A 1,200-year perspective of 21st century drought in southwestern North America

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A key feature of anticipated 21st century droughts in Southwest North America is the concurrence of elevated temperatures and increased aridity. Instrumental records and paleoclimatic evidence for past prolonged drought in the Southwest that coincide with elevated temperatures can be assessed to provide insights on temperature-drought relations and to develop worst-case scenarios for the future. In particular, during the medieval period, ~AD 900–1300, the Northern Hemisphere experienced temperatures warmer than all but the most recent decades. Paleoclimatic and model data indicate increased temperatures in western North America of approximately 1 °C over the long-term mean. This was a period of extensive and persistent aridity over western North America. Paleoclimatic evidence suggests drought in the mid-12th century far exceeded the severity, duration, and extent of subsequent droughts. The driest decade of this drought was anomalously warm, though not as warm as the late 20th and early 21st centuries. The convergence of prolonged warming and arid conditions suggests the mid-12th century may serve as a conservative analogue for severe droughts that might occur in the future. The severity, extent, and persistence of the 12th century drought that occurred under natural climate variability, have important implications for water resource management. The causes of past and future drought will not be identical but warm droughts, inferred from paleoclimatic records, demonstrate the plausibility of extensive, severe droughts, provide a long-term perspective on the ongoing drought conditions in the Southwest, and suggest the need for regional sustainability planning for the future.

climate change | water resources | paleoclimatology | medieval period

Climate-change projections clearly indicate what observations already suggest: Temperatures everywhere will be warmer in the future due to anthropogenic activities. General circulation models (GCMs) project continued warming, with annual temperatures 3–5 °C above current levels by the end of the century (1). As previous articles in this Special Feature have discussed, warming temperatures, even without reductions in precipitation, will have far-reaching impacts on hydrologic sustainability in the Southwest. Twenty-first century droughts will occur under warmer temperatures with greater rates of evapotranspiration than occurred during the major droughts of the 20th century. Warming may also directly and indirectly increase the propensity for droughts in the Southwest (2–4). However, major 20th century droughts pale in comparison to droughts documented in paleoclimatic records over the past two millennia (5). Thus, warm droughts of the prehistoric past might provide evidence useful in understanding the current climatological changes, and for providing scenarios for worst-case droughts of the future and evidence of hydroclimatic responses in the Southwest to warmer climatic conditions.

This paper examines recent temperature-drought relations and analyzes paleoclimatic data documenting droughts persisting for periods of a decade or more, develops evidence for drought linkages with elevated temperatures, and identifies "worst-case" scenarios for warm-climate drought to place the recent episode of drought in the Southwest in a long-term context. As the current early 21st century drought has occurred with elevated temperatures, warm-period paleo droughts may well be a preview of what can be expected for the future. The recent prolonged drought has already had significant impacts in the arid to semiarid Southwest. Currently, overallocated water resources are being further stressed by increased demands due to population growth, tribal settlements, changes in land use, recreation needs, and mandated requirements for instream flows for ecosystem functioning and endangered-species preservation (6–9). As a result, many water-supply systems have become increasingly vulnerable to drought impacts. The recent drought has underscored the critical need for sustainable water-resource management and development (10). Such strategies should be informed by as long and complete a record of drought behavior and impacts as possible.

Warm Droughts in the Southwest: Past Droughts as Analogues for the Future?

The Role of Temperature. Elevated temperatures can have direct, local effects on drought as well as impacts on circulation features that promote large-scale droughts. Southwestern droughts are, typically, accompanied by above average temperatures because of factors such as subsidence, a lack of cloud cover, drying soils, and reduced evapotranspiration (e.g., 11–13). Major 20th century droughts, including the 1930s and 1950s, have occurred during periods of elevated temperatures, with persistence of high pressure leading to surface heating and drying in both winter and summer (11, 14, 15) (Fig. 1) and storm tracks displaced around the drought region (16). However, droughts do not always coincide with above average temperatures (17), as exemplified in the U.S. Southwest by the drought at the start of the 20th century (Fig. 1).

