Water, climate change, and sustainability in the southwest

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The current Southwest drought is exceptional for its high temperatures and arguably the most severe in history. Coincidentally, there has been an increase in forest and woodland mortality due to fires and pathogenic outbreaks. Although the high temperatures and aridity are consistent with projected impacts of greenhouse warming, it is unclear whether the drought can be attributed to increased greenhouse gasses or is a product of natural climatic variability. Climate models indicate that the 21st century will be increasingly arid and droughts more severe and prolonged. Forest and woodland mortality due to fires and pathogens will increase. Demography and food security dictate that water demand in the Southwest will remain appreciable. If projected population growth is twinned with suburb-centered development, domestic demands will intensify. Meeting domestic demands through transference from agriculture presents concerns for rural sustainability and food security. Environmental concerns will limit additional transference from rivers. It is unlikely that traditional supply-side solutions such as more dams will securely meet demands at current per-capita levels. Significant savings in domestic usage can be realized through decreased applications of potable water to landscaping, but this is a small fraction of total regional water use, which is dominated by agriculture. Technical innovations, policy measures, and market-based solutions that increase supply and decrease water demand are all needed. Meeting 21st-century sustainability challenges in the Southwest will also require planning, cooperation, and integration that surpass 20th-century efforts in terms of geographic scope, jurisdictional breadth, multisectoral engagement, and the length of planning timelines.

From prehistoric pueblos to today's burgeoning suburbs, water scarcity has posed sustainability challenges for the people of the Southwest. In the 21st century, these challenges are becoming acute. Since 2001, large portions of the arid Southwest (defined here as California, Nevada, Utah, Arizona, and New Mexico) have experienced prolonged drought. Particularly widespread drought occurred in 2002, 2003, 2007, and 2009 (1). During these years, the region's precipitation averaged as much as 22–25% below the 20th-century mean, with local deficits being greater. In 2002 and 2009, annual precipitation in Arizona was ∼40% below normal (2). The effects of low precipitation have been exacerbated by high temperatures, increased evapotranspiration, and decreased runoff. The average annual temperature for 2001–2009 was 0.8 °C warmer than the 20th-century mean (2).

The Colorado River is a critical conduit of water in the Southwest and is apportioned to supply 20,400 million m^3 (16.5 million acre feet; MAF) of water to the basin states and Mexico (3). Of that, about 12,400 million m^3 (10.0 MAF) are allocated to the arid Southwest. This represents approximately one sixth of the annual water use for irrigation, domestic needs, and industry (4). In Nevada, the river mainly supports the domestic and industrial demands of the Las Vegas region, whereas in southern California about 70% is used for agriculture. The allocation of Colorado River water was based upon an early 20th-century average annual flow of around 20,970 million m^3 (17.0 MAF) at Lees Ferry, Arizona. For 2001–2006, the estimated natural annual flow at Lees Ferry averaged 13,814 million m^3 (∼11.2 MAF), dropping as low as 7,647 million m^3 (∼6.2 MAF) in 2002 (3).

Higher temperatures, earlier spring warming, and decreased surface water contribute to an increase in wildfires. In California, the 2 largest wildfires on record and 11 of the 20 largest recorded fires occurred in the past decade (5). Outbreaks of forest pathogens such as bark beetles are also promoted by higher temperatures and drought. According to the US Forest Service, "the current outbreaks, occurring simultaneously across western North America, are the largest and most severe in recorded history" (6).

The purpose of this special issue is to assess current and future drought and chronic water-related challenges in the Southwest and consider the problems and prescriptions for 21st-century sustainability. A particular focus is placed on the potential impact of greenhouse warming on current and future hydroclimatology. This issue cannot address all aspects of the water resource questions facing the Southwest. Nor is it intended to present exhaustive reviews of earlier work. In this paper, I will set the spatial, temporal, and sustainability context for the Early 21st-Century Drought. I will draw upon the other papers in this issue to further explore the nature of the current drought. I will examine the possibility that arid conditions will persist and intensify due to climate warming and consider some of the sustainability challenges and solutions related to an arid 21st century.

Geography and Trajectory of the Southwest Sustainability Challenge

The spatial and temporal contexts of the Early 21st-Century Drought can be clearly demarcated relative to the climate of the last century (1895–2000 mean values from ref. 2). From 2001 through 2009, many regions of the conterminous United States experienced elevated annual temperatures (Fig. 1*A*), but temperatures in the Southwest have been exceptionally high (>1 to >2 SD above 20th-century means). The difference in annual precipitation between the early 21st century and the 20th century shows a strong geographic contrast between West and East. Many areas of eastern North America experienced precipitation >0.15 SD above the 1895–2000 mean. In contrast, much of the West experienced lower than average precipitation (Fig. 1*B*). The net result of the enhanced temperatures and decreased precipitation has been the development of persistent aridity (measured in terms of the Palmer Drought Severity Index; PDSI) in the Southwest and adjacent intermountain West—including the headwaters of the Colorado River (Fig. 1*C*). Although much of the conterminous United States experienced increased temperatures in the early 21st century, we are a nation divided in terms of changes in precipitation and resulting water resource challenges.

