



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 higher 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 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*).

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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 hierarchical 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.¹ Clearly these three characterizations of drought are related but are also different descriptions of water shortages with different target audiences and different time scales. 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 higher scenario (RCP8.5; 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.² 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,² illustrating the complex relationships between the various components of the hydrological system. Meteorological drought can occur on a range of time scales, in addition to seasonal or annual time scales. “Flash droughts” can result from just a few weeks of dry weather,³ 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 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.⁴ Tree ring archives reveal that such droughts (in the agricultural sense) have occurred occasionally over the last 1,000 years.⁵ Climate model simulations suggest that droughts lasting several years to decades occur naturally in the southwestern United States.⁶ The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5)⁷ 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,⁸ 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;⁹ Dai 2013¹⁰). 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.¹¹ 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.^{3,12} Furthermore, there is no detectable change in meteorological drought at the global scale.⁹ 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;¹³ Trenberth et al. 2014¹⁴). 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.¹⁵ 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.¹⁶ 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.

The Great Plains/Midwest drought of 2012 was the most severe summer meteorological drought in the observational record for that region.¹⁷ 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.¹⁷ Little influence of the global sea surface temperature (SST) pattern on meteorological drought frequency has been found in model simulations.¹⁷ No evidence of a human contribution to the 2012 precipitation deficit in the Great Plains and Midwest is found in numerous studies.^{17, 18, 19} However, an alternative view is that the 2012 central U.S. drought can be classified as a “heat wave flash drought”,²⁰ a type of rapidly evolving drought that has decreased in frequency over the past century.³ 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,²¹ 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.²² That study also noted that Great Plains root depth and deeper soil mois-

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 Angéilil et al.¹⁸ 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 et al. 2012 ¹³⁰ / Angéilil et al. 2017 ¹⁸	MAMJJA 2011	Texas	Meteorological	+/+
Hoerling et al. 2013 ¹⁶	2012	Texas	Meteorological	+
Rupp et al. 2013 ¹⁹ / Angéilil et al. 2017 ¹⁸	MAMJJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 ¹⁹ / Angéilil et al. 2017 ¹⁸	MAM 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 ¹⁹ / Angéilil et al. 2017 ¹⁸	JJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/+
Hoerling et al. 2014 ¹⁷	MJJA 2012	Great Plains/Midwest	Meteorological	0
Swain et al. 2014 ²⁴ / Angéilil et al. 2017 ¹⁸	ANN 2013	California	Meteorological	+/+
Wang and Schubert 2014 ²⁹ / Angéilil et al. 2017 ¹⁸	JS 2013	California	Meteorological	0/+
Knutson et al. 2014 ¹³¹ / Angéilil et al. 2017 ¹⁸	ANN 2013	California	Meteorological	0/+
Knutson et al. 2014 ¹³¹ / Angéilil et al. 2017 ¹⁸	MAM 2013	U.S. Southern Plains region	Meteorological	0/+
Diffenbaugh et al. 2015 ²⁸	2012–2014	California	Agricultural	+
Seager et al. 2015 ¹³	2012–2014	California	Agricultural	+
Cheng et al. 2016 ¹⁵	2011–2015	California	Agricultural	-
Mote et al. 2016 ³¹	2015	Washington, Oregon, California	Hydrological (snow water equivalent)	+

ture was higher than normal in 2012 despite the surface drying, due to wet conditions in prior years, indicating the long time scales relevant below the surface.²²

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.^{13, 23, 24} A slow-moving high sea surface temperature (SST) anomaly, referred to as “The Blob”—was caused by a persistent ridge that weakened the normal cooling mechanisms for that region of the upper ocean.²⁵ 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.^{23, 26} It was also favored by reduced arctic sea ice and from feedbacks with The Blob’s SST anomalies.²⁷ 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. 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. 2014²⁴), 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.¹⁸

