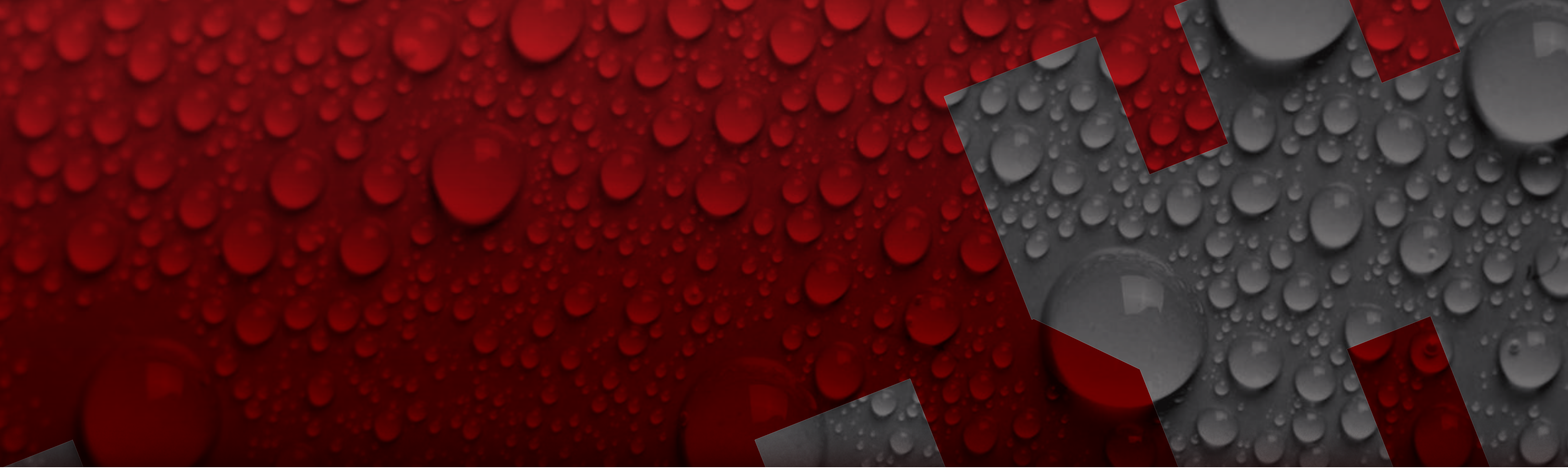

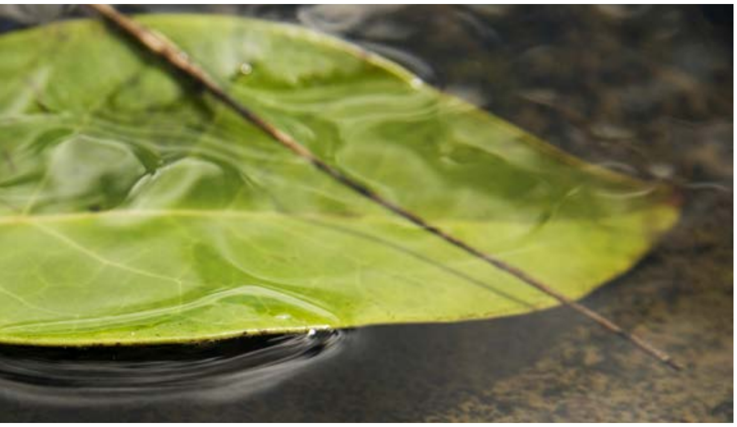

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

CALIFORNIA REGION 18

FINAL

July 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
02-07-2015	Civil Works Technical Series	2014 - 2015

4. TITLE AND SUBTITLE Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - California Region	**5a. CONTRACT NUMBER** W912HQ-10-D-0004
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) - Kathleen D. White, PhD, PE, Institute for Water Resources - US Army Corps of Engineers - Jeffrey R. Arnold, PhD, Institute for Water Resources - US Army Corps of Engineers - Support from CDM Smith	**5d. PROJECT NUMBER**
	5e. TASK NUMBER 147
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Directorate of Civil Works US Army Corps of Engineers Washington, DC	**8. PERFORMING ORGANIZATION REPORT NUMBER** CWTS-2015-18
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Institute for Water Resources 7701 Telegraph Road (Casey Building) Alexandria, Virginia 22315	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available through National Technical Information Service, Operations Division
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT
To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the California Region, is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

15. SUBJECT TERMS

California Region	Observed Hydrology	Business Line
Water Resources Region 18	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
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CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

CALIFORNIA REGION 18

July 2, 2015

CDM Smith
Contract # W912HQ-10-D-0004, Task Order 147

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Suggested Citation:

USACE (2015). Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions – Water Resources Region 18, California. Civil Works Technical Report, CWTS 2015-18, USACE, Washington, DC

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Water Resources Region 18: California Region

1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of the 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one Water Resources Regions included in this series of reports is shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and regional vulnerability assessment tools.

This report focuses on Water Resources Region 18, the California Region, the boundaries for which are shown in **Figure 1.2**. The California Region is within the USACE Los Angeles district, Sacramento district, and San Francisco district territories, with an exception of a small portion of the region which is within Mexico.

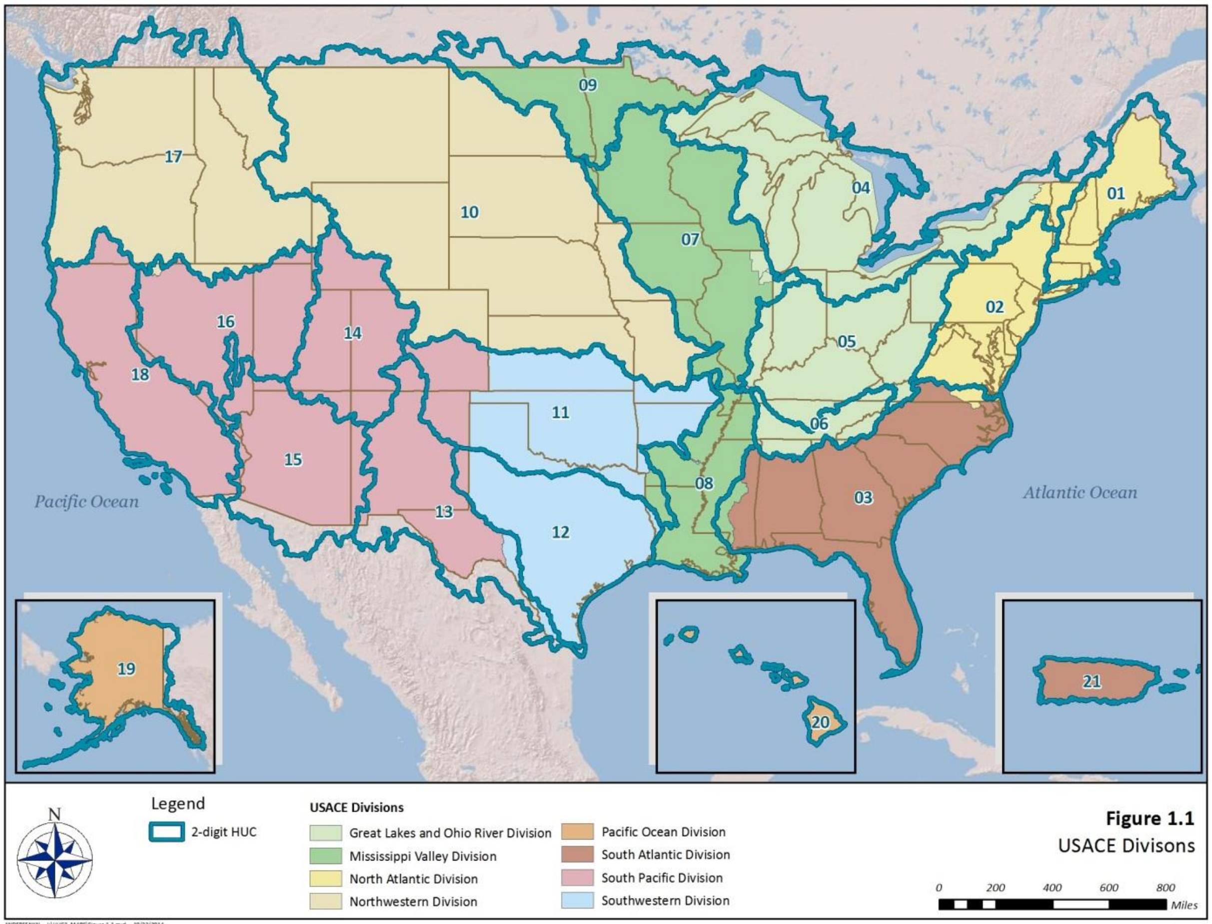

Figure 1.1. 2-digit Water Resources Region Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

Figure 1.2. Water Resources Region 18: California Region Boundary.

1.1. A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Regional scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 18, both the Region and Subregion (2-digit and 4-digit HUC) boundaries are shown in **Figure 1.2**.

2. Observed Climate Trends

Observed climate trends within the California Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA), which includes not only regional assessments, but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the California Region or its sub-watersheds were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region of the Water Resources Region or inclusive of the Water Resources Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), evapotranspiration (ET), and soil moisture.

The results presented below indicate increasing trends in temperature for the California Region. However, clear consensus does not exist for precipitation trends. Studies of regional streamflow reviewed here present low consensus and little evidence of significant trends in flow over the past 50 to 60 years.

2.1. Temperature

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national-scale studies inclusive of results relevant to the California Region and regional studies focused more specifically and exclusively on the California Region. Results from both types of studies are discussed below.

At a national scale, a 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed seasonal mean surface air temperature for most of the U.S. (**Figure 2.1**). For the California Region, seasonal differences were identified in the historical mean air temperatures. A primarily positive historical warming trend was identified for the California Region in the winter (December – February) and spring (March – May), and a historical cooling trend was shown for the fall (September – November). Spatial variability in historical temperature trends throughout the California Region is shown in summer (June – August) with some areas showing increasing temperature trends and others showing decreasing temperature trends. The authors do not provide information on statistical significance of the presented observed trends.

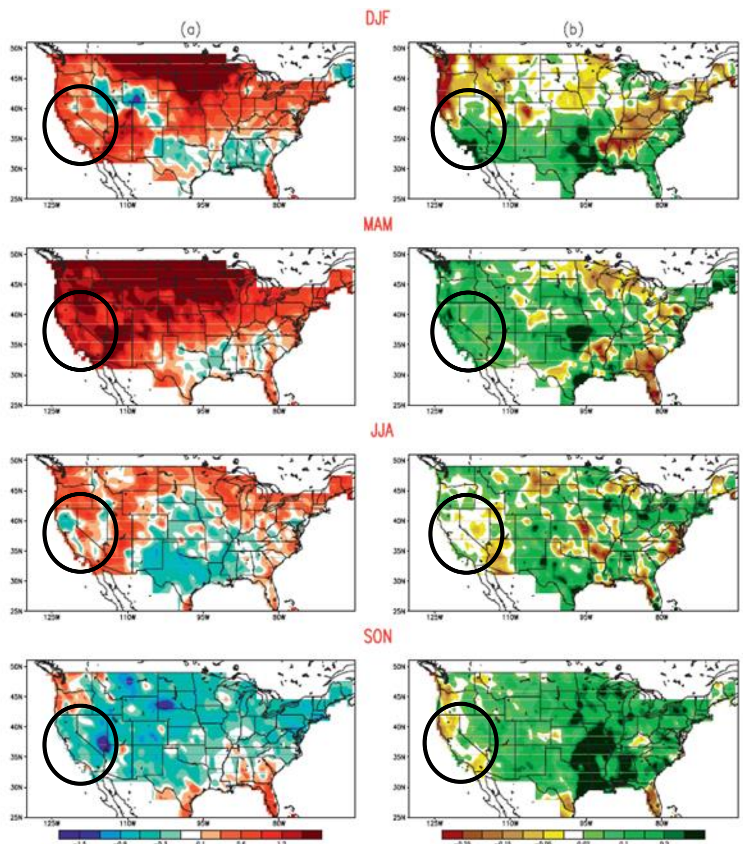

Figure 2.1. Linear trends in (a) surface air temperature in Kelvin and (b) precipitation in mm/day over the United States, 1950 – 2000. The California Region is within the black oval (Wang et al., 2009).

A later study by Westby et al. (2013), using data from the period 1949 – 2011, presents spatial variation in winter temperature trends for the California Region for this time period (**Figure 2.2**). General warming winter temperature trends illustrated by Westby et al. (2013) for the California Region agree with those reported by Wang et al. (2009). The temperature variability presented by Westby et al. (2013), was not statistically significant at a 95% confidence interval (C.I.) in the California Region.

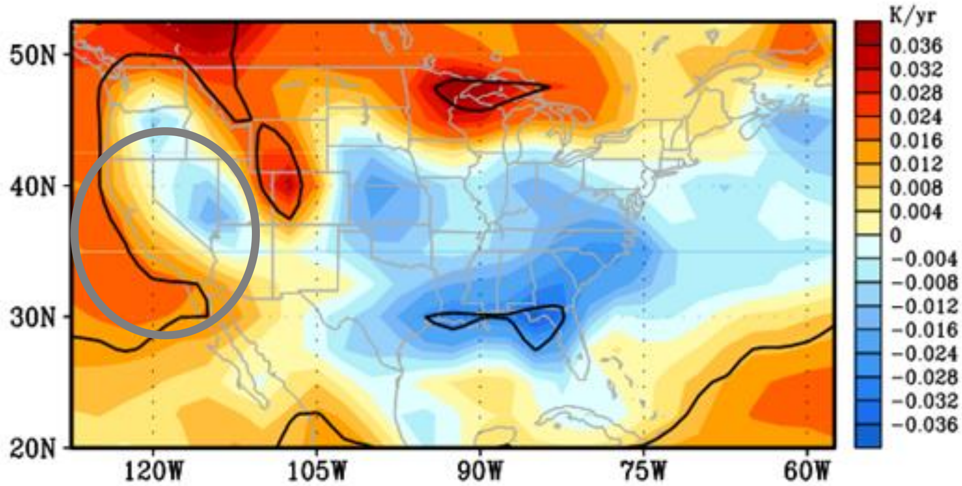

Figure 2.2. Mean winter (December through February) temperature trends from 1949 – 2011 (K / year). Black contours indicate statistical significance at the 95% confidence level. The California Region is within the gray oval (Westby et al., 2013).

An article by MacDonald (2010) evaluated average annual temperatures over 2001 – 2009 compared to 1951 – 1960. In the California Region annual temperatures were up to 1.5 standard deviations above the 20th century average (**Figure 2.3**). Details on statistical significance were not provided in the study.

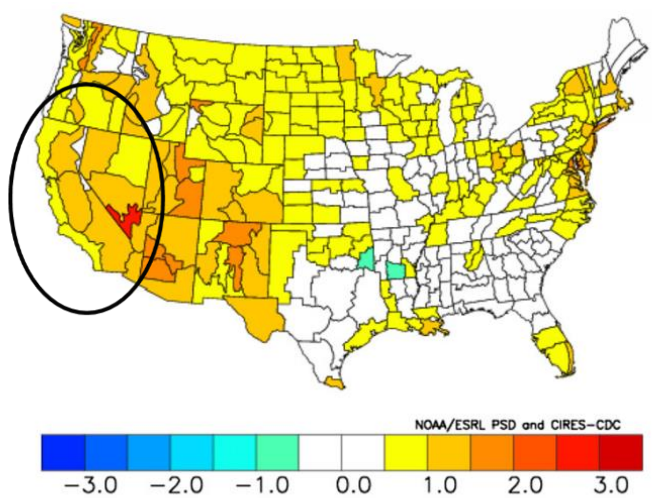

Figure 2.3. Composite standardized temperature anomalies for 2001 – 2009 relative to 1895 – 2000. The California Region is within the black oval (MacDonald, 2010).

A national study by Tebaldi (2012) evaluated average annual historical decadal changes in temperature. Based on data from 1912 – 2011, temperatures within the state of California (which the California Region is primarily within), increased in temperatures at a rate of 0.16 °F (0.09 °C) per decade respectively with a 95% confidence interval.

Similarly, Hoerling et al. (2013) assessed annually averaged daily temperature trends in the Southwest using observed climate and paleoclimate record. In the California Region, a statistically significant (95% C.I.) increase in average annual daily temperature of 0.9 to 4.5 °F (0.5 – 2.5 °C) was identified between 1901 and 2010.

The third NCA report (Garfin et al., 2014) presents trends in historical annual average temperatures for the southwestern U.S. For the southwestern U.S., including the California Region, historical data shows a general warming of average annual temperatures in the early part of the 21st century. Details on statistical significance are not provided. When comparing a recent 22-year span (1991 – 2012) to a historical average (1901 – 1960), temperatures have increased throughout the California Region by up to 2 °F (1.11 °C), as illustrated by **Figure 2.4**. (Walsh et al., 2014) This is consistent with an increasing trend in annual average temperatures within the California Region reported by MacDonald (2010), Tebaldi (2012), and Hoerling et al. (2013).

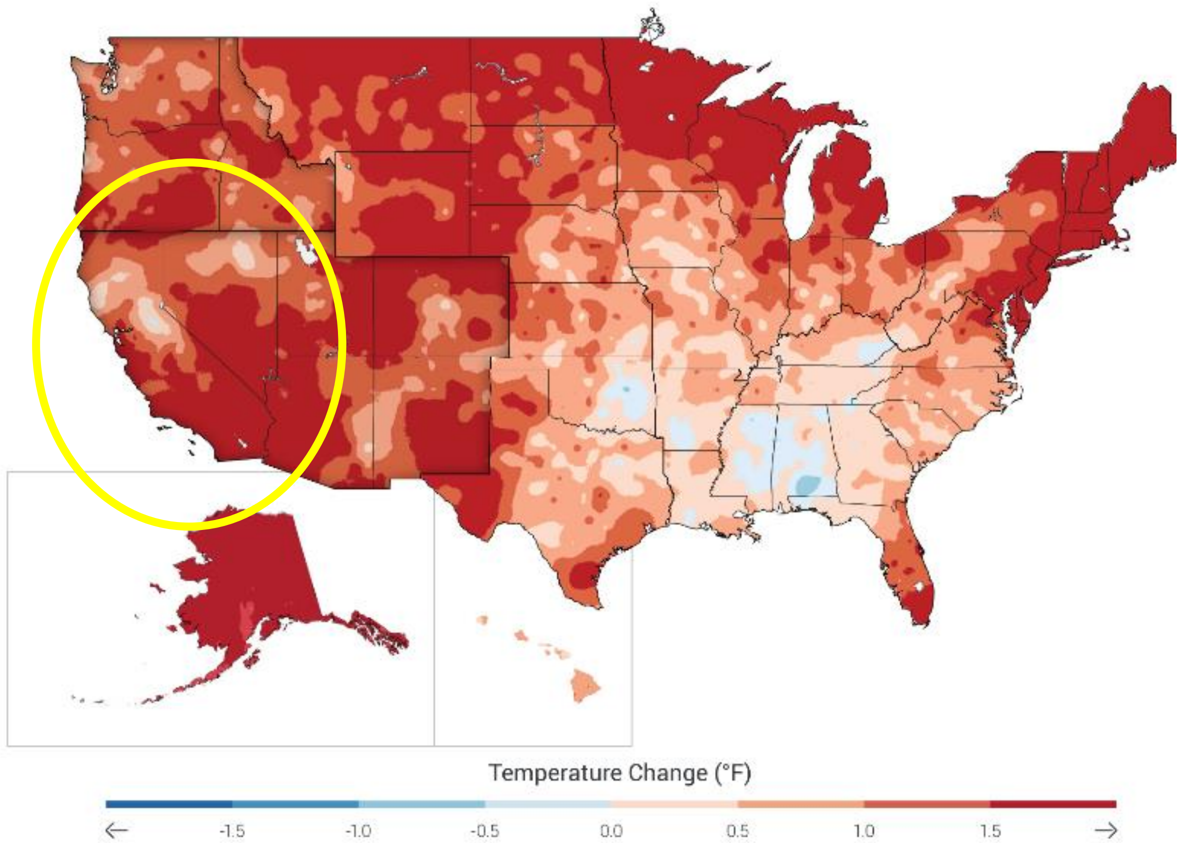

Figure 2.4. Changes in average temperatures for 1991 – 2012 compared to 1901 – 1960. The California Region is within the yellow oval (Walsh et al., 2014).

In a regional study of the southwestern U.S., Kunkel et al. (2013), as cited in Garfin et al. (2014), evaluated historical temperature trends. Comparing annual historical temperatures to the average temperature of 1901 – 1960, the authors identified upward and statistically significant, to the 95% confidence level, trends for seasonal and annual temperatures from 1895 – 2011. **Table 2.1** provides the annual and seasonal temperature trends. The authors further identify a steady historical increasing trend in night temperatures, while daytime temperatures exhibit less of a trend.

