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Natural Variability, Anthropogenic Climate Change, and Impacts on Water Availability and Flood Extremes in the Western United States

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CONTENTS

ABSTRACT The western United States (*the West*) undergoes considerable hydrologic variability in response to regional climate fluctuations that are termed *anomalous* by climate scientists because they depart from long-term average conditions. Regional climate fluctuations persist for seasonal to multidecadal durations, usually in association with larger-scale climate patterns. They play a crucial role in determining regional hydrologic variability by affecting trends of important drivers such as precipitation and temperature, sometimes by promoting particular blends of influential weather events. In California and other regions of the West, much of the annual precipitation is delivered by relatively few very large storms, which are usually atmospheric river events. Besides providing its water supply, these storms also drive year-to-year differences in annual precipitation totals, and cause most of the region's floods. During years or multiyear periods when these very large storms are absent, the region may fall into drought. Historically, droughts have had a strong presence in the West, but recent droughts have exhibited unusually warm temperatures, likely a harbinger of dry events in future decades when climate change threatens to make overall conditions even warmer. Other early signs of climate change that have been observed include declines of mountain snowpacks, which supply spring and summer runoff for the region. Along with warmer surface temperatures have come higher elevation freezing levels, more rain and less snow, and earlier snowmelt and earlier snowmelt runoff. Anthropogenic climate changes, which are projected to build as greenhouse gas concentrations rise, would result in further warming and amplified hydrologic changes. Global climate models suggest that precipitation may shift toward fewer overall wet days but somewhat increased extreme storm events. Further shifts in snowpack, runoff, and increased moisture loss to the atmosphere would reduce soil moisture and streamflows in summer. Annual discharge in arid western watersheds may decline, which would

exacerbate dry spells. Heavier winter precipitation events and higher elevation rain/snow transition zones would cause greater flood volumes in some mountain catchments by the latter half of the twenty-first century.

2.1 The Highly Variable Precipitation Regime

Shifting climate patterns have long been recognized as influencing seasonal, annual, and longer-term precipitation and other time-aggregated hydrologic measures. Increasingly, studies are revealing how certain patterns of climate variability may condition events on weather timescales, and how individual weather events can influence longer-term climate aggregates. In either case, there are associated effects on hydrologic variability. Thus, in this chapter, we emphasize linkages between climate patterns and weather events, with attendant impacts on terrestrial hydrology. Our overall geographic focus is the western conterminous United States (hereafter "the West"), a region noted for its extreme weather and hydroclimatic variability. This variability is structured around seasonal precipitation regimes. The heaviest precipitation season varies across the western United States, peaking in the winter season along the West Coast, shifting to a spring or summer maximum in the lee of the Rocky Mountains and on the High Plains and to a double-peaked pattern in areas strongly affected by the southwestern summer monsoon. It is important, however, that cool-season precipitation plays an unusually important role in determining hydrologic variability in most of the West, because in most locations, it provides a considerable fraction of the annual total and because much of the precipitation in the warm season simply evaporates. Cool-season precipitation in the Sacramento/San Joaquin watershed explains about 95% of the variance in annual flow. In the Columbia River Basin, it explains about 82% of the variance in annual flow, and even in the Colorado River Basin, it explains 57% of the variability in annual flow (Westerling et al. 2008).

"In the Columbia River Basin"—Edit OK?

Weather and climate phenomena also cause substantial irregular precipitation variability across all timescales (Figure 2.1). Strong seasonality and interannual and longer-term

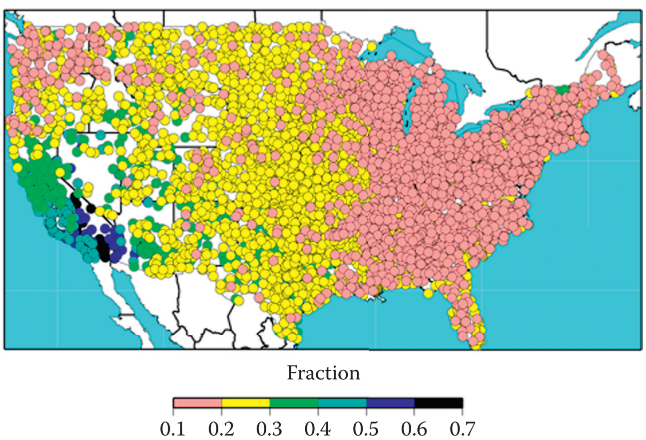

FIGURE 2.1
Coefficients of variation of water year precipitation total at long-term monitoring stations across the conterminous United States, water years 1951–2008. (From Dettinger, M.D. et al., *Water*, 3(2), 445–478, 2011.)

variability are especially pronounced in California, a region whose fluctuating hydroclimate has been the subject of many research investigations, in particular, several by the authors. Thus, a number of this chapter's examples are drawn from the California region.

The coastal states' strongly seasonal precipitation regime derives from the annual cycle of atmospheric circulation over the North Pacific. In late spring, North Pacific storminess subsides and shifts poleward so that conditions along the West Coast are relatively dry throughout summer and early fall. In fall, westerly winds and storminess begin to intensify over the North Pacific, and by winter, these features have migrated southward. These Pacific storms propagate into western North America, albeit sporadically and to varying degrees in different years.

Climate patterns associated with anomalously low or high precipitation over the region have Pacific Ocean roots but extend into North America (e.g., Klein and Bloom 1987; Cayan and Peterson 1989). Changing patterns of anomalous precipitation over the West Coast are modulated seasonally and also quite strongly affected by several important modes of Pacific and North American climate variability that operate at different timescales (Barnston and Livezey 1987). Some of these modes have a strong tropical Pacific influence. These include intraseasonal fluctuations associated with the Madden–Julian Oscillation (MJO, the most important mode of tropical intraseasonal variability); the El Niño/Southern Oscillation (ENSO), Earth's dominant seasonal-to-interannual climate variability mode; and longer-term shifts in sea surface temperature (SST) and atmospheric circulation patterns associated with the Pacific Decadal Oscillation (PDO).

- The MJO is an equatorial, propagating pattern of anomalous rainfall, cloud cover, pressure, and wind, occurring mainly in the Indian and Pacific Oceans (e.g., Wheeler and Hendon 2004). It is an eastward propagating coupled ocean–atmosphere mode, and when it reaches certain locations along the tropical corridor, it produces remote atmospheric patterns that can reinforce or divert regional storminess at particular locations along the West Coast (Mo and Higgins 1998). Please confirm whether this is Mo and Higgins 1998a or b.
- ENSO is a coupled ocean-atmosphere pattern of climate variability that features variations in SST over the tropical eastern Pacific Ocean (Sarachik and Cane 2010). ENSO oscillates irregularly at timescales of a few to several years between a warm phase, called El Niño and a cool phase, called La Niña. Although it is seated in the tropical Pacific, ENSO extremes are known to produce anomalous weather and climate patterns in many regions of the globe. When in its warm (El Niño) phase, it affects the winter storm track and intensity over the North Pacific and tends to produce drier-than-normal conditions in the Pacific Northwest and wetter-than-normal conditions in the Southwest (Redmond and Koch 1991; Cayan et al. 1999).
- The PDO is an irregular oscillation of broad-scale North Pacific SSTs, whose warm phase has positive (warmer-than-average, El Niño–like) anomalies in the eastern North Pacific and negative (cooler-than-average, La Niña–like) anomalies in the central and western North Pacific (Mantua et al. 1997). The oscillation from warm to cool and back to warm phases is irregular but happens over time periods of 10–40 years, and there may be shorter-period excursions in between.

