Chapter 7: The Southwest Weather and Climate Extremes of the Future

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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 evolving climate warming in the course of the current century.

Summertime heat waves and wintertime cold snaps are among the most impactful and most directly affected of the extremes considered. Not surprisingly, heat waves are projected to increase in magnitude (a very high confidence projection), but they are also projected to become more humid and therefore expressed relatively more strongly in nighttime rather than daytime temperatures. This change in the flavor of projected extremes is fully consistent with observations and associated with numerous impacts on public health, agriculture, ecosystems, the energy sector, etc. However, because this result is based at this time primarily on one model, it is associated with medium-low confidence.

Winter time cold snaps are projected with medium-high confidence to diminish in their intensity and frequency into late century. The following caveats apply, however: (i) the risk of very cold outbreaks will continue to be modulated by natural interannual and decadal variability and (ii) with future warming, there is a low confidence expectation for cold snaps to become more frequent, albeit less intense, in low-lying coastal valleys and east of the Front Range of the Rocky Mountains.

Projections for precipitation extremes in general do not present a consistent picture at this time. Nothing, for example, is known about future extremes of the Monsoon. However, enhanced precipitation specifically associated with atmospheric rivers is projected by most current climate models amounting to a medium-low confidence result.

Floods from winter storms on the western slopes of the Sierra Nevada range have been projected to increase in intensity (and in frequency) in winter by several climate models (all that have been analyzed thus far), including by models that otherwise project drier conditions, and it can also confidently be expected that snowmelt-driven spring and summertime floods will diminish in both frequency and intensity. 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.

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. This is a high-confidence result. However, northern Sierra Nevada watersheds may become wetter with climate change.

Santa Ana winds of coastal Southern California, not extreme in and of themselves but associated with extreme fire risk, are expected to diminish in frequency and intensity, but at the same time become drier and hotter. This is a medium confidence result. However, the combined effect of decreased winds and increased temperatures and dryness on fire risk is not clear.

Beyond these projections, the region is fraught with important uncertainties regarding future extremes.

7.1 Introduction

Extreme events can be and are defined in many different ways. Typical definitions of weather and climate extremes involve consideration of either the maximum value during a specified time interval (season, year, etc.) or exceedance of a threshold. In the latter, peaks over threshold (POT) approach, universal thresholds are frequently applied. For example, temperatures above 95°F are often considered extreme in most locations across the U.S. In low-lying deserts of Arizona and California, however, such temperatures are typical in summer. They are obviously extreme from the un-adapted physiological perspective and technological adaptation is required for day-to-day functioning in such temperatures, but they are not extreme from the statistical or local climate perspective. 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 locally relevant, i.e. relative to local climate. Over the Southwest, location-specific definitions of extreme temperature, precipitation, humidity or 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 actually considered future projections of extremes (e.g. Meehl et al. 2000, Tebaldi et al. 2006, Trenberth et al. 2007, Parry et al. 2007) and fewer 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 exceptional in this respect 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 projections study (Cayan et al. 2010). As a state, California has probably been the focus of more climate change research than any other in the Union – research that translated to pioneering 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.

Extremes are clearly the most immediately impactful manifestations of weather and climate variability and change. 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, it is necessary to spur and nurture close collaborations between science and the public/private/policy sectors. This process is under way, further along in the Southwest than in other parts of the Nation, but even here the necessary cross-sector relationships are still in their infancy. In the future, one of the goals of the Southwest Climate Alliance (SWCA) is to define extremes by first understanding their impacts in key sectors. For now, we define extremes based solely on climate records and models while being mindful of their impacts.

For meaningful projections of extremes, it is imperative to validate models with respect to the mechanisms that produce specific extremes, e.g. heat waves, atmospheric rivers, etc. A multi-mo el approach without careful validation can introduces uncertainties into projection of extremes rather than the typically assumed greater certainty when multi-model projections are averaged to study mean climate trends. In contrast to average climate, changes in extremes should not be assumed to be more adequately diagnosed from averaging across ensemble members and/or multiple models. The rare nature of extremes demands that they be carefully analyzed in each realization of modeled climate.

7.2 Heat waves

The 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 Southwestern U.S. (e.g. Diffenbaugh and Ashfaq 2010).

Gershunov et al. (2009) showed that heat waves over California and Nevada are not simply increasing in frequency and intensity, but that they are also changing their flavor: they are becoming more humid and therefore expressed more and more strongly in nighttime rather than daytime or minimum (Tmin) rather than maximum (Tmax) daily temperatures. These changes started in the 1980s and appeared to accelerate since 2000. Humidity, moreover, was shown not to have increased as a seasonal average, but rather that the rare synoptic circulations bringing 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) therefore, first identified a Global Circulation Model (GCM) from which daily data was available and which was able to simulate both the synoptic causes of California heat waves as well as the observed trend in the flavor of regional heat waves – the disproportionate intensification of their nighttime compared to their daytime expressions. They then considered downscaled projections[1] specifically over California and its sub-regions. 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, below, we first expand the observational diagnosis of Gershunov et al. (2009) and then

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

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

7.2.1 Heat wave index

Heat waves are hereby defined locally, but described over the entire southwestern region as follows. A local heat wave occurs when daily temperature exceeds the 95th percentile of the local summertime (May – September) daily climatology of maximum or minimum temperatures over a base period of 1971- 2000. In other words, when temperature rises to the level of the hottest five percent of summer days or nights, a local heat wave is registered. The local magnitude of the heat wave (the heat wave index – HWI) is measured as the difference between the actual Tmax or Tmin and its corresponding 95th percentile threshold and 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 using 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 includes the frequency, intensity, duration and spatial extent of heat waves across the Southwest (Figure 7.1).