Annual values and 5-y running means for temperature (Fig. 2*A*) indicate that in the late 20th and early 21st centuries the Southwest has experienced an unprecedented period of sustained high tem-

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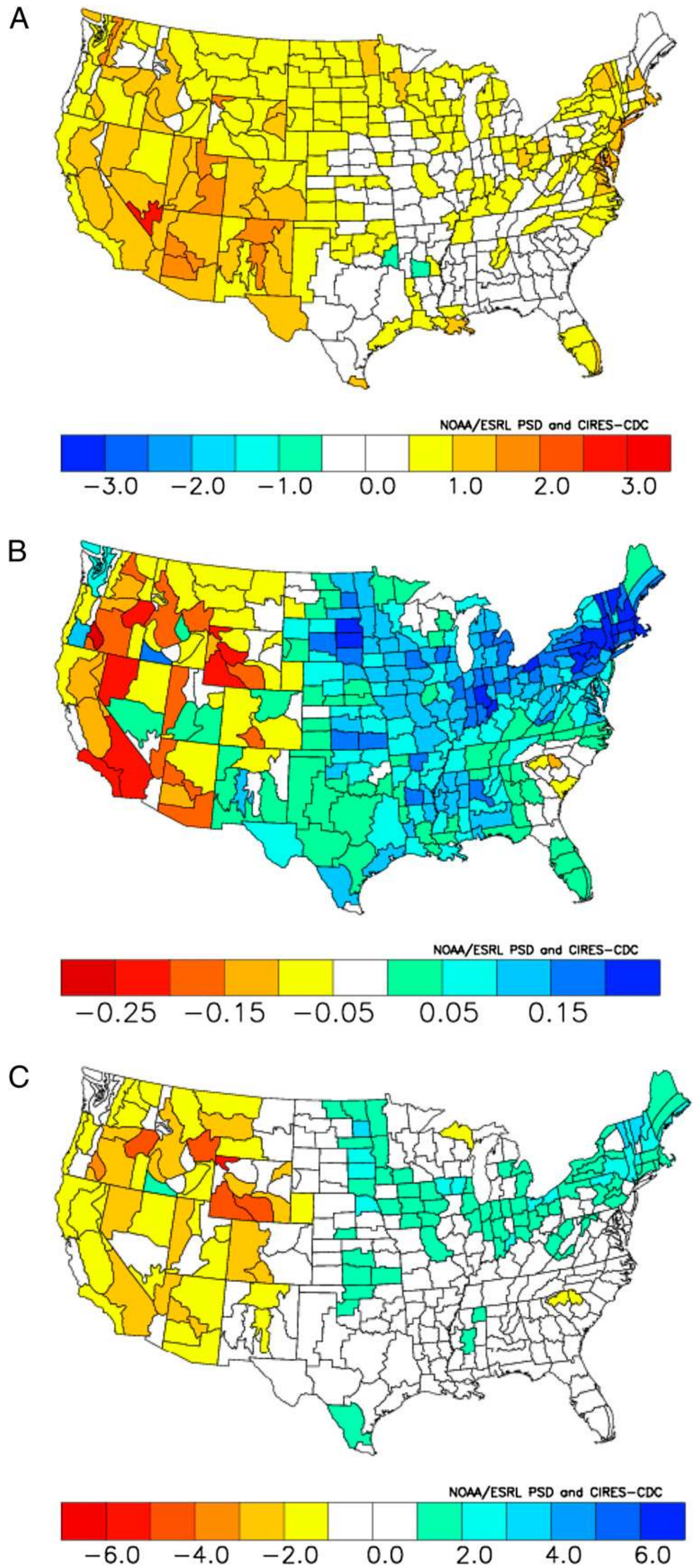

Fig. 1. (*A*) Composite standardized temperature anomalies for 2001–2009 relative to 1895–2000. (*B*) Composite standardized precipitation anomalies for 2001–2009 relative to 1895–2000. (*C*) Mean PDSI values for the period 2001–2009. Data are from ref. 2 and mapped by state climate divisions.

peratures relative to the 20th century. There has been a general, but episodic, decline in regional precipitation (Fig. 2*B*). During the 21st century, the regional PDSI for the Southwest reached its lowest level during the period of record (Fig. 2*C*). It is the high temperatures, rather than unprecedentedly low precipitation, that appear largely responsible for the exceptionally low regional PDSI values (Fig. 2 *A*–*C*). The Colorado River has also experienced the lowest 5-y mean flows on record (Fig. 2*D*). Other periods of region-wide aridity and coincidental declines in Colorado flow have occurred over the 20th century (1900–1904, 1924–1936, 1953–1964, and 1988–1991). These "perfect droughts" of widespread persistent aridity have also been associated with warmer regional temperatures (Fig. 2 *A*–*C*). However, the amount of warming during the Early 21st-Century Drought is exceptional.

