Chapter 7

Future Climate: Projected Extremes

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Executive Summary

This chapter summarizes the current understanding about how and why specific weather and climate extremes are expected to change in the Southwest with climate warming over the course of the current century.

Summertime heat waves and wintertime cold snaps are among the extremes most directly affected by climate change as well as the ones with the greatest impacts.

- Heat waves, as defined relative to current climate, are projected to increase in frequency, intensity, duration, and spatial extent. (high confidence)

- Heat waves are projected to become more humid and therefore expressed relatively more strongly in nighttime rather than daytime temperatures, with associated stronger impacts on public health, agriculture, ecosystems, and the energy sector. (medium-low confidence)

- Wintertime cold snaps are projected to diminish in their frequency, but not necessarily in their intensity, into the late twenty-first century. (medium-high confidence)

Precipitation extremes are projected to become more frequent and more intense in the wintertime. Summertime precipitation extremes have not been adequately studied.

- Enhanced precipitation extremes are generally expected due to greater moisture availability in a warming atmosphere, even if average precipitation declines. (medium-low confidence).

- Enhanced precipitation specifically associated with atmospheric rivers, a wintertime phenomenon typically yielding extreme precipitation, is projected by most current climate models. (medium-low confidence)

Flooding is expected to change in timing, frequency, and intensity, depending on season, flood type, and location.

- Floods from winter storms on the western slopes of the Sierra Nevada have been projected to increase in intensity in winter by all climate models that have been analyzed thus far, including models that otherwise project drier conditions. (medium-high confidence)

- Snowmelt-driven spring and summertime floods are expected to diminish in both frequency and intensity. (high confidence)

- Transition from hail to rain on the Front Range of the Rocky Mountains is expected to result in higher flash-flood risk specifically in eastern Colorado. (medium-low confidence)

Drought is generally expected to intensify in a warming climate, but some variation across basins can be expected, although few basins have been analyzed.

- Drought, as expressed in Colorado River flow, is projected to become more frequent, more intense, and longer-lasting, resulting in water deficits not seen during the instrumental record. (high confidence)

- Northern Sierra Nevada watersheds may become wetter, and in terms of flow, somewhat less drought-prone with climate change. (medium-low confidence)

- In terms of soil moisture, drought is expected to generally intensify in the dry season due to warming. (high confidence)

Extreme fire weather can be associated with a combination of factors, none of which need be particularly extreme. For example, dry and commonly warm Santa Ana winds

(which are not necessarily themselves extreme) are frequently associated with extreme fire potential in Southern California.

- Santa Ana winds are expected to diminish in frequency, but at the same time become drier and hotter. (medium-low confidence) However, the combined effect of decreased winds and increased temperatures and dryness on Southern California's fire risk is not clear.

Beyond these projections, the region is fraught with important uncertainties regarding future extremes, as many have yet to be projected.

7.1 Introduction

Extreme events can be defined in many ways. Typical definitions of weather and climate extremes consider either the maximum value during a specified time interval (such as season or year) or exceedance of a threshold (the "peaks-over-threshold" [POT] approach), in which universal rather than local thresholds are frequently applied. For example, temperatures above 95°F (35°C) are often considered extreme in most locations across the United States, except in areas such as the low-lying deserts of Arizona and California, where such temperatures are typical in the summer. Temperatures at these levels are obviously extreme for living organisms from a non-adapted, physiological perspective, and technological adaptation for humans is required for day-to-day functioning in such temperatures. But such temperatures are not necessarily extreme from the statistical or local climate perspectives. In statistics, extremes are considered low-probability events that differ greatly from typical occurrences. The IPCC defines extremes as 1% to 10% of the largest or smallest values of a distribution (Trenberth et al. 2007). Studies over large or complex regions marked by significant climatic variation require definitions that are relevant to local climate. Across the Southwest, location-specific definitions of extreme temperature, precipitation, humidity, and wind are required if a meaningful region-wide perspective is desired.

In spite of common claims that climate change will result in past extremes becoming more commonplace, only a few scientific studies have actually considered future projections of extremes (e.g., Meehl et al. 2000; Tebaldi, Hayhoe, and Arblaster 2006; Parry et al. 2007; Trenberth et al. 2007). Even fewer have focused on regional extremes, usually in response to specific events such as the European heat wave of 2003. Studies examining projections of temperature, precipitation, and hydrological extremes typically resolve the Southwest as part of a much larger spatial domain. Hydrological drought research is the exception, as it naturally focuses on river basins. Drought in the Colorado River Basin, which encompasses a large swath of the Southwest and channels a large part of its water supply, was the focus of a recent drought projection study (Cayan et al. 2010). As a state, California has probably been the focus of more climate-change research than any other in the United States—research that has translated to state policy action. Not surprisingly, some of the first regional extreme climate projections in the nation have been carried out for some of California's weather and climate extremes (e.g. Das et al. 2011; Mastrandrea et al. 2011; Gershunov and Guirguis 2012). Results of these and other relevant studies are described in the Southwestern context below.

For climate science to inform impact assessment and policy research, it is important to define the most relevant impact-based indices of environmental extremes. This impact-driven (or "bottom-up") approach represents the current thrust of climate science striving to be relevant to society. To accomplish this goal, close collaborations among science and the public-private policy sectors must be initiated and maintained. This process is perhaps further along in the Southwest than in other regions of the nation; but even for the Southwest, the necessary cross-sector relationships are still in their infancy. One of the future goals of the Southwest Climate Alliance (SWCA) is to define extremes by first understanding their impacts in key sectors. But for now, while keeping mindful of their impacts, we define extremes based solely on climate records and models.

For meaningful projections of extremes, models must be validated with respect to the mechanisms (such as heat waves or atmospheric rivers) that produce specific extremes. Without careful validation, a multi-model approach can introduce more uncertainties into projection of extremes than when multi-model projections are averaged to study mean climate trends, an approach that is typically assumed to increase certainty. In contrast to average climate, changes in extremes cannot be assumed to be more adequately diagnosed from averaging across a set of models, or ensemble members. The rare nature of extremes demands that they be carefully analyzed in each realization of modeled climate.

7.2 Heat Waves

Background climate warming can be expected to result in increased heat wave activity as long as the thresholds used to define heat waves remain unchanged. Multi-model and downscaled projections are clear on this, globally and specifically for the Southwest United States (see, for example, Diffenbaugh and Ashfaq 2010).

Gershunov, Cayan, and Iacobellis (2009) showed that heat waves over California and Nevada are not simply increasing in frequency and intensity but are also changing their character: they are becoming more humid and therefore are expressed more strongly in nighttime rather than daytime temperatures (i.e., in minimum [Tmin] rather than maximum [Tmax] daily temperatures). These changes started in the 1980s and appear to have accelerated since 2000. Moreover, the seasonal average humidity levels have not increased; rather, rare synoptic circulations (regional pressure patterns and their associated surface winds) that bring hot air to the extreme Southwest tend to also bring increased humidity. The trend in humid heat waves was shown to be due to the warming of the Pacific Ocean surface west of Baja California, a regionally intensified part of the global ocean warming trend. Following up on these observational results, Gershunov and Guirguis (2012) first identified a global climate model (GCM) from which daily data were available and which was able to simulate both the synoptic causes of California heat waves (i.e., the observed pressure and humidity patterns associated with regional heat waves) as well as the observed trend in the flavor of regional heat waves disproportionately intensifying at night compared to the daytime. They then considered downscaled projections[i] over California and its subregions. Given the lack of heat wave projections studies for the entire Southwest and the potentially disproportionate impacts of humid heat on a region where life is acclimatized to dry heat, in the section below we expand the observational diagnosis of Gershunov, Cayan, and Iacobillis (2009)

and then follow the approach of Gershunov and Guirguis (2012), extending their heat wave projections to the entire Southwest.

