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Drought in the United States: Causes and Current Understanding

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February 26, 2014

Congressional Research Service
7-5700
www.crs.gov
R43407

CRS REPORT
Prepared for Members and
Committees of Congress

Summary

Drought is a natural hazard, often with significant societal, economic, and environmental consequences. Public policy issues related to drought range from how to identify and measure drought to how best to prepare for, mitigate, and respond to drought impacts, and who should bear associated costs. Severe droughts in 2011 and 2012 in Texas and the midcontinent region, and the current drought in California and the American Southwest, have fueled congressional interest in drought and its near-term effects on water supplies and agriculture, as well as interest in long-term issues, such as drought forecasting and links between drought and human-induced climate change. Continuing drought conditions throughout the country contribute to ongoing interest in drought.

Some part of the country is almost always experiencing drought at some level. Since 2000, no less than 6.6% of the land area of the United States has experienced drought of at least moderate intensity each year. The land area affected by drought of at least moderate intensity varies by year and also within a particular year. For example, since 2000, the total U.S. land area affected by drought of at least moderate intensity has varied from as little as 6.6% (July 6, 2010) to as much as 55% (September 25, 2012). Based on weekly estimates of the areal extent of drought conditions since 2000, the average amount of land area across the United States affected by at least moderate-intensity drought has been 27%.

What is drought? Drought has a number of definitions; the simplest may be a deficiency of precipitation over an extended time period, usually a season or more. Higher demand for water for human activities and vegetation in areas of limited water supply, and warmer conditions, increase the severity of drought. For example, drought during the growing season may be considered more severe—in terms of its impacts—than similar conditions when cropland lies fallow.

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." Drought reconstructions from tree rings document that severe multidecadal drought occurred in the American Southwest during the 13th century, which anthropologists and archeologists suspect profoundly affected Pueblo society. One looming question is whether the United States, and in particular the American Southwest, including California, may be entering into a period that could be the beginning of a modern-era megadrought. Some scientists postulate that there exists a potential danger of slipping into a new megadrought era akin to the medieval megadroughts if the future climate is warmer due to the buildup of greenhouse gases in the atmosphere. However, regardless of the prospect of human-induced climate change, there is the possibility of return to long-term drought conditions experienced in previous centuries.

Despite advances in scientific understanding of climate and drought, predicting the severity and persistence of severe drought over a specific region of the country is not yet possible more than a few months in advance because of the many factors that influence drought (e.g., precipitation, heat, soil moisture). The prospect of extended droughts and more arid baseline conditions in parts of the United States may challenge existing public policy responses for preparing and responding to drought.

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Introduction

This report discusses how drought is defined (e.g., why drought in one region of the country is different from drought in another region), and why drought occurs in the United States. How droughts are classified, and what is meant by moderate, severe, and extreme drought classifications, are also discussed. The report briefly describes periods of drought in the country's past that equaled or exceeded drought conditions experienced during the 20th century. This is followed by a discussion of the nature and extent of recent droughts that affected Texas and the U.S. midcontinent, and the current drought in California. Lastly, the report discusses future prospects for a climate in the western United States that might be drier than the average 20th-century climate and the possible influence of human-induced climate change.

The likelihood of extended periods of severe drought, similar to conditions experienced centuries ago, 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. A discussion of these issues is beyond the scope of this report.

Drought in the United States—Overview

Drought has afflicted portions of North America for thousands of years. 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.[1] 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,[2] 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.

Drought conditions are broadly grouped into five categories: (D0) abnormally dry, (D1) moderate, (D2) severe, (D3) extreme, and (D4) exceptional.[3] Some part of the country is almost always experiencing drought at some level. Since 2000, no less than 6.6% of the land area of the United States has experienced drought of at least moderate intensity each year (**Figure 1**).[4] The land area affected by drought of at least moderate intensity varies by year and also within a particular year. For example, since 2000, the total U.S. land area affected by drought of at least moderate intensity (D1-D4) has varied from as little as 6.6% (July 6, 2010) to as much as 55% (September 25, 2012). Based on weekly estimates of the areal extent of drought conditions since

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

[2] 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.geosociety.org/meetings/06drought/roadmap.pdf.

[3] These are the categories used by the National Drought Mitigation Center (NDMC). The NDMC helps prepare the U.S. Drought Monitor and maintains its website.