ENSO teleconnections to North American and West Coast weather appear to be conditioned by lower-frequency variability (Gershunov and Barnett 1998). For example, greater and broader-scale precipitation anomalies along the West Coast are observed in Los Niños when the PDO is also in its warm phase, having anomalously warm SSTs in the eastern North Pacific and anomalously cool SSTs in the central and western North Pacific. However, MJO, ENSO, and PDO are not the only contributions to a broad mix of western US precipitation patterns. Precipitation occurs in response to many synoptic patterns, which may be favored or discouraged by different climate patterns (e.g., Weaver 1962; Mo and Higgins 1998; Cayan et al. 1999; Ralph and Dettinger 2011; Guan et al. 2013; Jones and Carvalho 2014). Shifts, even subtle ones, in the center of action of weather and climate patterns produce important changes in the distribution of precipitation over the coast and interior western United States (Klein and Bloom 1987; Cayan and Peterson 1989; Dettinger et al. 1998; Mo and Higgins 1998b).

Please confirm whether this is Mo and Higgins 1998a or b.

In California, the narrow window of storminess (typically between November and March) that supplies most of the year's precipitation is heavily affected by climate fluctuations. In other areas, such as the eastern part of the United States, each season has the potential to contribute significantly to the annual total at that location. But in California, the warm-season months are generally so dry that there is little chance to compensate for a dry winter. On the other hand, if storm conditions are very active during the winter season, the annual supply and generally other hydrologic measures such as annual discharge will be in excess of the long-term average. California's annual precipitation totals routinely vary from as little as 50% to greater than 200% of long-term averages, greater interannual variability than at than most other locations in the United States (Figure 2.1).

Among the winter storms that occur in a given year, the presence or absence of very large storms is a strong determinant of that year's overall precipitation and is a major source of the year-to-year variability observed at each location. Considering the entire region from the Rocky Mountains to the West Coast, large storms occur throughout the year, but in the far West, the largest storms are heavily weighted toward the winter season (Figure 2.2a). Somewhat surprisingly, the heaviest precipitation totals during the largest winter storms, in favored moist locations on windward slopes in the far West, are comparable to most of the heaviest tropical storm precipitation totals from Gulf Coast US locations (Figure 2.2b) (Ralph and Dettinger 2012). The disproportionately large contribution of a few large storms to annual precipitation is especially pronounced in California, where an impressive fraction of the year's precipitation and also its interannual variation arises from the relatively small number of large storms (Figure 2.3). Many of the floods and much of the water supply in the far western states are attributable to "atmospheric river" (AR) storms (e.g., Ralph et al. 2006, 2013; Neiman et al. 2008, 2011, 2013; Leung and Qian 2009; Dettinger et al. 2011; Ralph and Dettinger 2012; Cordeira et al. 2013; Guan et al. 2013). If particularly unfavorable large-scale patterns persist, and a few large storms happen to bypass California in a given winter, precipitation totals are much reduced, often leading to drought (Dettinger and Cayan 2014).

As underscored by recent dry spells, drought is a familiar occurrence in the West. In the Southwest United States, several intermittent dry spells have been described, both in the instrumental and in the preinstrumental record (e.g., Woodhouse et al. 2010; Cook et al. 2014). The areal extent of drought over the Southwest during 2001–2010 was the second largest observed for any decade from 1901 to 2010 (Hoerling et al. 2013). Streamflow totals in the four major drainage basins of the Southwest were 5–37% lower during 2001–2010 than their average flows in the twentieth century. Persistent dryness in the Colorado Basin and more recently in California and Nevada has occurred during the last two decades (MacDonald 2010; Borsa et al. 2014; California Department of Water Resources 2015).

Shukla et al. (in review) demonstrate that the high variability and unusual probability distribution of precipitation in California in comparison to other regions of the conterminous United States translates to some important drought-related properties: California

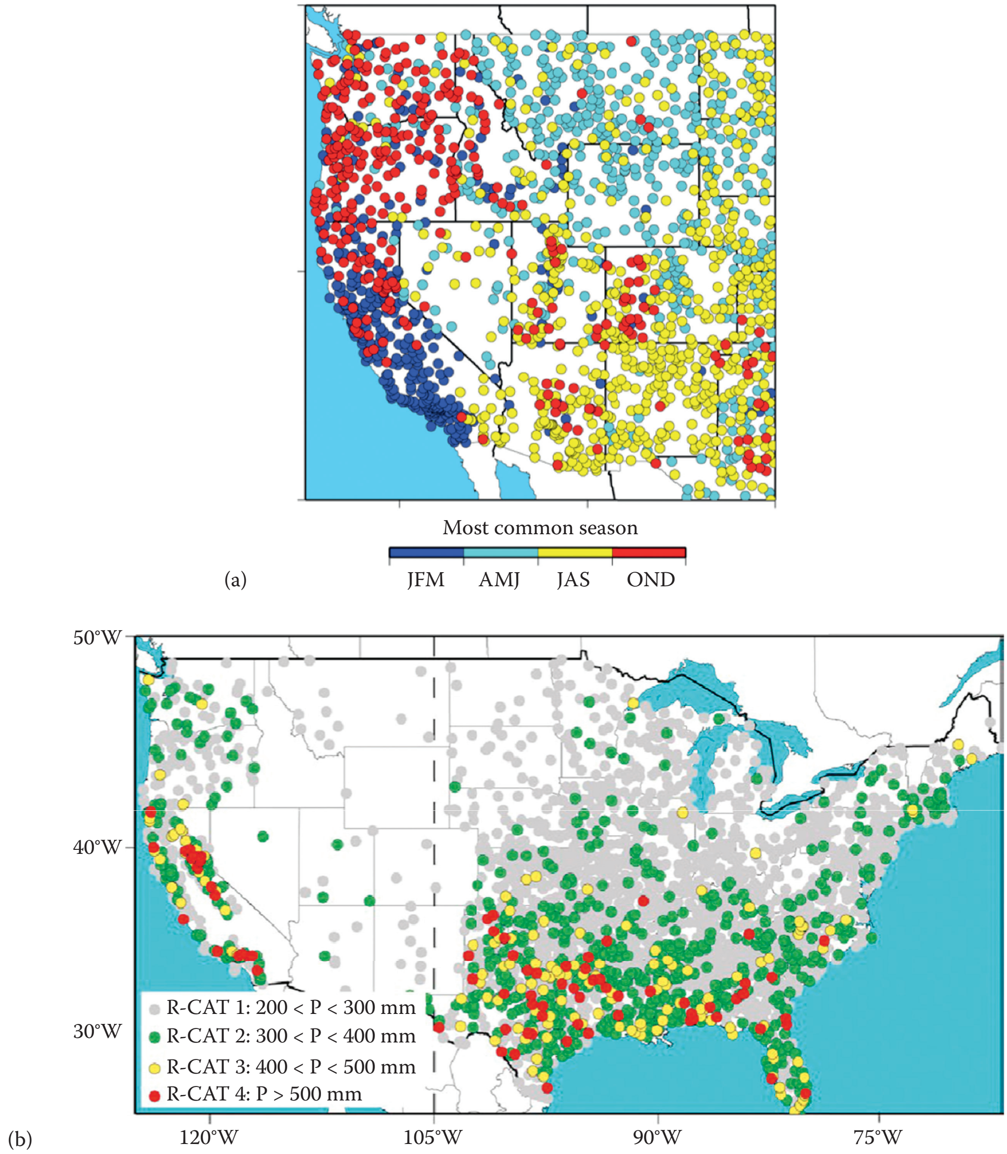

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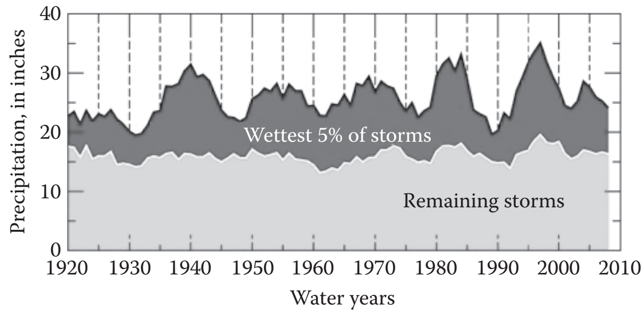
FIGURE 2.2
(a) Seasonality of extreme precipitation events based on daily precipitation totals from long-term monitoring stations (dots) with records for 30 years or longer. The dots are color coded, corresponding to the season when more of the top 10 daily precipitation events occurred than any other season. (From Ralph, F.M. et al., *J. Contemp. Water Res. Educ.*, 153(1), 16–32, 2014.) (b) Maximum 3-day precipitation totals at 5877 COOP stations in the conterminous United States during 1950–2008. Each site used here had to have at least 30 years of records. (From Ralph, F.M., and Dettinger, M.D., *Bull. Am. Meteorol. Soc.*, 93, 783–790, 2012.)