Table 2.1 Decadal trends in temperature and precipitation for 1895 – 2011 compared to average of 1901– 1960 for the southwestern U.S. Only significant values (> 95% C.I.) are reported. (Kunkel et al., 2013)

Season	Temperature (°F/decade)	Precipitation (inches/decade)
Winter	+0.21	—
Spring	+0.16	—
Summer	+0.17	—
Fall	+0.16	—
Annual	+0.17	—

On a smaller scale, a study by Bonfils et al. (2008a) was conducted to identify external influences on temperatures in California. The study evaluated data from up to seven gridded temperature datasets and from several U.S. Historical Climate Network (USHCN) stations. Trends were identified by least-squares linear fit to the datasets. Increasing trends in annual mean temperature from 1950 – 1999 were found with high statistical significance. Average annual temperatures increased by 0.36 °C (0.65 °F) to 0.92 °C (1.66 °F) depending on the datasets evaluated.

Mote et al. (2005) evaluated historical temperature and precipitation trends as they relate to mountain snowpack in western North America from the Continental Divide to the Pacific coast. Climate data from November through March was obtained from USHCN for the study. As illustrated in **Figure 2.5**, winter temperatures have mostly increased in the California Region, up to 3 °C (5.4 °F) from 1930 to 1997.

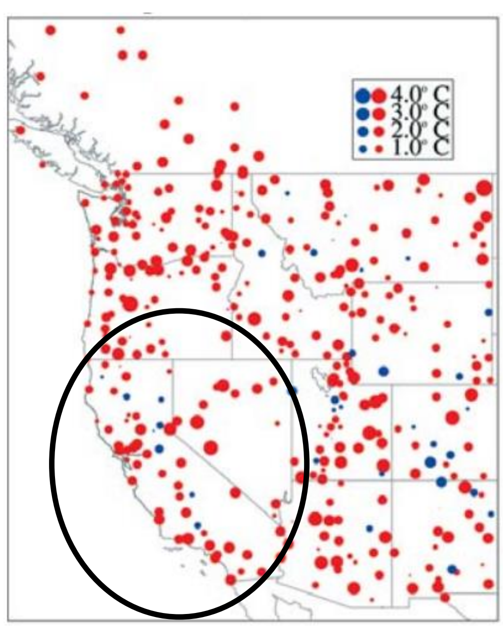

Figure 2.5. Linear trends in November through March temperature from 1930 to 1997. Positive trends are indicated by the red circles and negative trends are indicated by blue circles. The California Region is within the black circle. (Mote et al., 2005)

Extreme, minimum, or maximum temperatures were studied by Grundstein and Dowd (2011), Hoerling et al. (2013), Kunkel (2013), and Cordero et al. (2011). Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum apparent temperatures across the continental U.S. The study was based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 – 2010. Extreme minimum and maximum temperatures were defined as the number of days per month that exceeded the local 85th percentile for the one-day maximum and minimum temperatures. For the California Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum temperatures for three stations in the region. No trends were found in the number of one-day extreme maximum temperatures in the California Region.

Hoerling et al. (2013) compared seasonal and annual maximum and minimum temperatures averaged across the southwest, inclusive of the California Region, from 2001 – 2010, to the southwest average for the 20th century. An increase in seasonal and annual minimum and maximum temperatures over the 2001 – 2010 period compared to the 1901 – 2000 period was reported. Minimum and maximum annually averaged daily temperature trends from 1901 – 2010 were also evaluated by Hoerling et al. (2013). Generally positive statistically significant (95% C.I.) changes in maximum and minimum temperature were reported for the southwestern U.S., inclusive of the California Region, of up to 3 °C (5.4 °F) (**Figure 2.6**). Hoerling et al. (2013) also reported, with high confidence, an increase in the occurrence of heat waves in the southwestern U.S. during 2001 – 2010 compared to occurrences during the 20th century.

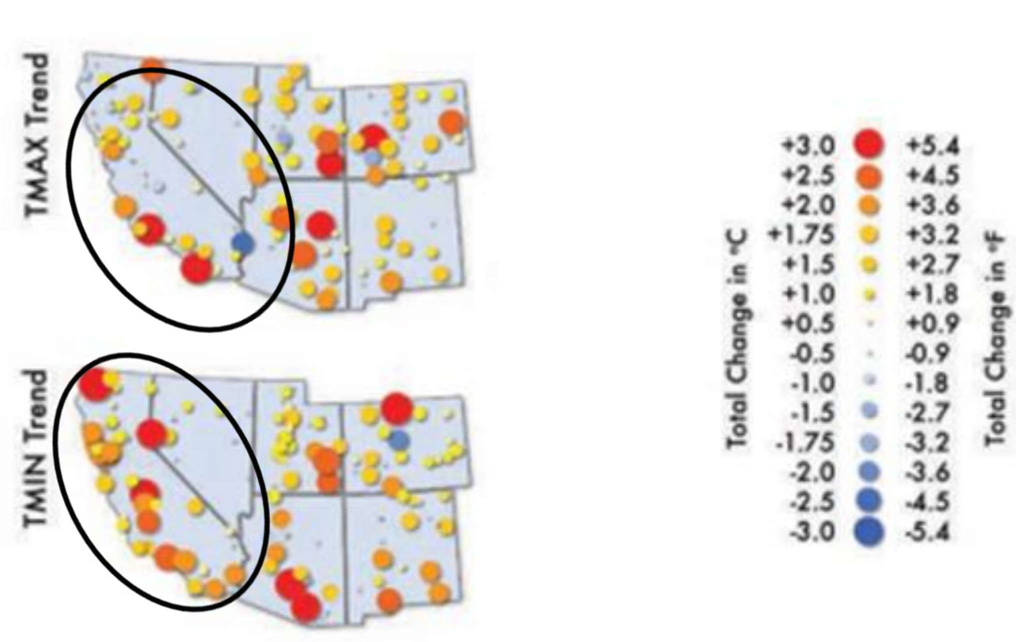

Figure 2.6. Minimum and maximum annually averaged daily temperature trends (95% C.I.) from 1901 – 2010. The California Region is within the black oval (Hoerling et al., 2013).

Kunkel et al. (2013) identified a statistically significant increasing trend in the frequency of extreme heat waves in the southwestern U.S., defined as four-day periods with temperatures exceeding a threshold of a one in five-year recurrence interval, and a statistically significant decreasing trend in extreme cold periods within the southwestern U.S., inclusive of the California Region.

Winter (January through March) maximum and minimum daily temperatures from 1950 – 1999 were the focus of a regional study of the mountainous western U.S. by Bonfils et al. (2008b). The study used climate data from the NCDC's Cooperative Observer Network and USHCN. For the entire spatially averaged mountainous western U.S., the study reported increasing trends in minimum and maximum daily temperatures from 1950 – 1999. The study also reported decreases in the number of days with daily average temperatures below freezing, and increases in the number of days where the average daily temperature exceeds the melting point for the winter season. The study found that the number of days with daily average temperatures below freezing and above melting point were sensitive to elevation and topography of the region. Trends in the California Region are consistent with the general trends of the mountainous western region as a whole. Increases in observed daily minimum temperatures were found of up to 2 °C (3.6 °F) with some spatial variability, as some areas exhibited no changes in minimum temperatures. Similarly, increases in daily maximum temperatures, from 1950 – 1999, were reported of up to 2 °C (3.6 °F), with increased spatial variability in the degree of increase in maximum daily temperatures. Decreases in the number of days that daily average temperatures drop below freezing are seen throughout the California Region, with the majority of the region experiencing changes of less than three days. For the mountainous areas of the California Region, trends have indicated a decrease in the number of daily temperatures below freezing by up to 12 days. Trends in the number of days with average temperatures above the melting point are up to 88 days (**Figure 2.7**). These results are consistent with general increasing in temperature trends in the California Region.

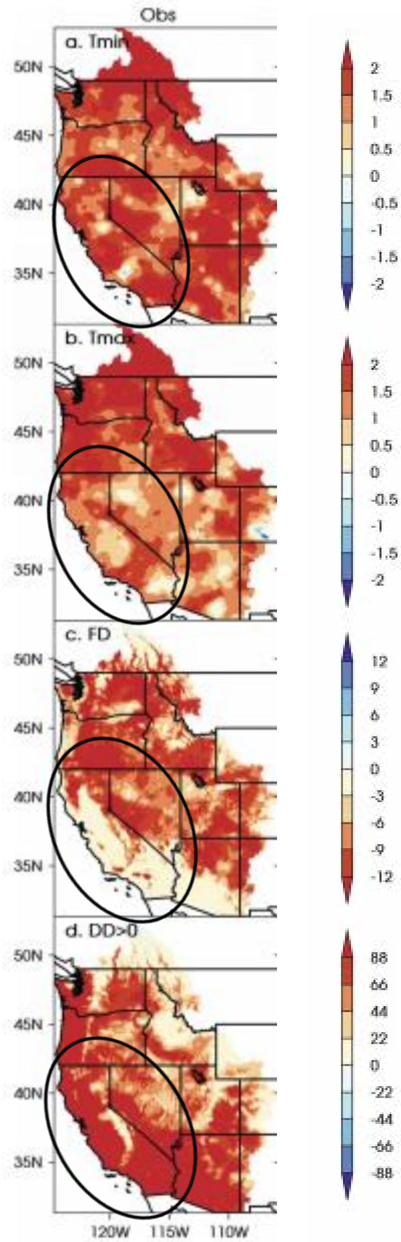

Figure 2.7. Linear trends in a. January through March average daily minimum temperatures, b. January through March average daily maximum temperatures, c. January through March number of days with daily average temperatures below freezing, d. January through March number of days with average daily temperatures above the melting point, from 1950 to 1999. The California Region is within the black circle (Bonfils et al., 2008b).

On a more regional scale, a study by Cordero et al. (2011) evaluated historical maximum and minimum temperature trends in California. The study evaluated monthly temperature data from 58 USHCN stations and daily temperature from 272 National Weather Service Cooperative Network stations from the NCDC. Analysis of statewide USHCN data from 1918 to 2006 revealed an increasing trend in minimum temperatures of approximately 0.17 °C (0.31 °F) per decade, and increasing trends in maximum temperatures of approximately 0.07 °C (0.13 °F) per decade. As part of this study, historical minimum and maximum temperature trends were evaluated for 11 defined climate regions throughout California. **Figure 2.8** illustrates the trends in minimum and maximum temperature for the 11 climate regions. Comparing trends in minimum and maximum temperatures from 1918 – 2006 to trends from 1970 – 2006 illustrate a general acceleration of trends in both minimum and maximum temperatures. Minimum temperature trends from 1918 – 2006 of 0.17 °C (0.31 °F) increased to 0.31 °C (0.56 °F) per decade during 1970 – 2006, and maximum temperature trends increased from 0.07 °C (0.13 °F) per decade to 0.27 °C (0.49 °F).

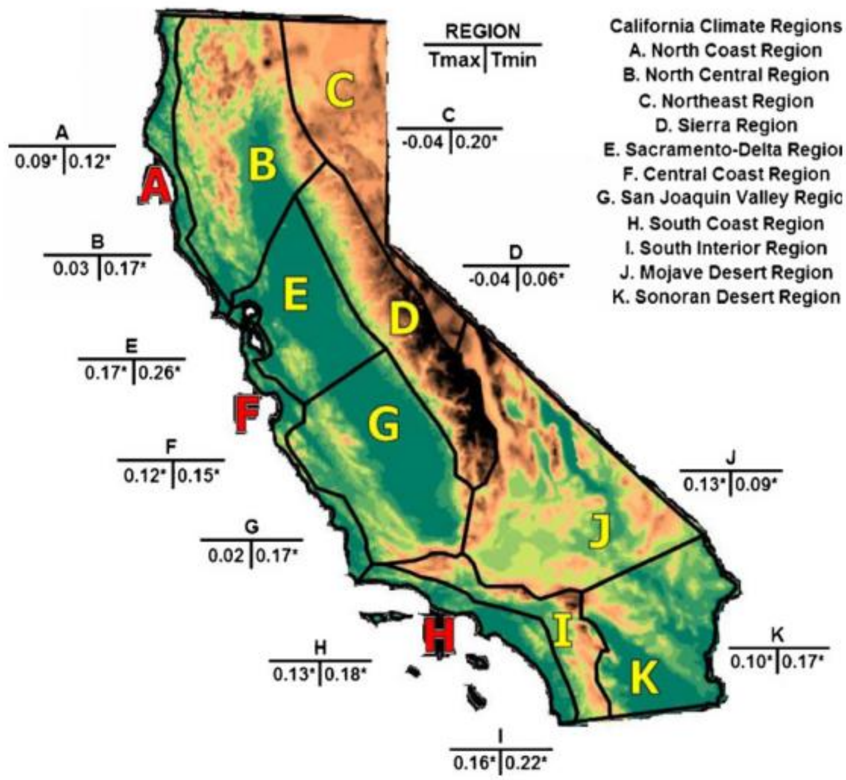

Figure 2.8. Annual maximum and minimum temperature trends (°C per decade) in 11 climate regions from 1918 – 2006. Maximum temperature trends are reported on the left, minimum temperature trends on the right. Those trends with an asterisk indicate statistically significant trends with 95% C.I. (Cordero et al., 2011).

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC with periods of record extending through 2010. Their findings indicate large spatial variability of spring onset throughout the California Region, with some areas illustrating onset occurring a few days earlier, and others showing onset occurring a few days later compared to an earlier baseline reference decade (2001 – 2010 vs. 1951 – 1960) (**Figure 2.9**).

Figure 2.9. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The California Region is within the red oval (Schwartz et al., 2013).

Key point: In general, there appears to be an increasing trend in both minimum and maximum historical temperatures in the California Region with relatively strong consensus in the literature.

2.2. Precipitation

Multiple authors, evaluating precipitation trends on a national scale, have not identified significant trends in total annual precipitation in recent historical records for the study region. Grundstein (2009) found no statistically significant (95% C.I.) trend in soil moisture index, and no trend in annual precipitation in the California Region based on annual data from 1895 to 2006. Very slight increasing potential evaporation trends with statistical significance were identified in two locations within the California Region (**Figure 2.10**). Soil moisture is a function of both supply (precipitation) and demand (ET), and therefore is an effective proxy for both precipitation and ET.

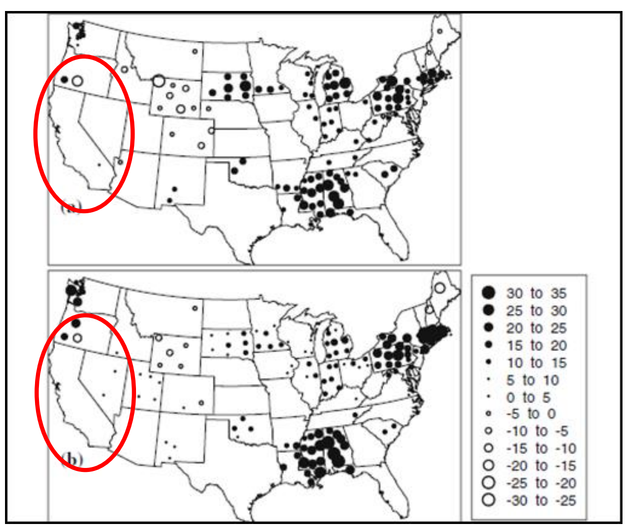

Figure 2.10. Statistically significant linear trends in (top) soil moisture index (unitless) and (bottom) annual precipitation (cm) for the continental U.S., 1895 – 2006. The California Region is within the red oval (Grundstein, 2009).

As described in Section 2.1, a similar study by Wang et al. (2009) also focused on historical climate trends across the continental U.S. using gridded climate data and a shorter period of record (1950 – 2000). The authors identified generally positive significant trends in annual precipitation for most of the U.S. For the California Region, large spatial variability was found in historical precipitation trends. Increasing trends were seen throughout the region in the spring. However, winter, summer, and fall trends show areas of increasing precipitation trends and areas of decreasing trends (**Figure 2.1**). The authors do not provide information on statistical significance of the presented observed trends.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous dataset to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (**Figure 2.11**). For the California Region, results indicate no change or slight increases (up to 10 percent change per century) for the majority of the region, with a small section of northeastern California displaying slight decreases (up to -5 percent change per century) in precipitation. The authors do not provide information on statistical significance of the presented observed trends.

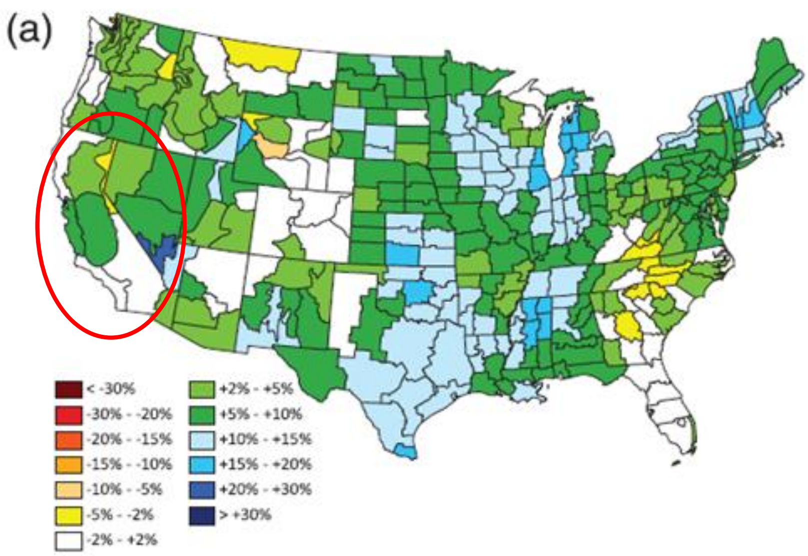

Figure 2.11. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The California Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Similarly, a study by MacDonald (2010) evaluated national precipitation from 2001 – 2009 standardized relative to data from 1895 – 2000. These results show a decrease in precipitation within the California Region (**Figure 2.12**).

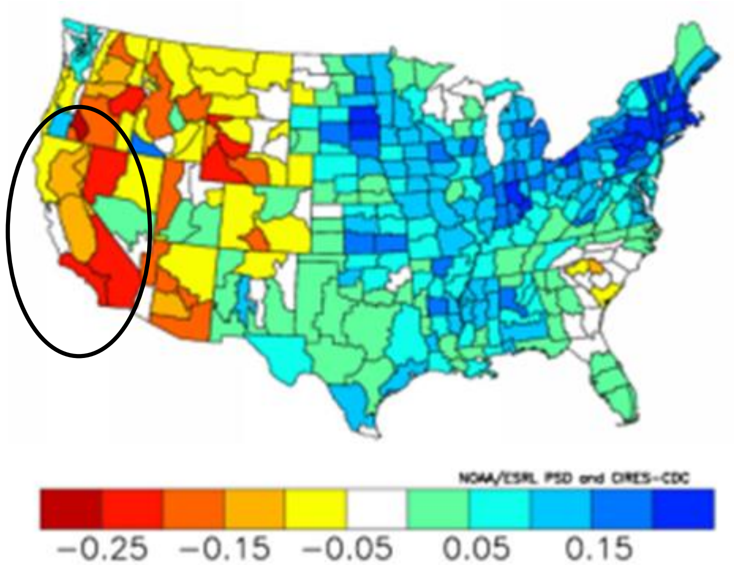

Figure 2.12. Standardized precipitation anomalies for 2001 – 2009 relative to 1895 – 2000. The California Region is within the black oval (MacDonald, 2010).

Palecki et al. (2005) examined historical precipitation data from across the continental U.S. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. A predominant decreasing trend in storm precipitation totals are projected for the California Region, with some areas showing statistically significant decreases (95% C.I.) in winter and fall precipitation storm totals, and statistically significant decreases (90% C.I.) in some areas during spring months. Across all seasons, storm durations have decreased and storm intensity has increased throughout the majority of the California Region.