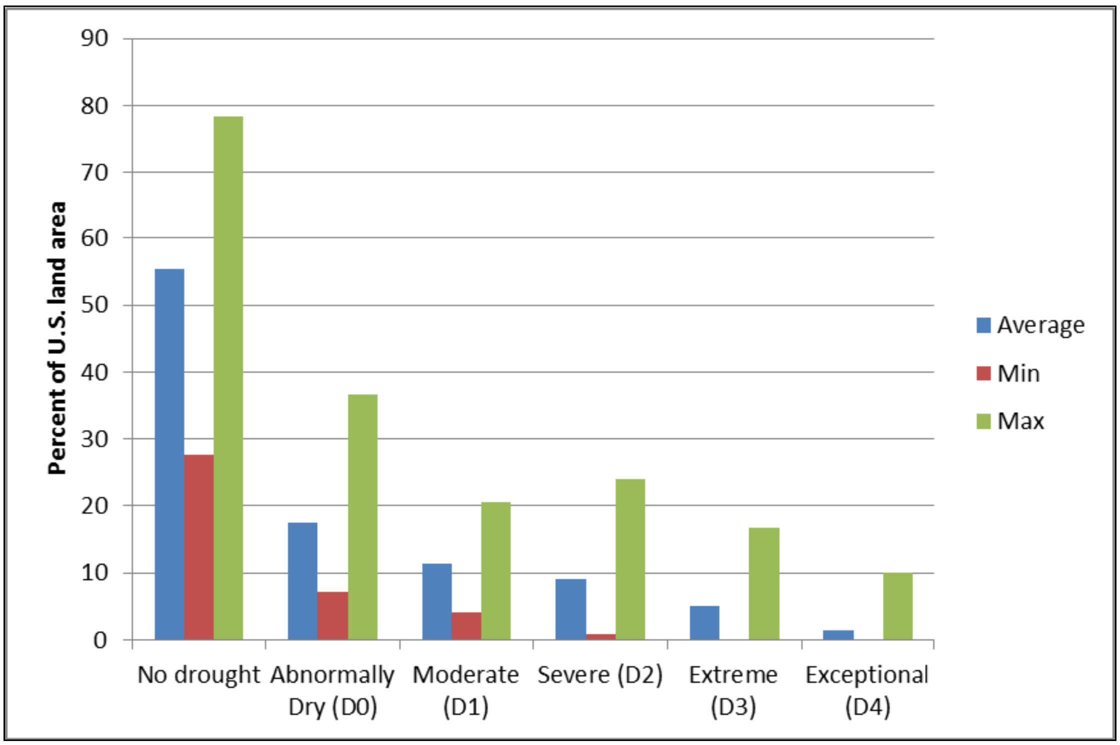
[4] NDMC data collected since 2000. U.S. Drought Monitor at the NDMC in Lincoln, NE. See http://droughtmonitor.unl.edu/DM_tables.htm?archive.

2000, the average amount of land area across the United States affected by at least moderate-intensity drought has been about 27%.

While the previous percentages refer to the extent of drought nationally, there is particular concern about those 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.[5] (See **Figure 1**.) Since 2000, exceptional drought (D4) conditions have affected approximately 1.4% of the nation on average. Of particular note were the conditions between June and October 2011; exceptional drought occurred over the largest land area—greater than 9%—during those months, 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 midsection of the United States.

Figure 1.Average, Minimum, and Maximum Percent of the U.S. Land Area by Drought Category

(January 4, 2000, through February 11, 2014)



Source: U.S. Drought Monitor, Tabular Data Archive, http://droughtmonitor.unl.edu/MapsAndData/DataTables.aspx. Modified by CRS.

Notes: Including Alaska, Hawaii, and Puerto Rico.

[5] 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.

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.[6] 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).[7] 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).[8]

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 would likely be considered more severe—in terms of its impacts—than similar conditions when cropland lies fallow. For policy purposes, drought often becomes an issue when it results in a water supply deficiency: Less water is available than the average amount for irrigation, municipal and industrial supply (M&I), energy production, preservation of endangered species, and other needs. These impacts can occur through multiple mechanisms: decreased precipitation and soil moisture affecting dryland farming; low reservoir levels decreasing 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; 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). At the national level, drought is monitored and reported by the National Drought Mitigation Center in an index known as the U.S. Drought Monitor, which synthesizes various drought indices and impacts, and represents a consensus view of ongoing drought conditions between academic and federal scientists. Drought can also relate and contribute to other phenomena, such as fires and heat waves.[9]

Drought Classification

To assess and classify the intensity and type of drought, certain measures, or drought indices, are typically used. Drought intensity, in turn, is the trigger for local, state, and federal responses that can lead to the flow of billions of dollars in relief to drought-stricken regions.[10] The classification of drought intensity, such as that shown in **Figure 1,** may depend on a single indicator or several indicators, often combined with expert opinion from the academic, public, and private sectors.

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[6] NDMC, http://www.drought.unl.edu/DroughtBasics/WhatisDrought.aspx.

[7] 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 manmade reservoirs.