[Figure 7.1 about here]

7.2.2 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 in minimum compared to 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), while 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 wave expression projected to continue increasing at a faster rate compared to that of daytime heat wave expression. 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 increasingly larger parts of the Southwest, all driving this cumulative index heat wave index dramatically upward. Mastrandrea et al. (2009, PIER report, and 2011, article in review) adopted a multi-model view on California heat waves examining 100-yr events. Their results also suggest a tendency towards higher minimum temperatures increasing more than maximum temperatures, but in the multimodel ensemble it is not as clear as in the well-validated CNRM-CM3 model as well as in observations. The main result from multi-model heat wave projections is that observed 100-yr return period heat waves become 10-yr return period or even more likely during the projected last half of the 21st century.

The disproportionate increase in nighttime versus daytime projected heat wave occurrence is consistent with observations and indicative of enhanced future impacts on (human, animal and ecosystem) health, agriculture and energy infrastructure due to the elevated humidity and diminished nighttime respite from heat making the intensifying heat more difficult to weather for the biota of the Southwest, acclimatized to dry daytime heat and cool nights. Given the high correspondence of observed and modeled trends, this should be considered a medium low confidence result. Agreement from additional models, if validated at least to produce realistic heat waves for correct synoptic dynamical reasons, will likely increase the confidence of this conclusion into the 'high-confidence' category.

Sub-regional modulation of heat wave trends is possible. For example, working with BCCA downscaled data over California, Gershunov and Guirguis (2012) find intriguing patterns of projected change in the magnitude of heat waves relative to median trends. An enhanced heat wave magnitude signal is observed and projected along the coast – the most highly populated and least adapted of all California's sub-regions. This should be considered low confidence result at this point.

7.3 Wintertime cold outbreaks

Cold snaps are certainly expected to diminish in intensity in most of the world's regions due to the mean global warming trend. A diminishing trend in cold spell intensity has been observed over the northern hemisphere and its sub-regions (Guirguis et al. 2011). Regionally, cold outbreaks are highly sensitive to topography which channels the cold dense air. They are also sensitive to changes in atmospheric circulation regimes, in particular to transient high pressure systems which cause cold air outbreaks. As the subtropical subsidence zones intensify and expand poleward (Lu et al. 2007, 2009) and the storm track contracts towards the pole in response to a progressively diminished equator-to-pole temperature gradient (IPCC 2007), fewer cyclones and more anticyclones are expected to arrive to the southwestern U.S. and northwestern Mexico, resulting in decreased precipitation frequency but increased frequency of cold outbreaks (Favre and Gershunov 2009). This counterintuitive result is a direct consequence of circulation changes projected for the northeastern Pacific and northwestern North America and is physically consistent with the climatology of synoptic weather systems under global warming. However, confidence in this result must be assessed as low as it is based on one model projection only. Because of the topographic complexity of the Southwestern U.S., this low-confidence result only applies to coastal low-lying valleys as well as east of the Rocky Mountains' Front Range, which channels the Arctic air spills. Agricultural impacts of future cold outbreaks, even at a diminishing intensity, may be significant.

In the rest of the Southwest, winter cold outbreaks in much of this mountainous region are not affected by transient anticyclones arriving from the North Pacific (see Favre and Gershunov 2009 Figure 14). Following the heat wave index definition of the previous section and the approach of Guirguis et al. (2011), we define cold outbreaks as the coldest five percent of the wintertime daily temperature distribution, aggregating the cold excursions below the local 5^{th} percentile thresholds over the cold season (November – March) and averaging over the region. 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 uniform, however, as the influence of natural interannual and decadal variability on the occurrence of cold extremes is projected to continue to strongly modulate cold outbreaks in the future. Kodra et al. (2011) project that occasional extreme cold events are likely to persist across each continent under 21st-century warming scenarios, however, and this agrees with recent results for California using multi-model downscaled projections (Pierce et al. 2011). The available results are somewhat contradictory and more research is necessary to reduce the currently high uncertainty for the Southwest, despite the intuitive expectation that global warming should lead to fewer and less extreme regional cold outbreaks.

[Figure 7.2 about here]

7.4 Precipitation

7.4.1 General results and key uncertainties

Although, the standard result on precipitation extremes is that both observed and projected high-frequency and intensity extremes are increasing over many continental regions in observations and models and projected to increase further, i.e. become more extreme, no such changes have been observed over the Southwest (Groisman et al. 2004, 2005). Models project augmented extreme precipitation 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 (at 100% relative humidity) and that therefore extreme storms should be able to produce more precipitation than similar events in the past. Global climate models are notoriously deficient in 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 modeling deficiencies in simulating precipitation and to rely more on model strengths, Wang and Zhang (2008) used a statistical downscaling scheme to relate large-scale atmospheric circulation and humidity to local observed station precipitation and then applied it in a global climate model projection. In this framework, the effects of circulation and humidity changes can be evaluated separately. Wang and Zhang (2008) diagnose changes in the daily extreme values of winter precipitation thus projected and downscaled. The result is that over much of North America, during the last half of the current century, precipitation extremes characterized by 20-yr return periods in the observed local climate are projected to become more frequent – up to twice as likely – even in regions that are projected to experience a decrease in precipitation (including extremes) due to circulation changes. This is Wang and Zhang's projection for the Southwest. In other words, increasing specific humidity in a warming atmosphere is expected to dominate future trends in extreme precipitation. Raw climate model precipitation trends support this result (e.g. Kharin et al. 2007), while some other downscaling schemes do not. Mastrandrea et al. (2011), for example, used a different (constructed analog) precipitation downscaling scheme that did not utilize atmospheric humidity as 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 models, downscaling schemes and extreme precipitation definitions and, therefore, amount to a high degree of uncertainty. 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 some of the world's regions (Groisman et al. 2004, 2005), especially in summer, but not over the Southwest where increasing extreme precipitation trends have not yet been observed, and this is in spite of the fact that the Southwest has been at the forefront of warming among regions of the contiguous U.S. Different results are not yet congruent and more research is clearly needed. In order to achieve more certainty, specific storm systems should be examined and specific physical processes considered.