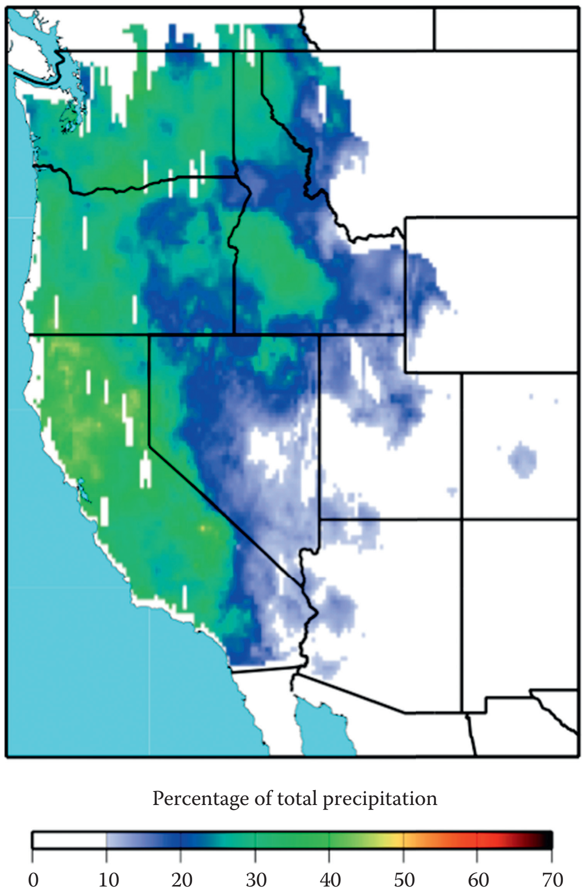
If “COOP” is an abbreviation, please define.

has lower precipitation amounts (relative to their overall mean values) for a given low percentile level yet higher percentile levels for a fixed 75% of normal precipitation amount, for example.

Drought indicators describing the beginning of drought or the recovery from drought are needed by decision makers and the public to detect and assess drought conditions



(a)



(b)

FIGURE 2.3
(a) Five-year moving averages of contributions to water year precipitation from upper 5% (dark gray) and remaining 95% (gray) daily precipitation events in San Francisco Bay delta catchment. (After Dettinger, M., and Cayan, D.R., *San Francisco Estuary Watershed Sci.*, 12(2), 7 pp., 2014.) (b) Contributions to yearly total precipitation from wet-season (November–April) days on which atmospheric rivers made landfall on the West Coast. From 1/8° gridded precipitation based on cooperative weather stations, water years 1998 through 2008. (From Dettinger, M.D. et al., *Water*, 3(2), 445–478, 2011.)

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and take action to reduce impacts (Steinemann et al. 2015). Dettinger (2013) found that droughts often end more abruptly than they begin; these sharp endings result from the arrival of an especially wet month via a few very large storms. A survey of the storm types that occurred during "drought-busting" months along the West Coast revealed that a major portion of the heavy precipitation events were produced by landfalling AR events, with the remainder resulting mostly from other forms of persistent low-pressure systems.

Characteristics of individual storms matter greatly in determining the amount and form of the annual supply of precipitation in the West. Ralph et al. (2013) studied landfalling AR storms striking windward slopes of California's coastal mountains and found that the amount of precipitation is governed largely by one primary measure—the amount of moisture transport in the upslope direction. Further, the duration of AR storms has a disproportionate impact on runoff—a doubling of AR duration produced nearly six times greater peak streamflow and more than seven times the storm total runoff volume. Storm tracks and topographic structure in the far West have a strong effect on precipitation downstream, whereby the moisture transport that fuels heavy precipitation events in the Intermountain West is fed through notches in coastal mountains including the Cascade, Sierra Nevada, and Peninsular Mountains of the West Coast (e.g., Alexander et al. 2015; Rutz et al. 2015). Antecedent conditions also matter—for example, when antecedent soil moisture was less than 20%, even heavy rainfall did not lead to significant streamflow (Ralph et al. 2013)—another way in which longer-period patterns are involved in governing hydrologic responses.

Historical records indicate that the heaviest daily precipitation in Sierra Nevada locations occurs during relatively warm storms (Cayan and Riddle 1992; Pandey et al. 1999), and the highest rainfall rates occur when snow lines are highest (White et al. 2010). Warmer storms generate higher runoff—in assessing snow levels and runoff in four different watersheds in California, White et al. (2002) found that a 600 m rise in the freezing level tripled the peak outflow in three of the four basins. Along the West Coast, many of these relatively warm heavy precipitation events occur during AR events (Ralph and Dettinger 2011).

A general pattern across the West is that most of the water supply is derived from precipitation falling in mountainous higher-elevation terrain. In comparison to low-lying upwind locations, precipitation amounts in higher-elevation windward slopes are enhanced by topographic lifting of moist air (Pandey et al. 1999), but due to variations in meteorological conditions such as wind speed and direction, humidity, and stability, the effect of this mechanism differs from case to case. Dettinger et al. (2004), studying orographic enhancement of winter storm precipitation in the Sierra Nevada, found that the orographic ratio (OR) between higher- and lower-elevation precipitation gauges ranged from nearly equal amounts of precipitation to 10 or more times as much precipitation at the higher altitudes. Strongly orographic storms in the Sierra Nevada were found to most commonly have winds that transport water vapor across the range from a nearly westerly direction, which contrasts with wind directions associated with the overall wettest storms, whose wind directions were somewhat more southerly. High-OR storms were found to be somewhat warmer than storms with very low OR values, yielding storm-time snow lines 150–300 m higher during high-OR storms. In the Sierra Nevada, La Niña winters have produced more storms with high ORs than have El Niño winters. Winters during negative (La Niña–like) PDO conditions tend to yield slightly more storms with large ORs than do positive-PDO winters. One important atmospheric dynamics phenomenon that affects the OR is the presence or absence of a barrier jet, either coastal (e.g., Neiman et al. 2002) or the Sierra barrier jet (e.g., Lundquist et al. 2010; Neiman et al. 2014). This occurs because the barrier jet is a virtual obstacle that displaces upward air motion (and thus condensation and precipitation) at a position "upwind" from the actual terrain (e.g., Neiman et al. 2002; Kingsmill et al. 2013).

Recently, Luce et al. (2013) found that, in the Pacific Northwest, a spate of diminished westerly winds in recent decades have likely reduced orographic precipitation enhancement in higher elevations, and thus contributed to reduced snowpack and declining streamflow. This mechanism has not previously been emphasized but warrants consideration, along with regional changes in temperature and other mechanisms, in explaining observed hydrologic changes as well as anticipating future changes.

