Aquat. Sci. 66 (2004) 346–356
1015-1621/04/040346-11
DOI 10.1007/s00027-004-0723-8

Aquatic Sciences

Review Article

A paleo perspective on hydroclimatic variability in the western United States

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Received: 13 October 2003; revised manuscript accepted: 10 February 2004

Abstract. Aquatic resources management has become increasingly challenging as human demands on water supplies compete with the needs of natural ecosystems, particularly in arid lands. A wide range of factors, both natural and human, influence aquatic environments, but an important underlying component is climate variability. Instrumental records of hydroclimatic variability from precipitation, streamflow, and snowpack are limited to 100 years or less in most areas of the western U.S., and are too short to provide more than a subset of the full range of natural climate variability. Paleoclimatic proxy data from a variety of sources can be used to extend instrumental records of climate back centuries to tens of thousands of years and longer. In this review, four drought events over the past three millennia, each documented with a number of proxy records, illustrate natural hydroclimatic variability characteristics over the western U.S. Although a small sample of paleoclimate data, these four events exemplify the wide range of natural hydroclimatic variability over space and time. Climate is now, and will continue to be, impacted by human activities, but natural climatic variability will likely be an important underlying factor in future climate variability and change.

Key words. Paleoclimatology; drought; western U.S..

Introduction

Aquatic resources management has become increasingly challenging as human demands on water supplies compete with the needs of natural ecosystems. In arid lands, management challenges are compounded because of the scarcity of surface water, highly variable rainfall, and periodic droughts. A wide range of factors, both natural and human, influence aquatic environments, but an important underlying component is climate variability. Natural variations in moisture-related climate variables such as precipitation, snowpack, streamflow, and drought have impacts on aquatic ecosystems on time scales that range from minutes to tens of thousands of years and longer. Understanding the influence of hydroclimatic variability on aquatic ecosystems is necessary for the study of these ecosystems and the management of aquatic resources. Knowledge about the possible range of natural climate variability at a variety of time scales is critical for management that balances ecosystem requirements with agricultural, economic, and social demands, and is key to planning for the future, particularly in arid regions.

Instrumental records of hydroclimatic variability provide some baseline information about the range of climate variability. However, in many areas of the western U.S., these records only extend about 100 years, and thus may represent only a subset of the range of natural climate variability possible. This period of time is not long enough to assess whether major hydroclimatic events of the 20th century such as the droughts of the 1930s and 1950s are characteristic over longer time spans. Fortunately, natural landscapes and ecosystems have recorded hydroclimatic variability as physiological and geological responses to the environment, and a number of these nat-

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ural records are far longer than the instrumental records kept by humans. We can use these natural climate proxies to extend the modern instrumental climate record back in time to assess the representativeness of the period of instrumental record, and to place extreme events of the 20th and 21st centuries into a broader temporal context.

Proxy records of hydroclimatic variability originate from a variety of sources, each characterized by a set of strengths and weaknesses that are related to spatial and temporal resolution, and precision and accuracy of dating. In the western U.S., proxies range from precisely-dated annual records from tree rings, extending hundreds to several thousands of years, to lake sediment data that extend back tens of thousands of years, but with a coarser temporal resolution and lower dating accuracy. Paleoclimatic records from different sources can be pieced together to provide a history of hydroclimatic variability over many time scales and regions. The paleoclimatology of the western U.S. is too large a topic to cover in one review. Instead, this paper will provide some perspective on the range of natural climate variability in the western U.S. by focusing primarily on drought in the southwestern U.S. (including California, Nevada, Arizona, New Mexico, Utah, and Colorado), and through the discussion of four different drought events of varied temporal and spatial scales, including some of their impacts on ecosystems and human activities. These include:

- The 2002 Colorado drought in a 300-year context
- Widespread drought conditions in the late 16th century
- The "Great Drought" of the 13th century and the Ancient Puebloans
- Late Holocene aridity and the Medieval Climatic Anomaly.

Before discussing the paleoclimatic records of drought, 21st and 20th century droughts will be examined to provide a point of reference for the paleodroughts.

Drought in the 20th and 21st centuries

The most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts (Karl and Heim, 1990). Other less extensive droughts had severe regional impacts, such as drought in the 1960s, primarily impacting the northeastern U.S., and the late 1980s drought in the mid-west and northern Great Plains (Diaz, 1983; Riebsame et al., 1991). The 1930s Dust Bowl, which lasted most of the decade of the 1930s, occurred in several waves. It most strongly affected the northern half of the country, and in particular, the Great Plains (Karl and Heim, 1990). The drought had a tremendous impact on agriculture, exacerbated by farming practices that resulted in loss of topsoil due to wind erosion (Lockeretz, 1978), and accompanied by migration of up to 50% of the population out of some areas. (Bowden et al., 1981). The 1950s drought was centered in the southern half of the country, most severe in the Southern Plains and southwestern U.S, and also occurred in several waves over the years 1951 to 1956 (Diaz, 1983; Karl and Heim, 1990). Some of the farming techniques put into practice after the Dust Bowl drought helped mitigate the impacts of the 1950s drought, but drought devastated agriculture across large areas of the southern Plains (Lockeretz, 1978). By the time the drought subsided in 1957, many counties across the region were declared federal drought disaster areas, including 244 of the 254 counties in Texas (Jensen, 1996).

