A summary of current trends and probable future trends in climate and climate-driven processes for the Klamath National Forest and surrounding lands

Ramona J. Butz*, Northern Province Ecologist, USDA Forest Service, Pacific Southwest Region. rbutz@fs.fed.us; 707-441-3584

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

I. Local trends in climate over the past century

The data presented in this section are derived primarily from six weather stations with long-term meteorological data on and adjacent to the Klamath National Forest (KNF) (WRCC 2010). One of the longest quasi-continuous weather records is provided by the Happy Camp Ranger Station (1916-1998; WRCC 2010) at 1090 feet (332 m) above sea level at approximately 41° 48' N, 123° 23' W. The Happy Camp weather record has incomplete annual temperature data from the years 1916-1994 and precipitation data from 1916-1981 (missing the period 1921-31). The Callahan weather station is located in the town of Callahan at approximately 41° 18' N, 122° 48' W at 3190 feet (972 m) above sea level and provides quasi-continuous temperature data for the period 1954-2009 and precipitation data for the period 1944-2009. The Fort Jones Ranger Station has temperature data for the period 1937-2002 and precipitation for the period 1937-1981. The Fort Jones station is located at approximately 41° 36' N, 122° 51' W at 2720 feet (829 m) above sea level. The Yreka weather station, located at approximately 41° 43' N, 122° 38' W at 2630 ft. (802 m) above sea level, is one of the longest quasi-continuous weather records for the area. Temperature data are available for the period 1894-2008 (but missing 1902-13 and other one to two year periods); precipitation data are available for the period 1944-2008. The Mount Shasta weather station has both temperature and precipitation data from 1949-2009 with no missing records. It is located at approximately 41° 19' N, 122° 19' W at 3590 ft. (1094 m) above sea level. The final station used for this analysis is the Mount Hebron Ranger Station weather station located at approximately 41° 47' N, 122° 02' W at 4250 ft. (1295 m) above sea level. Temperature data are available for the period 1952-2002 (missing 1961-64 and 1992-2000). Precipitation data are highly discontinuous and are not included in this summary. Years with more than 15 days of missing temperature data in a single month or 5 days of missing precipitation data in a single month are excluded from the analyses. We also present spatial data from the PRISM climate dataset, which extrapolates weather station records to the landscape for all years beginning in the late 19th century (Daly et al. 1994, PRISM 2010).

Temperature

The PRISM data suggest that most of the Klamath NF area has experienced increases in mean annual temperature of 1°C (1.8° F) or less over the last ¾ century, although some mountainous areas have seen decreases in temperature (Fig. 1). The weather station data

*Corresponding author

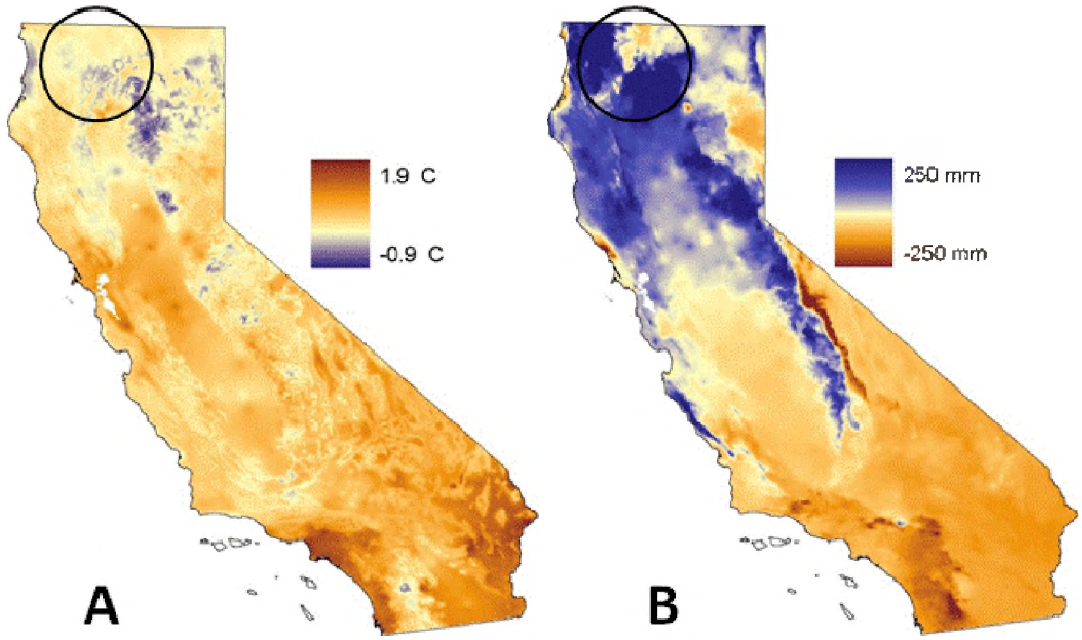

Figure 1. Spatial differences in mean annual temperature (A), and mean annual precipitation (B) between the 1930's and 2000's, as derived by the PRISM climate model. The Klamath NF area is found within the circle. Temperatures have risen only moderately across most of the KNF area, and many areas have seen minor decreases in temperature. The PRISM model suggests that precipitation has increased across most of the area, with the exception of the area north of Mt. Shasta. Graphic courtesy of S. Dobrowksi, Univ. of Montana.

confirm these patterns, with only one station (Mt. Hebron, with an admittedly highly incomplete dataset) reporting a significant positive trend in mean annual temperature (Figs. 2-7). Trends in mean maxima are up at three stations, steady at two stations, and negative at Callahan; mean minimum temperatures are rising at only two of the six stations (Figs. 2-7).

Precipitation

The PRISM dataset suggests that the landscape of the Klamath NF is experiencing very disparate trends in precipitation, depending on the location (Fig. 1). The Trinity and Marble Mountains, and the highlands south of Mt. Shasta are getting wetter, while the eastern portion of the KNF is not changing or getting drier. The weather station records weakly corroborate these patterns. There are no statistically significant changes in mean annual precipitation at any of the five weather stations analyzed, but there are qualitative increases in precipitation at both Happy Camp and Mt. Shasta (Figs. 8-12). There is very high interannual variability in all five precipitation records, such that the value predicted by the regression line in each figure is rarely representative of the actual annual mean. There were no significant increases in seasonal precipitation at any station, and the distribution of precipitation across the year has remained similar through the record.

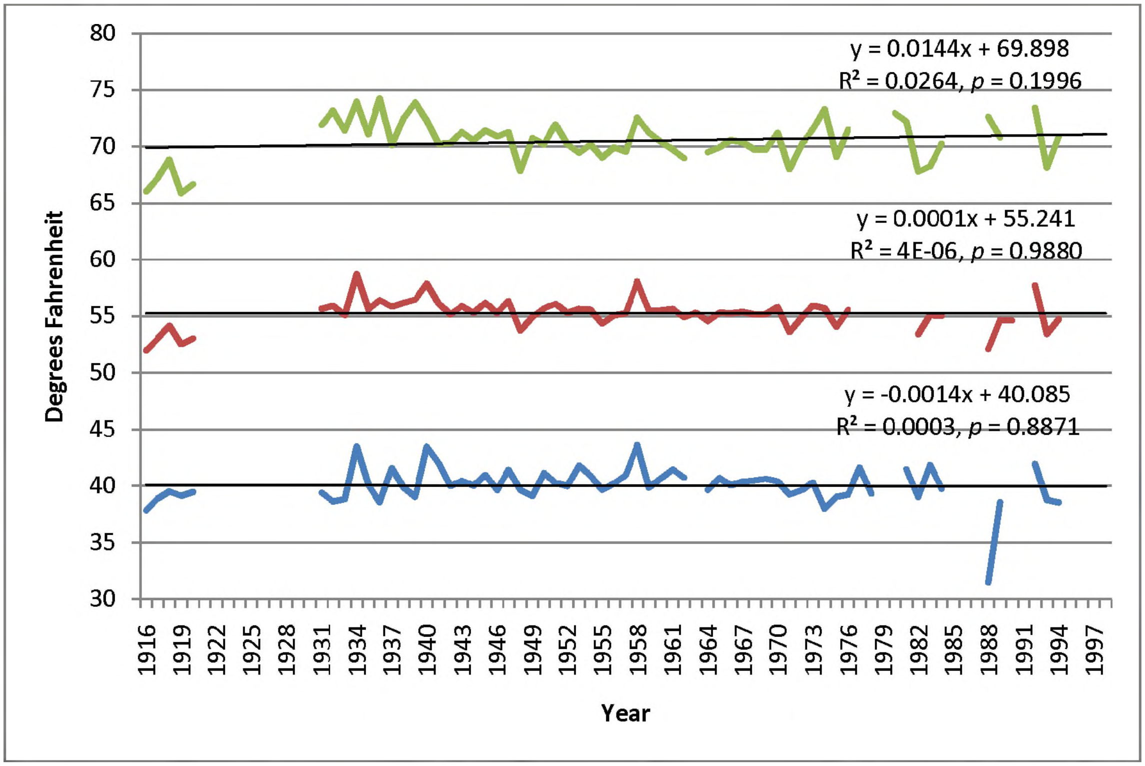

Figure 2. Annual mean, mean maximum, and mean minimum temperatures at Happy Camp Ranger Station, California, 1916-1998. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

