A summary of current trends and probable future trends in climate and climate-driven processes in the Sierra Cascade Province, including the Lassen, Modoc, and Plumas National Forests

Kyle Merriam*, Sierra Cascade Province Ecologist, USDA Forest Service, Pacific Southwest Region. Email: kmerriam@fs.fed.us; phone: (530) 283-7777.

Hugh Safford, Regional Ecologist, USDA Forest Service, Pacific Southwest Region. Email: hughsafford@fs.fed.us; phone: (707) 562-8934.

Sarah Sawyer, Assistant Regional Ecologist, USDA Forest Service, Pacific Southwest Region. scsawyer@fs.fed.us; 707-562-8924

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I. Local and regional trends in climate over the past century

Province Weather Station Data

The data presented in this section are derived from eight weather stations located in the Sierra Cascade Province, comprised of the Plumas, Lassen, and Modoc National Forests (Fig. 1) and including three climate regions (Fig 1; Abatzoglou *et al.* 2009). Stations were chosen based on their geographic location and on the length and completeness of their records. In order to best represent the wide range of elevations and vegetation types found within the Sierra Cascade Province, we focused our analyses on stations located in different biogeographical regions and at opposite extremes of the province's elevation gradient. Data collected from individual stations within each climate region are presented to illustrate local trends and climatic variations at specific locations within the Plumas, Lassen, and Modoc National Forests. Although these data are not subjected to the same kind of quality assurance and control as the regional climate center data described below, they provide more locally specific information than the regional datasets. Descriptions of each weather station used in this report are provided in Table 1.

Western Regional Climate Center Data

In addition to data collected at individual weather stations, we present data compiled by the Western Regional Climate Center (WRCC). These data are grouped by climate regions developed for California by Abatzoglou *et al.* (2009). The climate regions encompass weather stations that experience similar large-scale weather and climate patterns to help better identify regional climate trends across California. Regional data sets are compiled only from weather stations that reported over 75% of observations over the time period 1949-2005, and continued to report in 2006. The WRCC adjusts these data to correct for non-climate related shifts in temperature. They caution that the dataset contains larger uncertainties prior to 1918 due to the limited number of stations reporting statewide. Most of the Sierra Cascade Province is within the Northeast climate region, but the western portions of the Lassen and Plumas National Forest also include the Sierra and North Central climate regions (Fig. 2). To evaluate differences between climate regions in the Sierra Cascade Province, we evaluate data from two weather stations in both the Sierra and North Central climate regions, and from four weather stations in the Northeast climate region.

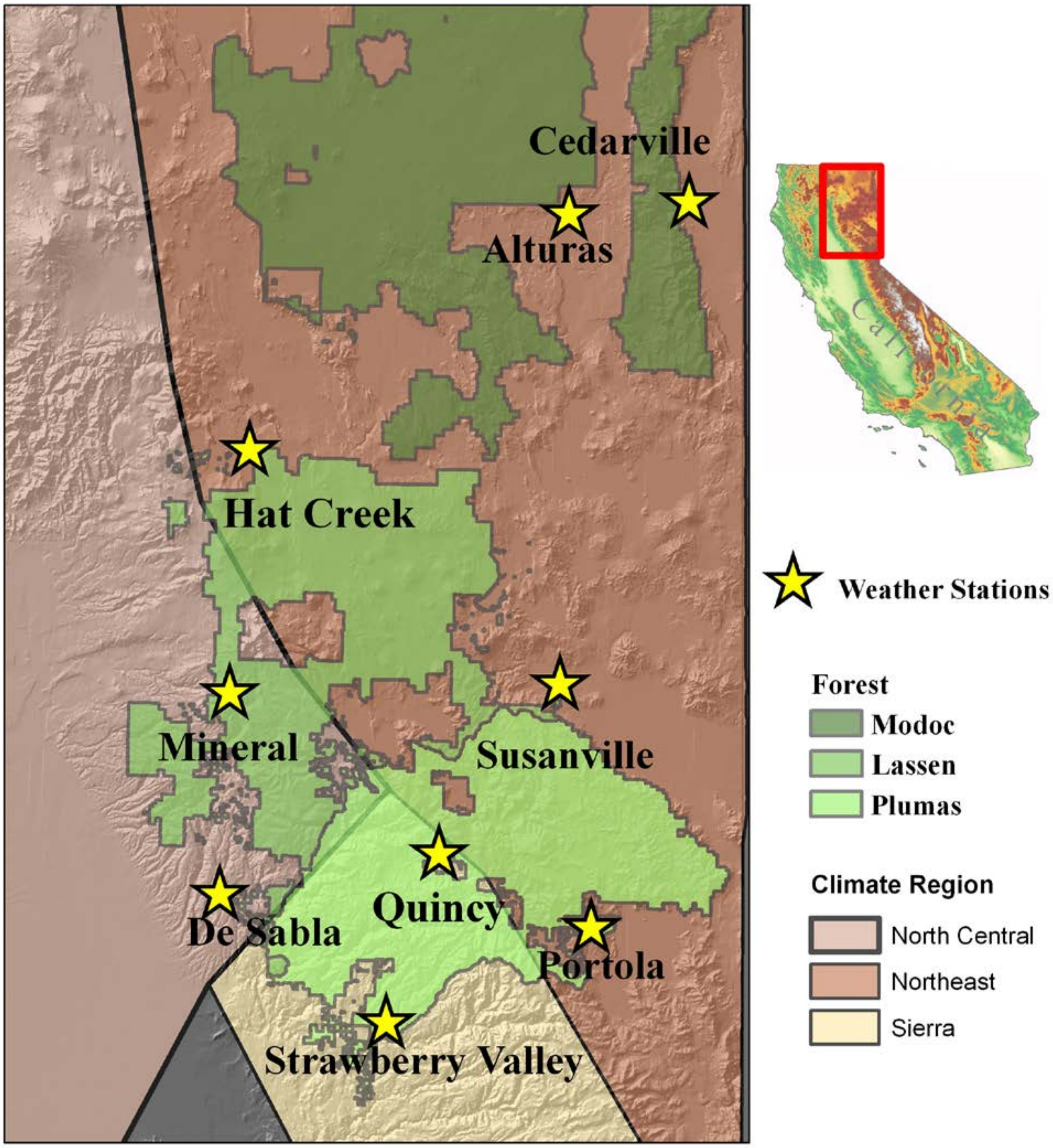


Figure 1. Locations of weather stations across the Sierra Cascade Province evaluated in this report. The Sierra Cascade Province includes portions of the Sierra, Northeast, and North Central climate regions (Abatzoglou et al. 2009). At least two weather stations from each region were evaluated for this report.

Table 1. **Descriptions of weather stations evaluated for this report.**

Station	Forest	Elevation (ft)	Climate Region	Predominant Vegetation	Latitude	Longitude	Length of Record	Missing Years
Quincy	Plumas	3500	Sierra	Mixed Conifer	39°58'	120°56'	1895-present	1979-1980
Alturas	Modoc	4460	Northeast	Grassland/ Sagebrush	41°30'	120°32’	1905-present	1920-1931
Cedarville	Modoc	4650	Northeast	Western Juniper/ Eastside Pine	41°32'	120°10'	1894-present	none
Hat Creek	Lassen	3020	Northeast	Montane Chaparral	40°56’	121°33'	1927-present	1996
Susanville	Lassen	4270	Northeast	Sagebrush/ Eastside Pine	40°25'	120°40’	1896-present	1919-1926, 1991
Portola	Plumas	4830	Northeast	Mixed Conifer/ Eastside Pine	39°48'	120°28'	1915-present	none
Mineral	Plumas	4950	North Central	Mixed Conifer/ Fir	40°21'	121°34'	1927-present	none
Strawberry	Plumas	3780	Sierra	Mixed Conifer	39°34’	121°06'	1948-present	none
De Sabla	Plumas	2720	North Central	Mixed Conifer/ Hardwood	39°52'	121°37'	1906-present	none

PRISM Data

We present spatial data from the PRISM climate dataset (Daly *et al.* 1994, PRISM 2010), which uses a regression model to extrapolate individual weather station records to the landscape scale for all years, beginning as early as the late 19th century. We compare PRISM datasets from 1931 through 2010 to provide information about landscape scale climate trends in the Sierra Cascade Province.

Temperature

Western Regional Climate Center

Temperature data compiled by the WRCC (2012) from the Northeast, North Central, and Sierra climate regions show significant increases in minimum, mean, and maximum temperatures since 1895 (Fig. 2).

Over the last century, mean annual temperatures have increased by 1.7 degrees Fahrenheit (° F) in both the Northeast and Sierra climate regions and by almost 2° F in the North Central climate region (values based on regression equations). The trend in the Sierra region is driven primarily by significant increases in mean minimum (i.e., nighttime) temperatures, which have risen by 2.5° F since 1895. In the Northeast and North Central climate regions, the trend in temperature is influenced equally by significant increases in mean minimum (nighttime) and mean maximum (daytime) temperatures.

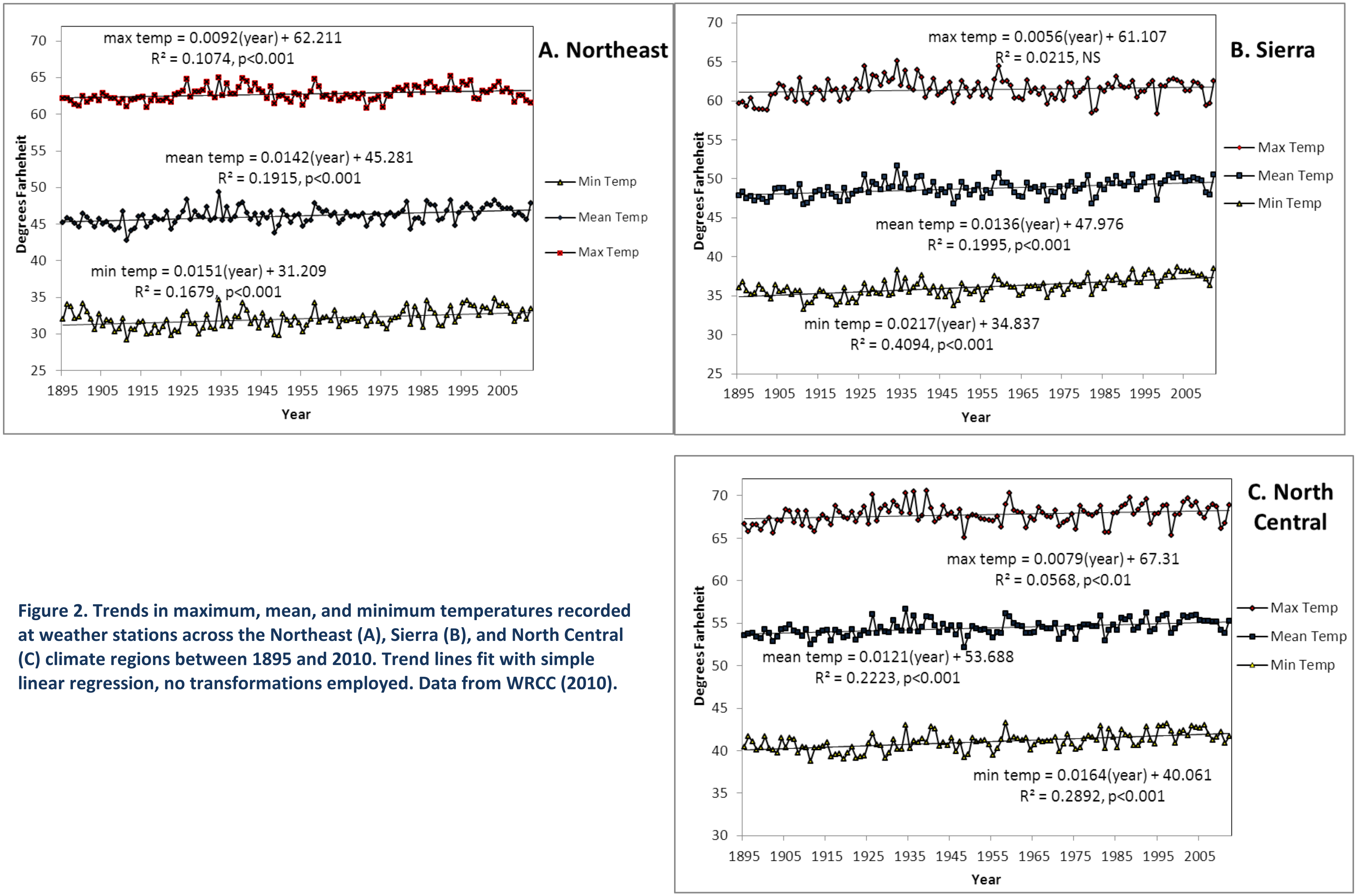


Figure 2. Trends in maximum, mean, and minimum temperatures recorded at weather stations across the Northeast (A), Sierra (B), and North Central (C) climate regions between 1895 and 2010. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC (2010).

