151 Temperature and precipitation trends in California: Global warming and Pacific Ocean influences

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Introduction

Recently, in the last decade, extreme weather events in California and, in general, the western US have increased discussion of the role of global warming in influencing weather-related hazards such as floods, droughts, heat waves, snow melt and wildfires. In California establishing precipitation and temperatures trends is especially important for resource management, flood and drought predication, and for managing future energy demands. Consequently, establishing the impacts, if any, of global warming on changing temperature and precipitation patterns in California is important to forecasting trends in these weather variables.

California has some of the most diverse microclimates in North America. Its complex topography and large latitudinal extent lead to the whole spectrum of climates, tropical climates excepted. Generally though, as with most of North America, California, regardless of which microclimate is examined, has been warming over the last several decades. LaDochy et al. (2007a) showed that the state warmed by about 1.1°C (2° F) from 1950-2000, although regional differences occur. The fastest warming rates are in the southern regions of the state where fast growing cities contributed to the warming trend through landscape changes related mostly to urbanization. Temperatures rose the fastest in counties with the largest populations and rural counties showed the slowest increases (Christy and Goodridge 1995). In most regions minimum temperature rates exceeded maximum temperature rates, leading to a decreasing diurnal temperature range (DTR). In agricultural areas, irrigation added to the warming, which is especially reflected in minimum summer temperatures, as increased water vapor reduced long-wave radiation cooling at night (Christy and Norris 2004; Nemani et al. 2001). Furthermore, differential heating between inland valleys and coastal regions during summer and early fall may be intensifying the sea breeze and increasing marine influences on warming trends. These enhanced marine influences may have led to recent maximum temperature cooling along the immediate coast (Thomas et al. 2011).

As temperatures climb, heat waves have become more frequent. Peterson et al. (2008) found that both maximum and minimum temperatures, when averaged over North America, have increased with the largest increases occurring in the West. The authors also noted that since 1950 the number of heat spells also increased. In California, Tamrazian et al. (2008) showed an increased frequency and duration of heat spells over the last 100 years in metropolitan Los Angeles. Deadly heat waves such as those occurring over several regions of California in 2006 point to an increasing danger to the growing state population (Gershunov et al. 2009). The all-time temperature maximum of 45^{o}C (113 ^{o}F) for downtown Los Angeles was broken during the latest heat wave on September 27, 2010 (NWS 2010).

While increasing temperature trends in the state have been documented, identifying similar trends in precipitation is not as simple. Several studies have looked at recent trends in precipitation, both in the United States and in California. Karl and Knight (1998) found a 10% increase in annual precipitation in the United States between 1910 and 1996 with over half of this increase coming from the upper 10th percentile of daily precipitation. Higgins et al. (2007) also found that daily precipitation events increased over much of the western U.S. in the last 5 decade period. The increased daily precipitation events correspond to similar increases in total annual rainfall amounts. Higgins et al. (2007) noted that the total number of heavy precipitation days increased substantially over portions of the West during the same five decade period. The increased intensity of rainstorms is particularly apparent in the summer for the U.S. in general. However, in the West, the largest increases in the frequency of daily precipitation (>1 mm) and in heavy precipitation totals in recent decades occur in the January-February-March (JFM) season (Higgins et al 2007). This seasonality nearly corresponds to the December, January, and February peak of California's annual precipitation, which accounts for fifty percent of the state's total precipitation (Mitchell and Blier 1997). Killam et al. (2011) discussed precipitation trends in California and documented increased annual precipitation means, number of days of rain, and increased intensities for the state as a whole. The authors also found regional differences.

Natural variability in the Pacific Ocean also appears to influence California temperature and precipitation trends. The Pacific Decadal Oscillation (PDO), a commonly recognized term in the scientific literature, was described by Mantua et al. (1997) to denote shifts in North Pacific sea surface temperature associated with swings in climate commonly persisting for 20-30 years. In the cool or negative phase, east Pacific sea surface temperatures (SSTs) are below normal. For the positive or warm phase, east Pacific SSTs are above normal. According to Mantua, cool or negative PDO phases occurred from 1890-1924 and from 1947-1976. Warm or positive phases typified the periods from 1925-1946 and from 1977 through the mid-1990's. A shift to the cool phase started in 1998, but was interrupted by two short periods of positive values from 2003-2007 and again in 2009-early 2010. Alfaro et al. (2004) showed that spring PDO values correlated well with summer temperatures in coastal California. A warming trend occurring around the Lake Tahoe basin in the east-central part of California correlates well with the PDO and to a lesser extent with El Nino-Southern Oscillation (ENSO) when monthly and annual temperature data are examined (Coats 2010). For the 331 California stations used in their study, LaDochy et al. (2007b) found a positive correlation between annual temperatures and the PDO throughout the state.