Heat wave index

Heat waves are hereby defined locally, but are described over the entire Southwest as a period lasting at least one day when daily temperature exceeds the 95th percentile of the local daily May-to-September climatology of maximum or minimum temperatures for 1971–2000. In other words, a local heat wave is registered when temperature rises to the level of the hottest 5% of summer days or nights.[ii] The local magnitude of the heat wave (the heat wave index, or HWI) is the difference between the actual Tmax or Tmin and its corresponding 95th percentile threshold, summed over the consecutive days of the heat wave, or over the entire season if a measure of *summertime* heat wave activity is desired. This measure is similar to the familiar *degree days*, except that the threshold temperature is defined relative to local climatology, as opposed to an absolute threshold, making the HWI consistent and comparable for all locations representing a region. The regional HWI is then constructed by taking the regional average of the local values. HWI reflects the frequency, intensity, duration, and spatial extent of heat waves across the Southwest (Figure 7.1).
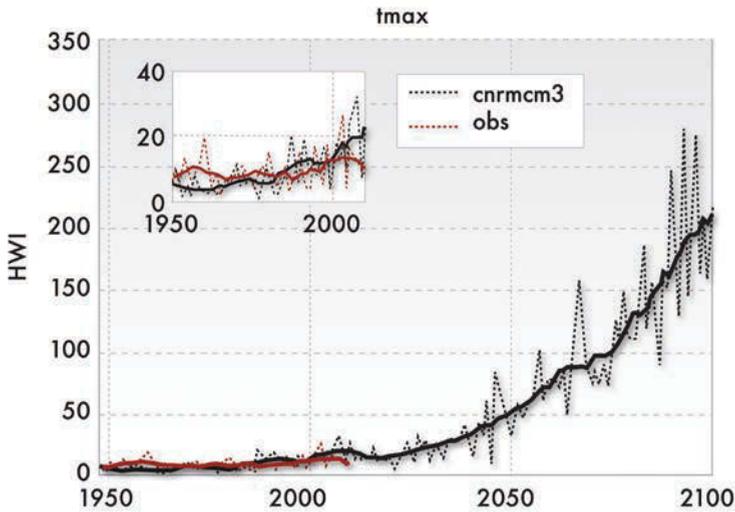
Projections

Observations and modeling indicate that Southwestern heat wave activity is increasing as expected with climate change, however as in California, it is increasing disproportionately relative to minimum versus maximum temperatures (Figure 7.1). The Tmin trend is clearly visible during the historical period and it is comparable to the modeled trend (inset on panel B), in contrast, the historical modeled Tmax trend has not yet been observed. For the future, heat waves are projected to increase at an accelerating rate, with nighttime heat waves projected to increase at a faster rate than daytime heat waves. Much of the projected increase in Southwestern heat wave activity is to be expected simply from average seasonal warming driving temperatures to exceed the stationary local 95th percentile thresholds—by larger margins, more often, for more consecutive days, and over larger parts of the Southwest—driving this cumulative heat wave index dramatically upward.

Mastrandrea and others (2011) adopted a multi-model view on California heat waves to examine 100-year events.[iii] Their results also suggested higher minimum temperatures are projected to increase more than maximum temperatures, but their modeling results were not as clear on this point as those from the well-validated CNRM-CM3 model or from observations. The main result from multi-model heat wave projections is that observed 100-year return period heat waves become heat waves with a 10-year or even shorter return period during the last half of the twenty-first century.

The disproportionate increase in nighttime versus daytime projected heat wave occurrence is consistent with observations and is indicative of enhanced future impacts on health (of humans, animals, and ecosystems), agriculture, and energy infrastructure, due to the elevated humidity and diminished nighttime respite from heat. The intensifying heat thus becomes more difficult for the biota of the Southwest to tolerate, acclimatized as they are to dry daytime heat and cool nights. Given the high correspondence of

a) Observed and projected daytime Heat Wave Index

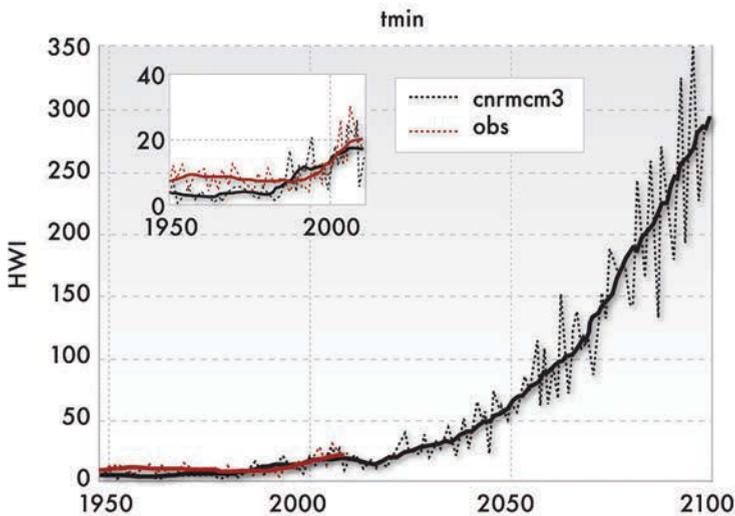

b) Observed and projected nighttime Heat Wave Index

Figure 7.1 The summertime (May–September) Heat Wave Index (HWI) for Tmax (a) and Tmin (b) for the Southwest region. Solid line is the 5-year running mean. HWI values show °C above the local 95th historical percentile. Inset shows the same data on a scale appropriate for the historical period (1950-1999). Historical observed and modeled data as well as twenty-first century projections (according to the SRES-A2 "high-emissions" scenario) are shown from observations as well as from a GCM (CNRM-CM3) historical simulation and projection averaged over the Southwest. Adapted for the Southwest based on the work of Gershunov and Guirguis (2012) for California. Data source: Salas-Mélia et al. (2005); see also http://www.ipcc-data.org/ar4/model-CNRM-CM3-change.html.

observed and modeled trends, we consider this to be a medium-low confidence result. Agreement from additional models, if validated to produce realistic heat waves, will likely increase the confidence of this conclusion into the "high-confidence" category.

Sub-regional variation of heat wave trends is possible. For example, working with BCCA-downscaled data for California, Gershunov and Guirguis (2012) found intriguing patterns of change in the magnitude of coastal heat waves relative to median summer-time warming of coastal regions. Although average warming is projected to be weaker at the coast than over inland areas in summer (see Chapter 6), a trend in heat waves of pro-gressively enhanced magnitude through the twenty-first century is projected along the
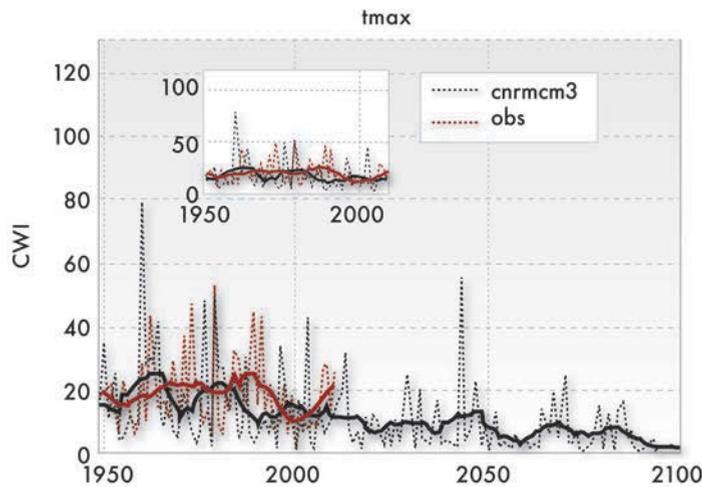
coast—the most highly populated and least heat-adapted of all California sub-regions. This trend is already observed over coastal Northern California.