7.4.2 North American Monsoon (NAM)

NAM is the source of summertime precipitation for most of the Southwest, particularly Arizona and New Mexico. The core region of NAM is along the Sierra Madre Occidental in

Northwestern Mexico (Cavazos et al. 2008, Arriaga-Ramírez and Cavazos, 2010). These studies examined observed trends in specifically extreme summertime rainfall, but did not detect any significant trends related specifically to the NAM[2]. The northern tip of NAM penetrates into the Southwestern U.S. Monsoonal precipitation modeling and projections present many uncertainties (see Chapter 6), which all translate into 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 emission scenario) in conjunction with statistical downscaling, show a weakening of the monsoon rainfall and stronger 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 modulated by large scale patterns of natural variability and enormous challenges in monsoon modeling prevent confident conclusions about the future of NAM, especially its extremes. However, Chou and Lan (2011) show a negative trend in maximum precipitation in the monsoon region during the 21st century associated with increased subtropical subsidence induced by global warming. Projected increase in subtropical subsidence (as discussed in Chapter 6 and in Lu et al, 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.

[2] 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.

7.4.3 Atmospheric Rivers (ARs)

So far, atmospheric rivers have been the only extreme-precipitation-producing systems in the Southwest that are large-scale enough to be adequately modeled and that have received recent careful attention in the context of climate change. Much of the Southwest is within reach of an important class of Pacific storms, often referred to as "atmospheric rivers" (ARs), storms in which enormous amounts of water vapor are delivered to the region in low level (<2 km above sea level), long (>2000 km) and narrow (less than about 500 km wide) corridors from over the Pacific Ocean (Ralph and Dettinger 2011). 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 release many of the most intense precipitation events that define the storm and flood climatologies of the region (Ralph et al. 2006, Ralph et al. 2011). The storms are present in the kinds of climate-change simulations by the coupled atmosphere-ocean global and even regional climate models of AR4 (and presumably, AR5) (e.g., Dettinger 2011, Bao et al. 2006, Dettinger et al. 2011). A preliminary study of their occurrences and intensities in AR4 projections of climate changes in response to SRES A2 emissions by seven GCMs (Dettinger 2011) indicates that, as the climate warms in response to increasing greenhouse-gas concentrations in the atmosphere, ARs making landfall on the California coast carry more water vapor in general. As a result, an average of about 30% more days have storm conditions that would be classified as ARs and about twice as many years have many more than historical numbers of landfalling ARs by mid 21st century. Also, all seven models yielded occasional 21st 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 21st century; however the analyses and even our understanding of historical ARs (Ralph and Dettinger 2011, Dettinger 2011) are still preliminary and warrant further investigations.

[Figure 7.3 about here]

7.4.4 Hail on the Colorado Front Range

Parts of the Southwest are prone to precipitation from summertime intense thunderstorms that falls in the form of hail rather than heavy rain. In addition to inflicting 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 U.S. is the lee 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. In a multi-tiered downscaling first a GCM (GFDL) was downscaled to 50-km grid as a part of North American Regional Climate Change Assessment Program (NARCCAP), using business-as-usual emissions scenario (SRES A2). Then extreme precipitation events in NARCCAP were further downscaled using a the Weather Research and Forecasting (WRF) model. High-resolution WRF simulations (up to 1.3 km horizontal grid), initialized using composite future and past conditions were produced. The authors found a near-elimination of surface hail in the future time period, despite an increase in in-cloud hail, due to a higher melting level (0°C isotherm). The initial melting level increased from about 5,000 m (above sea level) to about 5,500 m over the study region from the past to future time period. The model simulations suggest this deeper vertical layer of above freezing temperatures is sufficient to melt the hailstones before they would reach the surface. Additionally, across most elevations in the region the future simulations produce larger total maximum precipitation and surface run-off. The combination of decreased surface hail and increased rainfall implies flash flooding may become more likely in mountainous regions (where the surface is relatively impervious) that currently experience hail. Potential sensitives of model microphysical parameterization, especially hail size distribution, to melting hail merits further investigation. Nevertheless, although based on one GCM projection only, authors claim robustness of result due to consistency with different initialized climate projections, and different WRF methodologies (event and composite).

7.5 Surface Hydrology

7.5.1 Flood

Changes in the type of intense precipitation due to warming will affect flooding. Just as summertime hail on the Rockies' Front Range turning to rain will increase the risk of flash flooding, so will wintertime snow turning to rain. Projected changes in winter storms, including both intensities and temperatures, are expected and projected (Das et al. 2011) to yield enhanced 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). Enhanced storms are an important cause of the enhanced flooding, but warming also plays an important role as it results in more precipitation falling as rain and less as 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 shown in Figure 7.3. 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. monsoon-region in the summertime), uncertainties about future changes in precipitation extremes translate directly into uncertainties about future flooding.

