

CMIP5 and regional models support the surface soil moisture key finding. Confidence is assessed as “medium” as this key finding—despite the high level of agreement among model projections—because of difficulties in observing long-term changes in this metric and because, at present, there is no published evidence of detectable long-term decreases in surface soil moisture across the United States.

Summary sentence or paragraph that integrates the above information

In the northern United States, surface soil moisture (top 10 cm) is *likely* to decrease as evaporation outpaces increases in precipitation. In the Southwest, the combination of temperature increases and precipitation decreases causes surface soil moisture decreases to be *very likely*. In this region, decreases in soil moisture at the root depth are *likely*.

Key Message 4

Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

Description of evidence base

First principles tell us that as temperatures rise, minimum snow levels also must rise. Certain changes in western U.S. hydrology have already been attributed to human causes in several papers following Barnett et al. (2008) and are cited in the text. The CMIP3/5 models project widespread warming with future increases in atmospheric GHG concentrations, although these are underestimated in the current generation of global climate models (GCMs) at the high altitudes of the western United States due to constraints on orographic representation at current GCM spatial resolutions.

CMIP5 models were not designed or constructed for direct projection of locally relevant snowpack amounts. However, a high-resolution climate model, selected for its ability to simulate western U.S. snowpack amounts and extent, projects devastating changes in the hydrology of this region assuming constant water resource management practices (Rhoades et al 2017). This conclusion is also supported by a statistical downscaling result shown in Figure 3.1 of Walsh et al. 2014 and Cayan et al. 2013 and by the more recent statistical downscaling study of Klos et al. 2014.

Major uncertainties

The major uncertainty is not so much "if" but rather "how much" as changes to precipitation phase (rain or snow) are sensitive to temperature increases that in turn depend on greenhouse gas (GHG) forcing changes. Also, changes to the lower-elevation catchments will be realized prior to those at higher elevations that, even at 25 km, is not adequately resolved. Uncertainty in the final statement also stems from the usage of one model but is tempered by similar findings from statistical downscaling studies. However, this simulation is a so-called "prescribed temperature" experiment with the usual uncertainties about climate sensitivity wired in by the usage of one particular ocean temperature change. Uncertainty in the equator-to-pole differential ocean warming rate is also a factor.

Assessment of confidence based on evidence and agreement

All CMIP5 models project large-scale western U.S. warming as GHG forcing increases. Warming is underestimated in most of the western United States due to elevation deficiencies that are a consequence of coarse model resolution.

Summary sentence or paragraph that integrates the above information

Warmer temperatures lead to less snow and more rain if total precipitation remains unchanged. Projected winter/spring precipitation changes are a mix of increases in northern states and decreases in the Southwest. In the northern Rocky Mountains, snowpack is projected to decrease even with a projected precipitation increase due to this phase change effect. This will lead to, at the very least, profound changes to the seasonal and sub-seasonal timing of the western U.S. hydrological cycle even where annual precipitation remains nearly unchanged with a strong potential for water shortages.

Key Message 5

Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change and the timing of any emergence of a future detectible anthropogenic change in flooding is unclear. (*Medium confidence*)

Description of evidence base

Observed changes are a mix of increases and decreases and are documented by Walsh et al. 2014 and other studies cited in the text. No attribution statements have been made.

Major uncertainties

Floods are highly variable both in space and time. The multivariate nature of floods complicates detection and attribution.

Assessment of confidence based on evidence and agreement

Confidence is limited to *medium* due to both the lack of an attributable change in observed flooding to date and the complicated multivariate nature of flooding. However, confidence is *high* in the projections of increased future extreme precipitation, the principal driver (among several) of many floods. It is unclear when an observed long-term increase in U.S. riverine flooding will be attributed to anthropogenic climate change. Hence, confidence is *medium* in this part of the key message at this time.

Summary sentence or paragraph that integrates the above information

The key finding is a relatively weak statement reflecting the lack of definitive detection and attribution of anthropogenic changes in U.S. flooding intensity, duration, and frequency.

Key Message 6

The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms with profound changes to certain ecosystems (*medium confidence*).

Description of evidence base

Studies by Dennison et al. 2014 (western U.S.) and Kasischke and Turetsky 2006 (Alaska) document the observed increases in fire statistics. Projections of Westerling et al. (2011) (western U.S.) and Young et al. 2016 and others (Alaska) indicate increased fire risk. These observations and projections are consistent with drying due to warmer temperatures leading to increased flammability and longer fire seasons.

Major uncertainties

Analyses of other regions of the United States, which also could be subject to increased fire risk do not seem to be readily available. Likewise, projections of the western U.S. fire risk are of limited areas. In terms of attribution, there is still some uncertainty on how well non-climatic confounding factors such as forestry management and fire suppression practices have been accounted for, particularly for the western United States. Other climate change factors, such as increased water deficits and insect infestations could reduce fuel loads, tending towards reducing fire frequency and/or intensity.

Assessment of confidence based on evidence and agreement

Confidence is *high* in the observations due to solid observational evidence. Confidence in projections would be higher if there were more available studies covering a broader area of the United States and a wider range of ecosystems.

Summary sentence or paragraph that integrates the above information

Wildfires have increased over parts of the western United States and Alaska in recent decades and are projected to continue to increases as a result of climate change. As a result, shifts in certain ecosystem types may occur.

