Chapter 5

Present Weather and Climate: Evolving Conditions

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Executive Summary

This chapter assesses weather and climate variability and trends in the Southwest, using observed climate and paleoclimate records. It analyzes the last 100 years of climate variability in comparison to the last 1,000 years, and links the important features of evolving climate conditions to river flow variability in four of the region's major drainage basins. The chapter closes with an assessment of the monitoring and scientific research needed to increase confidence in understanding when climate episodes, events, and phenomena are attributable to human-caused climate change.

- The decade 2001–2010 was the warmest and the fourth driest in the Southwest of all decades from 1901 to 2010. (high confidence)

- Average annual temperature increased 1.6°F (+/- 0.5°F) over the Southwest during 1901–2010, while annual precipitation experienced little change. (high confidence)

- Fewer cold waves and more heat waves occurred over the Southwest during 2001–2010 compared to their average occurrences in the twentieth century. (high confidence)

- The growing season for the Southwest increased about 7% (seventeen days) during 2001–2010 compared to the average season length for the twentieth century. (high confidence)

- The frequency of extreme daily precipitation events over the Southwest during 2001–2010 showed little change compared to the twentieth-century average. (medium-high confidence)

- The areal extent of drought over the Southwest during 2001–2010 was the second largest observed for any decade from 1901 to 2010. (medium-high confidence)

- Streamflow totals in the four major drainage basins of the Southwest were 5% to 37% lower during 2001–2010 than their average flows in the twentieth century. (medium-high confidence)

- Streamflow and snowmelt in many snowmelt-fed streams of the Southwest trended towards earlier arrivals from 1950–1999, and climate science has attributed up to 60% of these trends to the influence of increasing greenhouse gas concentrations in the atmosphere. (high confidence)

- Streamflow and snowmelt in many of those same streams continued these earlier arrivals during 2001–2010, likely in response to warm temperatures. (high confidence)

- The period since 1950 has been warmer in the Southwest than any comparable period in at least 600 years, based on paleoclimatic reconstructions of past temperatures. (medium-high confidence)

- The most severe and sustained droughts during 1901–2010 were exceeded in severity and duration by several drought events in the preceding 2,000 years, based on paleoclimatic reconstructions of past droughts. (high confidence)

5.1 Introduction

Wallace Stegner (1987) expressed a sentiment held by many familiar with the Southwest: "If there is such a thing as being conditioned by climate and geography, and I think there is, it is the West that has conditioned me."

As the twenty-first century unfolds, two principal concerns make it important to take stock of the region's climate. One concern is that the annual demand for water in the Southwest—especially from the Colorado River, which supplies water to each of the region's states—has risen to an amount that nearly matches the natural annual flow in the Colorado River. With only a small margin between supply and demand—both of

which are sensitive to climate variability and change—the importance of reservoirs in the Colorado River Basin increases (Barnett and Pierce 2008, 2009; Rajagopalan et al. 2009). Droughts, whose periodic occurrences in the Southwest have tested the resilience of the region's indigenous populations (Liverman and Merideth 2002), have increasingly significant effects. In particular, excess (unconsumed) water supply capacity has been diminishing, virtually vanishing, as was especially evident during the region's drought that began in 2000 (Fulp 2005). The second concern is the expectation, based on a growing body of scientific evidence, that climate change in the Southwest will most likely reduce water resources, including a decline in the annual flow of the Colorado River (Milly, Dunne, and Vecchia 2005; Christensen and Lettenmaier 2007; McCabe and Wolock 2008; see also the discussion of the effects of climate change on the water supplies of the Southwest in Chapter 10.)

This chapter reviews the nature of weather and climate variability in the Southwestern United States based on recorded observations and measurements that span the last century. The chapter links how changing climate conditions affect the variability of river flows specifically in four of the region's major drainage basins: Sacramento-San Joaquin, Humboldt (in the Great Basin), Upper Colorado, and Rio Grande. To place current climatic conditions in a longer-term context, the chapter looks at the indirect evidence (*paleoclimatic reconstruction*, as from tree rings, pollen, sediment layers, and so on) of climatic conditions over the last thousand years, showing the variations that occurred before humans substantially increased emissions of greenhouse gases. The chapter concludes by appraising the data gaps and needs for monitoring the evolving climate and hydrological conditions in the Southwest.

5.2 Climate of the First Decade of the Twenty-first Century

"Exceptionally warm" aptly describes temperatures in the Southwest during the first decade of the twenty-first century. Annual temperatures for 2001–2010 were warmer than during any prior decade of the twentieth century, both for the Southwest as a whole and for each state in the region (Table 5.1).[i] Annual averaged temperatures for 2001–2010 were 1.4°F (0.8°C) warmer than the 1901–2000 average. The intensity of warming is related to changes in temperatures at particular times of the day and in particular seasons. For example, greater warming has occurred due to increases in daily minimum temperatures than to increases in daily maximum temperatures, though the reasons for this difference are not well-known and may be related to local effects and to adjustments applied to station data (as discussed further below; see also Fall et al. 2011). The key features of a warming Southwest appear robustly across various data sets and methods of analysis, as shown further in Appendix Table A5.1.

With respect to the seasons, when looking at average seasonal temperatures for the period 2001–2010 versus those for the twentieth century, greater warming (i.e., larger differences) occurred during the spring and summer than occurred during the other seasons, especially winter. Based on results of a rigorous detection and attribution study, the recent rapid increase in late winter/early spring minimum temperatures are *very unlikely* due to natural variability alone, but are consistent with a regional sensitivity to increased greenhouse gases and aerosols (Bonfils et al. 2008). During winter, maximum

Table 5.1 Comparison of Southwest annual and seasonal surface temperatures averaged for 2001–2010

AVERAGE TEMPERATURE

	1901–2000 6-State Avg.		2001–2010 Decadal								
Season	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank	AZ	CA	CO	NV	NM	UT
DJF	35.1 (1.7)	0.7 (0.4)	36 (2.2)	+0.9 (0.5)	2	3	2	3	2	3	2
MAM	50.0 (10.0)	0.9 (0.5)	51.8 (11)	+1.8 (1.0)	1	1	1	1	1	1	1
JJA	70.0 (21.1)	0.9 (0.5)	72 (22.2)	+2.0 (1.1)	1	1	1	1	1	1	1
SON	53.2 (11.8)	0.7 (0.4)	54.7 (12.6)	+1.4 (0.8)	1	1	1	1	1	1	1
Annual	52.2 (11.2)	0.7 (0.4)	53.6 (12)	+1.4 (0.8)	1	1	1	1	1	1	1

MAXIMUM TEMPERATURE

	1901–2000 6-State Avg.		2001–2010 Decadal								
Season	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank	AZ	CA	CO	NV	NM	UT
DJF	47.7 (8.7)	0.7 (0.4)	47.8 (8.8)	+0.2 (0.1)	5	4	3	8	6	3	4
MAM	64.6 (18.1)	0.9 (0.5)	66.2 (19)	+1.6 (0.9)	1	1	2	1	2	1	1
JJA	86.0 (30.0)	0.7 (0.4)	87.4 (30.8)	+1.4 (0.8)	1	1	1	2	1	2	1
SON	68.2 (20.1)	0.7 (0.4)	68.9 (20.5)	+0.7 (0.4)	3	2	3	5	3	2	4
Annual	66.6 (19.2)	0.7 (0.4)	67.6 (19.8)	+1.1 (0.6)	1	1	1	2	1	1	1

MINIMUM TEMPERATURE

	1901–2000 6-State Avg.		2001–2010 Decadal								
Season	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank	AZ	CA	CO	NV	NM	UT
DJF	22.5 (-5.3)	0.9 (0.5)	24.1 (-4.4)	+1.6 (0.9)	2	2	2	2	1	2	2
MAM	35.6 (2.0)	0.9 (0.5)	37.4 (3.0)	+1.8 (1.0)	1	1	2	1	1	1	1
JJA	54.1 (12.3)	0.9 (0.5)	56.5 (13.6)	+2.3 (1.3)	1	1	1	1	1	1	1
SON	38.3 (3.5)	0.9 (0.5)	40.6 (4.8)	+2.3 (1.3)	1	1	1	1	1	1	1
Annual	37.6 (3.1)	0.9 (0.5)	39.7 (4.3)	+2.2 (1.2)	1	1	1	1	1	1	1

Note: Comparison of annual and seasonal surface temperatures for the six Southwestern states, averaged for 2001–2010 versus 1901–2000, and a ranking of the 2001–2010 decadal averages relative to the ten individual decades of the twentieth century. Results shown for daily averaged, maximum, and minimum temperatures.

Source: PRISM monthly gridded analysis for 1901–2010 (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu).

temperature changes have been muted, being only 0.2°F (0.1°C) above the twentieth-century average for the Southwest. These data further indicate that the winter maximum temperatures for 2001–2010 averaged over Colorado were actually colder than during the majority of decades in the twentieth century.