Although meteoric and extraregional supplies of water may have diminished, the human demand for water remains considerable. Over the 20th century, the population of the Southwest has increased from about 2,100,000 to over 50,000,000 people (7) (Fig. 2*E*). More than 36 million of those people live in California. Initially, the amount of irrigated acreage increased in tandem with population and reached over 4.8 million ha (~12 million acres) in the 1970s (Fig. 2*F*) (8, 9). The vast majority of that land is in California. Since then, there have been a flattening and decreases in irrigated farm acreage (Fig. 2*F*). Factors at play include the full development of most practically farmable lands by the 1970s, fallowing of land during the 1987–1991 drought and the conversion of some farms to suburbs and cities. Between 1990 and 2004, more than 200,000 ha (500,000 acres) of California farmland were converted to urban and suburban land uses (10). This trend is widespread, with the conversion of 809,000 ha (1,999,082 acres) in the seven states of the Colorado River Basin between 1997 and 2007 (8).

To support the growing population, water withdrawals for domestic use in the Southwest increased to over 12,334 million m^3 (10 MAF) annually (4) and continue on an upward trajectory (Fig. 3*C*). However, the largest use of water is for agriculture. Industrial uses are relatively negligible in comparison with agriculture and have declined in recent decades (Fig. 3*C*). Roughly 80% of all water withdrawals are used for agricultural purposes. Agricultural water use in the Southwest rose to over 700,000 million m^3 by the 1970s and then flattened and declined. This is contemporaneous with, but not wholly attributable to, the accelerated withdrawal of irrigated farm lands for other uses

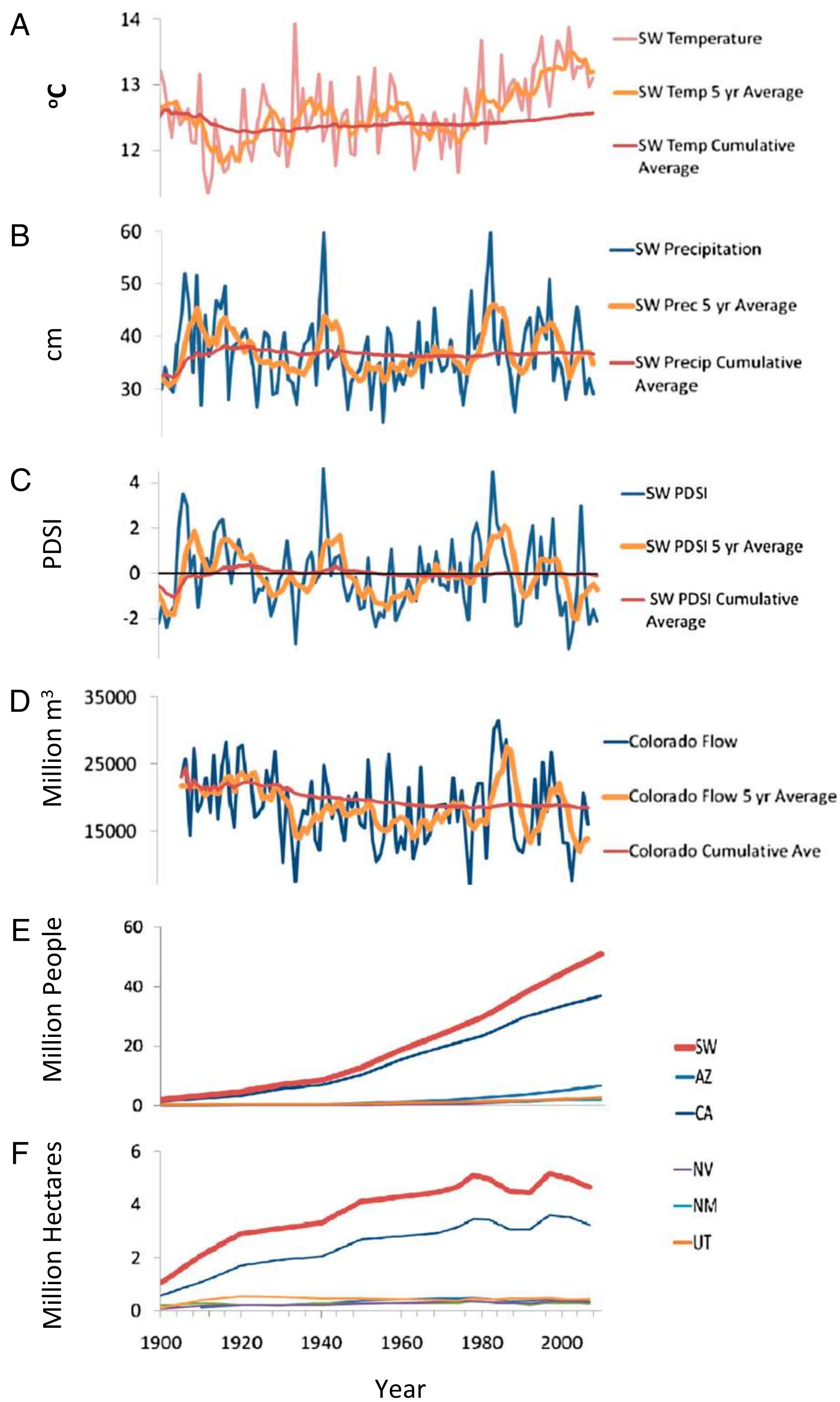

Fig. 2. (*A*) Southwest (California, Nevada, Arizona, New Mexico, Utah) average annual temperature (2). (*B*) Southwest average annual precipitation (2). (*C*) Southwest average annual Palmer Drought Severity Index (2). (*D*) Naturalized discharge of the Colorado River at Lees Ferry, AZ (3). (*E*) Southwest population size (7). (*F*) Southwest irrigated agricultural land area (8, 9).