2.2 Temperature-Related Changes

Climate warming in recent decades has affected multiple aspects of the hydrologic system in the West (e.g., Mote 2006; Barnett et al. 2008; Hoerling et al. 2013). Although temperature instruments, especially in mountains, have generally not been installed for purposes of tracking climate changes, a widespread network of stations indicate a broad footprint of warming surface temperatures over the West (e.g., Bonfils et al. 2008). The upward trend in the region has roughly paralleled the warming of global average surface temperatures (Figure 2.4, lower), which have risen steadily since the late 1970s at a rate of +0.15°C to +0.20°C per decade (Hansen et al. 2010). Hoerling et al. (2013) reported that annual averaged temperatures over the Southwest for 2001–2010 were 0.8°C warmer than the 1901–2000 average, noting, "Key features of a warming Southwest appear robustly across various data sets and methods of analysis" (p. 76), and "The period since 1950 has been warmer in the Southwest than any comparable period in at least 600 years, based on paleoclimatic reconstructions of past temperatures" (p. 75).

Greater warming has occurred in the nighttime than in the daytime (Bonfils et al. 2008), and temperatures during California heat waves have become increasingly expressed in warmer nighttime temperatures than in the past (Gershunov et al. 2009). Looking throughout the West, warming has occurred in each season (e.g., Cordero et al. 2011). Importantly, wet days have warmed as much or more than dry days during the interval from 1949 to 2004, which helps to explain a trend toward lower fractions of snowfall relative to rainfall in mountain settings across the West (Knowles et al. 2006). One key aspect of the warming in recent years can be described as a shift toward earlier warm weather—Regonda et al. (2005) found that, over 1950–1999, the date of earliest occurrence of a persistent (7 days or longer) warm spell has advanced by 5 to more than 15 days earlier in many parts of the West.

Warming at the surface has been accompanied by changes in the altitude of freezing in the atmosphere, which in recent years has been about 200 m higher than during 1950–1975 (Figure 2.4a). The freezing altitude influences climate and hydrologic structure in multiple ways, including the elevation of the rain/snow transition, frozen versus thawed ground, the duration of snowpack, and various ecological functions.

Drought has been a prominent feature of climate in the West in the past two decades, and there is also plentiful evidence of dry spells in the historical instrumental record and well before that. Paleoclimatologists find widespread evidence of drought in sources ranging from tree-ring widths (Woodhouse et al. 2010) to lacustrine and riverine deposits to submerged trees or buried stumps. This includes several-decades-long and extremely severe "megadroughts" during the past 2000 years (Stine 1994). However, a distinguishing feature in recent droughts has been the occurrence of unusually warm conditions during a period

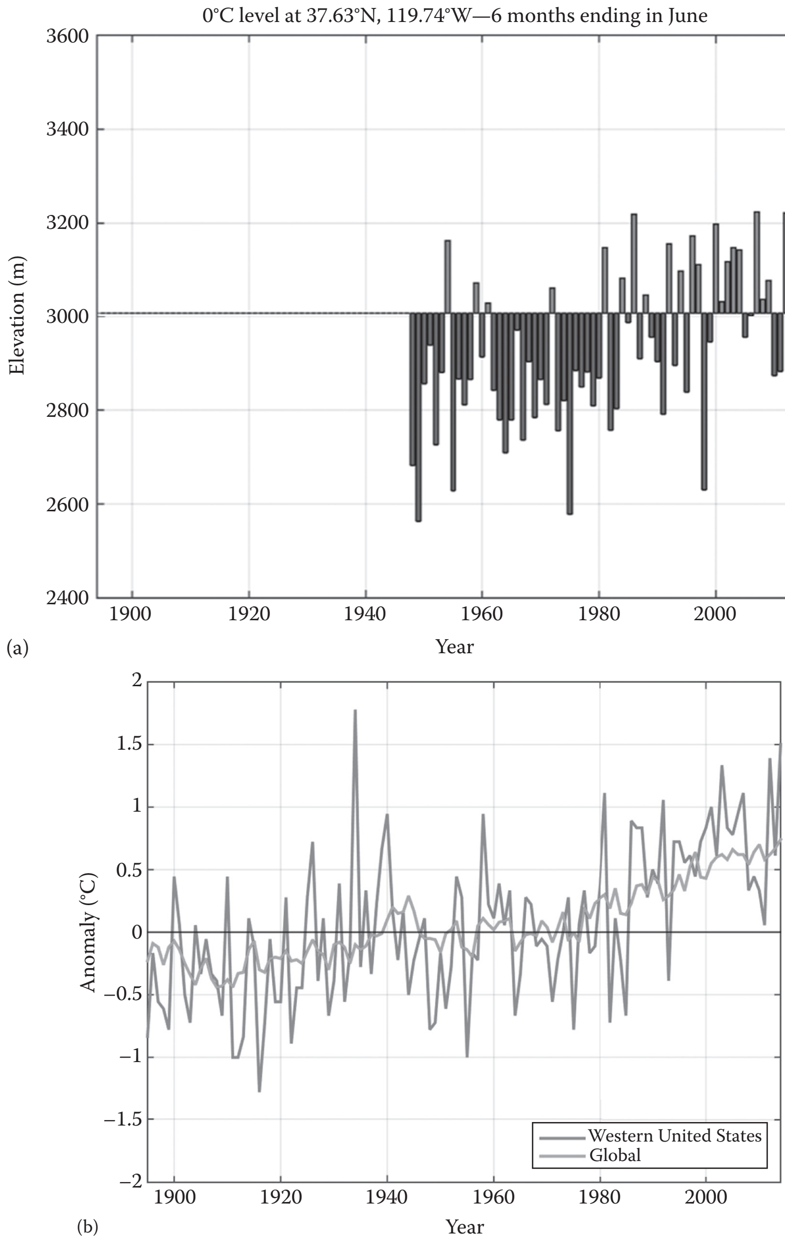

FIGURE 2.4
(a) January–June average freezing level (meters) in the central Sierra Nevada region. (From North American Freezing Level Tracker, Western Regional Climate Center, http://www.wrcc.dri.edu/cwd/products/). The baseline indicates 1981–2010 mean. (b) Global (light gray) and western US (dark gray) annual surface temperature anomalies between 1895 and 2014. The anomalies are based on the respective 1901–2000 averages. The global anomaly data set is obtained from NOAA NCDC. The western US anomaly data set is from DRI WRCC's WestMap tool.

If "NCDC", "DRI", and "WRCC" are abbreviations, please define.

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that is also unusually dry, e.g., in the Southwest (MacDonald 2010) and in California (Seager et al. 2014; California Department of Water Resources 2015). Griffin and Anchukaitis (2014) determined that the recent California drought registers as the strongest in the last 1000 years, to a great degree because of the precipitation deficit but also because of the exceptional warmth during recent winters (Figure 2.4) (Seager et al. 2014; Bond et al. 2015).

"the recent California drought"—Instead of "recent", please mention the date/time frame.

Other processes also have contributed to hydrologic changes. For example, wind-borne dust deposition in western watersheds has seen a several-fold increase since before the nineteenth century due to human activities (Neff et al. 2008). This darkens snow surfaces and may hasten melt-out of mountain snowpack by several days to weeks (e.g., Painter et al. 2010). Aerosols, from both remote and regional sources, may also be involved through varying effects on cloud seeding and cloud droplet concentrations (Rosenfeld et al. 2008; Ault et al. 2011; Creamean et al. 2013). Although many different mechanisms are likely contributing to the hydrologic changes observed in recent decades, increased winter and spring temperatures are clearly key factors.