TABLES

Table 8.1: A list of U.S. droughts for which attribution statements have been made. In the last column, "+" indicates that an attributable human induced increase in frequency and/or magnitude was found, "–" indicates that an attributable human induced decrease in frequency and/or magnitude was found, "0" indicates no attributable human contribution was identified. As in tables 6.2 and 7.1, several of the events were originally examined in the *Bulletin of the American Meteorological Society*'s (*BAMS*) State of the Climate Reports and reexamined by Angélil et al. (2017). In these cases, both attribution statements are listed with the original authors first. Source: M. Wehner.

Authors	Event Year and Duration	Region or State	Type	Attribution Statement
Rupp and Mote 2012 / Angélil et al. 2017	MAMJJA 2011	Texas	Meteorological	+/+
Hoerling et al. 2013	2012	Texas	Meteorological	+
Rupp et al. 2013 / Angélil et al. 2017	MAMJJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	MAM 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	JJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/+
Hoerling et al. 2014	MJJA 2012	Great Plains/Midwest	Meteorological	0
Swain et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	+/+
Wang and Schubert 2014 / Angélil et al. 2017	JS 2013	California	Meteorological	0/+

Knutson et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	0/+
Knutson et al. 2014 / Angélil et al. 2017	MAM 2013	U.S. Southern Plains region	Meteorological	0/+
Diffenbaugh et al. 2015	2012-2014	California	Agricultural	+
Seager et al. 2015	2012-2014	California	Agricultural	+
Cheng et al. 2016	2011-2015	California	Agricultural	-
Mote et al. 2016	2015	Washington, Oregon, California	Hydrological (snow water equivalent)	+

Table 8.2: Projected changes in western U.S. mountain range winter (DJF) snow-related hydrology variables at the middle and end of this century. Projections are for the RCP8.5 scenario from a high-resolution version of the Community Atmospheric Model, CAM5 (Rhoades et al. 2017).

Mountain Range	***Snow Water Equivalent (% Change)***		***Snow Cover (% Change)***		***Snowfall (% Change)***		***Surface Temperature (Change in K)***	
	2050	***2100***	***2050***	***2100***	***2050***	***2100***	***2050***	***2100***
Cascades	*-41.5*	*-89.9*	*-21.6*	*-72.9*	*-10.7*	*-50.0*	*0.9*	*4.1*
Klamath	*-50.7*	*-95.8*	*-38.6*	*-89.0*	*-23.1*	*-78.7*	*0.8*	*3.5*
Rockies	*-17.3*	*-65.1*	*-8.2*	*-43.1*	*1.7*	*-8.2*	*1.4*	*5.5*
Sierra Nevada	*-21.8*	*-89.0*	*-21.9*	*-77.7*	*-4.7*	*-66.6*	*1.1*	*4.5*
Wasatch and Uinta	*-18.9*	*-78.7*	*-14.2*	*-61.4*	*4.1*	*-34.6*	*1.8*	*6.1*
Western USA	*-22.3*	*-70.1*	*-12.7*	*-51.5*	*-1.6*	*-21.4*	*1.3*	*5.2*

