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Multidecadal Climate Variability and Drought in the United States

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Abstract

The history of multidecadal climate variability and drought in the United States during the past millennium is reviewed, and recent research into the physical mechanisms that produce long-term aridity is examined. Numerous multiyear droughts that have major social repercussions for contemporary and prehistoric societies can be identified in instrumental and proxy records. The 16th-century megadrought in the Southwest was the worst long period of aridity in the past 500 years. A prolonged period of aridity in the western United States from 900 to 1300 AD, which coincided with the Medieval Warm Period, is indicative of a mean shift in climate that ended in roughly 1400 AD. While the causes of these and other multiyear droughts are still under investigation, there is strong statistical and modeled evidence that persistent La Niña-like sea surface temperatures in the tropical Pacific force hemispheric and zonal symmetry in multidecadal droughts. In other words, persistent cooler than normal sea surface temperatures in the tropical Pacific force anomalous atmospheric circulations that produce multiyear droughts not only in the Great Plains and the Southwest, but also in the Mediterranean region of Europe, the Pampas region of South America, the steppes of Central Asia, and the outback of Western Australia. Other possible causes of long period drought include low-frequency variability in the north Pacific and Atlantic oceans and global warming in the Anthropocene.

Introduction

Prior to Hurricane Katrina, the two most expensive single-year weather-related disasters in the United States were the 1988 ($61.6 million) and 1980 ($48.4 million) droughts (costs normalized to 2002 US dollars; Ross and Lott 2006). According to the National Climatic Data Center's list of Billion Dollar US Weather Disasters Web site (http://www.ncdc.noaa.gov/oa/reports/billionz.html), single-year droughts have occurred somewhere in the United States about every 2 years since 1980, and have occurred in every region of the contiguous 48 states. The most basic definition of drought is that of an episode of unusually low precipitation that causes damage to agriculture, ecosystems and freshwater supplies (Heim 2002). Drought is not only economically expensive; it also carries an enormous social cost. While most people associate hurricanes and tornadoes with weather events that produce a large number of fatalities, droughts that are accompanied by heat waves kill several orders of magnitude more people than other forms of severe weather combined (Ross and Lott 2006). Both the 1980 and 1988 droughts and heat waves have been linked with nearly 10,000 deaths and the 2003 drought and heat wave in Europe killed more than 13,000 in Paris alone. Other social costs include losses due to wildfires, water restrictions, and decreased recreational opportunities on reservoirs. While there is no question that extreme single-year droughts can be economically and socially devastating, multiyear droughts, such as the one currently plaguing the western United States since 1999, can be even worse. Since the end of the 19th century, investigators have identified four major multiyear drought periods in the United States (Figure 1). The turn of the 20th-century drought struck the Southwest from 1899–1904 and is considered the worst in Arizona in the past 100 years (Goodrich and Ellis 2006). The Dust Bowl drought of the 1930s was worsened by poor agricultural practices and led to a massive out-migration in the Great Plains that continues to this day and is characterized in the *Grapes of Wrath* by John Steinbeck. The Southwest was struck by another devastating drought in the 1950s that was centered over New Mexico and Texas. Finally, parts of the western United States have suffered from drought conditions that have persisted in some locations since 1996 and continue to this day. While there are no exact figures of the economic costs of any of these droughts, there is no question that prolonged multiyear droughts have the capacity for even greater social cost than even the most extreme single-year drought. Recent tree-ring research suggests that 20th-century droughts pale in comparison to a 16th-century 'megadrought' that persisted for over 20 years in the southwestern United States (Stahle et al. 2000) and that even that megadrought pales in comparison to period of persistent aridity from 900 to 1300 AD that culminated with the demise of the Anasazi Indians from the Southwest (Cook et al. 2004). While droughts such as these are obviously exceptional, some have suggested that global warming from greenhouse gases may be accompanied by a return to multidecadal drought periods that were more common prior to 1600 AD (Cook et al. 2004). The implications for this are obviously important for a global society that will already be challenged by the other social and economic costs of global warming.

The goal of this review is to examine the current state of research on multidecadal climate variability and drought in the United States, to discuss current debates, and to highlight future research directions. While drought is a global phenomenon, this review will focus solely on the United States. Since the last comprehensive review of drought in the United States was prior to 2000 (Woodhouse and Overpeck 1998), this review will focus on research after 1998 in order to summarize new information from the numerous articles that have been published since then on drought. This review begins with a discussion of the four 20th-century