More recently, three consecutive years of drought, 2000–2002, affected much of the western U.S., with more persistent drought conditions continuing in Utah, Arizona, and parts of Nevada (Climate of 2003-June Utah Drought, National Climatic Data Center; Waple and Lawrimore, 2003). Although an extreme drought in some regions (e.g., Colorado experienced the driest year on record in 2002), this drought does not come close to matching the extent and duration of the Dust Bowl or the 1950s droughts. Drought conditions were most severe and widespread in the summer of 2002, when slightly more than 50% of the contiguous U.S. was under moderate to extreme drought. In contrast, in the worst year of the Dust Bowl drought, 1934, 80% of the U.S. was under moderate to extreme drought, and the areal extent of the 1950s drought topped 50% for five consecutive years (U.S. Drought, Climate of 2002 – Annual Review, National Climatic Data Center). In 2003, drought conditions still persisted in some areas, and the full outcome of this current drought is unknown. Given the limited length of the instrumental record, it is not possible to gage the abnormality of the 1930s and 1950s droughts, or to estimate how likely it is that similar droughts will occur in the future.

Information about drought from paleoclimatic proxy data

Instrumental records of climate can be augmented by other sources of climate information to extend the instrumental records back in time. Information on past droughts comes from historical documentary, biological, and geological sources, each with characteristics related to the length of record, dating accuracy and precision, inherent biases, and geographic availability. In the western U.S., some of the primary sources of information on past drought are historical documents, tree rings, eolian, lake, and to some degree, ocean sediments.

Historical documents

Historical documents in the form of letters, diaries, newspaper accounts, and early instrumental measurements are available in the western U.S., although limited in length and location. These records can provide accurately dated, detailed accounts of short-term climatic variability and events, but very few extend prior to the mid-19th century in the western U.S. The interpretation of some of these accounts can be problematic as they may be biased due to the perspectives of the observer. Although there are a number of early instrumental records for stations in the western U.S., most records are short and/or discontinuous, with irregular observations, and critical information about recording sites (station characteristics) may be inaccurate or missing completely (Bradley, 1976). However, some work has been done to piece records together to obtain a more complete record of 19th century climate for areas such as the Rocky Mountains (Bradley, 1976) and the Great Plains (Mock, 1991).

Tree-ring data

Tree rings provide annually or seasonally resolved data that are precisely dated to the calendar year. Tree-ring records commonly extend 300 to 500 years into the past, but a small number are thousands of years long (e.g., Hughes and Graumlich, 1996). Dendrochonology, the science that deals with the dating and study of annual growth rings, is based on the fact that trees at mid- to upper-latitudes grow one ring per year, and the current growth year ring is formed from the cambium, next to the bark (Fritts, 1976). This fact allows the establishment of the date of the most recent growth ring. Subsequent ring dates are determined through a ring-width pattern matching technique called crossdating (Fritts, 1976; Stokes and Smiley, 1968). Variations in ring width in trees that are primarily responding to climate (as opposed to those that are strongly affected by competition or disturbance such as insect infestation) reflect regional variations in climate. Thus, the ring patterns are similar from tree to tree and can be used as climate proxy data. Trees that are growing in arid or semi-arid areas, on open, dry, rocky, south-facing slopes, are stressed by moisture variability and are usually the most suitable trees for reconstructing hydroclimatic variability (i.e., precipitation, streamflow, drought indices) (Fritts, 1976).

To develop a reconstruction of a hydroclimatic record, tree-ring data, in the form of site chronologies (a composite time series from 20 to 30 trees in a site), are calibrated with an instrumental record for the period of time common to both. Typically a linear regression model is used, with tree-ring chronologies as the predictor variables, and the instrumental record as the variable to be estimated (Fritts, 1976; Cook and Kairiukstis, 1990). The resulting model is applied to the full length of the tree-ring data to generate the reconstruction.

Eolian sediments

Large areas of the intermountain basins of the western U.S. contain sand dunes and other eolian features, most of which are now stabilized by vegetation (Forman and Pierson, 2002; Muhs, 1997). The sand dunes and sheets were deposited by the wind in times of drought and contain a wealth of information about episodes of drought and aridity over the course of the Holocene, the past 10,000 years (the period since the end of the most recent widespread glaciation). The layers of sand, representing periods that became too dry to support vegetation, are interspersed with layers of soil, which reflect periods that were wet enough to allow soil to form and support plant life. The soil layers, which contain organic materials, can be dated with radiocarbon dating techniques. The dates from the soil layers between layers of sand can be used to bracket times of drought as signified by the presence of sand. Since there is a lag in time in the geomorphic response to climate conditions, this record is fairly coarse in terms of time scales that can be resolved (Muhs and Holliday, 1995). Radiocarbon dating, with a dating precision of +/– 5% or more during certain periods in the Holocene (Bradley, 1985; 1999), contributes to low temporal resolution of this record. However, recent work has used optically stimulated luminescence techniques to date sand grains, producing decadal scale resolution for the past 1,000 years (Forman and Pierson, 2003).