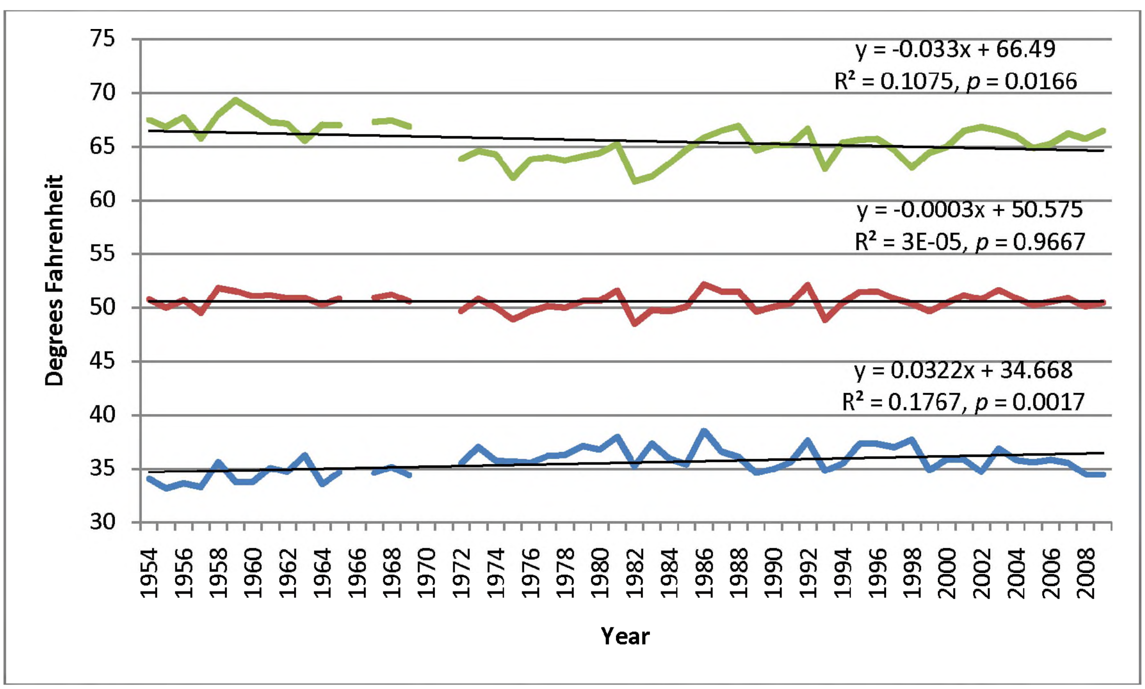

Figure 3. Annual mean, mean maximum, and mean minimum temperatures at Callahan, California, 1954-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

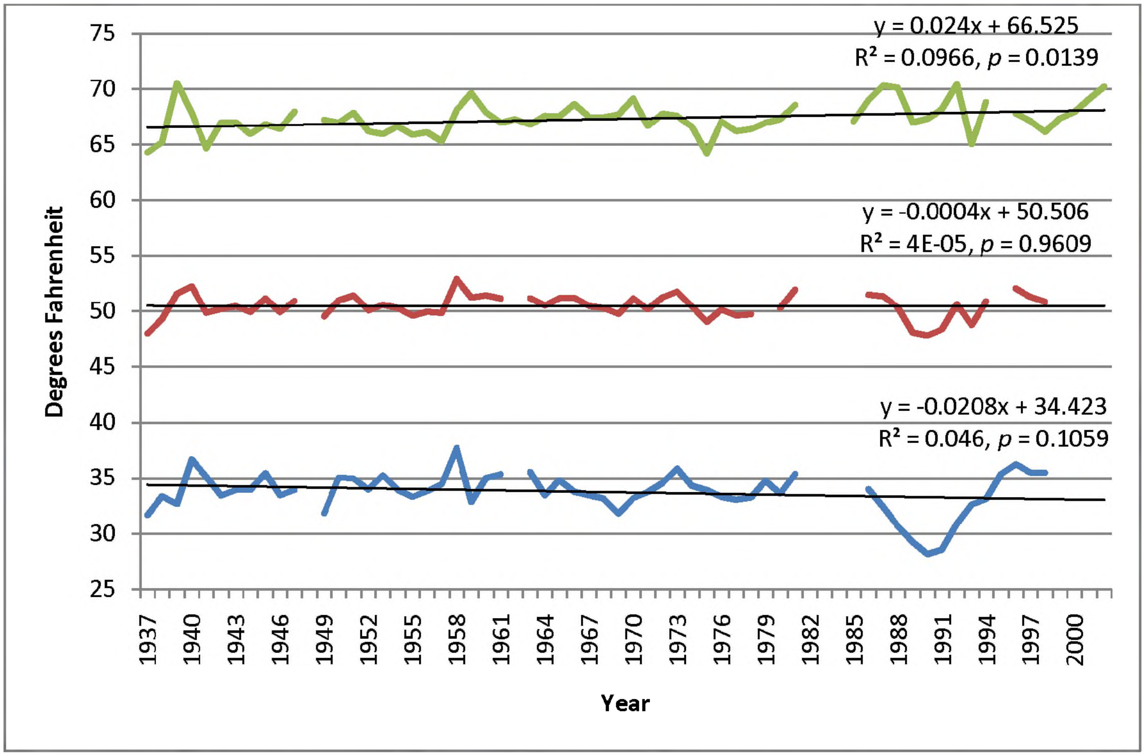

Figure 4. Annual mean, mean maximum, and mean minimum temperatures at Fort Jones Ranger Station, California, 1937-2002. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

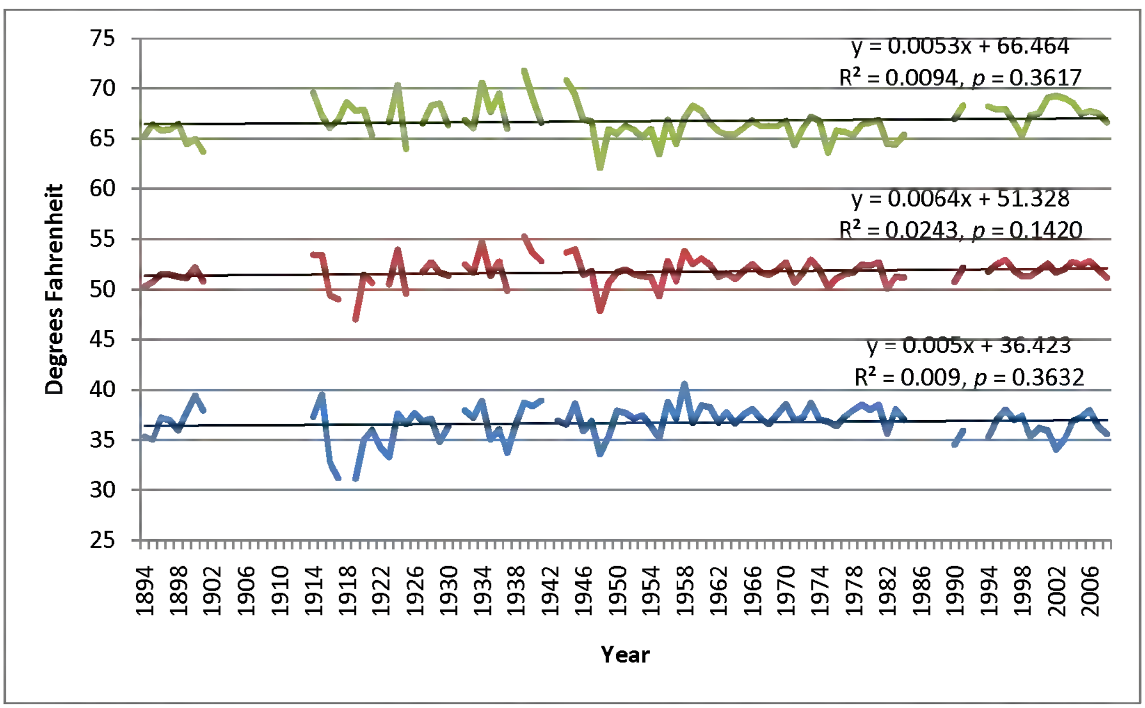

Figure 5. Annual mean, mean maximum, and mean minimum temperatures at Yreka, California, 1894-2008. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

