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# Drought in the United States: Causes and Current Understanding

Updated November 9, 2017

**Congressional Research Service**
https://crsreports.congress.gov
R43407

CRS REPORT
Prepared for Members and
Committees of Congress

# Summary

Drought is a natural hazard with potentially significant economic, social, and ecological consequences. History suggests that severe and extended droughts are inevitable and part of natural climate cycles. Drought has for centuries shaped the societies of North America and will continue to do so into the future. The likelihood of extended periods of severe drought and its effects on 21st-century society in the United States raise several issues for Congress. These issues include how to respond to recurrent drought incidents, how to prepare for future drought, and how to coordinate federal agency actions, among other policy choices. Understanding what drought is and its causes, how it has affected North America in the past, and how drought may affect the United States in the future all bear on actions Congress may take to prepare for and mitigate the effects of drought.

The 2012-2016 drought in California and parts of other western states, and 16 years of dry conditions in the Southwest, have fueled congressional interest in drought and its near-term effects on water supplies and agriculture, as well as in long-term issues, such as drought forecasting and possible links between drought and human-induced climate change. Surface water conditions in California have recovered dramatically in 2017 from the effects of the drought, but some consequences, such as the decline in groundwater levels from increased pumping, likely will linger for years and may even be permanent. In response to the California drought, the 114th Congress enacted legislation (P.L. 114-322) that altered the authorities regarding how federal water infrastructure in the state is managed and how new water storage may be developed. In the 115th Congress, there is both interest in and concern about the federal role and funding for new water infrastructure to cope with the next drought and with hydrologic conditions that can quickly transition from drought to flood conditions.

Some scientists refer to severe drought as a recurring natural disaster in North America. Reconstructions of drought conditions that extend back over 1,000 years—based on observations, historical and instrumental records, and tree rings—illustrate that portions of the conterminous United States have experienced periods of severe and long-lasting drought termed *megadroughts*. For example, drought reconstructions from tree rings document that severe multi-decadal drought occurred in the American Southwest during the 13th century. These megadroughts have affected flows in major western rivers. For example, during the years 1130-1154, estimated Colorado River flows were less than 84% of normal. Recent data suggest that Colorado River flows since 2000 are approaching those previous lows—flows have been below average for 13 of the 16 years between 2000 and 2015.

Part of the country is almost always experiencing drought at some level. The land area affected by drought can vary widely by year and also within a particular year. In May 2017, only 3.8% of the total U.S. land area was affected by drought of at least moderate intensity. In contrast, in September 2012, 55% of the nation faced drought of moderate or greater intensity, and 35% of the country was under severe drought.

Predicting the intensity and duration of severe drought over a specific region is not currently possible more than a few months in advance because of the many factors that influence drought. Even though forecasting drought at the regional scale is difficult, understanding potential changes in long-term trends is important for water managers at all levels—federal, state, local, and tribal. Water project operations and state water allocations typically are based on past long-term hydrological trends; significant deviations from such trends may result in difficult challenges for water managers and water users alike.

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Drought can affect any region of the country, and can have severe and long-lasting impacts on agriculture, energy production, environment, health and safety, fishing, recreation, and many other facets of the economic and social well-being of communities. The likelihood of extended periods of severe drought and its effects on 21st-century society in the United States raise several issues for Congress. These issues include how to respond to recurrent drought incidents, how to prepare for future drought, and how to coordinate federal agency actions, among other policy choices. Although a discussion of these issues is beyond the scope of this report,[1] understanding what drought is and its causes, how it has affected North America in the past, and how drought may affect the United States in the future all bear on actions Congress may take to prepare for and mitigate the effects of drought.

This report discusses why drought occurs in the United States; how drought is defined (e.g., why drought in one region of the country is different from drought in another region); and how droughts are classified and reported (e.g., what is meant by moderate, severe, extreme, and exceptional drought). The report briefly describes periods of drought in the country's past that equaled or exceeded drought conditions experienced during the 20th century, and the effects of those droughts on major western rivers such as the Colorado. Lastly, the report discusses the possible influence of human-induced climate change on drought, and current limits on our understanding for forecasting droughts. The **Appendix** contains case histories of the 2012-2016 California drought, and previous major droughts in Texas and across the Midwest.

# Drought in the United States—Overview

Drought has affected portions of North America throughout history. Severe, long-lasting droughts may have been a factor in the disintegration of Pueblo society in the Southwest during the 13th century and in the demise of central and lower Mississippi Valley societies in the 14th through 16th centuries.[2] In the 20th century, droughts in the 1930s (Dust Bowl era) and 1950s were particularly severe and widespread. In 1934, 65% of the contiguous United States was affected by severe to extreme drought, resulting in widespread economic disruption and displacement of populations from the U.S. heartland—many relocating to California's Central Valley—and revealing shortcomings in agricultural and land-use practices.[3]

Today, the National Drought Mitigation Center (NDMC) monitors and reports on drought conditions across the nation. Drought conditions are broadly grouped into five categories: D0 (abnormally dry), D1 (moderate), D2 (severe), D3 (extreme), and D4 (exceptional).[4] Some part of

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[1] For a discussion of various policy issues regarding drought, see, for example, CRS In Focus IF10702, *Drought Response and Preparedness: Policy and Legislation*, by Nicole T. Carter and Charles V. Stern; CRS In Focus IF10133, *California Drought: Water Supply and Conveyance Issues*, by Charles V. Stern; CRS Report R44986, *Subtitle J of the Water Infrastructure Improvements for the Nation (WIIN) Act: Bureau of Reclamation and California Water Provisions*, by Charles V. Stern, Pervaze A. Sheikh, and Nicole T. Carter; CRS In Focus IF10565, *Federal Disaster Assistance for Agriculture*, by Megan Stubbs; CRS Report R43408, *Emergency Water Assistance During Drought: Federal Non-Agricultural Programs*, by Nicole T. Carter, Tadlock Cowan, and Joanna Barrett; among others.

[2] Edward R. Cook, et al., "North American drought: reconstructions, causes, and consequences," *Earth-Science Reviews*, vol. 81 (2007): pp. 93-134. Hereinafter, referred to as Cook et al., 2007.

[3] Donald A. Wilhite, et al., *Managing Drought: A Roadmap for Change in the United States* (Boulder, CO: The Geological Society of America, 2007), p. 12, at http://www.riversimulator.org/Resources/Policy/ManagingDroughtRoadmapForChangeInTheUnitedStates2006GSA.pdf.

[4] These categories are compiled in an index known as the U.S. Drought Monitor, which synthesizes various drought indices and impacts, and represents a consensus view between academic and federal scientists of ongoing drought conditions. See http://droughtmonitor.unl.edu/.

the country is almost always experiencing drought at some level. Since 2000, some portion of the land area of the United States has experienced drought of at least moderate intensity (D1) each year (**Figure 1**).[5] The land area affected by drought can vary widely by year and also within a particular year. For example, in May 2017, only 3.8% of the total U.S. land area was affected by drought of at least moderate intensity (D1). In contrast, in September 2012, 55% of the nation faced drought of at least moderate intensity, and 35% of the country was under severe drought (D2) conditions at that time. Based on weekly estimates of drought conditions since 2000, on average about 26% of the land area across the United States experiences at least moderate intensity in any given year (see the horizontal blue bar in the Moderate [D1] column of **Figure 1**).

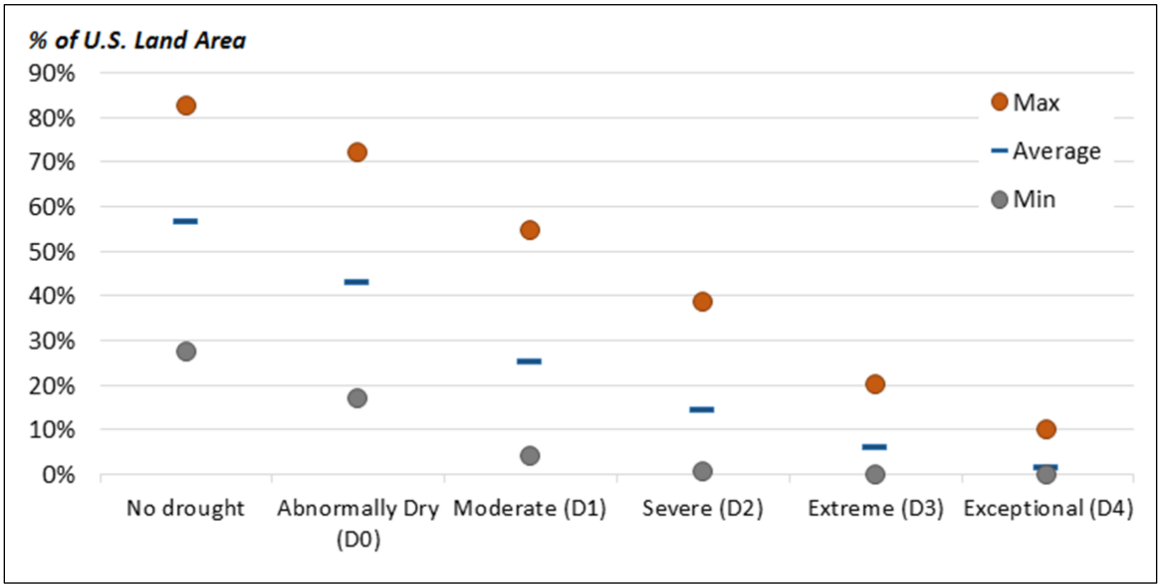
There is particular concern about locations experiencing the most intense drought conditions: *extreme* and *exceptional* drought. Nearly every year, extreme drought (D3) affects some portion of the country. Since 2000, extreme drought or drier conditions have affected approximately 6.5% of the nation on average (**Figure 1**).[6] Since 2000, exceptional drought (D4) conditions have affected approximately 1.4% of the nation on average. Of particular note were the conditions between June 2011 and October 2011: exceptional drought (D4) occurred over the largest land area—greater than 9%—during those months over the period starting January 2000 until present, with the affected areas concentrated in Texas. The following year, during August 2012, extreme and exceptional drought extended over 20% of the country and was concentrated in the central United States.

[5] Based on NDMC data collected since 2000, U.S. Drought Monitor at the NDMC, http://droughtmonitor.unl.edu/Data.aspx.

[6] In some years or months, however, no part of the country was under extreme or exceptional drought. For example, from January 2000 through early April 2000, extreme or exceptional drought did not affect any portion of the country. More recently, no part of the country was under exceptional drought conditions from late January 2017 through mid-July 2017.

**Figure 1. Average, Minimum, and Maximum Percentage of the United States, by Drought Category**

(January 4, 2000, through October 17, 2017)




**Source:** U.S. Drought Monitor, Data, Comprehensive Statistics, http://droughtmonitor.unl.edu/Data/DataDownload/ComprehensiveStatistics.aspx. Modified by CRS.