(Fig. 3*C*). There were also declines in water use during the 1987–1991 drought. Agricultural water use stood at about 61,859 million m^3 (~50 MAF) by the end of the 20th century. Although domestic use has steadily increased, declines in agricultural and industrial withdrawals produced a decrease in overall water use in the 1980s followed by a gradual increase over the 1990s in which increasing domestic consumption has played a significant (33%) role (Fig. 3*C*).

The net result of increasing population, agriculture, and industry over the 20th century is water use in the Southwest estimated to have totaled 77,425 million m^3 (~62.7 MAF) in 2000 (4). This is a decline from a peak of 88,218 million m^3 in 1980. However, through this period, net domestic consumption continued to rise.

Some Sustainability Challenges

Is the increasing aridity in the Southwest capable of posing significant challenges to socioeconomic and environmental sustainability as we move further into the 21st century? The paper by Sabo et al. (11) tackles the current water sustainability challenges in the broader West by focusing upon the concerns raised by the late Marc Reisner in his book *Cadillac Desert—The American West and Its Disappearing Water.* Sabo et al. calculate that humans now appropriate the equivalent of 76% of the West's streamflow for agriculture, domestic use, and other purposes.

It is not anticipated that population growth in the Southwest will abate over the long term. The US Census estimates that by 2030 over 67 million people will live in the region (12). California would add the greatest number and reach a population size of over 46 million. Nevada, Arizona, and Utah would be among the top 5 states in the nation in terms of percentage of population increase. Arizona is projected to add over 5 million people to become one of the 10 most populous states in the United States. Not only are populations increasing but the geographic distribution of the population is changing in an important fashion. Since 1950, there has been a strong increase in the proportional growth of suburban populations. In 2000, suburbanites accounted for 50% of the population (7). Southwestern suburban developments, in which 70% or more of the water is often used for landscaping (13), amplify the water demands exerted by the increasing population. Sabo et al. estimate that per-capita virtual water footprints are seven times higher for cities in the arid West than in the East. They suggest that with a doubling of population, the West would require the equivalent of more than 86% of its total streamflow to meet human use at current per-capita levels.

Agriculture remains an important sector of the Southwest's economy. California's farm receipts totaled $36.1 billion in 2008 (14). Aside from a fundamental role in domestic consumption and food security, its exports contributed some $13.6 billion (14) to the nation's international trade balance. Changes in the agricultural productivity of the Southwest in response to water shortages and/or reallocation will have direct implications for food supply and security. Aside from the negative

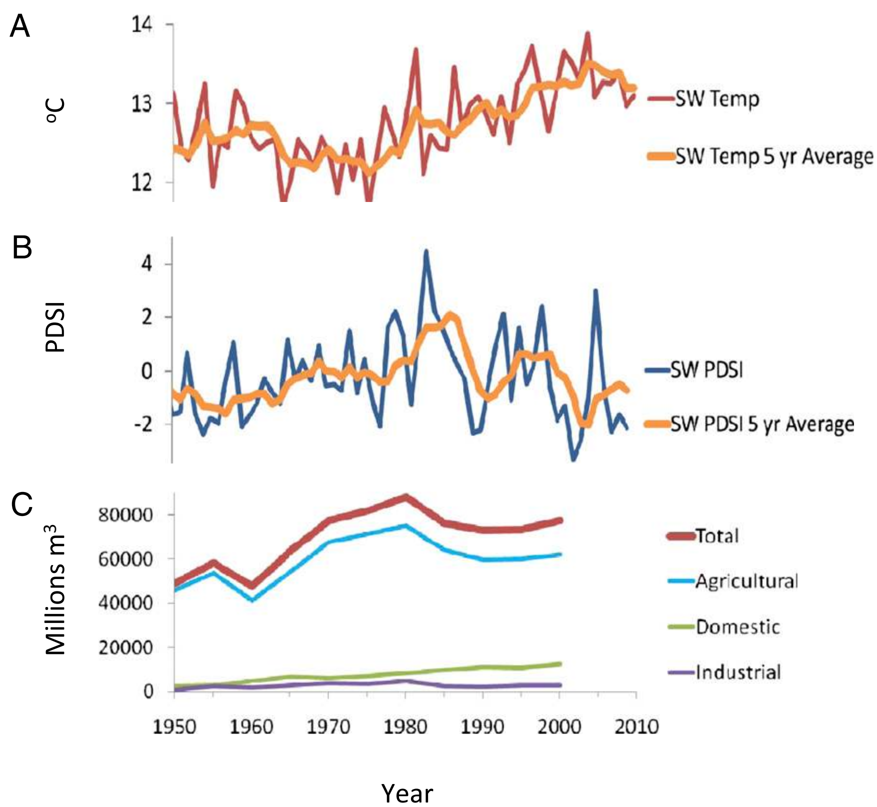

Fig. 3. (*A*) Southwest average annual temperature (2). (*B*) Southwest average annual PDSI (2). (*C*) Southwest water withdrawals by usage sector (4).