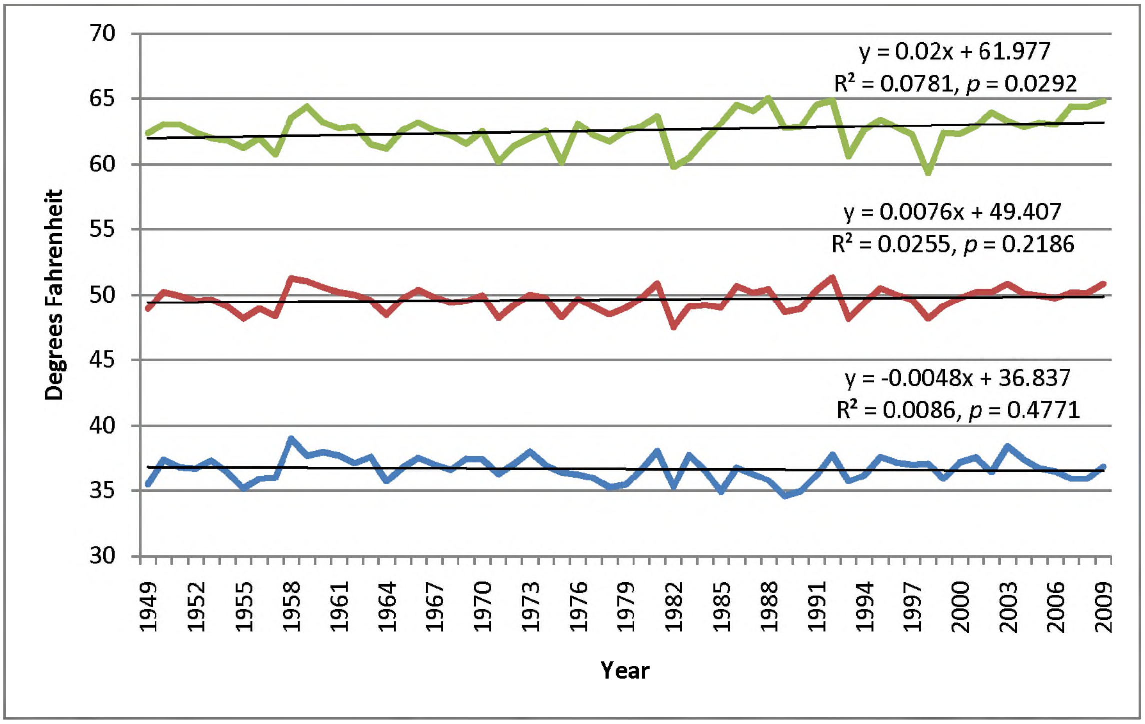

Figure 6. Annual mean, mean maximum, and mean minimum temperatures at Mount Shasta, California, 1949-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

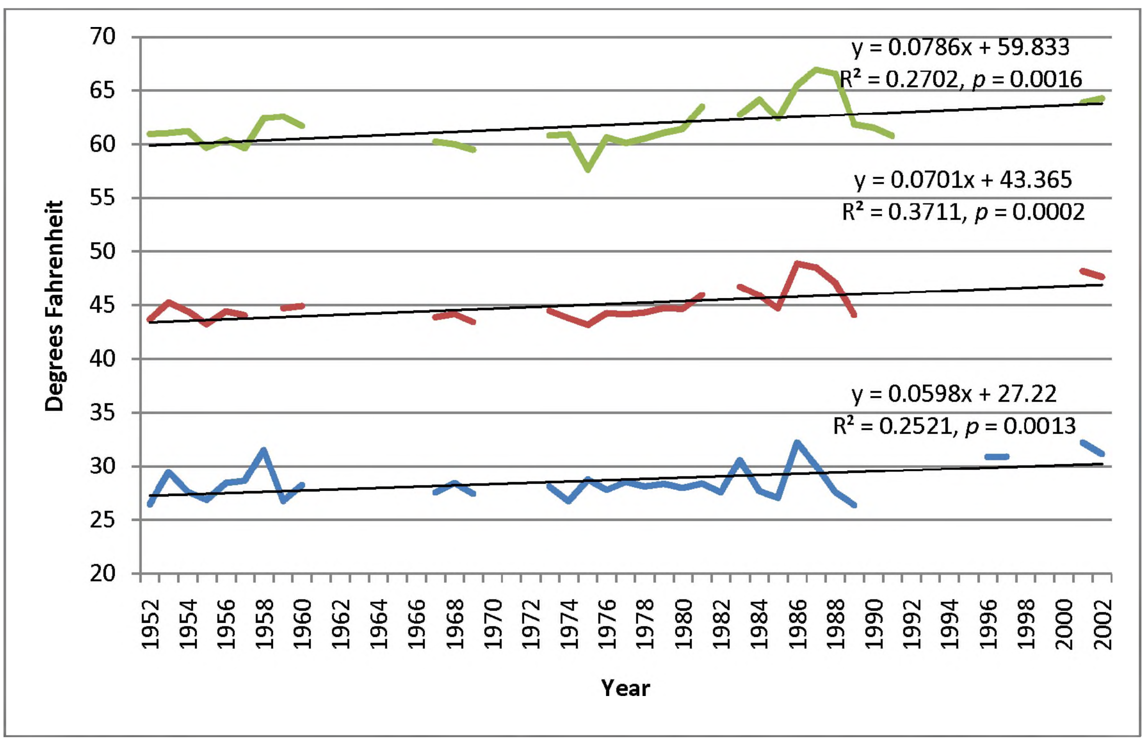

Figure 7. Annual mean, mean maximum, and mean minimum temperatures at Mount Hebron Ranger Station, California, 1952-2002. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

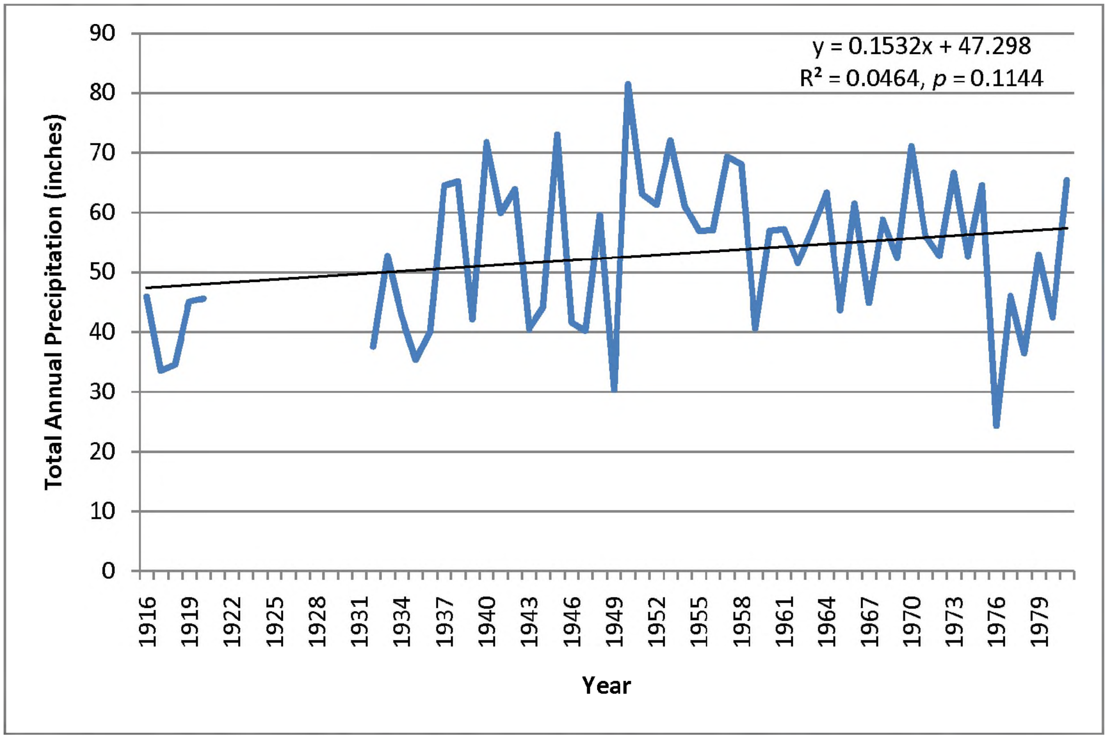

Figure 8. Total annual precipitation at the Happy Camp Ranger Station, California, 1916-1981. Data from WRCC 2010.