Pryor et al. (2009) performed statistical analyses on 20th century rainfall data to investigate for trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the California Region, the analysis showed an increasing trend in total annual precipitation, with one area on the eastern edge of the region with an increasing trend. A general increasing trend in extreme high precipitation events (90th percentile daily) was seen in the California Region, with the exception of part of the region in southern Oregon, which saw a slight decreasing trend in extreme precipitation events. Similarly, statistically significant increasing trends of precipitation intensity were reported in north-central California, while decreasing precipitation intensity trends were found at the California/Oregon border. Statistically significant increasing trends in number of precipitation days were found in several locations, particularly in northern California and southern Oregon, within the California Region. (**Figure 2.13 a, b, c, and d**). These trends were determined to be significant at the 90% C.I. The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most of the trends.

a) Annual precipitation

b) 90th percentile daily precipitation

c) Precipitation intensity (annual total/number of precipitation days)

d) Number of precipitation days per year

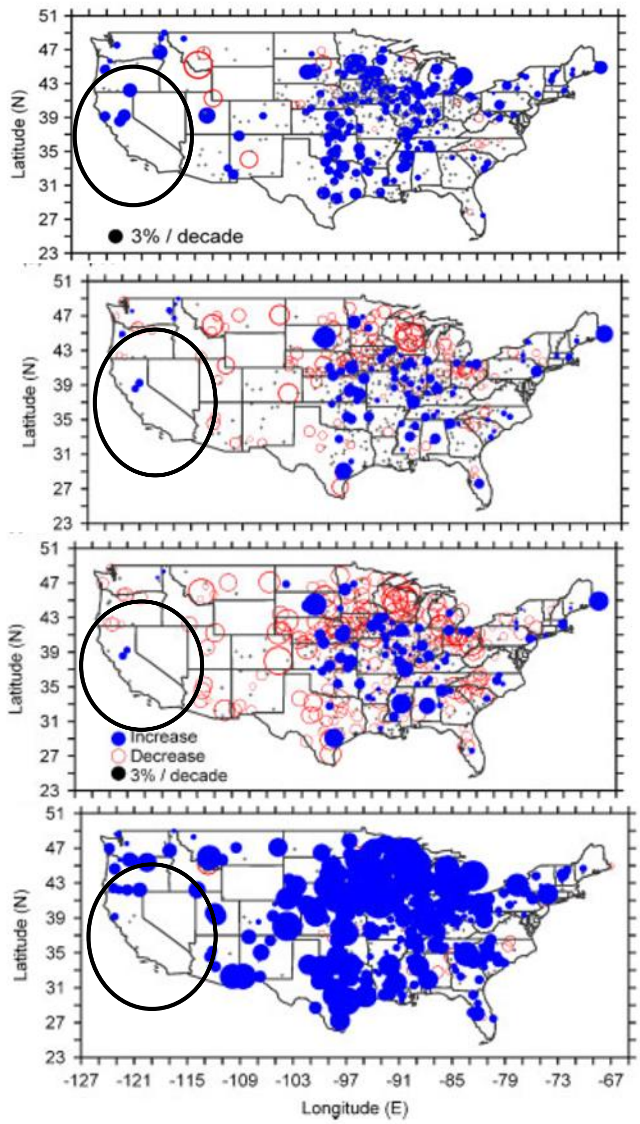

Figure 2.13. Historical precipitation trends (20th century). a) annual totals, b) 90th percentile daily, c) precipitation intensity (annual total/number of precipitation days), and d) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3 percent change per decade. The California Region is within the black circle (Pryor et al., 2009).

As part of the third NCA, Walsh et al. (2014) reported annual precipitation changes from 1991 – 2012 compared to the 1901 – 1960 average. For the California Region, precipitation primarily increased, in some areas greater than 15 percent, with some spatial variability throughout the region, and areas in southern California showing decreasing trends in precipitation (**Figure 2.14**). Statistical significance of trends was not provided in the report.

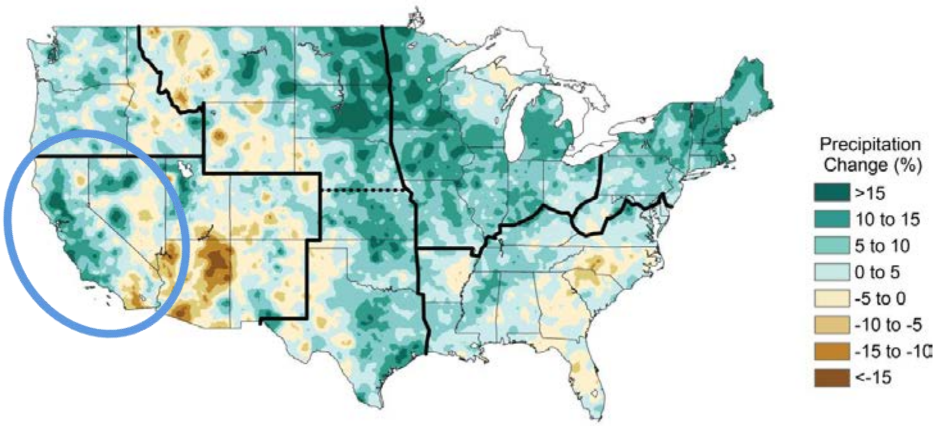

Figure 2.14. Annual total precipitation changes for 1991 – 2012 compared to the 1901 – 1960 average. The California Region is within the blue circle (Walsh et al., 2014).

A number of recent studies have focused more specifically on southwestern U.S., including the California Region. Kunkel et al. (2013) found no statistically significant trends in historical annual, seasonal, or extreme precipitation from 1895 – 2011 for the Southwest. No trends in the frequency of extreme precipitation events were found either.

A study by Hoerling et al. (2013), discussed in Section 2.1, reported a statistically significant (95% C.I.) trend in precipitation with spatial variability (+20 to -40 percent) across the California Region between 1901 and 2010 (**Figure 2.15**).

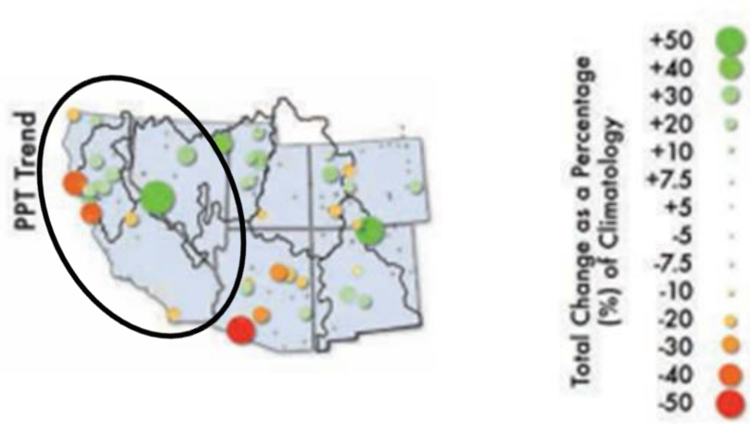

Figure 2.15. Precipitation trends (95% C.I.) from 1901 – 2010. Crosses shown in graphic indicate precipitation changes of less than 5 percent. The California Region is within the black circle. (Hoerling et al., 2013)

Mote et al. (2005) found increasing precipitation trends for the majority of the California Region, based on winter (November through March) precipitation data from 1930 to 1997, with some areas in northern California showing decreasing precipitation trends as illustrated in **Figure 2.16**. Statistical significance of the trends was not provided.

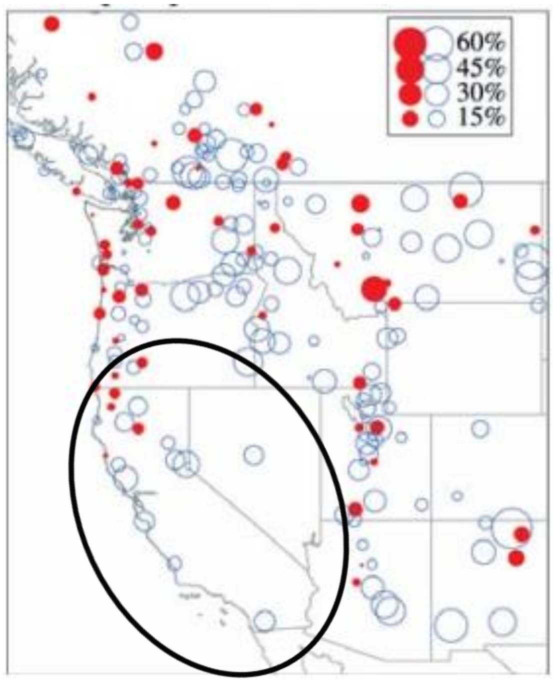

Figure 2.16. Linear trends in November through March temperature from 1930 to 1997. Positive trends are indicated by the blue circles and negative trends are indicated by red circles. The California Region is within the black circle (Mote et al., 2005).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on the intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Increases in the frequency of the 20-year storm event were determined. For the California Region, an increase in the recurrence of the 20-year daily maximum precipitation event for the period 1977 – 1999 was computed to be up to 1.3 times greater than the recurrence of the same storm during the period of 1949 – 1976.

Lavers et al. (2015) evaluated the contribution of atmospheric rivers to precipitation in Europe and the United States. Atmospheric rivers are concentrated near-surface water vapor that form about one mile up in the atmosphere and can extend for thousands of miles. (Dettinger et al., 2013). California's largest storms are generally fueled by landfalling atmospheric rivers and may contribute 20 to 50 percent of the precipitation and streamflow in California. (Dettinger et al., 2011). Lavers studied the percent of precipitation which was caused by atmospheric rivers from 1979 to 2012 using data from the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis. **Figure 2.17** illustrates the monthly average fraction of rainfall between 1979 -2012 which was caused by atmospheric rivers. These results illustrate that atmospheric rivers have the largest influence on precipitation from October to February in the California Region. Precipitation in the western U.S., and the California Region, in particular, is heavily influenced by atmospheric rivers due to the hills and mountains which cause orographic enhancement of precipitation. A zero-inflated beta regression model was used to examine changes in the contribution of atmospheric rivers to precipitation during the study period, and found an increasing trend in the probability of zero-atmospheric river contribution to cold season rainfall in the California Region and the southwestern U.S. (Lavers et al., 2015).

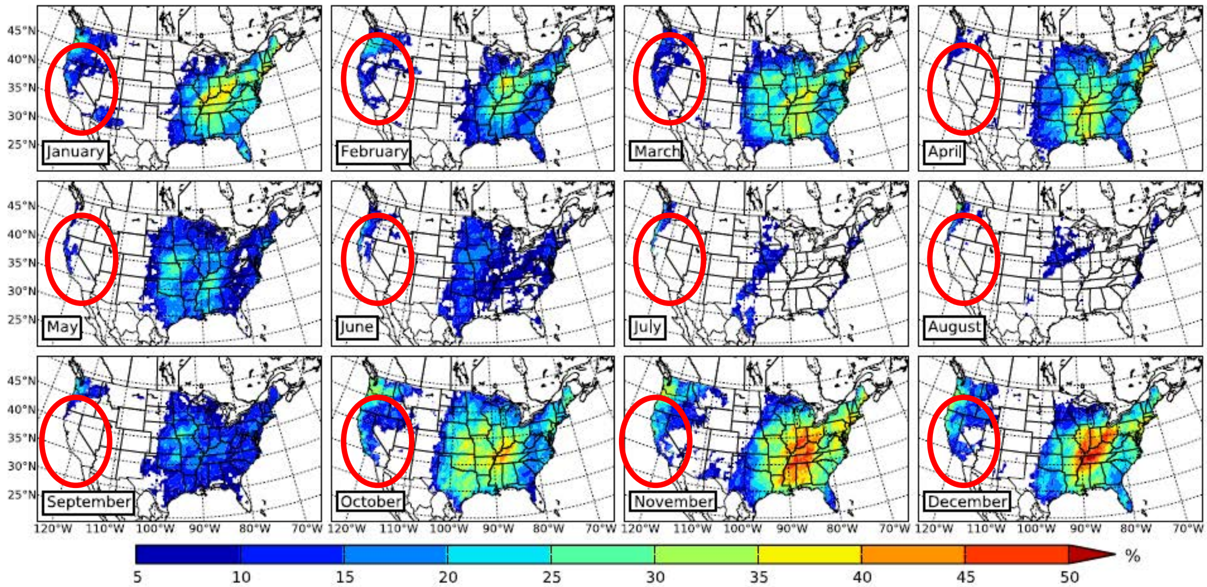

Figure 2.17. Average fraction of precipitation from atmospheric rivers (%) in each month for the U.S. from 1979 – 2012. The California Region is generally shown in the red oval (Lavers et al., 2015).

A study by Cook et al. (2014) used tree ring data to assess the frequency and severity of droughts over the past millennium (1000 – 2005) across the U.S. For the southwestern U.S., which includes the California Region, the authors identified a decline in the number of droughts per century, although the finding is not considered statistically significant (p=0.11). The authors also found a marginally significant increase in the balance between moisture supply (precipitation) and demand (evapotranspiration as a function of temperature) as defined by the Palmer Drought Severity Index (PDSI) over the same period (**Figure 2.18**).

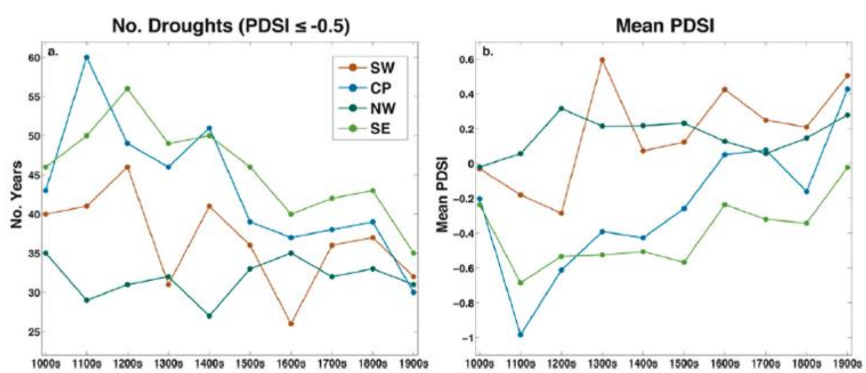

Figure 2.18. Trends in number of drought years per century (left) and mean PDSI across all years of each century. The California Region is within the Southwest (SW) (Cook et al., 2014).

Key point: No consistent trend has been identified in the region's historical precipitation data, with little consensus across the literature.

2.3. Hydrology

Studies of trends and nonstationarity in streamflow data collected over the past century have been performed throughout the continental U.S., inclusive of the California Region.

In 2013, Xu et al. investigated trends in streamflow for approximately five stations in the California Region. This study used the Model Parameter Estimation Experiment (MOPEX) dataset for the period 1950 – 2000. Gages within the California Region primarily reported no statistically significant (at 95% C.I.) trend in streamflow.

A study by Sangarika et al. (2014) evaluated data from 240 unimpaired streamflow stations throughout the U.S. from 1951 – 2010. Similar to Xu et al., no statistically significant (90% C.I.) trend was found within the California Region.

Kalra et al. (2008) performed a study using recorded streamflow data from 639 unimpaired stations to assess trends and step changes in streamflow between 1951 and 2002. Kalra et al. reported no significant (95% C.I.) trend in streamflow within the California Region.

Hydrological trends were evaluated by (Das et al., 2009) for the mountainous snow-affected regions of the western United States. The authors analyzed many variables including April 1 snow water equivalent (SWE) and October through March precipitation totals over a historical time period of 1950 – 1999. In addition, the ratio of these variables was evaluated in order to obtain a snow-based climate index that is more directly sensitive to temperature changes. These authors found primarily decreasing trends in the ratio of April 1 SWE compared to October through March precipitation totals, and slight increases in January through March runoff fractions within areas of the California Region for the study period.

Also with a focus on the western U.S., Regonda et al. (2005) evaluated the seasonal climate shifts in hydroclimatology from 1950 – 1999. Daily streamflow data analyzed in the study was obtained from the USGS Hydroclimate Data Network (HCDN) database. SWE data was obtained from snow-course surveys conducted by the Natural Resources Conservation Service (NRCS). Precipitation and temperature data for the study were obtained from the National Weather Service Cooperative Network (COOP). Regression analyses were used to evaluate trends in the datasets. For the California Region, spatial variability exists in the historical trends in the timing of spring streamflows, with some areas showing earlier timing and others showing later timing (**Figure 2.19a**), however, none of the trends in the California Region are statistically significant. Evaluation of the April 1 SWE trends indicated primarily a decrease in the California Region, with some areas of statistically significant trends (**Figure 2.19b**). Annual streamflow rates within the California Region have primarily increased, but not at a statistically significant level (**Figure 2.19c**).

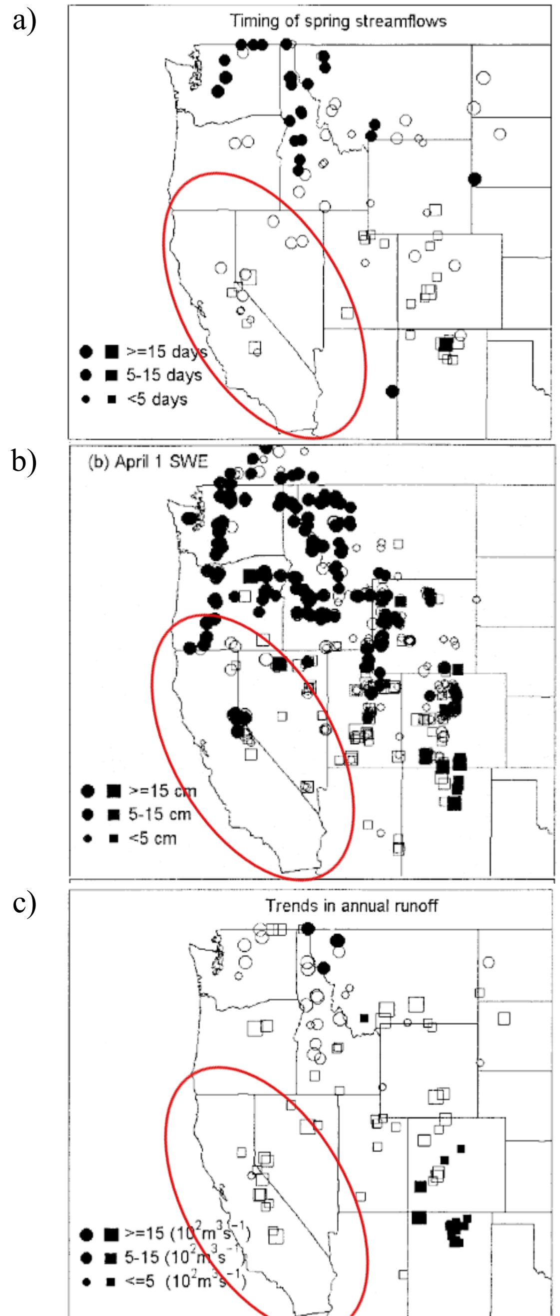

Figure 2.19. a) Changes in peak snowmelt streamflow timing (days), b) Changes in April monthly SWE (cm), and c) changes in annual streamflow (100 $m^3 s^{-1}$), from 1950 – 1999. Circles indicate earlier flow timing or decreasing trends, and squares indicate later timing or increasing trends. Filled (open) symbols represent stations passing (failing) significance tests, based on two-tailed *t* test. The California Region is with the red circle (Regonda et al., 2005).

Hoerling et al. (2013) used observed climate records to analyze the last 100 years of climate variability in the southwestern U.S. The authors compared the basin-mean daily streamflow of 2001 – 2010 to 1931 – 2000 for the Sacramento-San Joaquin Rivers, located within the California Region, and found the rivers had 37 percent less mean flow from 2001 – 2010 compared to the 1931 – 2000 time period. In addition, these authors evaluated the timing of streamflow by comparing the date at which half of the annual streamflow had been discharged. For the California Region, spatial variability of streamflow timing was observed, with streamflow timing occurring earlier by up to 10 days in some areas, and with streamflow timing occurring later by about 10 days in other areas. Streamflow timing observations were reported with 90 to 95% confidence (**Figure. 2.20**).

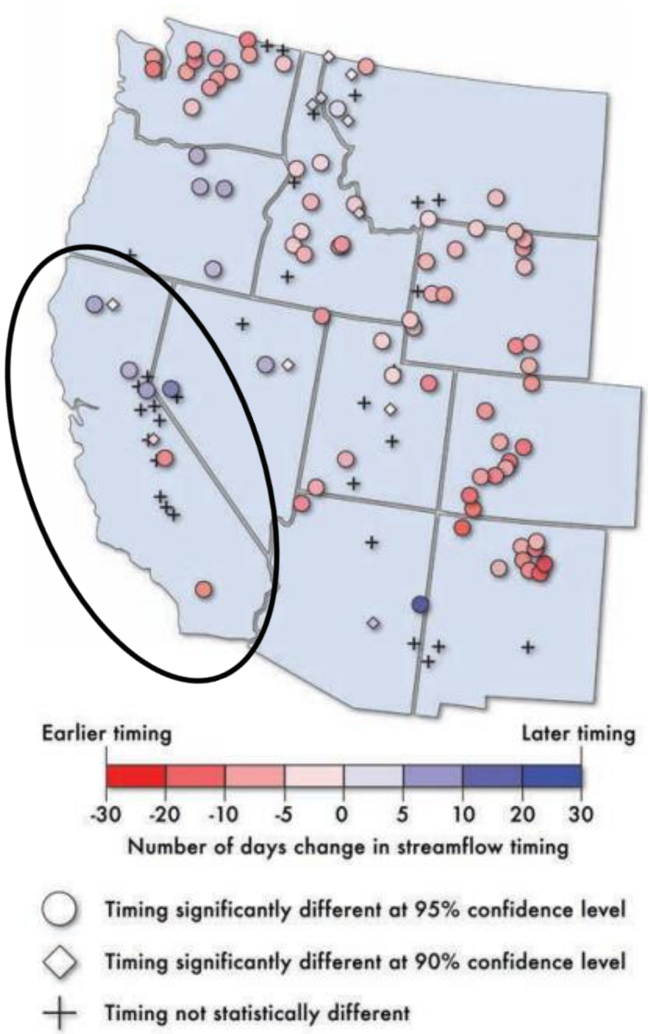

Figure 2.20. Changing streamflow timing 2001 – 2010 compared to 1950 – 2000. Differences between 2001 – 2010 and 1950 – 2000 average date when half of the annual streamflow has been discharged for snowmelt-dominated streams. The California Region is with the black circle (Hoerling et al., 2013).