Superimposed on the PDO cycles are smaller-scaled El Niño/La Niña events persisting for approximately a year.

These events are typically defined as significantly warmer or cooler than normal sea surface temperatures in the central and eastern equatorial Pacific (Null 2008). Oceanic changes producing El Niño/La Niña events are interrelated with Pacific atmospheric changes termed the Southern Oscillation (SO).The SO phenomenon originates when surface air pressure in the western and eastern tropical Pacific oscillates in opposite directions, i.e., as one increases the other decreases, and vice versa. When the difference between the pressure measured at Darwin (western Pacific) and at Tahiti (eastern Pacific) is calculated, an "index" number, the Southern Oscillation Index (SOI) is generated (Halpert and Ropelewski 1992). Strong negative SOIs are associated with El Niño events, while strong positive SOI values are tied to La Niña periods. The SOI is a useful indicator of California climate. The combined El Niño and Southern Oscillation events are termed ENSO events.

Several studies show that the Pacific, especially the tropical Pacific, influence precipitation patterns in the western U.S. Sheppard et al. (2002) showed that ENSO and PDO effects could amplify each other, resulting in increased annual variability in precipitation over the Southwest. Kenyon and Hegerl (2008) also show how ENSO and Pacific decadal variability, such as PDO, affect the mean North American climate and its extremes, especially when both are in phase. Goodrich (2007) reported that during neutral ENSO years more than 80% of western U.S. climate divisions were drier than normal during the cold phase of PDO years, while 82% of western divisions were wetter than normal during warm PDO years. The probability of experiencing an El Niño event during the positive PDO phase is 29% and only 13% during the negative PDO phase. During the positive PDO phase, California only has a 10% chance of experiencing a La Niña event, but those chances increase to 40% during the negative phase. During the negative PDO phase, droughts during La Niña events can be devastatingly frequent and intense (Goodrich 2007).

When comparing the 1948-1975 period to the later 1976-2004 years, Higgins et al (2007) showed that a large increase in total precipitation from the earlier to later period could be explained by the Pacific Decadal Oscillation (PDO). The PDO was especially useful for also explaining the increases in heaviest precipitation (>90%) during the later period.

El Niño events have also been linked to greater precipitation in California, with strong, Type 1 El Niños averaging between 113 and 174% of normal precipitation for the water year (July 1-June 30) by climatic divisions (Monteverdi and Null 1998). Precipitation during the Type 1 El Niño events also increases from north to south. For La Niña events, southern California is typically drier than normal, however, northern California, and the Pacific Northwest, show higher than normal amounts of precipitation (LaDochy et al. 1999). Focusing on floods, Andrews et al. (2004) showed that the ratio of El Niño to non-El Niño annual peak floods varied from more than 10 near 32^{o}N to less than 0.7 near 42^{o}N. The cross-over point, where the number of floods were the same whether El Niño or not, is near 39^{o}N. Higgins et al. (2007) found that in winter, southwestern California averages up to 15% more days with measureable (> 1 mm) precipitation during moderate/strong El Niño phases compared to moderate/strong (m/s) La Niñas. Northwest California averaged up to 15% fewer wet days in winter during (m/s) El Niño years compared to La Niña ones. This well-known dichotomy between the northern and southern part of the state in terms of precipitation variance is known as a dipole (Dettinger et al. 1998). However, the largest fraction of extreme precipitation events (above the 90th percentile) for the west coast part of the state occurred during neutral winters, often just prior to El Niño periods (Higgins et al. 2007). On the other hand, Becker et al. (2009) found that precipitation intensity in southern California increased more than 60% between El Niño and La Niña phases.