Recent hydroclimatic changes in the West can be seen as part of a larger shift in climate taking place over North America as a whole. Since 1950, North America has warmed considerably (Hansen et al. 2010), and remotely sensed observations reveal a large-scale decline in winter and spring snowpack, especially in Canada (Gan et al. 2013). Consistent with this continental decline, the West has experienced a marked increase in temperature, and substantial loss of spring snowpack has occurred in most of its mountainous terrain. These changes, seen from a series of manual snow course observations, shorter series of automated snow sensors, and hydrologic model estimates, have been described in a growing body of research (e.g., Roos 1987; Cayan et al. 2001; Mote et al. 2005; Regonda et al. 2005; Peterson et al. 2008; Pierce et al. 2008; Clow 2010; Kapnick and Hall 2012). Using 1950–1997 data, Mote et al. (2005) removed effects of variable precipitation and found that rising temperatures caused April 1 snow water equivalent (SWE) to decline by more than 30% at sites across the West, where average winter temperatures are relatively warm (December to February temperatures greater than −5°C). Most studies of the reductions of spring snowpack in the West have identified the warmer winters and springs after the mid-1970s as the key driver (e.g., Dettinger and Cayan 1995; Mote et al. 2005; Regonda et al. 2005; Knowles et al. 2006; Mote 2006; Pierce et al. 2008; McCabe and Wolock 2009; Clow 2010; Kapnick and Hall 2012). Associated effects of warming on hydrologic variables include a reduction in the fraction of precipitation falling as snow, an increase in the fraction falling as rain (Figure 2.5) (Knowles et al. 2006), and a shift to earlier flows in snow-dominated rivers from western Canada southward to the southern Rocky Mountains, with streamflow shifted several days earlier than was observed the 1950s and 1960s, as illustrated in Figure 2.6 (Dettinger and Cayan 1995; Cayan et al. 2001; McCabe and Clark 2005; Regonda et al. 2005; Stewart et al. 2005). Furthermore, the fraction of streamflow occurring during winter and early spring has increased (Dettinger and Cayan 1995; Stewart et al. 2005), and the date of peak SWE has shifted to earlier in the season (Hamlet et al. 2005; Kapnick and Hall 2012).

McCabe and Wolock (2009) demonstrated that a West-wide decline in spring SWE is related to temperature variation over the region, at both interannual and decadal timescales, and that reductions in SWE since the 1980s have only partially been counteracted by increases in precipitation. These winter and spring temperature changes are tied, partly, to large-scale atmospheric circulation shifts in the Pacific and North America region (Dettinger and Cayan 1995; Abatzoglou 2011; Johnstone and Mantua 2014), but it is unclear to what extent such circulation shifts may also reflect anthropogenic climate change mechanisms (Hartmann 2015).

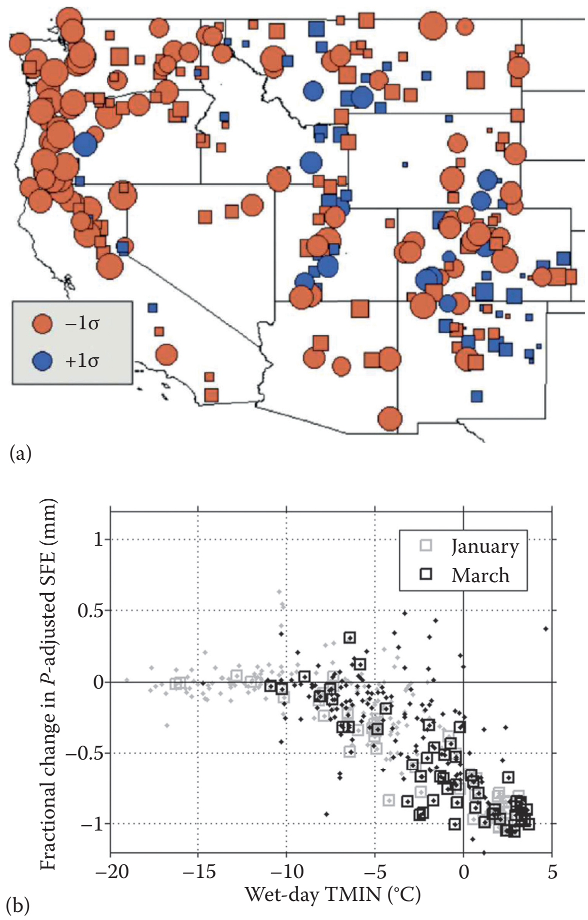

FIGURE 2.5
(a) Linear trends in precipitation falling on snowy days as a fraction of total precipitation (snowfall equivalent/precipitation total [SFE/P]) during November–March 1949–2004: red symbols indicate negative trends (decreasing snowfall fraction), and blue indicates increasing fractions; symbol radius is proportional to magnitude of change over record period, measured in standard deviations of the detrended time series as indicated; circles indicate high trend significance ($P < .05$), and squares indicate lower trend significance. (b) SFE changes (1949–2004) versus average minimum temperature on wet days (TMINw) for January and March. SFE change has been adjusted to remove changes that result from precipitation change over the period. The greater number of very cold (TMINw < −10°C) stations in January compared to March results in less widespread SFE/P declines in January. Statistically significant ($P < .05$) trends are highlighted with squares. (From Knowles, N. et al., *J. Clim*., 19, 4545–4559, 2006.)

The warmer parts of mountain catchments, primarily low and mid elevations, have exhibited the greatest losses of spring snowpack (e.g., Mote 2006; Kapnick and Hall 2012). However, even the colder, higher elevations of Colorado have exhibited earlier snowmelt, by 2–3 weeks, as shown by Clow (2010), who determined snowmelt directly from a network of snow sensor records from 1978 to 2007. Reductions in accumulated spring snowpack that have occurred were found to be caused, mostly, by losses in the mid to latter portion of the snow accumulation season, when daytime temperatures rise above freezing in most elevations (Kapnick and Hall 2012; Pederson et al. 2013). Hamlet et al. 2005 used model simulations to demonstrate that most of the region-wide decline of spring SWE in the West

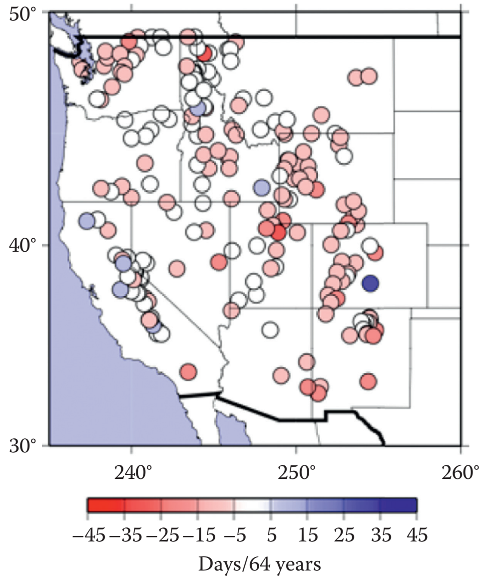

FIGURE 2.6
Change in streamflow timing (days/64 years) as measured by linear trend over 1950–2013 of center of mass (date when half of the annual streamflow has been discharged) for snowmelt-dominated streams in the West. (After Stewart, I.T. et al., *J. Clim.*, 18, 1136–1155, 2005.)

in recent decades has been associated with warming temperatures, rather than changes in precipitation. McCabe and Wollock (2009), in a different modeling exercise, showed that anomalously warm temperatures since about 1980 have produced lower spring snowpack than would otherwise have occurred if temperature had been closer to long-term averages.

If recent warming-related "changes" are simply multidecade fluctuations, they could be expected to revert to cooler conditions as in previous decades, but evidence is mounting that indicates that anthropogenic effects are playing a role. To determine the extent to which recent changes are caused by anthropogenic climate change, efforts have focused on questions of *detection* and *attribution*—in other words, detection of changes that are unusually large in comparison to historical variation and attribution of those changes to natural or man-made sources. Recent studies have employed multicentury natural climate "control" simulations along with observational time histories to address these questions. Results indicate that the recent warming in North America has been caused, to some degree, by the continuing accumulation of greenhouse gases (GHGs) and other human impacts on the climate system (Karoly et al. 2003; IPCC 2013).