PRISM

PRISM data indicate that temperatures across the Sierra Cascade Province have increased slightly over the past 80 years. However, there is a great deal of variability in temperature trends since 1931 (Fig. 3). Temperatures have increased in the Sierra climate region and decreased in the North Central climate region. The portion of the Sierra Cascade Province in the Northeast climate region has generally experienced increased temperatures, but there are many areas of the Northeast climate region that have also experienced declines in temperature. This variability is reflected in individual weather station data presented below.

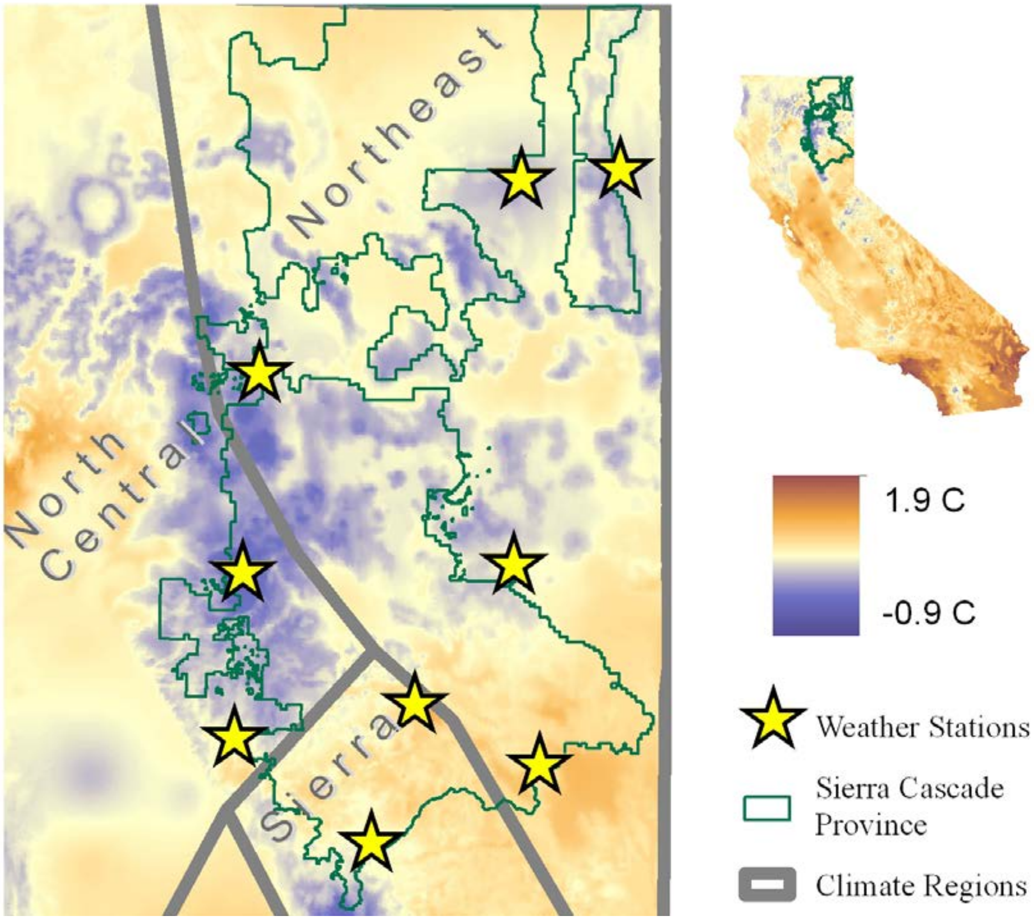


Figure 3. Mean annual temperature change between the 1930's and 2000's as derived by the PRISM climate model. Blue areas have experienced decreased mean temperatures, orange and red areas have experienced increased mean temperatures.

Individual Province Stations

Individual weather stations examined in the Sierra Cascade Province exhibit a range of temperature trends (Table 2). One station in each climate region exhibited an increase in temperature (De Sabla in the North Central, Portola in the Northeast, and Quincy in the Sierra; Table 2). Two stations in the Northeast and one in the Sierra climate regions exhibited decreases in temperature, and the rest of the stations showed no significant trends (Table 2).

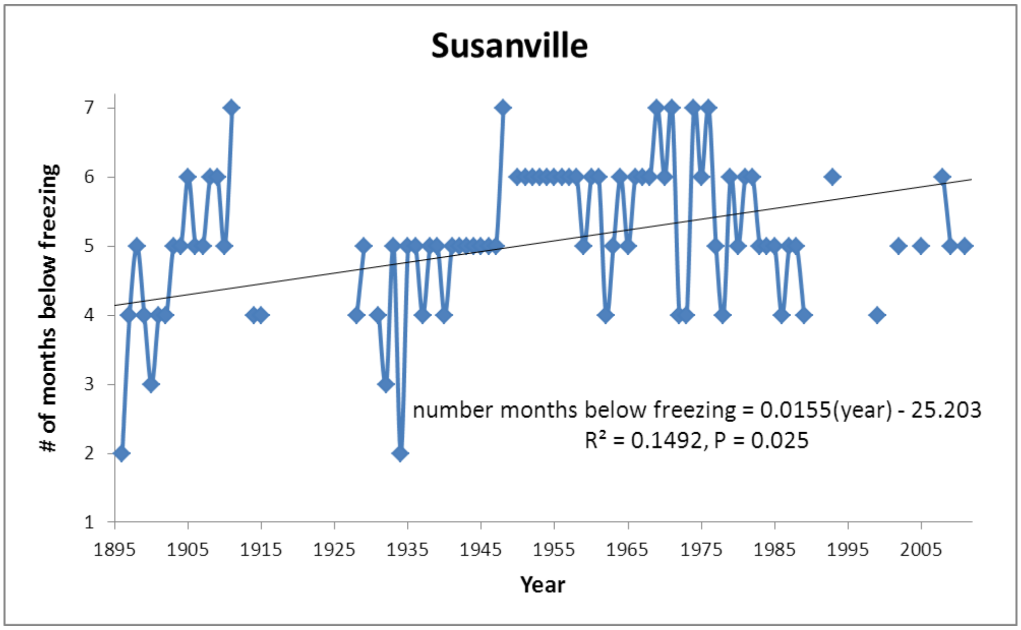
Table 2. Direction and magnitude of significant temperature shifts recorded at individual weather stations across the Sierra Cascade Province. Numerical values indicate the difference between the earliest and most recent years of each station's climate record in degrees Fahrenheit, as calculated using regression equation. Statistical significance of trends is indicated as follows: 'NS' = not significant, '*' = p<0.05, '' = p<0.01, '***' = p<0.001. Near significant trends are indicated in parenthesis.**

Station	Climate Region	Max Temp	Mean Temp	Min Temp	Months below freezing
Mineral	North Central	NS	NS	NS (-0.9, p = 0.06	NS
De Sabla	North Central	NS	**+1.3****	**+1.8****	NS (-0.8, p = 0.054)
Alturas	Northeast	NS	NS	NS	NS
Cedarville	Northeast	NS	NS	NS	NS (+0.6, p = 0.052)
Hat Creek	Northeast	**-3.2*****	**-1.5****	NS	NS
Susanville	Northeast	NS	NS	**-2.7****	**+ 0.9***
Portola	Northeast	**-3.1*****	**+1.4****	**+5.5*****	**-1.9*****
Quincy	Sierra	**+3.3*****	**+2.2*****	NS (+1.5, p = 0.06)	NS
Strawberry	Sierra	**-1.7***	**-1.3***	NS	NS

Months below freezing

Individual Province Stations

Although mean minimum temperatures across the Sierra Cascade Province have increased over the past 115 years (see Fig. 2), stations within the North Central and Sierra climate regions have not exhibited a significant change in the number of months with average minimum temperatures below freezing over each station's period of record (between 62 and 115 years). The Susanville station showed a significant increase in months below freezing, while at the Portola station, the number of months below freezing has decreased by 1.8 months over the past 95 years (Fig. 4). Two stations show near significant trends in opposite directions and patterns are not evident within this dataset.



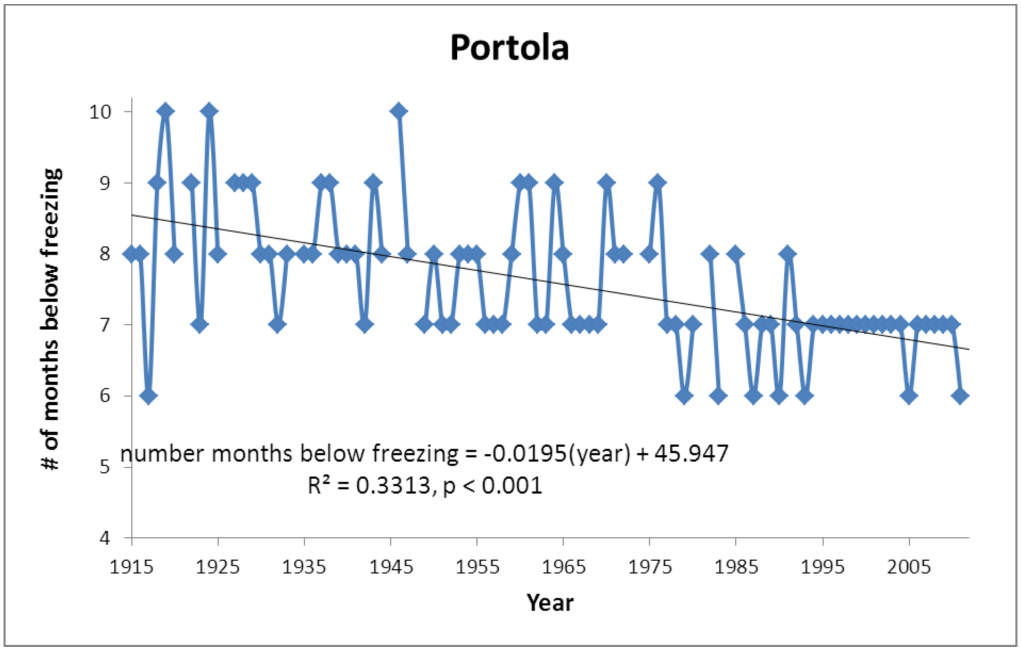


Figure 4. The number of months with average monthly minimum temperatures remaining below freezing have significantly changed at the Susanville station, 1896-2012 (A) and the Portola Station, (1915 – 2011). Trend lines fit with simple linear regression. Data from WRCC (2012).

Precipitation

Western Regional Climate Center

Local and subregional precipitation trends across California range from negative to positive and even trends at nearby stations can vary widely (WRCC 2012). WRCC data from the Northeast, North Central, and Sierra regions show no significant change in precipitation over the past century (Fig. 5).

PRISM

The PRISM model indicates that precipitation has generally increased across the Sierra Cascade Province. The Sierra and North Central climate regions currently receive almost five inches more annual precipitation than in 1931. In the Northeast climate region annual precipitation has increased by almost three inches over the past 80 years (Fig. 7).

Individual Province Stations

Most of the weather stations we evaluated across the Sierra Cascade Province showed no significant change in precipitation over their period of record (between 62 and 115 years). The Susanville station, located in the Northeast climate region, was the only station to show a significant trend in precipitation. Total annual rainfall at the Susanville station has decreased by almost eight inches since 1893 (Table 3; Fig. 7). Years with more than five days of missing precipitation data in a single month were excluded from these analyses.