7.5.2 Drought

The crucial importance of water resources and their natural volatility in the arid, thirsty and growing Southwest has motivated numerous hydrological studies over 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 21st century (MacDonald 2008).

This contemporary drought was examined in the context of past records and future projections utilizing a hierarchy of global model projections, statistical downscaling, and hydrologic modeling to focus in on southwestern drought and describe it in the context of past and likely future conditions (Cayan et al. 2010). We summarize these results 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 et al. (2010), based on the A2 emissions scenario, suggests that the current 100-yr drought will become commonplace in the second half of the century and that future droughts will be much more severe than recorded events. The possibility of this should not be surprising given the magnitude of megadroughts on the paleo record (Cook at al. 2004, 2009), but importantly, climate change is slowly tipping the balance in favor of more frequent, longer and more intense droughts. Figure 7.4 (right panel) shows the difference in the Colorado River flow deficit accumulated over consecutive years of observed versus projected 100-yr drought. This projected intensification of drought conditions on the Colorado River is not due to changes in precipitation, but rather due directly to warming through declining snowpack, soil moisture and enhanced evapotranspiration. The longer, more intense future droughts in the Colorado basin pose challenges to sustaining water supplies of the already over-allocated Colorado River. Increasing dryness is not expected for all river basins of the Southwest, however, some of which are projected to become slightly wetter, e.g. the Sacramento River basin (Cayan et al. 2010).

[Figure 7.4 about here]

7.6 Fire weather

Fire weather is persistent in the Southwest most of the year and actual outbreaks of fire there are significantly affected by human factor: (a) ignition/arson, (b) fire management, and (c) fire suppression practice that might (in the long run) provoke stronger wild fires (Westerling et al. 2003). Hot, gusty, dry winds can have extreme impacts on wildfire risk 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 either foehn- or rain-shadow-type such as the Chinook or katabatic drainage type winds such as the Santa Ana of southern California or the Diablo in the north. The Santa Ana, blowing down the west slopes of Southern California’s coastal ranges is particularly notorious for spreading uncontrollable fires as 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).

7.6.1 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 Santa Anas, blowing out of the desert. The Santa Ana winds are a dominant feature of the cool season climate of Southern California (Conil and Hall 2006), 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 (Moritz et al. 2010; Westerling et al. 2004). Santa Ana winds are driven by two dynamical mechanisms (Hughes and Hall 2010): When strong synoptically-forced offshore flow impinges on Southern California’s topography, offshore momentum can be transported to the surface via mountain wave activity, causing Santa Ana conditions. Either independently or in addition to this synoptic forcing, Santa Ana winds are also forced katabatically by a local temperature gradient between the cold desert and warmer air over the ocean at the same altitude. This temperature gradient induces a hydrostatic pressure gradient pointing from the desert to the ocean, which is reinforced by the negative buoyancy of the cold air as it flows down the sloped surface of the major topographical gaps.

Hughes et al. (2011) recently documented the potential impact of anthropogenic climate change on Santa Ana wind frequency and associated meteorological conditions with a high-resolution dynamical downscaling of an AR4 (NCAR CCSM3) model. They found the number of Santa Ana days per winter season is approximately 20% fewer in the mid-21st century compared to the late-20th century. The synoptic contribution to Santa Ana development is comparable in the two time slices; in contrast, the katabatic mechanism is significantly weaker during the mid-21st century time period. The reduction in katabatic forcing occurs because of the well-documented differential warming associated with transient climate change: More warming in the desert interior than over the ocean reduces the likelihood of a large temperature deficit developing in the desert in wintertime.

In addition to the change in Santa Ana frequency, Hughes et al. (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 these changes would favor fire, while the reduction in Santa Ana wind events would reduce fire risk. However, more work is necessary to ensure these changes 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 here 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 observed or projected climate. This is an important topic for future research.

7.7 Discussion and key uncertainties

Large scale climate drivers such as El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in particular, play an important role in the winter and spring precipitation extremes over the Southwestern and Western U.S. and consequently floods. A rich body of literature shows Southwestern hydroclimate, and in particular daily precipitation extremes, to be very sensitive to natural interannual and decadal variability (Cayan et al. 1999; Gershunov and Barnett, 1998; Gershunov and Cayan, 2003). Thus, changes to flood risk can be affected by changes to moisture delivery processes (i.e. variability of teleconnections the aforementioned climate drivers, e.g., Gershunov and Barnett, 1998, Cayan et al. 1998; Dettinger et al. 1998; Rajagopalan et al. 2000), temperature and land surface conditions. An important uncertainty for the Southwest therefore is how will the relevant modes of natural variability in the Pacific sector (ENSO and PDO) and their teleconnected influences on Southwestern climate respond to climate change. The most predictable climate regime in the Southwest is dry winter associated with La Nina and the negative phase of the PDO. For the first time in over a century, this combination of natural forcings did not result in a dry winter; instead, great snow accumulations ended the early 21st century drought in spring 2011[3]. The influence of climate change on the stability of traditional teleconnections and the skill of traditionally reliable seasonal climate forecasts should be investigated in future research.