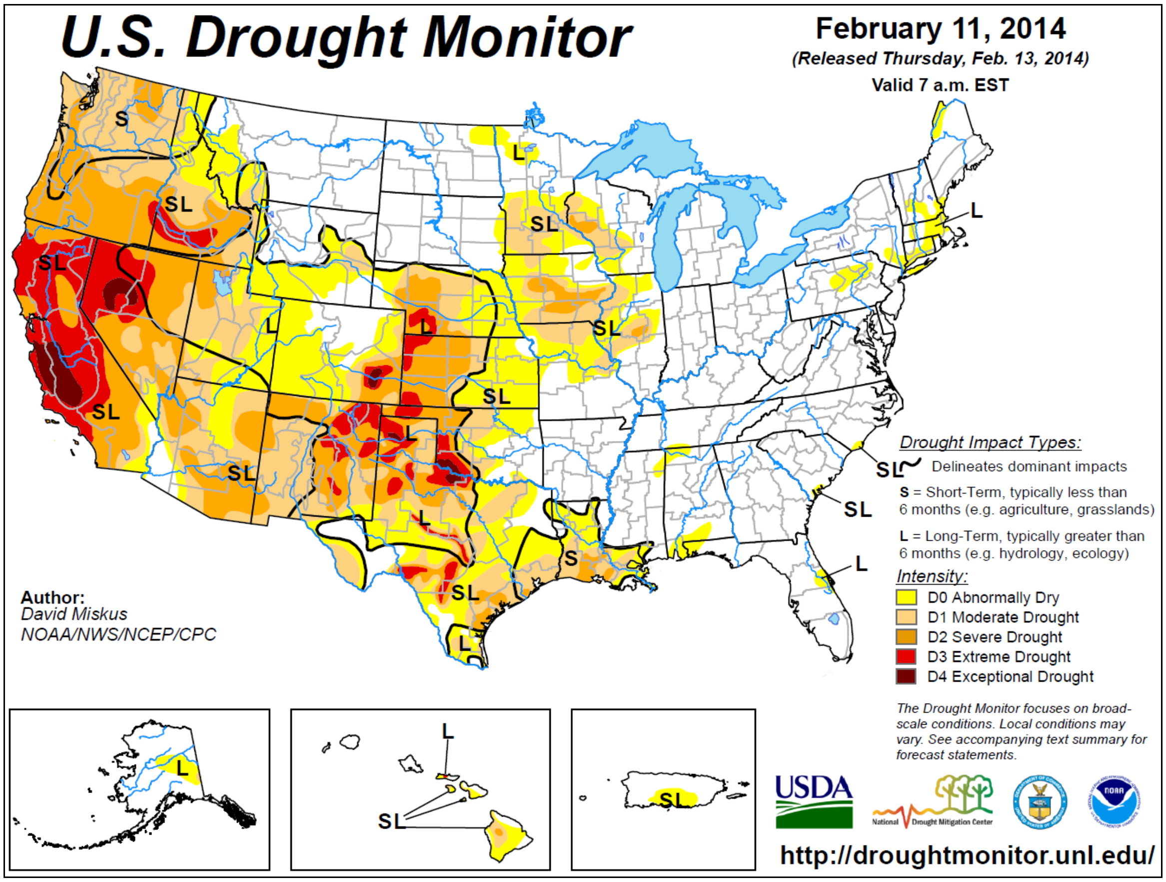
[8] Permanently arid conditions reflect the *climate* of the region, which is the composite of the day-to-day weather over a longer period of time. Climatologists traditionally interpret climate as the 30-year average. See NDMC, http://www.drought.unl.edu/DroughtBasics/WhatisClimatology.aspx.

[9] For more on fire, see CRS Report RL30755, *Forest Fire/Wildfire Protection*, by Kelsi Bracmort.

[10] For example, the Palmer Drought Index has been widely used by the U.S. Department of Agriculture to determine when to grant emergency drought assistance. See NDMC, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro/PDSI.aspx.

The U.S. Drought Monitor uses five key indicators,[11] together with expert opinion, with indices to account for conditions in the West where snowpack is relatively important, and with other indices used mainly during the growing season.[12] 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 large regions depicted as red in **Figure 2** faced extreme to exceptional drought conditions for the week of February 11, 2014, but they may contain local areas and individual communities that experienced less (or more) severe drought.

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



Source: U.S. Drought Monitor, http://droughtmonitor.unl.edu/.

Notes: The U.S. Drought Monitor national maps are updated weekly.

Drought Is Relative

Drought and "normal" conditions can vary considerably from region to region. For example, the U.S. Drought Monitor shows that the San Francisco Bay Area faced extreme drought in mid-February 2014. Similarly, the city of Reno, Nevada, was in extreme drought during the same time

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[11] 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 indices, see NDMC, http://droughtmonitor.unl.edu/current.html.

[12] U.S. Drought Monitor, http://www.drought.unl.edu/dm/classify.htm.

period. However, Reno receives on average a total of 2.36 inches of precipitation over the three-month period prior to February: November through January.[13] In contrast, San Francisco receives on average 10.6 inches of precipitation over the same period.[14] Both cities faced extreme drought in early February 2014, but what was normal for San Francisco was very different from what was normal for Reno.[15]

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 Reno and San Francisco.

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. (See **Figure 2**.) The "S" designation is intended to indicate a combination of drought indices that reflect impacts that respond to precipitation over several days up to a few months (short-term effects). These would include impact to agriculture, topsoil moisture, unregulated streamflows, and aspects of wildfire danger. The "L" designation approximates responses to precipitation over several months up to a few years (long-term effects). These 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 mid-February 2014 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 semi permanent 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.[16]

Prolonged droughts occur when these atmospheric conditions persist for months or years over a certain region that typically does not experience such conditions for a prolonged period.[17]

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[13] National Weather Service Forecast Office, Reno, NV, http://www.nws.noaa.gov/climate/index.php?wfo=rev.

[14] National Weather Service Forecast Office, San Francisco Bay Area/Monterey, http://www.nws.noaa.gov/climate/index.php?wfo=mtr.

[15] 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.

[16] See NDMC, at http://drought.unl.edu/DroughtBasics/PredictingDrought.aspx.

[17] Ibid.