FIGURES

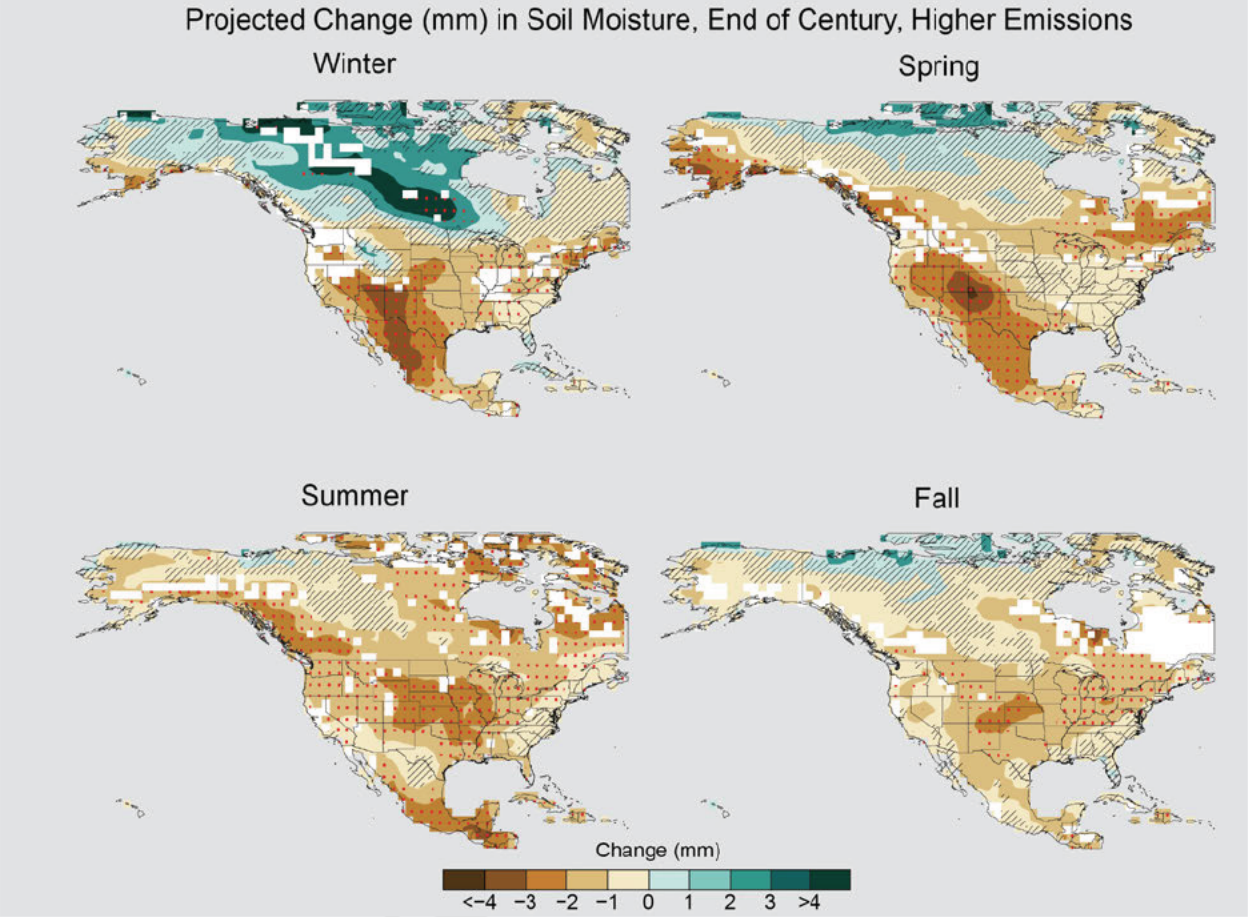

Figure 8.1. Projected end of the 21st century weighted CMIP5 multimodel average percent changes in near surface seasonal soil moisture (mrsos) under the RCP8.5 scenario. Stippling indicates that changes are assessed to be large compared to natural variations. Hashing indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI / CICS-NC).

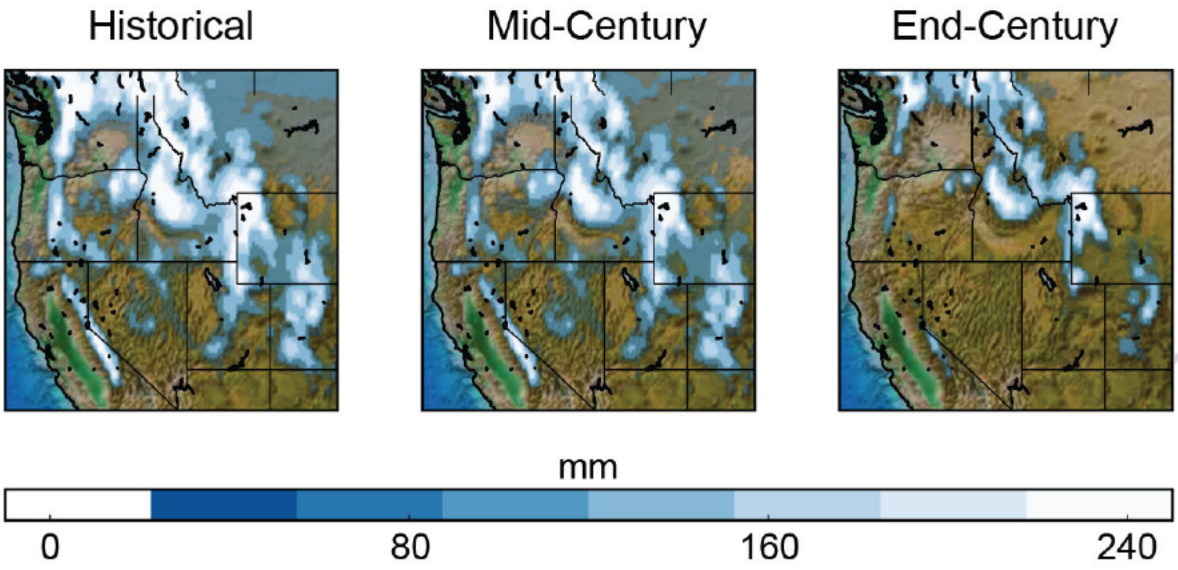

Figure 8.2. Projected changes in winter (DJF) snow water equivalent at the middle and end of this century under the RCP8.5 scenario from a high-resolution version of the Community Atmospheric Model, CAM5 (Rhoades et al. 2017). (Figure source: H. Krishnan, LBNL).