Lake sediments

Materials that flow, wash, or blow into lakes (e.g., water, dust, macrofossils, pollen) and materials produced in lakes (biological or chemical) are indicative of the environment at the time of deposition (Bradley, 1999). Consequently, cores taken from lake bottoms contain a record of past environmental variability. Samples taken from cores at regular intervals are subject to a variety of analytic processes to examine the biologic and geochemical composition of the core over time. Analyses produce indirect evidence of a range of environmental conditions including temperature, salinity, vegetation, geomagnetic field variations, water balance, chemical composition of water, and changes in these conditions (Bradley, 1999). Biological indicators of environmental variability include changes in diatom (Fritz et al., 1999) or ostracode (Smith, 1993) species composition or shell chemistry which reflect changes in lake salinity or depth. In chemical analyses, the oxygen isotope, $\delta^{18}O$, found in calcareous materials, is commonly analyzed as an indicator of hydrologic variability (e.g., evaporation, lake volume change, air and water temperature, and inflows). Variations in total inorganic carbon (TIC) from aragonite generally indicate changes in wetness, with decreased TIC corresponding to increased wetness (Benson et al., 2002). Magnetic susceptibility is also a hydrologic indicator, with the amount of magnetite (in sediments washed into a lake and an element of magnetic susceptibility) an indication of lake size (Benson et al., 2002). The time series of biological and chemical variations are anchored in time using radiocarbon dating and paleomagnetic secular variations (50–100 year accuracy) (Benson et al., 2002). Records extend tens of thousands of years and longer (Bradley, 1999).

Ocean sediments

Ocean sediments provide information about past ocean surface conditions as well as conditions on adjacent land. Similar to lake sediments, ocean sediments are comprised of materials that are washed, blown, or otherwise transported into the ocean from land, and biological materials produced in the ocean. Materials that originate in ocean environments make up the bulk of marine sediments and include remains of planktic and benthic organisms, that are near surface- and bottom-dwelling organisms, respectively. Cores taken from the sea floor are sampled, dated, and analyzed at discrete intervals to produce a time series of environmental change. Terrestrial materials, such as dust, ash, and materials imbedded in sediments can provide information about aridity, ice sheet growth and decay, and wind strength and direction (Bradley, 1999). Analyses of biological materials (oxygen isotope and trace metal composition of plankton shells, assemblages of organisms, and species morphology) can provide information about past oceanic conditions including sea surface temperatures, salinity, and upwelling (Bradley, 1999). The ratio of the two stable isotopes of oxygen (^{16}O and ^{18}O) is particularly useful in hydroclimatic studies because it is influenced by evaporation and precipitation over the ocean, as well as runoff of isotopically-light water from the adjacent land surface. Ocean sediment cores that are undisturbed by bioturbation and have high sedimentation rates can be sampled at annual to centennial scales, and radiocarbon dated to provide a fairly high-resolution record for the Holocene (e.g., Kennett and Kennett, 2000). Longer ocean sediment records, up to 170 million years, are sampled at 1000-year intervals and longer, and are dated using a variety of techniques (based on uranium/thorium, potassium/argon radioisotopic techniques), that become less precise going back in time (Crowley and North,1991; Kennet, 1982).

The 2002 Colorado drought in a 300-year context

Severe drought in 2002 impacted much of the western U.S., but was particularly severe in Colorado (U.S. Drought, Climate of 2002 – Annual Review, National Climatic Data Center). A tree-ring based record of mean annual streamflow for the South Platte River, in the Colorado Front Range, can be used to evaluate the 2002 drought and other droughts in the gage record within context of past centuries. Three gage records on the South Platte River, reconstructed with tree-ring chronologies from western Colorado and the Colorado Front Range, were combined to create a composite streamflow reconstruction for the South Platte River for 1685–1987 (Woodhouse et al., 2003) (Fig. 1a). When the annual flow value for 2002 is compared to the full record, the reconstruction suggests that the severity of 2002, as a single year, has been matched or exceeded about eight times, taking into account the uncertainty in the reconstruction model. Although a severe and relatively rare drought year, the intensity of 2002 is not unprecedented. When 2002 is considered the third year of a three-year drought, as many water managers have, it is a less rare occurrence. In fact, a number of gages in the Front Range show the drought years of 1954–56 to be cumulatively more severe than 2000–2002. Similar results are found in streamflow reconstructions for the Upper Colorado River (Woodhouse et al., 2003).