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.[18] 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.[19] A number of studies have made the connection between cooler SSTs in the eastern Pacific and the 1998-2004 western drought,[20] three widespread and persistent droughts of the late 19th century,[21] and past North American "megadroughts" that occurred between approximately 900 and 1300 A.D.[22] 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.[23]

Although the relationship between cooler than normal eastern tropical Pacific SSTs (La Niña-like conditions) and drought is becoming more firmly established, meteorological drought is probably never the result of a single cause. Climate is inherently variable, and accurately predicting drought for one region in the United States for more than a few months or seasons in advance is not yet possible because so many factors influence regional drought. What is emerging from the scientific study of drought is an improved understanding of global linkages—called teleconnections by scientists—between 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 with the occurrence of near-simultaneous drought in the southern United States, Southern Europe, and Southwest Asia.[24]

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[18] Ibid.

[19] Cook et al., 2007.

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

[21] Herweiger, Celine, 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. Hereafter referred to as Herweiger et al., 2006.

[22] Cook et al., 2007.

[23] 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.

[24] Hoerling and Kumar, 2003.

El Niño-Southern Oscillation (ENSO)

Under normal conditions, the trade winds blow toward the west in the tropical Pacific Ocean, 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 El Niño, 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 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, 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-Nino drying in the western Pacific Ocean, and increasing rainfall in the central and eastern equatorial Pacific. Other studies, including the 2007 IPCC report, point to a lack of consensus over global-warming driven changes in the timing and intensity of El-Nino driven events, and 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. 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.

Source: 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; Meehl, G. A. *et al.,* in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change,* eds Solomon, S. *et al.*, Cambridge Univ. Press, 2007; 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 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."[25] 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 on tree-ring records or other proxies in the absence of direct measurements.[26] 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. The drought reconstructions from tree rings document that severe multidecadal drought occurred in the American Southwest during the 13th century, which anthropologists and archeologists suspect profoundly affected Pueblo society. Tree ring drought reconstructions also

[25] Cook et al., 2007.

[26] 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.

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.[27]

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.[28] The 1856-1865 drought, centered on the Great Plains and Southwest, was the most severe drought to strike the region over the last two centuries, according to one study.[29] 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.[30] Congressional debate also occurred over a much larger federal role in western states irrigation, which led to the Reclamation Act of 1902.[31]

In the 20th century, the 1930s "Dust Bowl" drought and the 1950s Southwest drought are commonly cited as the two most severe multiyear droughts in the United States.[32] (The 1987-1989 drought was also widespread and severe, mainly affecting the Great Plains but also instigating extensive western forest fires, including the widespread Yellowstone fire of 1988.) According to several studies, however, the 19th and 20th century severe droughts occurred during a regime of relatively less arid conditions compared to 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 to today, but the average climate conditions were much drier and led to more severe droughts.[33]

Recent Droughts: Texas, the Midcontinent, and California

Over the past five years, portions of the country have been gripped with extensive and extreme to exceptional drought. As noted above, drought conditions nearly always occur in some part of the United States; however, the intensity of the Texas drought in 2011-2013, the widespread nature of the midcontinent drought in 2012-2013, and the return of drought to California in 2013-2014 have focused national and congressional attention on those regions. The national importance of

[27] Cook et al., 2007.

[28] Herweiger et al., 2006.

[29] Ibid.

[30] The Carey Act, signed into law on August 18, 1894 (Chapter 301, Section 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. Some observers have suggested that the failure of the Carey Act to foster irrigation projects in all the land made available, compounded in part by the 1890-1896 drought, led to the Reclamation Act of 1902 and the emergence of the Bureau of Reclamation in the 20th century. (See Marc Reisner, *Cadillac Desert* (New York, New York, Penguin Books, 1986)).

[31] 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.

[32] Fye, F., D. W. Stahle, and E. R. Cook, "Paleoclimate analogs to twentieth century moisture regimes across the United States," *Bulletin of the American Meteorological Society*, 2003, vol. 84, pp. 901-909.

[33] 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.

agriculture in those regions combined with drought conditions (i.e., lack of precipitation combined with demand from farming and ranching) illustrates the nature of drought: namely, it is the combination of lack of precipitation and acute demand for water. The following section briefly describes these specific regional droughts.

Drought in Texas: 2011-2013

In mid-February 2011, nearly 90% of Texas was experiencing abnormally dry to drought conditions, and nearly 8% of the state was in extreme drought (D3).[34] The 2011 drought in Texas represented a dramatic shift compared to the same time period in 2010, when approximately 7% of the total land area in Texas was abnormally dry, without even moderate drought in any part of the state.[35] (See **Figure 3**, comparing 2010, 2011, 2012, 2013, and 2014.)

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 extreme or exceptional drought).[36] 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 of 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.[37] Although drought conditions persisted in parts of Texas up through early 2014, 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.[38] Compounding the effects of abnormally low precipitation, the June-August average temperature in Texas was approximately 2.5 degrees Fahrenheit (F) greater than any previous Texas summer since 1895 and 5 degrees F greater than the long-term average.[39]

[34] U.S. Drought Monitor, February 15, 2011, http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx.

[35] U.S. Drought Monitor, February 16, 2010.