Flooding is a result of complex interactions between the type and characteristics of moisture delivery, catchment attributes and land surface features. In a broad sense the common mechanisms are 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 – operating in conjunction with temperature regimes, 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. These are lucidly described in detail in (USGS 1997, http://geochange.er.usgs.gov/sw/changes/natural/floods/; Hirschboeck 1991; Sheppard et al. 2002).

Significant changes to flood risks during 20th century have been observed over the entire Western U.S. as a result of the general warming signal (Hamlet and Lettenmaier 2007). Winter temperature changes modify the precipitation patterns – especially, higher temperatures reduce

[3] In winter 2011-2012, at the time of this writing, similar forcings are producing more than expected dryness, however.

the winter snowfall thus reducing the spring flooding. In addition warm and cold phases of ENSO and PDO strongly modulate the flooding risks – for example, cold ENSO and PDO phases reduce the overall precipitation in the Colorado River Basin thereby reducing the flood risk. These insights provide a template for flood risk changes under a warmer climate in the 21st 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 in populous regions that cause severe property damage and loss of life are predominantly from severe precipitation events over small catchment areas often coupled with wet antecedent moisture conditions. As discussed above, the region might experience increased flood risk from short duration extreme atmospheric river precipitation events. This is a medium confidence result. As far as rain-on-snow, 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 and underestimate precipitation intensity (e.g. Gershunov et al. 2000). Correcting this deficiency in the modeled shape of the precipitation probability density function (PDF) may not be a simple matter of increasing spatial resolution. Sophisticated new statistical downscaling procedures may need to be developed if models are to simulate the true heavy-tailed nature of precipitation (Panorska et al. 2007). Given the known modeling precipitation biases, how certain can we be of projected trends in untreated precipitation extremes?

Occurrence of compound 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 modulate the clearly projected trends in heat wave activity. Research on the interaction between drought cycles and heat wave activity is needed to understand possible decadal modulation 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. In particular, the marine layer is highly sensitive to inland temperatures and can respond to heat waves in different ways depending on regional-large scale atmospheric circulation, coastal upwelling 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 (e.g. July 2006) can severely impact public health (see chapter 15), agriculture and the energy sector. Marine layer dynamics are not well understood or modeled. Future behavior of marine layer in general and specifically in conjunction with extreme heat is unknown.

The Southwest is demarcated by an international border that transforms, but fails to confine, the impacts of extreme weather and climate. The North American Monsoon with its core region in northwestern Mexico is an excellent example of a climate phenomenon straddling both sides of the border. The U.S.-Mexican border, however, separates the types and severities of impacts due to the same extremes as well as ability to observe and mitigate them. The border is obviously not impermeable to migration and it creates regional uncertainties by delineating non-uniformity in response to impacts of the same climate extremes affecting both sides of the border.

7.7.1 Irreversible changes and tipping points

In addition to these and numerous other uncertainties, possibilities for abrupt and/or irreversible changes and tipping points exist, particularly in the non-linear 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.

a. Warmer winters and drought can and have led to bark beetle infestations threatening to kill of the pine forest.
b. The Southwest appears prone to abrupt shifts in climate regime, so altered forcing may result in an abrupt shift (e.g. not gradual). Such a shift seems plausible from the evidence repeating in the paleo record, e.g. mega-drought that, likely coupled with enhanced heat wave activity can lead to irreversible impacts on ecology as well as methods of human adaptation.
c. Impacts forcing devastating wildfires can result in land/ecological irreversibilities.
d. Snow transition, declining snowpack has the capacity to irreversibly change the hydrologic regime.
e. Change in the atmospheric vertical temperature structure (lapse rate) can influence lift and orographic precipitation.
f. A shift in the jet stream may be gradual but could have irreversible consequences on human time scales.
g. The massive change in the Arctic may be impacting the Southwest in currently unknown ways.
h. Asian dust and aerosols can have a lasting influence on precipitation.