7.3 Wintertime Cold Outbreaks

A diminishing trend in cold spell frequency and intensity has been observed over the Northern Hemisphere and its continental sub-regions (Guirguis et al. 2011). Within regions, cold outbreaks are most intense in low-lying topography that channels the cold dense air. Their frequency also responds to changes in atmospheric circulation patterns, in particular to transient high pressure systems that cause cold air outbreaks. As the subtropical high-pressure zones intensify and expand poleward (Lu, Vecchi, and Reichler 2007; Lu, Deser, and Reichler 2009) and the storm track contracts towards the pole (IPCC 2007), fewer cyclones and more anticyclones are expected to reach the Southwest United States and northwestern Mexico, resulting in less-frequent precipitation but increased frequency of atmospheric circulation conditions leading to cold outbreaks (Favre and Gershunov 2009; Chapter 6). Considered with regional seasonal warming trends, this change may affect the frequency of future cold extremes. However, because of the topographic complexity of the Southwestern United States (Chapter 3, Section 3.1), this would apply only to cold extremes in coastal low-lying valleys west of the Sierra Nevada. Winter cold outbreaks in much of the rest of the mountainous Southwest are not affected by transient anticyclones arriving from the North Pacific (see Favre and Gershunov 2009, Figure 14).

Following the heat wave index definition provided above and the approach of Guirguis and others (2011), cold outbreaks are here defined as the coldest five percent of the wintertime daily temperature distribution, aggregating degree days below the local 5th percentile thresholds over the cold season (November–March), and averaging over the region. In other words, cold outbreaks occur when temperature drops below the local levels defining the coldest 5% of winter days or nights, and are measured by how far they drop below those levels over the entire region.[iv] The resulting cold spell index (CSI), derived from observations and the CNRM-CM3 model, is presented in Figure 7.2. It reflects frequency, intensity, duration, and spatial extent of wintertime cold spells over the entire Southwest. Cold spells are clearly projected to diminish in both maximum and minimum temperatures. The trend is not projected to be steady, as the influence of natural interannual and interdecadal variability on the occurrence of cold extremes is projected to continue to strongly modulate cold outbreaks in the future. Kodra, Steinhauser, and Ganguly (2011) project that occasional extreme cold events are likely to persist across each continent under twenty-first century warming scenarios, however, and this agrees with recent results for California using multi-model downscaled projections (Pierce et al. 2012). In the states of California and Northern Baja California, the more frequent occurrence of mid-latitude anticyclones that produce the cold snaps (Favre and Gershunov 2009) may be elevating the probability that some of the future cold snaps will be nearly as cold as those in the past. However, as warming continues into the late twenty-first century while the local thresholds used to define cold extremes remain static, this probability should diminish over the entire Southwest, leading to generally less frequent if not always less severe cold outbreaks by the end of the century.

a) Observed and projected daytime Cold Spell Index
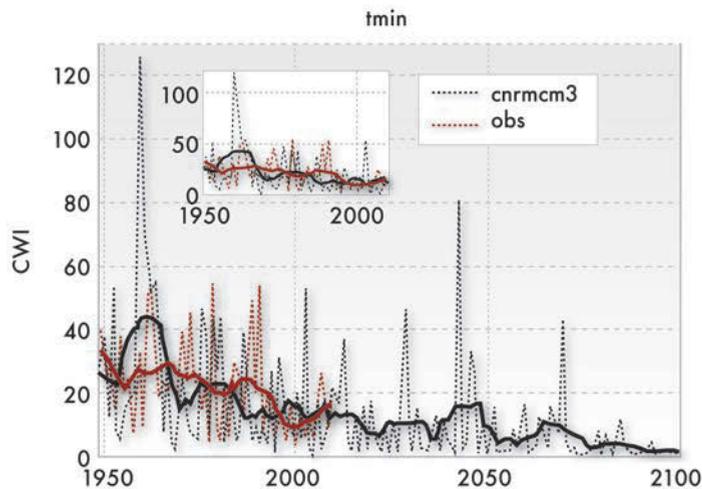

b) Observed and projected nighttime Cold Spell Index

Figure 7.2 The wintertime (November–March) Cold Spell Index (CSI) for Tmax (a) and Tmin (b) for the Southwest region. Explanation of lines, values, and insets as in Figure 7.1. Adapted for the Southwest based on the work of Gershunov and Guirguis (2012) for California. Data source: Salas-Mélia et al. (2005); see also http://www.ipcc-data.org/ar4/model-CNRM-CM3-change.html.

7.4 Precipitation

General results and key uncertainties

Models project that there will be augmented extreme precipitation events even in regions where total precipitation is generally expected to decrease (Groisman et al. 2005; Wang and Zhang 2008), such as in the southern portion of the Southwest in winter (see Chapter 6). The reason for this expectation is that warmer air holds more moisture at saturation (100% relative humidity) and therefore "extreme" storms should be able to produce more precipitation than similar events in the past. Global climate models are notoriously deficient at simulating high frequency precipitation, especially its extreme values, but they generally agree on this result (Groisman et al. 2005; Kharin et al. 2007).

To circumvent these deficiencies in simulating precipitation and to rely more on model strengths, Wang and Zhang (2008) used statistical downscaling to relate large-scale atmospheric circulation and humidity to locally observed precipitation and then applied this downscaling scheme to a global climate model projection. By doing this, the effects of changes in circulation and humidity could be evaluated separately, and changes in the daily extreme values of winter precipitation could be diagnosed. They found that over much of North America during the last half of the current century, extreme precipitation events that currently occur on average once in a twenty-year period are projected to occur up to twice as frequently, even in regions that are projected to have decreased precipitation due to circulation changes. In other words, increased specific humidity in a warming atmosphere is expected to dominate future trends in extreme precipitation.

Dynamically downscaled GCM projections support this result. Multi-model dynamically downscaled simulations project a significant increase (of 13% to 14% on average by mid-century) in the intensity of wintertime extremes with 20- and 50-year return periods under the high-emissions scenario (Dominguez et al. 2012), even though the same simulations project average precipitation to decrease over the Southwest. Increased water vapor content in a warming atmosphere seems a key element in such projections, and statistical downscaling schemes that do not include explicit accounting for this increasing moisture content do not necessarily support these findings. Mastrandrea and others (2011), for example, used a precipitation downscaling scheme that did not use atmospheric humidity as a predictor. When applied in a multi-model context over California, this approach did not yield clear or significant changes in precipitation extremes.

Such studies are not directly comparable due to different choices of global climate models, downscaling schemes, and definitions of extreme precipitation. However, simple physical reasoning suggests that in a warming and moistening atmosphere, greater precipitation extremes can co-evolve with generally drier conditions. This argument is consistent with observations and modeling over many of the world's regions (Groisman et al. 2004; Groisman et al. 2005), especially in summer, but increasing extreme precipitation trends have not yet been observed over the Southwest. This is in spite of the fact that the Southwest has been at the forefront of warming among regions of the contiguous United States. Although different projection results are not yet perfectly congruent and more research is clearly needed, modeling schemes that explicitly resolve increasing moisture content in a warming atmosphere consistently result in more frequent and larger future precipitation extremes over the otherwise drying Southwest and their results should be regarded with more confidence.

Next, we examine precipitation extremes due to specific storm systems and physical processes.