Lastly, the third NCA report indicates a decreasing trend in streamflows in the California Region (Garfin et al., 2014). Between 2001 and 2010, streamflows within the Sacramento-San Joaquin watershed (located in the California Region) were reported to have been 5 to 37 percent lower than the 20th century average. Statistical significance of this information was not provided.

Key point: Literature on observed streamflow trends in the California Region have very low consensus. The majority of studies suggest that no statistically significant trends have been identified in the region's streamflow data for the latter half of the 20th century, although advances in the timing of spring runoff and reductions in April 1 SWE were observed.

2.4. Summary of Observed Climate Findings

Evidence has been presented in the recent literature of increases in both annual average, and minimum and maximum temperature in the California Region over the past century. High consensus exists in the literature supporting these general observed temperature trends. However, seasonal variability and spatial variability exists in many temperature trends within the region. Increases in annual average temperatures appear to be greatest along the coast and in southern California with less warming evident in the mountainous areas of the region. Seasonally, less consensus exists regarding the variability in temperature changes. Trends in maximum temperatures have generally illustrated the largest increases occurring in southern and central California. Minimum temperatures are also projected to decrease slightly in the mountainous areas of northern and central California with increases in minimum temperatures in the central and southern California at lower elevations within the California Region.

Trends in annual precipitation totals have been variable within the California Region in the 20th century. For the California Region as a whole, changes in annual precipitation totals are spatially variable. Observed precipitation trends may be influenced by the topographic diversity of the region or possibly the beginning and end dates over which each study was evaluated thus, making it difficult to develop general trends for the entire California Region.

Similarly, variability has been observed in historical streamflow trends and other hydrologic data for the California Region with relatively low consensus across the literature. The majority of the studies report no statistically significant trends in historical streamflows over the second half of the 20th century.

3. Projected Climate Trends

While historical data is essential to understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities have begun using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed GCMs, are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the California Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview, and similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures and extreme precipitation events will increase over the next century in the California Region. Little consensus exists supporting a changes in hydrology and precipitation for the California Region.

3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. Results of studies inclusive of the California Region typically fall in line with these generalizations.

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the California Region, results show a shift to a more arid climate by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

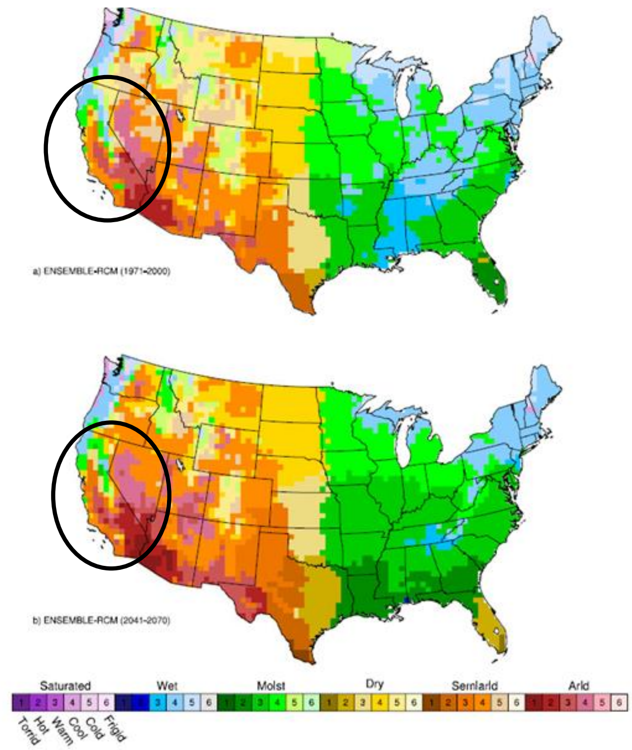

Figure 3.1. Revised Thornthwaite climate types projected by regional climate models. The California Region is within the black oval (Elguindi and Grundstein, 2013).

In a regional study, Cayan et al. (2013) investigated projected temperature trends for the southwestern U.S. Several Coupled Model Intercomparison Project 3 (CMIP3) GCMs were used, coupled with dynamically downscaled models and biased correction and spatial downscaling. The A2 (high) and B1 (low) emissions scenarios were evaluated for future projections. An increase in annual average temperature is predicted with high confidence for the southwestern U.S. from 2001 to 2100. Seasonal temperatures trends are projected to increase, with the highest increases in summer temperatures (**Figure 3.2**). Within the Klamath Basin in California, historical and projected temperature trends for January and July were evaluated for the A2 (high) and B1 (low) emissions scenarios from 1950 – 2100 (**Figure 3.3**). Similar to the southwest U.S. as a whole, temperature increases are projected within the California Region for January and July, with the largest potential temperature increases in summer under high emissions scenarios. With the increase in temperatures, the length of the freeze-free season in the California Region is projected to increase by approximately 10 to 45 days, spatially varying, in 2041 – 2070 compared to a baseline period of 1971 – 2000. Specific information on confidence intervals was not provided with the study.

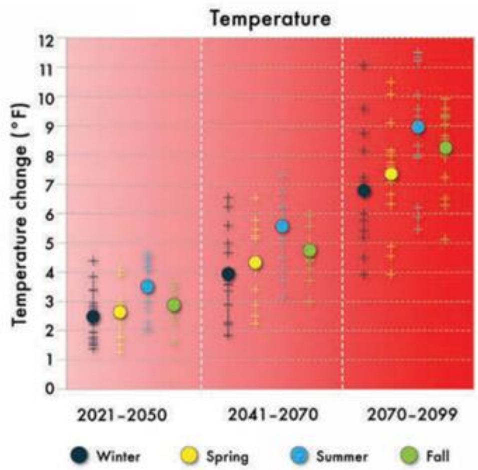

Figure 3.2. Projected trends in seasonal (winter: December – February, spring: March – May, summer: June – August, and fall: September – November) temperatures for the southwestern U.S, based on a fifteen-model average for the high emissions scenario relative to the 1971 – 2000 reference period (Cayan et al., 2013).

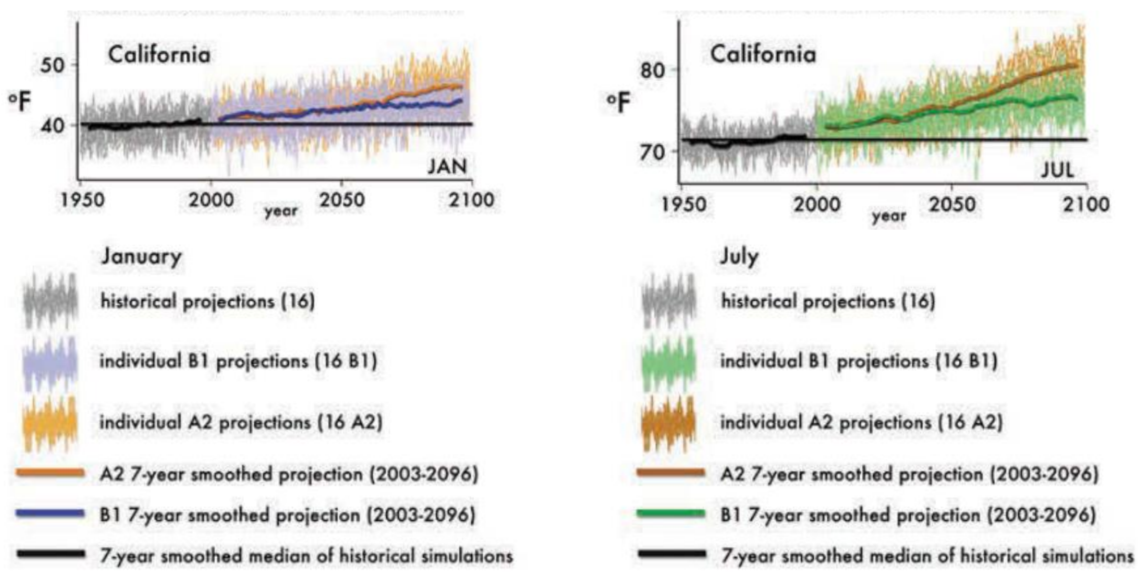

Figure 3.3. Biased corrected and spatially downscaled CMIP3 climate prediction average temperatures (Cayan et al., 2013).

A regional study by Gutzler and Robbins (2010) applied an ensemble of 18 GCMs, forced by a middle of the road (A1B) emissions scenario, to project temperature, precipitation, and drought changes for the western U.S. through 2100. Results for the California Region (**Figure 3.4**) indicate a projected increase in annual average temperature of approximately 2.0 to 3.5 ºC (3.6 to 6.3 ºF) for the last quarter of the 21st century compared to the last quarter of the 20th century.

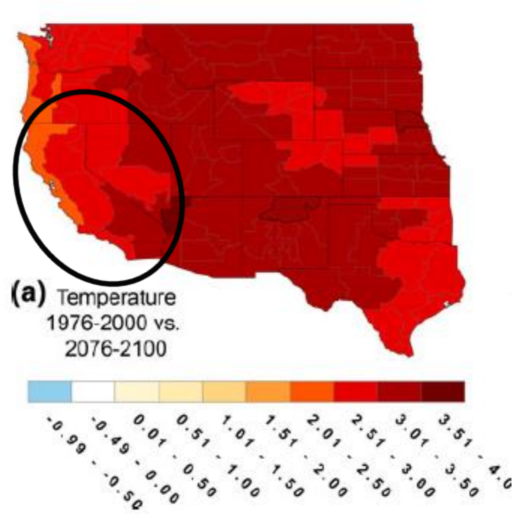

Figure 3.4. GCM projections of annual average temperature change, western United States. The California Region is within the black oval (Gutzler and Robbins, 2010).

The third NCA (Garvin et al., 2014) generally supports the findings presented above. Climate model projections for the southwestern U.S., inclusive of the California Region, presented in this report indicate an increase in annual average temperature over the next century by up to 8.5 °F (4.7 °C) depending on emissions scenario (**Figure 3.5**).

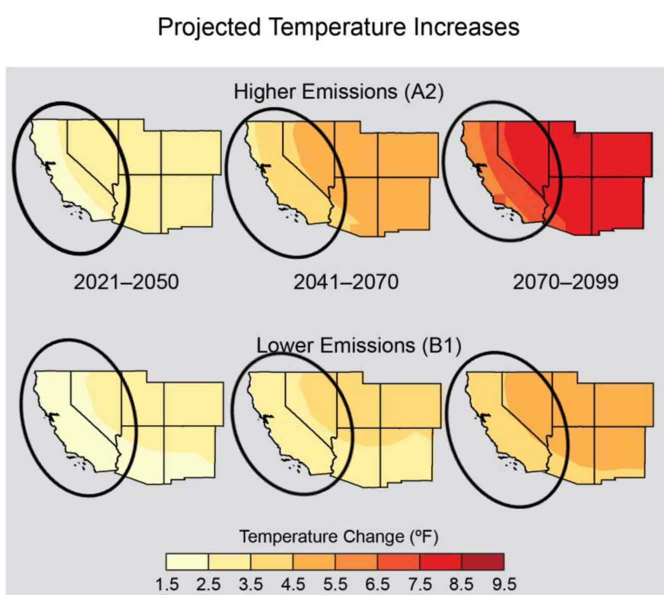

Figure 3.5. GCM projections of temperature change in the southwestern U.S. The California Region is within the black oval (Garfin et al., 2014).

For the California Region specifically, Cayan et al. (2008) evaluated future climate scenarios. Two GCMs were simulated with the B1 (low) and A2 (medium-high) emissions. The study predicted temperature increases of 1.5 ºC (2.7 ºF) to 4.5 ºC (8.1 ºF) by the end of the 21st century, depending on the model and emissions scenario evaluated, with the largest increases occurring in summer months.

Within the California Region, a study by Cloern et al. (2010) evaluated climate change within the San Francisco Estuary Watershed. The study compared projected climate scenarios to the baseline period of 1970 – 1999. Two different GCMs were used to simulate the B1 (low) and A2 (medium-high) emissions scenarios. Climate projections were downscaled for use in a variable infiltration capacity (VIC) model, the results of which are discussed in Section 3.3. Increasing temperature trends in the San Francisco Estuary Watershed were projected by the two GCMs in this study, as illustrated in **Figure 3.6**. The higher emissions scenario produced higher projected increases in temperature by the end of the 21st century.

Figure 3.6. Temperature projections from two GCMs (A2 scenario on the left, B1 scenario on the right) of temperature change in the San Francisco Estuary Watershed (Cloern et al., 2010).

Also within the California Region, Das et al. (2011) investigated climate change trends in the north and south Sierra Nevada areas as they relate to projected impacts on flooding. The study used results from three GCMs and evaluated trends through the 21st century compared to historical trends from 1951 – 1999. Projections were determined considering an A2 emissions scenario. All climate models project an increase in annual temperature by 2099 of 2.1 to 3.5 °C (3.8 to 6.3 °F) in the Sierra Nevada area compared to annual temperatures of 1951 – 1999.

A study by Maurer (2007) investigated the uncertainty in hydrologic impacts of climate change in the Sierra Nevada area, but also reported on temperature trends in this mountain region. The study evaluated results of 11 GCMs under the A2 (higher) and B1 (lower) emissions scenarios. Results of this study indicated increasing average temperatures of 2.3 to 3.8 °C (4.1 to 6.8 °F) by 2100 compared to the baseline period of 1961 – 1990, depending on emissions scenario and model results evaluated.

Trends in minimum and maximum temperatures across the continental U. S. were the focus of a study by Ashfaq et al. (2010). The study applied a single regional climate model to compare future projections (2071 – 2100) to historical climate (1961 – 1990). They quantified changes in summer and fall daily maximum temperature of up to approximately 5 K (9 ºF or 5 ºC) for the California Region, and spring and winter maximum temperature changes of approximate 3 to 4 K (5.4 to 7.2 ºF or 3 to 4 ºC). Daily minimum temperature changes were also projected to increase by approximately 5 K (9 ºF or 5 ºC) for the summer and fall, and approximately 3.5 K (6.3 ºF or 3.5 ºC) for winter and spring in the California Region.

Daily maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case) in a national analysis.

For the California Region, the results of their study show a projected increase in winter and spring maximum air temperature of 1.5 – 3.0 ºC (2.7 – 5.4 ºF) for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.7**). The results of the study project increases in maximum air temperature from 2 to 4 ºC (3.6 – 7.2 ºF) for summer and fall temperatures.

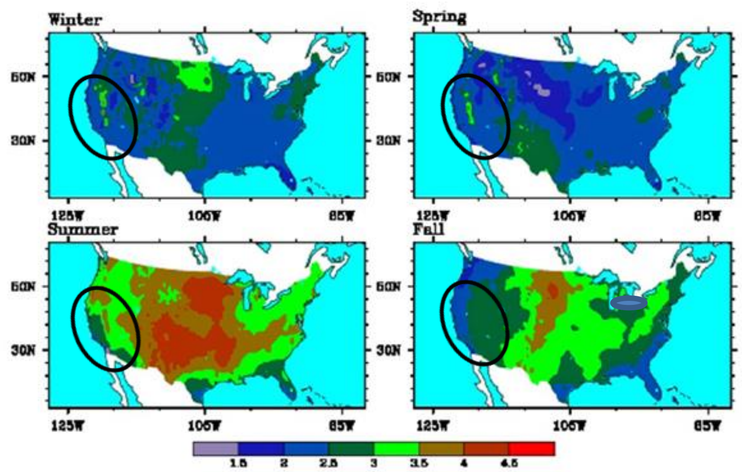

Figure 3.7. Projected changes in seasonal maximum air temperature, ºC, 2055 vs. 1985. The California Region is within the black oval (Liu et al., 2013).

Scherer and Diffenbaugh (2014) applied a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the southwestern U.S., including the California Region, model projections indicate steadily increasing air temperatures throughout the 21st century for both daily maximum summer and winter minimum temperatures (**Figure 3.8**). By 2090, projections show an increase of 4.0 ºC (7.2 ºF) in the summer maximum air temperature and 3.4 ºC (6.1 ºF) in the winter minimum temperature, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).

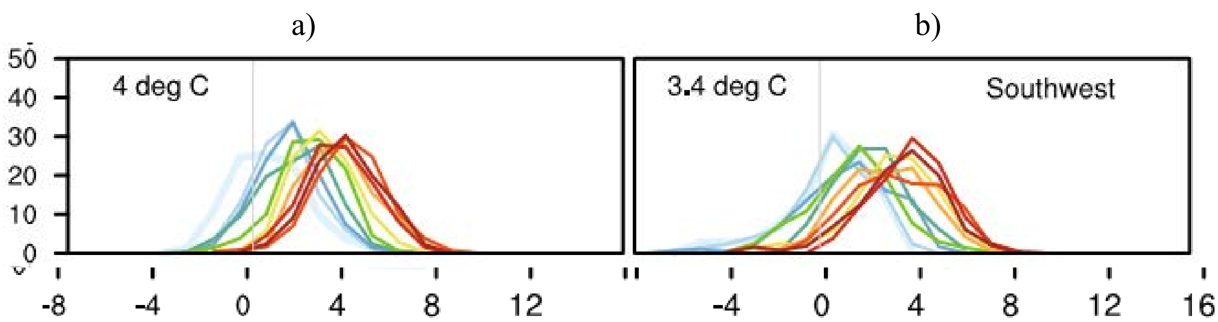

Figure 3.8. Probability distributions of GCM projections of years 2000 – 2100 by decade, southwestern U.S. a) Summer maximum temperatures months: June – August, b) Winter minimum temperatures months: December – February (Scherer and Diffenbaugh, 2014).

Projections of changes in temperature extremes have been the subject of several recent studies. A 2006 study by Tebaldi et al. applied nine GCMs at a global scale focused on extreme precipitation and temperature projections. Model projections of climate at the end of the century (2080 – 2099) were compared to historical data for the period 1980 – 1999. For the general California Region, using an A1B climate scenario, spatial variability in extreme temperature range (annual high minus annual low temperature) is illustrated, with some areas of slight increases and some areas of slight decreases. A statistically significant (indicated by concurrence of at least five out of nine models) increase in a heat wave duration index (increase of 3 to 4.5 days per year that temperatures continuously exceed the historical norm by at least 5 ºC or 9 ºF), and a statistically significant moderate increase in the number of warm nights (6 to 7.5 percent increase in the percentage of times in the year when minimum temperature is above the 90^{th} percentile of the climatological distribution for the given calendar year), compared to the baseline period in the California Region. The number of frost days, (defined as the annual number of days with minimum temperatures below 0 ºC or 32 °F) is predicted to decrease, with statistical significance, by up to 5 days per year in the southwestern U.S., inclusive of the California Region.

In a study by Kunkel et al. (2010), two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the California Region, projections indicate spatial variability, with up to a 7.5 ºC (13.5 ºF) increase in three-day heat wave temperatures and up to an 80-day increase in the annual number of heat wave days for a 2086 planning horizon compared to a recent historical baseline of 1976. A later study of the southwestern U.S. by Kunkel et al. (2013) showed a statistically significant decrease in the number of days with a minimum temperature less than 32 °F (0 ºC) for the 2041 – 2070 time period compared to the reference period of 1980 – 2000 based on the output from the eight North American Regional Climate Change Assessment Program (NARCCAP)'s Regional Climate Model simulations of the A2 emissions scenario (**Figure 3.9)**. Similarly, the number of days with maximum temperatures exceeding 95 °F (35 ºC) is projected to increase by up to 30 days per year in 2041 – 2070 compared to the baseline period of 1980 – 2000 (**Figure 3.10**). In this study, the reduction in the projected number of days with temperatures below 32 °F is concentrated in northern and mountain regions whereas projected increases in the number of days with maximum temperatures above 95 °F are greatest in the central valley and extreme southeastern California.