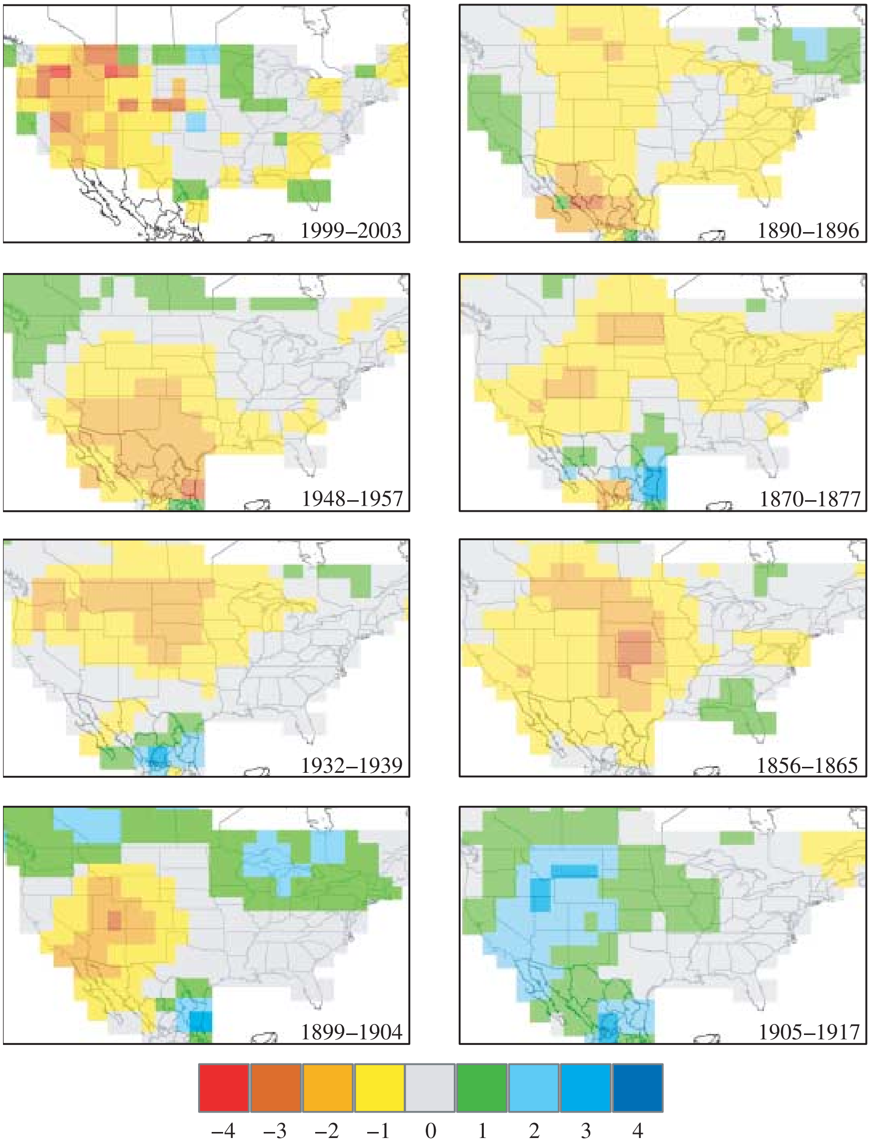

Fig. 1. Major multiyear drought and pluvial periods since 1856 AD. The 1999–2003, 1948–1957, and 1932–1939 drought periods are from Seager et al. (2005b); the 1899–1904 drought period is from Goodrich and Ellis (2006); the 1890–1896, 1870–1877, and 1856–1865 drought periods are from Herweijer et al. (2006); and the 1905–1917 pluvial is from Fye et al. (2003). All images were created from Cook et al.'s (2004) gridded historical Palmer Drought Severity Index (PDSI) dataset. Note that the 1999–2003 drought actually extends to 2006 but the Cook et al.'s (2004) dataset terminates in 2003.

multiyear drought periods that have been observed in the instrumental era. Since the 20th century is not representative of the full variability of drought in the United States (Woodhouse and Overpeck 1998), the second section discusses research that explores the paleoclimatic record of drought using tree-rings, coral, and lake sediments. Section three examines research that uses computer models to simulate historical drought patterns and multidecadal climate variability in order to understand and predict future multiyear drought patterns. Two current debates in the drought literature are presented: (i) which ocean basin is most responsible for forcing drought in the United States, and (ii) the expected impact of global warming on drought. The fourth section covers research relating to the social and biological impacts of multiyear drought. The article concludes with a summary and discussion of future directions for drought research.

Instrumental Era (1895–2006)

The Palmer Drought Severity Index (PDSI; Palmer 1965) is a drought index that uses temperature and precipitation values from the climate division dataset of the National Climatic Data Center along with other components of the water balance equation to measure the departure of soil moisture supply from normal. The output of the PDSI consists of positive (wet) or negative (dry) values centered on 0 (normal) with values above +4.0 or below –4.0 generally considered extreme. The PDSI is calculated for all 344 of the climate divisions (Guttman and Quayle 1996) in the United States back to 1895, which is considered to be the beginning of the instrumental era in the United States. Heim (2002) provides an excellent review of the PDSI and other drought indices that covers the methodology and limitations of the PDSI in more detail. Keyantash and Dracup (2002) provide a quantitative comparison of the PDSI and other commonly used drought indices such as the Standardized Precipitation Index (McKee et al. 1993, 1995). While the PDSI has been criticized for its complexity and has been found to be nonstationary through space and time (Guttmann 1998; Guttmann et al. 1992), the PDSI remains an important part of present-day drought monitoring (Svoboda et al. 2002). It also has been the primary drought index used in tree-ring reconstructions since the 1970s (Cook et al. 1999).

Karl and Koscielny (1982) and Diaz (1983) developed definitions for individual drought periods that involves the PDSI falling below a certain threshold of negative PDSI (i.e. –2.0) and then counting the number of months until the PDSI returned to positive values. While this works well for identifying individual drought events, it does not work for multiyear drought periods. Identifying the specific dates of the onset and termination of multiyear droughts can be difficult because most multiyear drought periods have brief wet spells (Meko and Woodhouse 2005) that may briefly allow the PDSI to rise above 0. A classic example of this is the 1999–2006 drought in the Southwest where the second wettest winter since 1895 in Arizona (which was believed by some to have ended the drought; Cook et al. 2006; Seager 2007) was followed by the driest winter of all time (which re-established the drought). It should be noted that the specific dates of the droughts mentioned in this section will vary from study to study (e.g. Fye et al. 2003 considered the Dust Bowl drought from 1929–1940 while Seager et al. 2005b used 1932–1939). The slight difference in onset and termination of the drought periods occurs because of differences in drought definitions and reconstruction methods. The specific drought periods used in this review will be cited back to the original authors for consistency and will be noted in each figure.

The variability of drought in the United States since 1895 is a subject that has been well studied (Dai et al. 1998; Diaz 1983; Englehart and Douglas 2002; Herweijer and Seager 2006; Herweijer et al. 2006; Karl and Koscielny 1982; Karl and Riebsame 1984; Mauget 2003a,b; Rajagopalan et al. 2000; Seager et al. 2005b; Zhang and Mann 2005). Using the 100-year plus record of the PDSI, investigators have identified four major multiyear drought periods during the instrumental era (Figure 1). From a climatological, social, economic, or cultural viewpoint, the 1930s Dust Bowl Great Plains is far and away the dominant drought period of the instrumental era (Fye et al. 2003) and remains the most widely studied (Cook et al. 1999; Schubert et al. 2004b). Severe drought during the Dust Bowl was centered over the northern Plains although mild drought occurred as far away as the southern Plains and the Mississippi Valley. The Southwestern drought periods of 1899–1904 and 1948–1957 represent the worst drought conditions during the instrumental record in Arizona and New Mexico, respectively. It is uncertain where the current drought that began in parts of the West in 1996 fits in with regards to the other 20th-century droughts, because there is not clear how long it will persist.