Global or hemispheric warming may also strongly impact Southwest drought indirectly through influences on global sea surface temperatures (SSTs) and ocean/atmosphere dynamics. Increased radiative heating over the tropical Pacific has been shown to enhance the development of La Niña-like conditions that promote drought in the Southwest (4, 5, 18). It has been suggested that the influence of global warming on the western tropical Pacific and Indian Oceans may already be detectable, and along with cool SSTs in the eastern tropical Pacific, may have been a cause of drought conditions at the turn of the 21st century that affected regions including southwestern North America (19). One projected (and possibly already detected) result of global warming is an extension of the poleward arm of the Hadley cell that will cause an expansion of the area under the drying

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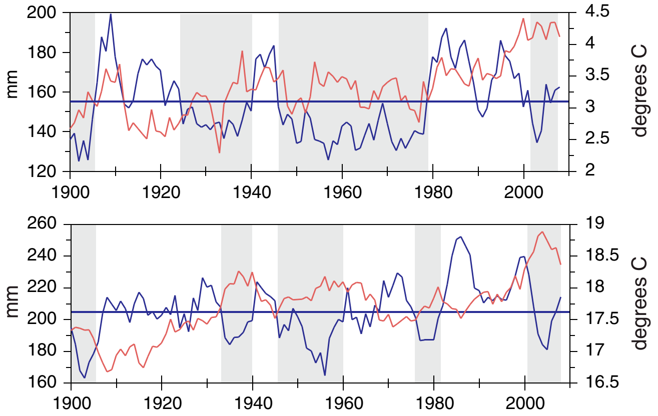

Fig. 1. Total seasonal precipitation and mean seasonal temperature averaged over Colorado, Utah, New Mexico, and Arizona (17); five-year running means, 1900–2008. Precipitation in *Blue Line* (*Horizontal Line* is the average), temperature in *Brown*. Cool season (November–March), *Top*. Warm season (May–October), *Bottom*. *Shading* indicates periods of below average precipitation.

influence of subtropical high pressure (2, 20). Whereas some of these large-scale responses to warming may not have operated in the past others, such as SSTs anomalies in the tropical oceans, have been critical drivers. Past droughts best suited as analogues for the future are those accompanied by hemispherical temperature changes favoring drought-inducing circulation and directly amplifying regional drought conditions and impacts.

Warm Paleodrought. Paleoclimatic data for southwestern North America provide extensive documentation of past droughts (21, 22). Records collectively suggest a broader range of hydroclimatic variability than contained in instrumental records, particularly with respect to drought extent, duration, and severity. Several notable droughts extended across much of western North America, including severe and sustained droughts in the late 16th century and the medieval period, between 900–1300 AD (23–25). In this period, episodes of extensive severe drought are documented by a variety of proxy data, but most dramatically by evidence of trees rooted in lakes and river courses in the Sierra Nevada and northwestern Great Basin (26, 27). These droughts appear to have exceeded the duration and magnitude of any subsequent droughts in western North America (5, 25).

Whereas the medieval period is now acknowledged as a time of increased aridity over western North America, it has more generally been known as a period of warmer temperatures, especially over Europe (28, 29). An effort has been made to document the degree to which global and hemispheric temperatures were elevated at this time using a wide variety of proxy records, and with an emphasis on understanding the low-frequency component of variability (1, 30, 31). A recent analysis of a number of different proxy temperature records suggests that Northern Hemisphere decadal-scale averages over land may have been as much as approximately 0.2–0.4 °C above the 1850–2006 mean from roughly 950–1150 AD (32). The medieval warming is, however, markedly exceeded by late 20th and early 21st century warming, as temperatures now stand more than 0.8 °C above the 1850–2006 mean (32).

Ocean/atmosphere teleconnections provide a plausible causative link between hemispheric-scale warm temperatures and drought in the Southwest during the medieval period. Associations between SSTs and Southwestern drought during this period have been explored with paleoclimatic data and modeling (4, 33–35) and although the paleoclimatic data that document Pacific Ocean conditions during the medieval period are not in total agreement, most show temperatures in the eastern Pacific indicative of cool El Niño/Southern Oscillation, or La Niña-type conditions (22). More unequivocal evidence exists for a warm North Atlantic (36). Recent modeling efforts, assuming cool Pacific and warm Atlantic SSTS, have replicated the main features of medieval drought in North America documented in paleoclimatic data (36). It is worth noting that droughts of the 1950s and of recent years were both accompanied by cool Pacific and warm Atlantic SSTs (37).