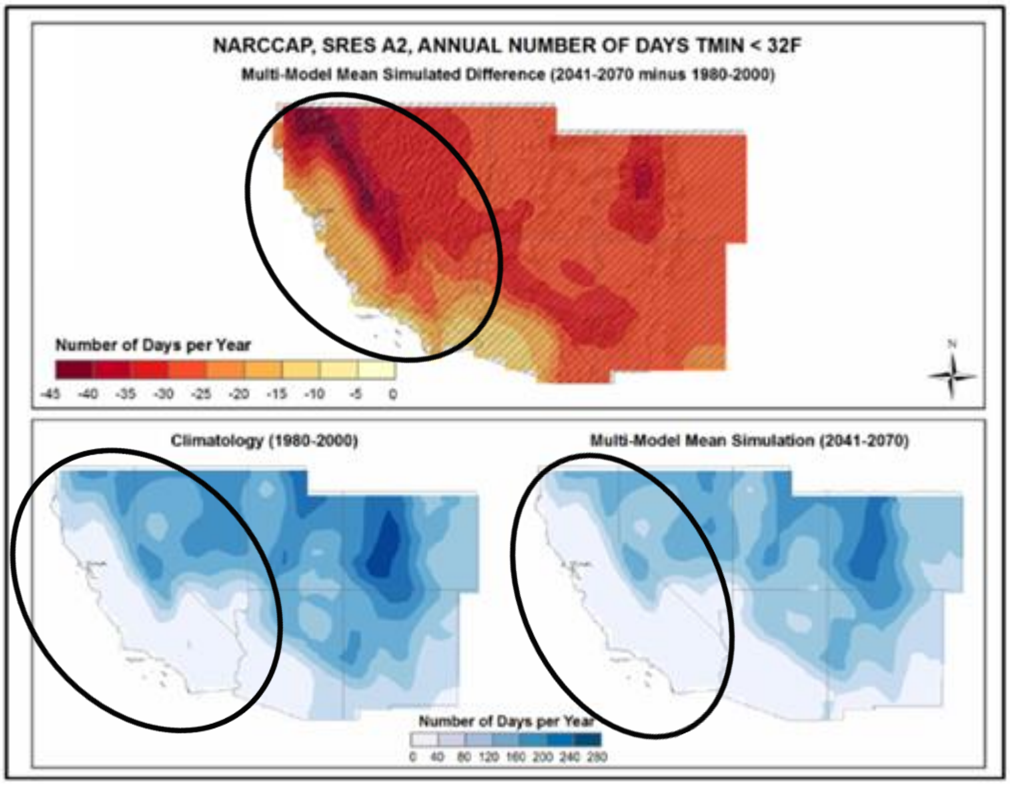

Figure 3.9. (Top) Simulated difference in mean annual number of days with a minimum temperature less than 32 °F (0 °C) for the 2041 – 2070 time period compared to a 1980 – 2000 reference period. Hatching indicates statistical significance (> 50 percent of the models show a statistically significant change with 67 percent agreeing on the sign of the change). (Bottom left) Mean annual number of days with minimum temperatures less than 32 °F (0 °C) for the 1980 – 2000 reference period. (Bottom right) Simulated mean annual number of days with minimum temperatures less than 32 °F (0 °C) for the future time period (2041 – 2070). The California Region is within the black ovals (Kunkel et al., 2013).

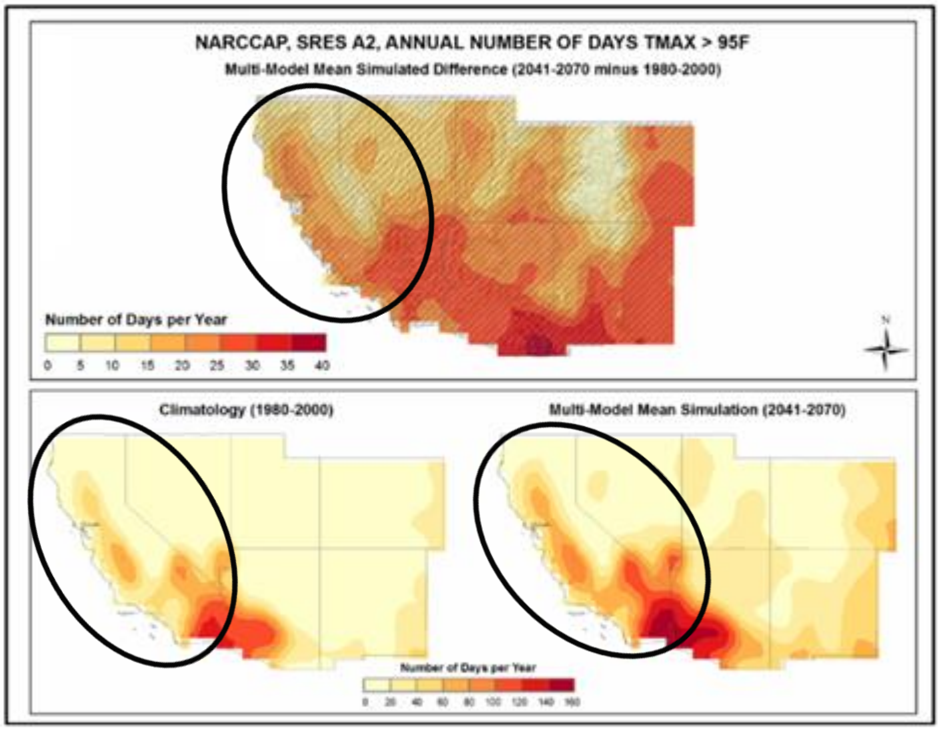

Figure 3.10. (Top) Simulated difference in mean annual number of days with a maximum temperature greater than 95 °F (35 °C) for the 2041 – 2070 time period compared to a 1980 – 2000 reference period. Hatching indicates statistical significance (> 50 percent of the models show a statistically significant change with 67 percent agreeing on the sign of the change). (Bottom left) Mean annual number of days with maximum temperatures greater than 95 °F (35 °C) for the 1980 – 2000 reference period. (Bottom right) simulated mean annual number of days with maximum temperatures greater than 95 °F (35 °C) for the future time period (2041 – 2070). The California Region is within the black ovals (Kunkel et al., 2013).

Another regional study by Dettinger et al. (2012) evaluated trends in annual minimum temperature and annual mean precipitation (the latter of which is discussed in Section 3.2) for the southwestern U.S. using results from National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean atmospheric GCM model and National Center for Atmospheric Research's Parallel Climate Model (PCM1) simulating the A2 (middle of the road) and B1 (low) emissions scenarios over the 21st century. Results from this analysis show an increasing trend in annual average minimum temperature, up to 6 °C (10.8 °F), for all models and associated emissions scenarios (**Figure 3.11**).

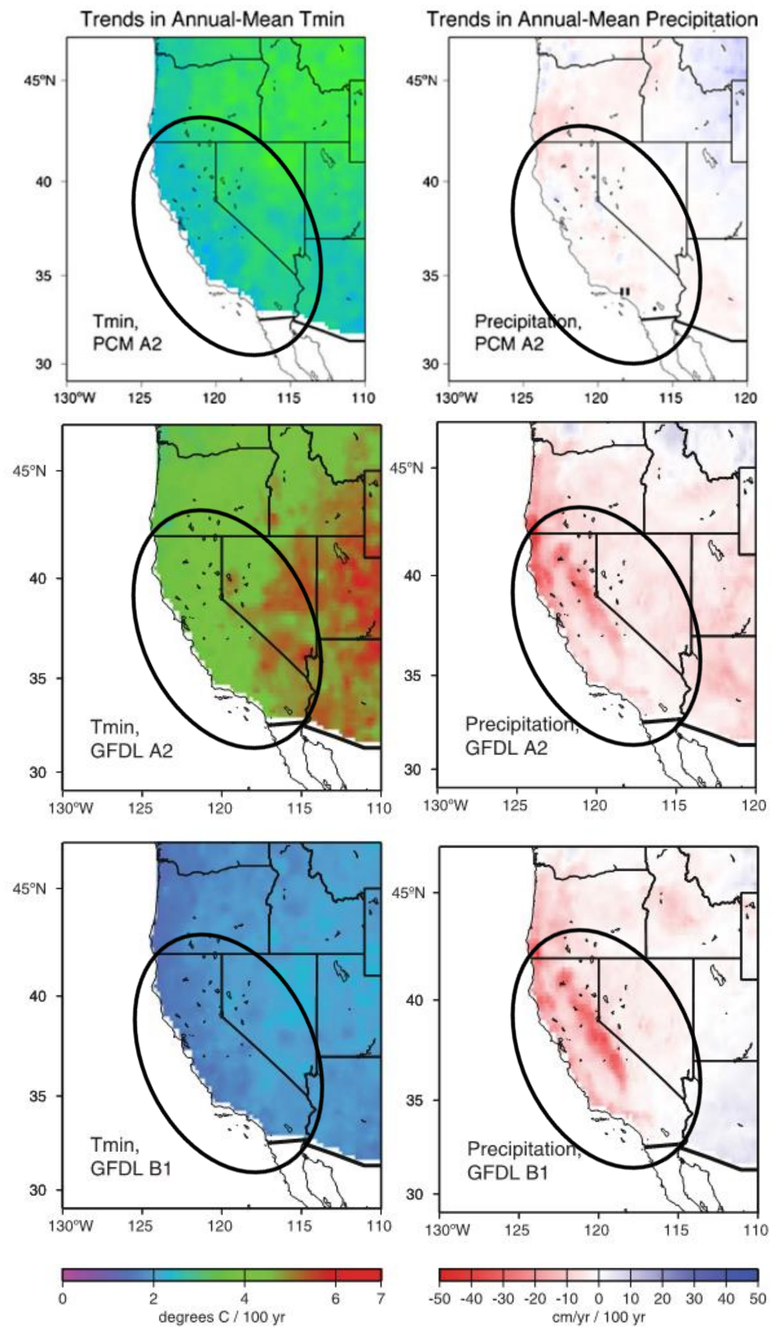

Figure 3.11. Downscaled temperature (left) and precipitation (right) trends for the 21st century under the A2 and B1 emissions scenarios from the GFDL and PCM1. The California Region is within the black ovals (Dettinger, 2012).

Gershunov et al. (2012) studied trends in heat waves in California. The study used four GCMs and an A2 emissions scenario to evaluate heat waves, defined as a group of consecutive days in which maximum or minimum temperatures exceed the 95th percentile threshold. Projected heat wave trends were compared to a baseline period of 1950 – 1999. Heat waves were categorized into two types for the purposes of this study: Type 1 heat waves, which are dry daytime heat waves, and Type II heat waves, which are humid nighttime accentuated events. All four GCMs showed significant increases in heat wave activity of both types. Type II heat waves are predicted to increase more intensely than the Type I events. The study predicts that desert heat waves will become less intense in the future, while coastal heat waves are projected to intensify.

The study of the California Region by Cayan et al. (2008), mentioned previously, also evaluated projected changes in the occurrence of extreme daily temperatures between June and September in northern and southern California. The study illustrates a projected increase in the occurrence of 99.9 percentile temperatures, in some cases increasing from 4 days per year during the period of 1961 – 1990 to over 200 occurrences by the end of the 21st century under the high emissions scenario. These projections of increased extreme temperatures are consistent with the projections from other studies.

Key point: Strong consensus exists in the literature that projected mean, minimum, maximum, and extreme temperatures in the study region show an increasing trend over the next century.

3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the California Region are variable with topography and latitudinal changes throughout the region.

From a global analysis using three GCM projections, Hagemann et al. (2013) projects spatial variability in annual precipitation changes, with a range from -20 mm per year in southern California to up to 200 mm per year in the northern parts of the region (**Figure 3.12**).

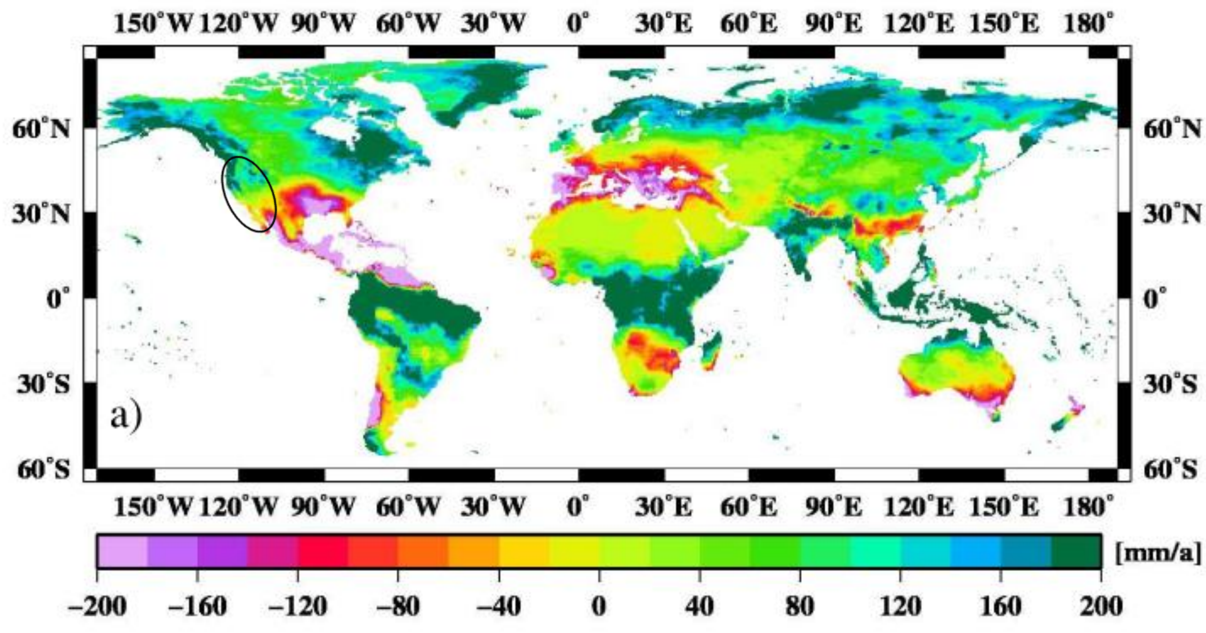

Figure 3.12. Projected (2071 – 2100) changes in annual precipitation compared to baseline, 1971 – 2000, conditions, mm/year. The California Region is within the black oval (Hagemann et al., 2013).

The Liu et al. (2013) study of the continental U.S., mentioned in Section 3.1, quantified spatial and seasonal variability in projected precipitation trends within the California Region. The study projects spatial variability in all seasons, with the largest increases and decreases in winter, with increases in southern California and decreases in northern California for a 2041 – 2070 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985) in the California Region (**Figure 3.13**). Decreasing precipitation trends for this time period are projected in summer and spring, with pockets of slight increases in southern California projected for summer, and areas of larger decreases projected in the mountainous areas of the region in spring. Fall precipitation trends are projected to primarily increase, with the largest increases occurring in southern California and the mountainous areas of northern California.

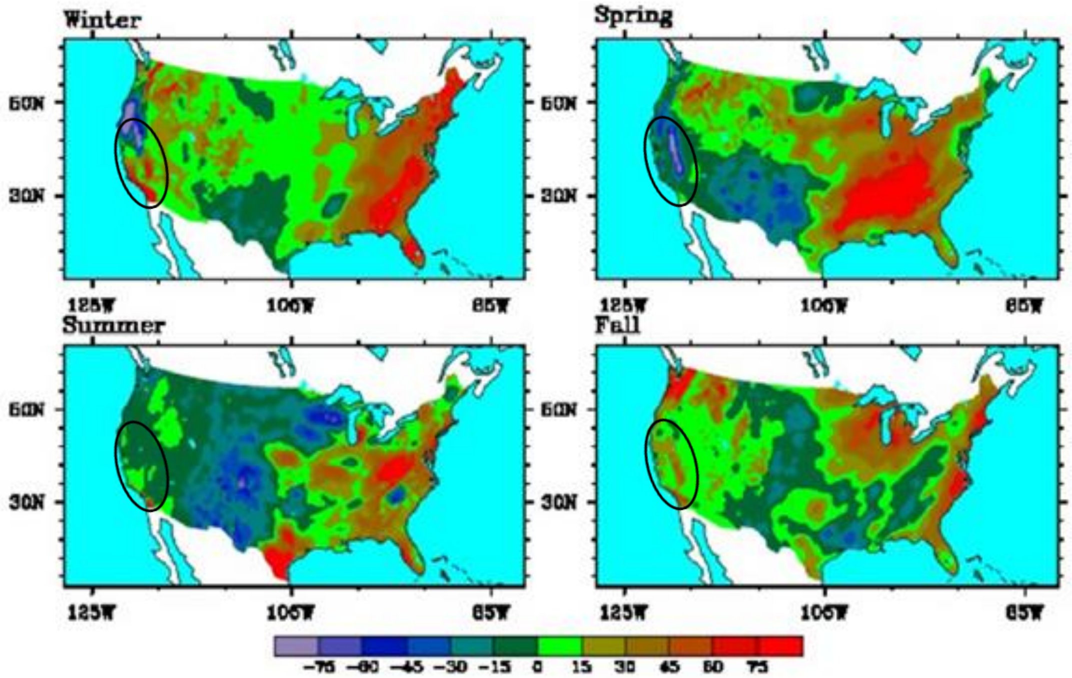

Figure 3.13. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The California Region is within the black oval (Liu et al., 2013).

In a study of the western U.S. by Gutzler and Robbins (2010), discussed in Section 3.1, the middle of the road (A1B) ensemble of projections show spatial variability in precipitation trends throughout the California Region. Areas of southern California exhibit decreasing trends or no change, while northern areas of the California Region exhibit no change or slight increasing trends in annual average precipitation (**Figure 3.14**) for the last quarter of the 21st century compared to the last quarter of the 20th century. The authors also project an increase in future drought indices for the region, as a function of changing climate, that indicate reduced soil moisture and more drought-prone conditions.

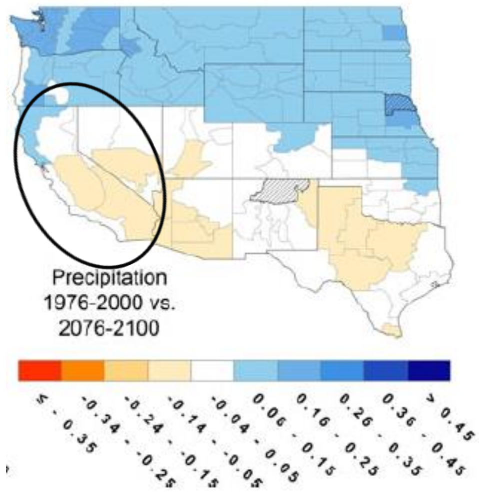

Figure 3.14. GCM projections of annual average precipitation change (mm $month^{-1}$), western United States. The California Region is within the black oval (Gutzler and Robbins, 2010).

Several regional studies have been performed on precipitation trends in the southwestern U.S., inclusive of the California Region. In support of the third NCA, Cayan et al. (2013) prepared a report that summarizes the most recent understanding of projected climates in the southwest United States. These authors calculated the median of sixteen downscaled simulations for three future time horizons: 2021 – 2050, 2041 – 2070, and 2070 – 2099. For the California Region, Cayan et al. (2013) found that under a high-emissions scenario, annual average precipitation is projected to be 80 – 100 percent of the historical average by the end of the 21st century, with decreases mainly in southern and central California. The results are summarized in **Figure 3.15**.

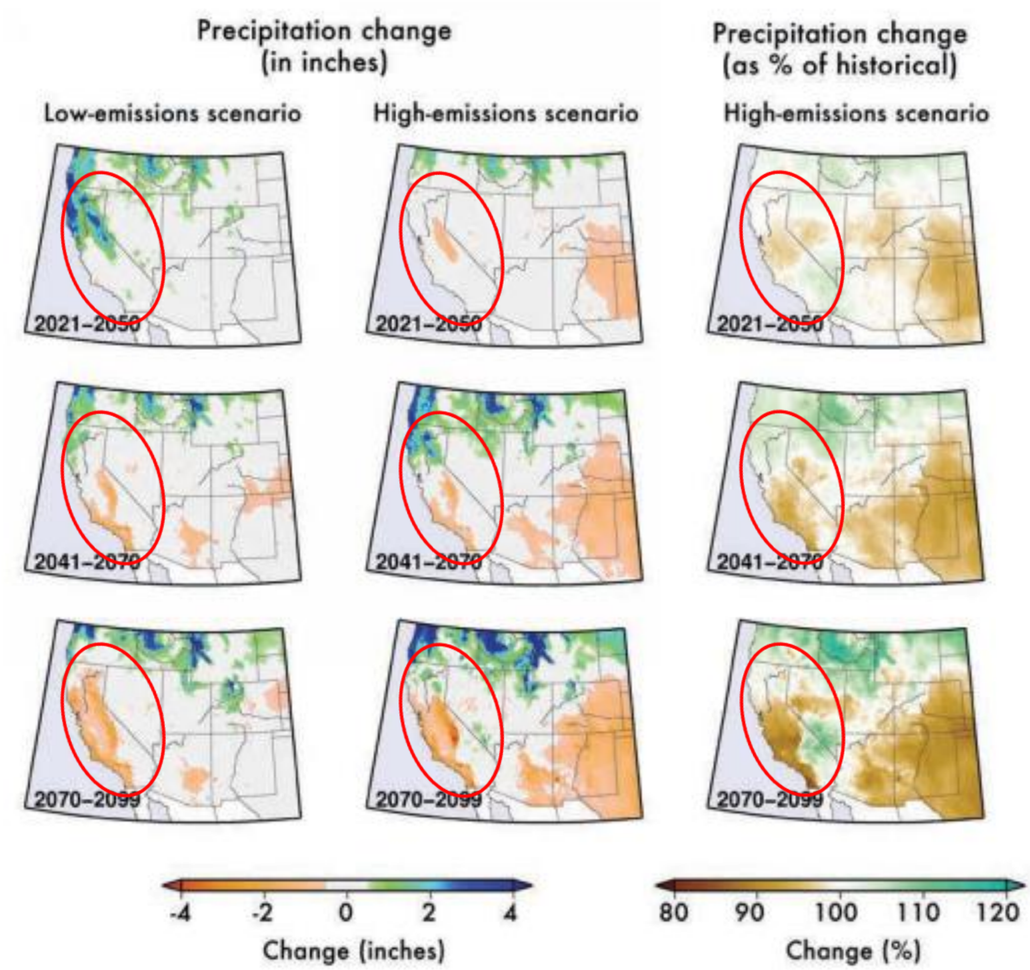

Figure 3.15. Ensemble projections of future precipitation (mid-21st century vs. historical baseline). The California Region is within the red oval (Cayan et al, 2013).