**Note:** Including Alaska, Hawaii, and Puerto Rico.

# What Is Drought?

Drought has a number of definitions; the simplest may be a deficiency of precipitation over an extended period of time, usually a season or more.[7] Conceptually, it may be easier to understand drought through its impacts. For example, when evaluating the impact to agriculture, drought could be defined as a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield.[8] Drought is usually considered relative to some long-term average condition or balance between precipitation, evaporation, and transpiration by plants (evaporation and transpiration are typically combined into one term: evapotranspiration).[9] An imbalance could result from a decrease in precipitation, an increase in evapotranspiration (from drier conditions, higher temperatures, higher winds), or both. It is important to distinguish between drought, which has a beginning and an end, and aridity, which is restricted to low-rainfall regions and is a relatively permanent feature of an area's climate (e.g., deserts are regions of relatively permanent aridity).[10]

Higher demand for water for human activities and vegetation in areas of limited water supply increases the severity of drought. For example, drought during the growing season likely would

[7] NDMC, "What Is Drought?" at http://www.drought.unl.edu/DroughtBasics/WhatisDrought.aspx.

[8] Ibid.

[9] Evapotranspiration may be defined as the loss of water from a land area through transpiration from plants and evaporation from the soil and surface water bodies such as lakes, ponds, and man-made reservoirs.

[10] Permanently arid conditions reflect the *climate* of the region, which is the composite of the day-to-day weather over a longer period of time. Climatologists traditionally interpret climate as the 30-year average. See NDMC, "What is Climatology?" at http://www.drought.unl.edu/DroughtBasics/WhatisClimatology.aspx.

be considered more severe—in terms of its impacts—than similar conditions when cropland lies dormant. For policy purposes, drought often becomes an issue when it results in a water supply deficiency. During these deficiencies, less than the average amount of water is available for irrigation, municipal and industrial (M&I) supply, energy production, preservation of endangered species, and other needs. These impacts can occur through multiple mechanisms, such as

- decreased precipitation and soil moisture affecting dryland farming;
- low reservoir levels reducing allocations for multiple purposes (including irrigation, navigation, energy production, recreation, fish and wildlife needs, and other water supplies);
- low stream flows limiting withdrawals for multiple purposes, including M&I supplies, among others; and
- decreased exchange of water in lakes resulting in water quality problems limiting recreation (e.g., blue-green algae restrictions in multiple lakes in Oklahoma and Texas during 2011 and 2012 drought conditions).

Drought also can relate and contribute to other phenomena, such as wildfires and heat waves.[11]

## Drought Classification

To assess and classify the intensity and type of drought, certain measures, or drought indicators, are typically used. Drought intensity, in turn, can be a trigger for local, state, and federal responses to drought.[12] The classification of drought intensity, such as that shown in **Figure 3**, may depend on a single indicator or several indicators, often combined with expert opinion from the academic, public, and private sectors. For example, the U.S. Drought Monitor (**Figure 2**) uses five key indicators, together with expert opinion, with indicators to account for conditions in the West where snowpack is relatively important and with other indicators used mainly during the growing season.[13]

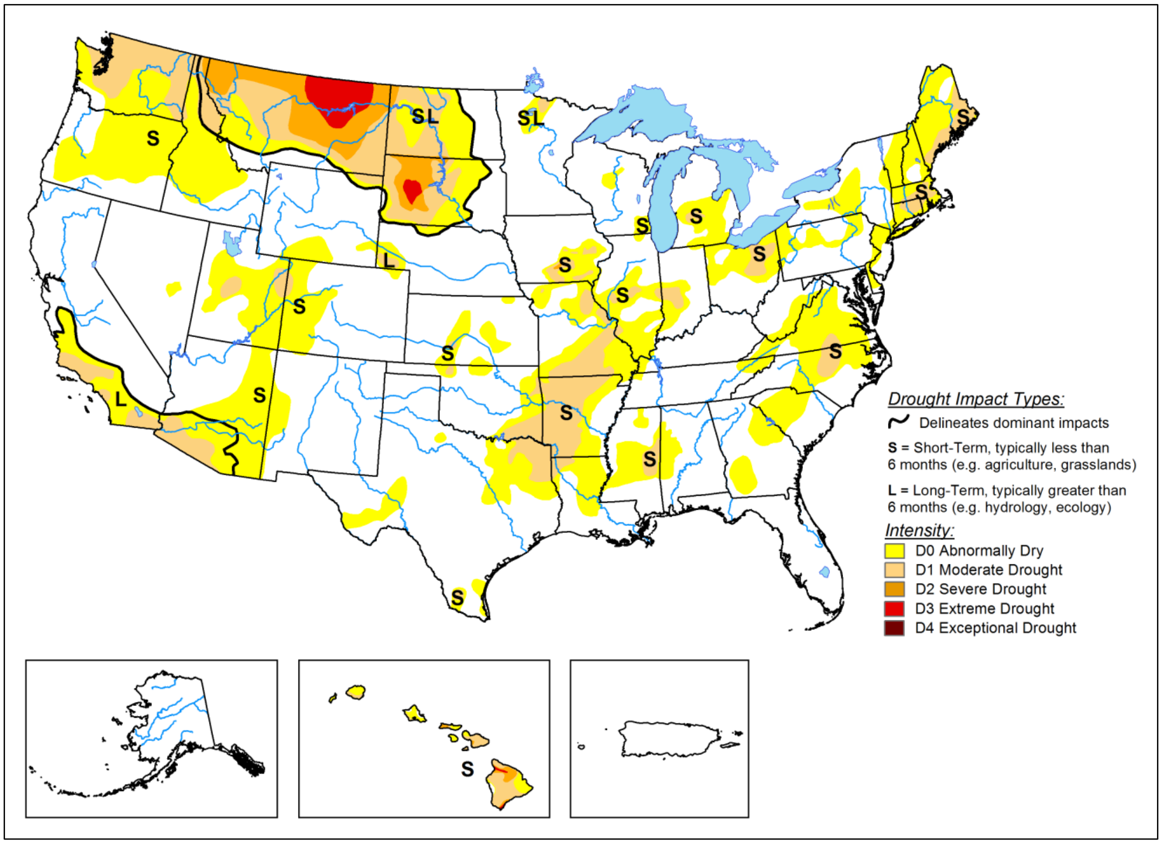
[11] For more on wildfire, see CRS In Focus IF10732, *Federal Assistance for Wildfire Response and Recovery*, by Katie Hoover; and CRS Report R44966, *Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress*, by Katie Hoover and Bruce R. Lindsay; and others.

[12] For example, the Farm Service Agency (FSA) Livestock Forage Disaster Program uses the U.S. Drought Monitor to help determine eligibility for assistance during drought. See https://www.fsa.usda.gov/Internet/FSA_File/lfp_long_fact_sht_2014.pdf.

[13] The five key indicators include the Palmer Drought Index, the Climate Prediction Center soil moisture model, U.S. Geological Survey weekly streamflow data, the Standardized Precipitation Index, and short- and long-term drought indicator blends. For a discussion of drought indicators, see NDMC, see http://droughtmonitor.unl.edu/AboutUSDM/DroughtClassification.aspx.

**Figure 2. Example of a U.S. Drought Monitor Map**

(October 17, 2017)



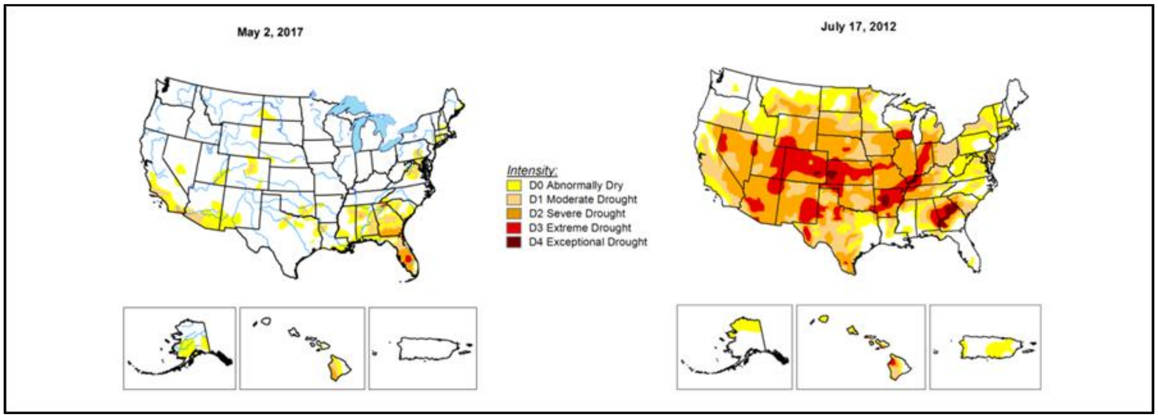

**Source:** U.S. Drought Monitor, http://droughtmonitor.unl.edu/CurrentMap.aspx. Modified by CRS.

**Note:** U.S. Drought Monitor national maps are updated weekly.

The U.S. Drought Monitor intensity scheme—D0 to D4—is used to depict broad-scale conditions but not necessarily drought circumstances at the local scale. For example, the regions depicted as red in **Figure 2** faced extreme drought conditions for the week of October 17, 2017, but they may have contained local areas and individual communities that experienced less (or more) severe drought.

**Figure 3** illustrates how drought can stretch across nearly the entire nation, or only affect a comparatively small region. On July 17, 2012, abnormally dry or drought conditions covered roughly 72% of the United States, with 35% of the nation experiencing severe drought or worse. In contrast, on May 2, 2017, about 17% of the country faced abnormally dry or drought conditions, and only 4% was classified as experiencing severe drought or worse.

**Figure 3. Comparing Widespread Drought and Regional Drought**




**Source:** U.S. Drought Monitor, http://droughtmonitor.unl.edu/. Modified by CRS.

## Drought Is Relative

Drought and "normal" conditions can vary considerably from region to region. For example, the U.S. Drought Monitor shows that Augusta, GA, faced severe drought in July 2012 (right side of Figure 3). Similarly, the city of Colorado Springs, CO, also was in severe drought during the same time period. However, Colorado Springs receives on average a total of 7.63 inches of precipitation over the six-month period of January through June.[14] In contrast, Augusta receives on average of 22.2 inches of precipitation over the same period.[15] During the first six months of 2012, Augusta received 13.28 inches of precipitation, only 60% of its average amount. However, that same amount—13.28 inches—would constitute almost 174% of the amount Colorado Springs typically receives over the same period. Both cities faced severe drought in July 2012, but what is "normal" for Augusta is different from what is "normal" for Colorado Springs.[16]

To deal with these differences, meteorologists use the term *meteorological drought*—usually defined as the degree of dryness relative to some average amount of dryness and relative to the duration of the dry period. Meteorological drought is region-specific because atmospheric conditions creating precipitation deficiencies vary from region to region, as described above for Augusta and Colorado Springs.

## Drought Is Multifaceted

In addition to the color-coded D0-D4 designations, U.S. Drought Monitor maps often include an "S" and "L" designation to provide additional information about the nature of drought (**Figure 2**). The "S" designation is intended to indicate existence of short-term effects: a combination of different drought indices that approximates responses to precipitation over days up to a few months. These effects would include impact to agriculture, topsoil moisture, unregulated streamflows, and aspects of wildfire danger. The "L" designation indicates the existence of long-

[14] U.S. Climate Data, *Climate Colorado Springs–Colorado*, https://www.usclimatedata.com/climate/colorado-springs/colorado/united-states/usco0078.