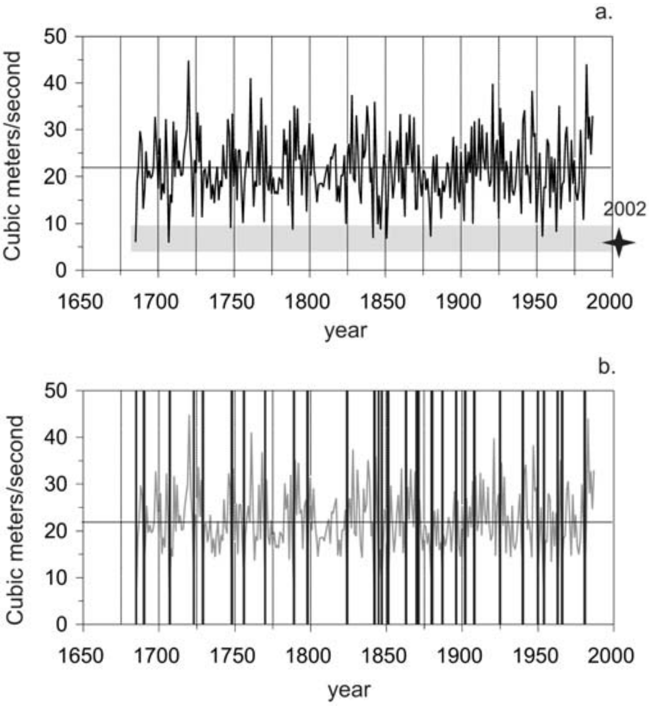

Figure 1. a) Reconstruction of annual streamflow for the South Platte River (composite of three gage reconstructions), A.D. 1685–1987. The 2002 value is marked with a star. The gray horizontal bar indicates years with reconstructed values that match or exceed 2002, taking into account the uncertainty in the reconstruction. b) South Platte annual streamflow reconstruction with years in the driest 10th percentile indicated by vertical bars.

The annual flow values in the South Platte composite reconstruction can be categorized into percentile classes. When the extreme low flow years (lowest 10th percentile) are examined, their distribution is found to be uneven over time (Fig. 1b). In the 20th century up to 1987, nine years fall into this category and the gage record suggests no additional years between 1988 and 1999 fell into this category. In comparison, 11 extremely dry years occurred in the 19th century, but 10 of these are clustered between 1840 and 1899, and in particular, four extreme years occur between 1842 and 1851. In the 18th century, there are just eight extremely dry years, distributed quite evenly over the century. The drought year of 2002 falls within this driest 10th percentile, and the reconstructions suggests that extremely dry years, such as 2002, can be evenly spaced or clustered in time. As a single year extreme event, the 2002 drought has been remarkable, but manageable. The spatial extent of drought had contracted by 2003, but if severe widespread drought conditions were to return, impacts would likely have much greater consequences.

The cluster of extremely dry years in the mid-19th century is a notable feature in the full reconstruction (Fig 1b). This period of drought occurred just before the settlement of the western Great Plains in the late 1850s (West, 1995). Thus, there are no early instrumental records of precipitation or temperature, although written accounts do exist that provide some evidence of drought conditions at the time. Muhs and Holliday (1995) assessed accounts by 18th and 19th century explorers that documented blowing sand and dune activation from the Nebraska Sand Hills to northern Texas, areas now stabilized by vegetation. Multiple observations of eolian activity were reported between 1845 and 1860 suggesting intensified drought conditions, although because of the lag in geomorphic response to aridity, it is not possible to attribute this activity to a specific drought year or set of years (Muhs and Holliday, 1995).

The impacts of this drought are difficult to assess. The decimation of the bison population coincides with this period of drought, but other factors complicate the evaluation of drought impact on bison, including hunting by both Native Americans and Euro-Americans, and land use changes (Flores, 1991; West, 1995; Isenberg, 2000). Bison evolved under a climate regime that included periods of prolonged aridity far more severe than the mid-19th century drought (Muhs, 2000). However, the environment to which bison had been long-adapted was disrupted by human activities in the mid-19th century (Bamforth, 1987), possibly causing the multi-year drought to have a more significant impact than it would have under more natural conditions. Competition for grasslands from cattle and horses on ranges already affected by drought, in combination with limited access to the riparian areas that formerly offered refuge from drought, likely compounded the effects of this drought on the bison population and may have been an important factor in the population demise (Flores, 1991; West, 1995; Isenberg, 2000; Woodhouse et al., 2002).

The impact of such a drought would be considerable if it were to occur today. The 2002 drought caught Colorado water managers by surprise, and brought the realization that 20th century gage records do not contain the full range of hydroclimatic variability possible. The tree-ring reconstructions allow 2002 flow values to be evaluated in a longer time frame and indicate that, as severe as it was, the 2002 drought was not unprecedented in the past three centuries.

Drought in the late 16th century – the "16th Century Megadrought"

A remarkably widespread and persistent period of drought in the late 16th century was identified in a review of proxy records for the Great Plains and western U.S. (Woodhouse and Overpeck, 1998). Stahle et al. (2000) further investigated this drought using a network of tree-ring data for North America to document the spatial coverage of drought conditions at this time in regions that ranged from northern Mexico, to British Columbia, and to the eastern seaboard of the U.S. The period stands out as one of widespread, spatially and temporally overlapping drought conditions across much of North America.