"Unusually dry" best describes Southwest moisture conditions during the first decade of the twenty-first century (Table 5.2). Annual precipitation, averaged across the entire Southwest, ranked 2001–2010 the fourth driest of all decades since 1901, a condition that is found to be robust across various data sets (see Appendix Table A5.2). The departure of -0.59 inches (-15 mm) represents a reduction of 4% of the twentieth-century average annual total. Much of the deficit was accumulated in the early half of the decade in association with one of the most severe droughts on (instrumental) record (Hoerling and Kumar 2003; Pielke et al. 2005). It is *likely* that most of recent dryness over the Southwest is associated with a natural, decadal coolness in tropical Pacific sea-surface temperatures, and is mostly unrelated to influences of increased greenhouse gases and aerosols (Hoerling, Eischeid, and Perlwitz 2010). The strongest percentage declines occurred during spring and summer, which were 11% and 8% below normal,[ii] respectively. The winter season, when the bulk of the region's precipitation is delivered, actually experienced a small increase relative to twentieth-century averages. Precipitation conditions during 2001–2010 varied considerably among the six Southwestern states, with Arizona experiencing its driest decade since 1901 and Utah experiencing one of its wetter decades.

Table 5.2 Comparison of Southwest annual and seasonal precipitation totals averaged for 2001–2010

| | PRECIPITATION | | | | | | | | | |
| | 1901–2000 6-State Avg. | | 2001–2010 Decadal | | | | | | | | |
Season	Mean inches (mm)	Std.Dev. inches (mm)	Mean inches (mm)	Anom inches (mm)	Rank	AZ	CA	CO	NV	NM	UT
DJF	5.1 (129.3)	0.38 (9.6)	5.2 (133.3)	+0.16 (4.0)	5	7	5	2	4	2	3
MAM	3.8 (96.6)	0.32 (8.2)	3.4 (86.8)	-0.39 (9.8)	10	11	9	10	5	7	9
JJA	3.3 (83.4)	0.26 (6.7)	3.0 (77.1)	-0.25 (6.3)	9	10	9	7	10	6	9
SON	3.4 (85.3)	0.39 (9.9)	3.2 (82.3)	-0.12 (3.0)	6	11	7	3	5	7	3
Annual	15.5 (394.6)	0.8 (20.2)	15.0 (381.0)	-0.60 (15.1)	8	11	7	6	5	5	3

Note: Comparison of annual and seasonal precipitation totals for the six Southwestern states, averaged for 2001–2010 versus 1901–2000, and a ranking of the 2001–2010 decadal averages relative to the ten individual decades of the twentieth century.

Source: PRISM monthly gridded analysis for 1901–2010 (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu).

5.3 Climate Trends for 1901–2010

The trend in surface temperature during 1901–2010 was upward over all of the stations in the Southwest that have long-term climate records (Figure 5.1, upper panel). Average annual temperature increased 1.6°F (0.9°C) over the Southwest during 1901–2010, with a range of magnitudes from 1.4°F to 2.0°F (+0.8°C to +1.1°C) based on analyses conducted with other data sets (see Appendix). The 95% confidence interval for the linear trend is +/- 0.5°F (0.3°C).

The linear warming trend continued in the first decade of the twenty-first century, the warmest over the region during the 110-year period of record (see Table 5.1). Increases have been more than 1.8°F (1°C) in many parts of the Southwest over the last 110 years, with isolated 3.6°F (2°C) increases occurring in southwestern portions of the region. Both daytime high temperatures (Figure 5.1, second panel) and nighttime low temperatures (Figure 5.1, third panel) have exhibited widespread warming trends. In this data set, which has been homogenized, minimum temperatures are found to increase at about the same rate as the maximum temperatures for the Southwest as a whole, though there is considerable variability from one station to another. Note that the trends in unadjusted raw data show somewhat higher minimum temperatures (Figure A5.1).

In light of the warming over the Southwest in all seasons, it is not surprising that the growing season duration has increased over the last century. Figure 5.2 shows the growing season departures for each year during 1901–2010, based on a 32°F (0°C) threshold, for some sixty Southwest stations that form part of the National Weather Service Cooperative Observing Network (COOP) (see Kunkel et al. 2004). The average growing season over the Southwest during 2001–2010 was seventeen days longer (about 7% longer) than the twentieth-century average and one month longer than that of the first decade of the twentieth century.[iii]

The trend in annual precipitation during 1901–2010 (expressed as percent of annual precipitation climatology) is shown for individual stations in Figure 5.1 (bottom panel). Plotted atop the regional map of precipitation trend are outlines of four major drainage basins in the Southwest (clockwise from upper left: Sacramento-San Joaquin, Great Basin, Upper Colorado, and the Rio Grande). A summary of the climate conditions and river runoff characteristics for these hydrologic regions will be subsequently provided.

Although the decade 2001–2010 has been relatively dry for the Southwest as a whole (Table 5.1), the trend in annual precipitation computed for the entire 1901–2010 period reveals little change over the 110-year period (Figure 5.1, bottom panel). Some significant local trends (filled colored circles) can be discerned, however, including wet trends at select stations in the Great Basin. It should be noted that the bulk of the region's precipitation falls at high elevations, areas not well observed. Although water supplies for the region's major drainage basins are especially dependent on the precipitation falling in these remote areas, the long-term trends in such resources are not well known.