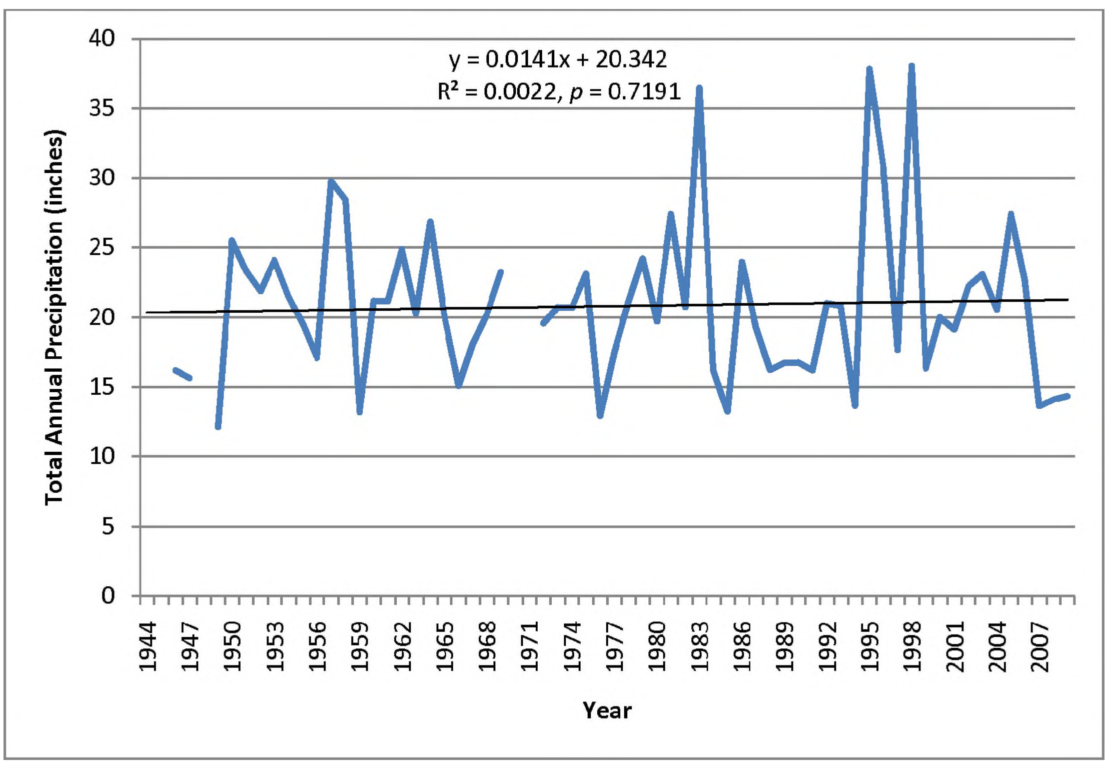

Figure 9. Total annual precipitation at Callahan, California, 1944-2009. Data from WRCC 2010.

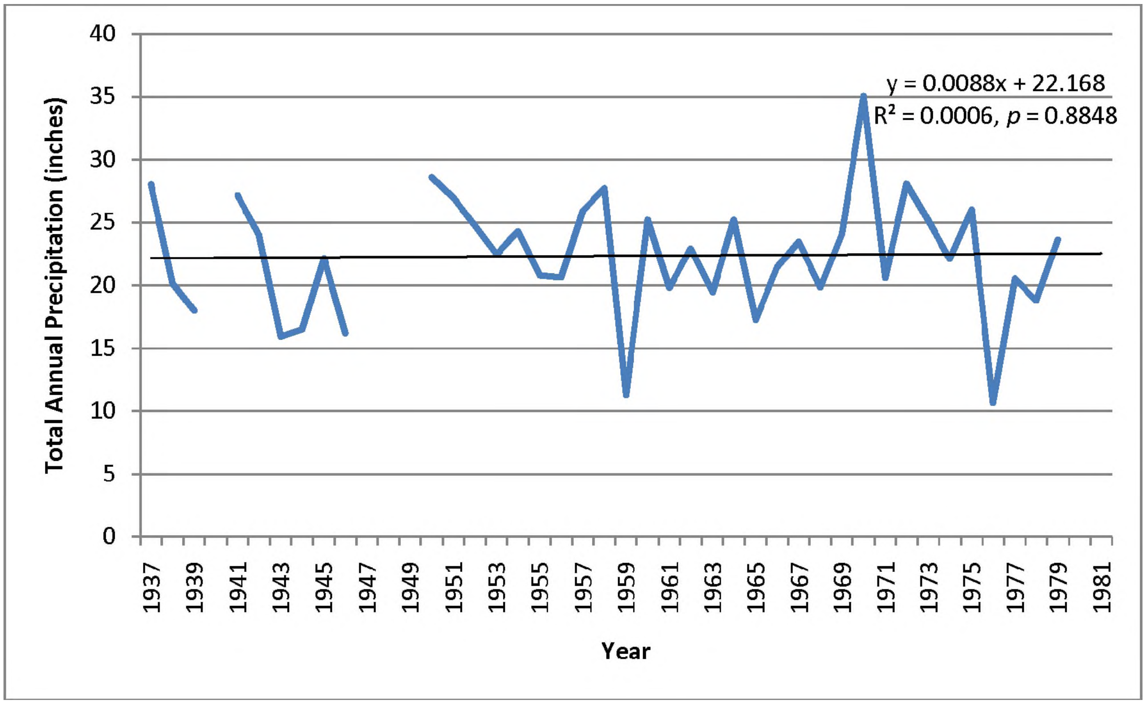

Figure 10. Total annual precipitation at the Fort Jones Ranger Station, California, 1937-1981. Data from WRCC 2010.

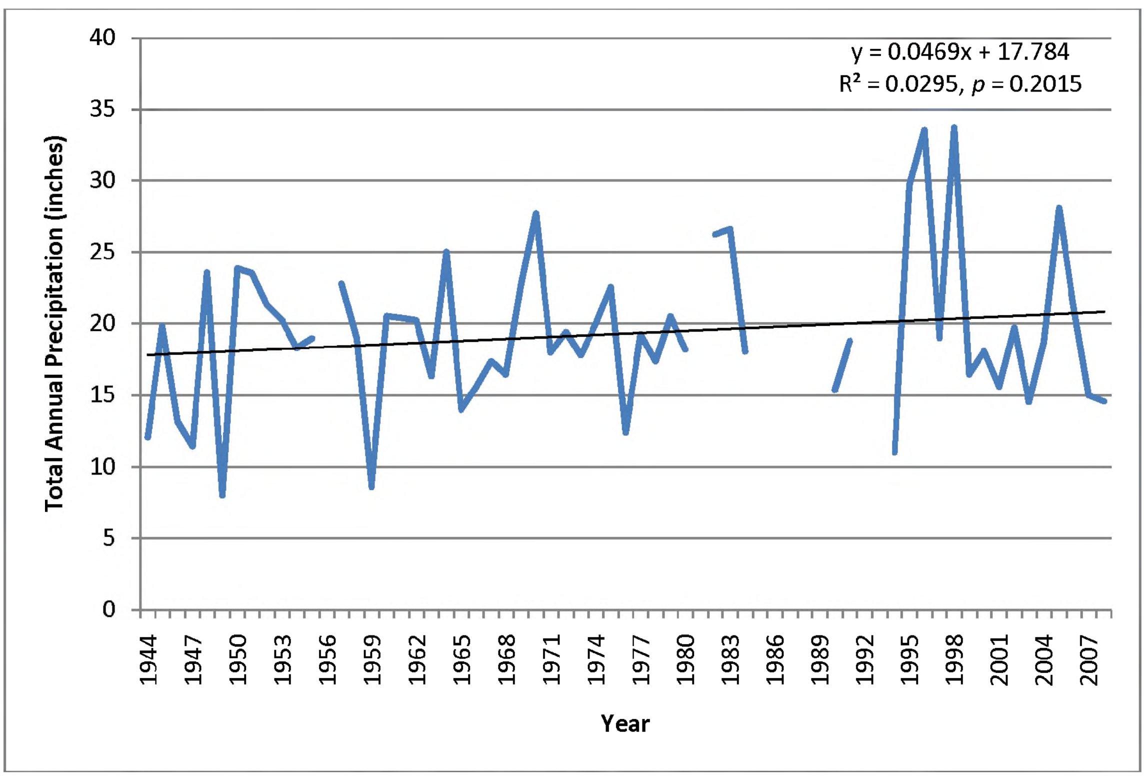

Figure 11. Total annual precipitation at Yreka, California, 1944-2008. Data from WRCC 2010.