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,^{13, 28, 29} 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 control³⁰ to temperature control. There is some evidence to support a relationship between mild winter and/or warm spring temperatures and drought occurrence,³¹ but long-term warming trends in the tropical and North Pacific do not appear to have led to trends toward less precipitation over California.³² An anthropogenic contribution to commonly used measures of agricultural drought, including the Palmer Drought Severity Index (PDSI), was found in California^{28, 33} and is consistent with previous projections of changes in PDSI^{10, 34, 35} and with an attribution study.³⁶ 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.³⁷ 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.¹³ 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.^{15, 38} Berg et al.³⁹ 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.³⁰ 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 subsurface 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^{40, 41, 42, 43, 44} showed that annual runoff reductions in a warmer western United 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 runoff⁴⁵ reduced the fraction of precipitation falling as snow⁴⁶ and the snowpack water content at the end of winter,^{47, 48} 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.⁴⁹ Similarly, observed declines in the snow water equivalent in the region have been formally attributed to anthropogenic climate change⁵⁰ as have temperature, river flow, and snowpack.^{41, 51} As a harbinger, the unusually low western U.S. snowpack of 2015 may become the norm.³¹

In the northwestern United States, long-term trends in streamflow have seen declines, with the strongest trends in drought years⁵² that are attributed to a decline in winter precipitation.⁵³ 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 years⁵⁴ and are in addition to changes in snowpack properties.

We conclude with *high confidence* that these observed changes in 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.³⁴

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.^{55, 56} Climate projections indicate greater frequency of atmospheric rivers in the future (e.g., Dettinger 2011,⁵⁵ Warner et al. 2015;⁵⁷ Gao et al. 2015;⁵⁸ 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.⁵⁹ 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 tempera-

tures 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.² 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 higher scenario (RCP8.5), indicating widespread drying over the entire continental United States. Previous National Climate Assessments^{34, 60} have discussed the implication of these future drier conditions in the context of the 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.⁴²

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.³⁸ 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.⁶¹ 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