5.4 Extreme Weather Variability During 1901–2010

Further indicators of a warming Southwest climate are provided by indices for occurrences of cold waves and heat waves, shown in Figure 5.3. Cold waves (defined as four-day periods colder than the threshold of a one-in-five-year frequency) have been
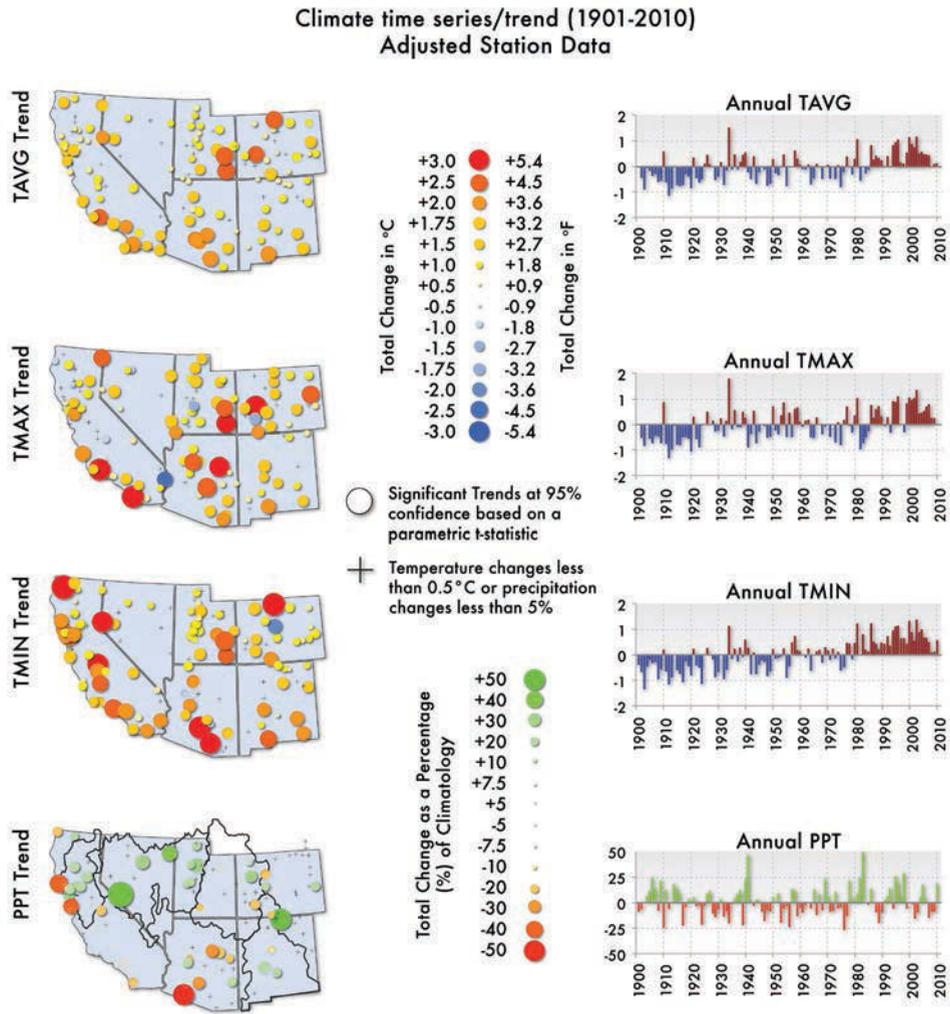
Figure 5.1 Trends in temperature and precipitation, 1901–2010. Shown in the first three (upper) panels are the pattern and intensity of 110-year trends in the Southwest in annually averaged daily temperature (TAVG), and daily maximum temperature (TMAX) and daily minimum temperature (TMIN), respectively, as estimated from station data for which there are at least 90 years of available data during the period. The magnitude of trends is indicated by a station circle's size, with warming (cooling) trends denoted by red (blue) shades. Bottom panel shows trend in annual averaged precipitation for 1901-2010, showing data for individual stations plotted with outlines of four major basins in the Southwest (Sacramento-San Joaquin, Great Basin, Upper Colorado, and Rio Grande). Units are the total change expressed as percent of annual climatology, and positive (negative) trends are shown in green (orange). Larger circle sizes denote greater magnitude trends. Filled stations denote statistically significant trends at 95% confidence based on a parametric t-statistic. Stations with temperature (precipitation) changes less than 0.5°C (5%) are denoted with a + symbol. The figure uses so-called "homogenized" data, in which adjustments to remove artificial temperature changes at a station are made by using the method of pairwise difference comparisons between monthly temperatures from a network of reporting stations. The trends calculated from the raw data that preserve various inhomogeneities in the original time series are provided in Appendix Figure A5.1. Results from both the raw and the homogenized data show substantial warming. Source: Menne and Williams (2009).
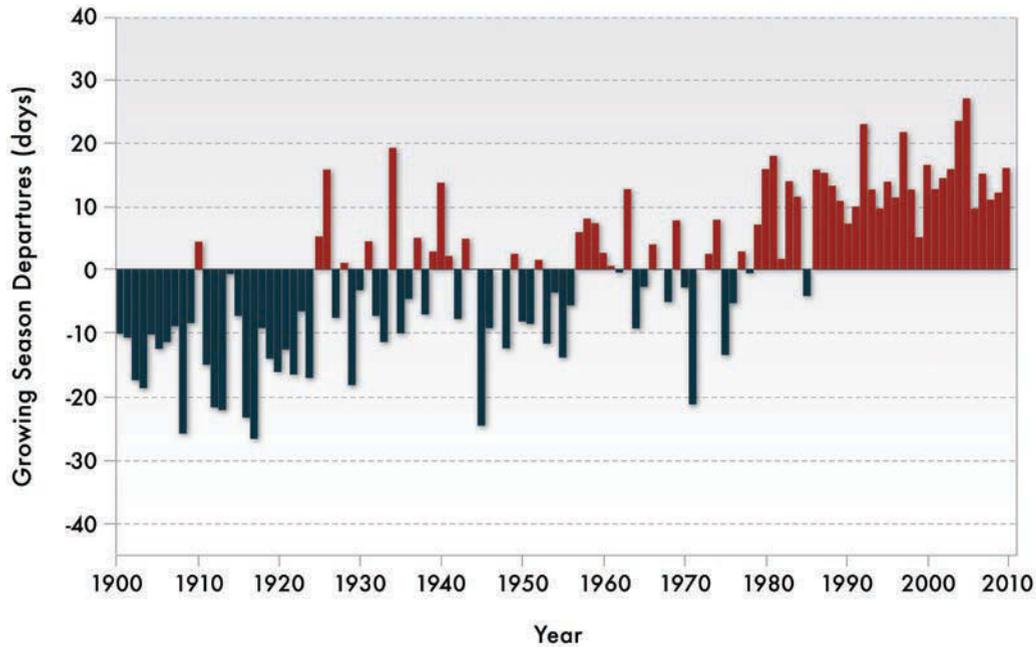
Figure 5.2 Growing season anomalies for 1900 to 2010. Departure from the normal number of days in the growing season are shown as number of days per year. Length of the growing season is defined as the period between the last freeze in spring and the first freeze in the subsequent fall. Source: NOAA National Climatic Data Center for the Cooperative Observer Network (http://www.ncdc. noaa.gov/land-based-station-data/cooperative-observer-network-coop).

especially rare since about 1990, while the frequency of heat waves (defined similarly to cold waves) increased.[iv] Heat-wave frequency during 2001–2010, however, is not appreciably different from that occurring during the 1930s. Both periods were characterized by drought, and the feedback from dry soils and clear skies likely enhanced the severity of summertime heat during both decades. The increase in heat waves in tandem with a decrease in cold waves is consistent with other research findings that showed an increase in record high maximum temperatures relative to record low minimum temperatures over the entire United States since 1950 (Meehl et al. 2009).

COOP station data have also been used to derive an extreme precipitation index (Kunkel et al. 2003); Figure 5.4 shows an index time series of five-day rainfall extremes (events wetter than a threshold for a one-in-five year-frequency). There is no discernible trend in this statistic of heavy precipitation events, with the time series characterized by appreciable decadal variability. Nor is there evidence for trends in precipitation extremes using other indices such as for extreme daily precipitation totals (not shown). Bonnin, Maitaria, and Yekta (2011) diagnosed trends in rainfall exceedences (exceeding precipitation thresholds over multiple timescales as defined in the NOAA Atlas 14) for the semiarid Southwest encompassing much of our six-state region but excluding Colorado and central and Northern California. For their 1908–2007 period of analysis, they found negative trends in rainfall exceedences for the semi-arid Southwest for all multi-day durations, though only the one-day duration negative trends were statistically

Southwest U.S. Cold Waves
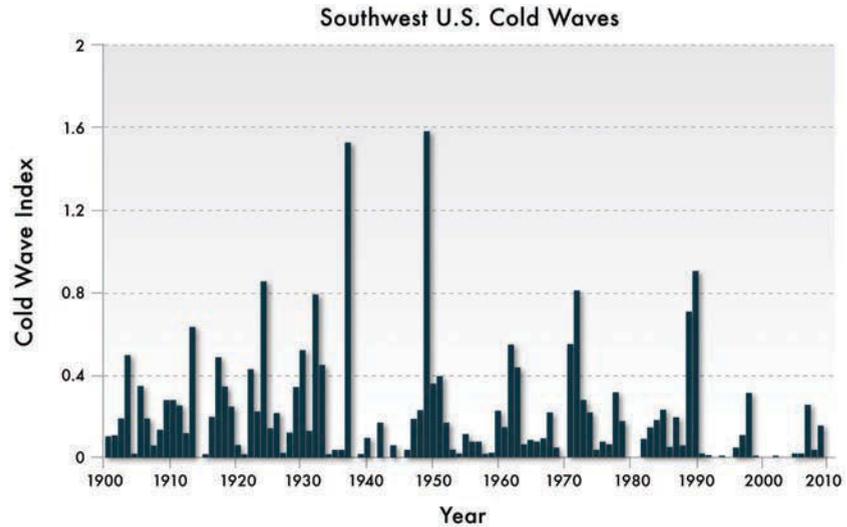
Figure 5.3 Occurrence of cold waves and heat waves, 1901–2010. Cold waves (top) are defined as four-day periods that are colder than the threshold of a one-in-five-year occurrence; heat waves (bottom) are four-day periods warmer than the same threshold. The thresholds are computed for the entire 1901–2010 period. Source: NOAA National Climatic Data Center for the Cooperative Observer Network (http://www.ncdc.noaa.gov/land-based-station-data/cooperative-observer-network-coop).
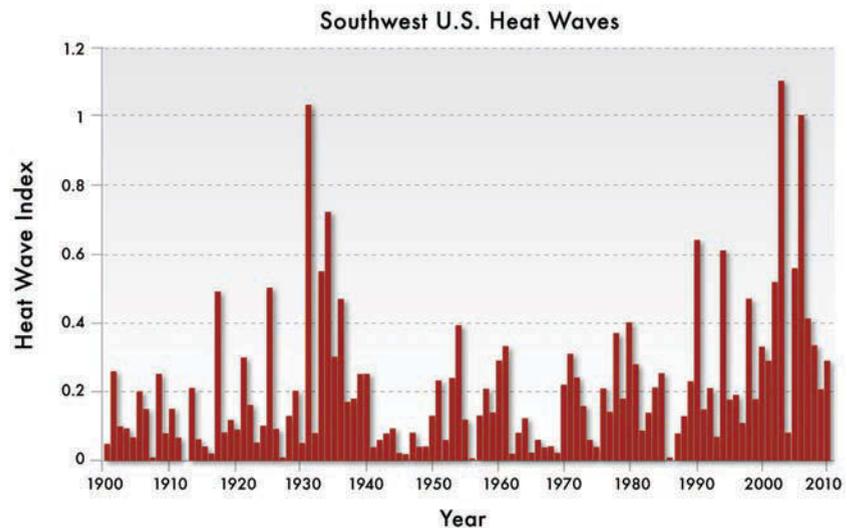
significant. This means that in recent years there were fewer events exceeding high precipitation thresholds for multi-day episodes than during earlier in the period of analysis. The Southwest is thus unlike some other areas of the United States, such as the Great Lakes and Ohio Valley regions, where significant upward trends in very heavy daily precipitation (during 1908–2000) have been noted (Groisman et al. 2004).