Table 3. Direction and magnitude of significant shifts in total annual snowfall recorded at individual weather stations across the Sierra Cascade Province. Numerical values indicate the difference between the earliest and most recent years of each station's total annual snowfall in inches, as calculated using regression equation. Statistical significance of trends indicated as follows: 'NS' = not significant, '*' = p<0.05, '' = p<0.01, '***' = p<0.001. Near significant (p≤0.06) values are noted, with p values indicated in parenthesis. Regression coefficients are also presented to indicate the strength of the relationship between snowfall and year.**

Station	Climate Region	Total Annual Precipitation (in.)	Precipitation Coefficient of Variation	Total Annual Snowfall (in.)
Mineral	North Central	NS	+0.4***	NS[6]
De Sabla	North Central	NS	+0.4*	-56.4***[7]
Alturas	Northeast	NS	NS	NS
Cedarville	Northeast	NS (1947-2012)	NS (1947-2012)	-49***
Hat Creek	Northeast	NS	NS	-35***[1]
Susanville	Northeast	-7.7**[2]	+0.4*[2]	-22.5*[3]
Portola	Northeast	NS[4]	NS[4]	-49 (near sig, p = 0.06)[5]
Quincy	Sierra	NS	NS	-56 (near sig, p = 0.06)
Strawberry	Sierra	NS	NS	NS (-43, p = 0.08)

1. 1949 – 2009; 2. 1894-1989; 3. 1933 – 1989; 4. 1931 – 2012; 5. 1950-2012; 6. 1944 – 2012; 7. 1925-1938 & 1948-2012

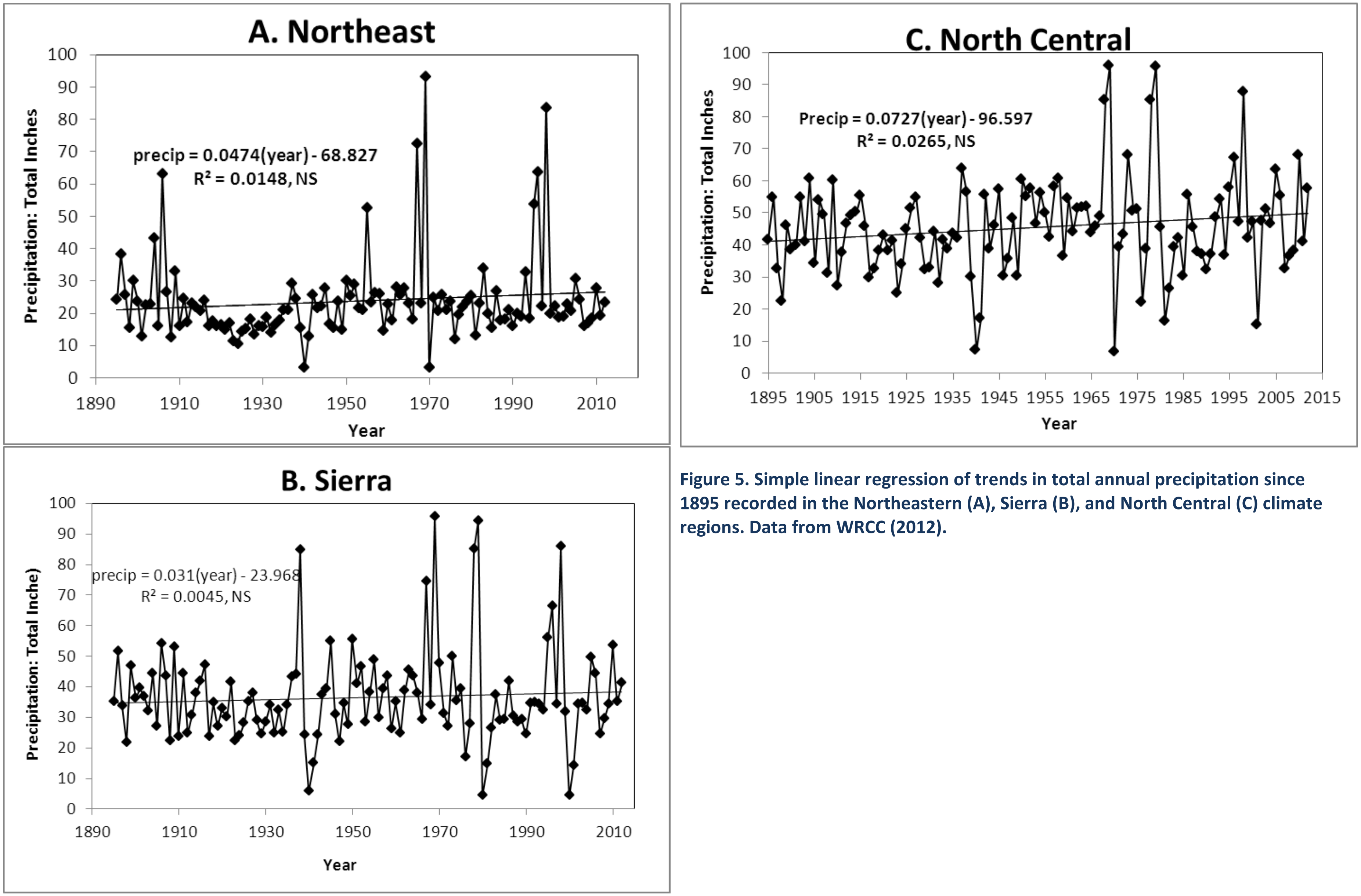


Figure 5. Simple linear regression of trends in total annual precipitation since 1895 recorded in the Northeastern (A), Sierra (B), and North Central (C) climate regions. Data from WRCC (2012).

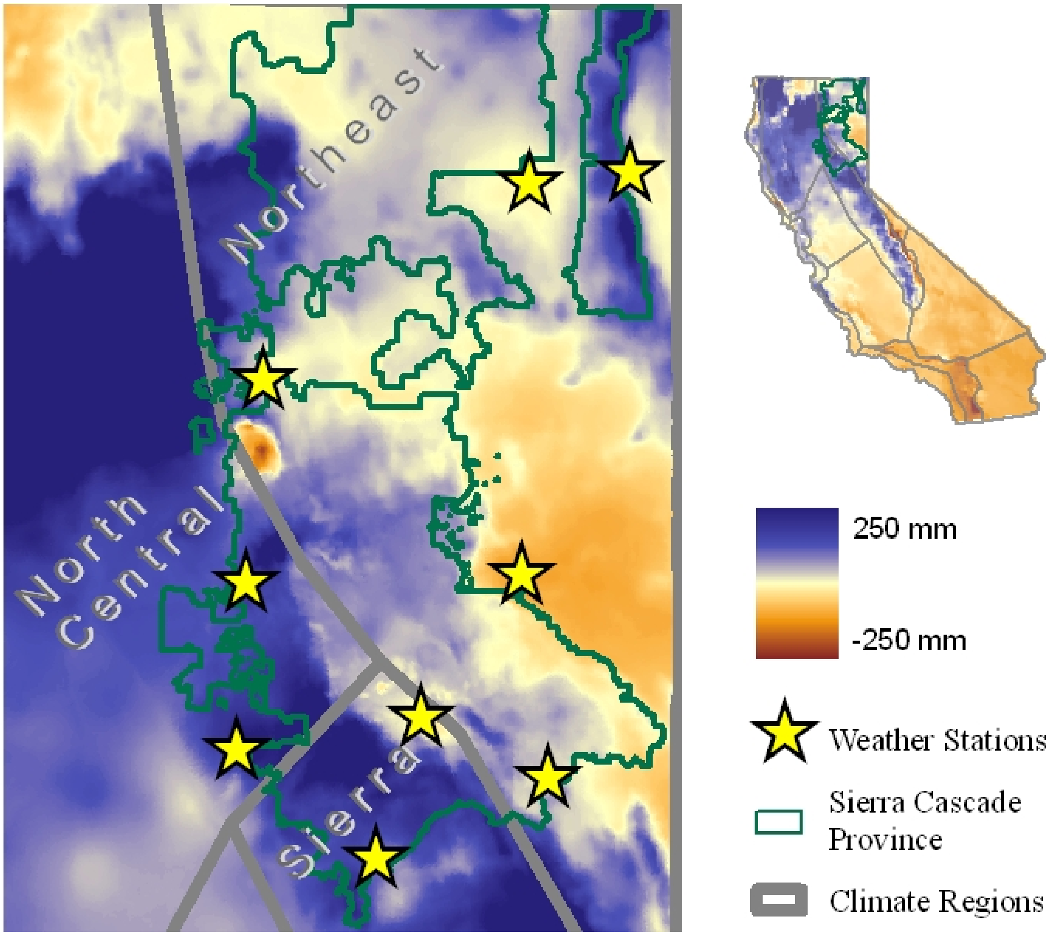


Figure 6. Mean annual precipitation change between the 1930's and 2000's as derived by the PRISM climate model. Blue areas have experienced increased precipitation, orange and red areas have experienced decreased precipitation.

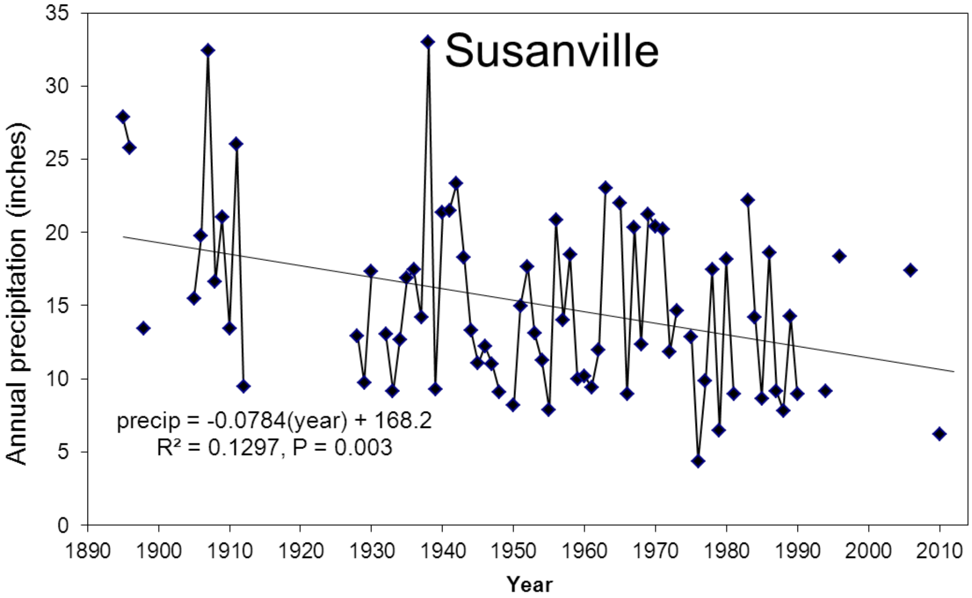


Figure 7. Total annual rainfall has significantly declined at the Susanville station, 1893-1991. Trend lines fit with simple linear regression. Data from WRCC (2012).

Variation in Precipitation

To evaluate variation in precipitation we computed the five-year coefficient of variation for the WRCC regional and individual weather station datasets. The coefficient of variation is calculated as the ratio of the standard variation to the mean, and provides a measure of variability. An increasing coefficient of variation demonstrates that year-to-year variability in precipitation has increased.

Western Regional Climate Center

Data from the WRCC show that within the Northeast climate region the five year coefficient of variation in precipitation has not changed significantly over the past 115 years (Fig. 8a). However, in both the North Central and Sierra climate regions variation in annual precipitation has significantly increased since 1895 (Fig. 8b, c).

Individual Province Stations

There is very high inter-annual variability in precipitation at all stations, such that the value predicted by the regression line is rarely representative of the actual annual mean. In the Sierra Cascade Province, six of the nine stations we evaluated showed no significant change in the coefficient of variation in precipitation over their respective periods of record, ranging from 115 to 62 years (Table 3). Three stations, Mineral, De Sabla, and Susanville, showed significant increases in precipitation variation over the last century (Fig. 9a, b, c).