The seasonality of drought is very important depending on the geographic location. Droughts in the Great Plains have a greater impact in the summer months because that is the heart of the agricultural growing season. Droughts west of the Rockies have more impact in the winter and spring because that is when snowfall accumulates in high-elevation watersheds that supply water throughout the dry summer months. It is no surprise then that the Dust Bowl was associated with extremely dry summers but had winters of normal precipitation (Herweijer et al. 2006). In contrast, the 1950s drought was dry in both the winter and summer seasons (Herweijer et al. 2006). While a series of wet years ended all of the 20th-century droughts, the termination of the 1899–1904 drought was notable because it was immediately followed by the wettest period (pluvial) of the past 500 years (Fye et al. 2003). The pluvial from 1905–1917 has an important impact on current-day water resource management in the West because it led to the Colorado River Compact of 1922 that divides the flow of the Colorado river between the upper and lower Colorado River Basin states. The flow of the river that preceded the compact was anomalously high and many believe that continued withdrawals based on the flow from this pluvial are not sustainable (Woodhouse et al. 2005). Without question the four great droughts of the instrumental era all caused socioeconomic damage to the United States, but does the 20th century represent the full variability of drought in the United States? The following sections review research that use a variety of paleoclimatic proxies to study drought for thousands of years.

Proxy Record

Because the instrumental record of the 20th century represents only a small fraction of Earth's history, researchers of multidecadal drought have developed a number of ways to indirectly measure drought. A proxy is an indirect way of assessing climate by measuring the variability of the response of a proxy to climatic conditions. The proxy record is then gridded to account for differences in the density of proxy locations and calibrated to known instrumental records in order to determine the correlation between the proxy and climatic conditions (Cook et al. 1999; Woodhouse and Overpeck 1998). For example, tree growth as measured by annual rings is sensitive to temperature and precipitation during the growing season. When growing conditions are optimal, ring growth is maximized. However, when growing conditions are poor, such as during a drought, ring growth is minimized. For studying drought, tree-rings are best suited to create long-term records of PDSI dating back a thousand years due to the broad spatial coverage of trees, high sensitivity to temperature and soil moisture, long life-span, and annual resolution (Meko et al. 1995). For longer records of drought that extend back several thousand years, it is often necessary to supplement tree-ring chronologies with other proxies such as corals or lake sediments. Obviously with proxies, the quality of the resultant climate data strongly depends on the type of proxy used and the statistical methods used to generate the calibrations. For a thorough review of proxies used to study drought and their sources for and magnitudes of error, see Woodhouse and Overpeck (1998), Cook et al. (1999), Woodhouse (2004), and Cook et al. (2006). For alternative tree-ring methodologies that have been developed in recent years, see Hidalgo et al. (2000), Ni et al. (2002), and Zhang et al. (2004). Table 1 has a list of prominent US-based tree-ring laboratories and other institutions involved in developing paleoclimate proxies.

When paleoclimate proxies are used to extend the drought record, it becomes very clear that 20th-century drought does not come close to representing the full range of historical drought variability in the United States (Gray et al. 2004a; Pederson et al. 2006; Woodhouse and Overpeck 1998). Table 2 lists examples of important works and findings from studies

Table 1. Prominent research centers for the study of multidecadal drought variability.

Paleoclimate proxies
Lamont-Doherty Earth Observatory of Columbia University Tree-Ring Laboratory
Scripps Institute of Oceanography
University of Arizona Tree-Ring Laboratory
University of Arkansas Tree-Ring Laboratory
University of Colorado INSTAAR Dendrochronology Laboratory
University of Tennessee Laboratory of Tree-Ring Science
Climate modeling and climate variability
Lamont-Doherty Earth Observatory of Columbia University Division of Ocean and Climate Physics
National Center for Atmospheric Research
NOAA Climate Diagnostics Center
NOAA Climate Prediction Center
Scripps Institute of Oceanography
University of Washington/NOAA Joint Institute for the Study of the Atmosphere and Ocean (JISAO) Center for Science in the Earth System

Table 2. Major multi-year drought periods since 900 AD and findings from important works in dendroclimatology.

Western United States	Citation
16th-century megadrought (1560–1589 AD)	Stahle et al. 2000
900–1300 AD period of persistent aridity	Cook et al. 2004
Multi-year droughts rare in Northern Rockies since 1750 AD	Gray et al. 2004a
16th-century megadrought dry impulses w/wet years	Meko and Woodhouse 2005
Six major multi-year drought periods since 1856	Herweijer et al. 2006
Southwest	
1579–1598 AD worst drought since 1500 AD. 1660s most recent severe drought prior to 20th century	Meko et al. 1995
1855–1863 AD multi-year La Niña drought	Cole et al. 2002
16th-century megadrought worst since 1500 AD	Fye et al. 2003
1999–2004 drought seventh worst since 1500 AD	Piechota et al. 2004
1896–1904 drought worse than 1996–2004 in Arizona	Goodrich and Ellis 2006
Great Plains	
1930s Dust Bowl most severe drought since 1700 AD	Cook et al. 1999
1930s Dust Bowl most severe drought since 1500 AD	Fye et al. 2003
1856–1865 Civil War drought worse than Dust Bowl	Herweijer et al. 2006
Eastern/Central United States	
16th- and early 17th-century megadrought (East Coast) 14 wet/dry cycles since 1500 AD	Cronin et al. 2000
1300 AD most recent multidecadal drought (Great Lakes)	Booth et al. 2006

using paleoclimate proxies. Herweijer et al. (2006) showed that there have been three other multiyear drought periods (1856–1865, 1870–1877, and 1890–1896) in the 19th century that are similar in severity and geographic location to the four 20th-century droughts (Figure 1). The Civil War drought of 1856–1865 in the Great Plains is especially notable because it appears to be climatologically more severe than the Dust Bowl, although agricultural disaster was avoided because this region had not yet been farmed extensively (Herweijer et al. 2006). It has also been suggested that this period of aridity may have helped decimate the great Bison herds of the Great Plains (Woodhouse et al. 2002). Others, using different methodologies, conclude that the Dust Bowl is still the drought with the greatest severity and extent of the past several hundred years (Cook et al. 1999; Fye et al. 2003). Researchers have used the tree-ring record to find analogs, or historical drought patterns that are similar to modern-day droughts, to place the other 20th-century droughts into historical perspective. Fye et al. (2003) found that the 1950s drought in the Southwest was one of 12 droughts of similar severity over the past 500 years, while Piechota et al. (2004) used streamflow records and other proxies to determine that that the 1999–2004 drought period was the worst west of the Rockies since the 1899–1904 drought and was the seventh worst since 1500 AD.