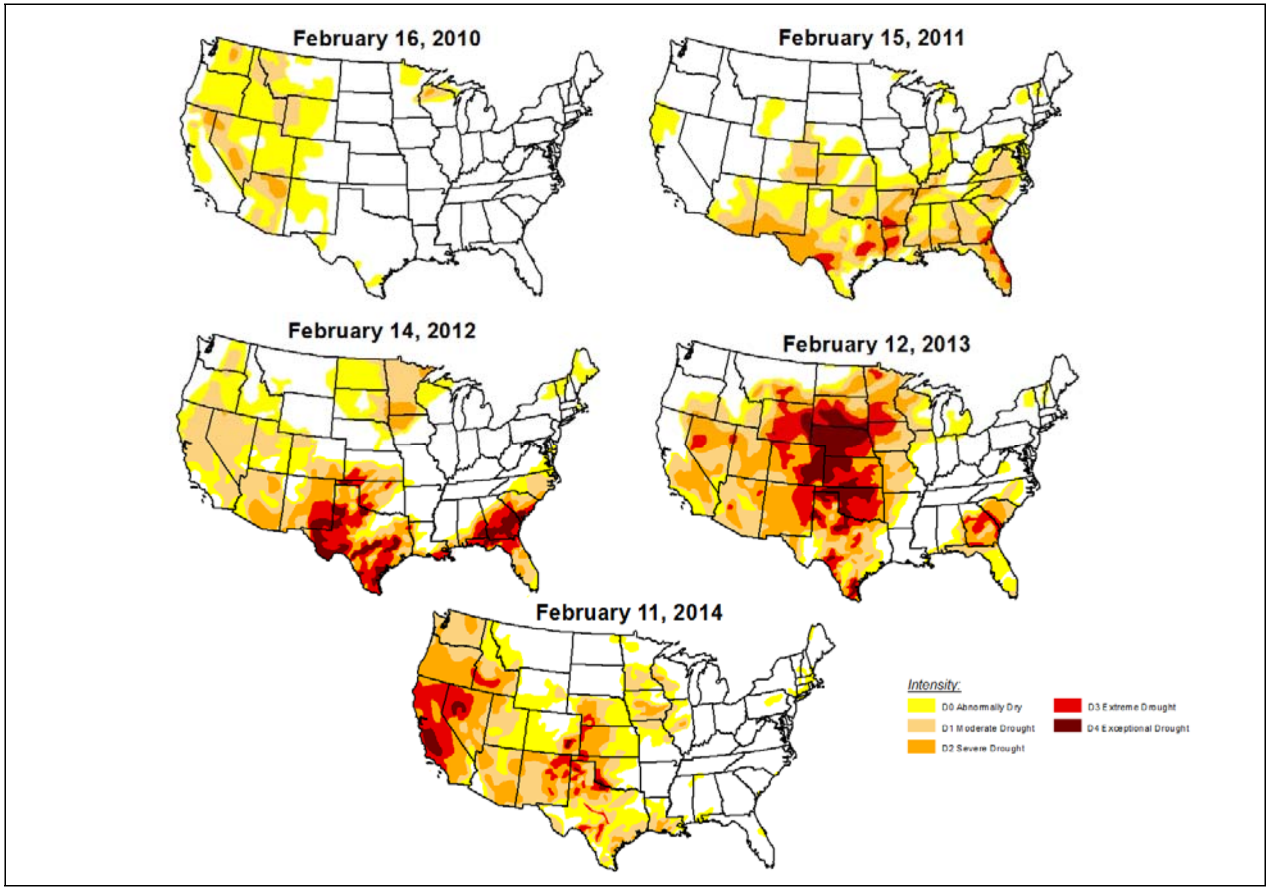
[36] See the U.S. Drought Monitor, Texas, on October 4, 2011http://droughtmonitor.unl.edu/archive.html.

[37] "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/.

[38] 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/.

[39] 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 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 3.Drought Conditions in the United States: 2010-2014



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

Note: Alaska and Hawaii not shown.

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.[40] 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 were clustered across the Midwest, Great Plains, Southwest, and in the Southeast, particularly Georgia in 2012. (See **Figure 3**.)

Figure 3 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 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.[41] 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 3**). 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 multi-year surface storage or ample groundwater resources—are important in addition to the relative severity of drought conditions.

Origin of the 2012-2013 Drought

Figure 3 shows a snapshot of drought conditions for mid-February in the United States for 2010-2014. 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 3** 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 concludes that the 2012 intense drought in the midcontinent region was a discrete extreme event.[42] The report states 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."[43] Instead, the report asserted that the drought developed suddenly, with near normal precipitation during winter and spring 2012 over the Great Plains. The drought resulted from an extreme lack of precipitation during the summer months: 2012 was the

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

[41] U.S. Drought Monitor, *Drought Monitor Archive Tables*, http://droughtmonitor.unl.edu/dmtabs_archive.htm.

[42] 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, ftp://ftp.oar.noaa.gov/CPO/pdf/mapp/reports/2012-Drought-Interpretation-final.web-041113.pdf.

[43] Ibid., p.1.

driest summer in the historical record for the region, experiencing even less rainfall than the years 1934 and 1936, when the central Great Plains were about 0.5° C warmer than 2012.[44] 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.[45] 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.[46] (See section on "Drought and Climate Change," below, for a brief discussion of climate change and drought.)