Snowfall

While trends in total precipitation vary greatly from site-to-site, some general changes in precipitation patterns have been observed across the western United States since the mid-1900s. These shifts include: more rainfall and less snowfall (Knowles et al. 2006); decreased snow depth (particularly at low elevation sites; Grundstein & Mote 2010; Barnett et al. 2008; Mote et al. 2005); and decreased snow-water-equivalent (SWE) as proportion of precipitation (by 2-8% per decade with the exception of high elevation areas like the Southern Sierra Nevada; Barnett et al. 2008, Mote et al. 2005). Total annual snowfall has not been compiled from the WRCC and PRISM data sets. However, data collected by individual stations demonstrate that four of the nine stations evaluated across the Sierra Cascade Province have experienced significant declines in snowfall over the past century and two additional stations have exhibited near significant declining trends (Table 3).

At several of the stations, the relationship between snowfall and year is much stronger than that observed for temperature or precipitation. For example, at the Susanville Station over 40 percent of the variation in snowfall was a result of year and total annual snowfall has declined from about 40 inches in 1933 to eighteen inches in 1989 and the scant data since 1989 suggest even larger declines to about eight inches in 2010 (Table 3; Fig. 10a). At the Cedarville Station annual snowfall has declined from 53 inches in 1947 to about four inches in 2012. Over forty percent of the variation in snowfall at the Cedarville Station was related to year (Fig. 10b). At the Hat Creek Station year explains over 25 percent of the variation in snowfall, which has declined from 38 inches in 1949 to under four inches in 2012 (Fig. 10c). Moser *et al*. (2009) also report decreases in early spring (April 1) snowpack and snow-water equivalents between 1950 and 1997 for most of the stations they surveyed in the northeastern California (Fig. 11).

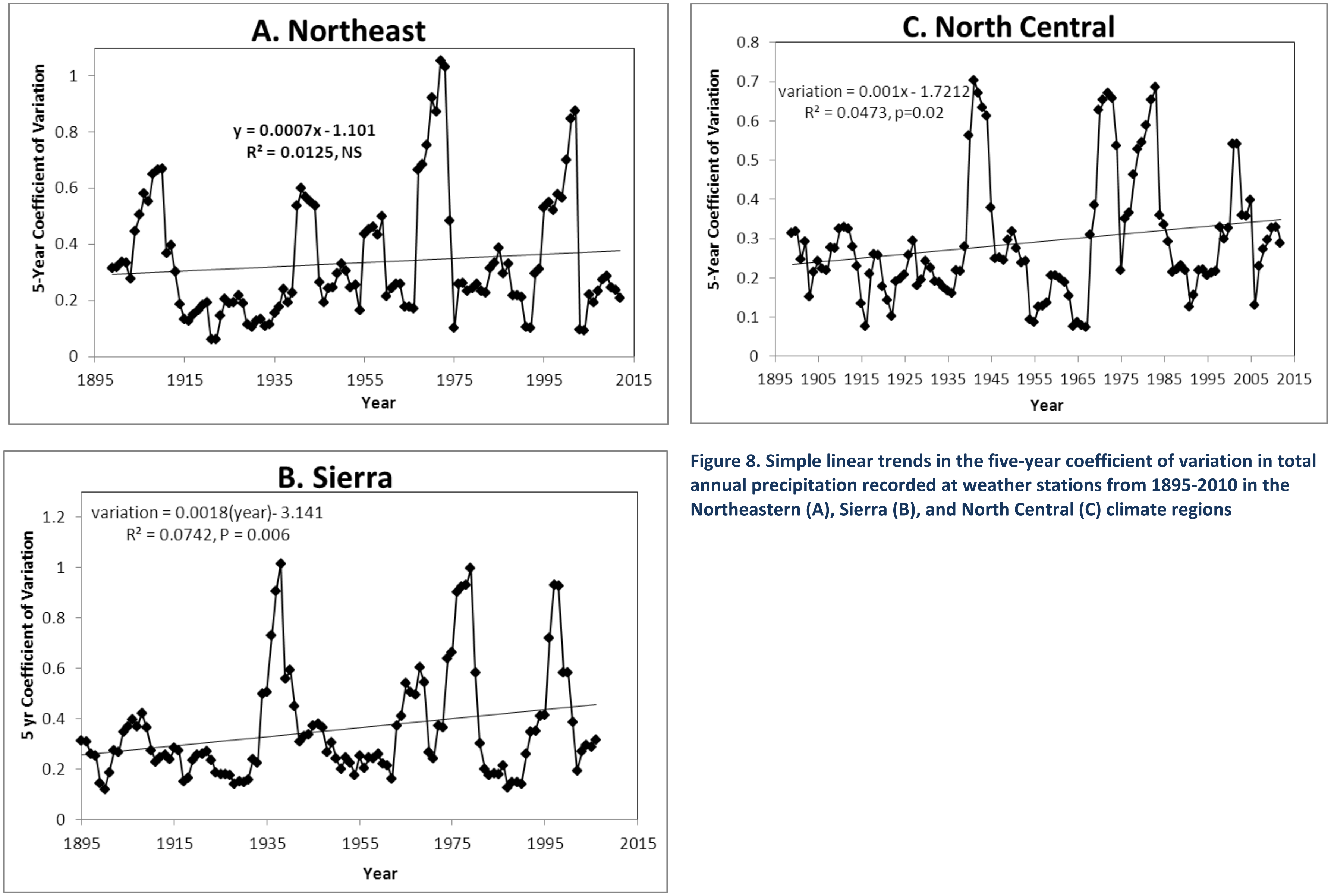


Figure 8. Simple linear trends in the five-year coefficient of variation in total annual precipitation recorded at weather stations from 1895-2010 in the Northeastern (A), Sierra (B), and North Central (C) climate regions

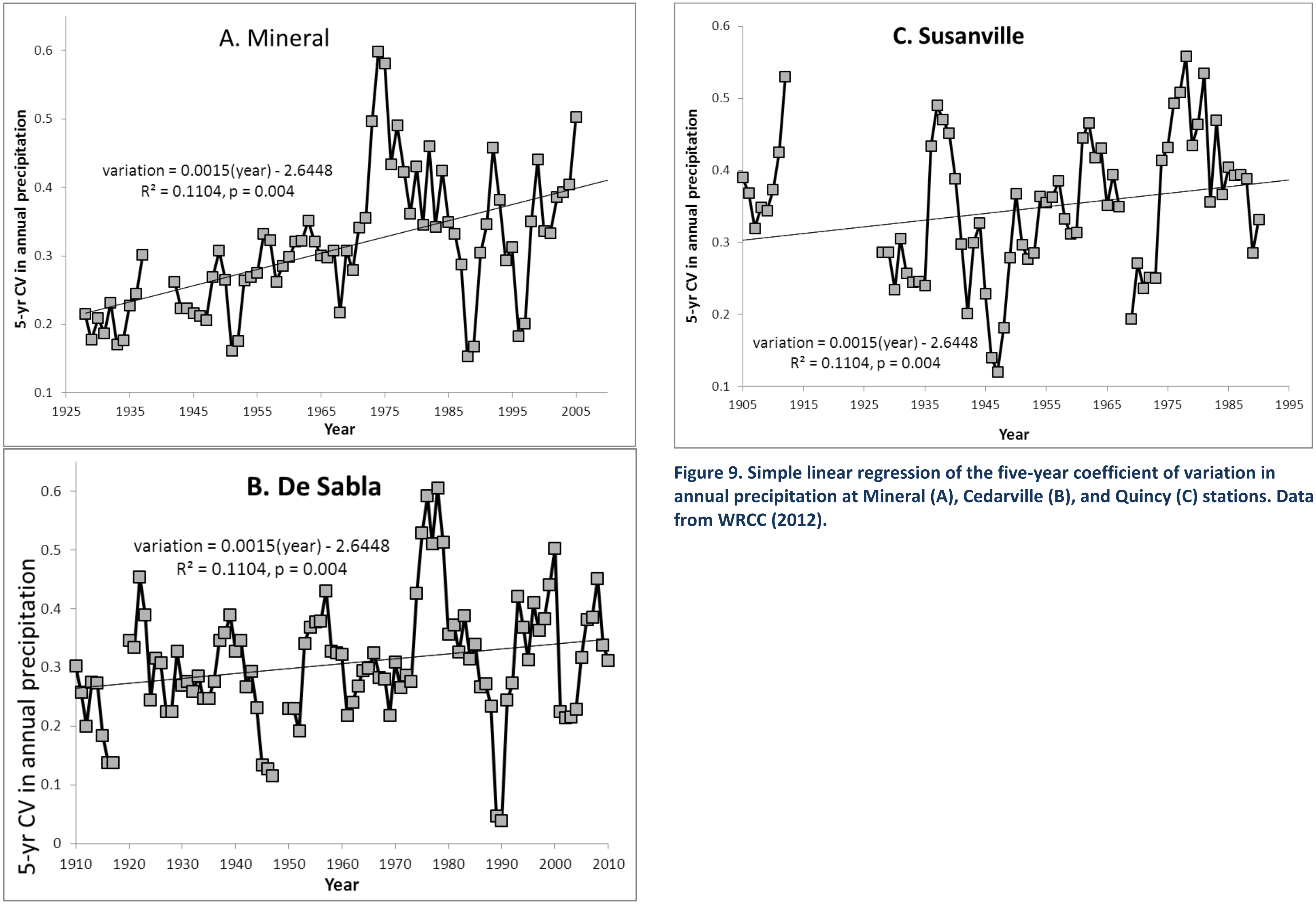


Figure 9. Simple linear regression of the five-year coefficient of variation in annual precipitation at Mineral (A), Cedarville (B), and Quincy (C) stations. Data from WRCC (2012).

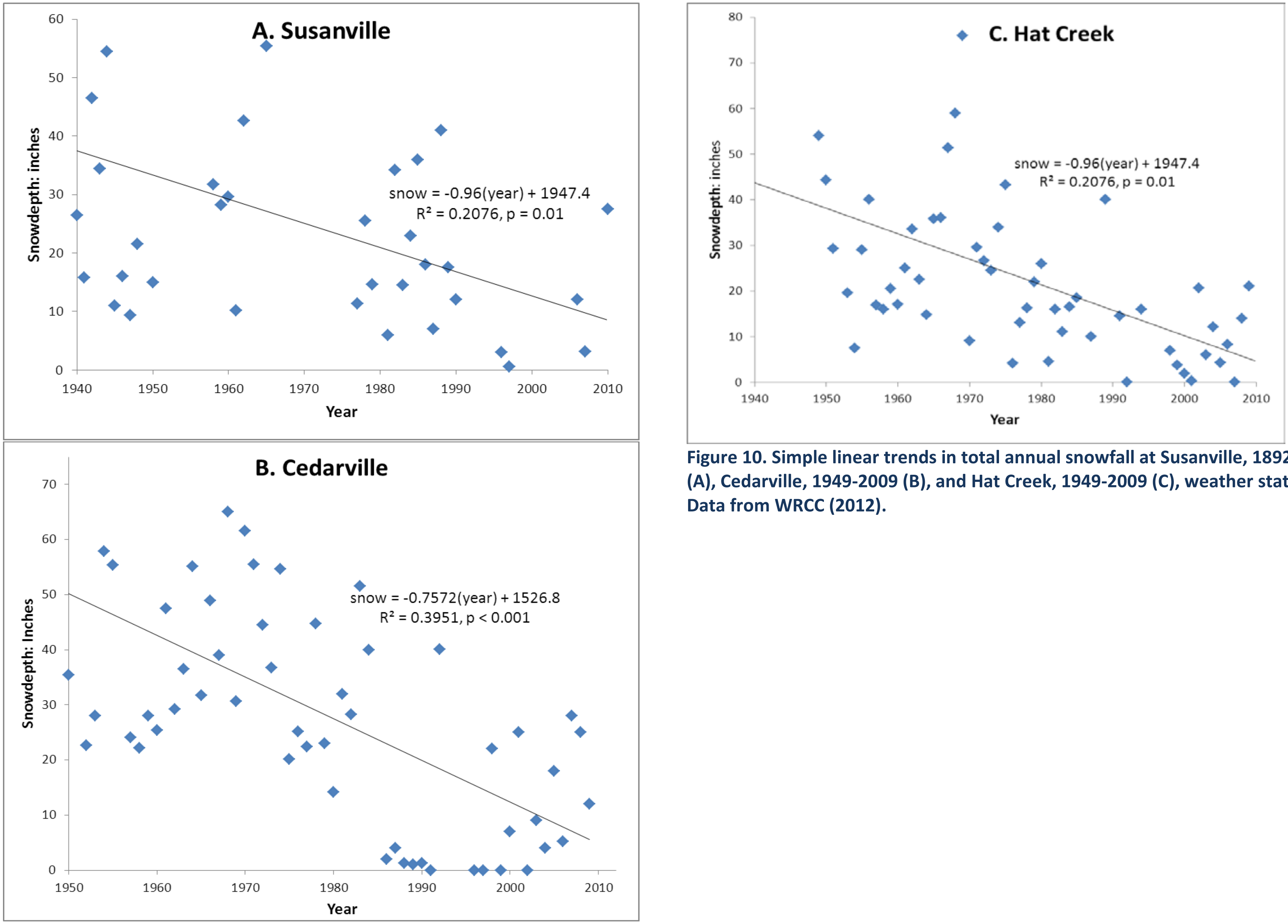


Figure 10. Simple linear trends in total annual snowfall at Susanville, 1892-2009 (A), Cedarville, 1949-2009 (B), and Hat Creek, 1949-2009 (C), weather stations. Data from WRCC (2012).