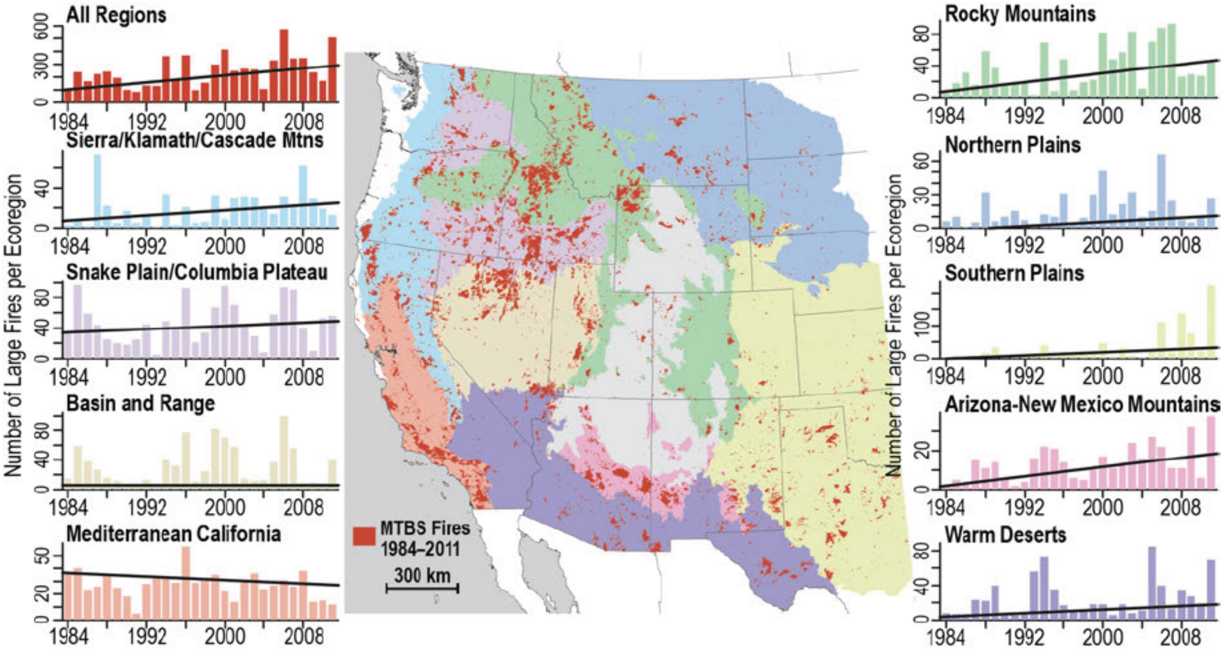

Figure 8.3. Trends in the annual number of large fires in the western United States for a variety of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all regions except the Snake Plain/Columbian Plateau, Basin and Range, and Mediterranean California regions. (Figure source: Dennison et al. 2014).

REFERENCES

Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences,* **113,** 11770-11775. http://dx.doi.org/10.1073/pnas.1607171113

AECOM, 2013: The Impact of Climate Change and Population Growth on the National Flood Insurance Program Through 2100. 257 pp. http://www.acclimatise.uk.com/login/uploaded/resources/FEMA_NFIP_report.pdf

Andreadis, K.M. and D.P. Lettenmaier, 2006: Trends in 20th century drought over the continental United States. *Geophysical Research Letters,* **33,** L10403. http://dx.doi.org/10.1029/2006GL025711

Angélil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *Journal of Climate,* **30,** 5-16. http://dx.doi.org/10.1175/JCLI-D-16-0077.1

Archfield, S.A., R.M. Hirsch, A. Viglione, and G. Blöschl. 2016. Fragmented patterns of flood change across the United States. Geophys. Rev. Let. **43**, 10,232-10,239

Armstrong, W.H., M.J. Collins, and N.P. Snyder, 2014: Hydroclimatic flood trends in the northeastern United States and linkages with large-scale atmospheric circulation patterns. *Hydrological Sciences Journal,* **59,** 1636-1655. http://dx.doi.org/10.1080/02626667.2013.862339

Barnett, T.P. and D.W. Pierce, 2009: Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences,* **106,** 7334-7338. http://dx.doi.org/10.1073/pnas.0812762106

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science,* **319,** 1080-1083. http://dx.doi.org/10.1126/science.1152538

Bennet, H.H., F.H. Fowler, F.C. Harrington, R.C. Moore, J.C. Page, M.L. Cooke, H.A. Wallace, and R.G. Tugwell, 1936: *A Report of the Great Plains Area Drought Committee*. Hopkins Papers Box 13. Franklin D. Roosevelt Library, New Deal Network (FERI), Hyde Park, NY. http://newdeal.feri.org/hopkins/hop27.htm

Berg, A., J. Sheffield, *and* P. C. D. Milly *(*2017*),* Divergent surface and total soil moisture projections under global warming, Geophys. Res. Lett., 44, 236–244, doi:10.1002/2016GL071921.

Berghuijs, W.R., R.A. Woods, C.J. Hutton, and M. Sivapalan, 2016: Dominant flood generating mechanisms across the United States. *Geophysical Research Letters,* **43,** 4382-4390. http://dx.doi.org/10.1002/2016GL068070

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters,* **42,** 3414-3420. http://dx.doi.org/10.1002/2015GL063306

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa, 2008: Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate,* **21,** 6404-6424. http://dx.doi.org/10.1175/2008JCLI2397.1

Brown, P.M., E.K. Heyerdahl, S.G. Kitchen, and M.H. Weber, 2008: Climate effects on historical fires (1630–1900) in Utah. *International Journal of Wildland Fire,* **17,** 28-39. http://dx.doi.org/10.1071/WF07023

Cayan, D.R., T. Das, D.W. Pierce, T.P. Barnett, M. Tyree, and A. Gershunov, 2010: Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proceedings of the National Academy of Sciences,* **107,** 21271-21276. http://dx.doi.org/10.1073/pnas.0912391107

Cayan, D., K. Kunkel, C. Castro, A. Gershunov, J. Barsugli, A. Ray, J. Overpeck, M. Anderson, J. Russell, B. Rajagopalan, I. Rangwala, and P. Duffy, 2013: Ch. 6: Future climate: Projected average. *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*. Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy, Eds. Island Press, Washington, D.C., 153-196. http://swccar.org/sites/all/themes/files/SW-NCA-color-FINALweb.pdf

Cheng, L., M. Hoerling, A. AghaKouchak, B. Livneh, X.-W. Quan, and J. Eischeid, 2016: How has human-induced climate change affected California drought risk? *Journal of Climate,* **29,** 111-120. http://dx.doi.org/10.1175/JCLI-D-15-0260.1

Christensen, N.S. and D.P. Lettenmaier, 2007: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences,* **11,** 1417-1434. http://dx.doi.org/10.5194/hess-11-1417-2007

Coats, S., B.I. Cook, J.E. Smerdon, and R. Seager, 2015: North American pancontinental droughts in model simulations of the last millennium. *Journal of Climate,* **28,** 2025-2043. http://dx.doi.org/10.1175/JCLI-D-14-00634.1