[15] U.S. Climate Data, *Climate Augusta–Georgia*, https://www.usclimatedata.com/climate/augusta/georgia/united-states/usga0032.

[16] Also, while drought may affect one region at a given time, other regions may experience too much water, and possibly flooding, at the same time. Water-related disasters, drought and flood, may occur simultaneously in different regions of the country.

term effects; it approximates responses to precipitation over several months up to a few years. These effects would include reservoir levels, groundwater, and lake levels. As **Figure 2** shows, some regions of the United States include both an "S" and "L" designation, indicating that in early October 2017 those regions are experiencing both short- and long-term impacts.

# What Causes Drought in the United States?

The immediate cause of drought is

> the predominant sinking motion of air (subsidence) that results in compressional warming or high pressure, which inhibits cloud formation and results in lower relative humidity and less precipitation. Regions under the influence of semipermanent high pressure during all or a major portion of the year are usually deserts, such as the Sahara and Kalahari deserts of Africa and the Gobi Desert of Asia.[17]

Prolonged droughts occur when these atmospheric conditions persist abnormally for months or years over a certain region.[18]

Predicting drought is difficult because the ability to forecast surface temperature and precipitation depends on a number of key variables, such as air-sea interactions, topography, soil moisture, land surface processes, and other weather system dynamics.[19] Scientists seek to understand how all these variables interact and to further the ability to predict sustained and severe droughts beyond a season or two, which is the limit of drought forecasting abilities today.

In the tropics, a major portion of the atmospheric variability over months or years seems to be associated with variations in sea surface temperatures (SSTs). Since the mid- to late 1990s, scientists have increasingly linked drought in the United States to SSTs in the tropical Pacific Ocean. Cooler-than-average SSTs in the eastern tropical Pacific region—"La Niña-like" conditions—have been shown to be correlated with persistently strong drought conditions over parts of the country, particularly the West.[20] A number of studies have made the connection between cooler SSTs in the eastern Pacific Ocean and the 1998-2004 western drought,[21] three widespread and persistent droughts of the late 19th century,[22] and past North American megadroughts that recurred between approximately 900 and 1300 A.D.[23] The precolonial megadroughts apparently lasted longer and were more extreme than any U.S. droughts since 1850, when instrumental records began. Some modeling studies suggest that within a few decades the western United States may again face higher base levels of dryness, or aridity, akin to the 900-1300 A.D. period.[24] The Southwest as a whole, in fact, has experienced a drought of fluctuating

[17] See NDMC, "Predicting Drought: High Pressure," at http://drought.unl.edu/DroughtBasics/PredictingDrought.aspx.

[18] Ibid.

[19] Ibid.

[20] Cook et al., 2007.

[21] Martin Hoerling and Arun Kumar, "The perfect ocean for drought," *Science*, vol. 299 (January 31, 2003), pp. 691-694. Hereinafter referred to as Hoerling and Kumar, 2003.

[22] Celine Herweiger, Richard Seager, and Edward Cook, "North American droughts of the mid to late nineteenth century: A history, simulation and implication for Mediaeval drought," *The Holocene*, vol. 15, no. 2 (January 31, 2006), pp. 159-171. Hereinafter referred to as Herweiger et al., 2006.

[23] Cook et al., 2007.

[24] Richard Seager et al., "Model projections of an imminent transition to a more arid climate in southwestern North America," *Science*, vol. 316 (May 25, 2007): pp. 1181-1184.

severity for the past 16 years, possibly foreshadowing conditions that could become more common in the coming decades.[25]

Although the relationship between cooler-than-normal eastern tropical Pacific SSTs (La Niña-like conditions) and drought in the United States is becoming more firmly established, meteorological drought is probably never the result of a single cause. What is emerging from the scientific study of drought is an improved understanding of global linkages—called teleconnections by scientists—among interacting weather systems, such as the El Niño-Southern Oscillation, or ENSO. (See box for a description of ENSO.) For example, some scientists link La Niña conditions between 1998 and 2002 to the occurrence of near-simultaneous drought in the southern United States, Southern Europe, and Southwest Asia.[26]

### El Niño-Southern Oscillation (ENSO)

Under normal conditions, the trade winds blow toward the west in the tropical Pacific Ocean,[27] piling up the warm surface waters so that the ocean surface off Indonesia is one-half meter higher than the ocean off Ecuador. As a result, deep and cold water flows up to the surface (upwelling) off the west coast of South America. The upwelling waters are 8 degrees Celsius (14.4 degrees Fahrenheit) cooler than waters in the western Pacific. During an El Niño event, the trade winds relax, upwelling off South America weakens, and sea surface temperatures rise. The El Niño events occur irregularly at intervals of 2-7 years, and they typically last 12-18 months. These events often occur with changes in the Southern Oscillation, a see-saw of atmospheric pressure measured at sea level between the western Pacific and Indian Ocean, and the eastern Pacific. Under normal conditions, atmospheric pressure at sea level is high in the eastern Pacific and low in the western Pacific and Indian Oceans. As implied by its name, the atmospheric pressure oscillates, or see-saws, between east and west, and during El Niño the atmospheric pressure builds up to abnormally high levels in the western tropical Pacific and Indian Oceans—the El Niño-Southern Oscillation, or ENSO. During a La Niña event, the situation is reversed: abnormally high pressure builds up over the eastern Pacific, the trade winds are abnormally strong, and cooler-than-normal sea surface temperatures occur off tropical South America. La Niña-like conditions have been shown to be correlated with persistently strong drought conditions over parts of the country, particularly the West. Scientists use the terms *ENSO* or *ENSO cycle* to include the full range of variability observed, including both El Niño and La Niña events.

It is widely recognized that ENSO drives substantial variability in rainfall and severe weather, including drought. Some recent studies indicate that human-forced changes in climate may alter the spatial pattern of ENSO-driven variability in precipitation and temperature, for example increasing El Niño drying in the western Pacific Ocean and increasing rainfall in the central and eastern equatorial Pacific. Other studies, including a 2014 Intergovernmental Panel on Climate Change (IPCC) report, point to a lack of consensus over global warming-related changes in the timing, intensity, and spatial pattern of El Niño-driven events, and they suggest that it is not yet possible to say that ENSO activity will be enhanced or damped and whether the frequency of ENSO events will change. The 2014 IPCC report, in fact, states that changes in ENSO intensity for the 21st century are uncertain, but that there is *high confidence* that ENSO will remain the dominant mode of natural climate variability in the tropical Pacific, with global effects in the 21st century. Some scientists share the opinion that the instrumental record is too short to document the spectrum of ENSO variability and there is little knowledge of how variability alters with changes in the climate.

**Sources:** Tropical Ocean Atmosphere Project, Pacific Marine Environmental Laboratory, at http://www.pmel.noaa.gov/tao/proj_over/ensodefs.html; Scott Power et al., "Robust Twenty-First-Century Projections of El Niño and Related Precipitation Variability," Nature, published online October 13, 2013; J. H. Christensen et al., "Climate Phenomena and their Relevance for Future Regional Climate Change," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* T. F. Stocker et al., eds., Cambridge University Press, Cambridge, United Kingdon and New York, NY; Mat Collins et al., "The Impact of Global Warming on the Tropical Pacific Ocean and El Niño," *Nature Geoscience*, published online May 23, 2010; Pascale Braconnot et al., "Editorial: El Niño-Southern

[25] Richard Seager, Columbia University, quoted in Justin Gillis, "Science Linking Drought to Global Warming Remains Matter of Dispute," *New York Times*, February 16, 2014, p. A11.

[26] Hoerling and Kumar, 2003.

[27] Trade winds occur as warm air around the equator rises and flows north (in the Northern Hemisphere) or south (in the Southern Hemisphere), and is deflected by the Coriolis effect. The results are steady winds that blow roughly the same direction in a given latitude all the time. Ships historically took advantage of the trade winds to sail between Europe and the Americas.

Oscillation-Observations and Modeling," *PAGES news*, vol. 21, no. 2, August 2013, p. 48.

# Prehistorical and Historical Droughts in the United States

Some scientists refer to severe drought as "the greatest recurring natural disaster to strike North America."[28] That claim stems from a reconstruction of drought conditions that extends back over 1,000 years, based on observations, historical and instrumental records where available, and tree-ring records or other proxies in the absence of direct measurements.[29] What these reconstructions illustrate is that the conterminous United States has experienced periods of severe and long-lasting drought in the western states and also in the more humid East and Mississippi Valley. Drought reconstructions from tree rings document that severe multi-decadal drought occurred in the American Southwest during the 13th century, which anthropologists and archeologists suspect profoundly affected Pueblo society. Tree-ring drought reconstructions also document severe drought during the 14th, 15th, and 16th centuries in the central and lower Mississippi Valley, possibly contributing to the disintegration of societies in that region.[30]

More recently, a combination of tree-ring reconstructions and other proxy data, historical accounts, and some early instrumental records identify three periods of severe drought in the 19th century: 1856-1865 (the "Civil War drought"), 1870-1877, and 1890-1896.[31] The 1856-1865 drought was centered on the Great Plains and Southwest and was the most severe drought to strike the region over the last two centuries, according to one study.[32] The 1890-1896 drought coincided with a period in U.S. history of federal encouragement of large-scale efforts to irrigate the relatively arid western states under authority of the Carey Act.[33] At that time, Congress debated a larger federal role in western states' irrigation. This debate led to the Reclamation Act of 1902, which was enacted largely to "reclaim the arid West."[34]

In the 20th century, the 1930s "Dust Bowl" drought and the 1950s Southwest drought are commonly cited as the two most severe large-scale, multiyear droughts in the United States.[35] In addition, the 1987-1989 drought was widespread and severe, mainly affecting the Great Plains and California but also instigating extensive western forest fires, including the Yellowstone fire of

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[28] Cook et al., 2007.

[29] Proxies are indirect measurements typically used where direct measurements are unavailable. Tree rings can be used as a proxy for measuring dryness and drought. Similarly, ice cores from glaciers and polar caps can be used as proxies for measuring atmospheric temperatures and carbon dioxide concentrations from thousands of years ago.

[30] Cook et al., 2007.

[31] Herweiger et al., 2006.

[32] Ibid.

[33] The Carey Act, signed into law on August 18, 1894 (Chapter 301, §4, 28 Stat. 422), initially made available up to 1 million acres of federal land in each state, provided that the state met several requirements for the eventual development of water resources for reclamation.

[34] Under the Reclamation Act of 1902, the federal government constructed hundreds of dams, reservoirs, and related facilities to provide water to local farmers to "reclaim" the arid West through irrigation of arid lands. See U.S. Bureau of Reclamation, *Brief History of the Bureau of Reclamation*, July 2000, https://www.usbr.gov/gp/employment/neo/tab1/briefhis.pdf.

[35] Falko K. Fye, David W. Stahle, and Edward R. Cook, "Paleoclimate Analogs to Twentieth Century Moisture Regimes Across the United States," *Bulletin of the American Meteorological Society*, vol. 84 (2003), pp. 901-909.