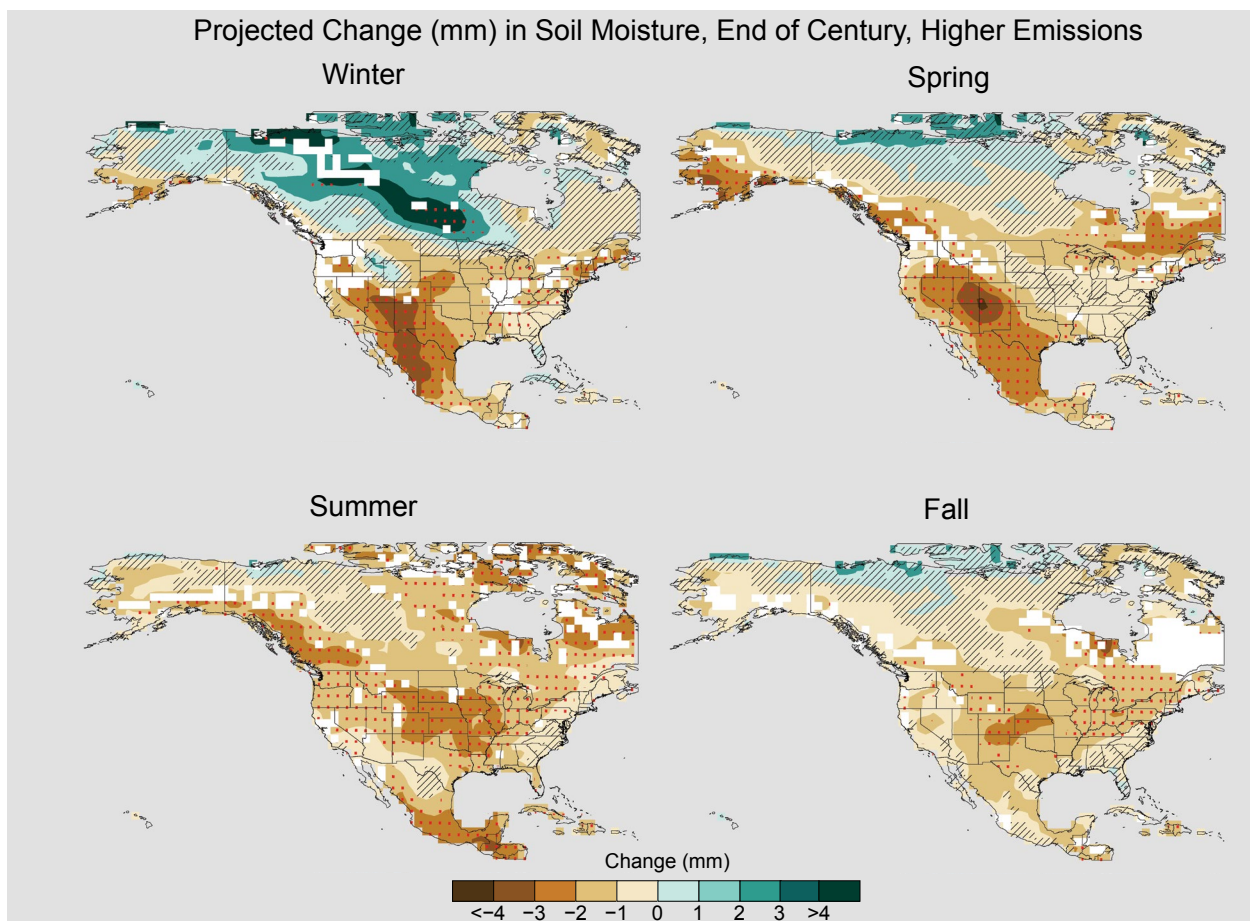


Figure 8.1: Projected end of the 21st century weighted CMIP5 multimodel average percent changes in near surface seasonal soil moisture (mrsos) under the higher scenario (RCP8.5). Stippling indicates that changes are assessed to be large compared to natural variations. Hashing indicates that changes are 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 and CICS-NC).

precipitation is projected to increase, consistent with increased evapotranspiration due to elevated temperatures.³⁸

Widespread reductions in mean snowfall across North America are projected by the CMIP5 models.⁶² 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.^{40, 41, 50, 63, 64} 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.⁶⁵ 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 higher scenario (RCP8.5). These projections indicate dramatic reductions in all aspects of snow⁶⁶ and are similar to previous statistically downscaled pro-

jections.^{67, 68} Table 8.2 reveals that the reductions in snow water equivalent accelerate in the latter half of this century under the higher scenario (RCP8.5) 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.⁶⁹ Given the larger projected increases in temperature at high altitudes compared to adjacent lower altitudes⁷⁰ 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,⁶⁸ and a large ensemble simulation of a global climate model.⁷¹

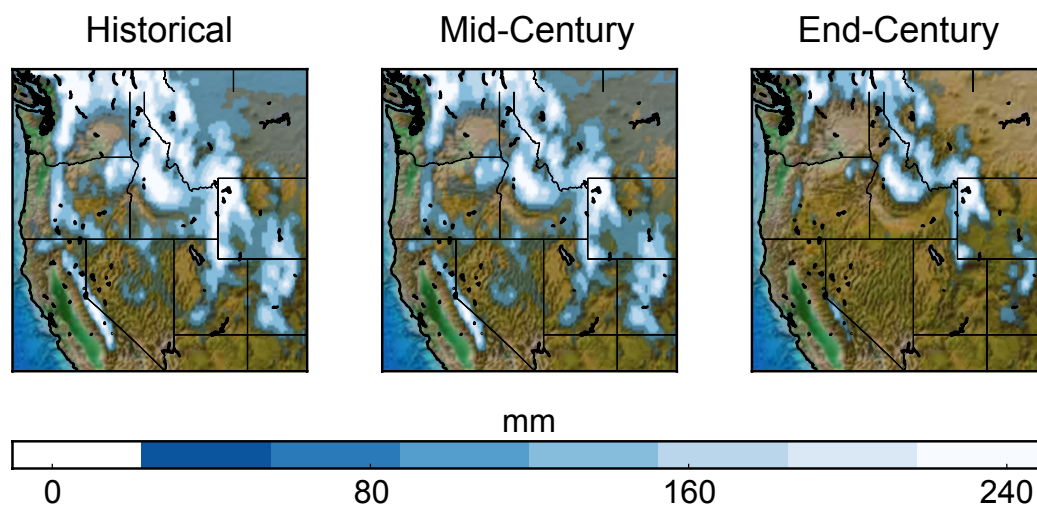


Figure 8.2: Projected changes in winter (DJF) snow water equivalent at the middle and end of this century under the higher scenario (RCP8.5) from a high-resolution version of the Community Atmospheric Model, CAM5.⁶⁶ (Figure source: H. Krishnan, LBNL).

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 higher scenario (RCP8.5) from a high-resolution version of the Community Atmospheric Model, CAM5.⁶⁶

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	-50.75	-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

As earlier spring melt and reduced snow water equivalent have 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 continues to warm (*very high confidence*). Under higher 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*).