A recent study has taken a regional look at this 16th event by comparing drought conditions for two major watersheds of the western U.S., the Sacramento and the Upper Colorado River basins. Tree-ring based streamflow reconstructions for both the Sacramento River and Blue River (in the Upper Colorado R. watershed) show concurrent drought conditions in the late 16th century (Meko and Woodhouse, unpublished). Drought was particularly severe in the Sacramento River reconstruction which indicated the driest three-year period in the entire reconstruction (extending to A.D. 869) was 1578–1580 (Meko et al., 2001). The late 16th century was one of the few periods of drought shared by both the Sacramento and Blue River reconstructions over the 500 years common to both records (Fig. 2). Were drought conditions in the two

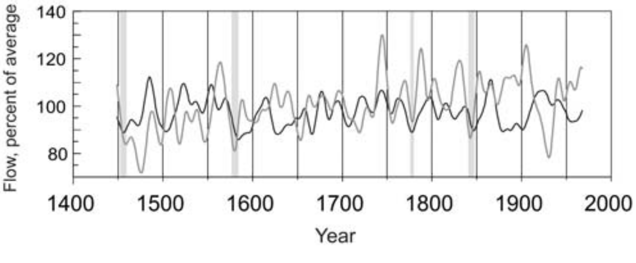

Figure 2. Smoothed time series of annual streamflow for Sacramento (light line) and Blue (dark line) Rivers, reconstructed from tree rings, A.D. 1440–1977. The smoothing is based on a 20-year Gaussian filter. Values are percent of average, based on the 1916–1977 reconstructed mean for both rivers. Periods of shared drought are indicated by vertical bars.

basins due to two separate but coinciding droughts, or to one widespread drought? A network of 169 moisture-sensitive tree-ring chronologies across the western U.S., proxies for drought, provided a more detailed analysis of the spatial and temporal patterns of this drought period (Meko and Woodhouse, unpublished). Maps of annual tree-growth anomalies showed that from 1580–1600, widespread drought (flows at less than the 80th percentile for both basins and broad areas of tree growth in the lowest quartile) occurred in six years, 1580, 1581, 1584, 1585, 1590, and 1600. This study indicates that the drought was indeed severe and widespread for several sets of consecutive years, broken by wetter years or years in which drought was less widespread across the region. It is likely that one atmospheric circulation mechanism was responsible for drought in both watersheds, but more work is needed to further investigate this idea.

The regions most severely affected by drought in the 16th century extended beyond U.S. borders to include northwestern Mexico and as well as the southwestern U.S., where drought conditions were the most intense and persistent in over 500 years (Stahle et al., 2000). Impacts on human society and natural ecosystems were undoubtably considerable, and several studies have documented the impacts of this drought on landscapes and human life in these areas. Swetnam and Betancourt (1998) surveyed stand ages of 143 conifer sites in Arizona and New Mexico. They utilized tree-ring data from collections for climate reconstructions that had been compiled from old-aged living trees over several decades. By examining the innermost rings of all trees (a total of 1967) and dividing them into 20-year age classes, they were able to plot the numbers of trees and their approximate dates of establishment over time. The distribution of establishment dates show that few old-age trees recruited into stands before about 1600, though many established after the turn of the 17th century, suggesting harsh climatic conditions through the end of the 16th century (Figure 12 in Swetnam and Betancourt, 1998). In addition to the southwestern U.S., there is also evidence of vegetative response to drought in the western Great Plains, where widespread mobilization of sand dunes in the dune fields of eastern Colorado and the Nebraska Sand Hills was found to have occurred about this time (Muhs et al., 1997; Stokes and Swinehart, 1997).

Two severe epidemics of cocoliztli in the highlands of Mexico coincided with drought in the 16th century documented with tree rings (Stahle et al., 1999; Acuna-Soto et al., 2002). Cocoliztli is thought to be an indigenous virus carried by rodents (Acuna-Soto et al., 2002). It is hypothesized that during drought, rodent populations were concentrated around resources, facilitating the spreading of the virus. When favorable climate conditions returned, the infected rodent population burgeoned, spreading the virus to homes, farmland, and human populations (Acuna-Soto et al., 2002). Historical accounts indicate that vast numbers of people were killed by these two epidemics, with estimates of up to 80% of the indigenous population killed in the outbreak from 1545–1548, and an additional 50% of the remaining population in the 1576–1578 outbreak. Epidemics of cocoliztli appear to have been exacerbated by severe drought and poor living conditions.

The details of the nature of this drought remain to be explored, and of particular interest are possible causal mechanisms for such widespread drought occurrence. Examining the timing and spatial coverage of drought conditions over the second half of the 16th century may provide some insights on different circulation mechanisms that, together, may have resulted in drought across the continent. For example, conditions in the North Atlantic that are conducive to drought along the east coast may have coincided and persisted along with a cool phase ENSO event which typically causes drought in the southern and southwestern U.S. (Cook and Lall, 2002). An understanding of drought forcing mechanisms and their interactions is critical for assessing current and future vulnerabilities to drought.

"The Great Drought" of the 13th century and the Ancient Puebloans

Tree-ring data document a drought in the last quarter of the 13th century (1276–1299) that came to be known as the "Great Drought" after being identified by A. E. Douglass (1929) in his archaeological work in the southwestern U.S. Douglass was attempting to bridge the gap between the undated timbers collected from ruins, and wood from living trees and more recent Hopi dwellings, and in the process, identified several "great droughts" (Douglass, 1929). However, the coincidence between drought in the late 13th century and the abandonment of large areas of the Colorado Plateau by prehistoric Ancient Puebloans led to a theory that this "great drought" was the primary cause of the abandonment. In recent years, this has been hotly debated and new agent-based modeling studies have suggested that the drought alone was not enough to depopulate the region. (Van West, 1991; Dean et al., 1999). Other causes have been suggested that include warfare, cultural and ideological factors, and the over-use of natural resources (e.g., Dean, 1969; Lipe, 1995).