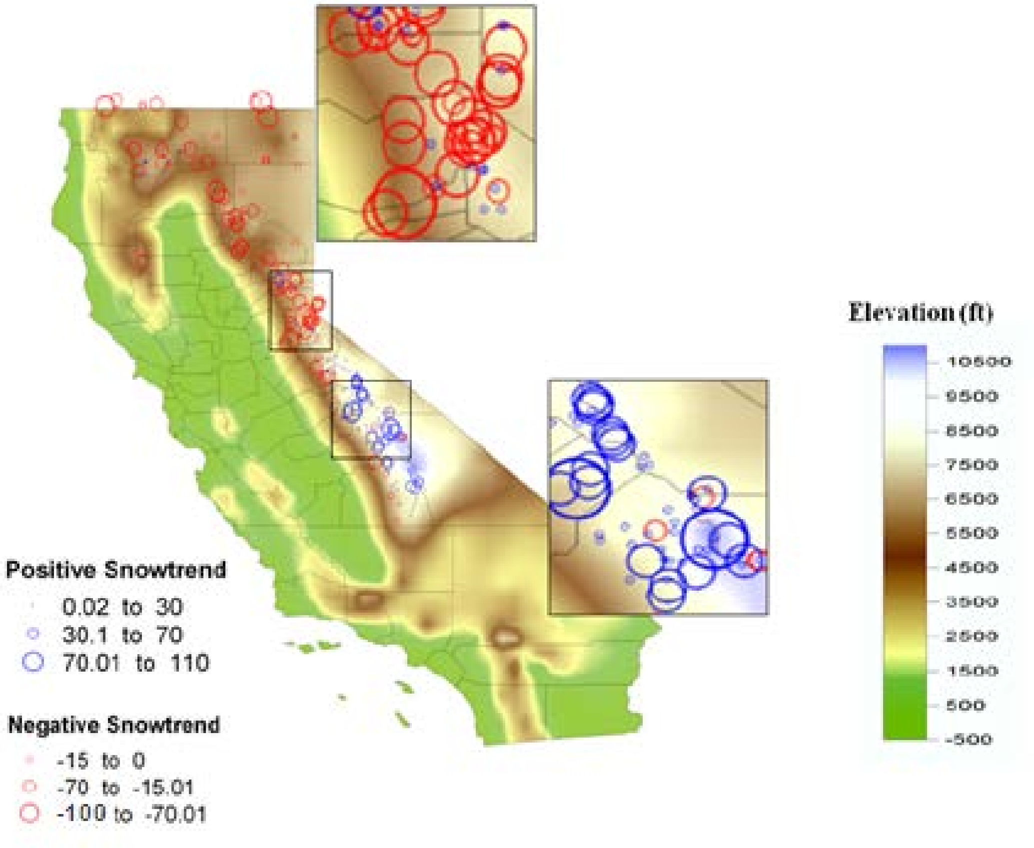


Figure 11. Trends in the amount of water contained in the snowfall ("snow water equivalent") on April 1, for the period 1950-1997. Red circles indicate percent decrease in snow water, blue circles indicate increase in snow water. From Moser et al. (2009).

II. Regional trends over the last century linked to climate change

Hydrology

Across the western United States, widespread changes in surface hydrology have been observed since the mid-1900s. These shifts include: earlier snow melt and spring runoff (by 0.3 to 1.7 days per decade; Barnett et al.2008; Hamlet et al. 2007; Stewart *et al*. 2005; Maurer 2007); decline in total runoff occurring in the spring (Moser et al. 2009); rising river temperatures (Kaushal et al. 2010), and increased variability in streamflow (Pagano & Garen 2005). While individual watershed response to climate change is highly variable (Null et al. 2010), the broad scale trends observed across the Western US have been mirrored on a smaller scale across California and the Sierra Nevada. Over the last half-century, peak runoff/streamflow (measured as the center of mass annual flow) has shifted earlier in the year for many Sierra Nevada watersheds (Young et al. 2009; McCabe and Clark, 2005; Regonda et al., 2005; Stewart et al., 2005). Stewart et al. (2005) showed that the onset of spring thaw in most major streams on the western slopes of the southern Sierra Nevada occurred 5-20 days earlier in 2002 than in 1948, and peak streamflow occurred 0-15 days earlier. Moser et al. (2009) reported that over the past 100 years, the fraction of annual runoff that occurs during April–July has decreased by 23% in the Sacramento basin and by 19% in the San Joaquin basin in

California. March flows in Sierra Nevada streams were significantly higher by 3-10%, whereas June flows were mostly lower by the same amount, and overall spring and early summer streamflow was down in most studied streams (Stewart et al. 2005). Baldwin et al. (2003) found that in the Sierra Nevada and northeastern California, the timing of spring snowmelt driven streamflow is now about 10 to 15 days earlier than in the mid-1900s (Baldwin *et al.* 2003). In addition to temporal shifts, California has also exhibited one of the greatest increases in variability in streamflow in the Western U.S. since the 1980s (Pagano & Garen 2005). This increased variability, coupled with high year-to-year persistence (i.e. the probability that a wet year is followed by another wet year, or a dry by a dry year) has resulted in extended and extreme dry and wet spells that are particularly challenging to manage for (Pagano & Garen 2005).

Beneath these general trends, there is much variation in the range of hydrologic response to climate change in the Sierra Nevada, due principally to variation in the locations and elevations of studied watersheds. For example, while the northern Sierra Nevada shows a decrease in snow-water-equivalent as proportion of precipitation (SWE/P) since 1950, the southern Sierra Nevada actually shows a positive trend (Barnett et al. 2008). This discrepancy is largely owing to the generally higher elevations in the southern Sierra Nevada, as cold, high elevation areas, and those with very large increases in precipitation, showed positive trends in SWE from 1950 to 1997 (Mote et al. 2005). Null et al. (2010) assessed the vulnerability to climate warming of 15 west-slope watersheds in the Sierra Nevada and found differing vulnerabilities for different segments of the mountain range. They found that mid- and high-elevation watersheds in southern-central Sierra Nevada were most likely to exhibit earlier runoff, while watersheds in the northern Sierra Nevada were most likely to show the greatest reductions in mean annual flow, and central Sierra Nevada watersheds were most likely to experience extended periods of low flow conditions (Null et al. 2010).

The Pitt River and Feather River hydrologic units occupy 75% of the total land area in the Sierra Cascade Province (California Interagency Watershed Map 1999). The Pitt and North Fork Feather River are mostly volcanic watersheds characterized by relatively porous basalt rock flows with high infiltration capacity. Much of the precipitation in these watersheds recharges large aquifers scattered across the Southern Cascade and Modoc Plateau regions. Streamflow in these regions is largely from large springs and groundwater outflow, and not directly related to short-term patterns of precipitation (Davisson and Rose 1997). For example, approximately 80-90 percent of annual runoff in the Pit River is from springs that emerge as aquifer outflow, some of which has been in the aquifer for 100 years or more (Davisson and Rose 1997). Although these watersheds have experienced a large reduction in the April 1 snow pack, the timing of runoff in these rivers has remained essentially unchanged over the past century (Freeman 2010).

Watersheds south of Lake Almanor, including some reaches of the North Fork Feather River, are characterized by large proportions of exposed granite with low infiltration capacity. Unlike watersheds north of Lake Almanor, run off in granitic watersheds is directly proportional to patterns of precipitation. For these granitic watersheds a decline in snow pack has caused a significant shift in the quantity and timing of runoff. The Feather River watershed has exhibited some of the largest changes in timing of runoff and loss of low elevation snowpack observed in

California (Freeman 2008, 2009). For example, on the East Branch of the North Fork Feather River, April 1 snowpack has decreased by 37% since 1949, and April-June runoff has declined by 27%. March runoff, on the other hand, has increased by 39% (Freeman 2010).

Fire

Forest fire frequency, size, total area burned, and severity have all increased across northern California over the last two to three decades. Westerling *et al.* (2006) showed that increasing frequencies of large fires (>1000 acres) across the western United States since the 1980's were strongly linked to increasing temperatures and earlier spring snowmelt. Northern California, including the Sierra Cascade Province, was one of two geographic areas of especially increased fire activity, which Westerling *et al*. (2006) ascribed to an interaction between climate and increased fuels due to fire suppression. Westerling *et al.* (2006) also identified northern California as being one of the geographic regions most likely to see further increases in fire activity due to projected future shifts in temperature. Northern California forests have already had substantially increased wildfire activity, with most wildfires occurring in years with early springs (Westerling *et al.* 2006).

Miller *et al.* (2009) showed that mean and maximum fire size and total burned area across the Sierra Nevada and Southern Cascade mountains, including the Sierra Cascade Province, have increased strongly between the early 1980's and 2007. Climatic variables explained very little of the pattern in fire size and area in the early 20th century, but 35-50% of the pattern can be explained by spring climate variables (spring precipitation and minimum temperature) in the last 25 years. The mean size of escaped fires in the Sierra Nevada and Southern Cascade Mountains was about 750 acres until the late 1970's, but the most recent ten-year average has climbed to about 1100 acres. The model that best explained the increase in area burned in the Sierra between 1977 and 2003 included effects of summer drought, and precipitation in both growing season and winter in the year prior to fire (Littell et al. 2009). High temperatures, increased fuel production due to winter precipitation, and more severe summer droughts have led to increases in area burned in the past 30 years (Littell et al. 2009). Miller *et al.* (2009) also showed that forest fire severity (a measure of the effect of fire on vegetation) rose strongly during the period between 1984 and 2007, with the pattern centered in middle elevation conifer forests. Fires at the beginning of the record burned at an average of about 17% high (stand-replacing) severity, while the average for the last ten-year period was 30%. Miller *et al.* (2009) found that both climate change and increasing forest fuels were necessary to explain the patterns analyzed.

Forest structure

The role of climate in observed changes is forest structure over the past century is confounded by land use practices such as fire suppression and logging, particularly in lower-elevation forests which are largely altered by these kinds of activities. In higher elevation forests, on the other hand, impacts by logging or recreation are minimal because these forests are much more remote, less likely to have economic uses, and are often protected in Wilderness Areas and National Parks. Fire frequencies in high elevation forests such as red fir (>50 years in most places) and subalpine forest (>100 years) were long enough that fire suppression has had little or no impact on ecological patterns or processes (Miller *et al.* 2009). Subalpine tree growth has been shown to be strongly influenced by higher precipitation and warm summers (Graumlich

1991). Long-term changes in stand structure in higher elevation forests are thus more likely to represent responses to changes in exogenous factors like climate.