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),^{72, 73} with mountain snowpack being vulnerable to these typically warmer-than-normal storms and their potential for rain on existing snow cover.⁷⁴ 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.³⁴

The IPCC AR5⁷ 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.^{34, 75, 76} Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude⁷⁷ 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.⁷⁸ 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.⁷⁹ 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.⁸⁰ 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.⁸¹

Recent analysis of annual maximum streamflow shows statistically significant trends in the upper Mississippi River valley (increasing) and in the Northwest (decreasing).⁴⁴ In fact, across the midwestern United States, statistically significant increases in flooding are well documented.^{78, 82, 83, 84, 85, 86, 87, 88} These increases in flood risk and severity are not attributed to 20th century changes in agricultural practices^{87, 89} but instead are attributed mostly to the observed increases in precipitation shown in Figures 7.1 through 7.4.^{78, 84, 89, 90} Trends in maximum streamflow in the northeastern United States are less dramatic and less spatially coherent,^{44, 80} although one study found mostly increasing trends⁹¹ in that region, consistent with the increasing trends in observed extreme precipitation in the region (Ch. 6: Temperature Change).^{34, 80}

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 water allocations from the Colorado River were made during one of the wettest periods of the past five centuries.⁹² 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.⁹³

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.⁹⁴ 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.⁷⁸

A projection study based on coupling an ensemble of regional climate model output to a hydrology model⁹⁵ 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.² 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.^{55, 96} Projections indicate greater frequency of heavy atmospheric rivers in the future (e.g., Dettinger et al. 2011,⁹⁶ Warner et al. 2015,⁵⁷ Gao et al. 2015,⁵⁸ 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 database⁹⁷ 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 the central part of the country and the Gulf Coast.⁹⁸

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.^{99, 100}

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".¹⁰¹

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.¹⁰² describe 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.¹⁷ analyzed the 2013 northeastern Colorado heavy multi-day precipitation event and resulting flood, finding little evidence of an anthropogenic influence on its occurrence. However, Pall et al.¹⁰³ 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.¹⁰³ 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.^{104, 105, 106, 107} 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