impacts of discrete droughts, chronic salt accumulation in soils promoted by hot and arid climate can also produce agricultural losses. In the West today these losses are already on the order of \$2.5 billon/y (11). Avoiding salt accumulation places additional restrictions on agricultural water management in the Southwest.

The reservoir system on the Colorado River is one of the most important buffers against drought in the Southwest. Although significant loss of reservoir capacity due to sedimentation may not be imminent (11), water supply and demand challenges for the reservoir system are clearly acute today. The Colorado system has seen storage levels decline precipitously, and they stood at 40,766 million m^3 (33.05 MAF) or 55.6% of capacity as of October 1, 2010 (3). The level of Lake Mead has now fallen more than 40 m below capacity level. A further decline of a few meters will trigger a level 1 water shortage declaration. At the extreme end of the spectrum, a recent study suggests that Lake Mead and Lake Powell have a 50% chance of receding to inoperable status by the 2020s (15). Loss of reservoir storage also produces loss of hydroelectric production and decreases energy supplies.

The recent drought has prompted emergency restrictions on outdoor water use by residents in cities such as Las Vegas, Tucson, Albuquerque, Los Angeles, and San Diego. The Metropolitan Water District of Southern California serves ~17 million people and in April 2009 voted to cut deliveries in its largely urban and suburban service area by 10%. Although urban water restrictions may be inconvenient, drought conditions have an appreciable financial impact on agriculture. In 2008, California alone experienced at least \$308 million in lost agricultural revenue due to drought (16).

The increasing temperatures and aridity of the early 21st century also pose challenges for wildlands and land management. For example, experimental studies have found that a 4 °C warming produces a 30% increase in piñon pine mortality among drought-stressed trees (17). Earlier spring warming and decreased surface water appear to contribute to a recent increase in fires (18). The annual cost of wildland fire suppression in California alone now typically exceeds \$200 million (5). In 2007, over 3,000 structures were destroyed and total suppression costs plus damages was almost \$780 million (5). Total costs of bark beetle damage are difficult to calculate, but during the 5-y period of 2005–2009, over \$75 million of federal, state, and local funds were spent on prevention, suppression, and restoration. That produced treatment of only about 200,000 ha (500,000 acres) throughout the West—a fraction of the more than 8 million hectares (22 million acres) of forest and woodland area under threat (19).

The 21st Century

The remaining papers in this issue look at the Early 21st-Century Drought and the remainder of the century. The studies tackle various aspects of water sustainability with an array of approaches that include analysis of current meteorological, socioeconomic, and ecological data, paleoenvironmental data analysis, model simulations, and policy analysis. From the papers presented here, several important insights emerge—often possessing particular weight because they arise from more than one research approach. These insights can be organized around four critical questions.

1. Is the Early 21st-Century Drought Exceptional Compared with Earlier Droughts and Is This Attributable to Increasing Greenhouse Gasses?

Cayan et al. (20) examine the Early 21st-Century Drought relative to historical droughts of the 20th century. They conclude that for the Colorado River Basin, the Early 21st-Century Drought has been the most extreme in over a century, and might occur in any given century with a probability of about 60%. They point out that 3 of the 11 driest years experienced over the past 100 y have occurred in the past decade (2002, 2007, and 2008). Only the 1930s experienced a comparable run of dry years. Similarly, Seager and Vecchi (21) conclude that the Southwest has been experiencing a general drought that is at least as severe as any in the past 100 y. They also note that the drought appears to be part of a longer-term trend of strong drying that began around 1979 (Figs. 2 and 3). Woodhouse et al. (22) use paleohydrological reconstructions to show that although the 21st-Century Drought is severe by standards of the past 100–200 y, it "pales" in terms of spatial extent and duration compared with the prehistoric drought of the 12th century. As bad as things might seem, they have the demonstrated potential to become worse.

Both Cayan et al. and Woodhouse et al. point out that warmer temperatures are typically associated with prolonged droughts in the Southwest. Cayan et al. find that summer temperature anomalies during past Southwest droughts have ranged from +0.5 °C to +1 °C. Similar to the present drought, this warming in the Southwest occurred in concert with widespread warming over the conterminous United States. Although the current drought is consistent with the observed relationship between extreme droughts and high temperatures, the magnitude and prolonged nature of the high temperatures of the Early 21st-Century Drought have no analog in the 20th century (Fig. 2*A*). Woodhouse et al. use paleoclimatic records to show that the current warming in the Southwest may exceed any other warming episode experienced over the past 1,200 y. Cayan et al. and Seager and Vecchi also note the influence of warm temperatures in the impact of the current drought on decreased snowpack, earlier timing of snowmelt, and greater evaporation rates and transpiration demands. The current drought is therefore exceptional in terms of the magnitude of warming and additional evapotranspiration stresses.