In a regional detection and attribution effort that focused on water resource–related changes specific to the West, Bonfils et al. (2008) assessed observed (1950–1999) temperature trends, Pierce et al. (2008) studied changes in spring SWE as a fraction of precipitation (SWE/P) over nine mountainous regions in the West, and Hidalgo et al. (2009) investigated shifts in streamflow timing in the combined flow of the Sacramento and San Joaquin Rivers, the Colorado River at Lees Ferry, and the Columbia River at the Dalles. Combining these measures, Barnett et al. (2008) considered coincident changes in the temperature, spring snowpack, and river discharge timing. These studies indicated that warming-associated changes, including hydrological measures, are *unlikely*, at a high statistical confidence, to have occurred due to natural variations. Furthermore, they concluded that changes in the climate due to anthropogenic GHGs, ozone, and aerosols are causing part of the recent changes. Importantly, precipitation variations tend to be dominated by natural variability (e.g., Hoerling et al. 2010), so detection of long-term changes that might have anthropogenic drivers is unlikely to emerge for many decades (e.g., Pierce and Cayan 2013).

Detection and attribution results were reinforced and broadened by Das et al. (2009), who investigated changes in recent decades across the West, finding that the observed winter temperature and several hydrologic measures have undergone significant trends over considerable parts (37–89%, depending on measure) of the snow-dominated landscape. These observed trends are not likely to have resulted from natural variability alone, as gauged from the distribution of trends produced from a long control simulation. Significant trends toward lesser snow accumulation and earlier runoff were found in a relatively large portion of the Columbia River Basin and to a lesser extent in the California Sierra Nevada and in the Colorado River Basin. The greatest trends occurred in regions with a mean spring temperature close to freezing, where warming might be most effective in changing snow to rain and in causing earlier melt of accumulated snowpack. Das et al. (2009) found that nearly all of the changes that registered as statistically significant were in the sense that is consistent with warming (not cooling) conditions—e.g., earlier runoff and diminished spring snow accumulation.

2.3 Projected Climate Changes

Climate changes caused by projected greenhouse-forced warming would have growing impacts on western US water resource management and distribution (e.g., Barnett et al. 2005; Christensen and Lettenmaier 2007; Udall and Bates 2007; Cayan et al. 2008). A major concern is that more of the annual flow will occur in winter and much of the water in the West that is stored as snow in winter and spring will melt earlier. Limited reservoir capacity and the need for flood control storage makes it difficult to store increased winter runoff, and earlier snowmelt in spring reduces summer inflows to reservoirs. Another concern is that climate change may exacerbate various forms of extreme events, including both droughts and flood flows.

In fact, increasing hydrologic changes over many parts of the West will probably occur (e.g., Lettenmaier and Gan 1990; Barnett et al. 2005; Overpeck et al. 2013; Lukas et al. 2014) because GHGs are almost certain to continue to accumulate in the atmosphere, making further warming highly likely (IPCC 2013). Under both moderate and relatively high (RCP 8.5) emissions,* surface temperatures projected by an ensemble of downscaled global climate model (GCM) simulations rise by 1°C or more over recent historical averages, by the middle of the twenty-first century (Figure 2.7). Emissions scenarios, of course, matter greatly, but in the first half of the twenty-first century, the warming produced by the high-emissions scenario is not much greater than that of the lower-emissions scenario. By the latter half of the twenty-first century, considerably higher GHG concentrations under the higher-emissions scenario are projected to lead to increasingly greater warming than

If "RCP" is an abbreviation, please define at first mention.

* For its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) used multiple climate models to estimate the effects of four distinct Representative Concentration Pathways (RCPs). These were constructed by varying assumptions about demographic, technological, economic, and land-use trends to achieve different projected levels of radiative forcing by the year 2100 (about 2.6, 4.5, 6.0, and 8.5 W/m^2).

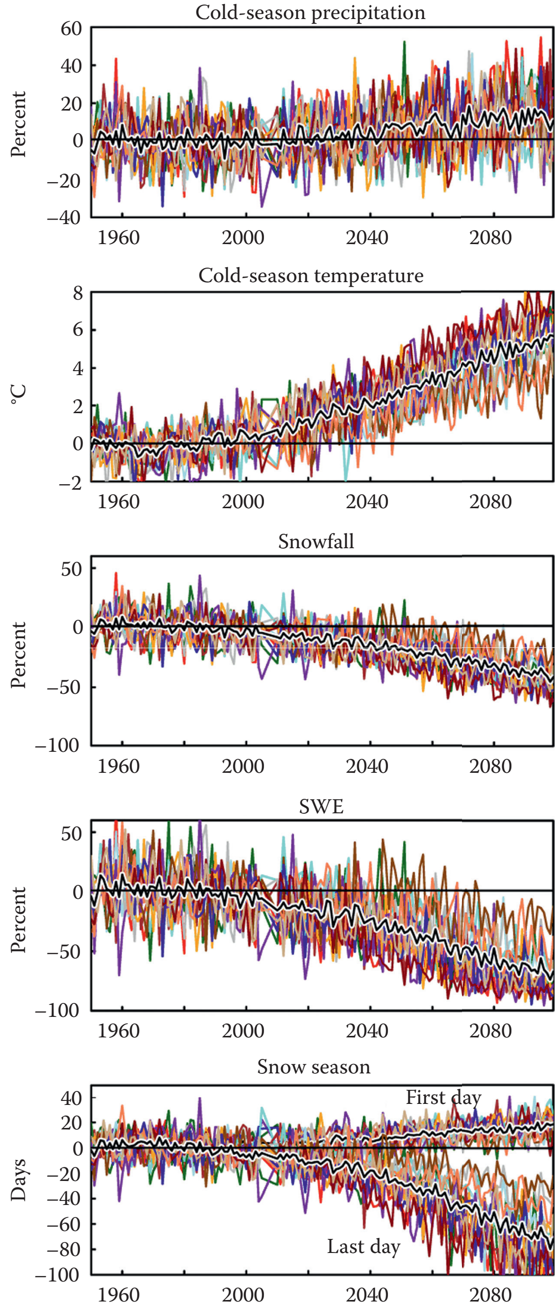

FIGURE 2.7
Observed and projected changes in cold-season (October–March) precipitation and temperature, snowfall, SWE, and the length of snow season from 1950 to 2100, for mountain snow regions of the West. From VIC hydrologic model simulations based upon an ensemble of 13 downscaled RCP 8.5 CMIP5 GCM projections. The bottom figure shows the changes of both the first day (getting later in the fall or early winter) and the last day (getting earlier in the spring) of the snow season. Colors indicate each of the 13 GCMs included in the ensemble so that color envelope shows intermodel spreads. Black contours indicate the multimodel ensemble means. (From Pierce, D.W., and Cayan, D.R., *J. Clim.*, 26, 4148–4167, 2013.)

If "CMIP5" is an abbreviation, please define.

would occur in the low-emissions scenario. Although temperature projections are broadly consistent across GCMs, precipitation changes seen in simulations by a suite of GCMs are dominated by shorter-timescale natural variability (Deser et al. 2012), considerable fluctuations in regional climate structure, and great diversity across individual GCMs. This leads to considerable differences in precipitation projections. Nonetheless, there is a 70% consensus toward drier conditions in Mexico, extending into the southern portions of the western United States (IPCC 2013; Polade et al. 2014).