## 5.5 Summertime Drought During 1901–2010

To quantify variability in drought across the region, the Palmer Drought Severity Index (PDSI) was used, based on data from the NOAA National Climate Data Center (NCDC). The PDSI is a widely used indicator of dryness, representing the balance of water inputs
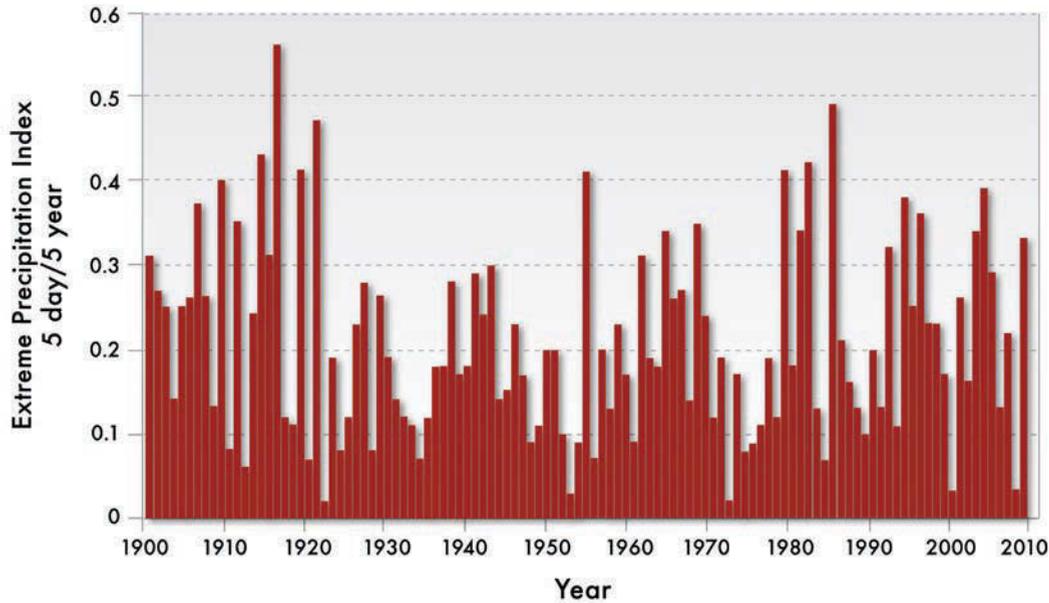
Figure 5.4 Occurrence of extreme precipitation events, 1900–2010. Extreme precipitation events are defined as five-day totals that are wetter than the threshold of a one-in-five-year occurrence. Source: NOAA National Climatic Data Center for the Cooperative Observer Network (http://www.ncdc. noaa.gov/land-based-station-data/cooperative-observer-network-coop).

to the soil (based on observed monthly precipitation) and water losses from the soil (based on observed monthly temperature). This soil-moisture balance calculation incorporates the water-holding ability of soil, and thus PDSI for a given month or season actually reflects the previous nine to twelve months of weather conditions (Palmer 1965; Alley 1984). Thus, while summer PDSI captures moisture anomalies that peak during three months of summer, it also incorporates conditions from the previous fall, winter, and spring. For this assessment, the divisional monthly data were averaged by area across the six Southwest states, then summer (June, July, August) PDSI was averaged to represent drought conditions during the height of the growing season.

Figure 5.5 shows variations in the areal extent of drought[v] in the Southwest from 1901 to 2010. Over that period, there is a trend towards increasing drought extent, in large part due to widespread drought during the 2001–2010 decade, which had the second-largest area affected by drought (after 1951–1960) and the most severe average drought conditions (average summer PDSI = -1.3) of any decade. The severity of drought in 2001–2010 reflects both the decade's low precipitation and high temperatures, since both affect the surface water balance that enter into the calculation of PDSI (see Table 5.2). An analysis of PDSI trends over the globe by Dai (2011) indicates that the warmer temperatures across the Southwest in recent decades are at least partly responsible for the increasing drought coverage. Widespread and severe drought also occurred in the Southwest from 1950 to 1956, whereas the Dust Bowl conditions of the 1930s (though having a severe impact on the eastern portions of the region and the rest of the Great Plains) did not extend significantly into the Southwest except in 1934.
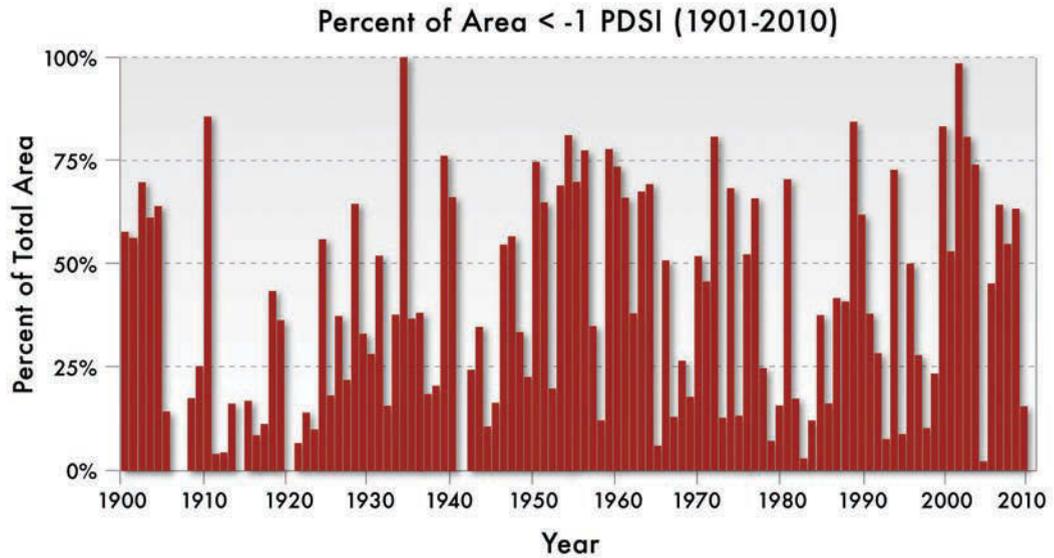
Figure 5.5 Areal coverage of drought in the Southwest United States, 1900–2010. Data is for drought during summer (June through August). Graph based on the Palmer Drought Severity Index (PDSI) and monthly data from the NOAA National Climatic Data Center for 1901–2010.

PDSI is a useful indicator of local-to-regional meteorological drought (low precipitation) and agricultural drought (low soil moisture). It is less useful for indicating hydrologic drought (low water supply), especially if the PDSI measurements do not adequately capture the specific locations where the water supply for a given area originates—often in mountain headwaters remote from the point of use. Also, while PDSI can be closely correlated with annual streamflow in basins where runoff is mainly from the melting of the winter snowpack, this is not the case in basins where streamflow mainly derives from infrequent large rainfall events or from groundwater discharge. The most consistently useful indicator of hydrologic drought across the Southwest is streamflow itself, which is the subject of the next section.

5.6 Hydroclimatic Variability During 1901–2010

The water resources of the Southwest, and especially its rivers, reflect variations of precipitation, evaporation, and transpiration (the uptake of water by plants) over the region, with evaporation and transpiration strongly modulated by temperature. They also reflect human interventions into the hydrologic system—dams, diversions, and water uses such as irrigation. The climatic conditions of the 2001–2010 period described previously thus resulted in significant deviations of the flows of rivers in the region from twentieth-century norms. Here we will focus on naturalized or near-natural flows in four major hydrologic basins—the Sacramento-San Joaquin system, central Great Basin (represented by the Humboldt River at Palisade), Upper Colorado River, and Rio Grande (see Figure 5.1, bottom panel)—to represent recent hydrologic variations. Naturalized flows are best estimates of the total streamflow that would have reached the

outlet of the river system in the absence of human actions and are based on historic measured flows, corrected for human influences including diversions and other uses.

As noted earlier, the 2001–2010 period was unusually warm in the Southwest, with many areas also drier than normal (Table 5.2). The four river systems analyzed here all responded to those climatic conditions with lower-than-normal measured flows (and, where available, lower-than-normal naturalized flows) (Table 5.3). Naturalized flows in the Sacramento-San Joaquin Rivers system reflected drier than normal conditions, with a 2001–2010 average daily flow of 6.8 million acre-feet/year compared to the 1931–2000 average flow of 10.8 million acre-feet/year. This 37% overall deficit ranked 2001–2010 as the lowest-flow decade since 1931 in the Sacramento-San Joaquin system. Flows in the Humboldt River at Palisade during 2001–2010 averaged 134,000 acre-feet/year during the 2001–2010 period, or 5% below the 141,000 acre-feet/year average of the 1921–2000 period, ranking that decade as the sixth driest in nine decades of record. Warm temperatures and dry conditions reduced average naturalized flows in the Colorado River (measured at Lees Ferry) to 12.6 million acre-feet/year, compared to the 1901–2000 average of 15.0 million acre-feet/year (Cayan et al. 2010). This 16% decadal deficit (Table 5.3) made 2001–2010 the second-lowest-flow decade at Lees Ferry (among eleven) since 1901. Observed flows for 2001–2010 in the Rio Grande at El Paso (where the river leaves the Southwest region) were about 23% lower than the period from 1941 to 2000, even though overall precipitation in the basin was 3% above normal.