The studies by Cayan et al. and Seager and Vecchi suggest that the recent warming is consistent with the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4) projections of anthropogenic climate change (23). However, both studies conclude that it is not possible to definitively attribute the Early 21st-Century Drought to increased greenhouse gasses. Cayan et al. conclude that the Early 21st-Century Drought, although severe, is not outside the realm of natural variability in the Southwest. Seager and Vecchi argue that the great North American droughts of the past 200 y were caused by very small sea surface temperature (SST) anomalies. They note that there has been a general cooling trend in the eastern Pacific following 1979 and that such cooling typically is associated with drought in the Southwest. The drivers of such SST anomalies remain poorly understood, as does the potential impact of increasing greenhouse gasses on Pacific SSTs. Seager and Vecchi conclude that the general drying in recent decades and the 21st-Century Drought could be a result of natural decadal variability in Pacific SSTs.

2. Is It Likely That the Southwest Will Experience a More Arid Climate Due to Global Climate Change Driven by Increasing Greenhouse Gasses? The climate model estimates analyzed by Cayan et al. and Seager and Vecchi all indicate that continued warming could produce increased aridity, overprinted by more severe droughts. Analysis of the results of 15 and 24 different general circulation models lead Seager and Vecchi to argue that increasing aridity in the Southwest would be an expected outcome that results from a poleward expansion of the subtropical dry zones as the planet warms. Southwest drying is mainly being driven by a decline in winter precipitation associated with increased moisture divergence due to changes in mean atmospheric flow and reduced moisture convergence via transient eddies. The drying of the Southwest and similar subtropical regions is a highly robust result from the model simulations. Seager and Vecchi anticipate that anthropogenic aridity will be as large in magnitude as the droughts caused by natural decadal variability in climate by around 2050. They also conclude that it is unlikely that the Southwest will see a return of any prolonged periods of moist conditions similar to the long wet spells experienced in the 20th century. The analysis by Cayan et al. similarly indicates that the Southwest is likely to become drier and experience more severe droughts than witnessed over the 20th century. Drought activity is likely to increase toward the end of the 21st century, particularly in the Colorado River Basin. Drought episodes typified by continuous soil moisture depletion will increase from 4–10 y to periods of 12 y or more.

The paleohydrological analysis of Woodhouse et al. provides evidence in support of the potential for prolonged aridity and greater droughts if warm temperatures persist in the 21st century. The driest and most widespread interval of drought documented in the paleorecords occurred in the mid-12th century and is coincidental with the period of greatest prolonged temperature increase. The 12th century, typified by warm temperatures produced by increased insolation, decreased volcanic activity, a coincidental cooling of the eastern Pacific Ocean, and widespread, prolonged, and intense drought in southwestern North America, has been used as a comparison for the current drought (24). During the decade of 1146–1155, the flow of the Colorado River averaged about 78% of its 20th-century mean. The portion of the Southwest experiencing drought in any given year averaged 65.5% of the total land area. The paleorecords also show a general consistency between warmer temperatures and prolonged drought, and indicate that the observed droughts of the 20th century do not capture the full potential severity and duration of droughts exacerbated by warm conditions. Even in the absence of manmade climate change, the region is prone to periods of prolonged warming and exceptional drought that should be considered in planning efforts for a sustainable Southwest.

3. What Are the Potential Impacts of Increasing Aridity on Wildland and Urban/Suburban Systems? Williams et al. (25) examine correlations between climate and the radial growth of trees across North America. They show that conifer trees in the Southwest are particularly sensitive to temperature and aridity relative to other regions. They use climate–tree growth relations calculated for the past 100 y, combined with IPCC climate model estimates for the 21st century, to predict the likely fate of important Southwest tree species such as piñon pine (*Pinus edulis*), ponderosa pine (*Pinus ponderosa*), and Douglas fir (*Pseudotsuga menziesii*). Williams et al. conclude that woodlands and forests will experience substantially reduced growth rates and increased mortality at many Southwest sites as the century progresses.