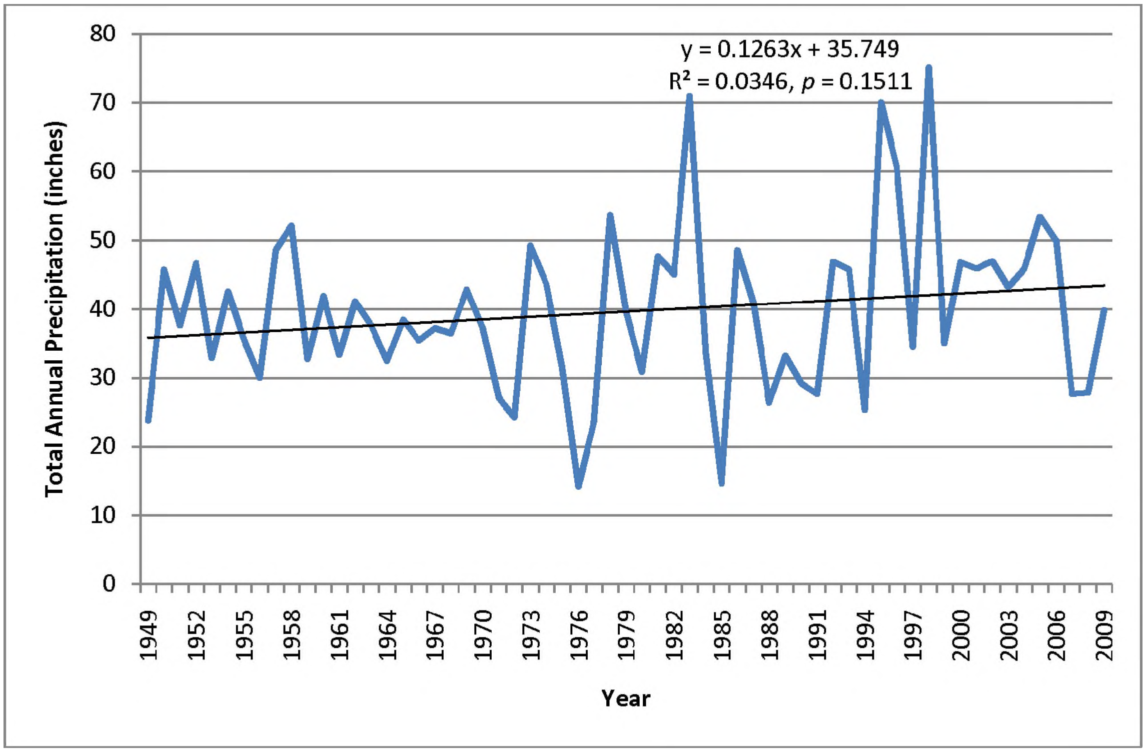

Figure 12. Total annual precipitation at Mount Shasta, California, 1949-2008. Data from WRCC 2010.

The 5-yr coefficient of variation of annual precipitation is steady at the Happy Camp Ranger Station and Yreka weather stations (Figs. 13 & 16) and increasing over time at the other stations (Figs. 14, 15, & 17). An increasing coefficient of variation in annual precipitation demonstrates that year-to-year variability in precipitation has increased over the course of the last century, while a steady coefficient of variation denotes that year-to-year variability remains relatively stable. Total annual snowfall records on the KNF are too incomplete to allow for analysis.

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

Hydrology

Analyses of hydrometeorological data from the lower Klamath Basin show a decrease in the percentage of precipitation falling as snow and accelerated snowpack melt, resulting in earlier peak runoff and lower base flows (Hamlet et al. 2005; Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2005; Mote 2006; Van Kirk and Naman 2008). Since the 1940s, snow water equivalent (SWE) has decreased while water use has increased (Van Kirk and Naman 2008). Trends in April 1 SWE appear to be driven by temperature, which, along the Pacific Coast, is a function of elevation and latitude (Knowles and Cayan 2004; Mote 2006), and secondarily by precipitation (Hamlet et al. 2005; Mote et al. 2005; Stewart et al. 2005).

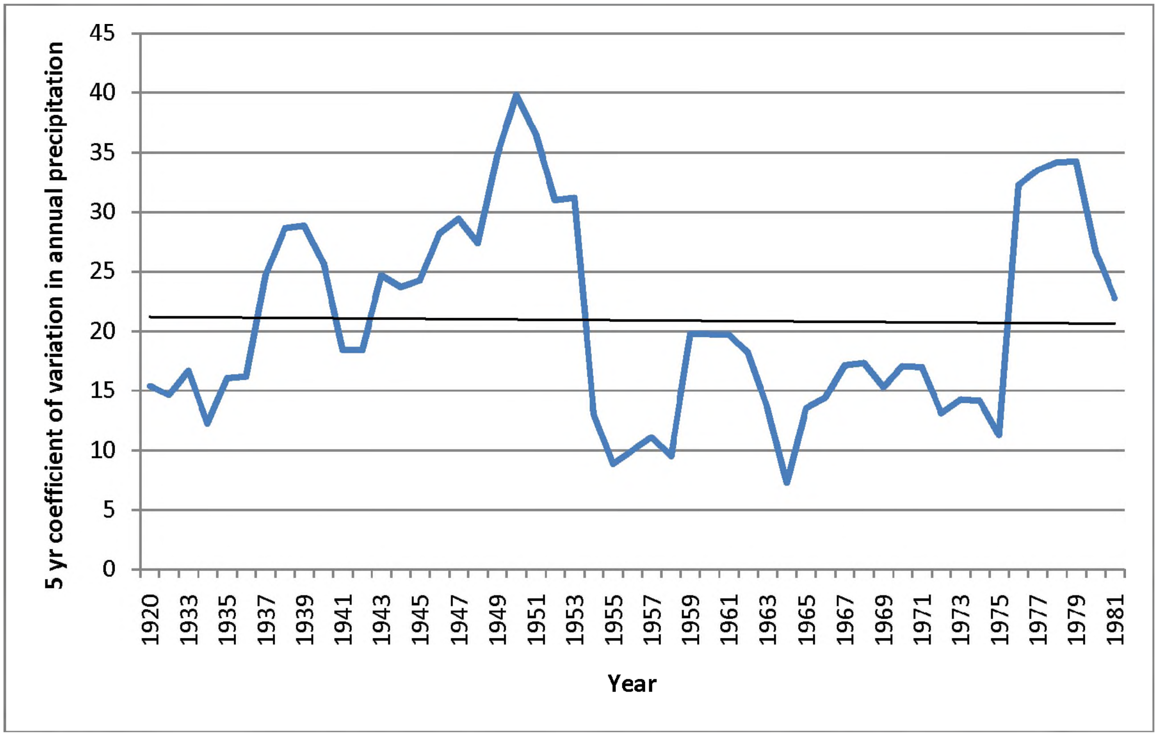

Figure 13. Five-year coefficient of variations in annual precipitation at Happy Camp Ranger Station, California. Data from WRCC 2010.