North American monsoon (NAM)

The North American monsoon (NAM) is the source of summertime precipitation for much of the Southwest, particularly Arizona and New Mexico. The core region of NAM is along the Sierra Madre Occidental in northwestern Mexico (Cavazos, Turrent, and Lettenmaier 2008; Arriaga-Ramírez and Cavazos 2010). These studies examined observed trends in extreme summertime rainfall, but did not find any significant precipitation trends related specifically to NAM.[v] The northern tip of NAM penetrates into

the Southwestern United States. Monsoonal precipitation modeling and projections present many uncertainties (see Chapter 6), which translate to key uncertainties for the extremes. Projections of extremes have not been specifically evaluated for NAM rainfall; however, in a new study, Cavazos and Arriaga-Ramirez (2012), found that model scenarios of increased greenhouse gases (A2 "high-emissions" scenario) in conjunction with statistical downscaling, show a weakening of the monsoon rainfall due to longer and more frequent dry periods in the monsoon region by the end of this century. However, as explained in Chapter 6, the North American monsoon system is also influenced by large-scale patterns of natural variability. Great challenges in monsoon modeling prevent confident conclusions about the future of NAM, especially its extremes. Chou and Lan (2011) show a negative trend in the annual total maximum precipitation in the monsoon region during the twenty-first century associated with increased subtropical subsidence induced by global warming. Projected increase in subtropical subsidence (as discussed in Chapter 6 and in Lu, Vecchi, and Reichler 2007) could negatively impact NAM precipitation; however, its potential impact on NAM extremes is, even intuitively, less clear. The low confidence in projected decreased total NAM precipitation and the lack of understanding about its extremes make NAM an important topic for ongoing research. Future research should consider NAM in its entirety on both sides of the U.S.-Mexico border.

Atmospheric rivers

Much of the Southwest is within reach of an important class of Pacific storms that are often referred to as "atmospheric rivers" (ARs). ARs are storms in which enormous amounts of water vapor are delivered to the region from over the Pacific Ocean in corridors that are low-level (less than about 6,600 feet [2000 m] above sea level), long (greater than 1,200 miles [2000 km]), and narrow (less than about 300 miles [500 km] wide) (Ralph and Dettinger 2011). So far, atmospheric rivers have been the only extreme-precipitation-producing systems in the Southwest that are large enough to be adequately modeled by GCMs even without downscaling and that have received recent careful attention in the context of climate change.

When these ARs encounter the mountains of the Southwest—most often in California, but occasionally penetrating as far inland as Utah and New Mexico (Figure 7.3)—they produce many of the most intense precipitation events that define the storm and flood climatology of the region (Ralph et al. 2006; Ralph et al. 2011). These storms are present in climate-change simulations by the coupled atmosphere-ocean global climate models included in the IPCC Fourth Assessment Report (e.g., Bao et al. 2006; Dettinger 2011; Dettinger, Ralph, Das et al. 2011; Dettinger, Ralph, Hughes et al. 2011), and presumably will be better represented in the generally better-resolved models of the Fifth Assessment Report. A preliminary study of their occurrences and intensities in the Fourth Assessment Report projections of climate changes in response to the SRES A2 "high-emissions" scenario by seven GCMs (Dettinger 2011) indicates that in a warmer climate, ARs making landfall on the California coast will carry more water vapor in general. By the mid-twenty-first century, ARs are projected to increase by an average of about 30% per year and about twice as many years are projected to have many more than historical numbers of ARs. Also, all seven models yielded occasional twenty-first century ARs

that were considerably more intense than any simulated (or observed) in the historical period. Together these results suggest that the risks of storm and flood hazards in the Southwest from AR storms may increase under the changing climate of the twenty-first century; however the analyses and even our understanding of historical ARs (Dettinger 2011; Ralph and Dettinger 2011) are still preliminary and warrant further investigation.
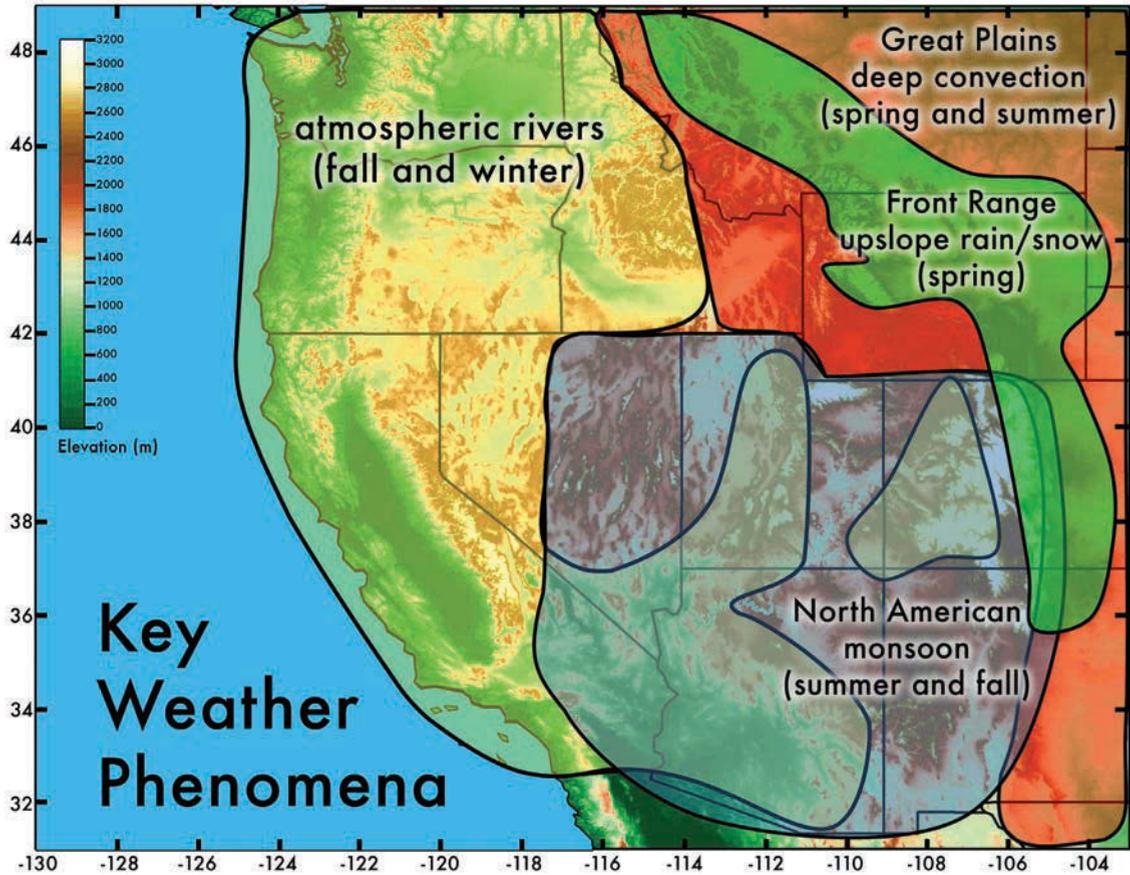

Figure 7.3 Key weather phenomena that cause extreme precipitation in the Southwest. Schematic illustration of regional patterns of the primary weather phenomena that lead to extreme precipitation and flooding, while also contributing to water supplies (Guan et al. 2010; Dettinger et al. 2011), across the western United States. Modified from Ralph et al. (2011); see http://www.westgov.org/wswc/167%20council%20meeting%20-%20id/167%20council%20mtg%20-%20oct2011.html.

Hail on the Colorado Front Range

Parts of the Southwest are prone to precipitation from intense summertime thunderstorms that fall as hail rather than heavy rain. Although it can inflict significant damage on property and agriculture, hail may help prevent or delay flash flooding. The most active region in terms of hailstorm intensity, frequency, and duration in the United

States is the leeward (eastern) side of the Rocky Mountains, especially eastern Colorado. Mahoney et al. (2012) used a dynamical downscaling framework to compare past (1971–2000) and future (2041–2070) warm-season convective storm characteristics, with a focus on hail, in the Colorado Front Range and Rocky Mountain regions.[vi] The authors found that surface hail in the 2041–2070 time period was projected to be nearly eliminated, despite an increase in in-cloud hail, due to a higher altitude level of melting (32°F [0°C] isotherm). The initial level of melting increased from about 16,400 feet (5,000 m) above sea level to about 18,000 feet (5,500 m) over the study region over time. The model simulations suggest this deeper vertical layer of above-freezing temperatures will be sufficient to melt the hailstones before they reach the surface. Additionally, across most elevations in the region, the future simulations produced greater total maximum precipitation and surface runoff. The combination of decreased surface hail and increased rainfall as well as overall precipitation intensity, implies flash flooding may become more likely in mountainous regions that currently experience hail, especially where the surfaces are relatively impervious.[vii]

7.5 Surface Hydrology

Flooding

Changes due to warming in the type of intense precipitation received will affect flooding. Just as the change of summertime precipitation on the Rockies' Front Range from hail to rain will increase the risk of flash flooding, so too will the change from wintertime snow to rain for areas of the Southwest. Projected changes in winter storms, including both intensities and temperatures, are expected and projected (Das et al. 2011) to yield increased winter floods, especially in the Sierra Nevada, where winter storms are typically warmer than those farther inland. Even in global climate model scenarios with decreased total regional precipitation, flood magnitudes are projected to increase (Das et al. 2011). More frequent and/or intense precipitation extremes are an important cause of increased flooding, but warming also plays an important role as it results in wintertime precipitation falling more as rain rather than snow. The projected late-century increase in flooding generated in the Sierra Nevada watersheds is therefore due to wintertime storm-driven runoff, while spring and early summer snowmelt-driven floods are expected to wane.