1988. According to several studies, however, the 19th and 20th century severe droughts occurred during a regime of relatively less arid conditions, especially when compared with the average aridity in the American West during the 900 to 1300 A.D. "megadroughts." One study indicates that the drought record from 900 to 1300 A.D. shows similar variability—drought periods followed by wetter periods—compared with today, but the average climate conditions were much drier and led to more severe droughts.[36]

## Droughts Affect Flows in Major Western Rivers

Paleoclimate reconstructions using precipitation proxies like tree rings have enabled researchers to estimate and plot the history of flows for important western rivers such as the Colorado River in the Rockies, the Sacramento and San Joaquin Rivers draining the Sierra Nevada Mountains in California, and the Klamath River draining southern Oregon and northern California.[37]

### Colorado River: Approaching Historic Low Flows?

The Colorado River basin has experienced generally lower-than-normal flows for the past 16 years (based on roughly 100 years of observed flow records), affecting lake levels in Lake Mead and Lake Powell. Comparing previous low-flow periods compiled from other sources may indicate what could be in store for the Colorado River and its major storage components. For example, a 2007 study showed that for the years 1130-1154, estimated Colorado River flows were less than 84% of normal (with *normal* defined as the mean annual flow between 1906 and 2004, about 15 million acre-feet, or MAF, measured at Lee's Ferry, AZ).[38] Prior to the 2000-2016 dry period, the lowest 25-year mean of observed flows occurred between 1953 and 1977, but Colorado River flows were 87% of normal, still higher than the 1130-1154 period.[39] In addition, the 25-year period of exceptionally low flow in the mid-1100s occurred within a generally dry 62-year period, 1118-1179, that was characterized by a series of multiyear low-flow pulses and the absence of years with flow much above 15 MAF.

Whether the current dry spell in the Colorado basin is creating low-flow levels on the Colorado River that are similar to the low-flow levels experienced in the mid-1100s—and how likely it is that the dry period could extend for years or even decades more—remains an outstanding question. Flow data seem to suggest that Colorado River flows since 2000 are approaching those historic low levels. According to Bureau of Reclamation data, during 13 of the 16 years between 2000 and 2015, the Colorado River flows at Lee's Ferry were below the 1906-2015 average, and the average amount of flow calculated for the 16-year period was about 12.4 MAF, or 83% of the 1906-2015 average.[40] This indicates that Colorado River flows since 2000 equal or are slightly

[36] For example, one report showed that 42% of the area studied in the American West was affected by drought during the years 900 to 1300, versus 30% between 1900 and 2003, a 29% reduction in the average area affected by drought between the two periods. See Cook et al., 2007.

[37] See David M. Meko, et al., "Medieval Drought in the Upper Colorado River Basin," *Geophysical Research Letters*, vol. 34, no. 10 (May 24, 2007); and David M. Meko, Connie A. Woodhouse, and Ramzi Touchan, *Klamath/San Joaquin/Sacramento Hydroclimate Reconstructions from Tree Rings*, Draft Final Report to California Department of Water Resources, February 7, 2014, at http://www.water.ca.gov/waterconditions/docs/tree_ring_report_for_web.pdf.

[38] Meko et al., 2007.

[39] Ibid.

[40] U.S. Bureau of Reclamation, Lower Colorado Region, "Colorado River Basin Natural Flow and Salt Data-Current Natural Flow Data 1906-2015," at http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html. Data from the spreadsheet provided by Reclamation on that website were extracted from the AnnualWYTotal Natural Flow worksheet, column U, per recommendation of Dr. David Meko, University of Arizona, Laboratory of Tree-Ring

lower than flows during the 1130-1154 period. That outcome would suggest that dry conditions since 2000 may have rivaled the extreme dry periods during medieval times.[41]

### California Rivers: Low Flows in the 16th and 20th Centuries

For the Sacramento and San Joaquin Rivers, both of which are critical to California's water supply and the agricultural production in the Central Valley, paleoclimate reconstructions have shown that low flows in the 1920s and 1930s rank among the most extreme in the context of the last millennium.[42] However, 1580 was the driest single year. In 1580, flows on the Sacramento River were only 45% of the Sacramento River flow in 1924, and flows on the San Joaquin River were only 54% of the San Joaquin River flows for 1924, the second-driest single year of the entire reconstructed period. Thus, it appears that despite the severity of drought in the 1920s and 1930s, and more recent California droughts in 1975 to 1977 and in the late 1980s to early 1990s, flows on both rivers were lower during the 1500s due to drought. An outstanding question is whether the 2012-2016 California drought affected flows on the Sacramento and San Joaquin Rivers to a similar extent as did the 1920s-1930s drought or even the exceptionally dry year in 1580 (see **Appendix** for a discussion of the California drought).

## Drought and Climate Change

The relationship between climate change and future trends in droughts is complex, and the scientific understanding of this relationship is evolving. In 2007, the Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report, which stated that, globally, very dry areas have more than doubled since the 1970s due to a combination of ENSO[43] events and global surface warming.[44] The 2007 IPCC report added that very wet areas declined by about 5% globally. The report asserted that documented trends in severe droughts and heavy rains showed that hydrological conditions were becoming more intense in some regions.[45]

In 2012, the IPCC issued a new report stating that "there are still large uncertainties regarding observed global-scale trends in droughts."[46] The newer report noted that although its earlier assessment had stated that very dry areas have more than doubled since the 1970s, that observation was based largely on only one study, which relied on a measurement primarily related to temperature, not moisture.[47] A different study, which looked at soil moisture simulations, found

Research, personal communication, October 19, 2017. Documentation for the natural flow calculation methods is available at http://www.usbr.gov/lc/region/g4000/NaturalFlow/NaturalFlowAndSaltComptMethodsNov05.pdf.

[41] The 1130-1154 low-flow period lasted 25 years, so those flows and the current dry period and accompanying low flows for the 2000-2015 16-year period in the upper Colorado River are not directly comparable. For comparison, Colorado River flows at Lee's Ferry for the 25-year period between 1991 and 2015 were 92% of the 1906-2015 average, higher than the average flows during the 25-year period from 1130 to 1154, which averaged 84% of the 1906-2015 average.

[42] Meko et al., 2014.

[43] A discussion of ENSO is provided in the text box entitled "El Niño-Southern Oscillation (ENSO)," above.

[44] S. D. Solomon et al., "Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change," 2007, Cambridge University Press, Cambridge, United Kingdom and New York, NY. Hereinafter referred to as IPCC 2007.

[45] Ibid., Summary for Policy Makers.

[46] C. B. Field et al., IPCC, "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation," 2012, Cambridge University Press, Cambridge, United Kingdom and New York, NY, p. 170. Hereinafter referred to as C. B. Field et al., IPCC, 2012.

[47] The 2007 IPCC fourth assessment noted that "difficulties in the measurement of precipitation remain an area of

that global trends in drought duration, intensity, and severity predominantly were *decreasing*, not increasing, but with strong regional variation.[48]

The 2012 IPCC report assigned medium confidence that there has been an overall slight tendency toward *less* dryness in North America (i.e., a wetting trend with increasing soil moisture and runoff).[49] It noted that the most severe droughts in the 20th century occurred in the 1930s and 1950s, where the 1930s drought was the most intense and the 1950s drought was the most persistent. In comparison to the severe megadroughts that occurred in North America hundreds and thousands of years ago, as documented using paleoclimate evidence (discussed earlier in this report), these recent droughts were not unprecedented, according to the 2012 IPCC report.

The 2012 IPCC report concluded that despite new studies that have furthered the understanding of mechanisms leading to drought, there is still limited evidence or ability to attribute observed changes. The IPCC assessed that there was medium confidence that anthropogenic influence has contributed to changes in drought patterns in the second half of the 20th century, but gave low confidence to the attribution of changes in drought patterns at the regional level.[50] The report noted that some regions of the world have experienced trends toward more intense and longer droughts, such as southern Europe and West Africa. In other regions, such as central North America and northwestern Australia, droughts have become less frequent, less intense, or shorter.[51]

In 2014, the IPCC released its most recent climate assessment, which stated that for North America, decreases in snowpack already are influencing seasonal stream flows. However, the report had medium-to-high confidence that recent droughts (and floods, and changes in mean streamflow conditions) cannot yet be attributed to climate change.[52] Further, the report stated that it is not yet possible to attribute changes in drought frequency in North America to anthropogenic climate change.[53] The report noted that changes in these events, however, may be indicative of future conditions.

## Did Human-Induced Climate Change Cause the 2012-2016 California Drought?

Two studies published in late 2014 and one published in 2016 provide examples of the ongoing scientific discussion about whether and how emissions of heat-trapping greenhouse gases by human activities influenced the California drought. All three studies found that although the lack of precipitation experienced during this period was within the expected range of variability based

concern in quantifying the extent to which global- and regional-scale precipitation has changed." IPCC 2007, *Changes in Surface Climate: Precipitation, Drought and Surface Hydrology*, chapter 3, section 3.3.1.

[48] C. B. Field et al., IPCC, 2012, p. 170.

[49] According to the report, confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence and on the degree of agreement. Confidence is expressed qualitatively: low, medium, high.

[50] C. B. Field et al., IPCC, 2012, p. 172.

[51] The IPCC report was referring primarily to hydrological drought and not to water demand, water infrastructure, and other factors that enhance the effects of hydrological drought.

[52] P. Romero-Lankao et al., *North America*, Intergovernmental Panel on Climate Change, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge, United Kingdom, and New York, New York, 2014, pp. 1443-1444, at http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap26_FINAL.pdf.

[53] Ibid., p. 1456.

on historical norms, the higher temperatures experienced (which exacerbated the effects of drought) may be due to climate change. These studies are discussed in more detail below.

One study claimed that the drought was the most severe in California's history over the past 1,200 years.[54] The study stated that diminished snowpack, streamflows, and reservoir levels resulted in a convergence of reduced surface water supply with increased demand, a combination that appears unique in California's history. The study stated that 2014 was the worst single drought year in at least the last 1,200 years in California but that it was not the driest year (in terms of precipitation). What made 2014 stand out was the combination of lack of precipitation and record high temperatures, resulting in extreme dryness according to a soil-moisture metric known as the Palmer Drought Severity Index (PDSI).[55] Attributing a human influence is more tenuous, according to the study, as attribution of a human influence in the form of greenhouse gases on California rainfall and Pacific storm tracks is ambiguous. The study, however, stated that "projections for a continued trend toward higher mean and extreme temperatures are robust." Further, the study linked the future warming to human activities, claiming that "future 'hot' droughts driven by increasing temperatures due to anthropogenic emissions of greenhouse gases ... are assured."[56]

Another study also published in 2014 found that the 2012-2014 dry conditions were not without precedent in California's history. The study found no clear trend toward wetter or drier conditions over the past 120 years in California.[57] It noted that the impacts of lack of precipitation were exacerbated by warm temperatures and that November 2013 through April 2014 was the warmest winter half-year on record.[58] This second study focused on the influence of sea surface temperatures (SSTs) on atmospheric behavior (SST forcing), and examined the role of natural atmospheric variability together with SST forcing as factors influencing the California drought. In its examination of the causes of the drought, the study observed that, generally, dry California winters arise from internal atmospheric variability, but that the 2012-2014 winters also contained a component of SST forcing. The study noted that many climate model projections show a future *increase* in California precipitation over the midwinter and that "the recent severe all-winter rainfall deficit is thus not a harbinger of future precipitation change."[59] However, this second study also stated that, in the future, California may experience a net surface moisture deficit due to the projected increase in evapotranspiration, driven by warmer temperatures—the effect of which would offset and exceed the projected increase in precipitation. Both studies appear to support that same prediction.