In the early 1930's, the Forest Service mapped vegetation on National Forest lands in the Sierra Nevada, and sampled thousands of vegetation plots (Wieslander 1935). Bouldin (1999) compared the Wieslander plots with the modern Forest Inventory and Analysis Program plots and described changes in forest structure for the Sierra Nevada from Yosemite National Park to the Plumas National Forest (Fig. 12). In red fir forest, Bouldin (1999) found that densities of young trees had increased by about 40% between 1935 and 1992, but densities of large trees had decreased by 50% during the same period. In old-growth stands, overall densities and basal areas were higher, and the number of plots in the red fir zone dominated by shade-tolerant species increased at the expense of species like Jeffrey pine and western white pine. In old-growth subalpine forests, Bouldin (1999) found that young mountain hemlock, a shade-tolerant species, was increasing in density and basal area while larger western white pine was decreasing. In whitebark pine stands, overall density was increasing due to increased recruitment of young trees, but species composition had not changed. Lodgepole pine appears to be responding favorably to increased warming and/or increased precipitation throughout the subalpine forest. Bouldin (1999) also studied mortality patterns in the 1935 and 1992 datasets. He found that mortality rates had increased in red fir, with the greatest increases in the smaller size classes. At the same time, in subalpine forests, lodgepole pine, western white pine, and mountain hemlock all showed decreases in mortality. The subalpine zone was the only forest type Bouldin (1999) studied where mortality had not greatly increased since the 1935 inventory. This suggests that climate change (warming, plus higher precipitation in some cases) is actually making conditions better for some tree species in this stressful environment. Dolanc *et al.* (2010) recently completed a study that resampled Wieslander plots in the subalpine zone between Yosemite National Park and the Lake Tahoe Basin, south of the Sierra Cascade Province. Corroborating Bouldin (1999), they found that growing conditions in the subalpine zone were probably better today than in the 1930's, as the density of small trees of almost all species had increased greatly in the 75 year period. Dolanc *et al.*'s (2010) direct plot to-plot comparison also found that mortality of large trees had decreased density of the subalpine forest canopy, but the overall trend was for denser forests with no apparent change in relative tree species abundances.

Van Mantgem *et al.* (2009) recently documented widespread increases in tree mortality in old-growth forests across the west, including the Sierra Nevada. Their plots had not experienced increases in density or basal area during the 15-40 year period between first and last census. The highest mortality rates were documented in the Sierra and Cascade ranges in California, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates, corroborating the Bouldin (1999) findings. Van Mantgem *et al.* (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress. Comparisons of the 1930's Wieslander vegetation inventories and map with modern vegetation maps and inventories show large changes in the distribution of many Sierra Nevada vegetation types over the last 70-80 years (Fig. 12; Bouldin 1999, Moser *et al*. 2009, Thorne and Safford, unpub. data). The principal trends are (1) loss of yellow pine dominated forest, (2) increase in the area of forest dominated by shade-tolerant conifers (especially fir species), (3) loss of blue oak woodland, (4) increase in hardwood dominated forests, (5) loss of subalpine and alpine vegetation, and (6) expansion of subalpine trees into previous permanent snowfields. Trends (4) through (6) appear to have a strong connection to climate warming, while trends (1) through (3) are mostly the product of human management choices, including logging, fire suppression, and urban expansion.

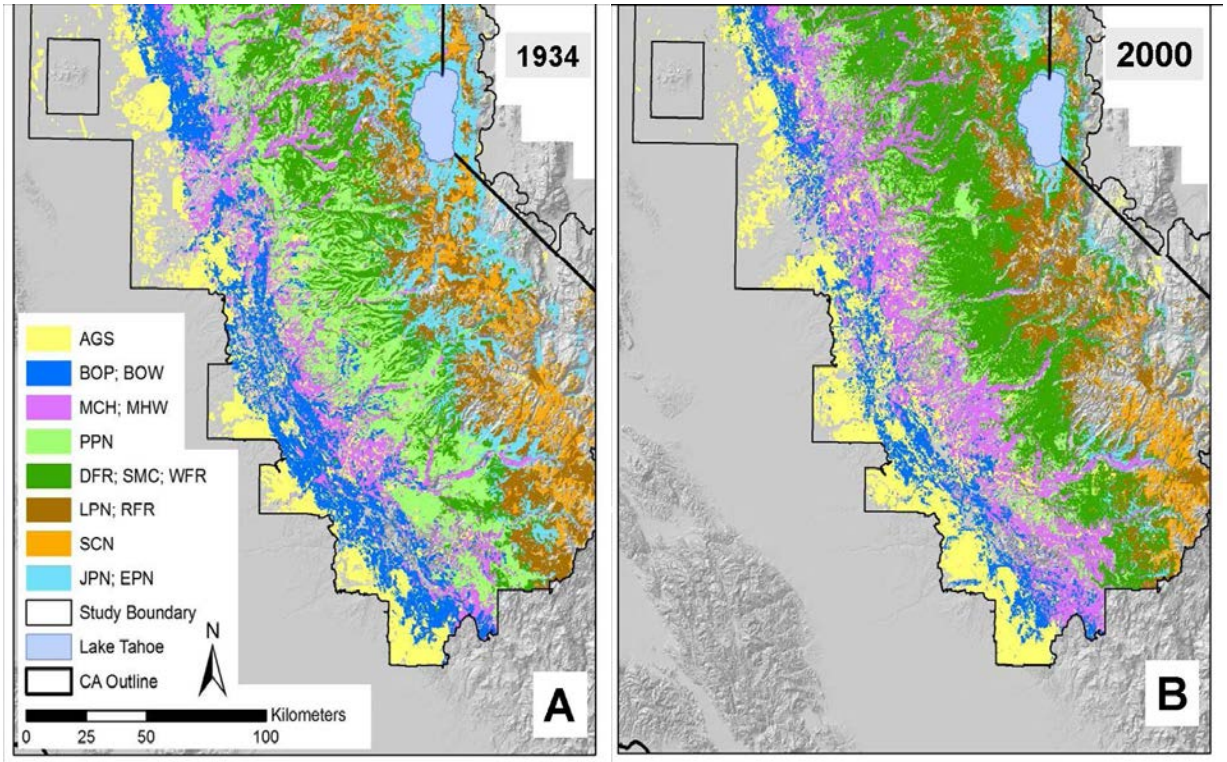


Figure 12. (A) Distribution of major vegetation types in the central and northern Sierra Nevada in the period 1932-1936. Mapped by the US Forest Service "Wieslander" mapping project. Maps digitized and vegetation types cross-walked to CWHR type by UC-Davis Information Center for the Environment. AGS = agriculture; BOP = blue oak/foothill pine; BOW = blue oak woodland; MCH = mixed conifer hardwood; MHW = mixed hardwood; PPN = ponderosa pine; DFR = Douglas-fir; SMC = Sierra mixed conifer; WFR = white fir; LPN = lodgepole pine; RFR = red fir; SCN = Subalpine conifer; JPN = Jeffrey pine; EPN = eastside pine. (B) Distribution of major vegetation types in the central and northern Sierra Nevada in 2000. Mapped by the US Forest Service Pacific Southwest Region Remote Sensing Laboratory. The major patterns of change between 1934 and 2000 are: (1) loss of yellow pine (ponderosa and Jeffrey pine) dominated forest; (2) expansion of shade tolerant conifers (DFR, WFR, SMC); (3) loss of blue oak woodland; (4) increase in hardwood dominated forests; and (5) loss of subalpine and alpine vegetation.

Wildlife

Changes in climate may have both direct (e.g. thermal stress) and indirect (e.g. changes in species interactions and vegetation) effects on wildlife distributions and abundances (Martin 2007; Rubidge *et al.* 2011). Direct effects of climate warming are predicted to force species upslope and upwards in latitude, while indirect effects leave a more complex signature. Recent work comparing historic (1914-1920; Grinnell and Storer 1924; the "Grinnell transects") and contemporary (Moritz et al. 2008) small mammal surveys conducted in Yosemite National Park by UC Berkeley's Museum of Vertebrate Zoology (MVZ) , came to several conclusions: (1) the elevation limits of geographic ranges shifted primarily upward, (2) several high-elevation species (e.g., alpine chipmunk; *Tamias alpinus*) exhibited range contraction (shifted their lower range limit upslope), while several low-elevation species expanded their range upslope (Moritz et al. 2008). Similar distribution patterns have been observed for other faunal taxa throughout the Sierra Nevada. Forister et al. (2010) tracked 159 species of butterflies over 35 years in the central Sierra Nevada and observed upward shifts in the elevational range of species, a pattern consistent with a warming climate. Tingley et al. (2009) resurveyed bird distributions along the Grinnell transects in the entire Sierra Nevada and concluded that 91% of species tracked changes in temperature or precipitation over time and 26% of species tracked both temperature and precipitation. While distributions of the American pika (*Ochotona collaris*) in the Sierra Nevada appear to be stable at present (Millar & Westfall 2010), pika distributions elsewhere appear to be moving upslope, as fast as 145 meters per decade (Beever et al. 2011), perhaps forecasting future threats to Sierra Nevada pika populations and highlighting the importance of Sierra Nevadan refugia for this species. These studies suggest that wildlife are moving in response to changing climates in order to maintain environmental associations to which they are adapted. Species with a high degree of habitat specialization and a smaller natural thermal range are more sensitive to climate change than other species and may be under more pressure to move as climates warm (Gardali et al. 2012; Jiguet et al. 2006).

Indirect effects of climate change can have complex impacts on wildlife communities, resulting in shifting, stable, or collapsing ranges and abundances. In their study of small mammals, Moritz et al (2008) concluded that: (1) many species showed no change in their elevational range, (2) elevational range shifts resulted in minor changes in species richness and composition at varying spatial scales, and (3) closely-related species responded idiosyncratically to changes in climate and vegetation. Those species exhibiting range contraction or upward shifting are likely limited by thermal tolerance and contracting suitable vegetation distributions (e.g. *T. alpinus and T. senex*), while those with stable or expanding distributions (e.g. *T. speciosus*) may have been released from interspecific competition by retreating species (Rubidge et al. 2011). However, as shifting species' distributions create novel species assemblages, many species will also face new competition and/or predation pressures that may negatively impact them (Stralberg et al. 2009). As climate-sensitive ecosystem engineers and keystone species (e.g. American pika) are extirpated from thermally stressful sites, this may also dramatically alter ecosystem ability to support particular species and assemblages (Beever et al. 2011). Another major indirect impact of climate change on wildlife populations is the loss of synchrony between reproductive or migratory phenology and resource availability (Seavy *et al.* 2009, MacMynowski & Root 2007). Breeding dates of birds like tree swallows have advanced during the last century (e.g. up to 9 days, Dunn & Winkler 1999) which may lead to a mismatch in timing of egg laying relative to availability of food. Migration of California overwintering songbirds like Swainson's Thrush, Warbling Vireo, and Wilson's Warbler among others have also advanced significantly since 1969 (MacMynowski & Root 2007).

Indirect climate change impacts may also include changes to patterns in parasitism, disease, and disturbances that impact wildlife species. Moritz et al. (2008) concluded that in the Yosemite area most observed upwards range shifts for high-elevation species were consistent with predicted climate warming, while changes in most lower- to mid-elevation species' ranges were more likely the result of landscape-level vegetation dynamics related primarily to fire history (Moritz et al. 2008). In other areas, decreasing songbird diversity and abundance has been indirectly attributed to decreasing snowfall patterns (Martin & Maron 2012). Low rates of snowfall allow for increased over-winter herbivory by ungulates like deer and elk, thus decreasing growth and abundance of some tree species (especially aspen and cottonwood), which may in turn decrease associated songbird abundances (Martin 2007; Martin & Maron 2012; Brodie et al. 2012). Drost and Fellers (1996) found that most frog and toad species in Yosemite exhibited widespread decline over the past several decades, regardless of elevation. Primary factors contributing to this faunal collapse throughout the Sierra Nevada include introduced predators, a fungal pathogen, pesticides, and climate change (Wake and Vredenburg 2008). The amount of food consumed by aquatic ectotherms (cold-blooded organisms) generally increases with temperature, so warmer water temperatures may be increasing predation rates by native and introduced predators on species like the yellow-legged frog in the Sierra Nevada (Rahel et al. 2008). Increased water temperatures also promote populations of parasites like copepods, which negatively affect the fitness of fish and amphibian species (Kupferberg et al. 2009). Species like the protected Foothill yellow-legged frog (*Rana boylii*) have been shown suffer higher outbreaks of copepod parasites with increased water temperatures and drought-induced decreases in water flows in Northern California (Kupferberg *et al.* 2009).