Change Over a Year: Drought in California, 2013-2014

By early 2014 extreme and exceptional drought conditions had fully developed in California and parts of the Pacific Northwest, while the Midcontinent drought of 2012-2013 lessened somewhat. (See **Figure 3**.) The percentage of the conterminous United States experiencing drought of any category—D0 through D4—shrunk between February 2013 and February 2014 (**Table 1**).

Although a smaller percentage of the U.S. land mass is experiencing drought in mid-February 2014 compared to a year earlier, the percentage of California undergoing drought has increased markedly over the same time period. **Table 1**shows that while 65% of the state experienced abnormally dry and drought conditions in February 2013, no portion of the state was in extreme or exceptional drought.

Table 1. Percentage of Area Affected By Drought—Conterminous United States and State of California—Comparison Between 2013 and 2014

Week	Region	No drought	D0-D4	D1-D4	D2-D4	D3-D4	D4
2/11/14	U.S.	44.54	55.46	37.60	21.41	6.86	0.88
2/12/13	U.S.	34.11	65.89	55.73	37.74	17.71	6.61
2/11/14	California	1.43	98.57	94.54	91.59	60.94	9.81
2/12/13	California	34.53	65.47	47.18	23.72	0	0

Source: U.S. Drought Monitor, http://droughtmonitor.unl.edu/MapsAndData/WeeklyComparison.aspx.

In contrast, a year later over 98% of the state was abnormally dry or in drought and nearly 61% of the state was facing extreme to exceptional drought, including portions of the Central Valley, one of the richest agricultural regions in the United States. (See **Error! Reference source not found.**.) Moreover, as of February 2014 snowpack in the Sierra Mountains was well below normal, and water levels in multi-year reservoirs were below average conditions for that time of

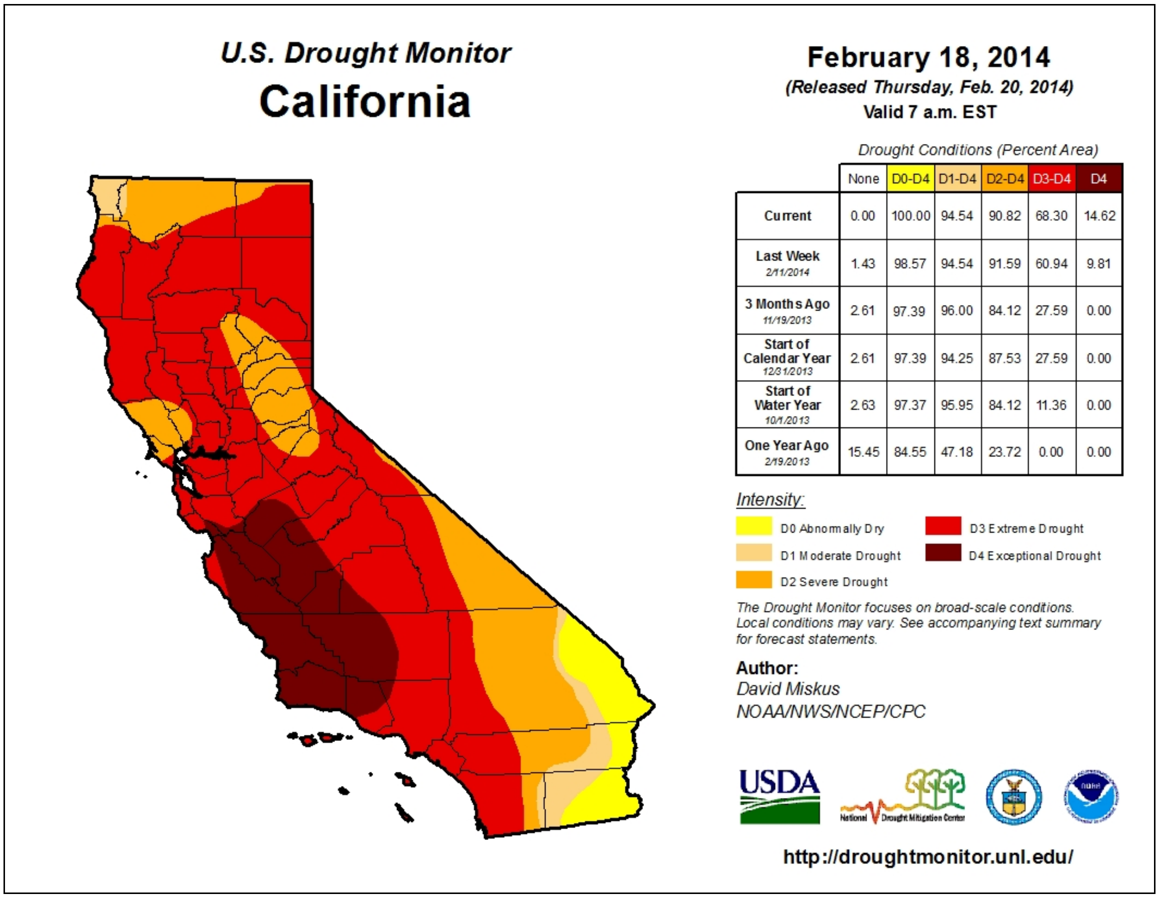
[44] Ibid., p. 4.