A study by Seager and Vecchi (2010) projected seasonal climate trends in southwestern North America based on 24 climate models used as part of the Intergovernmental Panel on Climate Change (IPCC) Assessment Report Four (IPCC AR4). Results of the analysis indicate a drop in precipitation in the winter and summer seasons across the 21st century, and an increase in winter evaporation. In summer, evaporation decreases in parallel with precipitation, reflecting decreases in moisture available for evaporation (**Figure 3.16**).

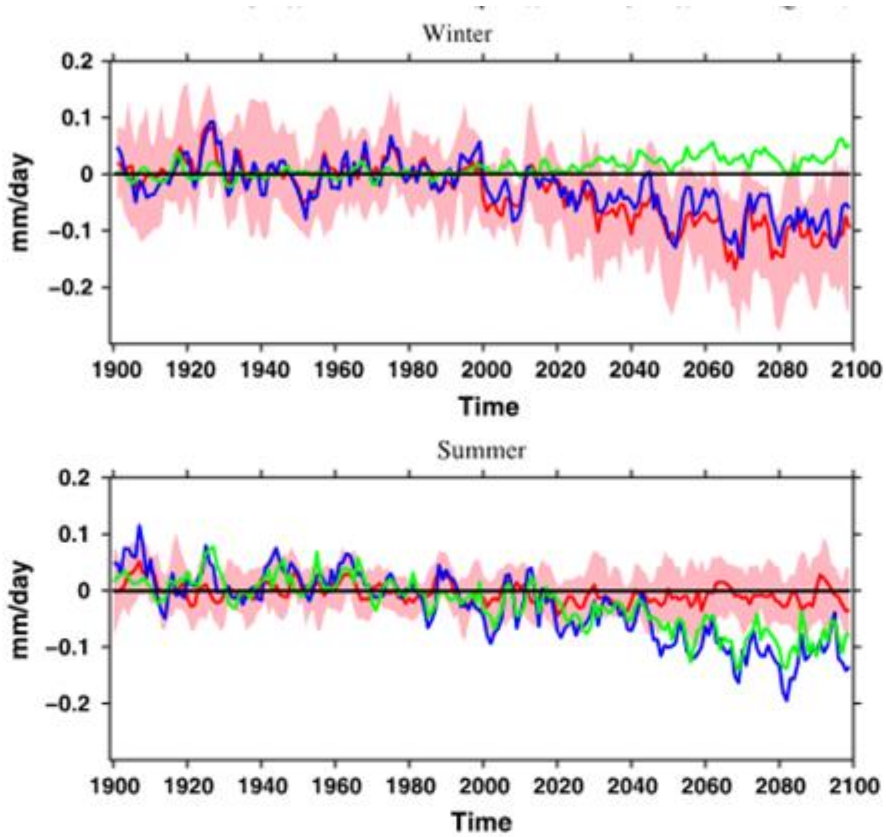

Figure 3.16. Timeseries of 1900 – 2009 of the median of 24 IPCC AR4 model's simulated and projected change in precipitation (blue), evaporation (green) and precipitation–evaporation (red) in the southwestern U.S., with the 25th and 75th percentiles of the distribution (shading) for winter (October through March) and summer (April through September) (Seager and Vecchi, 2010).

A study by Dettinger (2012), discussed in Section 3.1, simulated projected trends in annual mean precipitation over the 21st century based on two regionally downscaled model results with two emissions scenarios for the southwestern U.S. For the California Region specifically, the projections primarily indicate decreasing precipitation trends for the 21st century, as shown above in **Figure 3.11**.

In addition to the study's evaluation of the southwestern U.S., Cayan et al. (2013) also evaluated future precipitation trends at a watershed scale for three regions, one of which was the California Region. The study noted large spatial and temporal variability in historical and projected precipitation trends (**Figure 3.17**). This study found, with medium-low confidence, a decrease in precipitation in the southern portion of the southwestern U.S. and no change or an increase in precipitation in the northern portions of the southwestern U.S. Little change in precipitation volume was projected for the California Region.

An older study by Cayan et al. (2008), which focused specifically on the California Region, projected precipitation trends through the end of the 21st century based on two GCMs and two emissions scenarios. The study evaluated these projections in northern and southern California. The study predicted small changes in precipitation, with little consensus in projections across models and emissions scenarios. While there is little consensus with regard to increasing versus decreasing precipitation changes, results indicate that percent change in precipitation will be larger in summer than in winter.

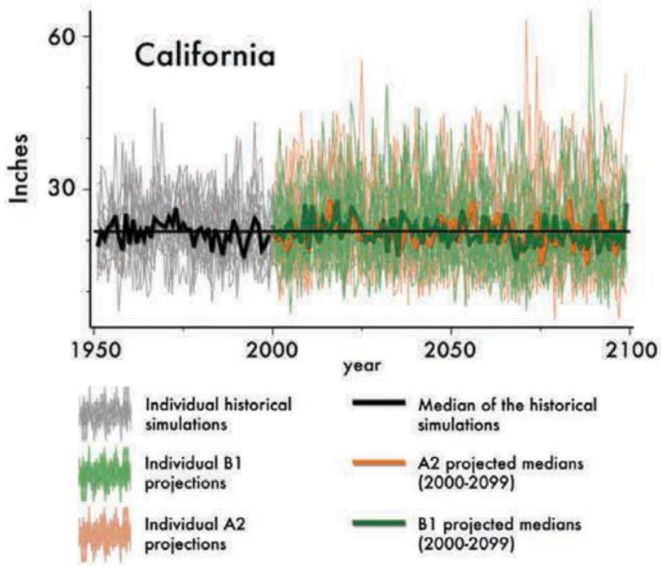

Figure 3.17. Bias corrected and downscaled CMIP3 precipitation model projections (inches) and historical simulations of the A2 and B1 emissions scenarios. (Cayan et al., 2013)

On a smaller scale, a study by Cloern et al. (2010), discussed in Section 3.1, evaluated the influence of climate change on the San Francisco Estuary Watershed. The two GCMs evaluated in the model project little change in precipitation trends through the end of the 21st century (**Figure 3.18**).

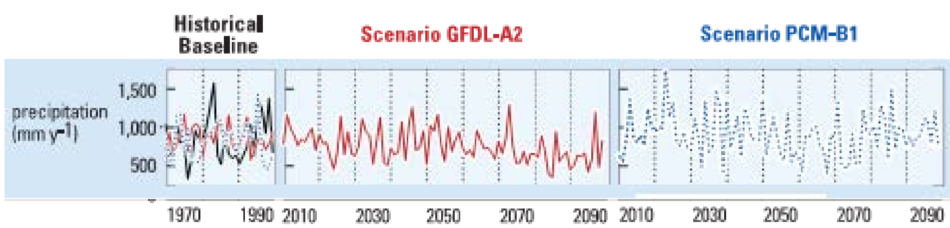

Figure 3.18. Precipitation projections from two GCMs (A2 scenario on the left, B1 scenario on the right) simulated with two different emissions scenarios in the San Francisco Estuary Watershed. (Cloern et al., 2010).

A study by Das et al. (2011), mentioned in Section 3.1, investigated climate change trends in the northern and southern Sierra Nevada areas as they relate to projected impacts on flooding. Projections in changes in precipitation by the end of the 21st century vary based on the model used, and vary spatially between northern and southern Sierra Nevada. The study predicts a range from decreases in annual precipitation of 14.5 percent to an increase in 5.4 percent of the 1951 – 1999 annual precipitation.

In addition, the study by Maurer (2007), discussed in Section 3.1, reported model variability as well as seasonal variability in projected precipitation trends. The 11 GCMs evaluated as part of the study projected general increasing trends in winter precipitation and decreasing trends in spring precipitation. Of the two emissions scenarios evaluated (A2 and B1), magnitudes of precipitation trends were greater under the A2, or higher emissions, scenario.

Future projections of extreme events, including storm events and droughts, are the subject of studies by Tebaldi et al. (2006) and Wang and Zhang (2008), and is captured in the study by Das et al. (2011). The first authors, as part of a global study, compared an ensemble of GCM projections for a 2080 – 2099 planning horizon with historical baseline data (1980 – 1999) with emissions scenario A1B. They report slight decreases, no change, or slight increases in the number of high (> 10 mm) precipitation days for the region, increases in the number of storm events greater than the 95th percentile of the historical record, and increases in the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast increases in the intensity and number of high volume storm events by the end of the 21st century for the general California Region.

Wang and Zhang (2008) also used downscaled GCMs to look at potential future changes in extreme precipitation events across North America. The GCMs were forced with the IPCC high emissions scenario (A2) to quantify a significant increase in the recurrence (1 to 2 times) of the current 20-year 24-hour storm event for their future planning horizon (2050 – 2099) in the California Region (**Figure 3.19**). They found a greater increase in extreme precipitation event risk in southern California than in areas to the north.

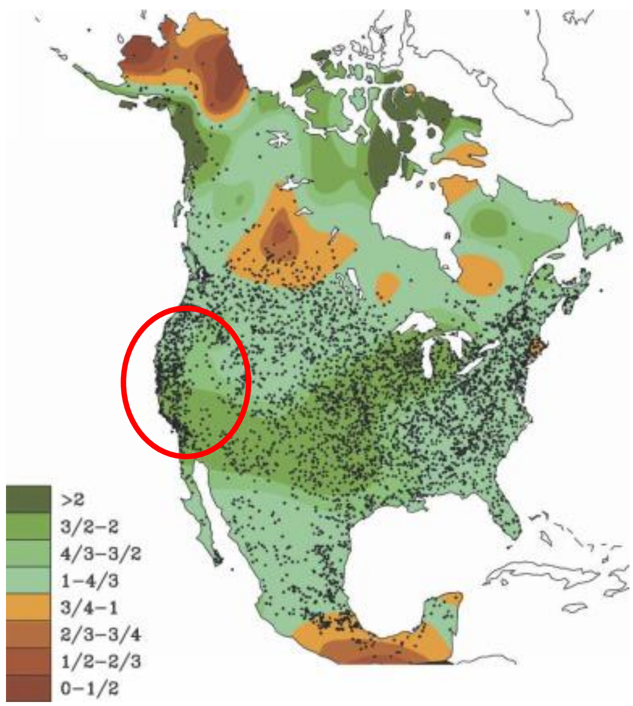

Figure 3.19. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The California Region is generally within the red oval (Wang and Zhang, 2008).

Das et al. (2011) evaluated trends in the frequency of extreme precipitation events over the north and south Sierra Nevada areas, within the California Region, as discussed in Section 3.1.

Extreme precipitation events in this study are defined as daily area-averaged precipitation larger than the 99th percentile values from the three GCMs used in the study over the baseline period of 1951 – 1999. The study reported increases in the frequency of extreme precipitation events, predicted by all GCMs in northern Sierra Nevada, and by two of the three GCMs in southern Sierra Nevada, by the end of the 21st century. The average number of extreme precipitation events per year for the baseline period of 1951 – 1999 was reported as 2.7. By the end of the 21st century, the average number of precipitation events is projected to increase, up to 4.2 events per year.

Precipitation in the California Region is often related to landfalling atmospheric rivers. Atmospheric rivers are long streams of concentrated, near-surface water vapor above the Pacific Ocean which deliver masses of warm, moist air to the California Region. They were the focus of several studies related to precipitation and streamflow trends throughout the region. Understanding the behavior of atmospheric rivers can help in identifying precipitation trends in the California Region. Atmospheric rivers have been identified as being responsible for 20 – 50 percent of precipitation and streamflow in the California Region (Dettinger et al., 2011). Dettinger (2011) studied changes in the frequency of days from December through February when atmospheric rivers most likely occur using a seven model ensemble of historical climate and projected future climate simulations. Using an A2 emissions scenario, this study projected an increase in the number of atmospheric rivers and a lengthening of the peak season of atmospheric river occurrence. Dettinger (2013) reports that six out of the seven climate models predict that the average rain and snow delivered to California by future atmospheric rivers will increase by an average of about 10 percent by the year 2100. The historical average of nine atmospheric rivers that impact the California coast each year is projected to rise to 11 by the end of the century. Atmospheric river landfalls in the mountains and hills in California often cause heavy precipitation and extreme streamflow events (Kim, 2013). Impacts of atmospheric rivers on the hydrology of the California Region is discussed further in Section 3.3.

A study by Warner et al. (2014) also investigated extreme precipitation events that occur along the west coast of North America associated with winter atmospheric river events. The study used phase 5 of the Coupled Model Intercomparison Project (CMIP5) to evaluate changes in precipitation trends from 2070 – 2099 compared to the baseline period of 1970 – 1999. The study found an increase of 11 – 18 percent in winter average precipitation along the west coast of the U.S. In addition, the frequency of days with vertically integrated water vapor transport is projected to increase as much as 290 percent by the end of the century.

Key point: Large variability exists, spatially, and across model projections, for future precipitation trends within the California Region. There is little consensus across the literature as to how precipitation trends will change, although many studies recognize this variability. Despite the low consensus in precipitation trends, extreme precipitation events are projected to increase in intensity and/or frequency with high consensus throughout the literature for the California Region.

3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models.

Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield (considered to be a surrogate for streamflow) across the U.S. Results are presented for both continuous spatial profiles across the country (**Figure 3.20**). For the California Region, and most of the U.S., contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts significant decreases in water yield, whereas the other projects significant increases in water yield.

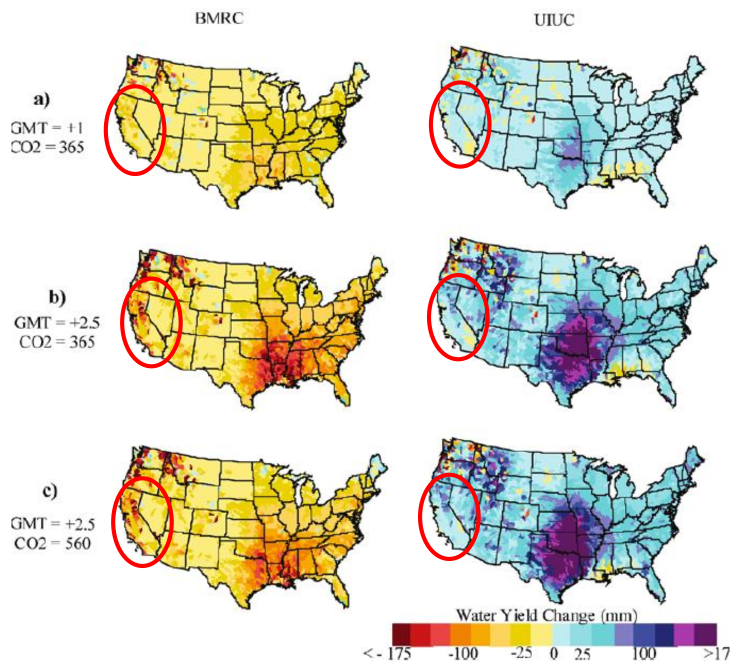

Figure 3.20. Projected change in water yield (from historical baseline), under various climate change scenarios based on two GCM projections. The California Region is within the red oval (Thomson et al., 2005).

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a 2013 study by Hagemann et al. In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections from Hagemann et al. (2013), for the California Region, show spatial variability, with some areas showing a decrease in runoff of up to 40 mm per year, and an increase of up to 20 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (**Figure 3.21**), assuming an A2 emissions scenario. Changes in seasonal runoff are similar, showing a trend in runoff between -20 to +10 mm, with changes during the fall seasons showing a potential sight increase in runoff and other seasons primarily projecting a decrease in runoff (**Figure 3.22**).

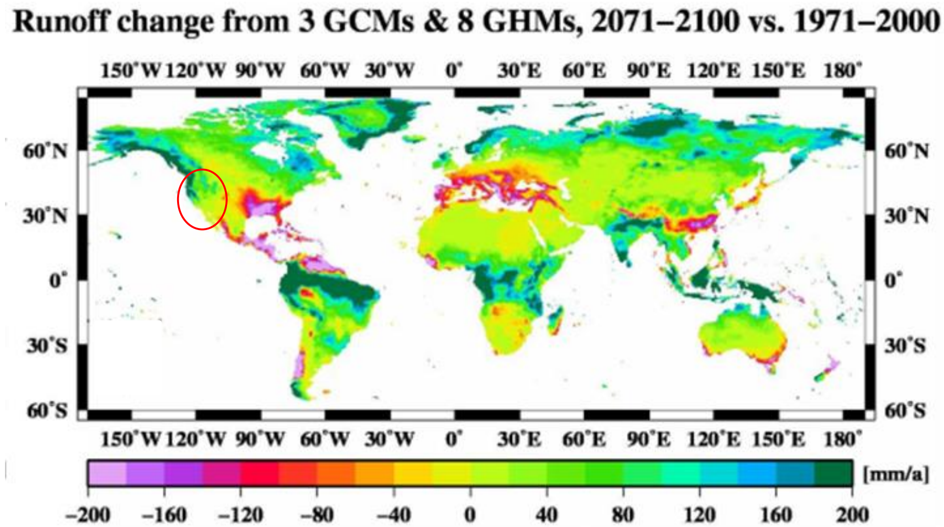

Figure 3.21. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The California Region is within the red oval (Hagemann et al., 2013).

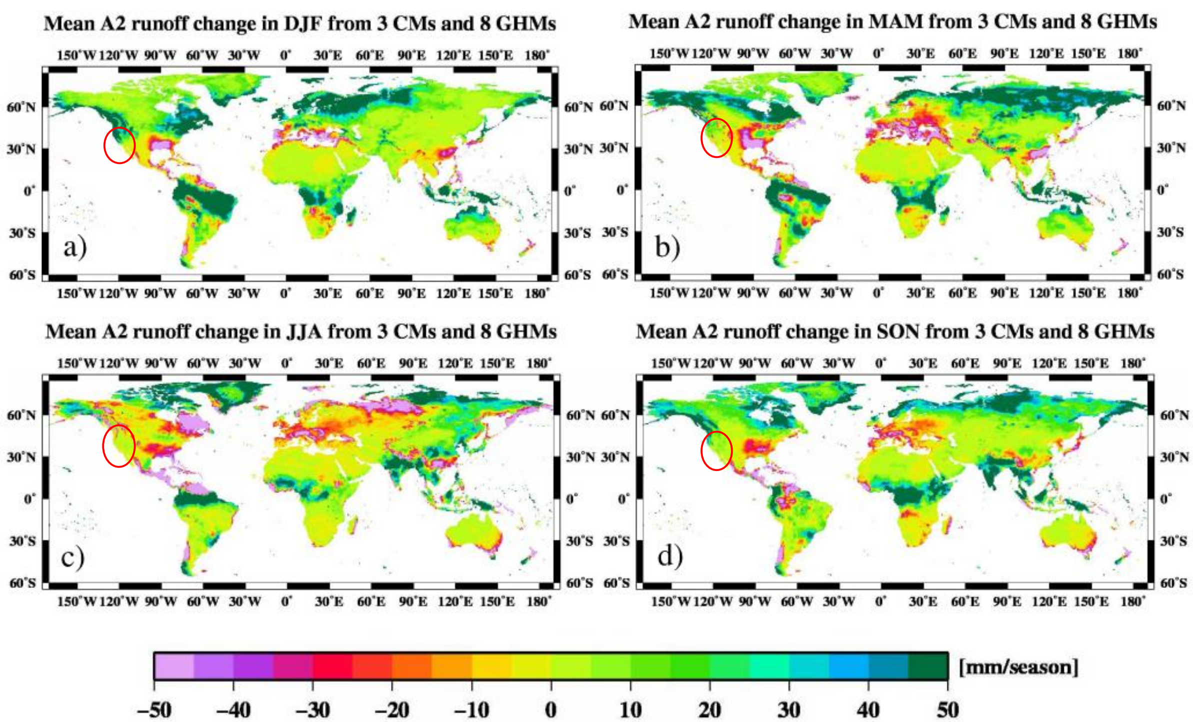

Figure 3.22. Ensemble seasonal (a. winter, b. spring, c. summer, d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071 – 2100 vs 1971 – 2000. The California Region is within the red oval (Hagemann et al., 2013).