Although likely not matching the magnitude of the recent increases in global temperatures, the increased large-scale hemispheric warming in medieval times coincided with widespread and persistent aridity across the Southwest. On a regional scale, paleoclimatic data indicate that similar to the instrumental period, warm and dry spells often concur in the Southwest, including during this period (13). Is it appropriate then to consider a medieval drought as a possible, although conservative (with respect to temperature), analogue for future warm droughts? The root causes of warming for the medieval period, increased solar irradiance coupled with decreased volcanic activity (38, 39), and in recent decades, anthropogenic activities with some contribution from solar irradiance (1), are not identical. Although important differences must be acknowledged—for example, the causes and the amplitudes of the warming, and the probable impacts of land cover change on temperatures—the medieval droughts can provide some direct evidence of the Southwest hydroclimatic response to warming and a plausible, but conservative, worst-case scenario to be considered in sustainable water-resource planning.

Medieval Drought and Temperatures in Southwestern North America

The medieval period was characterized by widespread and regionally severe, sustained drought in western North America. Proxy data documenting drought indicate centuries-long periods of increased aridity across the central and western U.S. (Fig 2*F*) (25, 22). In the Colorado and Sacramento River basins, reconstructions show decadal periods of persistently below average flows during several intervals including much of the 9th, 12th, and 13th centuries (40–42) (Fig 2*E*). The 12th century episode, also reflected in precipitation and drought extent (13, 25, 43, 44), was particularly severe and persistent and was associated with a peak in solar irradiance and nadir in volcanic activity (4) (Fig. 2*A*). Most of these paleohydrological records primarily reflect winter and spring precipitation. Proxy records that document summer precipitation are much less common and, of those that do exist, some suggest wetter summers during the medieval period (22, 45–47), whereas others indicate decadal variability of both drought and wetness (48).

The temperature signal of the medieval period, though relatively strong in averages over the Northern Hemisphere (32) (Fig. 2*B*), is more complex at the regional scale (29). In contrast to paleohydrological records, there are fewer high-resolution paleotemperature records in the Southwest and evidence for anomalous medieval warmth in this region is less comprehensive (5). Tree-ring reconstructions of temperature for the Southwest suggest warmer temperatures for at least portions of the medieval period (13, 29, 49–51). These reconstructions usually represent growing-season temperatures and, because of limitations of the paleoclimatic indicators generally do not preserve centennial-scale variations (52, 53), at least on these regional scales. Along with evidence for multiyear periods of enhanced temperatures approaching 1.0 °C during some intervals of the medieval period, records also indicate periods of normal to below average temperatures at other intervals (Figure 2*D*). Proxy records are consistent, however, in supporting periods of elevated warmth in the medieval period that coincide with periods of severe and widespread drought.

At multidecadal and longer timescales, evidence from treeline, glacier, and chironomid studies suggests southwestern North