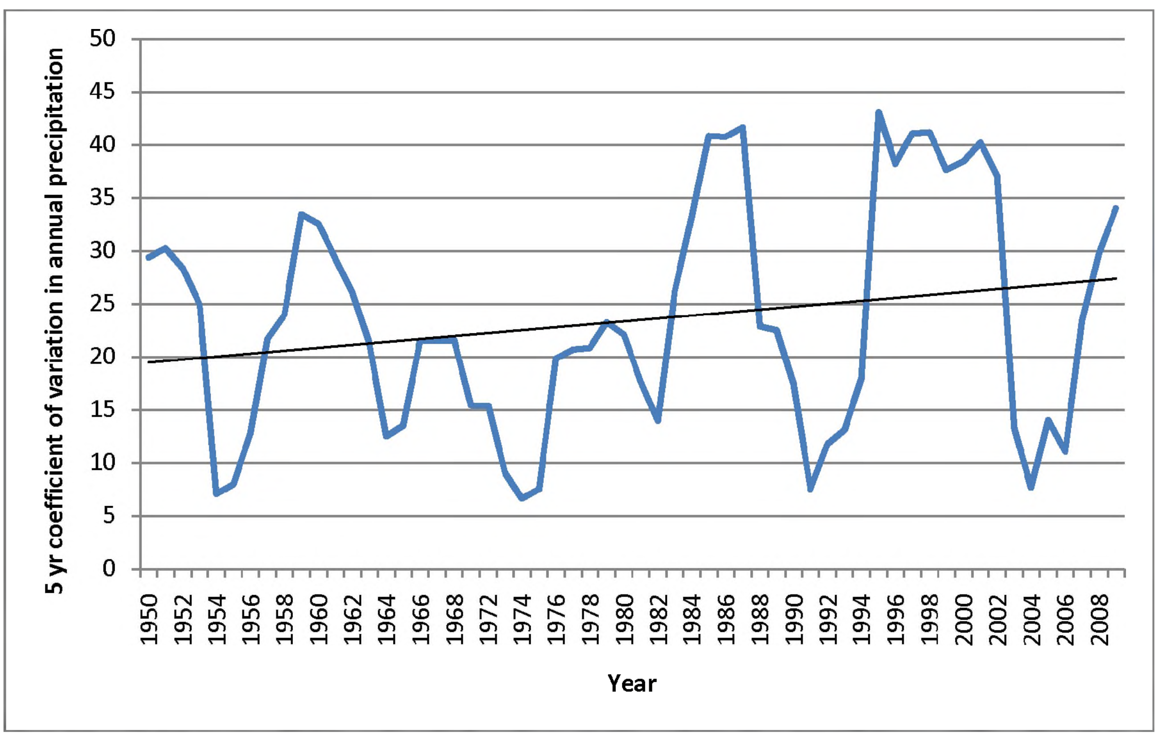

Figure 14. Five-year coefficient of variations in annual precipitation at Callahan, California. Data from WRCC 2010.

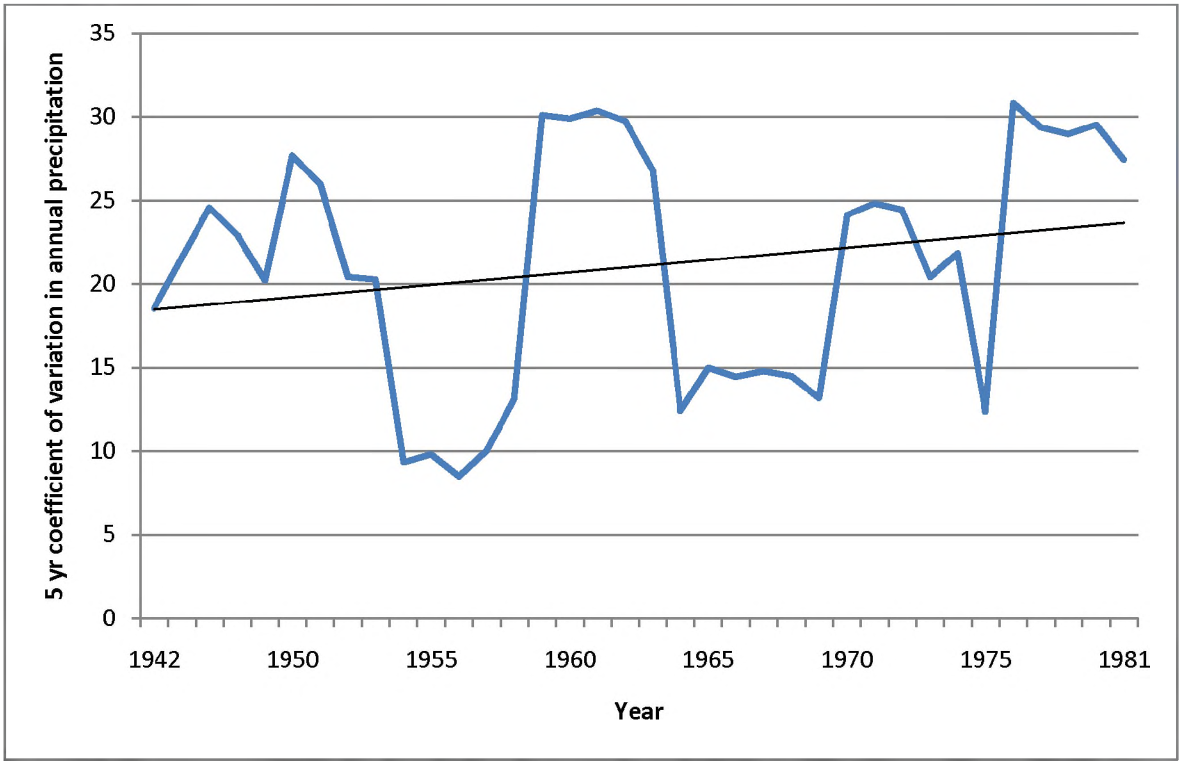

Figure 15. Five-year coefficient of variations in annual precipitation at Fort Jones Ranger Station, California. Data from WRCC 2010.

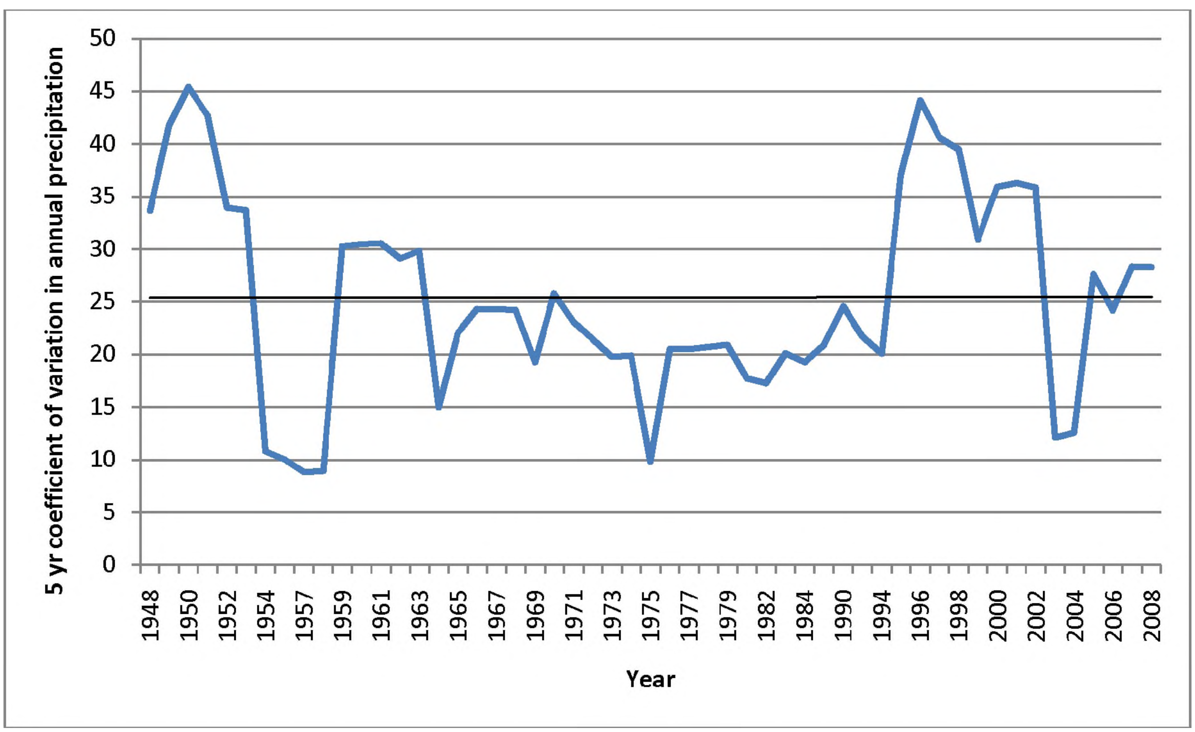

Figure 16. Five-year coefficient of variations in annual precipitation at Yreka, California. Data from WRCC 2010.