A regional study by Cayan et al. (2013) evaluated projected changes in annual runoff based on sixteen simulations of a variable infiltration capacity (VIC) hydrologic model for the high emissions scenarios, comparing future conditions (2041 – 2070) to historical conditions (1971 – 2000). Projected annual median runoff is spatially and temporally variable within the California Region. In general, the mid and southwestern area of the California Region show a decreasing trend in annual median runoff, while increases in annual mean runoff are observed in the southeastern and northern portions of the California Region (**Figure 3.23**). Similarly, June 1 soil moisture is projected to change with the majority of the California Region exhibiting a decrease in June 1 soil moisture, with the exception of areas in the southeastern corner of the California Region. April 1 SWEs are projected to primarily decrease dramatically in particular areas throughout the California Region, specifically the mountainous regions. (**Figure 3.24**). The authors did not provide specific information on confidence levels for the parameters in this study.

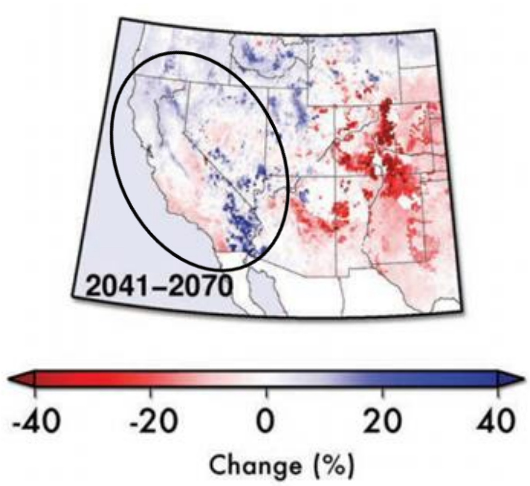

Figure 3.23. Projected changes in annual median runoff for the high emissions scenario for 2041 – 2070 compared to historical runoff (1971 – 2000). The California Region is within the black oval (Cayan et al., 2013).

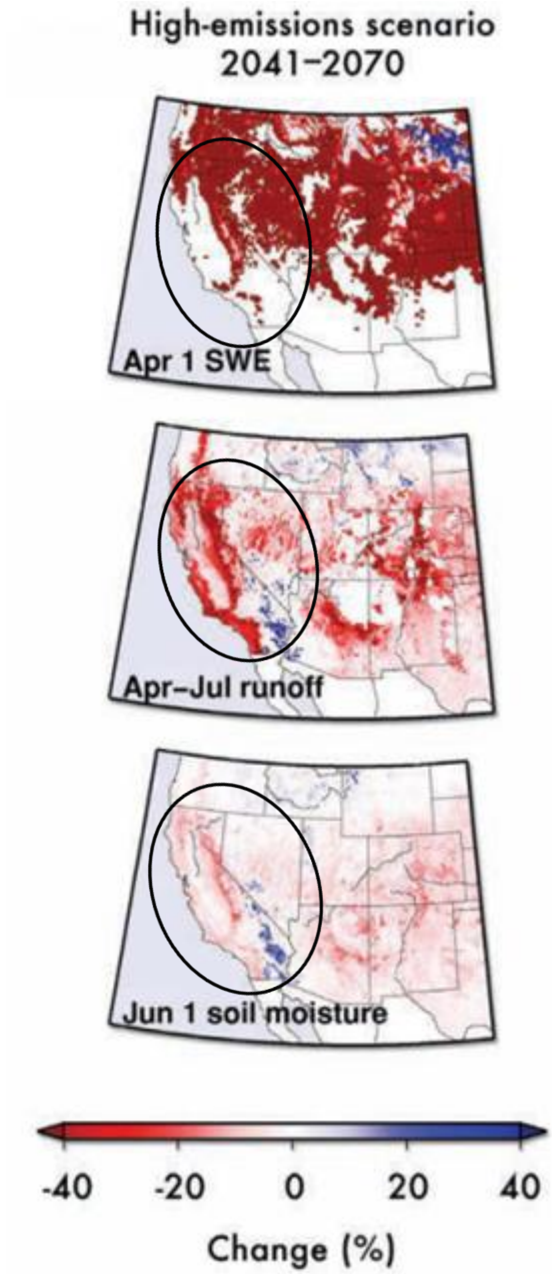

Figure 3.24. High emissions scenario changes in projected (2041 – 2070) compared to historical (1971 – 2000) snow water equivalents (top) April – July median runoff (middle) and June 1 soil moisture (bottom). The California Region is within the black ovals (Cayan et al., 2013).

Also on a regional scale, the third NCA's chapter which focuses on the southwest (Garfin et al., 2014) projects a decrease in snowpack for the southwestern U.S., including the California Region. Decreased snowpack, as measured by SWE, is strongly related to the amount of runoff and associated natural inflows to snowpack-supplied rivers, as is the case in many of the rivers within the California Region. Projected SWE for the southwestern U.S. is summarized in **Figure 3.25**.

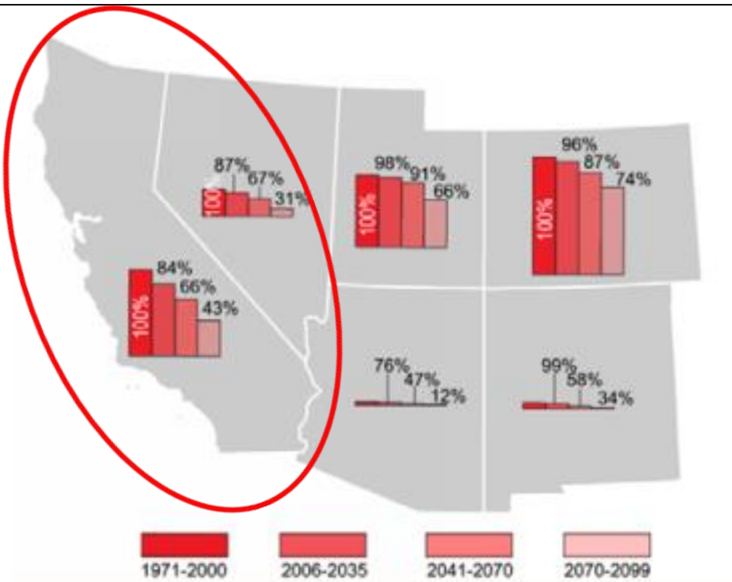

Figure 3.25. Projected snow water equivalent in the southwestern U.S. Each bar represents a future 30-year time period. The California Region is within the red oval (Garfin et al., 2014).

On a smaller scale, an earlier study by Cayan et al. (2008), discussed in Section 3.1, evaluated climate scenarios for the California Region. The study evaluated changes in April 1 SWE in the San Joaquin, Sacramento, and parts of the Trinity River drainage areas from a VIC hydrologic model. The study evaluated the changes in April 1 SWE through different elevation ranges at 1,000 meter increments. Results of the models indicate a decline in April 1 SWE across all elevations by the end of the 21st century compared to the baseline period of 1961 – 1990. The largest decline in April 1 SWE was predicted for areas of lower elevation, between 1,000 – 2,000 meters. Spatial representation of changes projected in the springtime snow accumulation from the VIC model simulated with output from two GCMs with two emissions scenarios, compared to the baseline period of 1961 – 1990 SWE is illustrated in **Figure 3.26**. Information on statistical significance of results was not provided in this study.

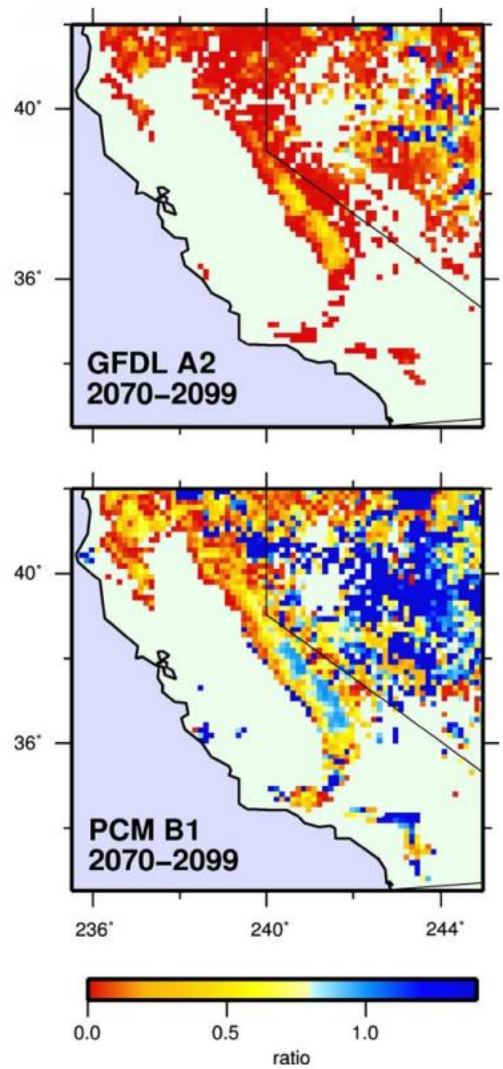

Figure 3.26. Projected changes in springtime snow accumulation by the end of the 21st century from two GCMs (top: GFDL, bottom: PCM) with two emissions scenarios (top: A2 scenario, bottom: B1 scenario) (Cayan et al., 2008).

Because atmospheric rivers are responsible for almost all major historical floods in California, understanding how they are likely to change in the future is critical for flood risk mitigation, particularly for the Central Valley. Dettinger (2011) used a seven-model ensemble of historical-climate and projected future climate simulations to evaluate changes to the frequency and intensity of atmospheric rivers under climate change. Under the A2 scenario by 2100, there is an increase in the number of years with multiple atmospheric river events, an increase in the number of atmospheric rivers with higher-than-historical water-vapor transport rates, and an increase in atmospheric river storm temperatures. In addition, the study showed a lengthening of the peak season of atmospheric river occurrence, with the potential to lengthen the flood-hazard season.

A study by Cloern et al. (2010), discussed in Section 3.1, focused on the evolution of the San Francisco Estuary Watershed due to climate change. The study used results from two GCMs with two emissions scenarios (A2 and B1) and a downscaled VIC watershed model to project hydrologic conditions at the end of the 21st century compared to the baseline period of 1970 –

1999. Results of this analysis illustrate the potential decline in snowmelt contribution in the San Francisco Estuary Watershed, but the degree of the trend depends on the model evaluated. Similarly, changes in unimpaired runoff depend on the emissions scenario and model employed. While the average annual unimpaired runoff appears to change only slightly, annual variability in runoff differs between the two GCMs (**Figure 3.27**). The PCM GCM simulating the B1 emissions scenario predicts years with higher unimpaired runoff compared to the GFDL GCM under the A2 emissions scenario by the end of the 21st century. Model variability is consistent with those results by Thomson et al. (2005).

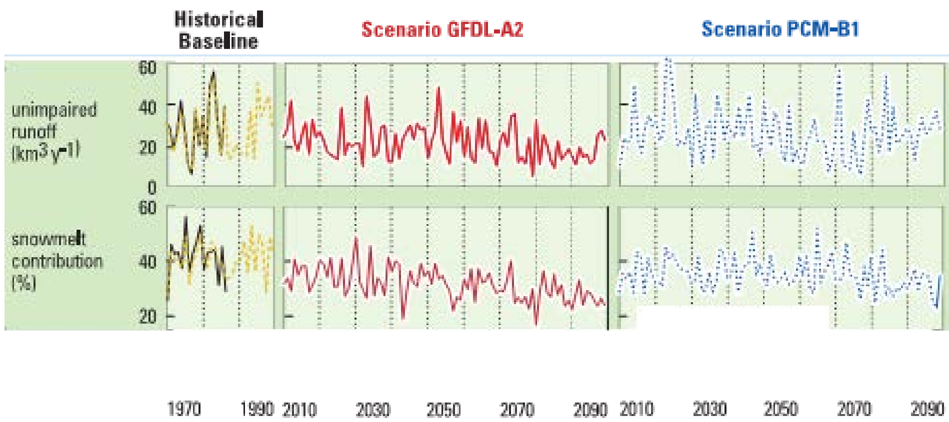

Figure 3.27. Unimpaired runoff (km^3 yr^{-1}) and snowmelt contribution (%) projections from two GCMs with two emissions scenarios (A2 scenario on the left, B1 scenario on the right) in the San Francisco Estuary Watershed located within the California Region (Cloern et al., 2010).

The Sierra Nevada area, within the California Region, was evaluated by several hydrologic studies, including those by Maurer (2007), Das et al. (2011), and Das et al. (2013). The first author evaluated the uncertainty in hydrologic impacts of climate change under two emissions scenarios in the Sierra Nevada area of California between 2071 – 2100 compared to a baseline period of 1961 – 1990. The study used 11 GCMs forced with two emissions scenarios, the A2 (higher) and B1 (lower) scenarios to evaluate four basins within the Sierra Nevada area of California (**Figure 3.28**). Low confidence exists in projections for future changes in annual streamflow. The A2 emissions scenario predicts small increases in annual flows of 7 to 8 percent, while the B1 scenario predicts slight decreases in annual flows. On a monthly basis, increases are projected in winter streamflow, while late spring and summer flows are projected to decrease across all basins (**Figure 3.29**). This study also found statistically significant (95% C.I.) decreases in April 1 SWE by the end of the 21st century across all basins under both emissions scenarios, with decreases ranging from 35 to 80 percent of the 1961 – 1990 mean SWE. The centroid of the annual flow volume is also predicted with statistical significance (95% C.I.) to occur earlier in the year by the end of the 21st century across all four basins, and is predicted (although with different magnitudes) with both emissions scenarios. Changes in the timing of the centroid of the annual flow volume are predicted to occur from 17 to 36 days earlier in the year depending on the basin evaluated and emissions scenario.

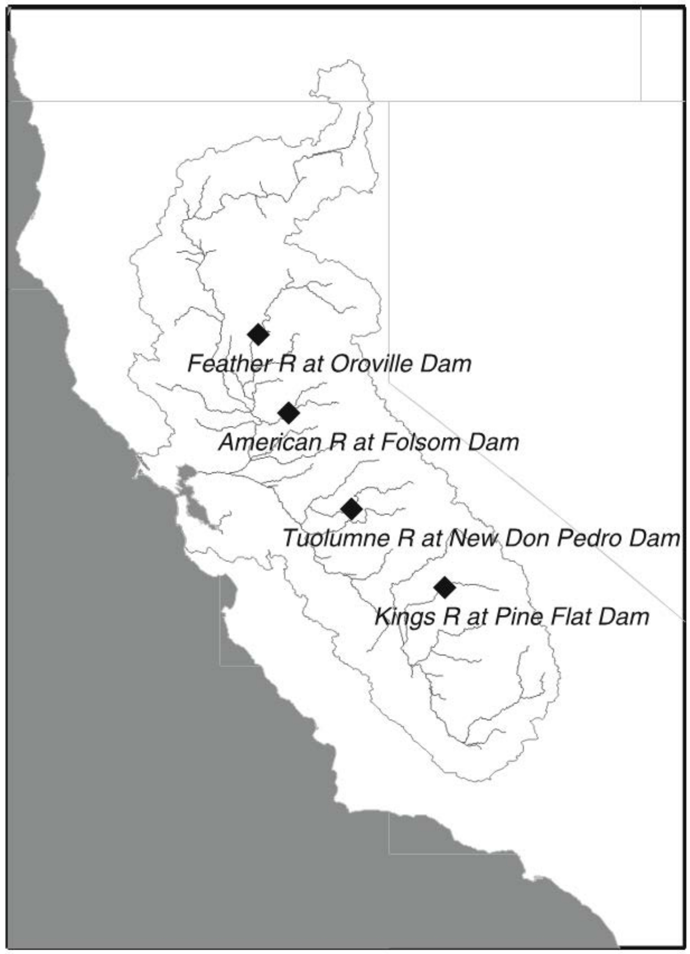

Figure 3.28. Location of the four basins within the Sierra Nevada area evaluated in a study by Maurer (2007). These four basins are within the California Region.

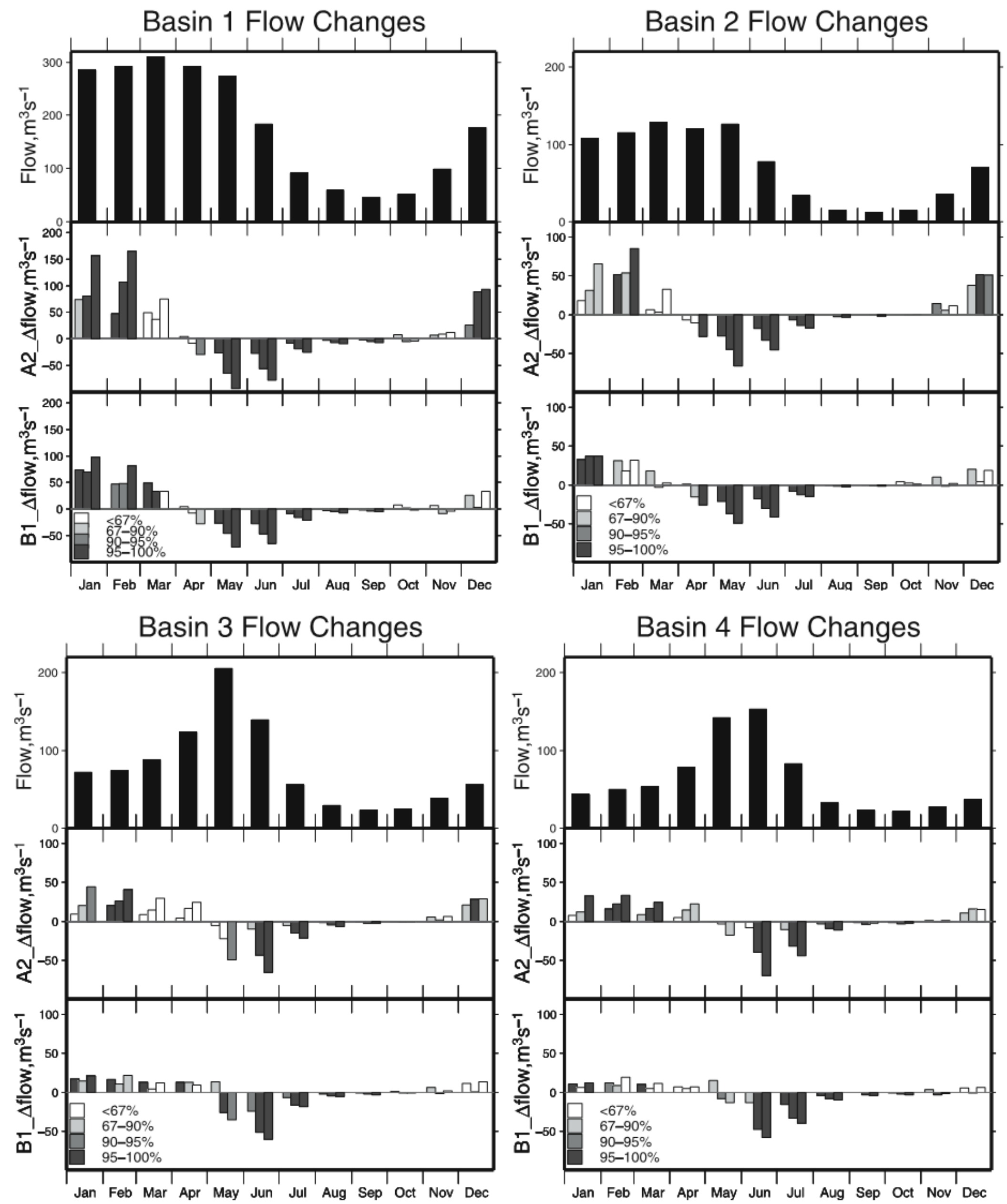

Figure 3.29. Projected changes in streamflow within the four basins illustrated in Figure 3.28, compared to historical streamflows (1961 – 1990) for the A2 and B1 emissions scenario simulations. Top panels show the mean historical monthly flows, and the projected changes under the A2 (center panel) and B1 (lower panel) emissions scenarios. Shading indicates statistical confidence. In the lower two panels, the three bars within each month indicate changes relative to the base period for the early 21st century (2011 – 2040; left bar), mid-century (2041 – 2070; center bar), and end of century (2071 – 2100; right bar). (Maurer, 2007).