While most recent drought research has taken place in the western half of the United States (where extended drought is more likely due to high interannual variability in precipitation; Diaz 1983), a few investigators have studied multidecadal drought in the eastern United States. Cronin et al. (2000, 2005), for example, found evidence of drought variability in Chesapeake Bay sediments over the past several millennia. More recently, they identified 14 dry/wet cycles since 1500 AD and found evidence of multidecadal droughts in the 16th and 17th centuries. Quiring (2004) also found evidence of multidecadal drought in the eastern United States during the 16th century and suggested that the droughts of 2002–2003 in the East were not unusual relative to the past 800 years.

Even worse than either the Civil War or Dust Bowl droughts is a multidecadal drought called the '16th century megadrought' that struck the southwestern United States (Stahle et al. 2000). This drought is widely believed to be the worst drought of the past 500 years (Cook et al. 2006; Herweijer et al. 2007; Gray et al. 2003; Meko et al. 1995; Stahle et al. 2000). Meko and Woodhouse (2005) show that drought in the Sacramento River Basin and Colorado River Basin is generally weakly correlated over the past 500 years but both were under the influence of the 16th-century megadrought. Fye et al. (2003) found that the 16th-century megadrought was ended by a pluvial similar to the one that ended the 1899–1904 drought. The 16th-century megadrought is linked with the demise of the native populations of northern Mexico (Acuna-Soto et al. 2002), where moderate drought conditions are believed to have persisted

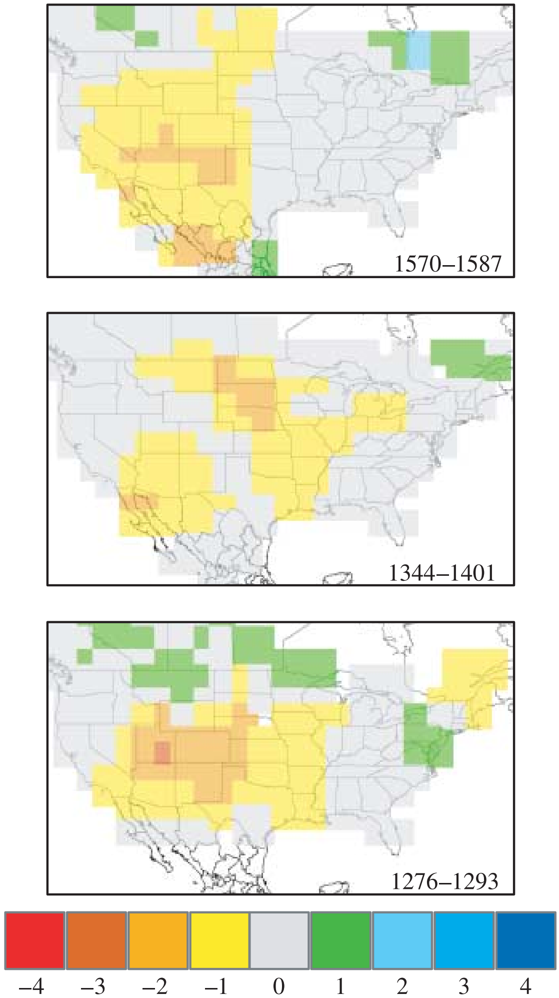

Fig. 2. Major historical drought periods related to the collapse of Native American societies. The 1570–1587 drought is associated with high death rates in Northern Mexico (Acuna-Soto et al. 2002), the 1344–1401 drought is linked to dissolution of Mississippi Valley chiefdoms (Cobb and Butler 2002), and the 1276–1293 drought is believed to have led to the collapse of the Anasazi of the Southwest (Axtell et al. 2002). All images were created from Cook et al.'s (2004) gridded historical Palmer Drought Severity Index (PDSI) dataset.

for over 40 years (Fye et al. 2003). Other multidecadal droughts have been linked with the collapse of native populations (Figure 2) include the Mississippi Valley chiefdoms at the end of the 14th century (Cobb and Butler 2002) and the Anasazi Indians in the Southwest at the end of the 13th century (Axtell et al. 2002). Cook et al. (2006) discussed the evidence of these notable droughts in detail.

The drought that coincided with the demise of the Anasazi Indians actually marked the end of a multicentury period of aridity from 900–1300 AD. (Cook et al. 2004; Stine 1994) that has been called the Medieval Warm Period (MWP). This 400-year dry period was marked by four peaks (936, 1034, 1150, and 1253) in drought intensity each separated by roughly 100 years (Figure 3). These peaks represent a drought intensity and coverage that is far greater than anything experienced in the United States since that time. Jones et al. (1999) suggested that this drought had a major impact on native populations throughout the western United States and forced tribes to constantly shift to find resources. It is believed that the aridity during the MWP represents a step-change in the mean state of drought in the United States because the variability of PDSI during this time is very similar to that experienced today (Cook et al. 2004). Figure 4 (adapted from Cook et al. 2004) represents the 60-year moving average of the Drought Area Index (DAI) that determines the percentage of grid points with PDSI < –1. The MWP can be seen to end abruptly around 1400 AD and the DAI exhibits a lower mean state with markedly less variability in the period known as the Little Ice Age (LIA; it should be noted that some scientists (Jones and Mann 2004 among others) disagree with the MWP and LIA terminology because they represent a regional viewpoint of the climate during this epoch (e.g. the tropical Pacific was cool during the MWP and warm during the LIA)). The DAI appears to increase in variability around 1850 AD, a period designated the beginning of the Anthropogenic Era due to the increased emissions of greenhouse gases. Cook et al. (2004) demonstrate that the DAI has increased steadily throughout the 20th century, although this is somewhat deceiving since the DAI at the beginning of the 20th century was at its lowest point since 800 AD because of the 1905–1917 pluvial. As seen from Figure 4, current levels of the DAI are similar to those that have occurred in the past 500 years.

