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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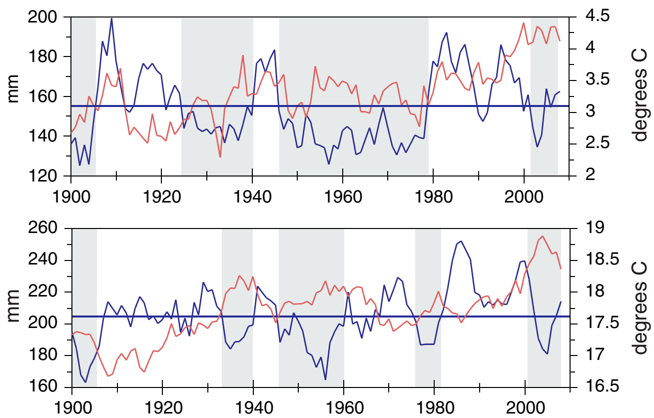

Fig. 1. Total seasonal precipitation and mean seasonal temperature averaged over Colorado, Utah, New Mexico, and Arizona (17); five-year running means, 1900–2008. Precipitation in *Blue Line* (*Horizontal Line* is the average), temperature in *Brown*. Cool season (November–March), *Top*. Warm season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

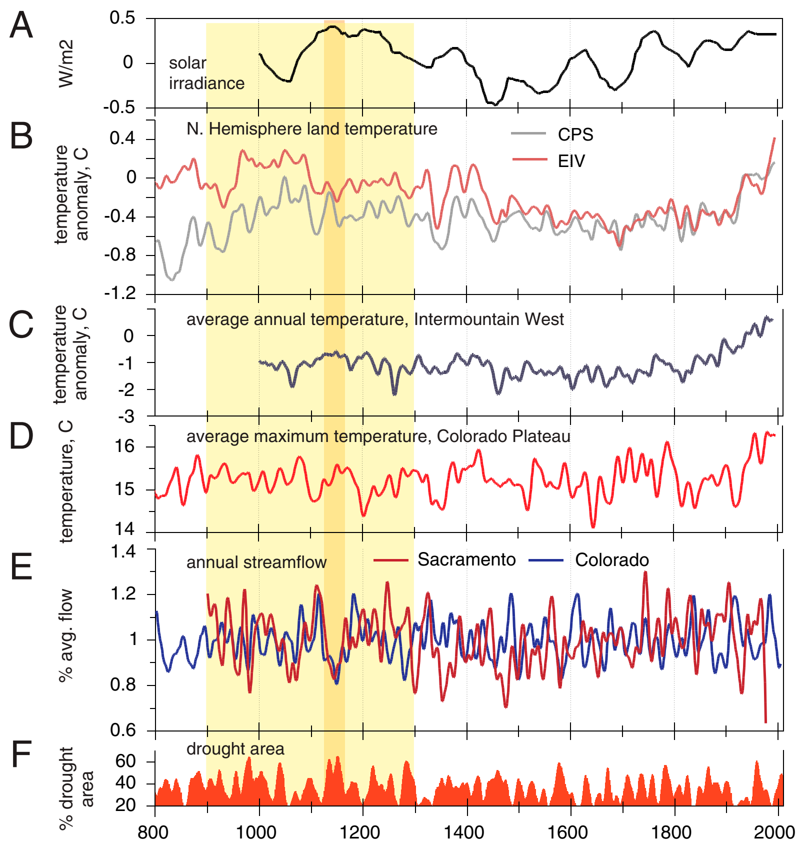

Fig. 2. Global, hemispheric, and regional proxy and model data documenting medieval period conditions. *A* Solar irradiance (69), *B* two estimates of Northern Hemisphere land temperatures, departures from 1850–1995 (32), *C* ECHO-G (60) modeled average annual temperature for 34°–40° N, 104°–124° W, 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