Future changes in flooding elsewhere in the Southwest will depend on the future of the storm mechanisms partially summarized in Figure 7.3. For example, where enhanced ARs drive extreme precipitation, wintertime flooding may be expected to increase, although probably not as much as on the western slopes of the Sierra Nevada, where much moisture is squeezed from these systems. In other regions and seasons (e.g. the monsoon region in the summertime), uncertainties about future changes in precipitation extremes translate directly into uncertainties about future flooding.

Drought

Global models suggest more dry days and drier soils in the future for the southern part of the Southwest (Field et al. 2011). Along with projected warming and increased

evapotranspiration, this can only mean that droughts will become more severe. The crucial importance of water resources and their natural volatility in the arid, thirsty, and growing Southwest has motivated numerous hydrological studies over the decades. The Colorado River—which provides at least partial water supply to all Southwestern states—has been the natural focus of many of these studies. Recent research was motivated by a prolonged drought that afflicted the Southwest, and particularly the Colorado River, for much of the first decade of the twenty-first century (MacDonald 2008).

This contemporary drought was examined in the context of past records and future projections utilizing a hierarchy of GCM projections, statistical downscaling, and hydrologic modeling to focus on Southwestern drought and describe it in the context of past and likely future conditions (Cayan et al. 2010). The results are summarized here.

The recent drought is a perfect example of droughts that the Southwest has been prone to experience about once per century. The analysis of Cayan and others (2010), based on the high emissions scenario, suggests that the current 100-year drought will become commonplace in the second half of this century and that future droughts will be much more severe than those previously recorded. This possibility should not be surprising given the magnitude of megadroughts on the paleorecord (Cook at al. 2004; Cook et al. 2009; Chapter 5), but importantly, climate change is slowly tipping the balance in favor of more frequent, longer, and more intense droughts. Figure 7.4 shows the difference in the Colorado River flow deficit accumulated over consecutive years of observed versus projected 100-year drought. This projection of intensified drought conditions on the Colorado River is not due to changes in precipitation, but rather due directly to warming and its effect on reducing soil moisture (Figure 7.5) by reducing snowpack and increasing evapotranspiration. The projected longer, more intense droughts in the Colorado Basin will pose challenges to sustaining water supplies of the already over-allocated Colorado River (Chapter 10). Increased drought may not be expected for all river basins of the Southwest, however; the Sacramento River Basin, for example, is projected to become slightly wetter (Cayan et al. 2010).

7.6 Fire Weather

Fire weather is persistent in the Southwest most of the year and actual outbreaks of fire in the region are significantly affected by human factors such as ignition and arson, fire management, and fire suppression practices that might (in the long run) provoke stronger wild fires (Westerling et al. 2003). Hot, gusty, dry winds can greatly exacerbate the risk of extremely large wildfires if they occur when the fuels are dry and plentiful and especially where the wind itself can influence the risk of a spark (e.g., when it contacts power lines). The topographically complex Southwest is home to several regional downslope winds of the rain-shadow-type (such as the Colorado Front Range chinook) or the gravity-driven type (such as the Santa Ana winds of Southern California). The Santa Ana winds, accelerating down the west slopes of Southern California's coastal ranges, are particularly notorious for spreading uncontrollable fires, since the beginning of the Santa Ana season in the fall coincides with the end of the long dry warm season (e.g. Westerling et al. 2004).
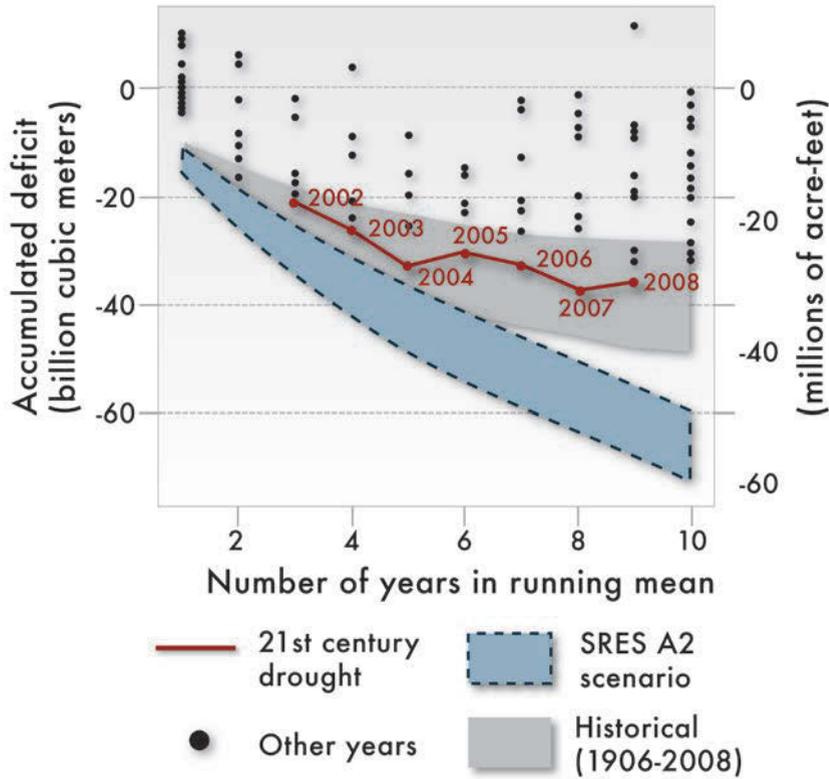
Figure 7.4 Drought associated anomalies in Colorado River streamflow. Accumulated deficit in flow (10^9 m^3, or billions of cubic meters) on the Colorado River at Lees Ferry relative to the mean flow observed over the period 1906–2008 (Y axis), as a function of drought duration in years (X axis). The twenty-first-century drought is shown in red; other years are shown as black dots. For example, the red 2007 indicates an eight-year drought (2000–2007), with an accumulated deficit of around 40 billion cubic meters (around 30 million acre-feet). Grey shading indicates where, two-thirds of the time, the worst drought (accumulated streamflow deficit) of the century should fall; the blue hatched region shows where the worst drought should fall for the end of this century, estimated from downscaled climate models. The twenty-first-century drought was consistent with the expected 100-year event, given the observed climate, whereas future 100-year droughts are expected to be much more severe in terms of accumulated flow deficit. Modified from Cayan et al. (2010).