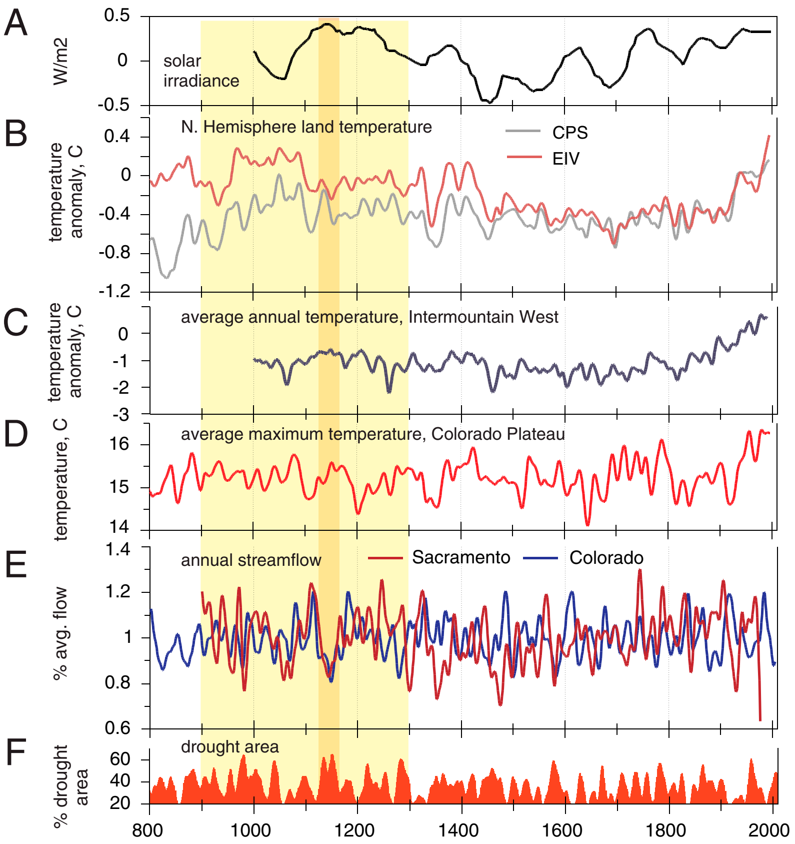

Fig. 2. Global, hemispheric, and regional proxy and model data documenting medieval period conditions. *A* Solar irradiance (69), *B* two estimates of Northern Hemisphere land temperatures, departures from 1850–1995 (32), *C* ECHO-G (60) modeled average annual temperature for 34°–40° N, 104°–124° W, and departures from 1890–1990, *D* reconstructed Colorado Plateau mean maximum temperatures (13), *E* reconstructed water year streamflow, Colorado River at Lees Ferry (41) and Sacramento Four Rivers index flow (40), percent of average based on AD 901–1977, and *F* reconstructed Southwest Drought Area Index (5). All series except (*A*) were smoothed with a 20-year spline. *Light Shading* indicates medieval period, *Dark Shading* indicates mid-1100s period.

America and adjacent regions experienced elevated temperatures on the order of 1 °C or less above long-term means during some or all of the medieval period (refs. 54–58). Medieval warming in western North America is also suggested by climate model simulations from the ECHO-g atmosphere-ocean general circulation model (GCM) (59, 60) that indicates annual temperatures in the region in the 12th and early 13th centuries were about 0.5 °C warmer than the long-term average (Fig. 2*C* and *SI Text*). The medieval period represents the longest episode of elevated temperatures outside of the 20th century, although 20th century temperatures clearly exceed those of the medieval period. Whether decadal-scale warm temperatures in high-resolution proxy records were superimposed on this baseline warming over the medieval period is unclear, but a medieval drought that occurred during a period of decadal-scale warmth could provide evidence for the propensity of hemispheric warming to generate prolonged aridity in the Southwest and a potential scenario for future warm droughts.

Placing the Current 21st Century Drought in a Medieval Context

Worst-Case Medieval Drought. High-resolution proxy data for the Southwest allow an assessment of the intensity, duration, and spatial extent of droughts. Although many proxy records exist, we select a few here to illustrate a worst-case warm drought from the past 1200 yr. One of the longest records of drought intensity and persistence in the Southwest, beginning in the 8th century and ending in the 21st century, is the reconstruction of water-year streamflow for Lees Ferry on the Colorado River (41). This tree-ring based reconstruction summarizes hydroclimatic variability in the most important river basin in the Southwest. Drought extent over the larger domain of the Southwest is documented by an index of drought-area (DAI) reconstructed from a network of moisture-limited tree-ring chronologies (5) (*SI Text*). The Colorado River reconstruction ends in 2005, whereas the DAI ends in 2006 [although from 1979, the data are based on observed Palmer Drought Severity Index (PDSI)]. Several temperature reconstructions exist for the Southwest; the most recent high-resolution reconstruction of temperature was generated by Salzer and Kipfmueller (13) for the southern Colorado Plateau (average annual maximum temperatures), and was used for this analysis (*SI Text*). This reconstruction extends from 663 BC to AD 1996, but is most robust after 266 BC.

Together, the Colorado River flow, Southwest DAI, and southern Colorado Plateau temperature reconstructions allow an assessment of the covariation of hydrologic drought with annual maximum temperatures, AD 762–1996. An analysis of 10-year averages of temperature and streamflow suggests that severe droughts coincide most often with warm temperatures in the medieval period and the 20th century, whereas cool droughts were more common during the pre- and post-medieval periods, before the 20th century (Fig. S1). The warmest, driest, most widespread interval of drought documented in the streamflow, DAI and temperature records occurred in the mid-12th century (Fig. 2 and Fig. S2). The driest 10-year period in the Colorado River reconstruction and the 6th most extensive drought-area in the Southwest was 1146 to 1155. Decades ending in 1153, 1154, 1156, 1157, and 1158 were similarly dry and warm. The decade 1146–1155 ranked in the 80th percentile of southern Colorado

Plateau temperatures. Several decades in the late 9th and 13th centuries were nearly as warm and dry.