A 2016 study also agreed that high temperatures associated with the California drought reflect increasing greenhouse gases, but noted that the low precipitation during the drought was within

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[54] Daniel Griffin and Kevin J. Anchukaitis, "How Unusual is the 2012-2014 California Drought?," *Geophysical Research Letters*, published online December 3, 2014, DOI: 10.1002/2014GL062433. Hereinafter, Griffin and Anchukaitis, 2014.

[55] For a description of the PDSI, see the National Drought Mitigation Center, at http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro/PDSI.aspx.

[56] Griffin and Anchukaitis, 2014.

[57] Richard Seager et al., *Causes and Predictability of the 2011-2014 California Drought*, National Oceanic and Atmospheric Administration, Assessment Report by the NOAA Drought Task Force, December 2014, http://cpo.noaa.gov/sites/cpo/MAPP/Task%20Forces/DTF/californiadrought/california_drought_report.pdf (hereinafter, Seager et al., 2014). The study dates the beginning of the drought as November 2011. This falls within the 2012 water year (defined as October through September). For the purposes of this CRS report, the beginning of the California drought is referred to as 2012.

[58] California receives most of its precipitation during the winter and early spring months, November through April.

[59] Seager et al., 2014.

bounds of past natural variability.[60] The study examined past climate data, and indicated a persistent relationship between SST shifts, past climate warming, and decades or longer periods of California aridity. A pair of 2016 modeling studies[61] examined how future greenhouse gas warming may affect atmospheric rivers,[62] which are critical sources of precipitation for California. The modeling results indicate that by the end of the century, under a greenhouse warming scenario, the frequency of ARs may change only slightly, but the duration and the intensity of precipitation may increase, and the track of the ARs may shift southward.

**2017 California Wildfires**

The northern California wildfires in early October 2017 were unusually widespread and severe, prompting questions about possible linkages to the 2012-2016 California drought. Although northern California was not classified as under drought conditions in the region of wildfire outbreaks (see right-hand map of **Figure A3**), hot and dry conditions in late summer into early October dried out vegetation that provided fuel for the fires. Some commentators reported that wet conditions during winter and spring, which ended the five-year drought, also created conditions leading to the abundant vegetation, which subsequently dried out during hot weather in late summer, providing ample fuel for the October wildfires.[63] Hot and dry conditions were exacerbated by strong, dry, seasonal winds, called Diablo winds,[64] which flow west over the Sierras and desert regions downslope into the San Francisco Bay region and Napa Valley where the wildfires were fiercest.

The twinning of dry, abundant fuels and seasonal Diablo winds sparked conditions that led to the northern California wildfires in 2017. The swiftly moving fires, combined with the abundance of structures and communities in their path, created the deadly and destructive natural disaster. It does not appear that the 2012-2016 drought had any direct influence on the wildfires, although the relationship between drought and wildfires is complex and an active area of research. Future drought trends and what those trends may imply about wildfires in the United States and globally, and any linkage to climate change, are also an area of active research.

**Source:** Iowa State University, Iowa Environmental Mesonet, *Area Forecast Discussion*, October 9, 2017, https://mesonet.agron.iastate.edu/wx/afos/p.php?dir=next&pil=AFDMTR&e=201710100018.

# Drought Forecasts for the United States

Predicting the intensity and duration of severe drought over a specific region is not currently possible more than a few seasons in advance because of the many factors that influence drought. Nevertheless, some modeling studies suggest that a transition to a more arid average climate in

[60] Glen M. MacDonald et al., "Prolonged California Aridity Linked to Climate Warming and Pacific Sea Surface Temperatures," *Nature Scientific Reports*, vol. 6, no. 33325 (September 15, 2016), http://www.nature.com/srep/2016/160915/srep33325/full/srep33325.html.

[61] Christine A. Shields and Jeffrey T. Kiehl, "Simulating the Pineapple Express in the Half Degree Community Climate System Model, CCSM4," *Geophysical Research Letters*, vol. 43 (July 28, 2016), pp. 7767-7773; and Christine A. Shields and Jeffrey T. Kiehl, "Atmospheric River Landfall-Latitude Changes in Future Climate Simulations," *Geophysical Research Letters*, vol. 43 (August 25), pp. 8775-8782.

[62] The studies label ARs affecting California as the Pineapple Express, defined as an atmospheric river extending out of the deep tropics and reaching the west coast of North America.

[63] Georgina Gustin, "4 Questions About Climate Change and California Fires," *Inside Climate News*, November 19, 2017, https://insideclimatenews.org/news/18102017/california-wildfires-global-warming-drought-wind-climate-change-fire; and Eleanor Cummins, "How the End of the Drought Likely Exacerbated the Deadly California Wildfires," *Slate*, October 10, 2017, http://www.slate.com/articles/health_and_science/science/2017/10/how_the_drought_fueled_california_s_wildfires.html.

[64] Diablo winds are technically termed katabatic winds. Katabatic winds descend from higher elevations, compressing and becoming warmer and drier, and sometimes reaching hurricane velocities. In southern California katabatic winds are often referred to as Santa Ana winds.

the American West, perhaps similar to conditions in precolonial North America, may be under way.[65]

Likely consequences of higher temperatures in the West include higher evapotranspiration, reduced precipitation, and decreased spring runoff.[66] These impacts would result from an *acceleration* of the hydrologic cycle, due to increased warming of the atmosphere, which in turn increases the amount of water held in the atmosphere.[67] A possible consequence is more frequent, and perhaps more severe, droughts and floods, although these changes are likely to occur unevenly across the United States. Yet the understanding of hydrologic extremes, such as drought, is confounded by other effects such as land cover changes, the operation of dams, irrigation works, extraction of groundwater, and other engineered changes. Forecasting drought conditions at the regional scale, for example for river basins or smaller features, is difficult because current climate models are less robust and have higher uncertainty at smaller scales.[68]

Even though forecasting drought at the regional scale is difficult, understanding potential changes in long-term trends is important for water managers at all levels—federal, state, local, and tribal. Water project operations and state water allocations typically are based on past long-term hydrological trends; significant deviations from such trends may result in difficult challenges for water managers and water users alike.[69]

Conversely, it is also difficult to predict when droughts will end, and in some cases significant regional droughts can end relatively abruptly with the occurrence of major precipitation events. In California, *atmospheric rivers* (ARs, or *drought busters*) are considered critical to ending droughts in the state (see **Appendix** for a discussion of atmospheric rivers).

Drought is a natural hazard with potentially significant economic, social, and ecological consequences. History suggests that severe and extended droughts are inevitable and part of natural climate cycles. Drought has for centuries shaped the societies of North America and will continue to do so into the future. Nonetheless, available technology and scientific understanding remain limited to forecasting any particular drought a few months in advance for a region. The prospect of extended droughts and more arid baseline conditions in parts of the United States and within regions such as the Southwest—possibly exacerbated by human-induced increases in atmospheric temperatures—represents a challenge to existing public policy responses for preparing and responding to drought.

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[65] Richard Seager et al., "Model projections of an imminent transition to a more arid climate in southwestern North America," *Science*, vol. 316 (May 25, 2007), pp. 1181-1184.

[66] Research results are emerging, however, that suggest that local and regional patterns of precipitation may be variable and that parts of a region or a state could receive higher precipitation than the current average, even if the overall trend over the broader area is towards less precipitation. See K. T. Redmond, "Climate Change in the Western United States: Projections and Observations," *Eos Trans. AGU*, 90(52), Fall Meet. Suppl., Abstract U11D-02, 2009.

[67] An acceleration of the hydrologic cycle includes the postulation of an increase in the mean, or average state of hydrologic fluxes, such as precipitation, evapotranspiration, water vapor content, and runoff, and an increase in the extremes of those fluxes. National Research Council, Committee on Hydrologic Science, *Global Change and Extreme Hydrology: Testing Conventional Wisdom*, Washington, D.C., 2011, p. 3.

[68] Ibid., p. 9.

[69] P. C. D. Milly et al., "Stationarity Is Dead: Whither Water Management?," *Science*, vol. 319 (February 4, 2008), p. 574.

# Appendix. Drought Case Studies: California, Texas, the Midwest

## California Drought: Busted?

The five-year California drought that began in 2012 has been at the center of congressional concern and action for several Congresses. Surface water conditions in California have recovered dramatically in 2017 from the effects of the 2012-2016 drought, but some consequences, such as the decline in groundwater levels from increased pumping, likely will linger for years. In response to the drought, the 114th Congress enacted legislation (P.L. 114-322) that altered the authorities regarding how federal water infrastructure in the state is managed and how new water storage may be developed. In the 115th Congress, there is both interest in and concern about the federal role and funding for new water infrastructure to cope with the next drought and with hydrologic conditions that can quickly transition from drought to flood conditions.[70]

### Why 2017 Is Different

A series of winter storms—known as *atmospheric rivers*, or ARs—tracked across California during the 2016-2017 winter and dropped snow and rain nearly statewide. ARs are also referred to as "drought busters" for their ability to deliver huge amounts of precipitation over a short period of time. Studies indicate that ARs are the source of 30%-50% of all precipitation along the U.S. West Coast.[71] The 2016-2017 winter storms were primarily responsible for statewide precipitation levels in January 2017 of 10.3 inches and in February 2017 of 8 inches, corresponding to 225% and 166%, respectively, above the average for those months since 1895. January and February are typically two of the wettest months for California.

ARs can erase one natural hazard, drought, but can cause another hazard—floods. They are the source of a large majority of floods along the U.S. West Coast, according to studies.[72] When ARs deliver above-average winter precipitation, reservoir managers must balance maintaining reservoir storage space to capture floodwaters with keeping reservoirs full (with little flood storage capacity) to meet water supply demands during the summer. This balancing act nearly failed in March 2017 at Lake Oroville, California's second-largest reservoir, as a series of storms caused the lake level to rise to 100% capacity.[73] Operators were forced to release water over a spillway, and dangerous conditions caused evacuations from downstream communities.

Snowpack levels over the 2017 winter and spring were well above the amounts during the 2012-2016 drought. By April 1, 2017, one estimate indicated, snowpack was greater than in the

[70] See, for example, CRS Report R44889, *H.R. 23, the Gaining Responsibility on Water Act of 2017 (GROW Act)*, by Charles V. Stern, Pervaze A. Sheikh, and Marnie Kremer; CRS Report R44986, *Subtitle J of the Water Infrastructure Improvements for the Nation (WIIN) Act: Bureau of Reclamation and California Water Provisions*, by Charles V. Stern, Pervaze A. Sheikh, and Nicole T. Carter; CRS In Focus IF10133, *California Drought: Water Supply and Conveyance Issues*, by Charles V. Stern; and CRS In Focus IF10536, *Water Infrastructure Improvements for the Nation Act (WIIN)*, by Nicole T. Carter et al.