Santa Ana winds

The cool, relatively moist fall and winter climate of Southern California is often disrupted by dry, hot days with strong winds known as the Santa Anas that blow out of the desert. The Santa Ana winds are a dominant feature of the cool-season climate of this region (Conil and Hall 2006; Hughes and Hall 2010), and they have important ecological impacts. The most familiar is their influence on wildfires: following the hot, dry Southern California summer, the extremely low relative humidities and strong, gusty winds associated with Santa Anas introduce extreme fire risk, often culminating in wildfires with large economic loss (Westerling et al. 2004; Moritz et al. 2010).
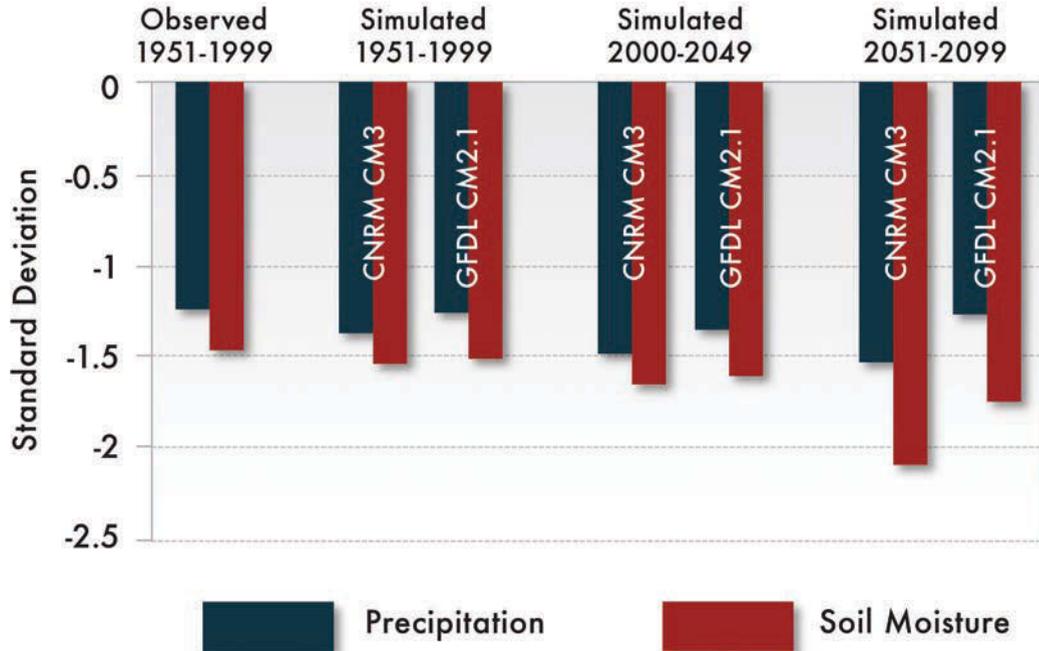
Figure 7.5 Drought-associated anomalies in precipitation and soil moisture. Composite average of water-year precipitation (blue) and water-year soil moisture (red) anomalies associated with extreme negative soil moisture anomalies for the Southwest estimated from observations and simulated climate input from CNRM CM3 and GFDL CM2.1 GCMs SRES A2 emission scenario, for 1951–1999, 2000–2049, and 2050–2099. Modified from Cayan et al. (2010).

Hughes, Hall, and Kim (2011) recently documented the potential impacts of human-generated climate change on the frequency of the Santa Anas and associated meteorological conditions with a high-resolution dynamical downscaling of a Fourth Assessment Report (NCAR CCSM3) model. They project that the number of Santa Ana days per winter season would be approximately 20% fewer in the mid twenty-first century compared to the late-twentieth century.

In addition to the change in Santa Anas' frequency, Hughes, Hall, and Kim (2011) also investigated changes during Santa Anas in two other meteorological variables known to be relevant to fire weather conditions—relative humidity and temperature—and found a decrease in the relative humidity and an increase in temperature. Both of these changes would favor fire, while the reduction in Santa Ana wind events would reduce fire risk. More work is necessary to ensure these results are robust across different climate models and emission scenarios, and to quantify the impact of these changes on fire weather. Santa Ana winds are treated as weather extremes in this report because they cause extreme fire danger conditions. However, Santa Ana winds are rather commonplace and not extreme in and of themselves. The extremes of Santa Ana winds have not been studied either in the observed or projected climate. This is an important topic for future research.

7.7 Discussion of Key Uncertainties

Large-scale climate drivers such as El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in particular, play an important role in the winter and spring precipitation extremes (and consequently floods) over the Southwest and West. A rich body of literature shows the Southwestern hydroclimate—in particular the daily precipitation extremes—to be very sensitive to natural interannual and decadal variability (Gershunov and Barnett 1998; Cayan et al. 1999; Gershunov and Cayan 2003). Thus, flood risk can be affected by changes to moisture delivery processes (see, for example, Dettinger et al. 1998; Gershunov and Barnett 1998; Cayan, Redmond and Riddle 1999; Rajagopalan et al. 2000), temperature, and land surface conditions. An important uncertainty for the Southwest therefore is how the relevant modes of natural variability in the Pacific sector (ENSO and PDO) and their combined influences on Southwestern climate may be affected by climate change. The most predictable climate regime in the Southwest is the dry winter associated with La Niña and the negative phase of the PDO. For the first time in over a century, in spring 2011 this combination of natural forcing did not result in a dry winter; instead, great snow accumulations ended the early twenty-first century drought.[viii] The influence of climate change on the stability of teleconnections[ix] and the reliability of traditional seasonal climate forecasts should be investigated in future research.

Flooding is a result of complex interactions between the type and characteristics of moisture delivery, water catchment attributes, and land surface features. In a broad sense, the common mechanisms of moisture delivery—heavy winter rainfall, runoff, heavy winter snow followed by spring melt, rain-on-snow events, and summer convection connected with the North American monsoon system—operate in conjunction with temperature regimes and catchment and land surface features. The key to flooding outcomes are the *processes* that deliver moisture to this region: an intricate choreography of large-scale, ocean-atmospheric climate drivers and orography (the physical geography of mountains).[x]

Significant changes to flood risks during the twentieth century were observed over the entire Western United States as a result of general warming (Hamlet and Lettenmaier 2007). Winter temperature changes modify the precipitation patterns; most significantly, higher temperatures increase winter rainfall at the expense of snowfall, thus reducing spring flooding while potentially increasing winter flooding. Warm and cold phases of ENSO and PDO also strongly modulate flooding risk. For example, cold ENSO and PDO phases reduce overall precipitation in the Colorado River Basin, thereby reducing flood risk. These insights provide a template for flood-risk changes under a warmer climate in the twenty-first century, assuming climate change does not affect the nature or stability of the teleconnections climate forecasters have come to trust. This is an assumption that needs to be verified.

Floods that cause severe property damage and loss of life in populous regions are predominantly caused by severe precipitation events on already saturated soils. As discussed above, the Southwest is likely to experience increased flood risk from short-duration extreme atmospheric river precipitation events. The future role of rain-on-snow events in twenty-first-century flood regimes remains highly uncertain (Dettinger et al. 2009).

The ability of climate models to reproduce extreme high-frequency precipitation is a key uncertainty in projections. Dynamical models typically overestimate the frequency of precipitation and underestimate precipitation intensity (e.g. Gershunov et al. 2000). Given the known modeling precipitation biases, how certain are projected trends in precipitation extremes?

Behavior of co-occurring high-impact extremes such as drought and heat waves is a key uncertainty that has not so far been adequately addressed. It is likely that soil moisture anomalies predetermine a region's capacity for extreme heat waves, while heat waves, in turn, deplete soil moisture. Decadal drought cycles can therefore modify the clearly projected trends in heat-wave activity. Research on the interactions between drought cycles and heat wave activity is needed to understand possible decadal variation of heat waves in a warming Southwest projected to experience deeper and longer droughts (Cayan et al. 2010).

Coastal climate is characterized by persistent low-level clouds in summer, to which coastal ecosystems and society are adapted. This "marine layer" responds to a host of natural weather and climate influences on global and local scales. The marine layer is particularly sensitive to inland temperatures and can respond to heat waves in different ways depending on regional to large-scale atmospheric circulation, coastal upwelling of cold nutrient-rich ocean water, and the state of the PDO. It typically protects the highly populated and sparsely air-conditioned coast from heat waves, but its absence during a heat wave (such as in July 2006 along the California coast) can severely impact public health (see Chapter 15), agriculture (Chapter 11), and the energy sector (Chapter 12). Marine-layer dynamics are not well understood or modeled. Future behavior of the marine layer in general and specifically in conjunction with extreme heat is unknown.