Based on these data, the 10-year period, 1146–1155, was selected as a scenario of worst-case warm drought from the paleoclimate data for the past 12 centuries over the Southwest. Over this period, reconstructed Colorado River flows averaged 14.2 billion cubic meters (BCM) per year, the area of the Southwest under drought averaged 65.5%, and average annual maximum temperatures were 15.65 °C. In contrast, the mean annual flow of the Colorado River over the 20th century (1906–2007) has been 18.3 BCM, average area under drought, 32.6% (1900–2006), and average temperature 15.72 °C (1909–2008) (Table S1). Proxy records that better reflect low-frequency temperature variability, such as lake sediments and treeline changes, suggest that warmth was underestimated by the tree-ring reconstructions of annual temperature for the Colorado Plateau. It is possible that, when conditions are dry enough, high elevations conifers do not respond to increased temperatures. As discussed above, climate model results and other types of proxy data suggest medieval temperatures were perhaps 1 °C above the long-term and equivalent to the 1961–1990 mean. The decadal-scale variability reflected in the temperature reconstruction from tree rings may well be superimposed over this warmer baseline, but the warmth still would not likely match the observed average maximum temperatures over the past decade (17.54 °C mean maximum average for 1999–2008, Fort Valley, AZ, Western Regional Climate Center) (Table S1).

In parts of the Southwest with appreciable summer rainfall, any comprehensive assessment of drought—particularly with regard to impacts on society and ecosystems—must also address the North American Monsoon (NAM). The NAM is indeed a key component of drought variability in north-central Mexico, Arizona, and New Mexico, but the paleoclimatic record of summer rainfall over the Southwest is very limited. Currently, one reconstruction reflecting NAM variability has been generated that includes the medieval period (48). This reconstruction of northern New Mexico July precipitation from latewood tree-ring widths is based on data from one location and, thus, may not reflect moisture conditions over the broader domain of the NAM. It does not show an obvious signature of drought in the medieval period, as do the streamflow and DAI records, but there is a multidecadal episode of warm season drought beginning in the 12th century that would have contributed to the overall dry conditions at the time (48).

21st Century Drought in a Long-Term Context. Drought conditions, especially in the cool season, have generally dominated over many parts of southwestern North America since at least 1999 (4, 61) (*SI Text*). Whereas in some parts of the Southwest, and by some measures, the recent drought has not (yet) been the most severe drought in the instrumental period (5, 61, 62), it is notable for warm temperatures (37, 61, 63) (Fig. 1). The combination of precipitation deficits and high temperatures has resulted in hydrologic conditions in some areas that match if not exceed the severity of the 1950s drought (Figs. 3*B* and 4). In addition to the period 2000–2004, which was the lowest five-year period of natural flow on the Colorado River (1906–2005) (64), the most recent decade, 2000–2009, is the lowest 10-year running-mean, followed by ten-year periods ending in 2008 and 2007 (Fig. 4).

The recent drought, thus far, pales hydrologically in comparison to the worst-case drought documented in the medieval period in both spatial extent (Fig. 3) and duration. Spatially, the mid-12th century drought covers all of the western U.S. and northern Mexico except for a small portion of the far northwestern Great Plains, whereas the 21st century drought has not impacted parts of the Pacific Northwest. The 21st century drought has lasted about a decade so far, whereas the 12th century medieval drought persisted with an extent and severity displayed in the worst-case decade, 1146–1155, for two decades, 1140–1159. Temperature, on a hemispheric scale, was elevated relative to the past 12 centuries for most of that period. The Colorado River reconstruction also highlights the exceptional persistence of medieval drought. Whereas the maximum number of consecutive years below median flow in the gage record is 5 yr, the long-term reconstruction contains a total of 17 longer runs. The longest is 13 yr in the mid-1100s, a period characterized by stretches of moderately low flows and lack of high flows (41). Whereas individual annual reconstructed flows were not exceptionally low in the mid-1100s, a lack of wet years translates into record-low averages over periods