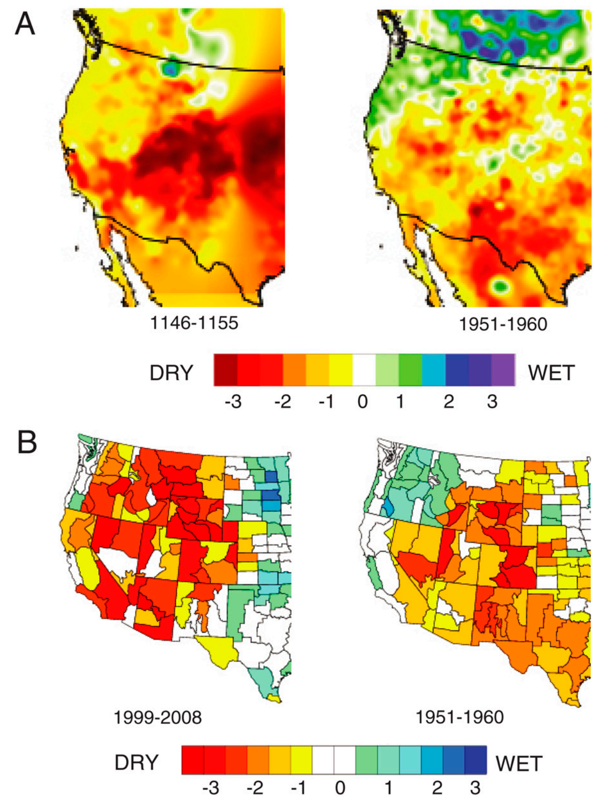

Fig. 3. Composite maps of summer PDSI. *A* Gridded PDSI, reconstructed, *1146–1145*, *Left*; instrumental, *1951–1960*, *Right* (5). *B*. Divisional PDSI, *1999–2008*, *Left*; *1951–1960*, *Right* for comparison with gridded PDSI (70, Image provided by the NOAA/ESRL Physical Sciences Division, Boulder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

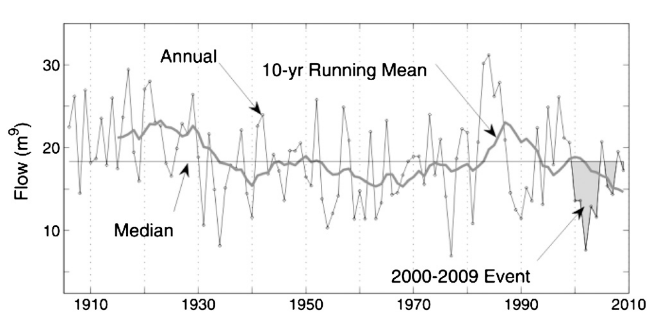

Fig. 4. Observed annual flow of the Colorado River at Lees Ferry. *Horizontal Line* is the median of the 1906–2006 observed flows (18.32 billion cubic meters). *Light Gray* line is the 10-year running average. Observed flows are version 6.18.08 of the natural flows from the U.S. Bureau of Reclamation (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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1. IPCCSolomon S, et al., ed. (2007) Climate change 2007: Synthesis report, summary for policymakers. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
2. Seager R, et al. (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184 DOI: 10.1126/science.1139601.
3. Seager R, Vecchi GA this volume.
4. MacDonald GM, et al. (2008) Climate warming and 21st-century drought in southwestern North America. *Eos Trans Amer Geophys Union* 89:82.
5. Cook ER, et al. (2009) Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *J Quaternary Sci* doi: 10,1002/jqs.1303.
6. U.S. Fish and Wildlife Service (2004) Final environmental impact statement and habitat conservation plan for the lower Colorado River multi-species conservation program. www.lcrmscp.gov.
7. Garrick D, Jacobs KL, Garfin GM (2008) Decision making under uncertainty: Shortage, stakeholders and modeling in the Colorado River basin. *J Am Water Resour As* 44:381–398.
8. Bark RH, Jacobs KL (2009) Indian water rights settlements and water management innovations: The role of the Arizona Water Settlements Act. *Water Resour Res* 45:W05417 doi: 10.1029/2008WR007130.
9. Phillips DH, Reinink Y, Skarupa TE, Ester CE, III, Skindlov JA (2009) Water resources planning and management at the Salt River Project, Arizona, USA. *Irrig Drain Syst* DOI: 10.1007/s10795-009-9063-0.
10. Jacobs KL, Morehouse B (2005) Why sustainability is not a four-letter word. *Southwest Hydrol* 4:14–15 26.
11. Namias J (1960) Factors in the initiation, perpetuation and termination of drought. *International Association of Scientific Hydrology Commission on Surface Waters Publication* 51:81–94.
12. Durre I, Wallace J, Lettenmaier D (2000) Dependence of extreme daily maximum temperatures on antecedent soil moisture in the contiguous United States during summer. *J Climate* 13:2641–2651.
13. Salzer MW, Kipfmueller KF (2005) Reconstructed temperature and precipitation on a millennial timescale from tree rings in the southern Colorado Plateau, USA. *Climatic Change* 70:465–487.
14. Namias J (1955) Some meteorological aspects of drought with special reference to the summers of 1952–54 over the United States. *Mon Weather Rev* 83:199–205.