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

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Figures

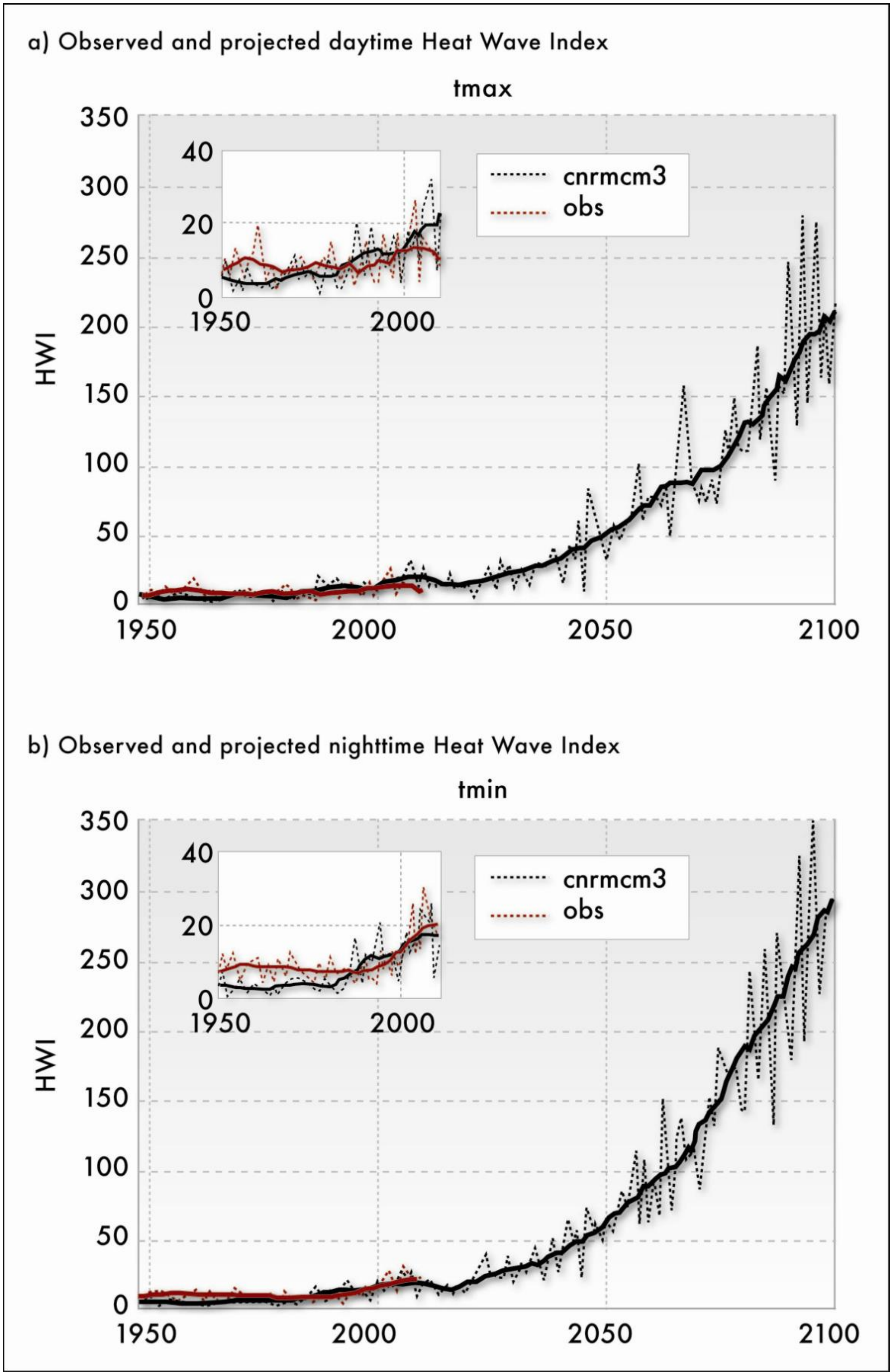
a) Observed and projected daytime Heat Wave Index
tmax
HWI
cnrmcm3
obs
350
300
250
200
150
100
50
0
40
20
0
1950
2000
1950
2000
2050
2100
b) Observed and projected nighttime Heat Wave Index
tmin
HWI
cnrmcm3
obs
350
300
250
200
150
100
50
0
40
20
0
1950
2000
1950
2000
2050
2100

Figure 7.1. The Southwestern Regional Summertime (May – September) Heat Wave Index (HWI) for Tmax (a) and Tmin (b). Solid line is the 5-year running mean. HWI values are in summertime accumulated °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 21st century projections (according to the SRES-A2 scenario) are shown from observations as well as from a GCM (CNRM-CM3) historical simulation and projection averaged over the Southwest.

(Original figure, data source provided in figure caption)

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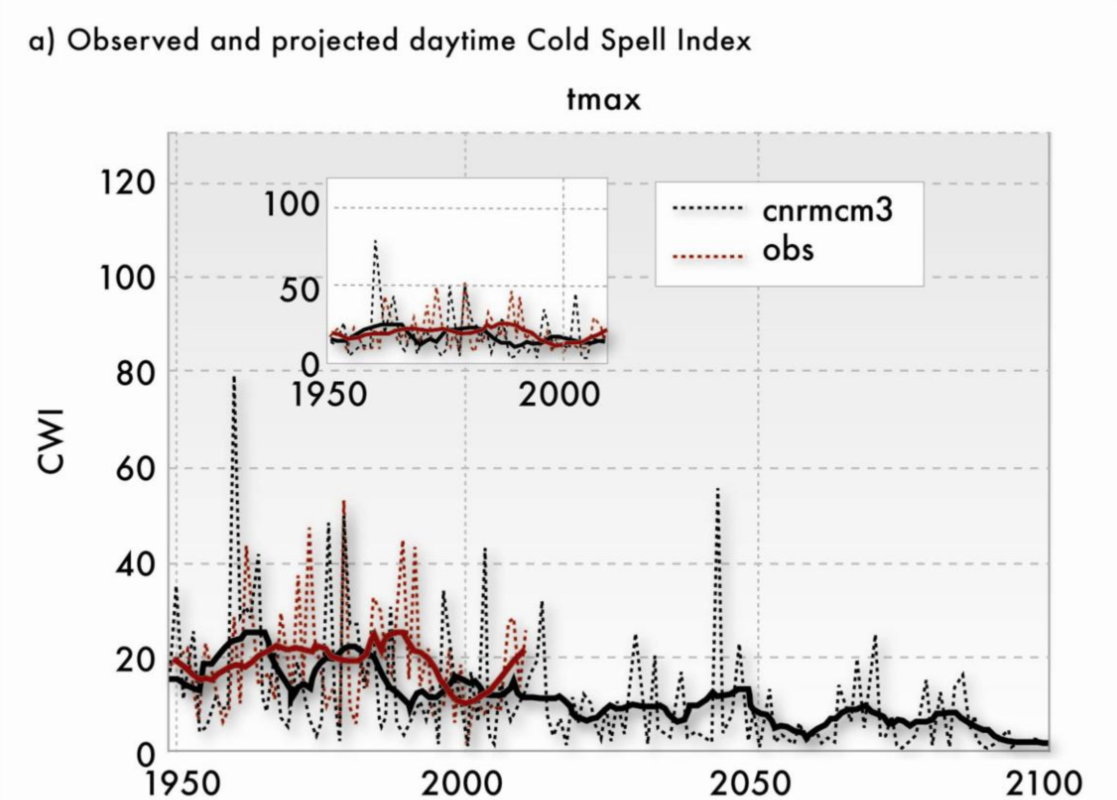