A study by Das et al. (2011) evaluated potential increases in floods in California's Sierra Nevada under future climate projections. The study evaluated results of three GCMs run with the A2 emissions scenario, which were used to feed a VIC model. The study evaluated the northern

Sierra Nevada and southern Sierra Nevada areas. Streamflow in the northern Sierra Nevada area is primarily a result of winter precipitation, while streamflows in the southern Sierra Nevada area is dominated by springtime snowmelt runoff. Floods were defined as daily streamflows which exceed the 99th percentile value of the 1951 – 1999 streamflow. In both the northern and southern Sierra Nevada areas, increases in flood volumes were found to be statistically significant (99% C.I.) across all three GCMs from 2051 – 2099 compared to the baseline period of 1951 – 1999. Magnitudes of the largest floods are projected to increase from 110 to 150 percent. Flood frequency was projected to increase in the northern Sierra Nevada area from 2.7 events per year to 5.9 events per year by the end of the 21st century. In southern Sierra Nevada, flood frequency was projected to increase from 2.7 events per year to 5.1 events per year by 2049, and then decline to 2.7 events per year by the end of the 21st century. In general, the study found a projected tendency for more frequent winter rainfall generated floods and fewer snowmelt floods as climate warms. The results also indicate increases in the size of the largest storms, increases in storm frequency, and an increase in the number of days with precipitation falling as rain than as snow (Das et al., 2011).

A study by Das et al. (2013) evaluated flood magnitudes in the Sierra Nevada area within the California Region. The study evaluated downscaled and hydrologically modeled projections from 16 GCMs under an A2 emissions scenario, comparing future hydrologic conditions by the end of the 21st century to baseline conditions from 1950 – 1999. The study projected slight increases in the median of mean annual flow in the northern Sierra Nevada area, and slight decreases in the southern Sierra Nevada area compared to the baseline conditions (**Figure 3.30**). Flood magnitudes for the 2-, 10-, 20-, and 50-year flood events are all projected to increase in both the northern and southern Sierra Nevada areas (**Figure 3.31**). Three-day flood magnitudes are also projected to increase by 2100.

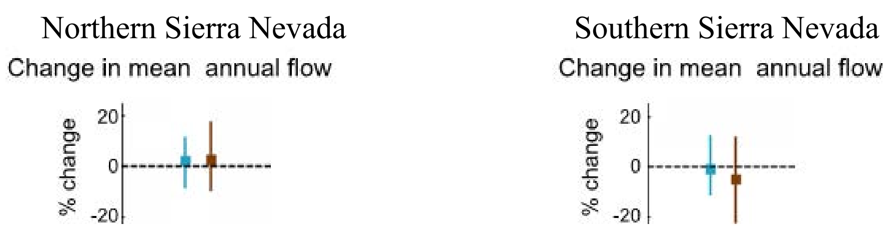

Figure 3.30. Rate of percentage changes in mean annual flow (relative to 1951 - 1999) in mean annual streamflow from VIC simulations as simulated by downscaled climate models. Filled square represent ensemble medians, and vertical whiskers extend from the 25th to the 75th percentile of the 16 climate model samples. Changes for the period 2001 – 2049 (cyan) and 2051 – 2099 (brown) are shown (Das et al., 2013).

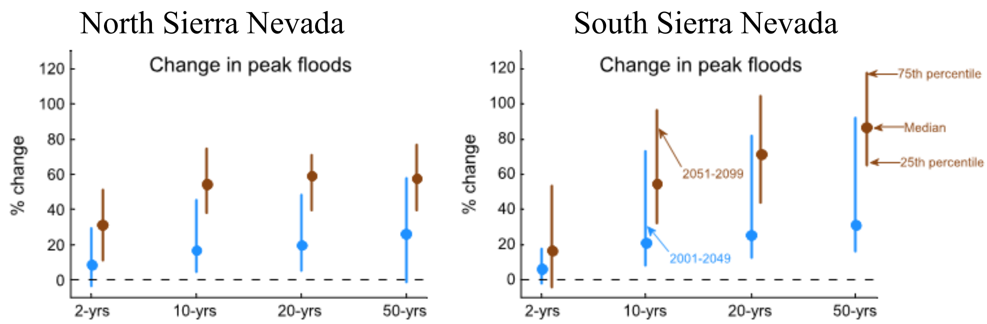

Figure 3.31. Percentage of changes in flood magnitudes for the 2, 10, 20, and 50-year floods. Filled circles represent ensemble medians and vertical whiskers extend from 25th to the 75th percentile of the 16 climate model samples. Changes in the period 2001 – 2049 (cyan) and 2051 – 2099 (brown) are shown (Das et al., 2013).

Key point: SWE is predicted to generally decrease throughout the California Region, however, little consensus exists in the literature with regard to projected trends in streamflow and runoff in the California Region.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study basin, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of up to 8 ºF (4.5 ºC), with extreme temperature projections increasing by the latter half of the 21st century for the California Region. The largest increases are generally projected for the summer months with temperature increases generally projected to be higher in inland areas compared to the coast. High consensus is also seen in the literature with respect to projected increases in both frequency and severity of extreme high temperature events compared to the recent past. Decreases in frequency of extreme cold temperatures are projected, with largest frequency decreases in the mountainous areas of the California Region, including northern California.

Projections of precipitation in the study basin are less certain than those associated with air temperature. Results of some studies conflict with one another. In addition, they show seasonal and spatial variability in projected precipitation results throughout the California Region, which may be related to topographic or latitudinal variations. This variability may also be attributed to differences in time period over which the precipitation studies were conducted. The dominant trend appears to suggest an increase in precipitation in the northern areas of the region and a decrease in precipitation in the southern areas of the California Region. Moderate consensus among the reviewed studies was found regarding extreme precipitation events. Future storm events in the California Region are predicted to increase in frequency and intensity compared to the recent past.

The literature presents a relatively clear consensus with respect to decreases in SWE; however, other hydrologic projections, such as streamflow and runoff are harder to compare, with seasonal variabilities, model variabilities, and spatial variabilities in results. Hydrologic models are generally consistent with projections of future precipitation in that the northern areas are that runoff increases, if they occur, are primarily modeled for northern areas (and in the southeast, possibly related to an enhanced summer monsoon). The models also consistently project advances in spring snowmelt runoff timing and reductions in April 1 SWE mountain regions (mainly the Sierra Nevada).

A number of studies reviewed here employed probabilistic modeling methods to capture and quantify some of this projection uncertainty, resulting from both climate and runoff modeling steps. These methods frame output in the form of probability distributions that can viewed as characterizations of likelihood of occurrence (risk) or levels of consensus among modeling scenarios.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.32**.

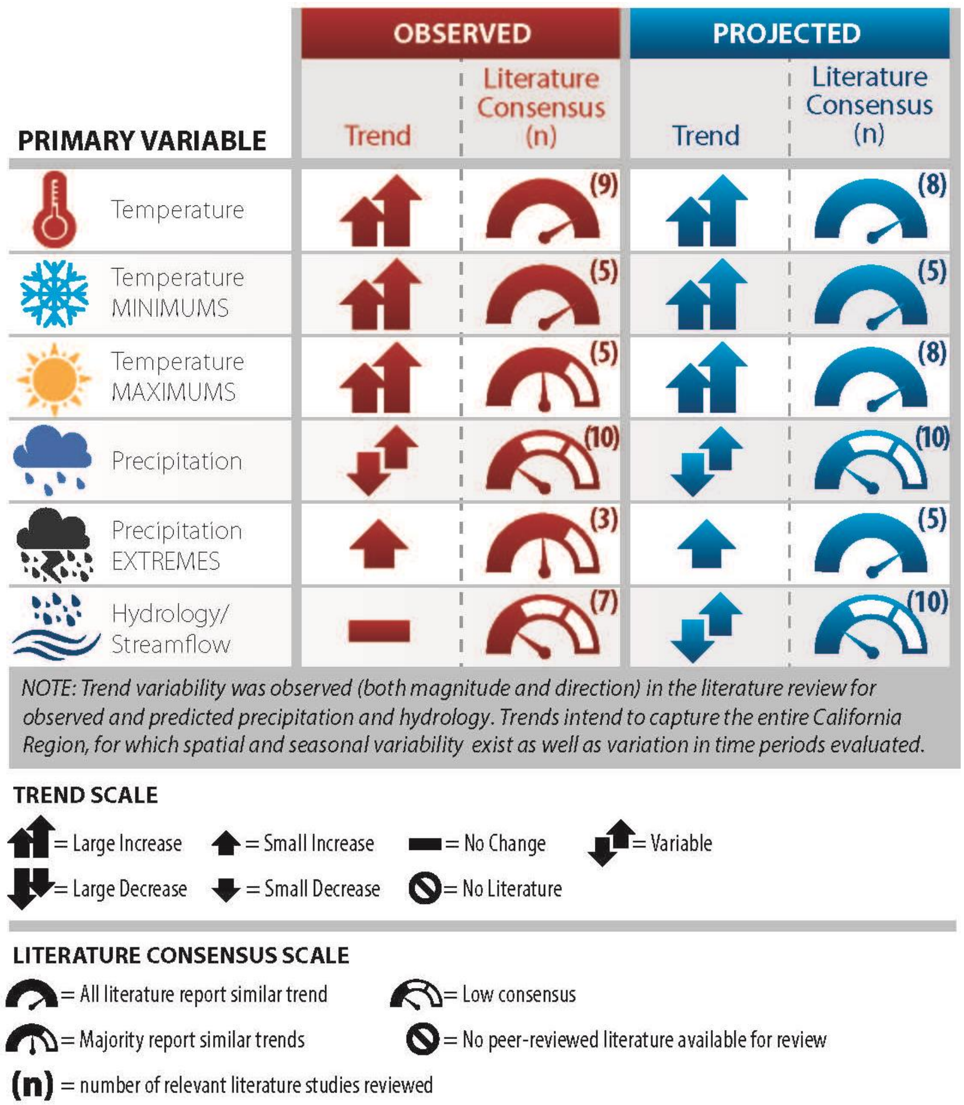

Figure 3.32. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The California Region encompasses nearly all of California, some edges of southwest Nevada, and a small pocket of south-central Oregon. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

Navigation is an important mission of USACE in the California Region, operating some of the nation's largest ports. By the middle of the century, the region is expected to experience increases in ambient air temperature. In addition, the frequency and intensity of large storm events and associated flooding may increase along with a broader range of extremes in water availability, which has implications for water levels and thus the ability for vessels to navigate and dock at river ports. Extreme events may also increase water turbidity and come with high winds, with possible navigation and docking impacts at ocean ports.

USACE implements flood risk management projects in the region to limit flooding. Increased extreme event frequency and intensity are predicted for the region. There may also be an increase in the flood volume and number of events in the Sierra Nevada mountain range. This may cause increased runoff and may cause flash floods if the storms are intense. Flood risk management projects may be very important for reducing the residual flooding impacts due to extreme storm events, which are predicted to be more frequent and intense.

USACE also maintains and operates several fresh water supplies to maintain water quality in the region. Streamflow variability along with the contrast between increasing mean air temperatures and the increased frequency and magnitude of heat waves will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

While this report does not highlight the impacts of sea level change, changes in coastal conditions can have impacts which penetrate to inland water bodies. Sea levels along the California coastline of the United States are projected to increase and may exacerbate salt water intrusion into freshwater water supply. Tools and information related to sea level change can be found on the USACE Responses to Climate Change website (USACE, 2014).

USACE implements ecosystem restoration projects in the California Region. Increased ambient air temperatures and heat wave days will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

Increased storm intensities and frequencies may pose complications to planning for ecosystem needs and lead to variation in flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply.

Hundreds of mega-watts (MW) of hydropower is generated in the California Region. By the end of the century, large storm events may increase in the region, which may be beneficial for the region's hydropower plants, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these project sites. Conversely, there may also be times during any given year where flows and reservoir levels are reduced due to high temperatures and drought conditions, which reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the California Region offer several benefits to visitors as well as positive economic impacts. Extended heat wave duration and increased heat wave temperatures along with the increased frequency and intensity of extreme storm events have the potential to decrease the number of visitors to USACE's recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities. An increase in extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the California Region. These types of storms are capable of intense precipitation and winds. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing for reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulations or an increase in the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. **Figure 4.1** summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	Air temperatures are expected to increase around 4°C by the end of the century, and are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation from increased periods of heat and variable streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. • Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Variable flows, have implications for maintaining water levels in the rivers and lakes. • Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management
Increased Maximum Temperatures	Air temperature extremes are expected to increase 7.5°C by the end of the century, with the number of heat wave days per year increasing by up to 80 days. This is expected to create the following vulnerabilities on business lines in the region: • Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies. • Increased evapotranspiration. • Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management. **BUSINESS LINES IMPACTED:** Recreation, Water Supply, Ecosystem Restoration, Flood Risk Management
Increased Annual Precipitation	Annual precipitation is highly variable depending on the location in California. In general, Northern California may expect an increase of no change in precipitation, and Southern California may expect a decrease or no change. Business lines in areas with a possible increase in precipitation may experience: • Increased flows and runoff from increased precipitation may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. Business lines in areas with a possible decrease in precipitation may experience: • Periods of drought resulting in a reduced streamflow, making it more difficult to maintain water levels in the rivers. • Loss of vegetation, which is important for sediment stabilization in the watershed. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management
Increased Storm Intensity and Frequency	Extreme storm events may become more frequent and intense over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased runoff during an event, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Change in engineering design standards to accommodate new extreme storms magnitudes. • Increased flash flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management
Streamflow Variability	Streamflow may have more variability depending on the location in California. Runoff changes may be between -40mm/yr to 20mm/yr. The region may also experience change in the timing of the peak flow and reduced snowpack by the end of the century. This may result in: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management

NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of projected climate trends and impacts on USACE business lines

Appendix A: References Climate/Hydrology Summary Table

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Ashfaq M, Bowling LC, Cherkauer K, Pal JS, Diffenbaugh NS (2010)												X	X							
Bonfils C, Duffy PB, Santer BD, Wigley TM, Lobell DB, Phillips TJ, Doutriaux C (2008a)	X																			
Bonfils C, Santer BD, Pierce DW, Hidalgo HG, Bala G, Das T, …, Wood AW, Mirin A, Nozawa T (2008b)		X	X																	
Cayan D, Maurer E, Dettinger M, Tyree M, Hayhoe K (2008)											X	X	X	X		X				
Cayan DR, Tyree M, Kunkel KE, Castro C, Gershunov A, Barsugli J, Overpeck J, Russell J, …, Duffy P (2013)											X	X	X	X		X				
CDMSmith (2012)																X				
Cloern JE, Knowles N, Brown LR, Cayan D, Dettinger MD, Morgan TL, Schoellhamer DH, …, Wagner RW, Jassby AD (2011)											X			X		X				
Cook BI, Smerdon JE, Seager R, Cook ER (2014)				X																
Cordero EG, Wittaya K, Abatzoglou J, Mauget SA (2011)		X	X																	
Das T, Cayan DR, Maurer EP, Pierce DW, Dettinger MD (2013)																X				
Das T, Dettinger MD, Cayan DR, Hidalgo HG (2011)											X			X	X	X				
Das T, Hidalgo HG, Pierce DW, Barnett TP, Dettinger MD, Cayan DR, Bonfils C, Bala G, Mirin A (2009)						X														
Dettinger MD (2011)														X		X				
Dettinger MD (2012)											X	X		X						

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Elguindi N, Grundstein A (2013)											X			X						X
Garfin G, Franco G, Blanco A, Comrie A, Gonzalez P, Piechota T, Smyth R, Waskom R (2014)	X					X					X					X				
Gershunov A, Guirguis K (2012)											X	X	X							
Grundstein A (2009)				X				X												
Grundstein A, Dowd J (2011)		X	X																	
Gutzler DS, Robbins TO (2010)											X			X			X			
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, Heinke J,….,Wiltshire AJ (2013)														X		X				
Hoerling MP, Dettinger M, Wolter K, Lukas J, Eischeid J, Nemani R, Liebmann B, Kunkel KE (2013)	X	X	X	X		X														
Kalra A, Piechota T, Davies R, Tootle G (2008)						X														
Kunkel KE, Liang X-Z, Zhu J (2010)											X		X							
Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Redmond KT, Dobson JG (2013)	X	X	X	X	X						X	X	X							
Lavers, DA and Villarini G (2015)				X																
Liu Y, Goodrick SL, Stanturf JA (2013)												X	X	X	X					
MacDonald (2010)	X			X																
Maurer EP (2007)											X			X		X				
McRoberts DB, Nielsen-Gammon JW (2011)				X																
Milly PC, Dunne KA, Vecchia AV (2005)											X									

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005)	X			X	X															
Palecki MA, Angel JR, Hollinger SE (2005)				X																
Pryor SC, Howe JA, Kunkel KE (2009)				X	X															
Regonda SK, Rajagopalan B, Clark M, Pitlick J (2005)						X														
Sagarika S, Kalra A, Ahmad S (2014)						X														
Scherer M, Diffenbaugh N (2014)											X	X	X							
Schwartz MD, Ault TR, Betancourt JL (2013)	X								X											
Seager R, Vecchi GA (2010)														X						
Tebaldi C (2006)												X	X		X					
Tebaldi C, Adams-Smith D, Heller N (2012)	X																			
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)																X				
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, Vose R, …,Kennedy J, Somerville R (2014)	X			X																
Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009)	X			X																
Wang J, Zhang X (2008)				X	X									X	X					
Warner MD, Mass CF, Salathe EP (2015)					X															
Westby RM, Lee Y-Y, Black RX (2013)	X	X																		
Xu X, Liu W, Rafique R, Wang K (2013)						X														

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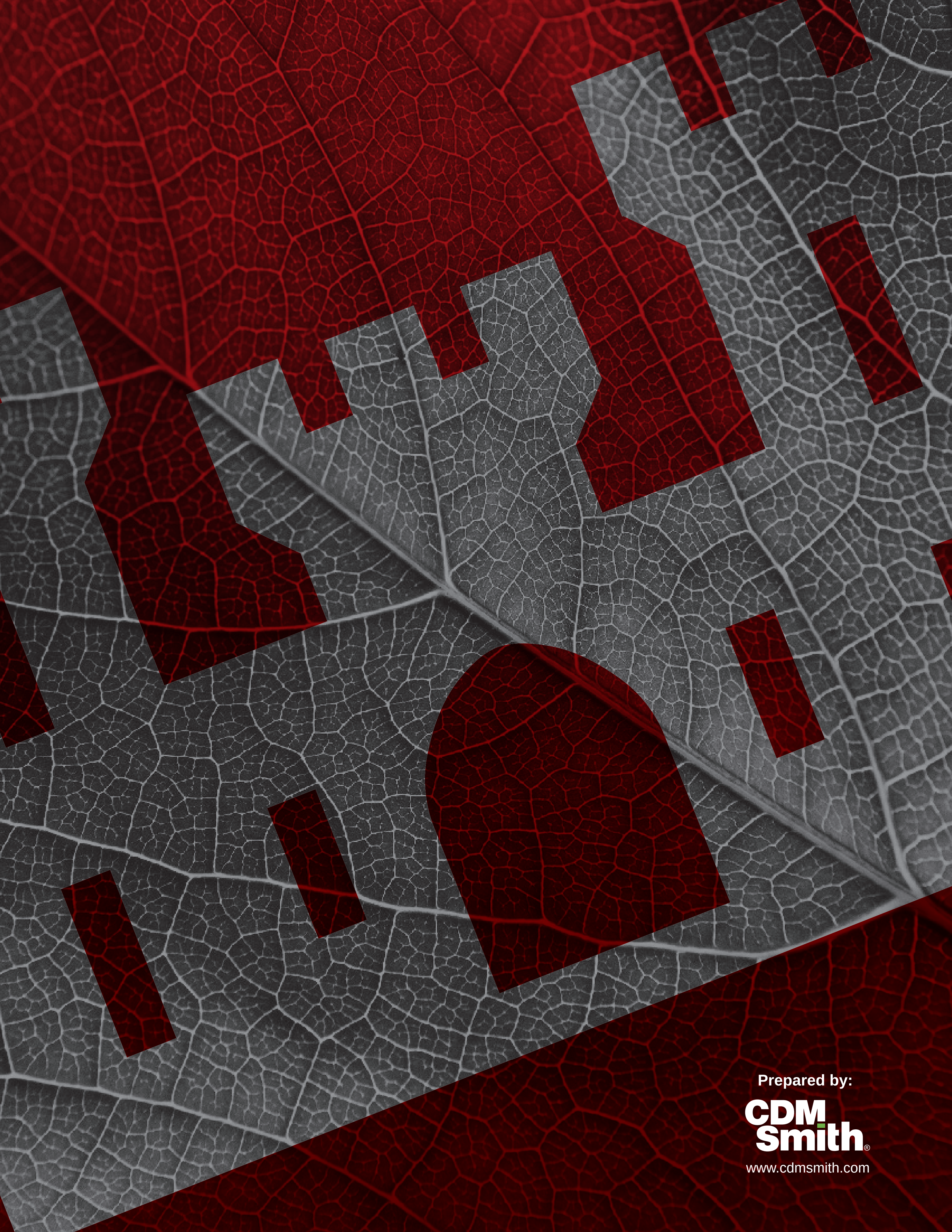

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