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

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**. http://dx.doi.org/10.1126/sciadv.1400082

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle, 2004: Long-term aridity changes in the western United States. *Science,* **306,** 1015-1018. http://dx.doi.org/10.1126/science.1102586

Dai, A., 2013: Increasing drought under global warming in observations and models. *Nature Climate Change,* **3,** 52-58. http://dx.doi.org/10.1038/nclimate1633

Das, T., D.W. Pierce, D.R. Cayan, J.A. Vano, and D.P. Lettenmaier, 2011: The importance of warm season warming to western U.S. streamflow changes. *Geophysical Research Letters,* **38,** L23403. http://dx.doi.org/10.1029/2011GL049660

Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters,* **41,** 2928-2933. http://dx.doi.org/10.1002/2014GL059576

Dettinger, M., 2011: Climate change, atmospheric rivers, and floods in California–a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association,* **47,** 514-523. http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x

Dettinger, M.D., 2013: Atmospheric rivers as drought busters on the U.S. West Coast. *Journal of Hydrometeorology,* **14,** 1721-1732. http://dx.doi.org/10.1175/JHM-D-13-02.1

Dettinger, M.D., F.M. Ralph, T. Das, P.J. Neiman, and D.R. Cayan, 2011: Atmospheric rivers, floods and the water resources of California. *Water,* **3,** 445-478. http://dx.doi.org/10.3390/w3020445

Diffenbaugh, N.S. and M. Scherer, 2013: Likelihood of July 2012 U.S. temperatures in pre-industrial and current forcing regimes [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S6-S9. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

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,** 3931-3936. http://dx.doi.org/10.1073/pnas.1422385112

EPA, 2016: Climate Change Indicators in the United States, 2016. 4th edition. U.S. Environmental Protection Agency, Washington, D.C., 96 pp. https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf

Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology,* **15,** 549-560. http://dx.doi.org/10.1111/j.1365-2486.2008.01660.x

Frans, C., E. Istanbulluoglu, V. Mishra, F. Munoz-Arriola, and D.P. Lettenmaier, 2013: Are climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi River Basin? *Geophysical Research Letters,* **40,** 1104-1110. http://dx.doi.org/10.1002/grl.50262

Frei, A., K.E. Kunkel, and A. Matonse, 2015: The seasonal nature of extreme hydrological events in the northeastern United States. *Journal of Hydrometeorology,* **16,** 2065-2085. http://dx.doi.org/10.1175/JHM-D-14-0237.1

French, N.H.F., L.K. Jenkins, T.V. Loboda, M. Flannigan, R. Jandt, L.L. Bourgeau-Chavez, and M. Whitley, 2015: Fire in arctic tundra of Alaska: Past fire activity, future fire potential, and significance for land management and ecology. *International Journal of Wildland Fire,* **24,** 1045-1061. http://dx.doi.org/10.1071/WF14167

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 [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S11-S15. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Fyfe, J.C., C. Derksen, L. Mudryk, G.M. Flato, B.D. Santer, N.C. Swart, N.P. Molotch, X. Zhang, H. Wan, V.K. Arora, J. Scinocca, and Y. Jiao, 2017: Large near-term projected snowpack loss over the western United States. *Nature Communications,* **8,** 14996. http://dx.doi.org/10.1038/ncomms14996

Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. *Geophysical Research Letters,* **42,** 7179-7186. http://dx.doi.org/10.1002/2015GL065435

Gochis, D., R. Schumacher, K. Friedrich, N. Doesken, M. Kelsch, J. Sun, K. Ikeda, D. Lindsey, A. Wood, B. Dolan, S. Matrosov, A. Newman, K. Mahoney, S. Rutledge, R. Johnson, P. Kucera, P. Kennedy, D. Sempere-Torres, M. Steiner, R. Roberts, J. Wilson, W. Yu, V. Chandrasekar, R. Rasmussen, A. Anderson, and B. Brown, 2015: The Great Colorado Flood of September 2013. *Bulletin of the American Meteorological Society,* **96 (12),** 1461-1487. http://dx.doi.org/10.1175/BAMS-D-13-00241.1

Groisman, P.Y., R.W. Knight, and T.R. Karl, 2001: Heavy precipitation and high streamflow in the contiguous United States: Trends in the twentieth century. *Bulletin of the American Meteorological Society,* **82,** 219-246. http://dx.doi.org/10.1175/1520-0477(2001)082<0219:hpahsi>2.3.co;2

Guan, B., N.P. Molotch, D.E. Waliser, E.J. Fetzer, and P.J. Neiman, 2013: The 2010/2011 snow season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability. *Water Resources Research,* **49,** 6731-6743. http://dx.doi.org/10.1002/wrcr.20537

Guan, B., D.E. Waliser, F.M. Ralph, E.J. Fetzer, and P.J. Neiman, 2016: Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers. *Geophysical Research Letters,* **43,** 2964-2973. http://dx.doi.org/10.1002/2016GL067978

Harvey, B.J., 2016: Human-caused climate change is now a key driver of forest fire activity in the western United States. *Proceedings of the National Academy of Sciences,* **113,** 11649-11650. http://dx.doi.org/10.1073/pnas.1612926113

Hegerl, G.C., F. W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin, A.W. Wood, C. Bonfils, B.D. Santer, and T. Nozawa, 2009: Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate,* **22,** 3838-3855. http://dx.doi.org/10.1175/2009jcli2470.1