Paleoclimatic data support the occurrence of a widespread drought at the end of the 13th century. Although less tree-ring data are available for this time compared to that for the 16th century, long moisture-sensitive tree-ring chronologies document persistent drought conditions in the western Great Plains, the southwestern U.S., the western Great Basin, and the Sierra Nevada (e.g., Weakly, 1965; Grissino-Mayer, 1996; Hughes and Graumlich, 1996). Less finely resolved paleoclimatic data from lake sediments in the Great Plains and submerged stumps in the Sierra Nevada also support evidence for widespread drought about this time (Dean et al., 1994b; Fritz et al., 2000; Stine, 1994; Woodhouse and Overpeck, 1998).

Ni et al. (2002) recently developed cool season precipitation reconstructions from tree rings for climate divisions in Arizona and New Mexico. The set of reconstructions extends from A.D. 1000 to 1988 and provides a temporal context for evaluating the late 13th century drought. Plots of the divisional precipitation reconstructions clearly show drought conditions across most of Arizona and New Mexico in the last quarter of the 13th century (Fig. 3). However, it is also evident that this drought was the last in a series of three 13th century droughts. In New Mexico the first two 13th century droughts appear to be even more severe than the last one. Additionally, there is a period of remarkably sustained drought in the second half of the 12th century. Since it appears that the Ancient Puebloans endured earlier droughts, these results support suggestions that other factors besides the late 13th century drought were important contributors to the abandonment of the Colorado Plateau.

Recent work suggests another climatic factor may have been an important contributing cause of the large-scale redistribution of the Ancient Puebloan population. A long tree-ring based reconstruction of annual mean-maximum temperature for northern Arizona indicates that much of the first three-quarters of the 13th century was characterized by extremely cold conditions (Salzer, 2000b). Summer temperatures in the early 1200s were more than two standard deviations below the long-term average (Fig. 4). This cold period and two that follow, centered around 1230 and 1260, may be related to large volcanic events that occurred about the same time (Salzer, 2000b). The "Great Drought" is the only period of persistently above average temperatures in the 13th century.

Cold summer temperatures dictate a shorter growing season and a higher frequency of early- and late-season frost events. The Ancient Puebloan populations were located near the upper limit (both northern and elevational) of where maize can be grown under non-irrigated modern climate conditions (Peterson, 1994). In addition, maize cultivation is limited at lower elevations by lack of moisture. Cooler temperatures combined with several major droughts in the 13th century may have severely limited the ability of the Ancient Puebloans to grow maize (Salzer, 2000b). The importance of colder temperatures as a causal factor for abandonment is supported by research on migration patterns that indicate movement of populations south and east of the Colorado Plateau and off the plateau throughout the 13th century, with an onset as early as 1200 (Ahlstrom et al., 1995; Dean et al., 1994a; Salzer, 2000b). These results are further supported by pollen analysis on the Colorado Plateau. Petersen (1994) found changes in spruce/pine pollen ratios at the lower spruce border and in conifer/non-arboreal plant ratios at timberline, suggesting cooler, drier conditions and a drop in the upper elevation limits of farming about 1200.

The 13th century contains an example of repeated droughts that are rather atypical in that during the course of two of the three droughts, temperatures were anomalously cool or near average (Salzer, 2000a). Within the period of below average temperatures, there were two peaks of relatively warmer, although still predominantly below or near average, temperatures that coincided with the first two droughts of the 13th century. However, tem-

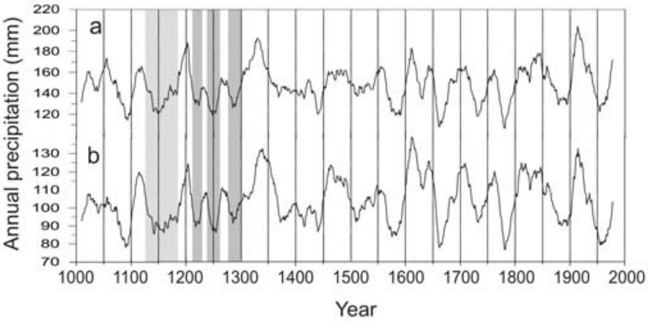

Figure 3. Tree-ring based reconstructions for November-April precipitation, A.D. 1000–1988, smoothed with a 20-year running mean, from Ni et al. (2002). Darker shading indicates the three 13th century droughts. Lighter shading indicates the period of persistent dryness in the 12th century. a) average precipitation for seven Arizona climate divisions. b) average precipitation for the eight New Mexico climate divisions.