Overall, then, the 2001–2010 climatic conditions contributed to unusually low annual flows in major drainage systems across the Southwest (Table 5.3). The low flows resulted from less precipitation, warm temperatures, and, to some extent, water-management impacts that have not been completely accounted for in the naturalized records. The influences of these various factors are known to differ from basin to basin. The extent to which the warmth and dryness of the decade might be attributable to greenhouse-gas-fueled climate change is not currently known, as no formal detection-and-attribution study has been conducted for temperature, precipitation, or runoff of this most recent decade, nor for individual basins. Generally, though, these lower flows for the decade are beyond what would be expected from the reduced precipitation; they could be symptomatic of the Southwest hydroclimates that are projected for the latter decades of this century under scenarios of continued warming (Cayan et al. 2010). Annual peak streamflow rates declined from 1901 to 2008 in the interior Southwest, the only region in the continental U.S. that has experienced a regional-scale significant decline (Hirsch and Rhyberg 2011).

Various other hydrologic changes in the Southwest symptomatic of a warmer climate occurred between 1950 and 1999 (Barnett et al. 2008). These include declines in the late-winter snowpack in the northern Sierra Nevada (Roos 1991), trends toward earlier snowmelt runoff in California and across the West (Dettinger and Cayan 1995; Stewart, Cayan, and Dettinger 2005), earlier spring onset in the western United States as indicated by changes in the timing of plant blooms and spring snowmelt-runoff pulses (Cayan et al. 2001), declines in mountain snowpack over Western North America (Mote et al. 2005), general shifts in western hydroclimatic seasons (Regonda et al. 2005), and trends toward more precipitation falling as rain instead of snow over the West (Knowles, Dettinger, and Cayan 2006).

Table 5.3 Differences between 2001–2010 and twentieth-century averages of basin-mean precipitation, average temperature, and streamflow for four major hydrologic basins in the Southwest

| River Basin	Periods Compared	Precipitation Difference	Temperature Difference	Streamflow Difference
Colorado River at Lees Ferry (naturalized)	2001–2010 vs 1901–2000	-4%	+0.7°C	-16%
Sacramento-San Joaquin Rivers (naturalized)	2001–2010 vs 1931–2000	-7%	+0.7°C	-37%
Humboldt River at Palisade, NV	2001–2010 vs 1921–2000	-3%	+0.7°C	-5%
Rio Grande at El Paso	2001–2010 vs 1941–2000	+3%	+0.6°C	-23%

Note: Different baselines reflect different periods of streamflow record.
Source: PRISM monthly gridded analysis for 1901–2010 (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu).

These various indicators have recently been studied in an integrated program of hydroclimatic trends assessment for the period 1950–1999. The research findings for a region of the Western United States[vi] demonstrated that during this period human-induced greenhouse gases began to impact: (a) wintertime minimum temperatures (Bonfils et al. 2008); (b) April 1 snowpack water content as a fraction of total precipitation (Pierce et al. 2008); (c) snow-fed streamflow timing (Hidalgo et al. 2009), and (d) a combination of (a), (b), and (c) (Barnett et al. 2008). These evaluations also indicated, with high levels of statistical confidence, that as much as 60% of the climate-related trends in these indicators were human-induced and that the changes—all of which reflect temperature influences more than precipitation effects—first rose to levels that allowed confident detection in the mid-1980s.

Analyses of differences between the average ratios of rain-to-snow in precipitation, snowpack water contents, and snowmelt-fed streamflow-timing indicators in the 2001–2010 period and available twentieth-century baselines indicate that the anomalous conditions in these indicators seen at the end of the twentieth century (Barnett et al. 2008) have persisted through the first decade of the present century. Differences between the averages of the central date of water-year hydrographs in snowmelt-fed rivers (i.e., the date when half of the annual streamflow has occurred) in the 2001–2010 period compared to twentieth-century baselines at 130 stream gauges across the Western states are shown in Figure 5.6, which corroborates recent findings of Fritze, Stewart, and Pebesma (2011). The pattern that has emerged (see Figure 5.6) is that snow-fed streamflows arrived five to twenty days earlier in the recent decade compared to twentieth-century

averages across broad areas of the West. These most recent changes in snowmelt timing cannot yet be formally attributed to climate change because the necessary formal detection-and-attribution studies have not been extended to the most recent decade.
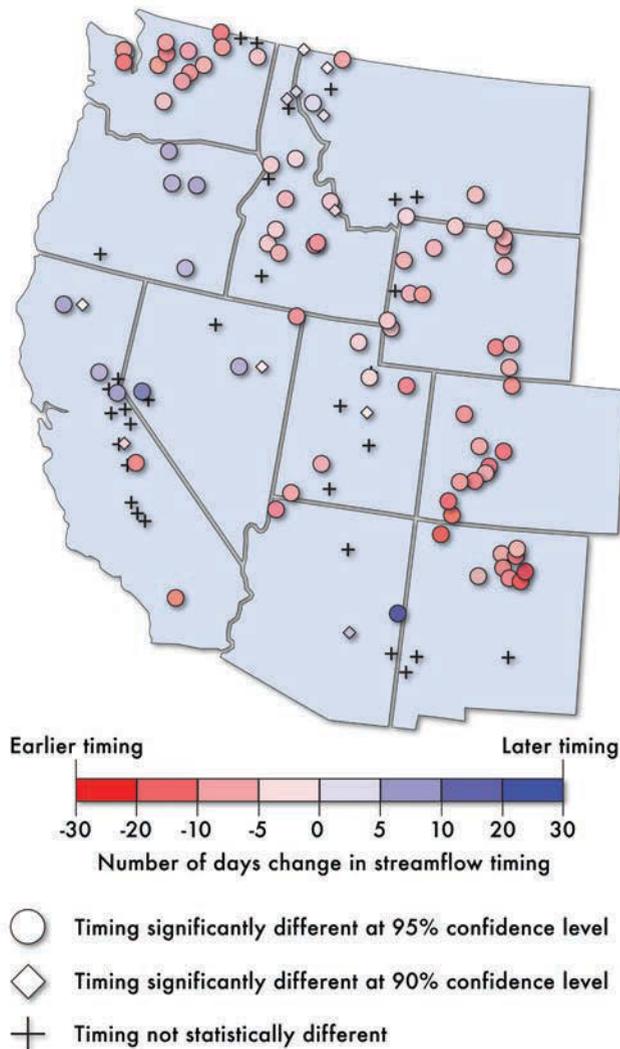
Figure 5.6 Changing streamflow timing 2001–2010 compared to 1950–2000. Differences between 2001–2010 and 1950–2000 average date when half of the annual streamflow has been discharged (center of mass) for snowmelt-dominated streams (Stewart, Cayan and Dettinger 2005).

Indeed, we must consider how temperature and precipitation have naturally varied over the region, since an important change in an apparently natural climate pattern bracketed the 2001–2010 period. There was a decisive switch from the negative to the positive PDO phase (more El Niño-like conditions) in the mid-1970s that may have favored subsequent wet and warm conditions in parts of the Southwest in the 1980s and 1990s (Gershunov and Barnett 1998). Yet, there was a transition back to negative PDO (more La Niña-like) conditions just prior to the turn of the century, which in turn might

have favored a drier and cooler Southwest in 2001–2010 (Ropelewski and Halpert 1986; Yarnal and Diaz 1986; Redmond and Koch 1991; Kahya and Dracup 1993). These inter-annual and decadal variations in oceanic conditions to which Southwest precipitation, snowpack, and hydrology are quite sensitive are mainly the result of the natural variability in the climate system (see also Hoerling, Eischeid, and Perlwitz 2010). These natural variations could readily explain the dryness of the past decade, but its exceptional warmth would seem, for now, to run counter to the temperature changes that might be expected from the natural variations alone.

Thus far, the temperature-driven changes in snowpack volumes and streamflow timing in the Southwest have not risen to levels that have disrupted water supplies; however, continuation of such trends—to be expected if recent warming in the region continues or accelerates—would eventually challenge water-resource systems that have historically relied on the (now) delicate pairing of manmade structures for storage of runoff with seasonal storage of water in natural snowpacks to meet warm-season water demands (Rajagopalan et al. 2009).