The tree-ring drought record before 800 AD becomes sparse due to a lack of tree-ring chronologies that cover a large geographical area. However, researchers using lake sediments have extended the drought record back several thousand years across the United States. Benson et al. (2002) extend the drought record back to the beginning of the Holocene in the western United States and shows that wet and dry periods of more than 1000 years have alternated during the past 11,000 years and that the most recent 3000 years in the West has been relatively wet. Laird et al. (1996) showed multicentury dry periods similar to that of the MWP have occurred in the Great Plains, while Booth et al. (2005, 2006) discovered that a major 200-year drought occurred in the central United States around 4200 years ago and that multidecadal drought periods occurred roughly every 150 years until the end of the MWP. Graham (2004) showed that the Southwest has little relationship between drought and El Niño-Southern Oscillation (ENSO) for much of the past 1200 years.

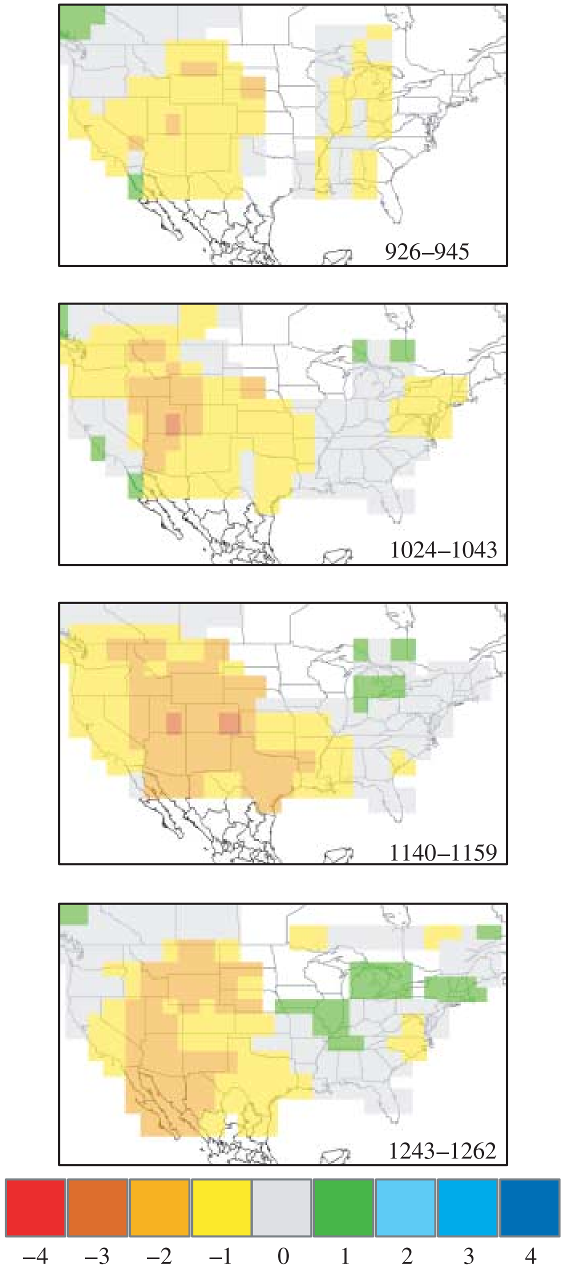

Fig. 3. Major 20-year drought periods during the Medieval Warm Period (900–1300 AD). The center of each period coincides with the peak in a drought epoch Cook et al. (2004) identified (Figure 4). All images were created from Cook et al.'s (2004) gridded historical Palmer Drought Severity Index (PDSI) dataset.

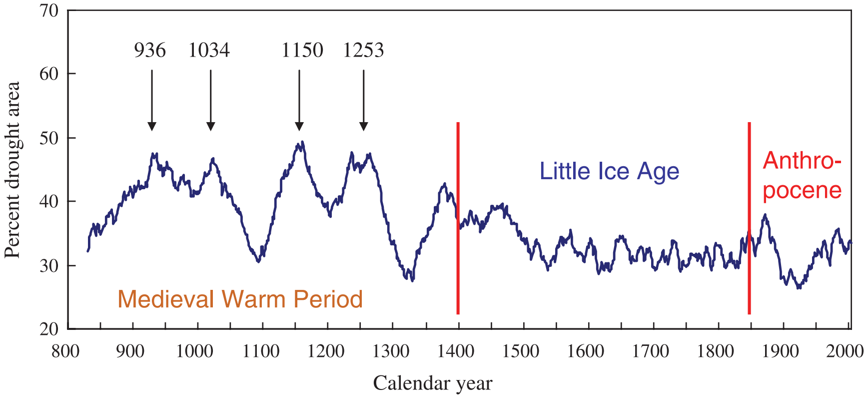

Fig. 4. Sixty-year moving average of the Drought Area Index (PDSI < –1) for the western United States. Note the marked shift to less drought variability and a lower mean state of aridity after roughly 1400 AD. The image was created from Cook et al.'s (2004) gridded historical Palmer Drought Severity Index (PDSI) dataset.

Millspaugh et al. (2000) go back the furthest in time (17,000 years) with their reconstruction of drought using charcoal records in Yellowstone National Park.

Modeling and Physical Mechanisms

Annual precipitation anomalies of only 15% below normal can lead to persistent drought (Cook et al. 2006). Any one year of 15% below normal rainfall will not cause major problems, but if these slightly dry years occur in succession for a decade the cumulative impacts become significant. Determining the cause of persistent drier than normal years is arguably the most important question in drought research. Not surprisingly, there is some disagreement concerning the dynamics of multidecadal drought. Nearly all drought researchers agree that multidecadal drought is forced by low-frequency variability of sea surface temperatures (SST). What is disagreed upon however is the location of the SSTs in question.