Higuera PE, Abatzoglou JT, Littell JS, Morgan P. 2015: The Changing Strength and Nature of Fire-Climate Relationships in the Northern Rocky Mountains, U.S.A., 1902-2008. PLoS ONE 10(6): e0127563. https://doi.org/10.1371/journal.pone.0127563

Hirsch, R.M. and K.R. Ryberg, 2012: Has the magnitude of floods across the USA changed with global CO_2 levels? *Hydrological Sciences Journal,* **57,** 1-9. http://dx.doi.org/10.1080/02626667.2011.621895

Hoerling, M., D. Lettenmaier, D. Cayan, and B. Udall, 2009: Reconciling future Colorado River flows. *Southwest Hydrology,* **8,** 20-21.31. http://www.swhydro.arizona.edu/archive/V8_N3/feature2.pdf

Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J. Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of Climate,* **26,** 2811–2832. http://dx.doi.org/10.1175/JCLI-D-12-00270.1

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager, 2014: Causes and predictability of the 2012 Great Plains drought. *Bulletin of the American Meteorological Society,* **95,** 269-282. http://dx.doi.org/10.1175/BAMS-D-13-00055.1

Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly, and M.C. Dietze, 2015: Arctic tundra fires: Natural variability and responses to climate change. *Frontiers in Ecology and the Environment,* **13,** 369-377. http://dx.doi.org/10.1890/150063

IPCC, 2012: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

Joly, K., P.A. Duffy, and T.S. Rupp, 2012: Simulating the effects of climate change on fire regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere,* **3,** 1-18. http://dx.doi.org/10.1890/ES12-00012.1

Kapnick, S.B. and T.L. Delworth, 2013: Controls of global snow under a changed climate. *Journal of Climate,* **26,** 5537-5562. http://dx.doi.org/10.1175/JCLI-D-12-00528.1

Karl, T.R., J.T. Melillo, and T.C. Peterson, eds., 2009: *Global Climate Change Impacts in the United States*. ed. Karl, T.R., J.T. Melillo, and T.C. Peterson. Cambridge University Press: New York, NY, 189 pp. http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf

Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters,* **33,** L09703. http://dx.doi.org/10.1029/2006GL025677

Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu, 2013: Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences,* **110,** 13055-13060. http://dx.doi.org/10.1073/pnas.1305069110

Klos, P.Z., T.E. Link, and J.T. Abatzoglou, 2014: Extent of the rain–snow transition zone in the western U.S. under historic and projected climate. *Geophysical Research Letters,* **41,** 4560-4568. http://dx.doi.org/10.1002/2014GL060500

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. *Journal of Climate,* **19,** 4545-4559. http://dx.doi.org/10.1175/JCLI3850.1

Knutson, Thomas R., Fanrong Zeng, and Andrew T Wittenberg, September 2014: Seasonal and Annual Mean Precipitation Extremes Occurring During 2013: A U.S. Focused Analysis [in "Explaining Extremes of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **95(9)**, S19-S23. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Kormos, P.R., C.H. Luce, S.J. Wenger, and W.R. Berghuijs, 2016: Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. *Water Resources Research,* **52,** 4990-5007. http://dx.doi.org/10.1002/2015WR018125

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecological Applications, 19, 1003–1021.

Littell, J.S., E.E., Oneil, D. McKenzie,J. A. Hicke, J.A. Lutz, R.A. Norheim, M.M. Elsner, 2010: Forest ecosystems, disturbance, and climatic change in Washington State, USA Climatic Change 102: 129. doi:10.1007/s10584-010-9858-x

Littell, J.S., D. L. Peterson, K. L. Riley, Y. Liu, and C. H. Luce, 2016: Global Change Biology 22, 2353–2369, doi: 10.1111/gcb.13275

Livneh, B. and M.P. Hoerling, 2016: The physics of drought in the U.S. Central Great Plains. *Journal of Climate,* **29,** 6783-6804. http://dx.doi.org/10.1175/JCLI-D-15-0697.1

Luce, C.H. and Z.A. Holden, 2009: Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophysical Research Letters,* **36**. http://dx.doi.org/10.1029/2009GL039407

Luce, C.H., J.T. Abatzoglou, and Z.A. Holden, 2013: The missing mountain water: Slower westerlies decrease orographic enhancement in the Pacific Northwest USA. *Science,* **342,** 1360-1364. http://dx.doi.org/10.1126/science.1242335

Luce, C.H., V. Lopez-Burgos, and Z. Holden, 2014: Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. *Water Resources Research,* **50,** 9447-9462. http://dx.doi.org/10.1002/2013WR014844

Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change,* **5,** 250-254. http://dx.doi.org/10.1038/nclimate2516

Mallakpour, I. and G. Villarini, 2016: Investigating the relationship between the frequency of flooding over the central United States and large-scale climate. *Advances in Water Resources,* **92,** 159-171. http://dx.doi.org/10.1016/j.advwatres.2016.04.008

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,** 2805-2813. http://dx.doi.org/10.1002/2015GL063456

Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao, and A. Timmermann, 2013: Information from paleoclimate archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 383–464. http://www.climatechange2013.org/report/full-report/

McCabe, G.J. and D.M. Wolock, 2014: Spatial and temporal patterns in conterminous United States streamflow characteristics. *Geophysical Research Letters,* **41,** 6889-6897. http://dx.doi.org/10.1002/2014GL061980

McGuire, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L. Guo, D.J. Hayes, M. Heimann, T.D. Lorenson, R.W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs,* **79,** 523-555. http://dx.doi.org/10.1890/08-2025.1

Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, 2009: Relative increase of record high maximum temperatures compared to record low minimum temperatures in the US. *Geophysical Research Letters,* **36,** L23701. http://dx.doi.org/10.1029/2009GL040736

Merz, B., S. Vorogushyn, S. Uhlemann, J. Delgado, and Y. Hundecha, 2012: HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series".