5.7 Paleoclimate of the Southwest United States

Since the relatively brief instrumental climate records in the Southwest (covering about 100 years) are unlikely to capture the full range of natural hydroclimatic variability, environmental proxies are used to reconstruct the pre-instrumental climate, or *paleoclimate*. The most broadly useful proxies for reconstructing the past one-to-two millennia of climate in the Southwest are tree rings, which can record either temperature or moisture variability, depending on the species, elevation, and location. Many other proxies—ice cores, glacier size and movement, sand dunes, lake sediments, cave speleothems (e.g., stalactites)—provide information that complements the tree-ring data. We assess here the evidence of past Southwest hydroclimate from these paleorecords.

Paleotemperature

There are far fewer high-resolution paleotemperature records for the past 1,000 to 2,000 years for the Southwest than paleodrought records (described below). But there are sufficient data, mainly from tree rings, to broadly describe the long-term variability in regional temperature, and place the observed temperatures in the Southwest since 1900 into a much longer context (Figure 5.7).

All paleotemperature records for the region indicate that the modern period (since about 1950) has been warmer than at any time in the past 600 years. Most of these records agree that the modern period was also warmer than the Medieval Climate Anomaly (MCA, a period of warm climate in the Northern Hemisphere from ca. AD 900–1350) or any other period in the past 2,000 years (Salzer and Kipfmueller 2005; Ababneh 2008; Salzer et al. 2009). Results of global climate model (GCM) experiments using estimates of past solar variability and volcanic activity also suggest that recent warmth in the Southwest exceeds MCA conditions (Stevens, González-Rouco, and Beltrami 2008; Woodhouse et al. 2010). However, other studies point to warmer conditions in the Southwest during some (Graumlich 1993) or all (Millar et al. 2006) of the MCA compared to the past fifty years.
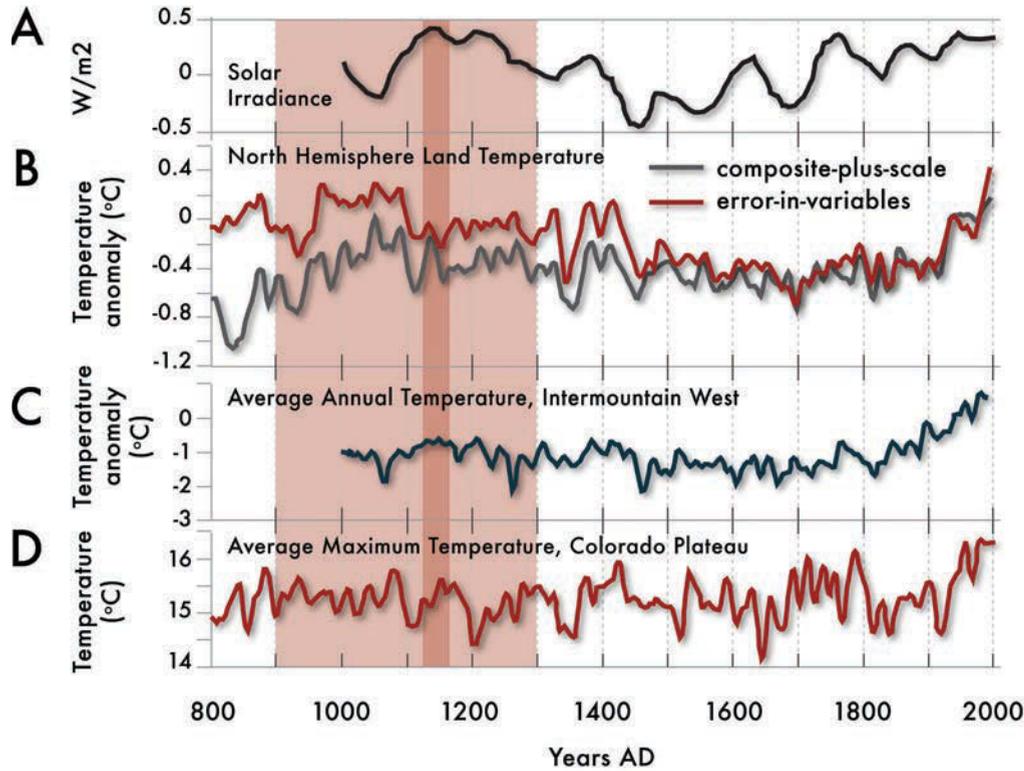
Figure 5.7 Proxy and modeled data for the past 2000 years. (A) Solar variability (solar irradiance) shown in watts per square meter (Bard et al. 2000), (B) Multi-proxy reconstructions of Northern Hemisphere temperatures, two estimates (Mann et al. 2008), (C) ECHO-G GCM simulations of temperatures for the U.S. Southwest-Intermountain region (Stevens, Gonzalez-Ruico and Beltrani 2008), (D) Temperature reconstruction for the Colorado Plateau from tree rings (Salzer and Kipfmueller 2005). The lighter shading indicates the period of the Medieval Climate Anomaly and the darker shading indicates the mid-12th century megadrought in the Colorado River Basin. Adapted from Woodhouse et al. (2010).

Regardless of how warm the MCA was, it is clear that the reconstructed warmest periods during the MCA were associated with widespread severe drought in the Southwest (MacDonald et al. 2008; Woodhouse et al. 2010; Woodhouse, Pederson, and Gray 2011), as indicated by the paleodrought records described below. More generally, the paleorecord indicates that warmer periods of the past 2,000 years have often been associated with increased aridity (Woodhouse, Pederson, and Gray 2011).

Paleodrought

The Southwest contains one of the greatest concentrations in the world of yearly paleodrought records, in the form of hundreds of highly moisture-sensitive tree-ring records. These site-level tree-ring data have been calibrated with observed records at regional to sub-regional scales to reconstruct summer and winter PDSI (see Figure 5.8; Woodhouse

and Brown 2001; Cook et al. 2004; Cook et al. 2009; MacDonald 2007; MacDonald and Tingstad 2007), seasonal and annual precipitation (Grissino-Mayer 1996; Ni et al. 2002; Touchan et al. 2010), April 1 snow-water equivalent (Woodhouse 2003; Tingstad and MacDonald 2010; Pederson et al. 2011), as well as annual streamflow in many basins (see below). All of these reconstructions extend back at least 350 years, and some up to 2,200 years. The annual paleodrought information from tree rings is complemented by coarser-resolution information derived from oxygen isotopes in lake sediments (Benson 1999; Anderson 2011), renewed movement of sand-dune fields (Muhs et al. 1997), low stands of lakes (Stine 1994), and speleothems (Asmerom et al. 2007).
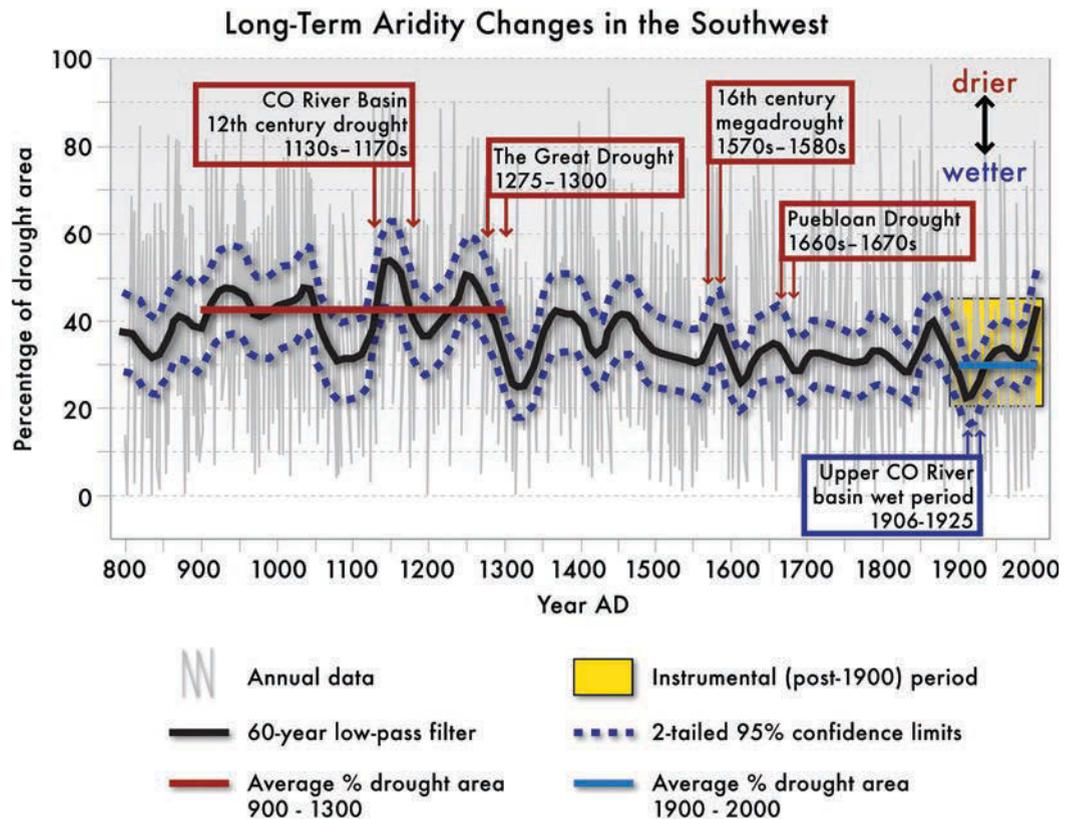
Figure 5.8 History of drought in the West. Percent area affected by drought (PDSI <−1) across the western United States, as reconstructed from tree-ring data. Modified from Cook et al. (2004), reprinted with permission from the American Association for the Advancement of Science.