[45] Ibid., p. 10.

[46] Ibid., p. 22.

year.[47] These conditions have resulted in record cut-backs to state and federal water supply contractors.

Figure 4.California Drought Conditions



	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.00	100.00	94.54	90.82	68.30	14.62
Last Week 2/11/2014	1.43	98.57	94.54	91.59	60.94	9.81
3 Months Ago 11/19/2013	2.61	97.39	96.00	84.12	27.59	0.00
Start of Calendar Year 12/31/2013	2.61	97.39	94.25	87.53	27.59	0.00
Start of Water Year 10/1/2013	2.63	97.37	95.95	84.12	11.36	0.00
One Year Ago 2/19/2013	15.45	84.55	47.18	23.72	0.00	0.00

Source: U.S. Drought Monitor, http://droughtmonitor.unl.edu/Home/StateDroughtMonitor.aspx?CA.

Although California experienced the driest year on record in 2013, the severity of drought impacts is not solely related to the lack of precipitation and the duration of dryness. For example, drought risks to U.S. citizens generally increase in proportion to the population affected by drought, as well as in proportion to the resources and economic activity dependent upon average water supply and soil conditions. This situation is illustrated currently in California where more than 22 million people rely on water delivered from the Sacramento and San Joaquin Rivers Delta confluence with San Francisco Bay (Bay-Delta) – also the home and nursery for several species of federal and state listed threatened and endangered species. Farms in the state's Central Valley also rely on water coming from the Bay-Delta, as well as run-off from the Sierra mountains. With snowpack and reservoirs both at record lows, and California being the top U.S. agricultural producer in terms of cash receipts, drought impacts in California could be felt nationwide.[48]

[47] For a more in-depth discussion of California water supply and issues affected by drought, see CRS Report IF00008, *California Drought: Water Supply and Conveyance Issues (In Focus)*, by Betsy A. Cody.

[48] California is the country's largest agricultural producer in terms of cash farm receipts—accounting for 11% (nearly $45 billion) of the U.S. total in 2012 (the last year for which data are available [www.cdfa.ca.gov/statistics/]).
(continued...)

The 2007-2009 California Drought: Setting the Stage for the 2014 Drought?

The 2007-2009 California drought[49] was complicated by decades of tension over water supply deliveries for irrigation and municipal and industrial uses, and the preservation of water flows to protect threatened and endangered species. Dry conditions that began in 2007 continued through the 2009 water year (October 2008 through September 2009) and into the fall of 2009. According to the California Department of Water Resources, the 2007-2009 drought was the 12th-driest three-year period in California history since measurements began.[50] Although hydrological conditions were classified as below normal in 2010 and "wet" (well above average) in 2011, the 2012 water year was classified as "below normal" for the Sacramento River basin and "dry" for the San Joaquin River basin.[51] Above-average reservoir storage at the end of 2011 mitigated reductions to water users. Although the drought was declared over[52] in spring 2011, by August 2012, the U.S. drought monitor again showed increasing severity of drought in the eastern portion of the state. Water deliveries to state and federal water project contractors were restricted again in 2012, as well as in 2013.[53]

California's dry conditions from 2007 through 2009 exacerbated an already tight water supply, where federal and state water deliveries had been reduced in response to a court order to prevent extinction of the Delta smelt.[54] These factors are still in play in 2014 and are challenging water managers charged with protecting certain species from extinction while also supplying water for farms, cities, and fish and wildlife.

Drought and Climate Change

The relationship between climate change and future trends in droughts is complex and its scientific understanding appears to be 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 El Nino-Southern Oscillation (ENSO)[55] events and global surface warming.[56] The 2007 IPCC report added that very wet areas

(...continued)

California is also the largest producer of many crops.

[49] For more information about the hydrology and policy issues involved in the 2007-2009 California drought, see CRS Report R40979, *California Drought: Hydrological and Regulatory Water Supply Issues*, by Betsy A. Cody, Peter Folger, and Cynthia Brougher.

[50] California Department of Water Resources, *California's Drought of 2007-2009—An Overview*, September 2010, http://www.water.ca.gov/waterconditions/drought/docs/DroughtReport2010.pdf.

[51] http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

[52] Office of Governor Edmund G. Brown, Jr., "A Proclamation by the Governor of the State of California—Drought," http://gov.ca.gov/news.php?id=16997.

[53] For information on current water supply conditions and historical water allocations to federal water contractors in California, see http://www.usbr.gov/mp/PA/water/.

[54] The Delta smelt is a species of fish listed as threatened under the federal Endangered Species Act and as endangered under the California Endangered Species Act. *Natural Resources Defense Council v. Kempthorne*, No. 1:05-cv-1207 OWW GSA (E.D. Cal., December 14, 2007).

[55] A discussion of ENSO is provided in the text box on page 7 of this report.