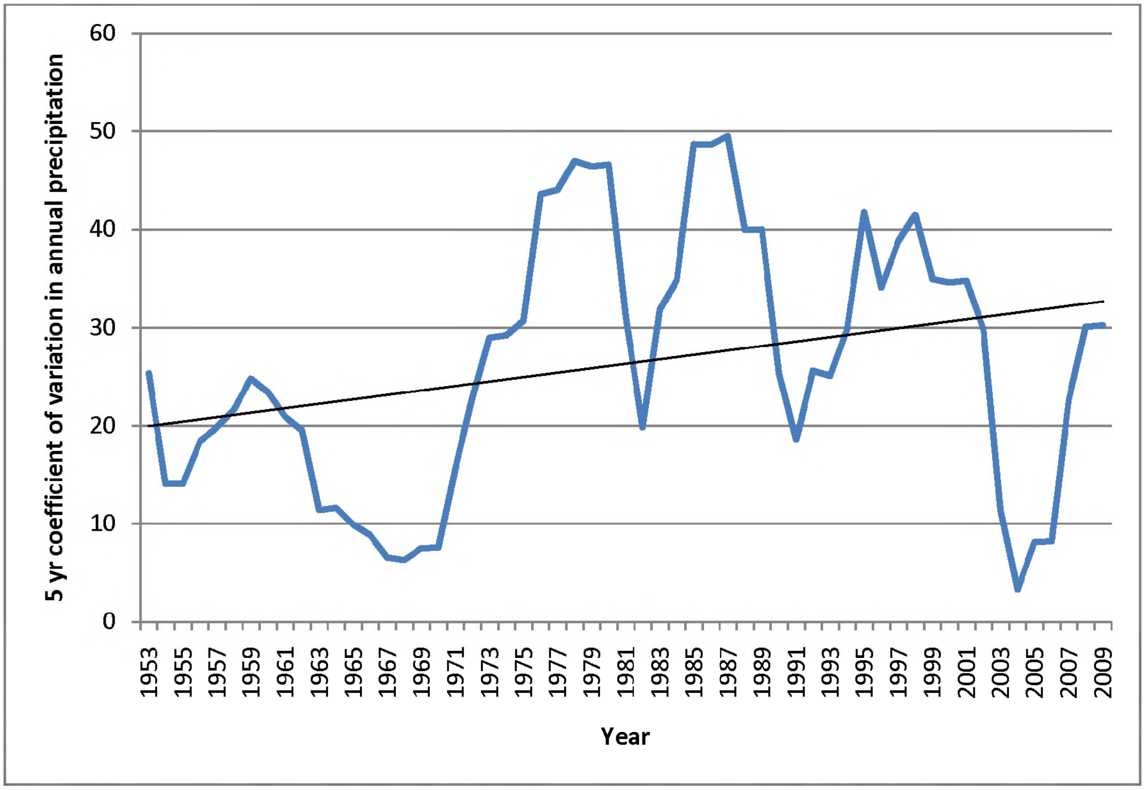

Figure 17. Five-year coefficient of variations in annual precipitation at Mount Shasta, California. Data from WRCC 2010.

Forest fires

Data on forest fire frequency, size, total area burned, and severity all show strong increases in 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 forests have had substantially increased wildfire activity, with most wildfires occurring in years with early springs (Westerling et al. 2006). This increase is likely attributable to both climate and land-use effects. Large percentage changes in moisture deficits in Northern California forests, according to Westerling et al. (2006), were strongly associated with advances in the timing of spring, but this area also includes substantial forested area where fire exclusion, timber harvesting, and succession after mining activities have led to increased forest densities and fire risks (McKelvey et al. 1996; Gruell 2001).

Miller et al. (2010) found no temporal trend in the annual proportion of fire area burning at high-severity within fires >400 ha occurring on the four National Forests of NW California during the period 1987-2008. However, mean and maximum fire size and total annual area burned all increased over the period from 1910 to 2008 and regional fire rotation fell to 95 years by 2008. During 1987-2008, Miller et al. (2010) found that the percentage of high-severity fire in conifer-dominated forests of smaller average diameter and lower percent cover was generally higher than in forests of larger diameter and higher cover. For areas that burned more than once during this period, severity (a measure of the effect of fire on vegetation) in conifer and hardwood forests was higher the second time burned versus the first time burned, regardless of tree density and size class. Closed forests of medium and large diameter trees that had previously burned between 1921 and 1986 burned at lower severities than similar forests that had last burned before 1921. Miller et al.'s (2010) data showed that years with larger fires and greatest area burned were produced by region-wide lightning events, and characterized by less winter and spring precipitation than in years dominated by smaller human ignited fires, but the percentage of high-severity fire was generally less in region-wide lightning events. Miller et al. (2010) also found that forests near the coast were not more susceptible to high severity fire than interior forests, but the size of forest patches burned at high severity was positively related to proximity to the coast.

Forest structure

Fire suppression has been practiced as a federal policy since 1935. In addition, many forests were harvested using even-aged systems early in the 1900s followed by a diverse group of silvicultural operations (Laudenslayer and Darr 1990). Fire exclusion has resulted in increased tree densities and a reduction in shade intolerant species (Parsons and DeBenedetti 1979; North et al. 2007), although the ecological significance of these changes is likely more important in drier, historically pine-dominated forests than in moister, fir-dominated forests. Skinner (1995) found that forest openings decreased and distances between openings increased from 1944 to 1985 in portions of the Dillon, Clear, and Swillup Creek watersheds near Happy Camp. Working at Whiskeytown National Recreation Area, west of Redding, Leonzo and Keyes (2011) documented major changes over the last ½ century in the structure and composition of "relict" old-growth ponderosa pine stands, with young individuals of shade tolerant species like Douglas-fir, white fir and tan oak comprising 10x higher stem densities than the originally dominant pine.

Van Mantgem et al. (2009) recently documented widespread increases in tree mortality in old-growth forests across the west, including northern California. 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 Nevada, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates. Van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress.

III. Future predictions

Climate

As of today, no published climate change or vegetation change modeling has been carried out for the Klamath National Forest. 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 comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1° 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 degrees 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.

Cayan et al. (2008) use simulations from the NCAR and DOE Parallel Climate Model (PCM1) and the NOAA 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. Barr et al. (2010) report projections of slightly less severe warming, from +2.5 to 4.6° C (4.5 to 8.3° F); their precipitation projections range from -11% to +24%, with all models agreeing that growing season precipitation will decrease.

Hydrology

Although climate models diverge with respect to future trends in precipitation over NW California, there is widespread agreement that the trend toward lower SWE and earlier snowmelt will continue (Leung and Wigmosta, 1999; McCabe and Wolock, 1999; Miller et al. 2003; Snyder et al. 2004; Barnett et al. 2005; Zhu et al. 2005; Vicuna et al. 2007; Van Kirk and Naman 2008). In basins without winter snow accumulation, base flow is relatively insensitive to increasing temperature (Miller et al. 2003). If precipitation does increase, streamflow volumes during high flow events could greatly increase. A 30 percent increase in precipitation translates into a 50 percent increase in mean maximum annual streamflow on the Smith River (Miller et al. 2003).

A downscaling of three climate models (CSIRO, MIROC, and Hadley) for the Rogue River Basin in southwest Oregon and the Klamath River Basin led to the following general future projections for hydrology in NW California and SW Oregon (Doppelt et al. 2008, Barr et al. 2010): Total precipitation may remain roughly similar to historical levels, but may shift in seasonality to fall predominantly in mid-winter months. Rising temperatures will increase the percentage of precipitation falling as rain and decrease snowpack considerably, particularly at lower elevations. The area is likely to experience more severe storm events, variable weather, higher and flashier winter and spring runoff events, and increased flooding. Both wet and dry cycles are also likely to last longer and be more extreme, leading to periods of deeper drought as well as periods of more extensive flooding.

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 Klamath National Forest as a unit. Based on their modeling results, Lenihan et al. (2003, 2008) projected significant declines in evergreen conifer forests in inland NW California, and their subsequent replacement by Douglas fir-tanoak forest and tanoak-madrone-oak forest under most future climate scenarios in the Klamath Mountains (Fig. 18). For the Southern Cascade Ecological Section, a decline in evergreen conifer forests and an increase in grasslands are only seen under their "dry future" scenarios. Hayhoe et al. (2005) 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.

Barr et al. (2010) report on a set of MC1 runs under three GCMs for the Klamath River Basin but do not provide quantitative outputs. In general, by 2100 the upper basin (Oregon) is projected to support primarily grassland in place of the sagebrush and juniper ecosystems that currently dominate the area. In the lower basin (California), conditions suitable for hardwood forests (oaks, tan oak, madrone, etc.) are projected to expand while those suitable for conifer-dominated forests are projected to contract.