Collectively, these paleodrought records for the Southwest provide unequivocal evidence that the most severe multi-year droughts observed during the past 110 years in the Southwest, such as in the 1950s and the early 2000s, were exceeded in severity and duration multiple times by droughts during the preceding 2,000 years. The most severe and sustained paleodroughts (sometimes called "megadroughts") occurred during the MCA from AD 900–1350, were associated with high temperatures in the Southwest, and were

likely caused by persistently cool La Niña-like conditions in the tropical Pacific Ocean (MacDonald 2007; MacDonald et al. 2008; Seager et al. 2008). Severe paleodroughts also occurred during other times, most prominently the late 1500s megadrought (Stahle et al. 2000) and the early second-century drought (Routson, Woodhouse, and Overpeck 2011). The Southwest paleorecords also clearly indicate that overall the twentieth century experienced less drought than most of the preceding four to twenty centuries (Barnett and Pierce 2009). The reconstructed Drought Area Index (DAI) for the Western United States since AD 800 (Cook et al 2004; Figure 5.8) nicely illustrates the conclusions drawn from the broader set of paleodrought records.[vi]

Paleostreamflow

Information recorded in the growth rings of moisture-sensitive trees has been used to reconstruct annual streamflows in three of the four major Southwest river basins described in section 5.6: the Sacramento-San Joaquin (since AD 901; Meko 2001; Meko and Woodhouse 2005; MacDonald, Kremenetski, and Hidalgo 2008), the Colorado (since AD 762; Meko et al. 2007; MacDonald, Kremenetski, and Hidalgo 2008), and the Rio Grande (since AD 1450; Meko 2008). As with the other records of paleodrought, all of these streamflow reconstructions indicate periods of hydrologic drought prior to 1900 that were more severe and sustained than any since 1900. During the regional droughts in the mid-1100s and in the late 1500s, the Sacramento-San Joaquin basin experienced sustained drought simultaneously with the Colorado and Rio Grande basins. This simultaneity apparently did not occur again until the regional drought that began in 1999–2000.

5.8 Future Monitoring and Science Needs

This chapter offered an account of how weather, climate, and hydrology varied over the Southwestern United States during the last century and in the paleoclimate record. The chapter focused on conditions during the first decade of the new millennium and compared those to conditions of the twentieth century. Emphasis was also given to climate-hydrology links in recognition that growing human populations in the Southwest are placing greater demands on water resources, demands that may create new vulnerabilities in the face of a varying climate. This hydroclimate assessment is also cognizant of concerns regarding human-induced climate change. Human-induced climate change for some variables (especially temperature) has already been detected on global to continental scales, and a human-induced change appears to now be emerging in the Southwest for some hydrology-sensitive variables (such as late wintertime elevated minimum temperatures, which accelerate runoff timing). Human-induced climate change since 1950 has also been detected at a regional scale over the greater western United States. These include detectable effects on hydrology as a consequence of warmer temperatures, reduced spring snowpack, and earlier runoff for a region that includes the Colorado Rocky Mountains and Sierra Nevada, but also the Cascades, Blue Mountains of Oregon, and the northern Rockies of Idaho and Montana. However, a scientific study, using advanced methods of detection and attribution, focused directly on the particular six-state Southwest region of this report, and including data updated through 2010, has not yet been conducted.

This assessment offers a reliable broad-scale view of meteorological and hydrological conditions over the Southwest as a whole, but the reader should be aware that confidence is considerably lower with respect to how local conditions have varied. This is a consequence of sparse observational networks (in time and space), poor monitoring of some key physical processes that connect climate and hydrology (such as high-elevation conditions, soil-moisture conditions, and groundwater variation), and a limited understanding of how weather, climate, and hydrology link at such scales.

If increasing confidence in quantifying how local conditions have varied is desirable, then there is a need for enhanced and especially more abundant observations to better monitor these processes at scales that are informative with respect to terrain. Enhanced monitoring is needed throughout the Southwest, particularly with respect to the water cycle. Augmented capabilities would address the occurrence of heavy precipitation during winter storms and summer convection (thunderstorms), precipitation falling as rain versus snow, rain-on-snow events, snowpack formation and melt off, and basin-scale runoff efficiency (the ratio of precipitation that infiltrates as groundwater as compared to runoff).

In addition to such enhanced data collection efforts, ongoing scientific assessments are needed that connect these data through physically based attribution studies. These would require improved climate and hydrological modeling at scales consistent with resolving the effects of terrain on weather and climate patterns throughout the Southwest. They would also require improved representation of physical processes such as atmospheric convection, evapotranspiration, snowpack formation, and runoff production. Efforts to improve monitoring must be complemented by improvements in our ability to detect and attribute changes in climate conditions and hydrology throughout the Southwest for years to decades. Attention to variations and changes in the region's water cycle, informed by these more precise and extensive science, modeling, and monitoring efforts, will allow us to create better early warning systems for the region and to also identify effective adaptation and mitigation strategies to address climate-change impacts (e.g. Ralph et al. 2011).

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Appendix

Table A5.1 Comparison of annual surface temperatures in the Southwest

NCDC AVERAGE TEMPERATURE

Season	1901–2000 6-State Avg.		2001–2010 Decadal		
	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank
DJF	36.0 (2.2)	0.7 (0.4)	36.7 (2.6)	+0.7 (0.4)	2
MAM	51.3 (10.7)	0.9 (0.5)	52.9 (11.6)	+1.6 (0.9)	1
JJA	70.9 (21.6)	0.7 (0.4)	72.9 (22.7)	+2.0 (1.1)	1
SON	54.1 (12.3)	0.5 (0.3)	55.4 (13.0)	+1.3 (0.7)	1
Annual	53.0 (11.7)	0.7 (0.4)	54.5 (12.5)	+1.4 (0.8)	1

STATION-ADJUSTED AVERAGE TEMPERATURE

Season	1901–2000 6-State Avg.		2001–2010 Decadal		
	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank
DJF	36.7 (2.6)	0.7 (0.4)	37.2 (2.9)	+0.5 (0.3)	2
MAM	52.2 (11.2)	0.9 (0.5)	53.6 (12)	+1.4 (0.8)	1
JJA	71.2 (21.8)	0.7 (0.4)	72.7 (22.6)	+1.4 (0.8)	1
SON	55.0 (12.8)	0.5 (0.3)	55.9 (13.3)	+0.9 (0.5)	1
Annual	53.8 (12.1)	0.5 (0.3)	54.9 (12.7)	+1.1 (0.6)	2

STATION-UNADJUSTED AVERAGE TEMPERATURE

Season	1901–2000 6-State Avg.		2001–2010 Decadal		
	Mean °F (°C)	Std.Dev. °F (°C)	Mean °F (°C)	Anom °F (°C)	Rank
DJF	37.2 (2.9)	0.5 (0.3)	37.4 (3)	+0.2 (0.1)	4
MAM	52.9 (11.6)	0.7 (0.4)	54.0 (12.2)	+1.1 (0.6)	1
JJA	71.8 (22.1)	0.7 (0.4)	73.0 (22.8)	+1.3 (0.7)	1
SON	55.6 (13.1)	0.4 (0.2)	56.3 (13.5)	+0.7 (0.4)	1
Annual	54.3 (12.4)	0.5 (0.3)	55.2 (12.9)	+0.9 (0.5)	2

Note: Temperatures are averaged for the decade 2001–2010 versus 1901–2000; there is also a ranking of the 2001–2010 decadal averages relative to the ten individual decades of the twentieth century. The Southwest is comprised of Arizona, California, Colorado, Nevada, New Mexico, and Utah.

Sources: National Climatic Data Center, climate division, station-based adjusted, and station-based unadjusted data (http://www.ncdc.noaa.gov/oa/ncdc.html).