The Southwest is demarcated by an international border that transforms the region but fails to confine the impacts of extreme weather and climate. With its core region in northwestern Mexico, the North American monsoon is an excellent example of a climate phenomenon straddling both sides of the border. Although the region experiences the same extremes on either side of the U.S.-Mexico border, the impacts of these extremes—and the ability to observe and mitigate them—are not equally shared because of socio-economic and sociopolitical disparities (see also Chapter 16 for an extensive discussion of climate change effects and adaptation in the U.S.-Mexico border region).

Irreversible changes and tipping points

In addition to these and numerous other uncertainties, the possibilities for abrupt or irreversible changes and tipping points exist, particularly in the impacts of climate change on biological and social systems. These issues, however, are highly speculative and uncertain and we only briefly list a few considerations here.

- Warmer winters and drought can and have led to bark beetle infestations that threaten the pine forests and influence wildfire risk (see Chapter 8, Section 8.4).
- The Southwest appears prone to abrupt shifts in climate regimes as evidenced by the paleorecord (e.g., historic megadroughts, see Chapter 5) that, coupled with enhanced heat wave activity, could lead to irreversible impacts on ecology as well as human adaptation, and may reduce the productive capacity of resources such as soils and rangelands.

- Impacts that promote devastating wildfires can result in irreversible land-cover and ecological changes.
- A declining snowpack has the capacity to irreversibly change the hydrologic regime.
- Change in the atmospheric vertical temperature profile can influence atmospheric stability and precipitation.
- A shift in the jet stream, although gradual, could have irreversible consequences on human time scales.
- The massive changes in the Arctic may be impacting the Southwest in ways currently unknown.
- Asian dust and aerosols may have a lasting influence on precipitation.

These and other uncertainties, coupled with the region's unique diversity and compounding vulnerabilities, create a highly volatile landscape for climate to write its story upon, employing an evolving lexicon and extreme punctuation marks.

References

Arriaga-Ramírez, S., and T. Cavazos. 2010. Regional trends of daily precipitation indices in northwest Mexico and southwest United States. *Journal of Geophysical Research* 115: D14111, doi:10.1029/2009JD013248.

Bao, J. W., S. A. Michelson, P. J. Neiman, F. M. Ralph, and J. M. Wilczak. 2006. Interpretation of enhanced integrated water vapor bands associated with extratropical cyclones: Their formation and connection to tropical moisture. *Monthly Weather Review* 134:1063–1080.

Barlow, M. 2011. Influence of hurricane-related activity on North American extreme precipitation. *Geophysical Research Letters* 38: L04705, doi:10.1029/2010GL046258.

Cavazos, T., and S. Arriaga-Ramírez. 2012. Downscaled climate change scenarios for Baja California and the North American monsoon during the 21st century. *Journal of Climate* 25:5904–5915.

Cavazos, T., C. Turrent, and D. P. Lettenmaier. 2008. Extreme precipitation trends associated with tropical cyclones in the core of the North American Monsoon. *Geophysical Research Letters* 35: L21703, doi:10.1029/2008GL035832.

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov. 2010. Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proceedings of the National Academy of Sciences* 107:21271–21276, doi:10.1073/pnas.0912391107.

Cayan, D. R., K. T. Redmond, and L. G. Riddle. 1999. ENSO and hydrologic extremes in the western United States. *Journal of Climate* 12:2881–2893.

Chou, C., and C-W. Lan. 2011. Changes in the annual range of precipitation under global warming. *Journal of Climate* 25:222–235.

Conil, S., and A. Hall. 2006. Local regimes of atmospheric variability: A case study of southern California. *Journal of Climate* 19:4308–4325.

Cook, E. R., R. Seager, R. R. Heim, R. S. Vose, C. Herweijer, and C. Woodhouse. 2009. Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term paleoclimate context. *Journal of Quaternary Science* 25:48–61, doi: 10.1002/jqs.1303. http://www.ldeo.columbia.edu/res/div/ocp/pub/cook/2009_Cook_IPCC_paleo-drought.pdf

Cook, E. R., C. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-term aridity changes in the western United States. *Science* 306:1015–1018.

Das, T., M. D. Dettinger, D. R. Cayan, and H. G. Hidalgo. 2011. Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change* 109 (Suppl. 1): S71–S94, doi:10.1007/s10584-011-0298-z.

Dettinger, M. D. 2011. Climate change, atmospheric rivers and floods in California – A multi-model analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association* 47:514–523.

Dettinger, M. D., D. R. Cayan, H. F. Diaz, and D. M. Meko. 1998. North–south precipitation patterns in western North America on interannual-to-decadal timescales. *Journal of Climate* 11:3095–3111.

Dettinger, M. D., H. Hidalgo, T. Das, D. Cayan, and N. Knowles. 2009. *Projections of potential flood regime changes in California.* Final Paper CEC-500-2009-050. Sacramento: California Climate Change Center. http://www.energy.ca.gov/2009publications/CEC-500-2009-050/CEC-500-2009-050-F.PDF.

Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. Cayan. 2011. Atmospheric rivers, floods, and the water resources of California. *Water* 3:455-478. http://www.mdpi.com/2073-4441/3/2/445/.

Dettinger, M. D., F. M. Ralph, M. Hughes, T. Das, P. Neiman, D. Cox, G. Estes, et al. 2011. Design and quantification of an extreme winter storm scenario for emergency prepared-ness and planning exercises in California. *Natural Hazards* 60:1085–1111, doi:10.1007/s11069-011-9894-5.

Diffenbaugh, N. S., and M. Ashfaq. 2010. Intensification of hot extremes in the United States. *Geophysical Research Letters* 37: L15701, doi:10.1029/2010GL043888.

Dominguez, F., E. Rivera, D. P. Lettenmaier, and C.L. Castro. 2012. Changes in winter precipita-tion extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters* 39: L05803, doi: 10.1029/2011GL050762.

Favre, A., and A. Gershunov. 2009. North Pacific cyclonic and anticyclonic transients in a global warming context: Possible consequences for western North American daily precipitation and temperature extremes. *Climate Dynamics* 32:969–987.

Field, C. B., V. Barros, T. Stocker, and Q. Dahe, eds. 2011. *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. http://ipcc-wg2.gov/SREX/report/.

Gershunov, A., and T. P. Barnett. 1998. ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous United States: Observations and model results. *Journal of Climate* 11**:**1575–1586.

Gershunov, A., T. Barnett, D. Cayan, T. Tubbs, and L Goddard. 2000. Predicting and downscaling ENSO impacts on intraseasonal precipitation statistics in California: The 1997–1998 event. *Journal of Hydrometeorology* 1:201–209.

Gershunov, A., and D. R. Cayan. 2003. Heavy daily precipitation frequency over the contiguous United States: Sources of climate variability and seasonal predictability. *Journal of Climate* 16:2752–2765.

Gershunov, A., D. Cayan, and S. Iacobellis. 2009. The great 2006 heat wave over California and Nevada: Signal of an increasing trend. *Journal of Climate* 22:6181–6203.

Gershunov, A., and K. Guirguis. 2012. California heat waves in the present and future. *Geophys-ical Research Letters* 39: L18710, doi:10.1029/2012/GL052979.

Groisman, P. V., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5:64–85, doi:10.1175/1525–7541.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. N. Razuvaev. 2005. Trends in intense precipitation in the climate record. *Journal of Climate* 18:1326–1350.

Guan, B., N. P. Molotch, D. E. Waliser, E. J. Fetzer, and P. J. Neiman. 2010. Extreme snowfall events linked to atmospheric rivers and surface air temperature via satellite measurements. *Geophysical Research Letters* 37: L20401, doi:10.1029/2010GL044696.