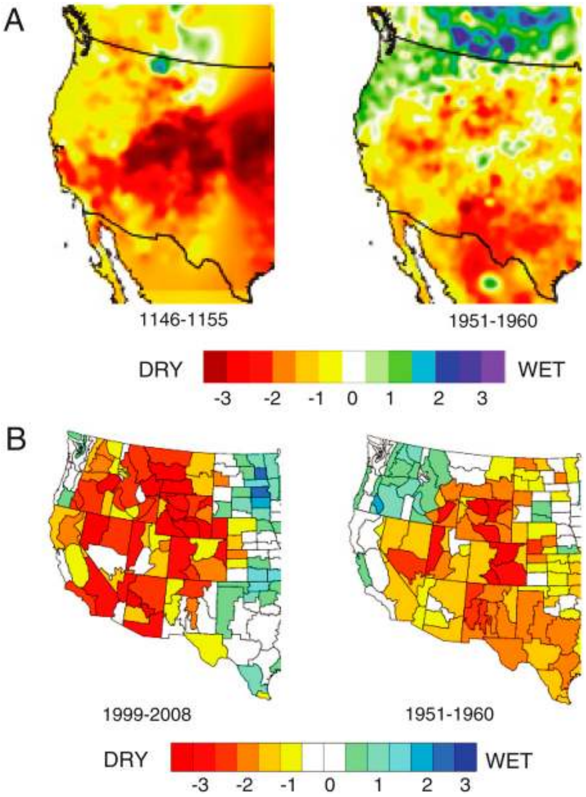

Fig. 3. Composite maps of summer PDSI. *A* Gridded PDSI, reconstructed, *1146–1145*, *Left*; instrumental, *1951–1960*, *Right* (5). *B*. Divisional PDSI, *1999–2008*, *Left*; *1951–1960*, *Right* for comparison with gridded PDSI (70, Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.psd.noaa.gov/). Note slightly different scales; *Red* indicates dry conditions and *Blue* indicates wet.

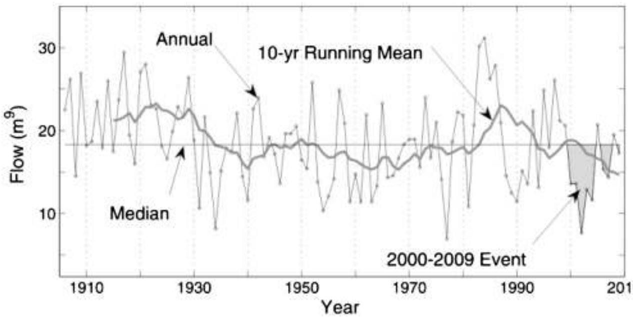

Fig. 4. Observed annual flow of the Colorado River at Lees Ferry. *Horizontal Line* is the median of the 1906–2006 observed flows (18.32 billion cubic meters). *Light Gray* line is the 10-year running average. Observed flows are version 6.18.08 of the natural flows from the U.S. Bureau of Reclamation (http://www.usbr.gov/lc/riverops.html), appended with provisional flows for water years 2007–09 that were estimated by the Bureau of Reclamation with data currently available.

of a few decades. The 10-year running-mean of reconstructed flow drops below the observed 2000–2009 mean (14.65 BCM) only four times in the entire reconstruction, and three of those are in the mid-1100s. Because regression-based tree-ring reconstructions tend to be conservative, this evidence strongly suggests the mid-1100s were at least as dry as the last 10 yr. In reconstructed Sacramento River streamflow, the 20-year period ending in 1158 was the second driest in this record that extends to AD 869 (40), indicating the impact of this drought in northern Sierra Nevada watersheds as well. However, one critical drought-related variable, temperature, was almost certainly higher during the 21st century drought than during the medieval droughts.

Summary and Conclusions

In both instrumental and paleoclimatic records, periods of sustained drought in the Southwest have often been concurrent with elevated temperatures. The warmest such episode, in the mid-12th century, was more extensive and much more persistent than any modern drought experienced to date, with cumulative streamflow deficits on the Colorado and Sacramento that would severely tax the ability of water providers to meet demands throughout the Southwest. However, temperature, an important feature of that drought, was very likely lower than in the recent period of drought. It should be noted that records of past temperature for the Southwest are still limited, and this assessment would be strengthened with additional paleoclimatic data for this region. Studies assessing the impact of elevated temperatures on Colorado River runoff indicate that warming will lead to intensified low flows and a greater probability of water shortages (65—67). A wide variety of modeling efforts have yielded results that suggest, for each 1 °C increase in temperature, runoff will decrease from 2–8% in the Colorado River basin (67). The medieval drought conditions documented by tree rings are biased towards the cool season, the most important season for water supply in much of the Southwest. While monsoon season moisture may increase with global warming, this would not be likely to offset winter drying in most regions.

Warming temperatures will likely further exacerbate drought in the Southwest in ways both with and without analogue in the past. The enhancement of the ocean/atmospheric circulation features that promote the establishment and persistence of drought in this region is a main driver of drought in the past. Paleoclimatic data can provide insights on the associated regional drought responses. The expansion of the region dominated by subtropical high pressure, an anthropogenic influence on drought extent (2), will need to be considered on top of naturally occurring forcings in the anticipation of future droughts.