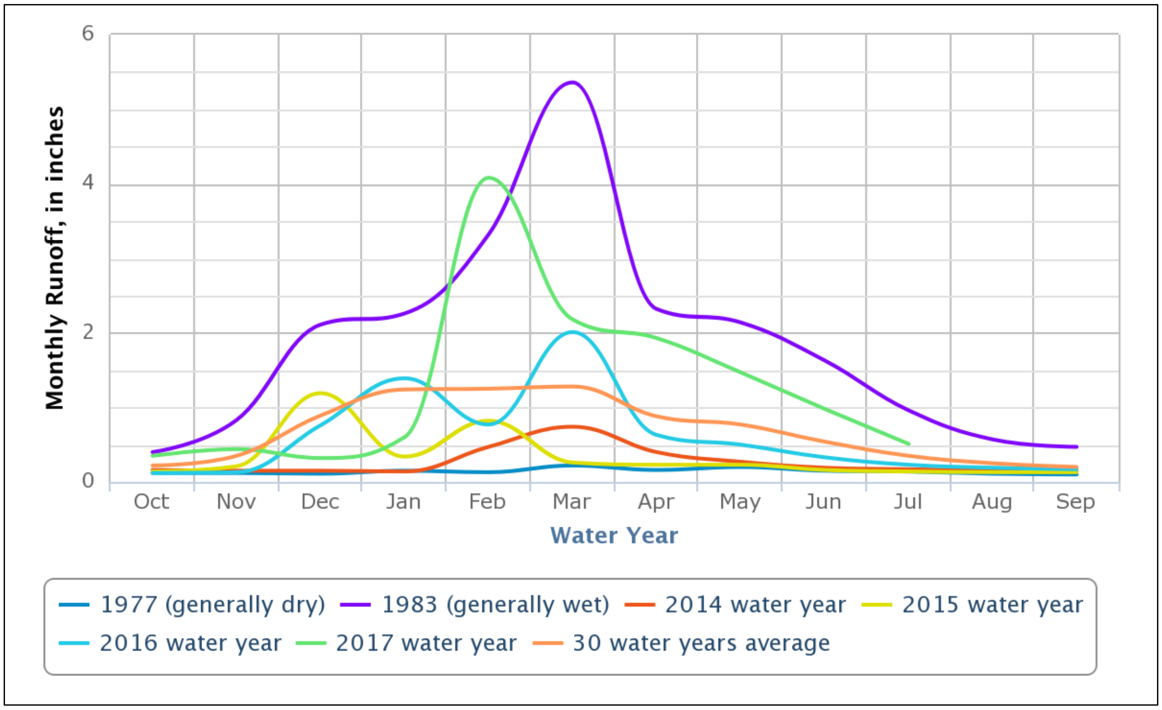
[71] Michael D. Dettinger, "Atmospheric Rivers as Drought Busters on the U.S. West Coast," *Journal of Hydrometeorology*, vol. 14, no. 6 (December 2013).

[72] Ibid.

[73] Sacramento Bee Staff, "From the Air: Images Show Ruined Oroville Dam Spillway, Hard-Hit Feather River," *Sacramento Bee*, March 1, 2017, http://www.sacbee.com/news/state/california/water-and-drought/article135860663.html.

previous four years combined.[74] High snowpack levels led to high amounts of runoff in the spring (**Figure A-1**), which filled California's reservoirs for the spring and summer, providing water for irrigation during the summer growing season. Reservoir levels have stayed at high levels into the fall of 2017, as indicated in **Figure A-2**.

**Figure A-1. Monthly Runoff for California**



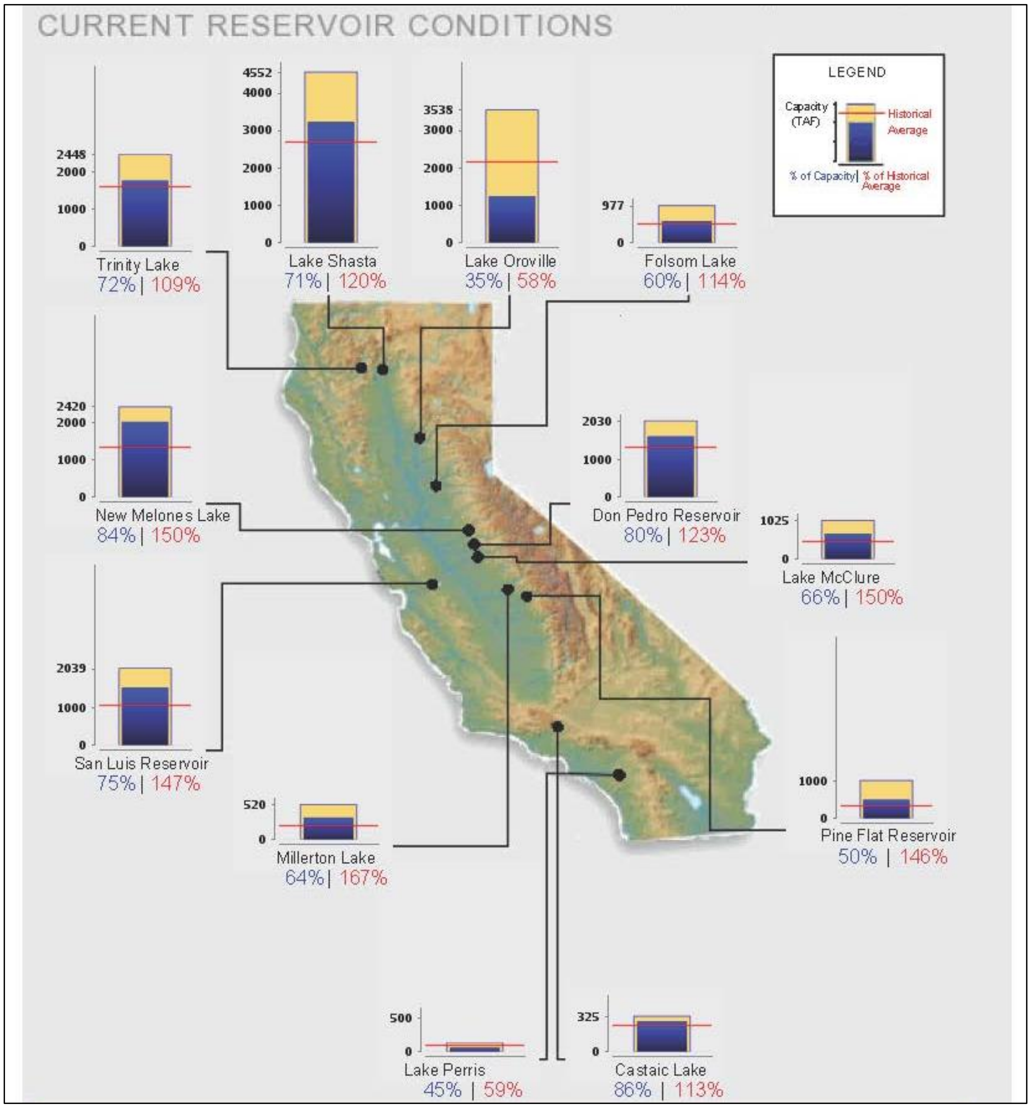

**Source:** U.S. Geological Survey, California Water Science Center, *Annual Runoff Estimate for California*, https://ca.water.usgs.gov/data/drought/runoff.html. Modified by CRS.

**Notes:** 2017 water year data are provisional and subject to change. The graph indicates that water year 2017 is among the six highest runoff years since water year 1983, and well above the 30-year average (orange line). Water year 1983 was the highest runoff year for California since records began, according to the USGS.

[74] Jet Propulsion Laboratory, California Institute of Technology, "Sierra Snowpack Bigger Than Last Four Years Combined," press release, April 18, 2017, https://www.jpl.nasa.gov/news/news.php?feature=6815.

**Figure A-2. Reservoir Conditions for Major California Reservoirs**

(October 23, 2017)




**Source:** California Department of Water Resources, California Data Exchange Center, http://cdec.water.ca.gov/resapp/RescondMain. Modified by CRS.

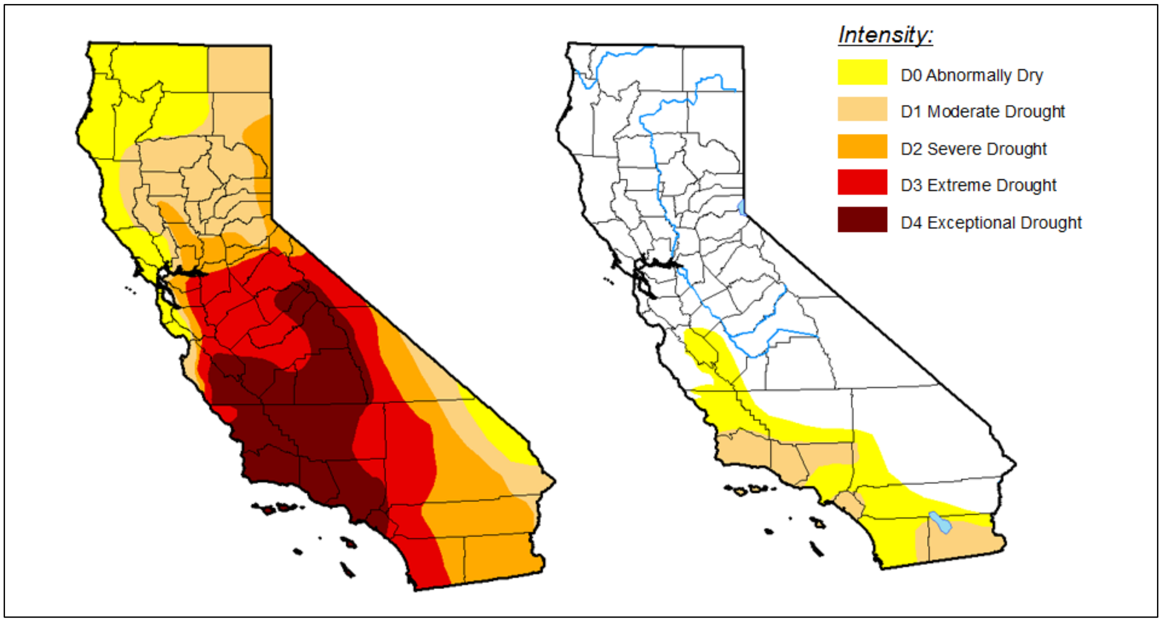
**Notes:** Only two reservoirs shown are below their historical average levels. Lake Oroville levels were reduced to effect repairs on the spillway damaged during March 2017 flooding.