III. Future predictions

Climate

As of today, no published climate change or vegetation change modeling has been carried out for the Sierra Cascade Province. Indeed, few future-climate modeling efforts have treated areas as restricted as the State of California. The principal limiting factor is the spatial scale of the General Circulation Models (GCMs) that are used to simulate future climate scenarios. Most GCMs produce raster outputs with pixels that are 10,000’s of km^2 in area. To be used at finer scales, these outputs must be downscaled using a series of algorithms and assumptions – these finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCMs disagree with respect to the probable outcomes of climate change. For example, a recent comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1º C increase in temperature to an 8% decrease (Gutowski *et al.* 2000, Hakkarinen and Smith 2003). That said, there was some broad consensus: all of the reviewed GCMs predicted warming temperatures for California, and 13 of 21 predicted higher precipitation (three showed no change and five predicted decreases). According to Dettinger (2005) the most common prediction among the most recent models (which are considerably more complex and, ideally, more credible) is temperature warming by about 9° F by 2100, with precipitation remaining similar or slightly reduced compared to today. Most models agreed that summers will be drier than they are currently, regardless of levels of annual precipitation.

The most widely cited of the recent modeling efforts is probably Hayhoe *et al.* (2004). Hayhoe *et al.* (2004) used two contrasting GCMs (much warmer and wetter, vs. somewhat warmer and drier) under low and high greenhouse gas emissions scenarios to make projections of climate change impact for California over the next century. By 2100, under all GCM-emissions scenarios, April 1 snowfall was down by -22% to -93% in the 6,700-10,000 feet elevation belt, and the date of peak snowmelt was projected to occur from 3 to 24 days earlier in the season.

Average temperatures were projected to increase by 2 to 4 °F in the winter and 4 to 8 °F in the summer. Finally, three of the four GCM-emissions scenarios employed by Hayhoe *et al.* (2004) predicted strong decreases in annual precipitation by 2100, ranging from -91 to -157 mm; the remaining scenario predicted a 38 mm increase.

Cayan *et al.* (2008) use simulations from the National Center for Atmospheric Research and Department of Energy Parallel Climate Model (PCM1) and the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory CM2.1 model (GFDL) to investigate possible future climate changes in California. In Northern California, by the end of the century, projected precipitation increases slightly or does not change in one model (PCM1) and decreases by 10-20% in the other model (GFDL). Although little change in northern California precipitation is projected during the twenty-first century, there is a modest tendency for increases in the numbers and magnitudes of large precipitation events. While the magnitude of warming varies by both model and emission scenario, California mean temperatures rise by between 1.7 and 5.8°C between 2000 and 2100 for the set of climate change model simulations.

Hydrology

Although climate models diverge with respect to future trends in precipitation over northeastern California, there is widespread agreement that the trend toward lower snow water equivalent and earlier snowmelt will continue (McCabe and Wolock 1999; Miller *et al.* 2003; Snyder *et al.* 2004; Barnett *et al.* 2005; Zhu *et al.* 2005; Vicuna *et al.* 2007). Sensitivity to decreasing snow accumulation is largely dependent on baseline temperature. In high elevation basins, where temperatures are far below freezing, small changes in temperature do not reduce snow pack. However, lower elevation basins such as the Feather River within the Sierra Cascade Province, are very vulnerable to small (i.e. 1.5-3° C) changes in temperature because current winter temperatures for a large percentage of the basin are currently just below freezing. A small increase in temperature leads to temperatures above freezing and therefore to less snow accumulation and earlier melting. Basins that are generally below the freezing line, such as the Sacramento River basin, are less sensitive to temperature changes and more sensitive to precipitation than snow producing basins. High flows in these low elevation basins are probably more related to rainfall that to snowmelt events (Miller *et al.* 2003). The Pitt and North Fork Feather river may be somewhat buffered from changes in temperature and patterns of precipitation because runoff is largely from aquifers and springs in the volcanic southern Cascade and Modoc Plateau watersheds.

Modeling future hydrological changes in California, Miller et al. (2003) found that annual streamflow volumes were strongly dependent on the precipitation scenario, but changes in seasonal runoff were more temperature dependent. Predicted spring and summer runoff was lower in all of the California river basins they modeled, except where precipitation was greatly increased, in which case runoff was unchanged from today (Miller et al. 2003). Runoff in the winter and early spring was predicted to be higher under most of the climate scenarios because higher temperatures cause snow to melt earlier. Flood potential in California rivers that are fed principally by snowmelt (i.e., higher elevation streams) was predicted to increase under all scenarios of climate change, principally due to earlier dates of peak daily flows and the increase in the proportion of precipitation falling as rain (Miller et al. 2003). Timing of peak flow may be expected to advance by up to seven weeks by 2100, depending on the climate scenario (Young et al. 2009).

Under the wettest climate scenario modeled by Miller et al. (2003), by 2100 the volume of flow during the highest flow days could more than double in many Sierra Nevada rivers, with the predicted increase in peak flow most pronounced in higher elevation basins, due to the greater reliance on snowmelt. Das et al. (2011) found that under simulated future climate scenarios, all models predict greater flood magnitude and most predict greater flood frequency in both the Northern and Southern Sierra Nevada (Das et al. 2011). Increases in extreme hydrologic events across the western US are predicted to be especially pronounced in the mountains of the California coast range and the Sierra Nevada (Kim 2005). Increased flood risk is thus a high probability outcome of the continuation of current climate change trends, because temperature, not precipitation, is the main driver of higher peak runoff (Miller et al. 2003).

Increased flooding is not the only predicted result of seasonal shifts in peak flows and warming temperatures. Warming temperatures are also expected to extend the period of summer drought, and decrease flow magnitude in the dry months (Reba et al. 2011). Increased variability in streamflow in California is already resulting in – and is predicted to continue to result in – extended wet and dry spells (Pagano & Garen 2005), with significant economic, social, and biological impacts (Mote et al. 2005).

Using the Precipitation Runoff Modeling System calibrated for the Feather River Basin, Hay *et al.* (2011) projected snowmelt to increase in December and January and to decrease between March and June. They also projected decadal oscillations of higher and lower flows, corresponding to wetter and drier precipitation cycles in the Feather River Basin through 2099.

Vegetation

Lenihan *et al.* (2003, 2008) used a dynamic ecosystem model ("MC1") which estimates the distribution and the productivity of terrestrial ecosystems such as forests, grasslands, and deserts across a grid of 100 km^2 cells. To date, this is the highest resolution at which a model of this kind has been applied in California, but it is not of high enough resolution to be applied to the Sierra Cascade Province as a unit. Based on their modeling results, Lenihan *et al.* (2003, 2008) projected that forest types and other vegetation dominated by woody plants in California would migrate to higher elevations as warmer temperatures make those areas suitable for colonization and survival.

In the Sierra Nevada (Fig. 13a), with higher temperatures and a longer growing season, the area occupied by subalpine and alpine vegetation was predicted to decrease as evergreen conifer forests and shrublands migrate to higher altitudes. Under their "wetter" future scenarios (i.e., slightly wetter or similar to today), Lenihan *et al.* (2003, 2008) projected a general expansion of forests in northern California. With higher rainfall and higher nighttime minimum temperatures, broadleaf trees (especially oak species) were predicted to replace conifer-dominated forests in many parts of the low and middle elevation Sierra Nevada. For the Southern Cascade Ecological Section (Fig. 13b), a decline in evergreen conifer forests and an increase in grasslands are only seen under their "dry" future scenarios. On the Modoc Plateau, an increase in evergreen conifer forest is also predicted under all but the driest future scenario (Fig. 13c).

Under their drier future scenarios, Lenihan *et al.* (2003, 2008) predicted that grasslands would expand, and that increases in the extent of tree-dominated vegetation would be minimal. An expansion of shrublands into conifer types was also predicted, due to drought and increases in fire frequency and severity (see below), but increasing fire frequency on the Modoc Plateau may replace much low to middle elevation shrubland with grassland (Fig. 13). Expansion of grassland was predicted under under all scenarios, especially in the semi-arid regions of the state such as the Modoc Plateau. Increases in grass biomass translated to more fine flammable fuels, promoting more fire which in turn reduced the cover of the woody life-forms, resulting in further expansion of grasslands (see below). Hayhoe *et al.* (2004) also used the MC1 ecosystem model to predict vegetation and ecosystem changes under a number of different future greenhouse gas emissions scenarios. Their results were qualitatively similar to the Lenihan *et al.* (2003, 2008) results.

Fire

The combination of warmer climate with higher CO_2 fertilization will likely cause more frequent and more extensive fires throughout western North America (Price and Rind 1994, Flannigan et al. 2000). Fire responds rapidly to changes in climate and will likely overshadow the direct effects of climate change on tree species distributions and migrations (Flannigan et al. 2000, Dale et al. 2001). A temporal pattern of climate-driven increases in fire activity is already apparent in the western United States (Westerling et al. 2006), and modeling studies specific to California expect increased fire activity to persist and possibly accelerate under most future climate scenarios, due to increased growth of fuels under higher CO_2 (and in some cases precipitation), decreased fuel moistures from warmer dry season temperatures, and possibly increased thundercell activity (Price and Rind 1994; Miller and Urban 1999; Lenihan et al. 2003, 2008; Westerling and Bryant 2006). Temperature has been shown to strongly influence fire frequency and area burned, and increased temperatures will lead to increased fire frequency and size (Guyette et al 2012; Spracklen et al. 2009). By 2100, Lenihan et al.'s (2003, 2008) simulations suggest a *c.* 5% to 8% increase in annual burned area across California, depending on the climate scenario (Fig. 14). Within the Western US, Spracklen et al (2009) found that the Pacific Northwest, including the Sierra Nevada and Cascade regions of California, showed the largest projected increase in area burned over the next half century.