As far as we know, there is no reason why droughts of the duration, severity, and spatial extent experienced in the medieval period could not occur in the future. Even without the anticipated increased warming in the 21st century, droughts of the magnitude of the medieval droughts would present enormous challenges to water management agencies. Worst-case droughts of the 20th century, unlike those of the paleo record, do not contain episodes of many consecutive decades without high flows, so critical for refilling of reservoirs (41). The large spatial extent of medieval droughts would also present management challenges, particularly in areas such as southern California, which relies on water supplies from both the Colorado River and Northern Sierra watersheds.

Although these "warm" medieval droughts may be considered conservative analogues for future droughts, it is important to recognize that there are many reasons that the mid-12th century drought cannot be considered an exact analogue for future worst-case droughts. Besides anthropogenic warming, there have been a multitude of changes in land cover throughout the Southwest due to human activities since the late 19th century. Conversion of desert and grassland to cropland, grazing, fire suppression, introduction of invasive species, disturbances leading to soil erosion and blowing dust, and the development of urban areas have all likely had impacts on regional climate. No systematic studies on these land cover changes and their impacts on climate or drought have been undertaken (68), but these changes are another important reason that droughts of the past are unlikely to be an exact analogue for current and future droughts. In addition, from an impacts standpoint, droughts have a much broader range of impacts on human activities today than in the past because of today's greater demands on limited water resources.

Analogues can provide a basis for planning, but realistic and plausible future scenarios must consider a host of other factors. The paleoclimatic record is invaluable for documenting the range of drought variability over the past and expanding the scope of worst-case scenarios. The mid-12th century drought provides a baseline worst-case in terms of the temporal and spatial characteristics of drought during a warm period, but future water resources and drought planning should consider a number of other factors including trends in temperature, water demands, disturbance legacies, and possible land cover feedbacks. The baseline worst-case is clearly just a starting point in planning for droughts that will be further exacerbated by these other factors. The challenge of dealing with such droughts argues strongly for innovative strategies for sustainable water management under a warmer, drier climate.

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Supporting Information

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Details on ECHO-g model. Goosse et al. (1) and Osborn et al. (2) have suggested that earlier ECHO-g simulations may have overestimated warming during the medieval period. To provide a more conservative estimate, the simulation results presented here were initiated from the cold conditions of the year AD 1700. In general, the results of this initiation produce estimates of medieval warming which are more consistent with other simulations (3). A time-series of annual temperature variations for the Intermountain West for the period AD 1000–1990 was constructed by averaging the annual surface temperature output from the 10 ECHO-g simulation grid points extending from 40–34ºN and from 104–124ºW and used for this study.

Details on drought variables and temperature. Both drought variables—summer Palmer Drought Severity Index (PDSI) and water year streamflow—strongly reflect cool season moisture. The largest contribution to water year streamflow in the Colorado River basin is winter snowpack, and the PDSI is a lagged measure of drought that reflects moisture conditions in the previous seasons (4). In addition, annual ring widths of Southwestern moisture-sensitive trees most strongly reflect variations in cool season climate (5). Instrumental data suggest that major droughts tend to persist across seasons (6), although in the Southwest, the degree to which warm-season and cool-season precipitation are out of phase is still being investigated (7, 8). Both PDSI and water year streamflow integrate temperature in their measures or calculation, but in both cases, moisture is the dominant variable reflected in the reconstruction. The temperature component in the reconstructions has not been isolated in either case, but understanding the degree to which temperatures were elevated during drought would be useful in considering analogues for future drought.

Additional details on PDSI and temperature reconstructions. Southwest Drought Area Index (DAI) is based on a set of gridded ($0.5^\circ \times 0.5^\circ$) reconstructions of summer Palmer Drought Severity Index (PDSI) (9, 10). The Southwest DAI is computed as the percentage of gridpoints each year experiencing mild-to-severe drought ($\text{PDSI} \leq -1.0$) in the region west of 97.5ºW between 27.5ºN and 40ºN. The Colorado Plateau temperature reconstruction was generated with tree-ring data from sites where trees are limited by average annual maximum temperatures (11). The series length (average of 384 yr) and conservative detrending used to compile the chronologies in the reconstruction help preserve the low-frequency information, but it is likely that centennial-scale variability is not well-represented.