Hydrology and Earth System Sciences, **16,** 1379-1387. http://dx.doi.org/10.5194/hess-16-1379-2012

Milly, P.C.D. and K.A. Dunne, 2016: Potential evapotranspiration and continental drying. *Nature Climate Change,* **6,** 946-969. http://dx.doi.org/10.1038/nclimate3046

Mo, K.C. and D.P. Lettenmaier, 2015: Heat wave flash droughts in decline. *Geophysical Research Letters,* **42,** 2823-2829. http://dx.doi.org/10.1002/2015GL064018

Mo, K.C. and D.P. Lettenmaier, 2016: Precipitation deficit flash droughts over the United States. *Journal of Hydrometeorology,* **17,** 1169-1184. http://dx.doi.org/10.1175/jhm-d-15-0158.1

Mote, P.W., 2003: Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters,* **30,** 1601. http://dx.doi.org/10.1029/2003GL017258

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society,* **86,** 39-49. http://dx.doi.org/10.1175/BAMS-86-1-39

Mote, P.W., D.E. Rupp, S. Li, D.J. Sharp, F. Otto, P.F. Uhe, M. Xiao, D.P. Lettenmaier, H. Cullen, and M.R. Allen, 2016: Perspectives on the causes of exceptionally low 2015 snowpack in the western United States. *Geophysical Research Letters,* **43,** 10,980-10,988. http://dx.doi.org/10.1002/2016GL069965

Munoz, S.E., K.E. Gruley, A. Massie, D.A. Fike, S. Schroeder, and J.W. Williams, 2015: Cahokia's emergence and decline coincided with shifts of flood frequency on the Mississippi River. *Proceedings of the National Academy of Sciences,* **112,** 6319-6324. http://dx.doi.org/10.1073/pnas.1501904112

Najafi, M.R. and H. Moradkhani, 2015: Multi-model ensemble analysis of runoff extremes for climate change impact assessments. *Journal of Hydrology,* **525,** 352-361. http://dx.doi.org/10.1016/j.jhydrol.2015.03.045

Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick, 2011: Flooding in western Washington: The connection to atmospheric rivers. *Journal of Hydrometeorology,* **12,** 1337-1358. http://dx.doi.org/10.1175/2011JHM1358.1

NOAA, 2008: Drought: Public Fact Sheet. National Oceanic and Atmospheric Administration, National Weather Service, Washington, D.C. http://www.nws.noaa.gov/os/brochures/climate/DroughtPublic2.pdf

Novotny, E.V. and H.G. Stefan, 2007: Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology,* **334,** 319-333. http://dx.doi.org/10.1016/j.jhydrol.2006.10.011

O'Gorman, P.A., 2014: Contrasting responses of mean and extreme snowfall to climate change. *Nature,* **512,** 416-418. http://dx.doi.org/10.1038/nature13625

Pall, P.C.M.P., M.F. Wehner, D.A. Stone, C.J. Paciorek, and W.D. Collins, To appear in: Diagnosing anthropogenic contributions to heavy Colorado rainfall in September 2013. *Weather and Climate Extremes*.

Partain, J.L., Jr., S. Alden, U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, R. Lader, P.Q. Olsson, T.S. Rupp, H. Strader, R.L.T. Jr., J.E. Walsh, A.D. York, and R.H. Zieh, 2016: An assessment of the role of anthropogenic climate change in the Alaska fire season of 2015 [in "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **97 (12),** S14-S18. http://dx.doi.org/10.1175/BAMS-D-16-0149.1

Pierce, D.W. and D.R. Cayan, 2013: The uneven response of different snow measures to human-induced climate warming. *Journal of Climate,* **26,** 4148-4167. http://dx.doi.org/10.1175/jcli-d-12-00534.1

Pierce, D.W., T.P. Barnett, H.G. Hidalgo, T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D. Dettinger, D.R. Cayan, A. Mirin, A.W. Wood, and T. Nozawa, 2008: Attribution of declining western US snowpack to human effects. *Journal of Climate,* **21,** 6425-6444. http://dx.doi.org/10.1175/2008JCLI2405.1

Prestemon, J.P., U. Shankar, A. Xiu, K. Talgo, D. Yang, E. Dixon, D. McKenzie, and K.L. Abt, 2016: Projecting wildfire area burned in the south-eastern United States, 2011–60. *International Journal of Wildland Fire,* **25,** 715-729. http://dx.doi.org/10.1071/WF15124

Ralph, F.M. and M.D. Dettinger, 2011: Storms, floods, and the science of atmospheric rivers. *Eos, Transactions American Geophysical Union,* **92,** 265-266. http://dx.doi.org/10.1029/2011EO320001

Rhoades, A.M., P.A. Ullrich, and C.M. Zarzycki, 2017: Projecting 21st century snowpack trends in western USA mountains using variable-resolution CESM. *Climate Dynamics,* **Online First,** 1-28. http://dx.doi.org/10.1007/s00382-017-3606-0

Running, S.W., 2006: Is global warming causing more, larger wildfires? *Science,* **313,** 927-928. http://dx.doi.org/10.1126/science.1130370

Rupp, D. E., and P. W. Mote, 2012: Did human influence on climate make the 2011 Texas drought more probable? Bull. Amer. Meteor. Soc., 93, 1052–1054.