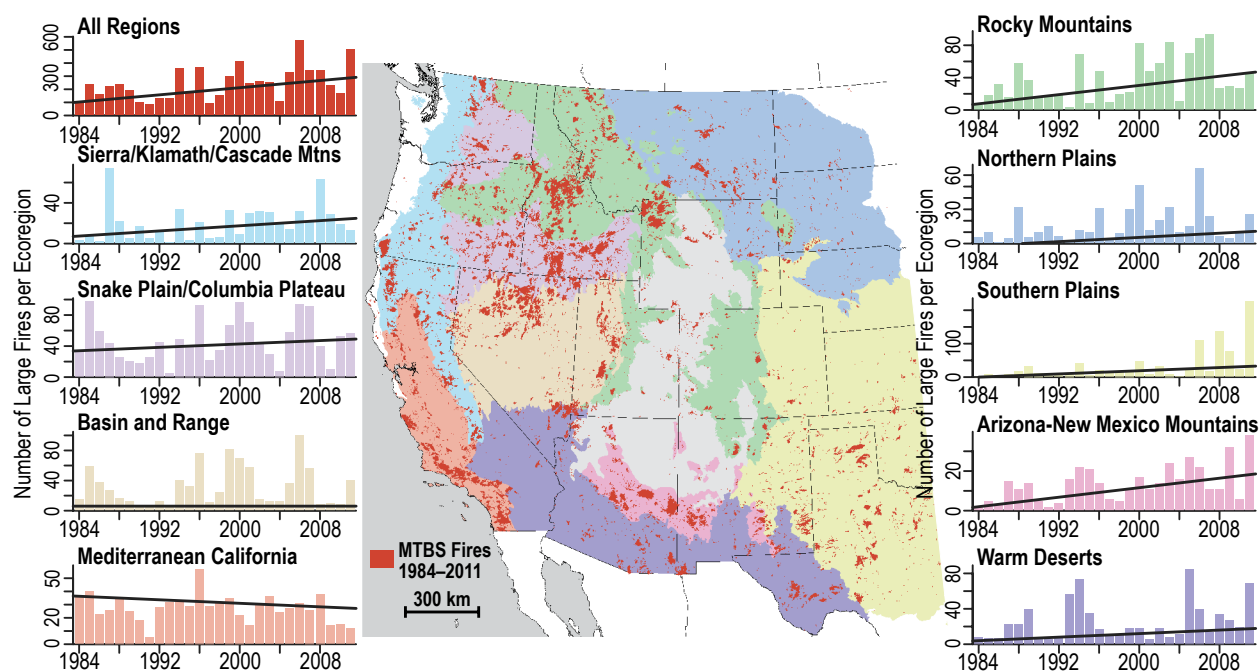


Figure 8.3: Trends in the annual number of large fires in the western United States for a variety of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all regions except the Snake Plain/Columbia Plateau, Basin and Range, and Mediterranean California regions. (Figure source: Dennison et al.¹⁰⁸).

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.¹⁰⁸ State-level fire data over the 20th century¹⁰⁹ 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 have increased forest fire activity in the western United States by increasing the aridity of forest fu-

els during the fire season.¹⁰⁴ 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 1984–2015.¹⁰⁴ Littell et al. (2009, 2010, 2016)^{109, 110, 111} found 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.¹¹¹ found a clear link between increased drought and increased fire risk. Yoon et al.¹¹² 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.^{113, 114, 115} 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.¹¹⁶ projected substantial increases in forest fire frequency in the Greater Yellowstone ecosystem by mid-century under

the older SRES A2 emissions scenario, and further stated that years without large fires in the region will become extremely rare. Stavros et al.¹¹⁷ projected increases in very large fires (greater than 50,000 acres) across the western United States by mid-century under both the lower and higher scenarios (RCP4.5 and RCP8.5, respectively). Likewise, Prestemon et al.¹¹⁸ projected 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.¹¹⁰

Historically, wildfires have been less frequent and of smaller extent in Alaska compared to the rest of the globe.^{119, 120} Shortened land snow cover seasons and higher temperatures have made the Arctic more vulnerable to wildfire.^{119, 120, 121} 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 1959.¹²² 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 change¹²³ and is projected to increase by up to a factor of four by the end of the century under the mid-high scenario (RCP6.0).¹²¹ 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.^{119, 124} Thresholds in temperature and precipitation shape Arctic fire regimes, and

projected increases in future lightning activity imply increased vulnerability to future climate change.^{119, 121} Alaskan tundra and forest wildfires will *likely* increase under warmer and drier conditions^{124, 125} and potentially result in a transition into a fire regime unprecedented in the last 10,000 years.¹²⁶ Total area burned is projected to increase between 25% and 53% by the end of the century.¹²⁷

Boreal forests and tundra contain large stores of carbon, approximately 50% of the total global soil carbon.¹²⁸ Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric CO₂ and alter the carbon cycle if ecosystems change from higher to lower carbon densities.^{126, 128} 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 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 for-



est 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 Finding 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 Lettenmaier¹² and Mo and Lettenmaier³.

Major uncertainties

Record-breaking temperatures are well documented with low uncertainty.¹²⁹ 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 Finding 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 Finding 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 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 the higher scenario (RCP8.5), and the multimodel average exhibits no significant annual soil moisture increases anywhere on the planet.²

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 degrees 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.¹² 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 the higher scenario (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 Finding 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 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.⁴¹ 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.⁶⁶ This conclusion is also supported by a statistical downscaling result shown in Figure 3.1 of Walsh et al.³⁴ and Cayan et al.⁶⁷ and by the more recent statistical downscaling study of Klos et al.⁶⁸

Major uncertainties

The major uncertainty is not so much “if” but rather “how much” as changes to precipitation phases (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, are 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 warming in the western United States as GHG forcing increases. Warm-

ing 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 Finding 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*)

Description of evidence base

Observed changes are a mix of increases and decreases and are documented by Walsh et al.³⁴ 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 Finding 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. (western United States)¹⁰⁸ and Kasischke and Turetsky (Alaska)¹²² document the observed increases in fire statistics. Projections of West-erling et al. (western United States)¹¹⁶ and Young et al.¹²¹ 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 as to how well non-climatic confounding factors such as forest-ry 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 increase as a result of climate change. As a result, shifts in certain ecosystem types may occur.



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