Climatic impacts associated with cool PDO phases are similar to La Niña events and those associated with warm PDO phases parallel El Niño episodes. Decadal-scale oceanic fluctuations account for 20 to 45 per cent of annual precipitation variance in the West (Cayan et al. 1998). Southern California climate is significantly modified by these interannual and interdecadal climate shifts.

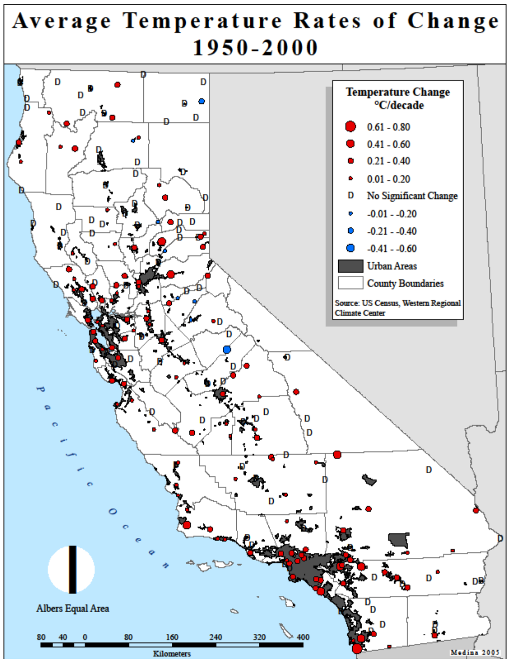
In this study, we look at temperature and precipitation trends in California and how well warming trends and Pacific Ocean variability explain the record over the last several decades.

Methods

To establish the relationship between Pacific oceanic and atmospheric annual and decadal variations and California temperatures and precipitation, data spanning a period from approximately 1900 to present were analyzed.

Temperature and precipitation monthly and annual data from 1895 to present were acquired for the eleven California climate divisions from the Western Regional Climate Center, Desert Research Institute, Reno, NV California Climate Tracker: (http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html). Precipitation values are based on water years, July 1-June 30, as the rainy season in California generally lasts from late fall through early spring. Temperature and precipitation anomalies were also calculated based on deviations from the long-term (1901-2009) average. Temperature records for 331 California cooperatives and first-order stations (Fig 1) showing long-term continuous data (since at least 1950) were also analyzed in a previous study (LaDochy et al. 2007).

Daily precipitation records for California stations from NOAA National Climate Data Center (NCDC) were also analyzed to select those with long, continuous datasets. Sixteen stations from various regions of the state met the criteria of having a continuous and long (since 1925) data record. Trends in annual and seasonal precipitation were calculated for these sites as well as trends in intensities and frequencies of precipitation events.



Source: US Census, Western Regional Climate Center

Fig. 1. Study area, California, showing mean annual temperature trends for 330 long-term stations.

Climatic indices included in the analyses are: PDO and SOI. Monthly and annual data, from 1900 to present, for these indices are from NOAA-CIRES CDC (http://www.cdc.noaa.gov/ClimateIndices/Analysis/). Other climatic indices were tested for their influence on southern California weather and climate, however the PDO and SOI were found to account for climate variations quite well.