[56] 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.

declined by about 5% globally. The report asserted that documented trends in severe droughts and heavy rains show that hydrological conditions are becoming more intense in some regions.[57]

In 2012, the IPCC issued a new report that noted: "There are still large uncertainties regarding observed global-scale trends in droughts."[58] The new report noted that its earlier assessment, that very dry areas have more than doubled since the 1970s, was based largely on only one study, which relied on a measurement largely related to temperature, not moisture. A different study, which looked at soil moisture simulations, found that global trends in drought duration, intensity, and severity predominantly were *decreasing*, not increasing, but with strong regional variation.[59]

The 2012 IPCC report assigned medium confidence[60] 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). 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 report concluded that despite new studies that have furthered the understanding of mechanisms leading to drought, there is still limited evidence 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.[61] The report noted that some regions of the world have experienced trends towards more intense and longer droughts, such as southern Europe and West Africa. But in other regions, such as central North America and northwestern Australia, droughts have become less frequent, less intense, or shorter. How the 2011-2012 drought in the central United States and the current California drought may change that assessment in the forthcoming IPCC report on impacts, adaptation, and vulnerability (expected later in 2014) remains to be seen.[62]

Further adding to the complexity and challenge to the scientific understanding of what causes drought was work presented at the European Geosciences Union meeting in April 2013 that attempted to simulate megadroughts that occurred in the past.[63] The simulations produced a number of megadroughts that lasted for decades; however, they did not match the timing of the past documented megadroughts. The scientists presenting their work at the meeting concluded that the model they used seemed to miss some of the dynamics that drive large droughts.

[57] Ibid., Summary for Policy Makers.

[58] 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.

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

[60] 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.

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

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

[63] Quirin Schiermeier, "Climate Models Fail to 'Predict' US Droughts," *Nature*, vol. 496, no. 7445 (April 16, 2013), http://www.nature.com/news/climate-models-fail-to-predict-us-droughts-1.12810.

Despite the current lack of predictive capability for forecasting megadroughts, work presented at the American Geophysical Union meeting in December 2013 underscored the finding that in the past the climate system has the inherent capacity to slip into a more extreme mode of climatic variability, namely one in which megadroughts are more frequent and long lasting.[64] These modes in the past occurred in the absence of human-caused buildup of greenhouse gases, but seem to be associated with periods of warmer climate conditions. The work presented at the meeting speculated that given the association between past megadroughts and warmer climate, there exists a potential danger of slipping into a new megadrought era akin to the medieval megadroughts if the future climate is warmer due to the buildup of greenhouse gases.[65]

Drought Forecasts for the United States

Predicting the severity and duration of severe drought over a specific region is not yet possible more than a few months 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 the American West, perhaps similar to conditions in precolonial North America, may be underway.[66] Some studies have suggested that human influences on climate, caused by emissions of greenhouse gases, may be responsible for a drying trend; [67] however, other studies appear to indicate an opposite trend or possibility (see above section on "Drought and Climate Change").[68] Whether future greenhouse gas-driven warming can be linked to La Niña-like conditions, or other phenomena related to the El Niño-Southern Oscillation, is unclear.

A likely consequence of higher temperatures in the West would be higher evapotranspiration, reduced precipitation, and decreased spring runoff.[69] 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.[70] A possible consequence is more frequent, and perhaps more severe, droughts and floods. However, these changes are unlikely to occur evenly across the United States. Observations of water-related changes over the last century suggest that runoff and streamflow in the Colorado and Columbia River basins has been decreasing, along with the amount of ice in mountain glaciers in the West, and the amount of

[64] Edward R. Cook, "Megadroughts: The scary past told by tree rings and its implications for the future," *Abstract 1797911 presented at 2013 Fall Meeting, San Francisco, CA*, American Geophysical Union, December 11, 2013.

[65] Some scientists suggest that it is too early to tell whether drought conditions in California and the southwest indicate the presence of a megadrought, and that even the Dust Bowl period of the 1930s didn't qualify as a megadrought. However, California has experienced more severe and longer lasting droughts in the past. See Elizabeth Harball, "Researchers warn Californians of epic droughts in the state's distant past," ClimateWire, February 20, 2014, http://www.eenews.net/climatewire/2014/02/20/stories/1059994822.

[66] 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.

[67] Tim P. Barnett, et al., "Human-induced changes in the hydrology of the western United States," *Science*, vol. 319 (February 22, 2008), pp. 1080-1082.

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

[69] Research results are emerging, however, that suggest that local and regional patterns of precipitation may be variable, and 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.

[70] National Research Council, Committee on Hydrologic Science, *Global Change and Extreme Hydrology: Testing Conventional Wisdom*, Washington, D.C., 2011, p. 3.

annual precipitation in the Southwest.[71] 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, is difficult because current climate models are less robust and have higher uncertainty at smaller scales.[72]

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 are typically based on past long-term hydrological trends; significant deviations from such trends may result in difficult challenges for water managers and water users alike.[73]

Conclusion

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. Current understanding is that the physical conditions causing drought in the United States are linked to sea surface temperatures in the tropical Pacific Ocean. For example, the 2011 severe drought in Texas is thought to be linked to La Niña conditions in the Pacific Ocean. Increasingly, studies are projecting the long-term role that droughts may play in regional climate patterns. Nonetheless, available technology and science remains limited to forecasting specific 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 represents a challenge to existing public policy responses for preparing and responding to drought.

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[71] Ibid., p. 7.

[72] Ibid., p. 9.

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