Pierce and Cayan (2013) investigated the time required for climate change–driven trends of snow-related variables to emerge from the "noise" of natural variation. They used VIC hydrologic model (Liang et al. 1994; Hamlet et al. 2005) simulations of 13 GCMs forced with two representative GHG concentration pathways (RCP 4.5 and RCP 8.5) and calculated linear trends in snow-related hydroclimate measures over the twenty-first century. In addition to rising temperatures, the model projections showed the earliest significant downward trends in the fraction of precipitation that falls as snow (snowfall equivalent/precipitation total [SFE/P]) and the fraction of SWE retained in the snowpack as of April 1 (SWE/P). In comparison, snowfall, next to precipitation, was the noisiest variable and took the longest time to detectably change. Of the model simulations, 80% showed a significant downward trend in the primary snow indicators by 2030 (Figure 2.7), when averaged over the snow-dominated regions of the West. The RCP 8.5 simulations produced stronger declines and earlier emergence of detectable statistically significant trends compared to those for RCP 4.5. Declining trends in SWE and snowfall were found to emerge earlier and more strongly in regions with warmer cold-season climate (e.g., the Oregon Cascades, Sierra Nevada, and Washington Cascades) and to emerge later in cooler climates (e.g., the Colorado Rockies and Wasatch). The season during which snow cover persists became shorter over the twenty-first century, with the end of the snow season changing (becoming earlier) more quickly than the start of the snow season. According to the simulations, all of these regions will still build a snowpack during some years by the end of the twenty-first century, but in most years, the snowpack will be diminished considerably from present-day levels. Concerning mechanisms involved in snow reduction, the model simulations indicated that as the climate warms, the transition of precipitation from snow to rain plays a more important role in the decline in April 1 SWE than does earlier snowmelt (Figure 2.8) during the historical snow accumulation seasons. In the Sacramento River and San Joaquin River watersheds that feed the San Francisco Bay, runoff changes and associated estuarine salinity effects from climate warming were most strongly driven by shifts in runoff from low to middle snowmelt-dominated elevations, ranging from 1300 to 2700 m (Knowles and Cayan 2004).

If "VIC" is an abbreviation, please define at first mention.

Definition of "SFE/P" correct?

In the southwestern United States, several studies have combined GCM and hydrologic models and concluded that streamflow in the Colorado Basin and some other catchments will likely decline in response to climate change (Milly et al. 2005; Christensen and Lettenmaier 2007; Seager et al. 2007; Cayan et al. 2010). As reported by Vano et al. (2013), estimated reductions from climate change impacts range from about −5% to about −20% by midcentury (Hoerling et al. 2010; Das et al. 2011; Vano et al. 2012). Models suggest responses of annual Colorado River discharge to changes in precipitation and temperature that range from approximately 1% to 2% change in flow per 1% increase in precipitation and −5% to −28% change in flow per 1°C increase in temperature (Hoerling et al. 2010; Vano et al. 2012).

The extent to which runoff would decline as climate warms appears to vary considerably across the West. Using estimates from VIC hydrological model experiments, Das et al. (2011) found that runoff and streamflow are more sensitive to warming in the Colorado

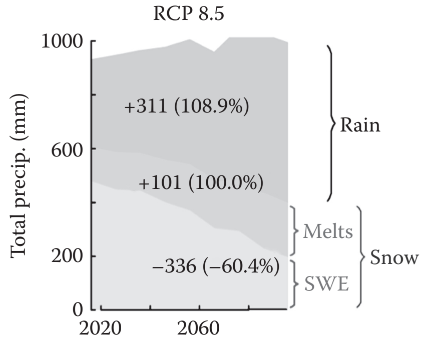

FIGURE 2.8
Projected change in the surface water budget by the end of the twenty-first century in Sierra Nevada based on ensemble mean of VIC model results from 13 downscaled RCP 8.5 GCM simulations. Note that total water (sum of all components) increases over the projected period due to incremental increase in multimodel mean precipitation over the period. Surface water components, accumulated from October 1 to March 31, from rain and snowmelt and stored in snowpacks, are indicated by gray, red, and blue wedges. (From Pierce, D.W., and Cayan, D.R., *J. Clim*., 26, 4148–4167, 2013.)

"gray, red, and blue" was mentioned here. Note that artwork is in grayscale. Please check.

Basin than in the Columbia River or west-slope Sierra Nevada drainages in California. The stronger response of the Colorado Basin to climate warming is associated with the low runoff in proportion to the precipitation that is delivered to this generally arid watershed. Thus, any increase in losses due to increased evapotranspiration and sublimation will have a relatively large impact on runoff and streamflow. In addition to warming-driven reductions in runoff, parts of the West, especially in the south near the Mexican border, could experience diminished precipitation, which would cause further reductions in runoff.

The GCM projections indicate that climate warming will occur throughout all months of the year (IPCC 2007, 2013), but the projections consistently exhibit greater warming in summer than in winter. From a set of downscaled SRES A2* simulations, Das et al. (2011) found, as an average across several GCMs, about 3°C warming in winter and nearly 5°C warming in summer. The same study used VIC hydrological model experiments to investigate the effect of warming on runoff and streamflow, and found that warming throughout the year produced reductions in annual flows in major western watersheds but that warming in the warmer months had stronger impacts than did warming in the cooler months of the year.

If "SRES" is an abbreviation, please define at first mention.

During droughts, when persistent reductions in precipitation occur, the effects of warming may come into even sharper focus. The added adverse impacts of warming add to the concern that, in parts of the West, water supplies may not be able to meet even current levels of demand (Barnett and Pierce 2009a,b). Warming has compounded the effects of precipitation deficits during the recent 2000s drought in the Southwest that was more or less focused on the Colorado River Basin, and during the ongoing 2012–2015 drought in California and neighboring states (California Department of Water Resources 2015). Comparing twenty-first-century Southwest drought characteristics from GCM climate change projections with those in the observed and modeled historical era, Cayan et al. (2010) found that projected future drought episodes became more extreme. As in the historical period, the driest years in the projections almost always occurred in the midst of longer dry periods. VIC hydrologic model calculations indicated that persistence of depleted soil moisture over the

"the ongoing 2012–2015 drought in California"—Please revise according to when the book is published.

* The IPCC (2000) Special Report on Emissions Scenarios (SRES) defined a set of emission scenarios that were used in GCM simulations for the Third and Fourth IPCC Assessment Reports. The A2 scenario is a fairly high-emissions scenario (https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf).

historical record ranged from 4 to 10 years, but in the twenty-first-century projections, some of the dry events persisted for more than 10 years. Moreover, summers in several of the projected droughts are even warmer than the already-warm adjacent years that were not in drought—i.e., warming is compounded when the land surface dries out.

"mid to late twenty-first century"—Edit OK?

Although climate change impacts on annual total precipitation are quite uncertain in much of western North America, the manner in which the precipitation is delivered at shorter timescales is very likely to shift. For California, ensemble mean projected changes in precipitation for the mid to late twenty-first century have been shown to favor somewhat wetter winters and drier springs (Pierce et al. 2012, 2013). These winter precipitation increases are largely driven by increases in daily precipitation intensity. In spring, any increases in intensity were overwhelmed by a diminished number of days with precipitation. Polade et al. (2014), in a study using 28 GCMs from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment analysis, found that the occurrence of dry days increased by 5–15 per year in California by the end of the twenty-first century under RCP 8.5 emissions, a result that was repeated over each of the Earth's Mediterranean climate regions. On the other hand, although it is projected that the overall frequency of wet days may decrease in many areas of California, there may be increases in the largest precipitation events (Pierce et al. 2013). These shifting distributions of daily precipitation affect projections of annual total amounts. Pierce et al. (2013) found that GCM-to-model disagreement regarding projected changes in California's annual precipitation were mostly attributed to the varying degrees of change in the frequency or intensity of the relatively few heavy precipitation events each year.