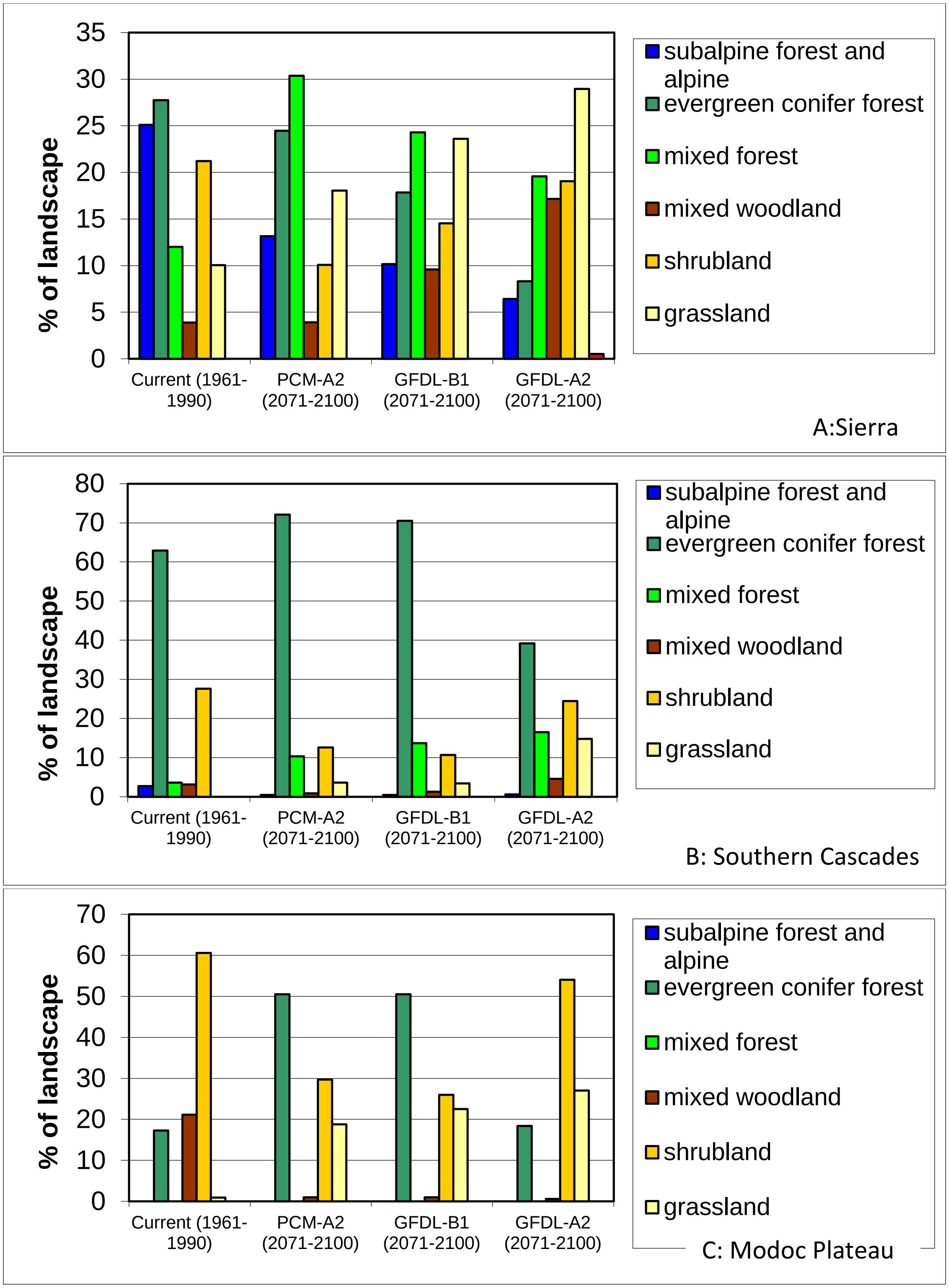
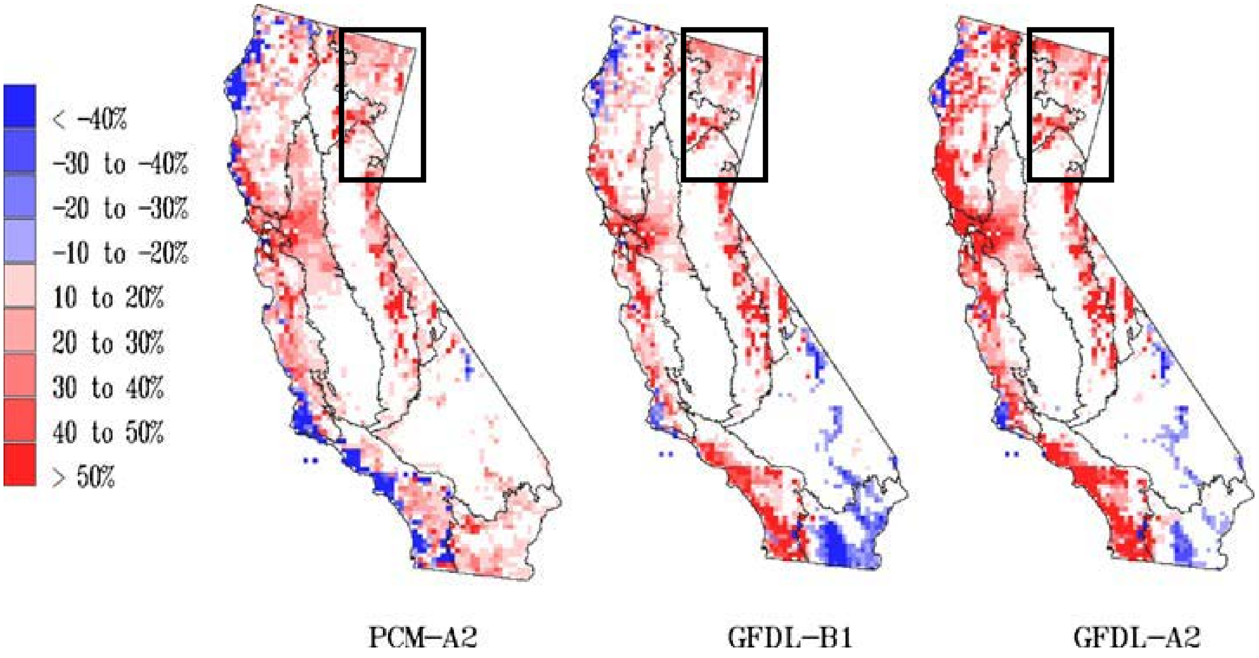


Figure 13. MC1 outputs for the Sierra Nevada (A), Southern Cascades (B), and Modoc Plateau (C) Ecoregion, current vs. future projections of vegetation extent. The GFDL-B1scenario = moderately drier than today, with a moderate temperature increase (<5.5ºF); PCM-A2 = similar ppt. to today, with <5.5ºF temp. increase; GFDL-A2 = much drier than today and much warmer (>7.2ºF higher. From Lenihan et al. (2008).

Within California, mid-elevation sites on the west side of the Sierras are likely to show the greatest increases in burned area in the next few decades (Westerling et al. 2011). Lutz et al. (2009) project that both the number of lightning ignited fires and the annual area burned at high severity in Yosemite National Park in the Sierra Nevada will increase by about 20% by 2020-2049 (19.1% and 21.9% respectively) due to projected decreases in snowpack. Westerling and Bryant (2008) predict a 10-35% increase in large fire risk by midcentury in California and Nevada. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species compositions (Lenihan et al. 2003, 2008), and will likely reduce the size and extent of late-successional refugia (USFS and BLM 1994, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for old growth forest and old growth-dependent flora and fauna.

A key question is to what extent future fire regimes in montane California will be characterized by either more or less severe fire than is currently (or was historically) the case. Fire regimes are driven principally by the effects of weather/climate and fuel type and availability (Bond and van Wilgen 1996). Seventy years of effective fire suppression in the American West have led to fuel-rich conditions that are conducive to intense forest fires that remove significant amounts of biomass (McKelvey *et al.* 1996, Arno and Fiedler 2005, Miller *et al.* 2009), and most future climate modeling predicts climatic conditions that will likely exacerbate these conditions. Basing their analysis on two GCMs under the conditions of doubled atmospheric CO_2 and increased annual precipitation, Flannigan *et al.* (2000) predicted that mean fire severity in California (measured by difficulty of control) would increase by about 10% averaged across the state.



PCM–A2 GFDL–B1 GFDL–A2

Figure 14. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). Sierra Cascade Province indicated with black square. Figure from Lenihan et al. (2008). See Fig. 13 for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

Vegetation growth models that incorporate rising atmospheric CO_2 show an expansion of woody vegetation on many western landscapes (Lenihan *et al.* 2003, 2008; Hayhoe *et al.* 2004), which could feedback into increased fuel biomass and connectivity and more intense (and thus more severe) fires. Use of paleoecological analogies also suggests that parts of the Pacific

Northwest (including northern California) could experience more severe fire conditions under warmer, more CO_2-rich climates (Whitlock *et al.*, 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for Sierra Nevada forests (e.g. Swetnam 1993, Miller and Urban 1999), but if fuels grow more rapidly *and* dry more rapidly – as is predicted under many future climate scenarios – then both severity and frequency may increase. In this scenario, profound vegetation type conversion is all but inevitable. Lenihan *et al.*'s (2003, 2008) results for fire intensity predict that large proportions of the Sierra Nevada landscape may see mean fire intensities increase over current conditions by the end of the century, with the actual change in intensity depending on future precipitation patterns.

Wildlife

Significant changes in California's terrestrial fauna and flora are projected over the next century. Stralberg et al. (2009) developed current and future species distribution models for 60 focal bird species and found that novel avian assemblages with no modern analogue could occupy over half of California. This implies a dramatic reshuffling of avian communities and altered patterns of species interactions, even in the upper elevations of the Sierra Nevada, where only a modest proportion of novel avian communities were projected. Using species distribution modeling, the California Avian Data Center (2011) projected that approximately 60% of coniferous forest bird species in the Sierra Nevada will exhibit substantial range reductions within the next 40 to 90 years (using 21 focal avian species). A total of 128 out of 358 (36%) of California's bird species of "special concern" (rare, threatened, endangered, or experiencing significant decline; Shuford & Gardali 2008) were ranked as vulnerable to climate change, especially species such as the Great gray owl, Greater sage grouse, and Gray-crowned rosy finch (Gardali et al. 2012). Based on bioclimatic models, Lawler et al. (2009a,b) projected high vulnerability of California's amphibian fauna and moderate vulnerability of California's mammalian fauna under a high greenhouse gas emissions scenario by the end of the century; Lawler et al. projected >50% change in the amphibian fauna and 10-40% change in the mammalian fauna . In a similar study, Loarie et al. (2008) projected that 66% of California's native flora will experience >80% reduction in range size by 2100.

Direct effects will continue to impacts wildlife species in the future, likely at an accelerating pace. Lawler et al (2012) investigated the possible effects of climate change on selected species of the genus *Martes* and found that macroclimate conditions closely correlated with Pacific fisher (*Martes pennanti*) presence in California were likely to change greatly over the next century, resulting in a possibly pronounced loss of suitable habitat. Their results suggested that martens and fishers will be highly sensitive to climate change, and would probably experience the largest climate impacts at their southernmost latitudes (i.e. in the southern Sierra Nevada). When combined with other stressors, predicted climate changes represent significant threats to aquatic communities (Schindler 1997). Diminished flow magnitude is one of the most important predictors of biological integrity of fish and macroinvertebrate communities (Carlisle et al. 2010). Where compounded with human-induced disturbance, increased flooding may negatively impact some aquatic communities (Herbst & Cooper 2010). Additionally, as air temperatures rise, water temperatures are expected to continue to warm as well, potentially resulting in local species extirpations, increased non-native species invasions, declines in macroinvertebrate communities, and temporal disruptions to spawning and larval life stages

(Kaushal et al 2010; Viers & Rheinheimer 2011). Those aquatic species with a competitive advantage in colder waters will also likely suffer losses due to both thermal stress and increased competition as water temperatures rise (Rahel et al. 2008; Kennedy et al. 2009). Salmonids may be particularly sensitive to warming water temperatures (ISAB 2007). In the Sierra Nevada, increases in water temperatures will likely reduce ranges for thermally sensitive species like rainbow trout, as physiological limitations eliminate low-elevation habitat options and natural topographic barriers limit dispersal to higher elevation waters (Viers & Rheinheimer 2011).

Indirect effects will also continue to impact wildlife species in complex ways in the future. Species that require older, denser, and more structurally complex forest conditions, like Sierra Nevada Fisher and the Northern Spotted Owl, will likely be negatively impacted by changes in fire regimes associated with climate change (Scheller *et al.* 2011). Lawler et al. (2012) noted that fisher habitat is driven to a great extent by local vegetation features and thus the authors examined stand-level implications of fire under a series of future fire scenarios, since fire occurrence and behavior, largely driven by climate/weather, have substantial effects on local vegetation. They recommended protecting fisher habitat through targeted forest-fuel treatment, and applying more liberal fire-management policies to naturally ignited fires during moderate weather conditions. Sensitive benthic invertebrate populations may also be reduced by increases in large and severe wildfires that are likely to be associated with climate warming (Oliver *et al.* 2012). Larger effects will likely be observed in small, first-order streams (e.g. Angora Creek, LTBMU; Oliver *et al.* 2012). Sierra Nevada fish species like the brook trout will likely decline in abundance due to alterations in frequency, intensity, and seasonal timing of floods in areas like Sagehen Creek, while other species like rainbow trout may then benefit from decreased competition (Meyers *et al.* 2010).

Loarie et al. (2008) identified the southern Sierra Nevada and the coastal mountains of Northwest California as climate change refugia, defined as areas projected to sustain species with otherwise shrinking ranges. Authors like Loarie et al. and Lawler et al. recommend novel adaptive management approaches and large-scale planning efforts that promote landscape/regional habitat connectivity. Loarie et al. (2008) also recommended serious consideration of human-assisted dispersal of California’s flora and prioritization of climate change refugia for conservation and restoration.

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