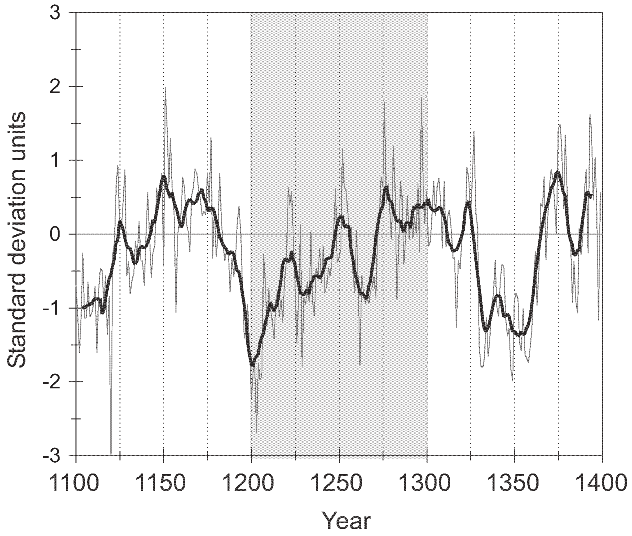

Figure 4. Reconstruction of maximum annual temperature from tree-ring data for northern Arizona, A.D. 1100–1400, from Salzer (2000b). Values are standard deviation units. The shaded area highlights the 13th century with three episodes of markedly below average temperatures.

peratures were suppressed throughout this period, likely due to the atmospheric response to a series of volcanic eruptions. Although the impacts of drought are often exacerbated by high temperatures, in this case, the stresses from a combination of drought and cool growing season temperatures may have been key to the abandonment of the Colorado Plateau by the Ancient Puebloans (Salzer, 2000b).

Late Holocene aridity and Medieval Climatic Anomaly

Although some multi-millennial-length tree-ring reconstructions of climate exist for the western U.S., few extend beyond A.D. 1000. Other sources of paleoclimatic data, such as from lake and ocean sediments, can provide information about past climate at longer time scales. Some of these sediment records are sampled at frequent intervals (subdecadal), providing relatively high-resolution information, but less precise dating (based on methods such as radiocarbon dating and paleomagnetic secular variations) is the trade-off for the longer records. These longer records, extending back tens of thousands of years and longer, are valuable for documenting periods of aridity rather than a single 1930s-type drought event.

The time frame considered in this section is the late Holocene, and specifically, the last 3,000 years. High-resolution (sampling interval of five to eight years) lake sediment records from Pyramid Lake, in the western Great Basin, document long-term variations in hydrologic variability and changes in lake size over the last 8,000 years (Benson et al., 2002). An analysis of $\delta^{18}O$ variations reflects the integrated effects of climate (e.g., precipitation, temperature, evaporation) on the hydrologic balance and documents the timing and duration of wet/dry oscillations in Pyramid Lake (Benson et al., 2002). The 3000-year $\delta^{18}O$ record shows a pattern of oscillations between wet and dry conditions (Fig. 5). These oscillations are not stationary over time, with intervals between hydrologic droughts ranging from 80 to 230 years. The duration of droughts is variable as well, with several lasting more than 100 years (some accentuation is due to 40-year running average). The frequency of drought periods appears to have increased over the last 900 years, but the record cannot be used to interpret changes in drought magnitude (Benson et al., 2002).

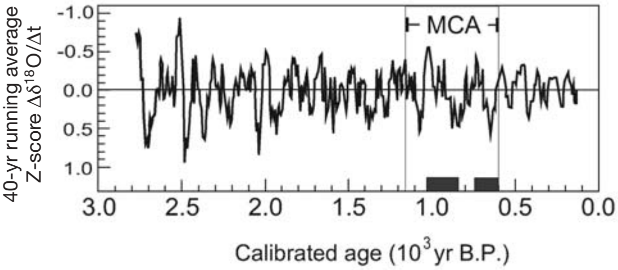

Figure 5. Pyramid Lake oxygen isotope record, $\delta^{18}O$, shown as derivative with respect to time, normalized, and smoothed with a 40-year running mean, to 3000 B.P. (from Benson et al., 2002). The Medieval Climatic Anomaly (MCA) is indicated as are the periods of drought documented by radiocarbon dated submerged tree stumps (black rectangles) (from Stine, 1994).

The Pyramid Lake record encompasses the period of time known as the Medieval Climatic Anomaly (or the Medieval Warm Period), which, in this record, is defined as about 1150–600 B.P. (Benson et al., 2002). The Medieval Climatic Anomaly (MCA) was initially identified with warm conditions in many parts of western Europe, the North Atlantic, southern Greenland, and Iceland (Lamb, 1977; 1982), but the notion that this was a global phenomenon or a period of consistently warm conditions throughout is not supported by the current body of research (Hughes and Diaz, 1994 and references within). However, at Pyramid Lake, this interval of time, regardless of whether it is related to climatic anomalies elsewhere, is characterized by three periods of drought, two of which are particularly persistent (Benson et al., 2002).

Several other paleoclimatic records in this area also indicate, directly or indirectly, persistent dry conditions at this time (in years A.D., about 800–1350). Trees now submerged in several lakes and bogs in the Sierra Nevada have been radiocarbon dated to determine when they were killed by rising water, which would indicate the termination of drought (Benson et al., 2002; Stine, 1994). Two periods of drought were deduced from these records, about A.D. 1000 and A.D. 1250 (Stine, 1994) that loosely coincide with two of the drought episodes in the Pyramid Lake record (Fig. 5). Both records indicate drought episodes were broken by wet conditions.