15. McNab AL, Karl TR (1989) Climate and droughts, in Paulson RW, Chase EB, Roberts RS, and Moody DW, Compilers, National Water Summary 1988–89—Hydrologic Events and Floods and Droughts. *US Geol Sur Water Supply Pap 2375* 89–95.
16. Barry RG, Chorley RJ (2003) *Atmosphere, weather, and climate* (Routledge, New York), 8th Ed.
17. Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P (2002) A knowledge-based approach to the statistical mapping of climate. *Clim Res* 22:99–113.
18. Clement AC, Cane MA, Seager R (1997) Patterns and mechanisms of twentieth century climate change. *World Resour Rev* 10:161–185.
19. Hoerling M, Kumar A (2003) The perfect ocean for drought. *Science* 299:691–694.
20. Seidel D, Fu Q, Randel WJ, Reichler TJ (2008) Widening of the tropical belt in a changing climate. *Nat Geosci* 1:21–24.
21. Woodhouse CA, Overpeck JT (1998) 2000 years of drought variability in the central United States. *B Am Meteorol Soc* 79:2693–2714.
22. Graham NE, et al. (2007) Tropical Pacific—mid-latitude teleconnections in medieval times. *Climatic Change* 83:241–285.
23. Stahle DW, Fye FK, Cook ER, Griffin RD (2007) Tree-ring reconstructed megadroughts over North America since A.D. 1300. *Climatic Change* 83:133–149 DOI 10.1007/s10584-006-9171-x.
24. Stahle DW, et al. (2000) Tree-ring data document 16th century megadrought over North America. *Eos Trans Amer Geophys Union* 81:121 125.
25. Cook ER, Woodhouse C, Eakin CM, Meko DM, Stahle DW (2004) Long-term aridity changes in the Western United States. *Science* 306:1015–1018.
26. Stine S (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature* 369:546–549.
27. Graham NE, Hughes MK (2007) Reconstructing the Mediaeval low stands of Mono Lake, Sierra Nevada, California, USA. *Holocene* 17:197–1210.
28. Lamb HH (1965) The early medieval warm epoch and its sequel. *Palaeogeogr Palaecol* 1:13–37.
29. Hughes MK, Diaz HF (1994) Was there a 'Medieval Warm Period'? *Climatic Change* 26:109–142.
30. NRC (National Research Council) (2006) *Surface Temperature Reconstructions for the Last 2,000 Years* (Natl Acad Press, Washington, DC).
31. Jansen EJ, et al. (2007) Palaeoclimate. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds S Solomon et al. (Cambridge Univ Press, Cambridge, UK).
32. Mann ME, et al. (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc Natl Acad Sci USA* 105:13252–13257 DOI: 10.1073/pnas.0805721105.
33. Herweijer C, Seager R, Cook ER (2006) North American Droughts of the mid-to-late Nineteenth Century: A history, simulation and implication for mediaeval drought. *Holocene* 16:159–171.
34. Cook ER, Seager R, Cane MA, Stahle DW (2007) North American drought: Reconstructions, causes, and consequences. *Earth-Sci Rev* 81:93–134.
35. Seager R, et al. (2008) Tropical Pacific forcing of North American medieval megadroughts: Testing the concept with an atmosphere model forced by coral reconstructed SSTs. *J Climate* 21:6175–6190.
36. Feng S, Oglesby RJ, Rowe CM, Loope DB, Hu Q (2008) Atlantic and Pacific SST influences on Medieval drought in North America simulated by the Community Atmospheric Model. *J Geophys Res* 113:D11101 doi: 10.1029/2007JD009347.
37. Weiss JL, Castro CL, Overpeck JT (2009) The changing character of climate, drought, and the seasons on the southwestern USA. *J Climate* 22:5918–5932.
38. Zebiak SE, Cane MA (1987) A model El Niño/Southern oscillation. *Mon Weather Rev* 115:2262–2278.
39. Mann ME, Cane MA, Zebiak SE, Clement A (2005) Volcanic and solar forcing of the tropical Pacific over the past 1,000 years. *J Climate* 18:447–456.
40. Meko DM, Therrell MD, Baisan CH, Hughes MK (2001) Sacramento River flow reconstructed to A.D. 869 from tree rings. *J Am Water Resour As* 37:1029–1039.
41. Meko DM, et al. (2007) Medieval drought in the upper Colorado River basin. *Geophys Res Lett* 34 doi: 10.1029/2007GL029988.
42. MacDonald GM, Kremenetski KV, Hidalgo H (2007) Southern California and the perfect drought: Simultaneous prolonged drought in Southern California and the Sacramento and Colorado River systems. *Quatern Int* doi: 101016/j.quaint.2007.06.027.
43. Hughes MK, Funkhouser G (1998) Extremes of moisture availability reconstructed from tree-rings from recent millennia in the Great Basin of Western North America. *Impacts of climate variability on forests*, eds M Beniston and JL Innes (Springer, Heidelberg), pp 99–107.