It is well known that year-to-year variability in precipitation across the United States is forced primarily from SST anomalies in the tropical Pacific Ocean by ENSO (Ropelewski and Halpert 1986) and that drought in the Southwest and Great Plains is linked to the cold phase of ENSO, or La Niña, while drought in the Pacific Northwest is associated with the warm phase of ENSO, or El Niño (Cayan et al. 1999; Dai et al. 1998; Piechota and Dracup 1996; Redmond and Koch 1991; Trenberth and Branstator 1992; Trenberth and Guillemot 1996; Trenberth et al. 1988). While single-year La Niña events involve SST anomalies that that can be as much as 1–2 °C, recent research suggests that multidecadal drought and pluvial periods are forced by small (on the order of 0.1–0.2 °C) but persistent SST anomalies in the tropical Pacific similar to La Niña events (Cole et al. 2002; Cook et al. 2004; Fye et al. 2004; Herweijer et al. 2006, 2007; Hoerling and Kumar 2003; Schubert et al. 2004a,b; Seager et al. 2003, 2005a,b). Herweijer et al. (2006) used the six major drought periods in the United States since 1856 to show that La Niña-like SSTs were found in every single case, while SSTs in other ocean basins were of variable sign. Schubert et al. (2004a), Seager et al. (2003, 2005a), and Herweijer and Seager (2006) used computer models to find hemispheric and zonal symmetry in global drought conditions from these La Niña-like SSTs, which they believe further suggests that the forcing is primarily tropical. In other words, when the Great Plains and the Southwest experience multiyear drought, similar conditions are also found in the Mediterranean region of Europe, the Pampas region of South America, the steppes of Central Asia, and the outback of Western Australia. Seager et al. (2003, 2005a) suggested three mechanisms are involved in creating global drought symmetry from persistent La Niña-like SSTs:

1. Cooler SSTs in the tropical Pacific (and hence cooler tropical troposphere) lead to a diminished pressure gradient between the mid-latitudes and tropics. This weakens the subtropical jet stream and forces it to move poleward, which leads to increased eddy transport of zonal momentum in the mid-latitudes. The poleward momentum transport leads to mass convergence in the upper troposphere, which then causes subsidence in the mid-latitudes (essentially a northward shift in the position of the subtropical high) leading to hemispheric symmetry of drought.
2. Zonal symmetry of drought is then caused by a Rossby wave train that is propagated from the tropics from the position of SST anomalies. Anticylonic circulation is teleconnected from the tropics to the southwestern United States and Great Plains.
3. Finally, multiyear droughts are strengthened by the persistence of dry soil moisture anomalies caused by a decrease in winter and spring precipitation. The reduced springtime soil moisture leads to a positive feedback mechanism whereby evapotranspiration is reduced which then decreases the amount of summer rainfall from convective storms.

This third mechanism is especially important in the Great Plains where the reduced soil moisture can actually lead to a reinforcement of the winter anticyclone during the spring and summer months over the Southwest that produces a northerly wind flow over the Plains, effectively shutting off the Gulf of Mexico as a moisture source. While the above studies used SSTs dating back to 1856 to force their models, there is also evidence that nearly all major multidecadal drought periods during the past two millennia, including the 400-year MWP, were also forced by persistent La Niña-like SSTs (Cook et al. 2004; Mann et al. 2005; Zhang and Mann 2005) that were a manifestation of solar and volcanic forcing. An increase in solar radiance due to increased sunspot activity along with a global decrease in volcanic activity during the MWP led to increased upwelling and a strengthened latitudinal pressure gradient in the tropical Pacific, which then created a positive feedback mechanism that led to a persistent La Niña-like state. The opposite occurred during the LIA when sunspot activity decreased and volcanism increased. See Cook et al. (2004, 2006) for a thorough discussion of the forcing of the Pacific Ocean during this time. Clearly, with such ample statistical and modeling evidence, the case for La Niña-like SSTs forcing drought is strong.

While the dynamics for the hemispheric and zonal symmetry of global drought have been well modeled in a number of recent articles, the authors do admit that there are some differences between the modeled results and observations (Herweijer et al. 2006, 2007; Seager et al. 2005b). In fact, some of their analyses, along with those of Schubert et al. (2004a,b) suggest that a secondary source of drought forcing may come from the Atlantic Ocean (Table 3). The Atlantic Multidecadal Oscillation (AMO; Delworth and Mann 2000) is a pattern of low-frequency variability in the North Atlantic Ocean with a period of roughly 60–80 years. The AMO has been shown to influence temperature and precipitation patterns in North America and Europe (Enfield et al. 2001; Gray et al. 2003, 2004b; Sutton and Hodson 2005) and is believed to be related to the thermohaline circulation. Others believe that low-frequency variability in the extratropical

Table 3. Multidecadal sea surface temperature (SST) variability from important works.

Atlantic Ocean	
70-year cycle in North Atlantic surface temperatures since 1670 AD	Delworth and Mann 2000
60–100 year cycle in North Atlantic SSTs since 1567 AD	Gray et al. 2004b
North Pacific Ocean	
1750, 1905, 1947, and 1976 major Pacific Ocean regime shifts	Biondi et al. 2001
PDO weakly related to drought prior to 20th century	Gedalof et al. 2002
Drought in Pacific Northwest related to low variance in PDO cycle	Knapp et al. 2002
Tropical Pacific Ocean	
900–1300 AD drought related to cool tropical Pacific SSTs	Cook et al. 2004
All multi-year droughts since 1856 have La Niña-like SSTs	Seager et al. 2005b
Multiple Ocean Basins	
La Niña/warm Indian ocean = perfect ocean for drought 1998–2002	Hoerling and Kumar 2003
US drought frequency controlled mainly by PDO and AMO	McCabe et al. 2004
Roughly 50-year cycles found in North Atlantic and North Pacific	Hidalgo 2004