Additional evidence for drought comes from ocean sediments in the Santa Barbara basin and tree-ring data in the southern Great Basin. A 5000-year oxygen isotope marine record from marine plankton (25-year resolution, radiocarbon dated) reflects sea surface temperature (SST) variations in the Santa Barbara basin (Kennett and Kennett, 2000). The record shows a period of cooler and highly variable SSTs from about A.D. 500 to A.D. 1300 (1500–600 BP), which is roughly the same timing as the MCA in the Pyramid Lake record, but with an earlier onset. Evidence for cooler SSTs was further validated with oxygen isotope analysis of California mussel shell deposits from undisturbed archaeological sites in the northern Channel Islands, as well as an increase in fishbone density in middens, indicating increased marine productivity and increased fishing (Kennett and Kennett, 2000; Kennett, 1998). An usually long tree-ring based reconstruction of annual precipitation for the southern Great Basin (Hughes and Graumlich, 1996) corresponds well to the Santa Barbara SST reconstruction, showing that cool

SSTs coincide with periods of dryness interspersed by fewer and shorter periods of wetness, particularly in the period from 1500–600 BP. Drought conditions are known to be associated with, (among other things), cold SSTs by promoting stable atmospheric conditions and inhibiting precipitation (Barry and Chorley, 1987). Although drought in the southern Great Basin may have been linked to the persistent cool SSTs documented in the Santa Barbara basin, a lack of other SST records makes it difficult to determine whether Pacific SST anomalies were extensive and responsible for MCA droughts in the Pyramid Lake region and northern Sierra Nevada.

This set of paleoclimatic records illustrates that the climate of the Great Basin has undergone a series of low-frequency fluctuations of arid conditions broken by periods of wetter conditions over the course of the last three thousand years. The magnitude of the change between wet and dry periods was great enough to lower Sierra Nevada lake levels 10–15 meters (Stine, 1994). Although the causal mechanisms for these low-frequency oscillations are not yet well understood, they appear to be part of the natural climate variability of the past, and there is no reason to believe they will not continue in the future. The period of time referred to as the MCA was characterized by periods of persistent drought interspersed with wet periods in the Pyramid Lake region and northern Sierra Nevada, although proxy data from the southern Great Basin and Santa Barbara basin indicate a more long-term anomaly. Whether these drought conditions were in some way linked to other MCA-related climate anomalies in other parts of the world has not been determined.

Summary

This review attempts to illustrate the range of natural hydroclimatic variability over the western U.S. through a description of four episodes of drought and/or aridity over the course of the last 3000 years. Each drought is well-documented by a number of sources of paleoclimatic data, but the type drought information for each event is dictated by the proxy data available and the qualities of those proxies. By using several types of proxies, more information about each drought can be gained than if just one source of information is used. The four droughts described vary with regard to their recentness, duration, extent, and accompanying climate characteristics. Consequently, the impacts of these droughts vary as well. The discussion of impacts is not meant to be comprehensive but provides examples of possible types of impacts.

The following points summarize some of the inferences that can be drawn from the four paleodroughts:

- The 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records. Management and planning based only on the 20th century instrumental record may not be adequately flexible if climatic conditions are as variable as the paleoclimatic records suggest.
- Sustained and widespread periods of drought have occurred in the past, and although the causes are not currently well understood, they are likely related to slowly varying modes of climate. Continued studies of paleoclimatic data can help expand our understanding of the large-scale, low-frequency underlying ocean and atmospheric circulation features that may cause concurrent drought across large regions.
- Paleoclimatic data indicate that severe droughts, which are commonly thought of as being hot and dry, have also been accompanied by cold temperatures. Although high temperatures exacerbate the impacts of drought, cold temperatures can introduce other types of stress on natural ecosystems and human activities.
- Low-frequency hydroclimatic variations are clearly evident in long paleoclimatic records. Slowly oscillating wet and dry periods, not discernable in the instrumental records or shorter paleoclimatic records, are likely to be an underlying feature of the current and future climate.
- Past climate may not be an analogue to the future, but the long-term natural climate variability will likely continue, with the human impacts on climate superimposed over it. Understanding and considering past climatic variability and range of extreme events in future planning may result in more sustainable natural resource management.

What should be evident, even from this very small sample of paleoclimatic data, is that climate, as illustrated by one variable – drought – varies widely over space and time, as well as in intensity, duration, and nature of impacts. Hydroclimatic variability is particularly critical in arid regions, where water is commonly, and perhaps ultimately, the most limiting factor to growth and survival of aquatic species as well as human populations.

Acknowledgments

I would like the thank the organizers of the Aquatic Resource in Arid Land Conference, David Cowley and Rossana Sallenave, for inviting me to be a participant in a very interesting and stimulating meeting. Thanks to David Anderson and two anonymous reviewers for their helpful suggestions. I also thank the multitude of paleoclimatologists whose research I have cited in this paper, and who have made their data and findings available, as well as the NOAA Office of Global Programs and the National Science Foundation who have provided funds for my work (OGP GC02-046, NSF-ATM 0080889, NSF-ATM 9729571).

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