44. Knight TA, Meko DM, Baisan CH (2009) A bimillennial-length tree-ring reconstruction of precipitation for the Tavaputs Plateau, Northeastern Utah. *Quaternary Res* doi: 10 .1016/j.yqres.2009.08.002.
45. Petersen KL (1998) *Climate and the Dolores River Anasazi: A paleoenvironmental reconstruction from a 10,000-year pollen record, La Plata Mountains, Southwestern Colorado* (University of Utah Press, Salt Lake City).
46. Petersen KL (1994) A warm and wet Little Climatic Optimum and a cold and dry Little Ice Age in the Southern Rocky Mountains, U.S.A.. *Climatic Change* 26:243–269.
47. Davis O (1994) The correlation of summer precipitation in the Southwestern U.S.A. with isotopic records of solar activity during the medieval warm period. Earth and Environmental. *Science* 26:271–287.
48. Stahle DW., et al. (2009a) Cool- and warm-season precipitation reconstructions over western New Mexico. *J Climate* 22:3729–3750 DOI: 10.1175/2008JCLI2752.1.
49. LaMarche VC, Jr (1974) Paleoclimatic inferences from long tree-ring records. *Science* 183:1043–1048.
50. Graumlich LJ (1993) A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Res* 39:249–255.
51. Ababneh L (2008) Bristlecone pine paleoclimatic model for archeological patterns in the White Mountain of California. *Quatern Int* 188:9–78.
52. Cook ER, Briffa KR, Meko DM, Graybill DA, Funkhouser G (1995) The "segment length curse" in long tree-ring chronology development for palaeoclimatic studies. *Holocene* 5:229–237.
53. Briffa KR, Jones PD, Schweingruber FH, Karlen W, Shiyatov SG (1996) Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals. *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, eds PD Jones, RS Bradley, and J Jouzel (Springer-Verlag, Dordrecht, Holland), pp 9–41.
54. Lloyd AH, Graumlich LJ (1997) Holocene dynamics of treeline forests in the Sierra Nevada. *Ecology* 78:1199–210.
55. Millar CI, King JC, Westfall RD, Alden HA, Delany DL (2006) Late Holocene forest dynamics, volcanism, and climate change at Whitewing Mountain and San Joaquin Ridge, Mono County, Sierra Nevada, CA, USA. *Quaternary Res* 66:273–287.
56. Scuderi LA (1987) Late-Holocene upper timberline variation in the southern Sierra Nevada. *Nature* 325:242–244.
57. Clark DH, Gillespie AR (1997) Timing and significance of late-glacial and Holocene glaciation in the Sierra Nevada, California. *Quatern Int* 38/39:21–38.
58. Reinemann SA, Porinchu DF, Bloom AM, Mark BG, Box JE (2009) A multi-proxy paleolimnological reconstruction of Holocene climate conditions in the Great Basin, United States. *Quaternary Res* doi: 10.1016/j.yqres.2009.06.003.
59. Legutke S, Voss R (1999) The Hamburg atmosphere-ocean coupled circulation model ECHO-g. *Tech Rep 18* Ger. Clim. Comput. Cent., Hamburg, Germany.
60. Stevens MB, González-Rouco JF, Beltrami H (2008) North American climate of the last millennium: Underground temperatures and model comparison. *J Geophys Res* 113:F01008 doi: 10.1029/2006JF000705.
61. Stahle Dave W., et al. (2009b) Early 21st century drought in Mexico. *Eos Trans Amer Geophys Union* 90:89–100.
62. Pielke RA, et al. (2005) Drought 2002 in Colorado—an unprecedented drought or a routine drought? *Pure Appl Geophys* 162:1455–1479
63. Breshears D.D., et al. (2005) Regional vegetation die-off in response to global-change-type drought. *Proc Natl Acad Sci USA* 102:15144–15148 doi: 10.1073/pnas.0505734102.
64. Prairie J, Callejo R (2005) *Natural flow and salt computation methods* U.S. Dept. of the Interior. Salt Lake City, UT.
65. McCabe GJ, Wolock DM (2007) Warming may create substantial water supply shortages in the Colorado River basin. *Geophys Res Lett* 34:L22708 doi: 10.1029/2007GL031764.
66. Barnett TP, Pierce DW (2009) Sustainable water deliveries from the Colorado River in a changing climate. *Proc Natl Acad Sci USA* doi: 10.1073/pnas.0812762106.
67. Hoerling M, Lettenmaier D, Cayan D, Udall B (2009) Reconciling projections of Colorado River streamflow. *Southwest Hydrol* 8:20–21 31.
68. Cook BI, Miller RL, Seager R (2009) Amplification of the North American "Dust Bowl" drought through human-induced land degradation. *Proc Natl Acad Sci USA* doi: 10 .107/3pnas.0810200106.
69. Bard E, Raisbeck G, Yiou F, Jouzel J (2000) Solar irradiance during the last millennium based on cosmogenic nucleides. *Tellus* 52B:985–992.
70. NCDC (1994) Time Bias Corrected Divisional Temperature-Precipitation-Drought Index. Documentation for dataset TD-9640. p 12 Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733.