Details of drought impacts on water resources. With regard to water resources in Colorado headwaters regions, drought conditions began in the fall of 1999 and peaked in 2002, with some of the lowest snowpacks and runoffs recorded in the Colorado River and other basins (12). In the upper Colorado River basin, 7 of the last 10 annual flows are below the long-term median, a frequency matched only twice before—during the 1930s and 1950s droughts (13). The story is similar for the headwaters of Rio Grande, where annual inflows into Elephant Butte Reservoir, the largest reservoir on the Rio Grande north of the US/Mexico border, have been below average for ten of the last 13 yr (14). In northern Mexico, drought conditions in the cool and warm seasons have persisted with limited relief since 1994 (15), but as in other regions have been particularly severe during the cool season since 1999 (16). In southern California, high precipitation in 2005 broke a drought that began in 1999, but since 2007 drought conditions have been widespread and severe (17). The impacts of the recent drought years have been most pronounced on cool-season precipitation deficits, which are critical for surface-water systems that require snowmelt runoff to fill reservoirs. Warm-season precipitation has also been affected, but in areas where the summer monsoon is a major contributor to annual moisture and a critical factor in water demand, precipitation has been more variable, with record wet conditions in 2006 over many locations, and extremely dry conditions in 2003 (18).

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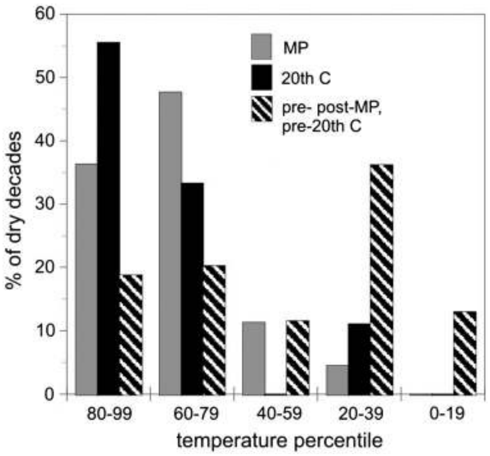

Fig. S1. Correspondence between extremely dry decades (10th percentile) in the Colorado River basin and five categories of Colorado Plateau temperature for three time periods, the medieval period (900–1300), the 20th century (1906–1996), and the combined pre- and post-medieval period years, prior to 1906 (771–899 and 1301–1905). An analysis of 10-year averages of temperature and streamflow for the three sets of years shows that periods of extreme drought (the driest 10 percent of the 10-year averages) correspond with Colorado Plateau temperatures that were in the warmest 60th percentile or warmer most often in the medieval period and the 20th century (84% and 89% of the periods, respectively). Cool droughts were more common during the pre and post medieval periods, before the 20th century (only 20% of the driest decades correspond to temperatures in the 60th percentile or warmer; 25% correspond to temperatures in the 40th percentile or cooler).

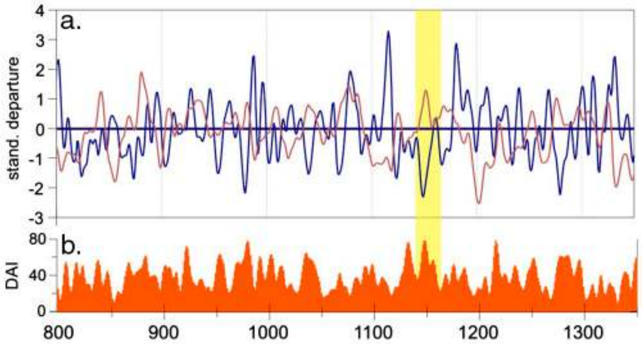

Fig. S2. (*A*) Reconstructions of Colorado (Lees Ferry) River flow, *Blue* (19) and maximum annual temperature for the Colorado Plateau region, *Brown* (11), AD 800–1350, as standardized departures based on the years AD 762–1996. (*B*) Southwest drought area index (DAI) (10). All series have been smoothed with a 10-year spline. *Shading* indicates the sustained period of warm, dry conditions centered on 1150.

Table S1. Comparison of mid-1100th century, 1950s, and 21st century droughts with 20th–21st century mean values for drought-related measures

Variable	20th/21st century	1999–2008	1951–1960	1146–1155
Drought Index (DAI) (10)	32.6% (1900–2006)	48.4% (to 2006)	59.8%	65.5%
Colorado River flow (20)	18.3 BCM (1906–2007)	14.65 BCM	16.35 BCM	14.2 BCM
Colorado Plateau mean maximum temperature* (11)	15.72°C (1909–2008) 16.17 °C (1961–1990)	17.54 °C	17.38 °C	15.65 °C

*20th and 21st century data for Fort Valley, AZ, Western Regional Climate Center, http://www.wrcc.dri.edu/. 12th century data.

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