Based on analysis of satellite data and aerial photographs, Williams et al. demonstrate that Southwest forests and woodlands have been experiencing significant impacts from wildfires and bark beetles in recent decades. Climate warming and drought promote forest flammability and can increase lightning ignition. Southwest forests are hosts to three important species of bark beetle—spruce beetle (*Dendroctonus rufipennis*), pine beetle (*Dendroctonus ponderosae*), and piñon ips beetle (*Ips* spp.), the last being the most widespread in the region (26). Climate warming allows for greater beetle reproduction and expansion of beetles' ranges to higher and cooler elevations. Drought weakens the resistance of trees to beetle infestations and promotes greater susceptibility and mortality when infestations occur. Dying trees can increase forest fuel loads and promote fires. Williams et al. estimate that from 1984 to 2006 some 2.7–3.0% (6,420 km^2) of the total area of southwestern forest and woodland has experienced mortality due to stand-clearing wildfires. A staggering 7.6–11.3% (18,177 km^2) of woodland and forest has experienced mortality due to bark beetles between 1997 and 2008. What is most disturbing is the high rate of forest loss. They estimate that 14–18% of the Southwest's forests have been impacted by fires or bark beetles in the period 1984–2008. There has also been a steady rise in the annual area burned by severe fires. It is likely that bark-beetle- and fire-related mortality will increase should 21st-century climate warming continue, and this will pose a significant challenge for conservation and resource management across the Southwest.

Gober and Kirkwood (27) look at Phoenix as an example of the water challenges facing cities in the Southwest. Phoenix displays and amplifies many of the attributes typical of the Southwest including increasing population, large suburban development, limited water supply, and shifting agricultural to urban land and water use. They use the WaterSim model to simulate conditions in the year 2030. Future climate scenarios from IPCC AR4 were used to develop a range of scenarios for the flows of the Salt/Verde and Colorado River systems. These two systems supply much of the city's water. Groundwater conditions were also estimated. The water demand estimates were based upon extrapolated population-size and land-use projections. Many of the scenarios indicated that achieving sustainability would require decreases in per-capita urban water use to slightly less than current indoor use. This suggests a dramatic curtailment of almost all usage for landscaping and pools in Phoenix. Even restricting population growth by 50% would not allow current per-capita water usage to be sustained under many water-supply scenarios. Increased groundwater reliance does not effectively mitigate the concerns. Under worse-case simulations, groundwater drawdowns range from 6 billion to 14 billion m^3. Gober and Kirkwood conclude that policy action to limit groundwater use will be necessary even without climate change to contend with. Limiting growth to 50% of projected levels and eliminating most irrigated outdoor landscaping and private backyard pools may be needed to achieve groundwater sustainability even under normal river flow conditions. The simulations suggest that with or without climate change, the Phoenix area faces clear sustainability challenges in the opening decades of the 21st century.

4. What Policy Prescriptions and Other Strategies Might Help Us to Develop Water-Use Sustainability in the Southwest? Water sustainability can be maintained through two basic variables: (*i*) increased supply or (*ii*) decreased demand. As is pointed out by Gleick (28), the preferred response to water challenges over the 20th century was based on engineered solutions on the supply side: "Build large-scale, centralized, federally subsidized infrastructure to move water in both space and time to meet current and projected demands." Such dependence upon extralocal water and engineering approaches predate the past century (29). Archeological evidence and early historical accounts tell us that peoples such as the Hopi, Zuni, Rio Grande Pueblo, and Pecos Pueblo built large villages and practiced irrigated agriculture along rivers including the Little Colorado, the Rio Grande, and the Pecos. Indeed, native peoples engineered small check dams and irrigation canals beginning about 2,000 y ago. In the 18th century, Spanish missions and settlements in California were typically established near rivers and developed masonry dams >3 m thick and stone aqueducts that ran for more than 10 km. In the 20th century, large infrastructure projects such as the Hoover Dam, which incorporates 2,600,000 m^3 of concrete, and the California Aqueduct, which is 1,151 km long, were built. After 2,000 y of application, there is certainly still a role for additional storage and transference capability; however, the engineering of water reservoir and transference systems as a comprehensive solution to Southwest water sustainability has run its course. Some of the limiting factors include the huge size of the current population, the importance and water demands of its agriculture, the limitations of meteoric and groundwater supply, the potential for decadal-length drought, and the challenges of global warming in terms of decreased precipitation and increased evapotranspiration. To these limitations should be added environmental concerns over the preservation of the ecosystems and species in places such as the Sacramento Delta, the riparian systems along the Colorado River, and the waterfowl habitat of the Salton Sea. In cases such as the Sacramento Delta, transference has already been significantly curtailed due to environmental concerns and resulting judicial restrictions. If the now-desiccated Colorado River Delta lay in the United States rather than a few kilometers over the border in Mexico, similar environmental concerns would likely be placing additional constraints on the usage of Colorado River water.

Aquifer drawdown and saltwater intrusion limit further extraction of groundwater (27, 29). Enhanced water harvesting, particularly stormwater capture, can augment supplies. In California, the Stormwater Resource Planning Act allows municipalities to access funds for projects that capture stormwater for reuse or to recharge groundwater. The City of Los Angeles estimates that during rainy days as much as 37,854,117 m^3 (~10 billion gallons) may flow through the stormwater system. However, such water still requires considerable treatment depending upon intended use (30). Sabo et al. call for increased urban desalination plants. Large-scale desalination, although technically feasible, requires significant energy and remains expensive (31). Treating brackish water is less expensive, and Gleick outlines how desalination of brackish groundwater is significantly augmenting municipal water supplies in El Paso. Improvements in technology and particularly the use of solar energy could help offset the energy and cost restrictions of desalination (32). Gray water recycling and use in landscaping is already being applied (33). This holds much promise given the prominent role of suburban lawns and gardens in Southwest water demand. Potable reuse of some recycled wastewater is possible, but faces economic and community acceptance challenges.