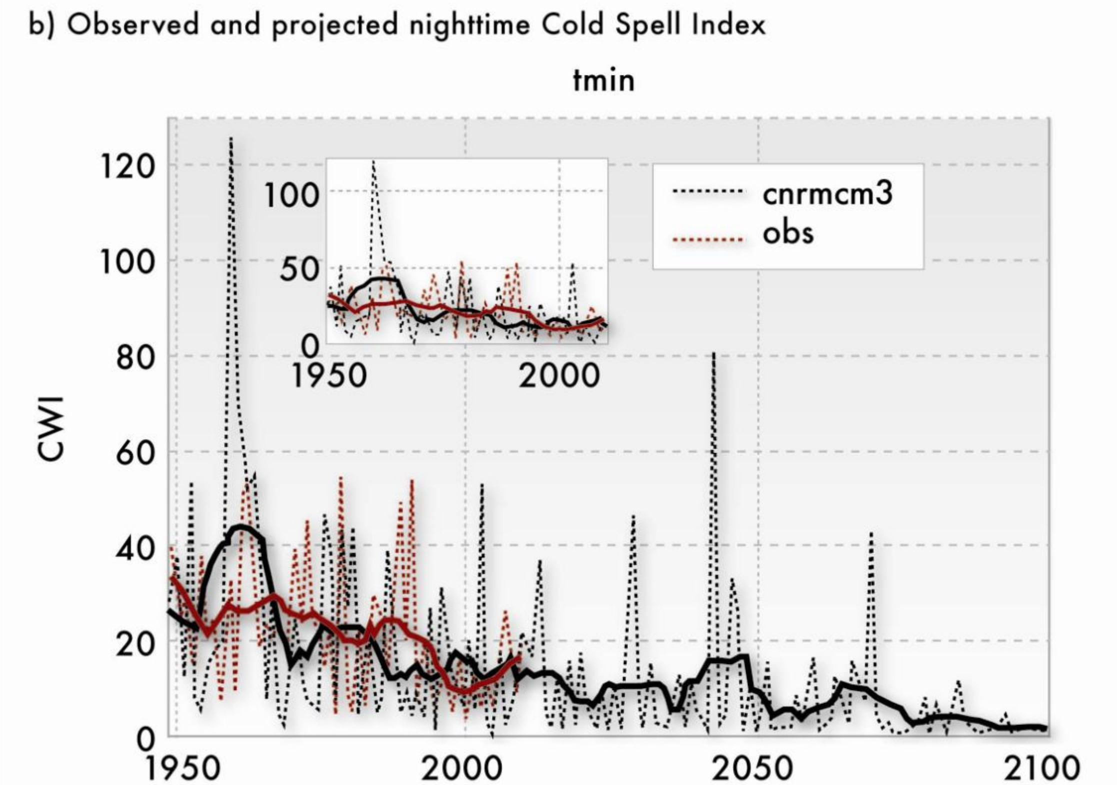

720

Figure 7.2. Same as Figure 7.1, but for Wintertime (November – March) Cold Spell Index (CSI) for Tmax (a) and Tmin (b).

(Original figure, data source provided in figure caption)