Table A5.2 Comparison of annual precipitation in the Southwest

PRISM PRECIPITATION

	1901–2000 6-State Avg.		2001–2010 Decadal		
Season	Mean inches (mm)	Std.Dev.inches (mm)	Mean inches (mm)	Anom inches (mm)	Rank
DJF	5.1 (129)	0.4 (10)	5.2 (133)	+0.2 (4)	5
MAM	3.8 (97)	0.3 (8)	3.4 (87)	-0.4 (10)	10
JJA	3.3 (83)	0.3 (7)	3.0 (77)	-0.2 (6)	9
SON	3.3 (85)	0.4 (10)	3.2 (82)	-0.1 (3)	6
Annual	15.6 (395)	0.8 (20)	15.0 (380)	-0.6 (15)	8

NCDC CLIMATE DIVISION PRECIPITATION

	1901–2000 6-State Avg.		2001–2010 Decadal		
Season	Mean inches (mm)	Std.Dev.inches (mm)	Mean inches (mm)	Anom inches (mm)	Rank
DJF	4.7 (120)	0.4 (11)	4.8 (122)	+0.04 (1)	5
MAM	3.5 (90)	0.3(8)	3.0 (77)	-0.5 (13)	10
JJA	3.3 (85)	0.3 (7)	3.0 (77)	-0.3 (8)	9
SON	3.2 (82)	0.4 (10)	3.0 (76)	-0.2 (6)	9
Annual	14.8 (377)	0.8 (21)	14.1 (359)	-0.7 (18)	10

NCDC STATION PRECIPITATION

	1901–2000 6-State Avg.		2001–2010 Decadal		
Season	Mean inches (mm)	Std.Dev.inches (mm)	Mean inches (mm)	Anom inches (mm)	Rank
DJF	6.0 (153)	0.5 (13)	6.1 (154)	+0.04 (1)	6
MAM	4.1 (104)	0.4 (9)	3.6 (91)	-0.6 (14)	10
JJA	3.3 (85)	0.4 (9)	3.0 (76)	-0.4 (9)	8
SON	3.5 (90)	0.5 (12)	3.3 (84)	-0.2 (6)	8
Annual	16.9 (429)	0.8 (20)	16.4 (417)	-0.5 (13)	7

Note: Precipitation is averaged for the decade 2001–2010 versus 1901–2000 along with a ranking of the 2001–2010 decadal averages relative to the ten individual decades of the twentieth century.

Sources: PRISM (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu); National Climatic Data Center (NCDC), climate division, and station-based data (http://www.ncdc.noaa.gov/oa/ncdc.html).
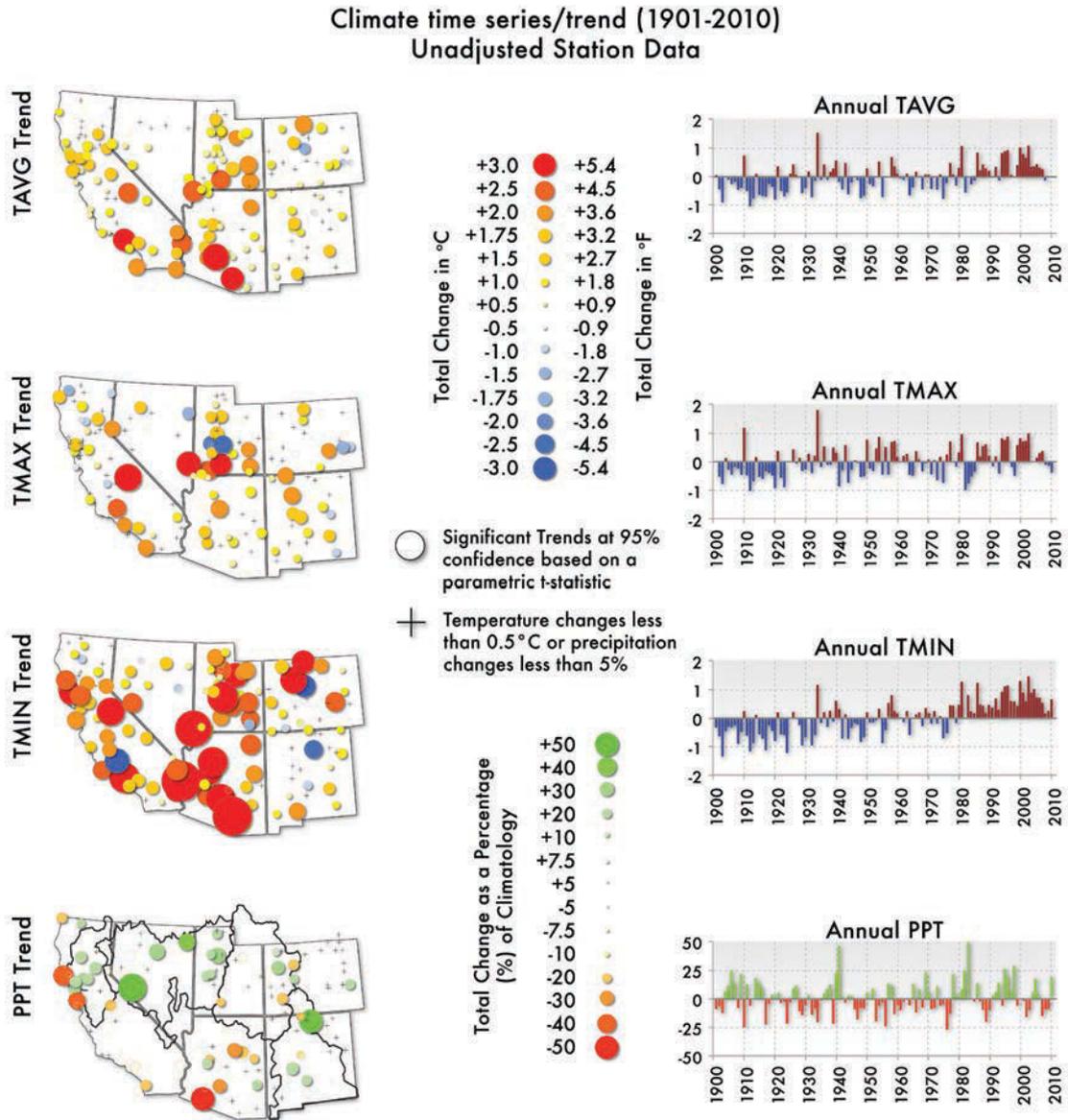
Figure A5.1 The 1901–2010 trends in annual averaged daily temperature (TAVG, top), daily maximum temperature (TMAX, second panel), and daily minimum temperature (TMIN, third panel). Units are the change in °C/110yrs, and stronger positive (negative) trends shown in red (blue). Bottom panel is the 1901–2010 trend in annual averaged precipitation. Units are the total change expressed as percent of annual climatology, and positive (negative) trends are shown in green (orange). Larger circle sizes denote greater magnitude trends. Trends are computed at station locations using the GHCN (Version 3) raw monthly (unadjusted) data. Results are shown only for locations having at least 90 years of available data. Filled stations denote statistically significant trends at 95% confidence based on a parametric t-statistic. Stations with temperature (precipitation) changes less than 0.5°C (5%) are denoted with a + symbol. The fraction of stations with significant trends is 61%, 40%, and 63% for TAVG, TMAX, and TMIN respectively. The fraction of stations with significant trends in precipitation is 16%. Source: Menne and Williams (2009).

Endnotes

i   Tables 5.1 and 5.2 present temperature and precipitation conditions for the first decade of the twenty-first century, respectively, and compare those conditions against 100-year averages of the previous century. Shown also are the rankings of the recent decadal conditions relative to the ten decades of the twentieth century, both for the Southwest as a whole and for the six individual states comprising the region. The tables assess average temperature, maximum temperature, minimum temperature, and precipitation. The data are based on the monthly PRISM analysis (Daly 2006) which incorporates physiographic features (e.g., complex topography and coastal zones) in the process of generating climate grids from available in situ data, the consequence of which is to substantially improve analyses in the Western United States relative to other climate analyses (Daly et al. 2008).

ii   Data used in Tables 5.1 and 5.2 are based on 2.5 mile (4km) resolution PRISM analyses (data available at: http://www.prism.oregonstate.edu/products/matrix.phtml?view=data). For purposes of long period trend estimates, we present diagnoses conducted at station locations, rather than from gridded data, and examine those sites that possess historical observations spanning most of the 1901–2010 period.

iii The trends were calculated at station locations based on Global Historical Climate Network (GHCN) Version 3 (Menne and Williams 2009; data available at http://www.ncdc.noaa.gov/ghcnm/v3.php).

iv   Another measure of heat and cold waves is discussed in Chapter 7, Sections 7.2 and 7.3.

v   Drought is defined here as having at least a -1 (or lower) PDSI intensity.

vi   These included the Southwest as well as drainage basins in the Cascades, Blue Mountains of Oregon, and the northern Rockies of Idaho and Montana.

vii Analysis of a subset of the Cook et al. dataset, covering only the Southwest region, shows DAI variability across the Southwest over the last 1,200 years to be very similar to that across the larger area depicted in Figure 5.7.