Pacific, or Pacific Decadal Oscillation (PDO; Mantua and Hare 2002; Mantua et al. 1997), is an important driver of drought in the western United States (Barlow et al. 2001; Englehart and Douglas 2002; Hessl et al. 2004; Hidalgo and Dracup 2003; Pohl et al. 2002; Sheppard et al. 2002). Goodrich (2007) suggests that the reason that the Southwest is more prone to drought than the Pacific Northwest, even though both are equally impacted by ENSO in a dipole fashion, is because the impact of the cold phase of the PDO on years of neutral ENSO is similar to that of La Niña in the Southwest, leading to drier than normal winters 75% of the time. A few investigators (Balling and Goodrich 2007; Englehart and Douglas 2003; Hidalgo 2004; Knapp et al. 2004; McCabe et al. 2004; Tootle et al. 2005) have even suggested that the PDO and/or the AMO, and not tropical SSTs are the primary drivers of multidecadal drought in the western United States, while Meko and Woodhouse (2005) suggest that neither ENSO or PDO are consistently related to drought. The findings of McCabe et al. (2004) are quite interesting in that they show that more than half of spatial and temporal variance in multidecadal drought frequency in the United States is caused by the PDO and AMO. When cold PDO and warm AMO occur at the same time (1944–1963), the Southwest experienced the 1950s drought, but when warm PDO and warm AMO occur together (1926–1943), the 1930s Dust Bowl occurred. Because the current PDO phase is unknown (Mantua and Hare 2002) and the AMO is recently believed to have started what could be a 30-year warm phase (Gray et al. 2004b), they suggest that the next decade could bring drought to either the Southwest (cold PDO) or the Great Plains (warm PDO) depending on the phase of the PDO. It must be noted that the findings of McCabe et al. (2004) should be viewed with some caution because the period of record of their study (1900–1999) is barely longer than the length of the period of the AMO (60–80 years), it is unknown if the relationships they found during the 20th century are repeatable. Gray et al. (2003) and Hidalgo (2004) used tree-rings to represent PDSI and other proxies to represent oceanic variability to suggest that it is possible that the 16th-century megadrought may have been linked to warm AMO/cold PDO conditions. However, it must be noted that none of the works contain any discussion of causality and are not backed up by modeling results. In fact, some have suggested (Newman et al. 2003; Schneider and Cornuelle 2006 among others) that the PDO actually is not a dynamical mode and is a response to changes in the Aleutian low, distant ENSO forcing, and ocean wave processes associated with Rossby waves. However, it would not be surprising if the correct answer as to the dynamics of multidecadal drought is somewhere in the middle. There is ample evidence that drought modes in different geographical locations in the United States (Cook et al. 1999; Karl and Koscielny 1982) have had varying relationships to ENSO, PDO, and AMO over time (Balling and Goodrich 2007; Cole and Cook 1998; Cole et al. 2002; Gray et al. 2003, 2004a; McCabe et al. 2004; Overpeck and Webb 2000; Rajagopalan et al. 2000; Schubert et al. 2004a,b). Perhaps, the ENSO teleconnections to drought are modulated in some way by the AMO and PDO. Obviously, more research is needed to further establish the relationships between the AMO, PDO, and drought as well as to understand their dynamical relationship to ENSO.

While the dynamics of drought is still being debated, there remains the question of what causes persistence of La Niña-like SSTs for multidecadal time periods as in the 16th-century megadrought or even multicentury time periods like the MWP. It is well documented that in addition to the well-known interannual variability of ENSO that results in the familiar El Niño and La Niña events, ENSO also displays multidecadal variability (Cayan et al. 1998; Dai et al. 1998; Diaz et al. 2001; Mauget 2003a,b; Zhang et al. 1997; Zhang and Mann 2005) that some have suggested results from a modulation by the PDO (Brown and Comrie 2004; Cole and Cook 1998; Gershunov and Barnett 1998; Goodrich 2004; Gutzler et al. 2002; McCabe and Dettinger 1999, 2002). A number of other studies show multidecadal variability in the North Pacific (PDO) to be the primary mode of variability in the Pacific Ocean (Biondi et al. 2001; D'Arrigo et al. 2001; Dima et al. 2005; Gedalof and Smith 2001; Gedalof et al. 2002, 2004). Although several researchers have attempted to model Pacific Ocean decadal variability (Kleeman et al. 1999; Meehl and Hu 2006; Miller and Schneider 2000; Newman et al. 2003; Schneider and Cornuelle 2006; Schneider et al. 2002; Seager et al. 2004; Walland et al. 2000), there is not a firm consensus on the mechanism other than a relationship between wind stress and ocean dynamics (e.g. Rossby waves) and much uncertainty remains. Karspeck et al. (2004) demonstrate a modest level of skill in predicting multidecadal variability in the tropical Pacific and suggest that La Niña-like SSTs (and hence the drought in the Southwest) should persist for the next decade. However, accurate decade-long forecasts of the tropical Pacific remain an active modeling problem because the interactions between tropical forcing and extratropical atmospheric variability are hard to predict (Karspeck et al. 2004).

Societal Impacts and Global Warming

Multidecadal drought has had a dramatic impact on societies in the ancient past (Acuna-Soto et al. 2002; Axtell et al. 2002; Cobb and Butler 2002; Jones et al. 1999) as well as during the 19th (Woodhouse et al. 2002) and 20th centuries (Steinbeck 1939) in the United States. With the prediction by some that the current drought in the West may continue for the next decade (Karspeck et al. 2004; McCabe et al. 2004) governments and water resource managers are working together to develop federal (US Department of Agriculture 2000) and state drought plans (Goodrich and Ellis 2006; Wilhite 1991, 1997; Wilhite et al. 2000) that bring together stakeholders and policy-makers for drought planning and mitigation efforts. Jacobs et al. (2005) discuss the relationship between climate science and policy that went into the creation of the Arizona state drought plan (Governor's Drought Task Force 2004). Other impacts that multidecadal drought has on natural resources include increased forest fires (Gedalof et al. 2005; Hessl et al. 2004; Millspaugh et al. 2000), heat waves (Sutton and Hodson 2005), water resources (Meko and Woodhouse 2005; Morehouse et al. 2002; Woodhouse 2004), agriculture (Meinke and Stone 2005; Salinger 2005), and ecosystems (Easterling et al. 2000; Pederson et al. 2006). The impact of multidecadal drought and climate change on water resources has been particularly well researched in the Pacific Northwest (Hamlet and Lettenmaier 1999; Miles et al. 2000; Mote et al. 2003; Payne et al. 2004), which is an area that depends heavily on winter snowfall to supply summer water for agriculture, recreation and hydropower. The potential that global warming could worsen drought conditions in the western United States (Houghton et al. 2001) has spurred a number of special issues in the journal *Climatic Change* that have centered on the effects of climate change on water resources in the West (Vol. 62) and the impact of climate variability and change on agriculture and forestry (Vol. 70). Principal findings include a large reduction in winter snowpack from rising temperatures and a reduction in reservoir storage (Barnett et al. 2004) that suggests that water resource demands in the West will not be met in a greenhouse future. Model simulations (Leung et al. 2004) suggest that extended drought conditions will exacerbate the problem and that the watershed most at risk is the Colorado River Basin (Christensen et al. 2004). Food supplies are not at as great a risk because while agricultural productivity is expected to decrease in the southern United States due to increasing temperatures and reduced soil moisture, the northern United States is expected to be more productive due to a longer growing season (Motha and Baier 2005). While the expected changes to natural resources because of global warming may indeed take place even without an increase in multidecadal drought, there is a growing concern about what global warming may do to ENSO (Houghton et al. 2001). Because most multidecadal droughts in history have been shown to be heavily influenced by La Niña-like conditions, any change to the base state of the tropical Pacific could have dramatic influences on the aridity of the United States. Again, this topic is rife with uncertainty.