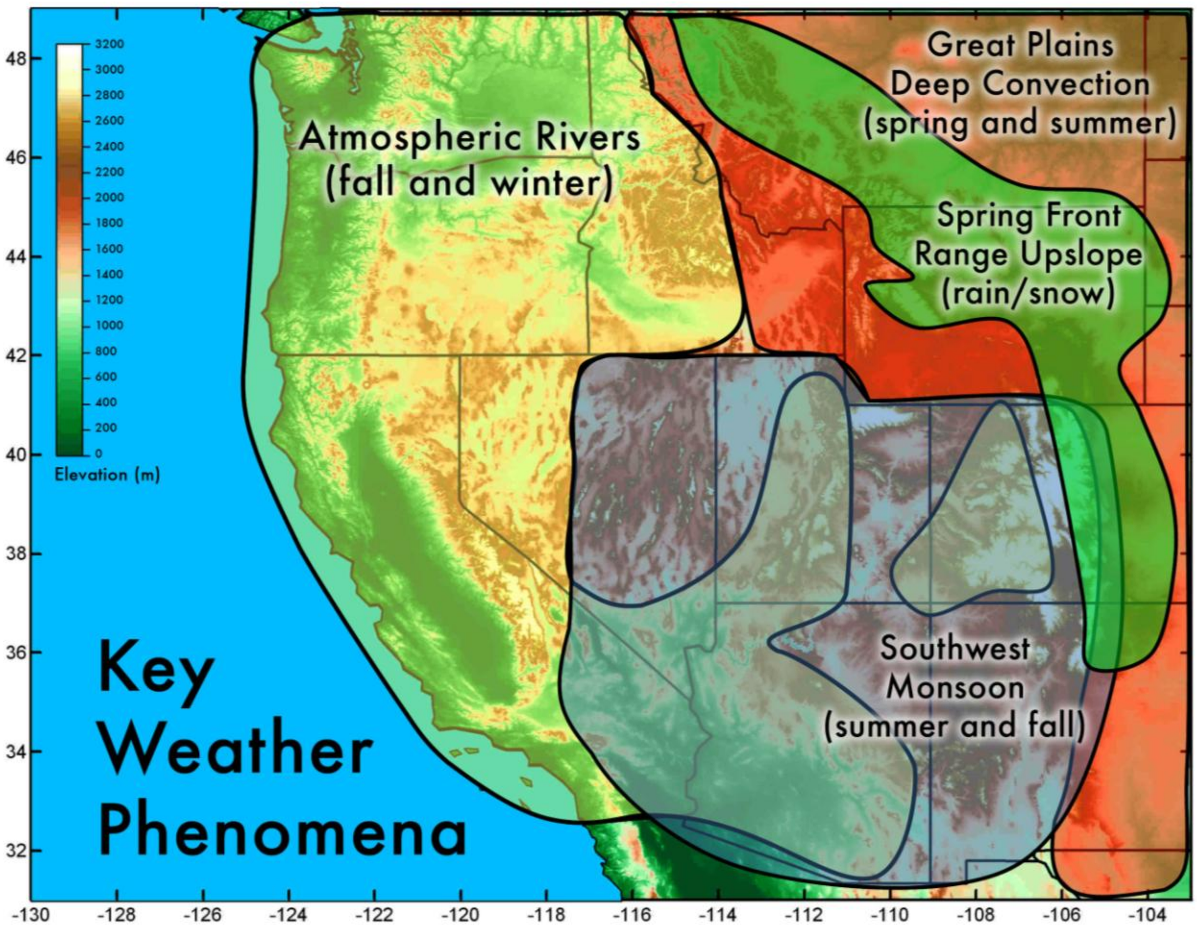

Figure 7.3. Schematic illustration of regional patterns on the primary weather phenomena that lead to extreme precipitation and flooding, while also contributing to water supplies (Guan et al. 2010, Dettinger et al. 2011), across the western US. From Ralph et al. (2011).

(Modified figure from previous publications, source information provided in caption)

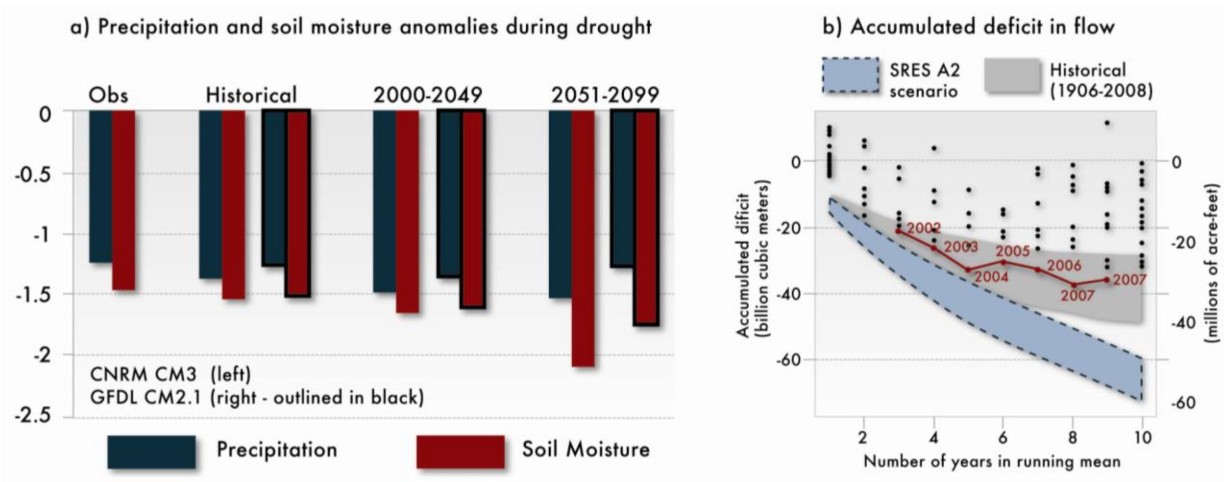

Figure 7.4. (Cayan et al. 2010, Figure 5). *Left panel:* Composite of water year precipitation (brown) and water year soil moisture (red) anomalies associated with extreme negative soil moisture anomalies for Southwestern US estimated from historical observation and simulated climate input from CNRM CM3 and GFDL CM2.1 GCMs SRES A2 emission scenario—historical period 1951-1999, early 21st Century 2000-2049 period, and late 21st Century 2050-2099 period. In this graph, precipitation and soil moisture composites are shown side by side. For climate model historical simulation and projection, composites from CNRM CM3 are shown first, and then from GFDL CM2.1, for each time epoch. *Right panel:* Accumulated deficit in flow (10^9 m^3, or billions of cubic meters [bcm]) on the Colorado River at Lees Ferry, relative to the mean flow observed over the period 1906-2008. Deficit is calculated in N-year running means (X axis). The 21st century drought is shown in red; other years are shown as black dots. Grey shading indicates where, 2/3rds of the time, the worst drought of the century should fall; the green hatched region shows the same thing for the end of this century, estimated from downscaled climate models. The right hand axis additionally shows values in millions of acre-feet (maf).

(Modified figure from previous publications, source information provided in caption)