## Is the Drought Over?

The U.S. Drought Monitor (**Figure A-3**) and other indicators (e.g., reservoir levels, **Figure A-2**) suggest that the drought has largely abated for most of California, and Governor Brown announced an end to the statewide Drought State of Emergency in April 2017. **Figure A-3** compares drought conditions a year apart, showing 100% of the state in drought or abnormally dry conditions on October 11, 2016, and 21% of the state in exceptional drought. In contrast, nearly 78% of California was drought-free on October 10, 2017, and none of the state was experiencing more than moderate drought.

**Figure A-3. Comparing Drought in California One Year Apart**

(October 11, 2016-left; October 10, 2017-right)




**Source:** U.S. Drought Monitor, http://droughtmonitor.unl.edu/Maps/CompareTwoWeeks.aspx. Modified by CRS.

However, the cumulative effects of the multiyear drought—particularly on groundwater supplies—are significant. Unlike surface water, which can recover from drought relatively quickly in a wet year, the amount of groundwater stored in many depleted aquifers likely will take much longer to recover and may never regain pre-drought levels. During the recent drought, California irrigators increasingly relied on groundwater to substitute for surface water. Consequently, groundwater levels in the state's Central Valley dropped, particularly in the San Joaquin Valley (SJV).[75] For example, aquifer levels in parts of the SJV experienced water-level drops of more than 50 feet between 2011 and 2016 (**Figure A-4**). In some locations, decreased groundwater levels caused the ground surface to drop in elevation (*land subsidence*). Subsidence was as much as 22 inches in some areas of the southern SJV between 2015 and 2016.[76]

In some locations the land surface may rebound a small amount (known as *elastic deformation*) with groundwater recharge; for many locations, the land surface does not recover (*inelastic deformation*). Parts of the southern SJV experienced nearly 27 feet of permanent land subsidence in the last century due to groundwater pumping.[77] Permanent subsidence means that the thickness of the aquifer shrinks, which decreases the aquifer's capacity to store groundwater. Another potential consequence is damage to surface structures, such as canals, levees, roads, and foundations of structures. Groundwater pumping during the recent drought, for example, resulted

[75] Jo Craven McGinty, "An End to California's Drought Isn't Cut and Dried," *The Wall Street Journal*, March 3, 2017, https://www.wsj.com/articles/an-end-to-californias-drought-isnt-cut-and-dried-1488537007.

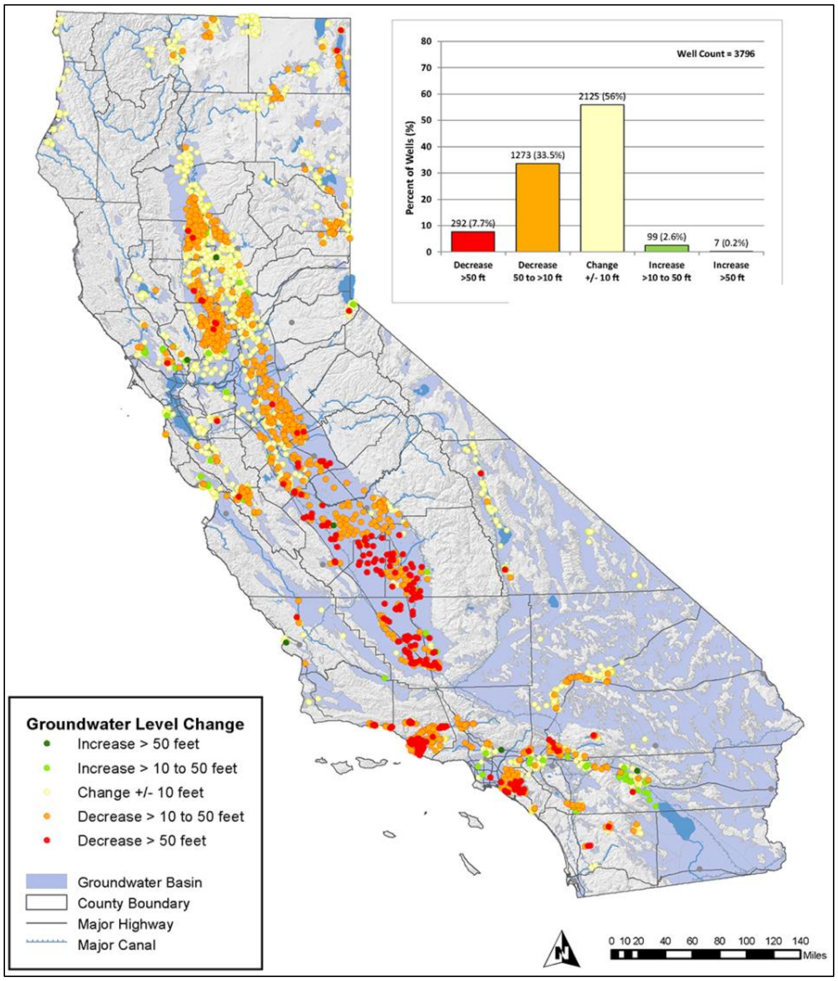
[76] Tom G. Farr, Cathleen E. Jones, and Zhen Liu, *Progress Report: Subsidence in California, March 2015-September 2016*, California Department of Water Resources, NASA Progress Report, 2017, http://www.water.ca.gov/waterconditions/docs/2017/JPL%20subsidence%20report%20final%20for%20public%20dec%202016.pdf.

[77] Devin Galloway, David R. Jones, and S. E. Ingebritsen, *Land Subsidence in the United States*, U.S. Geological Survey, U.S. Geological Circular 1182, 1999, pp. 23-34, https://pubs.usgs.gov/circ/circ1182/pdf/06SanJoaquinValley.pdf.

in land subsidence and damage to the Delta-Mendota Canal, buckling the concrete sides in some places. In one portion of the canal, a bridge dropped so low it nearly touched the surface of the water.[78]

**Figure A-4. Change in Groundwater Levels in California**

(fall 2011 to fall 2016)




**Source:** Tom G. Farr, Cathleen E. Jones, and Zhen Liu, *Progress Report: Subsidence in California, March 2015-September 2016*, California Department of Water Resources, NASA Progress Report, 2017, http://www.water.ca.gov/waterconditions/docs/2017/JPL%20subsidence%20report%20final%20for%20public%20dec%202016.pdf. Modified by CRS.

**Note:** Groundwater level changes determined from water level measurements in wells.

# Drought in Texas: 2011

Texas experienced varying levels of drought from 2011 to late spring 2015, when record amounts of rain fell in parts of the state, essentially ending the multiyear drought.[79] However, the drought

[78] Bettina Boxall, "Another Toll of the Drought: Land is Sinking Fast in the San Joaquin Valley, Study Shows," *Los Angeles Times*, August 19, 2015, http://www.latimes.com/local/lanow/la-me-ln-groundwater-20150819-story.html.

[79] As of June 2, 2015, only about 10% of Texas was experiencing abnormally dry or moderate drought conditions. One

in Texas was most extensive and most severe in 2011. For example, mid-February 2011 conditions in Texas were dramatically different compared with mid-February 2010, when only about 7% of the total land area in Texas was abnormally dry and no part of the state was experiencing even moderate drought.[80]

Drought conditions worsened in Texas through the beginning of October 2011, when 88% of the state experienced exceptional drought conditions and only 3% of the state was not classified as being in extreme or exceptional drought (**Figure A-5**).[81] Drought conditions generally improved throughout the rest of 2011, but large portions of the state were still affected by extreme or exceptional drought until late winter and early spring 2012, when the eastern portion of the state recovered to normal or abnormally dry conditions (the least severe category) because of above-normal rainfall from December 2011 through February 2012.[82] Drought conditions persisted in parts of Texas through early 2015, although the most severe, extreme, and exceptional conditions occurred in 2011.

According to Texas state climatologist John Nielsen-Gammon, 2011 may have been the worst one-year drought on record for Texas.[83] Compounding the effects of abnormally low precipitation, the June-August average temperature in Texas was approximately 2.5 degrees Fahrenheit higher than during any Texas summer since record keeping began in 1895 and 5 degrees Fahrenheit higher than the long-term average.[84]

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month earlier, 40% of the state was experiencing abnormally dry or drought conditions. Oklahoma also faced drought conditions earlier in 2015; as of May 5, 2015, nearly 60% of the state was in at least moderate drought conditions. As with Texas, late spring heavy rains have nearly eliminated the drought in Oklahoma.

[80] U.S. Drought Monitor, February 16, 2010. For comparison, the U.S. Drought Monitor on February 15, 2011, reported that over 87% of the state was experiencing abnormally dry or drought conditions, and only 12.5% of the state was not abnormally dry or in drought, http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx.

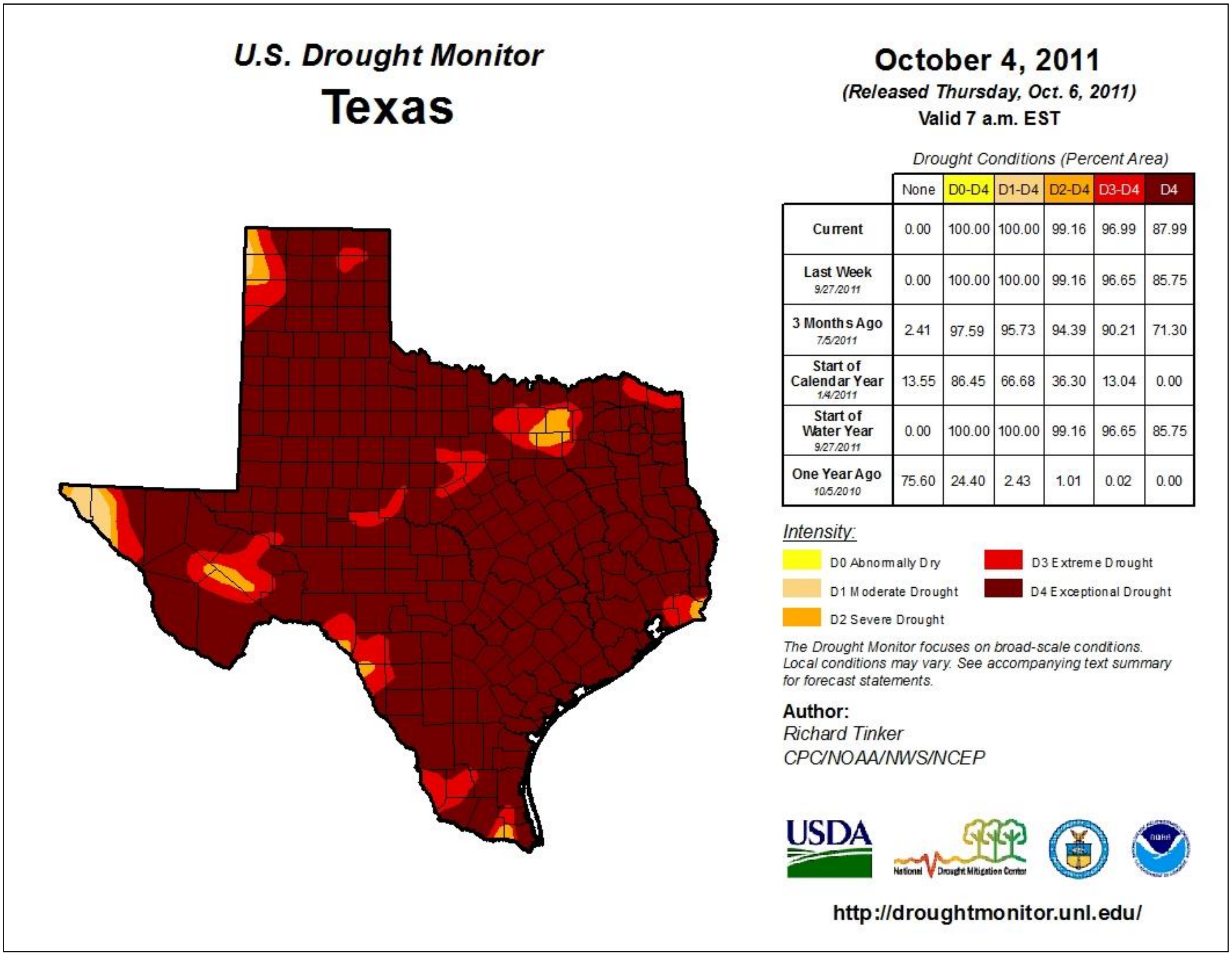
[81] See the U.S. Drought Monitor, Texas, on October 4, 2011, at http://droughtmonitor.unl.edu/MapsAndData/DataTables.aspxl.