An important consideration about climate warming and changes in event-scale weather characteristics is how they might conspire to impact flood flows. Mantua et al. (2010) investigated watershed changes in the Pacific Northwest under scenarios of climate change. In the latter half of the twenty-first century, they found that watersheds in the current climate that are *transitional* (both rain and snow runoff) would become more purely rainfall runoff landscapes, resulting in increased winter flood frequency and magnitudes. Tohver et al. (2014) found similar patterns using a more sophisticated downscaling technique and further highlighted the role of rising snow lines and increasing contributing basin area in basins with the largest increases in flood risk. Using dynamic downscaling techniques, Salathé et al. (2014) showed that flood impacts in rain-dominant basins in the Pacific Northwest may be much larger than predicted by previous studies due to increasing intensity of ARs and orographic effects on the west slopes of the Cascades not captured by statistical downscaling. Das et al. (2013) used outputs from 16 historic and projected twenty-first-century conditions under the SRES A2 emissions scenario, downscaled to the Sierra Nevada, to investigate possible climate change effects on flooding and found that the number of days of precipitation did not change over the twenty-first century. However, there was an increase in the most intense precipitation events. Additionally, warming projected over this period produced a greater proportion of precipitation falling as rain instead of snow, amplifying observed changes already occurring during the last few decades, as shown by Knowles et al. (2006). Using VIC hydrological model simulations whose input was the downscaled GCM simulations, Das et al. (2013) found that by the end of the twenty-first century, all 16 climate projections yielded larger floods (return periods ranging from 2 to 50 years) for both the Northern Sierra Nevada and Southern Sierra Nevada. The importance of shorter-period phenomena is underscored by the fact that there was a consensus of increasing flood magnitudes produced by the model runs, despite approximately half of the projections having reduced mean precipitation amounts, relative to the twentieth-century historic period (Figure 2.9).

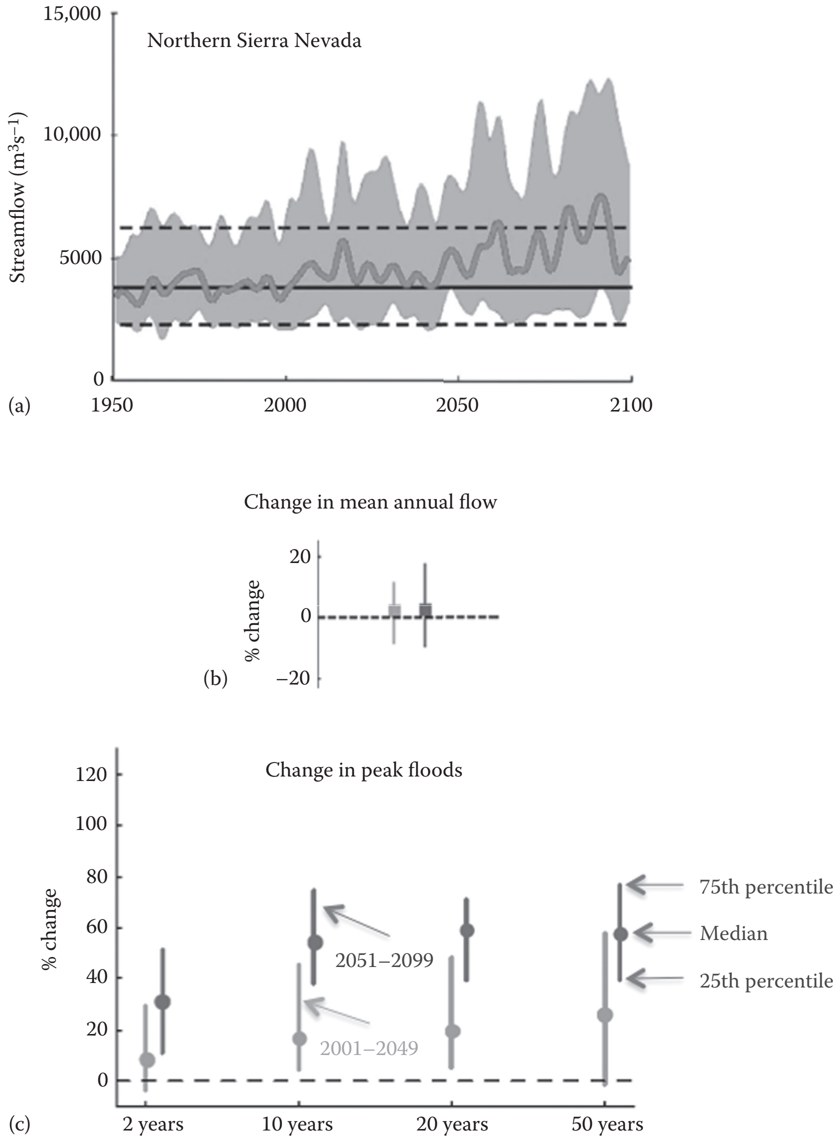

FIGURE 2.9
(a) VIC simulated northern Sierra Nevada annual maximum 3-day streamflow increase found in downscaled output from 16 GCMs, run under SRES A2 emissions scenario. Multimodel median is shown by red line; envelope of 3-day maximum flows between 25th and 75th percentiles is shown by gray shading. Horizontal lines represent historical median (solid black line) and 25th and 75th percentiles (dotted black lines) from 1951 to 1999. Results are smoothed using low-pass filter. (b) Very little change in annual total discharge is shown by percentage changes (relative to 1951–1999) in mean annual streamflow from VIC simulations as simulated by 16 downscaled GCMs. (c) Increases (in percent) of flood magnitudes for selected return periods from same model simulations as in upper panels. Changes in the period 2001–2049 (cyan) and 2051–2099 (dark red) are shown side by side. For each of the return periods, filled squares show ensemble medians, and vertical whiskers extend from 25th to the 75th percentile of the 16 GCM simulations. (From Das, T. et al., *J. Hydrol.*, 501, 101–110, 2013.)

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2.4 Conclusions

The western United States (the West) has a remarkably varied hydroclimate, in terms of temporal variability, spatial diversity, and the range of projected futures that it faces. Recent research demonstrates how a surprisingly large portion of this variation owes to the timing and high intensity of a relatively small number of extreme weather events. Other mechanisms may be more important than is presently recognized, including changes in wind flows that drive orographic precipitation and the varying effects of aerosols in the atmosphere and dust and soot deposited at the surface. These emerging findings add incentive to better understand processes that operate at the confluence of weather and climate, and sharpen focus upon forecasting at few-day to several-day lead times.

In addition to natural variation from synoptic to multidecadal timescales, conditions in the West appear to be undergoing long-term changes. An interconnected set of hydrologic shifts, including more rain and less snow, diminished spring snowpack, and earlier mountain runoff, have been observed in snow-dominated watersheds in response to warmer winters and springs since the mid-1970s. Although the region exhibits natural climate variability on decadal timescales and long droughts have occurred in the past, there is a striking similarity of observed trends to those that are projected under climate warming. This, combined with evidence from a series of detection and attribution studies, indicates that the hydrologic changes are, to some degree, the early phase of a response to anthropogenic climate change. Exceptionally warm dry spells in the Colorado Basin and over the West Coast during the past decade add to concerns about changing climate.

The projected effects of increasing concentrations of atmospheric GHGs on western US hydrology are substantial, even under moderate scenarios of climate change. Under higher (SRES A2 or RCP 8.5) scenarios, these changes and impacts would be extremely challenging. The region's water supply and its vulnerability to flood hazards depend on high-volume precipitation events, so understanding the disposition of the region's major storm events under climate change is vital in preparing for future impacts.

Many of the observed changes in the region's hydroclimate have been discovered from time series data of opportunity developed from strings of measurements that were not designed for climate purposes. Sustaining these traditional observations is vital to track and evaluate further changes. Additionally, to understand processes driving fluctuating and changing hydroclimate and to track long-term changes, a new cohort of carefully designed observations and monitoring networks is needed. Clearly, besides better surface observations, an evolving description of the 3-D atmospheric structure is required to explain how climate varies and may change. The Cal Water program of field studies (Ralph et al. 2015) has explored both the AR component and also emerging aerosol–cloud–precipitation dimensions of this challenge, and has led to some of the findings presented herein. Field campaigns like Cal Water, along with other institutionalized monitoring efforts to collect major new data sets, will be critical for evaluating climate model representation of these phenomena and for interpreting the underlying physical processes. Elucidating changes in specific physical processes will make detection and attribution of overall system changes that much more certain and will make those detections possible earlier.

Acknowledgments

The lead author was supported by the California Energy Commission, the US Geological Survey (USGS)–Sponsored Southwest Climate Science Center, and the National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Science Applications (RISA) program through the California Nevada Climate Applications Program (CNAP).

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