Guirguis, K., A. Gershunov, R. Schwartz and S. Bennett. 2011. Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophysical Research Letters* 38: L17701, doi:10.1029/2011GL048762.

Hamlet, A. F., and D. P. Lettenmaier. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resources Research* 43: W06427, doi:10.1029/2006WR005099.

Hirschboeck, K. K. 1991. Climate and floods. In *National water summary 1988-89: Hydrologic events and floods and droughts*, comp. R. W. Paulson, E. B. Chase, R. S. Roberts, and D. W. Moody, 99–104. U.S. Geological Survey Water-Supply Paper 2375. Washington, DC: U.S. Government Printing Office.

Hughes, M., and A. Hall. 2010. Local and synoptic mechanisms causing Southern California's Santa Ana winds. *Climate Dynamics* 34:847–857.

Hughes M., A. Hall, and J. Kim. 2011. Human-induced changes in wind, temperature and relative humidity during Santa Ana events. *Climatic Change* 109 (Suppl. 1): S119–S132, doi:10.1007/s10584-011-0300-9.

Intergovernmental Panel on Climate Change (IPCC). 2007. Summary for policymakers. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge: Cambridge University Press.

Kharin, V. V., F. W. Zwiers, X. Zhang, and G. Hegerl. 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. *Journal of Climate* 20:1419–1444.

Kodra, E., K. Steinhauser, and A. R. Ganguly. 2011. Persisting cold extremes under 21st-century warming scenarios. *Geophysical Research Letters* 38: L08705. doi:10.1029/2011GL047103.

Lu, J., C. Deser, and T. Reichler. 2009. The cause for the widening of the tropical belt since 1958. *Geophysical Research Letters* 36: L03803, doi: 10.1029/GL036076.

Lu, J., G. A. Vecchi, and T. Reichler. 2007. Expansion of the Hadley cell under global warming. *Geophysical Research Letters* 34: L06805, doi:10.1029/2006GL028443.

Mahoney, K., M. A. Alexander, G. Thompson, J. J. Barsugli, and J. D. Scott. 2012. Changes in hail and flood risk in high-resolution simulations over the Colorado Mountains. *Nature Climate Change* 2:125–131, doi:10.1038/nclimate1344.

Mastrandrea, M. D., C. Tebaldi, C. W. Snyder, and S. H. Schneider. 2011. Current and future impacts of extreme events in California. *Climatic Change* 109 (Suppl. 1): S43–S70, doi 10.1007/s10584-011-0311-6.

Maurer, E. P., and H. G. Hidalgo. 2008. Utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods. *Hydrology and Earth System Sciences* 12:551–563.

MacDonald, G. M., D. W. Stahle, J. Villanueva Diaz, N. Beer, S. J. Busby, J. Cerano-Paredes, J. E. Cole, et al. 2008. Climate warming and twenty-first century drought in southwestern North America. *Eos Transactions AGU* 89:82.

Meehl, G. A., T. Karl, D. R. Easterling, S. Changnon, R. Pielke, D. Changnon, J. Evans, et al. 2000. An introduction to trends in extreme weather and climate events: Observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bulletin of the American Meteorological Society* 81:413–416.

Moritz, M., T. Moody, M. Krawchuk, M. Hughes, and A. Hall. 2010. Spatial variation in extreme

winds predicts large wildfire locations in chaparral ecosystems. *Geophysical Research Letters* 37: L04801.

Nakićenović, N., and R. Swart, eds. 2000. *Special report on emissions scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Pierce, D. W., T. Das, D. R. Cayan, E. P. Maurer, N. Miller, Y. Bao, M. Kanamitsu, et al. 2012. Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling. *Climate Dynamics* published online, doi:10.1007/s00382-012-1337-9.

Rajagopalan, B., E. Cook, U. Lall, and B. Ray. 2000. Spatiotemporal variability of ENSO and SST teleconnections to summer drought over the United States during the twentieth century. *Journal of Climate* 13:4244–4255.

Ralph, F. M., and M. D. Dettinger. 2011. Storms, floods and the science of atmospheric rivers. *Eos Transactions AGU* 92:265–266.

Ralph, F. M., M. D. Dettinger, A. White, D. Reynolds, D. Cayan, T. Schneider, R. Cifelli, et al. 2011. A vision of future observations for western US extreme precipitation events and flooding: Monitoring, prediction and climate. Report to the Western States Water Council, Idaho Falls.

Ralph, F. M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White. 2006. Flooding on California's Russian River: Role of atmospheric rivers. *Geophysical Research Letters* 33: L13801, doi:10.1029/2006GL026689.

Salas-Mélia, D., F. Chauvin, M. Déqué, H. Douville, J. F. Guérémy, P. Marquet, S. Planton, J. F. Royer, and S. Tyteca. 2005. Description and validation of the CNRM-CM3 global coupled model. CNRM Working Note 53. Toulouse, France: Centre National de Recherches Météorologiques. http://www.cnrm.meteo.fr/scenario2004/paper_cm3.pdf.

Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21:219–238.

Tebaldi, C., K. Hayhoe, and J. M. Arblaster. 2006. Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change* 79:185–211.

Trenberth, K. E., P. D. Jones, P. Ambenje, R. Bojariu, D. R. Easterling, A. K. Tank, D. Parker, et al. 2007. Observations: Surface and atmospheric climate change. In *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, 235–336. Cambridge: Cambridge University Press.

Wang, J., and X. Zhang. 2008. Downscaling and projection of winter extreme daily precipitation over North America. *Journal of Climate* 21:923–937.

Westerling, A. L., D. R. Cayan, T. J. Brown, B. L. Hall, and L. G. Riddle. 2004. Climate, Santa Ana winds and autumn wildfires in Southern California. *Eos Transactions AGU* 85:289, 296.

Westerling, A. L., A. Gershunov, T. Brown, D. Cayan, and M. Dettinger. 2003. Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society* 84:595–604.

Endnotes

i   Downscaled using the Bias Corrected Constructed Analogue (BCCA) statistical downscaling method of Maurer and Hidalgo (2008).

ii   Another measure of heat waves is discussed in Chapter 5, Section 5.4.

iii   Events with a probability of occurrence of 1% in any given year or 100% in 100 years.

iv   Another measure of cold waves is discussed in Chapter 5, Section 5.4.

v   They detected tropical cyclone-related trends in the core NAM region. However, because this is in Mexico and since Barlow (2011) showed that hurricane-related activity contributes only 1% of Southwestern precipitation extremes, we did not consider hurricanes and tropical storms in this chapter.

vi   Mahoney et al. (2012) used a multi-tiered downscaling approach where first a GCM (GFDL) was downscaled to 31 mile (50-km) grid as a part of North American Regional Climate Change Assessment Program (NARCCAP), using the high-emissions scenario (Nakicenovic and Swart 2000). Then extreme precipitation events in NARCCAP were further downscaled using the Weather Research and Forecasting (WRF) model. High-resolution WRF simulations (up to 0.8 mile [1.3 km] horizontal grid), initialized using composite future and past conditions were produced.

vii   Potential sensitivities of model microphysical parameterization (especially hail size distribution to melting hail) merits further investigation. Nevertheless, although based on one GCM projection only, Mahoney and colleagues (2012) claim their results are robust due to consistency with different initialized climate projections, and different WRF methodologies (event and composite).

viii   In winter 2011–2012, at the time of this writing, similar forcings are producing more than expected dryness, however.

ix   *Teleconnections* are persistent large-scale patterns of atmospheric circulation that reflect changes in the jet stream or atmospheric waves over very large areas. They can derive from internal atmospheric dynamics or from changes in sea-surface temperatures and convection, as in the tropical Pacific ENSO cycle resulting in, for example, anomalous precipitation patterns in the Southwest.

x   These are described in detail in Hirschboeck (1991) and Sheppard et al. (2002).