[82] "Climate Abyss: Weather and Climate Issues with John Nielsen-Gammon," *Texas Drought Update*, March 23, 2012, http://blog.chron.com/climateabyss/2012/03/texas-drought-update/.

[83] Office of the Texas State Climatologist, "Texas Drought Officially the Worst Ever," August 4, 2011, http://tamunews.tamu.edu/2011/08/04/texas-drought-officially-the-worst-ever/.

[84] John W. Nielsen-Gammon, *The 2011 Texas Drought: A Briefing Packet for the Texas Legislature*, October 31, 2011, p. 29, http://climatexas.tamu.edu/files/2011_drought.pdf. Possibly the most severe Texas drought overall occurred from 1950 to 1957 and had substantial impacts on water supplies across the state because it lasted over many years. Because of the longevity and severity of the 1950s drought, municipal water supplies in Texas today are designed to withstand a drought of similar magnitude, according to the state climatologist. Long-term precipitation patterns in Texas—longer than year-to-year changes—are influenced by a configuration of sea surface temperatures known as the Pacific Decadal Oscillation (PDO). Similar conditions also prevailed from the 1940s through the 1960s, encompassing the Texas drought of record (1950-1957).

**Figure A-5. The Maximum Extent of Drought in Texas in 2011**




**Source:** U.S. Drought Monitor, U.S. Drought Monitor Map Archive, October 4, 2011, http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx. Modified by CRS.

**Note:** As shown in the table to the right of the map of Texas, 100% of the land area of the state was in drought and 97% of the state was in extreme to exceptional drought.

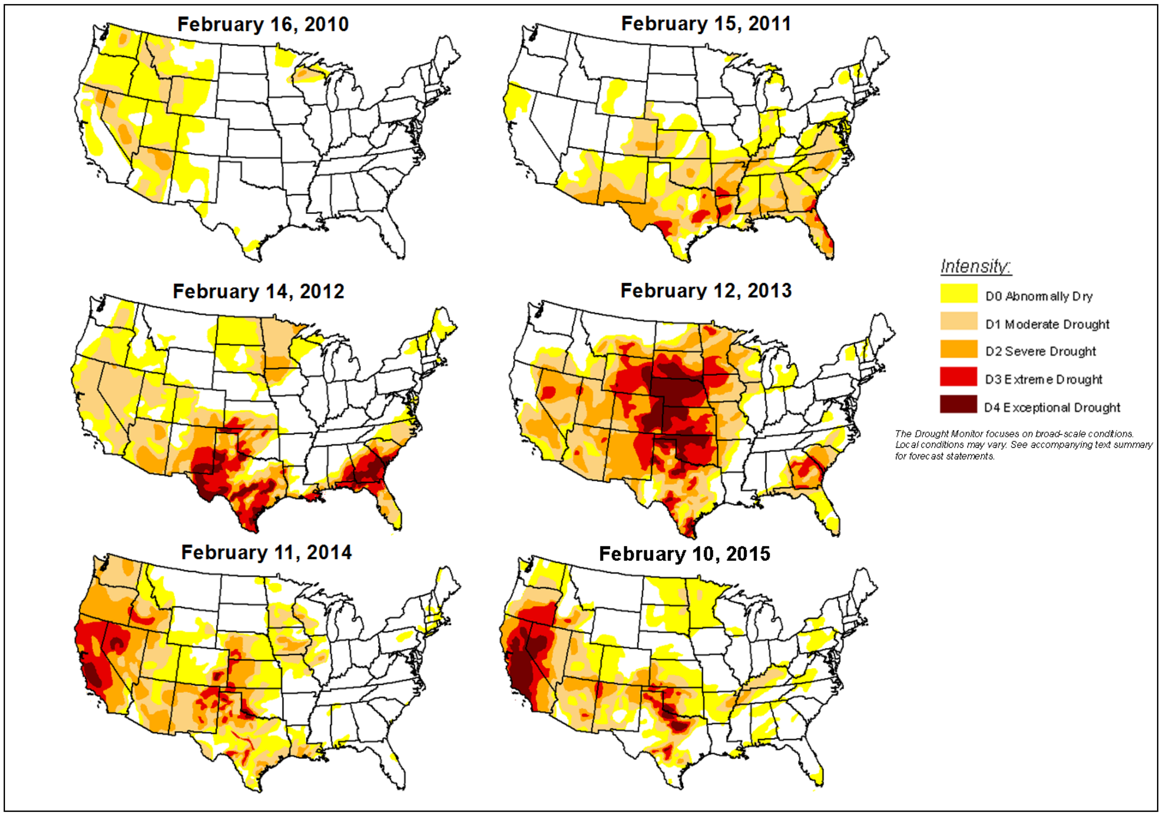
## Drought in the Midcontinent: 2012-2013

In mid-August 2012, approximately 70% of the land area of the United States (including Alaska and Hawaii) was affected by abnormally dry and drought conditions.[85] The land area affected by abnormally dry or drought conditions stayed at or above 65% through February 2013. The intensity of the drought varied, with the regions of extreme and exceptional drought clustered

[85] For the contiguous United States, nearly 80% of the land area was affected by abnormally dry or drought conditions. U.S. Drought Monitor, "U.S. Drought Monitor Map Archive," accessed August 14, 2012, at http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx.

across the Midwest, Great Plains, Southwest, and Southeast, particularly Georgia in 2012 (**Figure A-6**).

**Figure A-6. Drought Conditions in the United States: 2010-2015**




**Source:** U.S. Drought Monitor, http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx. Modified by CRS.

**Note:** Alaska and Hawaii not shown.

**Figure A-6** shows that Texas and portions of Florida and Georgia experienced exceptional drought conditions (the worst category of drought) in early 2012, while the upper Midwest, including most of the Mississippi Valley, experienced normal conditions. A year later, in early 2013, the drought had eased somewhat in portions of Georgia and Florida, but it had intensified throughout the center of the country from Texas to the Canadian border. Nearly 12% of the contiguous United States was in exceptional drought conditions from late June 2011 through October 2011, compared to approximately 6% of the country the following year.[86] However, exceptional drought conditions persisted over nearly 6% of the contiguous United States from mid-August 2012 through mid-February 2013. Although less severe for portions of the country, such as Texas and Florida, the 2012-2013 drought affected broader swaths of the agricultural heartland compared to 2011 (**Figure A-6**). The 2012-2013 experience illustrates that the extent, timing, and particular features of areas affected by drought—dryland versus irrigated farm regions, regions that are still recovering from previous droughts, or regions with multiyear surface storage or ample groundwater resources—are important in addition to the relative severity of drought conditions.

[86] U.S. Drought Monitor, *Tabular Data Archive*, http://droughtmonitor.unl.edu/MapsAndData/DataTables.aspx.

## Origin of the 2012-2013 Drought

**Figure A-6** shows a snapshot of drought conditions for mid-February in the United States for 2010-2015. In 2010, most of the United States was experiencing near-normal conditions. The extent and severity of the 2012-2013 drought raised questions regarding its origin and whether the drought was within the range of natural variability in the U.S. Midwest and Plains or whether it was linked to longer-term changes in the Earth's climate system, such as human-induced global warming.

Although the images presented in **Figure A-6** may seem to indicate a steady progression of drought in the middle portion of the country from near-normal conditions in 2010 to widespread and intense drought in 2012-2013, a March 2013 analysis concluded that the 2012 intense drought in the midcontinent region was a discrete extreme event.[87] The report stated that "the event did not appear to be just a progression or a continuation of the prior year's record drought event that developed in situ over the central U.S."[88] Instead, the report asserted that the drought developed suddenly, with near-normal precipitation during winter and spring 2012 over the Great Plains. According to the report, the drought resulted from an extreme lack of precipitation during the summer months: 2012 was the driest summer in the observed historical record for the region, experiencing even less rainfall than the years 1934 and 1936, when the central Great Plains were about 0.5 degrees Celsius warmer than 2012.[89] Essentially, the rains abruptly stopped in May over the central Great Plains and did not return for the summer.

The report further stated that the 2012 summer drought was a "climate surprise," because summertime Great Plains rainfall has been trending upward since the early 20th century and the last major drought occurred in 1988.[90] Further, the report concluded that neither sea surface temperatures, which have been rising generally due to global warming, nor changes in greenhouse gases in the atmosphere were responsible for producing the anomalously dry conditions over the central Great Plains in 2012.[91] (See section on "Drought and Climate Change" in the main text of this report.)

Although seasonal forecasts did not predict the summer 2012 drought in the Great Plains, a 2014 retrospective report stated that some modeling results indicated a broad shift toward warmer and drier western Great Plains and Southwest conditions during the 10 years to 15 years prior to the 2012 drought.[92] The report noted that the shift likely is due to natural decadal variability, but the existence of such variability would have increased the probability of a severe summer Great Plains drought, such as the 2012 event. The report concluded that the 2012 Great Plains drought resulted mostly from natural variations in weather.

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[87] Martin Hoerling et al., *An Interpretation of the Origins of the 2012 Central Great Plains Drought*, National Oceanic and Atmospheric Administration, Assessment Report: NOAA Drought Task Force Narrative Team, March 20, 2013, at ftp://ftp.oar.noaa.gov/CPO/pdf/mapp/reports/2012-Drought-Interpretation-final.web-041113.pdf.

[88] Ibid., p.1.

[89] Ibid., p. 4.

[90] Ibid., p. 10.

[91] Ibid., p. 22.

[92] M. Hoerling et al., "Causes and Predictability of the 2012 Great Plans Drought," *Bulletin of the American Meteorological Society*, vol. 95, no. 2 (February 2014), pp. 269-282.

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## Acknowledgments

This report was originally coauthored by Betsy A. Cody

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