The impact of global warming on multidecadal drought is an important research question that is far from being resolved. Seager (2007) demonstrated this in his examination of the 1999–2004 drought in the Southwest. The period from 1998–2002 fit well with the theory that the tropical Pacific is responsible for forcing drought as La Niña-like SSTs persisted during this time so consistently that Hoerling and Kumar (2003) labeled it the 'perfect ocean' for drought. El Niño conditions developed from 2002–2004 that normally would signal wetter than normal conditions in the Southwest. However, a localized ridge remained over the region, which breaks down the theory of hemispheric and zonal symmetry in the atmosphere from tropical Pacific forcing (e.g. the drought over the Pampas region of South America was ended during this time). Seager (2007) suggested a number of hypotheses to explain the continued drought, including forcing from another ocean basin and poor modeling, but Hoerling and Kumar (2003) hypothesized that global warming led to increased warming of the western tropical Pacific and Indian Ocean, which then teleconnected to a ridge over the Southwest.

Studies attempting to determine exactly how global warming will affect ENSO generate a wide range of results. In the late 1990s, it was initially believed that the increase in number and strength of El Niño events experienced because the late 1970s was a precursor of a shift to a mean El Niño state in a greenhouse future (Trenberth and Hoar 1997). Modeling results suggested this may indeed be true (Boer et al. 2004), which suggests multidecadal drought in the United States would occur less often in a warmer world. However, other recent modeling work (Cane 2005; Cook et al. 2004) predicted a shift to a mean La Niña state. Cook et al. (2004) argued that as heating in the tropics from increased solar radiance during the MWP led to persistent La Niña-like SSTs, so should an increase in tropical heating from greenhouse gases. This argument gets clouded by Mann et al. (2005) who used modeling results to demonstrate that the strong relationship between solar/volcanic forcing and tropical Pacific SSTs that has existed since at least 1000 AD appears to break down just prior to the 20th century. Meehl et al. (2004) performed a similar modeling experiment and found that the transition from natural (solar) to anthropogenic forcing occurred in the early 20th century. Both suggest that caution should be taken when interpreting any modeling results of tropical Pacific variability in a greenhouse environment. This line of thinking is bolstered by Zelle et al. (2005) who found no change in the variability of ENSO at all. Even if there is no change in the mean state of ENSO, it is possible that multiyear drought could easily persist in the United States due to the positive feedback mechanisms outlined by Trenberth et al. (2003) that posit that increased evaporation and precipitation intensity will lead to increased runoff and decreased soil moisture that can lead to persistence in drought, especially in the continental interior (Great Plains).

Summary and Future Directions

This review has outlined the history of multidecadal drought in the United States during both the instrumental era (1895–2006) and before. Four multiyear droughts were identified (Southwest 1899–1904, Dust Bowl 1932–1939; Southwest 1947–1958; western United States 1999–2006) with the Dust Bowl found by many investigators to be the worst drought since at least 1700 AD. A 16th-century megadrought that decimated native populations in northern Mexico persisted for as many as 40 years and is widely considered to be the worst drought in the past 500 years. However, none of the droughts in the second half of the past millennium compared to a 400-year period of aridity during what is known as the Medieval Warm Period. While the causes of these multiyear drought periods is still actively being investigated, there is strong statistical and modeled evidence that persistent La Niña-like SSTs in the tropical Pacific force hemispheric and zonal symmetry in multidecadal drought. Others suggest that the PDO and AMO are more influential in controlling multidecadal drought. Based on the evidence thus far, it appears the correct answer may be that ENSO teleconnections, which likely represent the primary forcing mechanism for drought in the United States, are modulated in some way by secondary forcing mechanisms represented by multidecadal changes in the extratropical Atlantic and Pacific. Another area of uncertainty in the study of multidecadal drought is the impact of greenhouse-gas-related global warming to drought, and more specifically, how increased radiative forcing will affect ENSO. Solutions range all the way from a change to a mean La Niña state to a change to a mean El Niño state. The wide range of solutions to this problem shows that much more work is needed regarding the topic of climate change and ENSO.

Governments and policy-makers are collaborating to develop drought plans that will incorporate scenarios that cover all manner of predictions that account for the uncertainties regarding the future of drought and climate change described in this review. The region seemingly most at risk at this time appears to the Colorado River Basin, whose system of water allotment was developed during a time of abnormally high runoff during the 1905–1917 pluvial. This region is also at risk due to positive feedback mechanisms that lead to increased runoff and decreased soil moisture that are expected to occur in a warming world. Some scenarios suggest that the entire system of water delivery on the Colorado River could collapse if the current drought in the Southwest persists. For this reason, I feel that one area of drought research that needs more emphasis is that of scenario modeling on the impacts of drought on natural resources such as water resources and agriculture, and how specific regions that are at risk for multiyear droughts can adapt to a range of climate futures. By developing decision-making strategies that account for the uncertain future of how drought in a greenhouse world might affect the United States we may better withstand socioeconomic implications of multiyear droughts.

Short Biography

Greg Goodrich is an Assistant Professor in the Department of Geography and Geology at Western Kentucky University in Bowling Green, KY, USA. His research is focused on the influence of low-frequency variability of sea surface temperatures on drought and precipitation patterns in the United States. He has authored or co-authored articles related to this topic in journals such as *The Professional Geographer*, *Weather and Forecasting*, *Climate Research*, and *Climatic Change*. He received his MA and PhD in Geography from Arizona State University in 2003 and 2005, respectively.

Note

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