Rupp, D.E., P.W. Mote, N. Massey, F.E.L. Otto, and M.R. Allen, 2013: Human influence on the probability of low precipitation in the central United States in 2012 [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S2-S6. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Ryberg, K.R., W. Lin, and A.V. Vecchia, 2014: Impact of climate variability on runoff in the north-central United States. *Journal of Hydrologic Engineering,* **19,** 148-158. http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000775

Sanford, T., R. Wang, and A. Kenwa, 2015: *The Age of Alaskan Wildfires*. Climate Central, Princeton, NJ, 32 pp. http://assets.climatecentral.org/pdfs/AgeofAlaskanWildfires.pdf

Schoennagel T, Veblen TT, and Romme WH. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience 54: 661–76.

Seager, R., M. Hoerling, D.S. Siegfried, h. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2014: Causes and Predictability of the 2011-14 California Drought. National Oceanic and Atmospheric Administration, Drought Task Force Narrative Team, 40 pp. http://dx.doi.org/10.7289/V58K771F

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,** 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

SFPUC, 2016: Flood Resilience: Report, Task Order 57 (Draft: May 2016). San Francisco Public Utilities Commission, San Francisco, CA. 302 pp. http://sfwater.org/modules/showdocument.aspx?documentid=9176

Sheffield, J., E.F. Wood, and M.L. Roderick, 2012: Little change in global drought over the past 60 years. *Nature,* **491,** 435-438. http://dx.doi.org/10.1038/nature11575

Slater, L.J., M.B. Singer, and J.W. Kirchner, 2015: Hydrologic versus geomorphic drivers of trends in flood hazard. *Geophysical Research Letters,* **42,** 370-376. http://dx.doi.org/10.1002/2014GL062482

Stavros, E.N., J.T. Abatzoglou, D. McKenzie, and N.K. Larkin, 2014: Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States. *Climatic Change,* **126,** 455-468. http://dx.doi.org/10.1007/s10584-014-1229-6

Stephens, S.L., J.K. Agee, P.Z. Fulé, M.P. North, W.H. Romme, T.W. Swetnam, and M.G. Turner, 2013: Managing forests and fire in changing climates. *Science,* **342,** 41-42. http://dx.doi.org/10.1126/science.1240294

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate,* **18,** 1136-1155. http://dx.doi.org/10.1175/JCLI3321.1

Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh, 2014: The extraordinary California drought of 2013/14: Character, context and the role of climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S3-S6. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl, 2006: Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change,* **79,** 185-211. http://dx.doi.org/10.1007/s10584-006-9051-4

Tomer, M.D. and K.E. Schilling, 2009: A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *Journal of Hydrology,* **376,** 24-33. http://dx.doi.org/10.1016/j.jhydrol.2009.07.029

Trenberth, K.E., A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, and J. Sheffield, 2014: Global warming and changes in drought. *Nature Climate Change,* **4,** 17-22. http://dx.doi.org/10.1038/nclimate2067

Villarini, G., and A. Strong, Roles of climate and agricultural practices in discharge changes in an agricultural watershed in Iowa, Agriculture, Ecosystems and Environment, 188, 204-211, 2014.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 19-67. http://dx.doi.org/10.7930/J0KW5CXT

Wang, D. and M. Hejazi, 2011: Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research,* **47,** W00J12. http://dx.doi.org/10.1029/2010WR010283

Wang, H. and S. Schubert, 2014: Causes of the extreme dry conditions over California during early 2013 [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S7-S11. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Warner, M.D., C.F. Mass, and E.P. Salathé Jr., 2015: Changes in winter atmospheric rivers along the North American West Coast in CMIP5 climate models. *Journal of Hydrometeorology,* **16,** 118-128. http://dx.doi.org/10.1175/JHM-D-14-0080.1

Wehner, M.F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model performance and projections. *Climate Dynamics,* **40,** 59-80. http://dx.doi.org/10.1007/s00382-012-1393-1

Wehner, M., D.R. Easterling, J.H. Lawrimore, R.R. Heim, Jr., R.S. Vose, and B.D. Santer, 2011: Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology,* **12,** 1359-1377. http://dx.doi.org/10.1175/2011JHM1351.1

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science,* **313,** 940-943. http://dx.doi.org/10.1126/science.1128834

Westerling, A.L. M.G. Turner, E.A.H. Smithwick, W.H. Romme, and M.G. Ryan 2011:Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proc. Nat. Acad. Sci. 108 (32) 13165-13170; doi:10.1073/pnas.1110199108

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,** 6819-6828. http://dx.doi.org/10.1002/2015GL064924

Williams, I.N. and M.S. Torn, 2015: Vegetation controls on surface heat flux partitioning, and land-atmosphere coupling. *Geophysical Research Letters,* **42,** 9416-9424. http://dx.doi.org/10.1002/2015GL066305

Winters, B.A., J. Angel, C. Ballerine, J. Byard, A. Flegel, D. Gambill, E. Jenkins, S. McConkey, M. Markus, B.A. Bender, and M.J. O'Toole, 2015: Report for the Urban Flooding Awareness Act. Illinois Department of Natural Resources, Springfield, IL. 89 pp. https://www.dnr.illinois.gov/WaterResources/Documents/Final_UFAA_Report.pdf

Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006: Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research,* **42**. http://dx.doi.org/10.1029/2005WR004455

Yoon, J.-H., B. Kravitz, P.J. Rasch, S.-Y.S. 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. http://dx.doi.org/10.1175/bams-d-15-00114.1

Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2016: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography,* **Early view**. http://dx.doi.org/10.1111/ecog.02205