Despite the innovations outlined above, increased supply will likely not provide the complete answer for the Southwest in the near future. Although there remains relatively greater uncertainties in projections of precipitation than temperature, the consensus is that global climate change due to increased greenhouse gasses will exacerbate surface water deficiencies in the Southwest (20, 21, 23). Much of the increase in demand is and will be driven by cities and their suburbs. Water could be transferred from farms to maintain urban growth. For example, a recent modeling study by Tanaka et al. (34) concludes "California's water system can adapt to the fairly severe representations of population growth and climate warming. This adaptation will be costly in absolute terms and include transaction, institutional, and fixed costs not quantified in the model, but, if properly managed, should not threaten the fundamental prosperity of California's economy or society, although it can have major effects on the agricultural and environmental sectors." As discussed above, environmental concerns are already curtailing water transference and it is unlikely such policies will be significantly reversed. However, significant transfers of water from agriculture to satisfy the domestic demands of a growing suburban population also raise a plethora of important concerns including loss of agricultural sector sustainability, rural socioeconomic decline, increased food prices, decreased food choice, decreased food security, increased carbon footprint for imported food, and decreased foreign trade balance. Thus, as pointed out by Gleick, Gober and Kirkwood, and Sabo et al., innovations and policies that decrease overall demand must figure prominently in planning for water sustainability. Sabo et al. estimate that to completely eliminate freshwater stress would require decreased water use to an appropriation of only 60% of the total streamflow in the region. They argue for a compromise target of a 15% decrease. Gleick suggests that increased efficiencies are to be found in domestic and industrial water uses. He notes that some 50% of agricultural water use in California is for "inefficient flood-irrigation." Sabo et al. also suggest greater water-use efficiencies can be implemented in the agricultural sector. Gober and Kirkwood articulate a three-pronged strategy of implementing policies in urban areas that will slow population growth, focus remaining growth in high-density developments, and alter outdoor consumption by encouraging xerophytic landscaping and decreasing private swimming pools. It is encouraging that even more modest policy prescriptions, such as public information campaigns, water-efficient building requirements, and limited restrictions, can have significant results. Water deliveries by the Metropolitan Water District of Southern California peaked in 1990 at about 3,207 million m^3 (2.6 MAF) and by 2008 had fallen to about 2,466 million m^3 (2 MAF), despite a population increase of 2 million people. In response to drought, the City of Los Angeles was able to reduce total water usage by 17% over the 1-y period of 2008–2009. Sabo et al. suggest that market-based pricing of water and the restriction of government subsidies to only those uses that fulfill basic human needs should also be used. In a region where the majority of water use is often for exterior landscaping, decreasing per-capita demand does not have to mean fundamental hardships in terms of drinking water and cleanliness. Efficiencies clearly remain to be realized in the Southwest in urban and suburban water use. For example, per-capita water use in Tucson is half that in Phoenix despite similarities in climate for the two cities (27).

In view of the broad scope of the problem, Gleick and Sabo et al. highlight the need for comprehensive, multisectoral, and transregional policies to formulate water strategies for Southwest sustainability. As Gleick demonstrates, these efforts must foster communication, planning, and implementation among a plethora of agencies and jurisdictions. In addition, as the climate models and paleoclimatic studies indicate, the region could become more arid and droughts could extend over decades. Typical 3- to 5-y drought plans are insufficient to address climate change and decadal-to-multidecadal droughts.

Discussion of sustainability must also incorporate consideration of ecosystem services and protection of endangered species. Williams et al. point out that the vegetation of the Southwest is likely undergoing profound changes. Management of forests, woodlands, streams, deltas, and other habitat to preserve ecosystem functioning and conserve biodiversity will be extremely challenging and at times come at an appreciable cost in terms of water-supply options for other demands. Sabo et al. point out the threats posed to native fish species should care not be taken in water-infrastructure projects.

Cooperation and strategic integration that surpass 20th-century efforts in terms of geographic scope, jurisdictional breadth, multisectoral engagement, and planning timelines are required to develop Southwest water sustainability. Given the impacts of the current drought on water supplies and infrastructure, those efforts should be undertaken with expediency.

However, with greenhouse gas concentrations at their current levels, we likely will not escape significant warming and resulting increased aridity over the 21st century (20, 21, 23). Coupled with the demographic projections, the climatic estimates for the next decades compel us to develop water resource strategies that adapt to these changing conditions and promote sustainability in the face of increasing general aridity as well as more severe episodic droughts. Finally, the proximal economic costs of reducing greenhouse gas emissions are often cited as a rationale for inaction on emissions reduction. Because climate warming will exacerbate water sustainability problems, the Southwest is likely to experience some of the highest economic expenses and environmental losses related to climate change. As the papers in this issue illustrate, the ultimate costs of inaction in curbing greenhouse gas emissions will be particularly high for the Southwest.

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