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, Westerling and Bryant 2006). By 2100, Lenihan et al.'s (2003) simulations suggest a *c.* 5% to 8% increase in annual burned area across California (Fig. 19), depending on the climate scenario. The MC1 runs reported in Barr et al. (2010) project increases in annual fire area in the Klamath River Basin of 11-22% by 2100, resulting in as many as 330,000 acres (134,000 ha) burned in an average year. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species

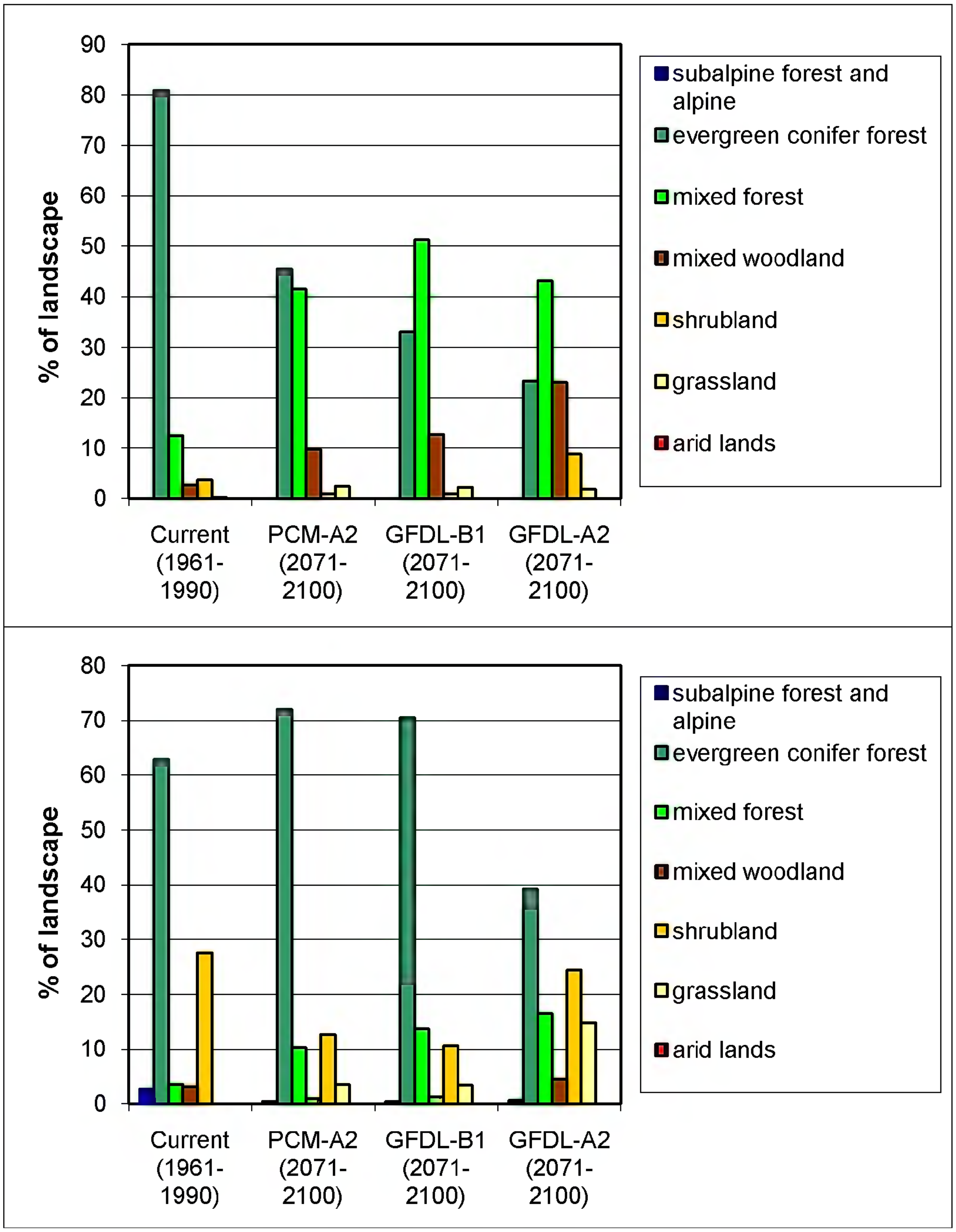

Figure 18. MC1 outputs for the Klamath Mountains and Southern Cascades Ecological Sections, current vs. future projections of vegetation extent. These Ecological Sections include all of the Klamath National Forest and some surrounding area. The GFDL-B1 scenario = moderately drier than today, with a moderate temperature increase (<5.5° F); PCM-A2 = similar ppt. to today, with <5.5° temp. increase; GFDL-A2 = much drier than today and much warmer (>7.2° higher). Under these scenarios, a decrease in evergreen conifer forest and an increase in hardwood-dominated forest types are projected for the Klamath Mountains. The Southern Cascades section is projected to see increases in hardwood forest and grassland and a decrease in subalpine and alpine vegetation under all scenarios. From Lenihan et al. (2008).

compositions (Lenihan et al. 2003), 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 biota.

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 (Agee 1993, Bond and van Wilgen 1996). 70 years of effective fire suppression in the semiarid 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. 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. 2005), 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 California 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.

It is important to note that although much of northern California is projected to experience more frequent and severe fires under future scenarios, Lenihan et al. (2003, 2008) predict a decrease in mean annual area burned for coastal northern California (Fig. 19). Lenihan et al. simulated changes in mean annual area burned for the future period based on changes in vegetation types. For the northwest coast of California, they projected no significant increase in grass or shrub vegetation types that promote higher rates of fire spread in their models. Data from Miller et al. (2010) suggest that fires in the Klamath Mountains, particularly in wetter areas along the western slope, are not experiencing a trend in increasing fire severity (although the overall area of high severity fire is increasing due to increases in annual burned area). This is likely due to the more maritime climate, the importance of the maritime inversion layer over the area in the summer, and the strong influence of topography on fire behavior. Increased upwelling in the California Current under increased CO_2 conditions may intensify fog development and onshore flow during the summer months (Bakun 1990, Snyder et al. 2003), potentially further buffering wetter regions of the North Coast from intensifying fire regimes. The Klamath NF does not manage any coastal forest, but the westernmost portions of the forest are gradational to coastal conditions.

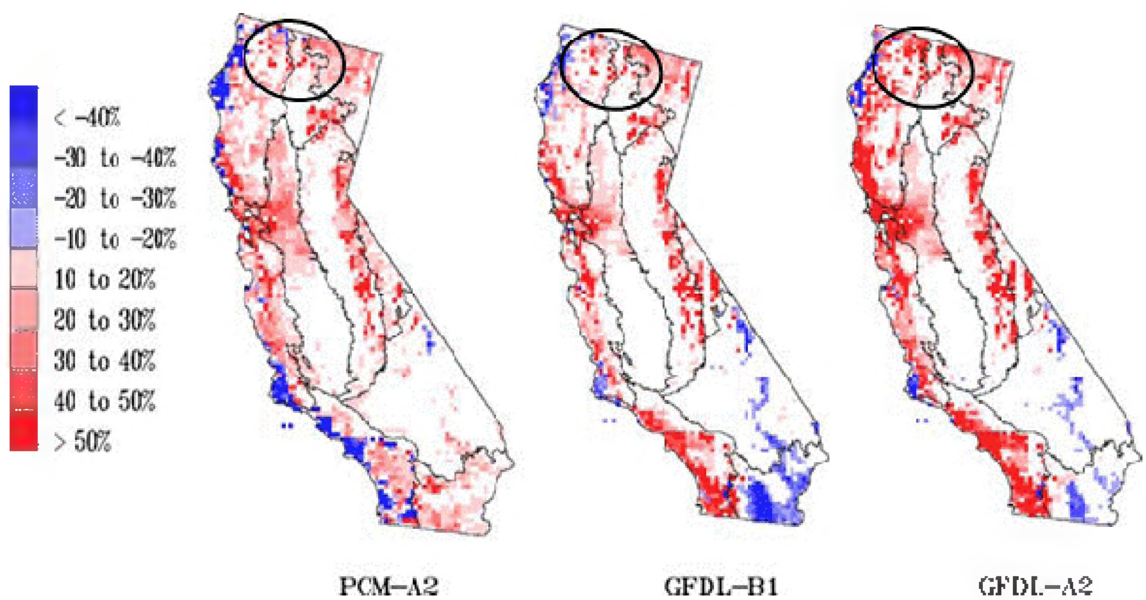

Figure 19. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). Figure from Lenihan et al. (2008). See Fig. 18 for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

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