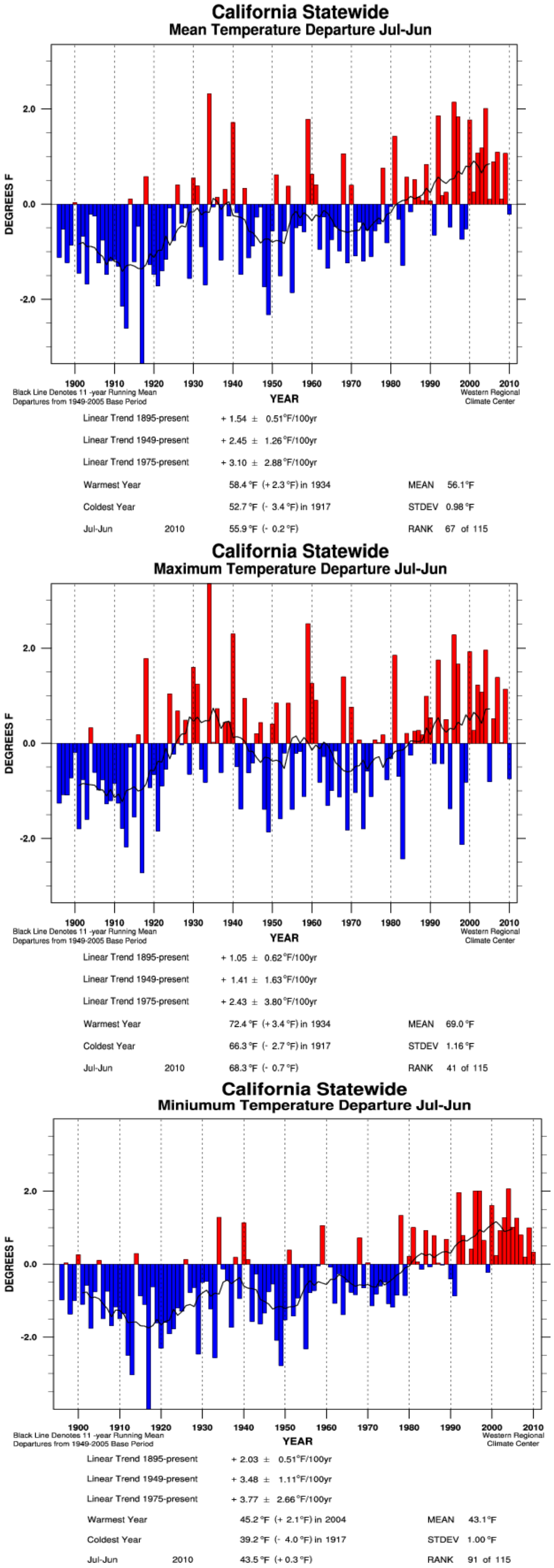
Pearson correlations were calculated between monthly and annual temperatures and monthly and annual PDO values from 1900 to 2009. Seasonal values were also used to show the strength of relationships at different lag periods. Temperature values lagging PDO values from one to 12 months were also tested. Both SOI and PDO values (monthly, annually) were correlated with California precipitation for the period 1900-2009. As with temperature, different lag periods were also tested.

Using different lag periods between Pacific climatic indices and southern California temperatures and precipitation can show how useful these indices are for forecasting weather and climate in the region. Daily precipitation characteristics were also compared for the 16 long-term stations with PDO and SOI values to show general magnitudes of differences in precipitation totals for positive and negative indices. El Niño and La Niña years were chosen for comparisons of precipitation totals between the 16 climatic stations used in this study. Criteria for classifying El Niño and La Niña years included SOI, water year precipitation anomalies for the whole state, northern and southern California precipitation anomalies, and MSLs (mean sea level anomalies) and SSTs off Scripps Pier. The list of El Nino and La Nina years closely matched those of Florida State and Jan Null's Golden Gate Weather (http://ggweather.com/enso/years.htm).

Results

For the period 1895 to 2009 California annual temperatures show rates of increases per century of 0.87, 0.61 and 1.14^{o}C (1.57, 1.10 and 2.05^{o}F) for mean, maximum and minimum averages, respectively (see Fig 2a-c). However, these rates of warming actually increased more when using records from 1949 to present and 1975 to present. Overall state averages since 1975 increased more than twice the longest record (1895-2009) in all three temperature categories (see Table 1). Of the warmest 15 annual mean temperatures, 10 occurred since 1990, and 7 since 2000. Seasonal differences show that the largest warming trends occur in summer, Table 1, followed closely by spring. Fall and winter show the least warming. Minima rose faster than maxima overall, leading to a decreased diurnal temperature range, which has been reported in other U.S. regions (Gallo et al. 1999).

The California temperature record (Fig 3) shows large year to year variation, while the 5-year running mean highlights a systematic pattern of rising and falling temperatures, similar to the PDO signal. Removal of the warming trend in the temperature series results in the illumination of the decadal PDO pattern (Fig. 4). The detrended temperature records show a distinct switch from negative values below the trend (detrended values below zero) to positive values in the late 1970s, when an abrupt change in the PDO phase occurred. A partial explanation of the warming trend evident in the California temperature record is likely the warming tied to the current positive cycle of the PDO, which extends from 1977-97. LaDochy et al. (2004) found that the PDO is a good predictor of California temperatures and suggested that temperatures could be predicted by PDO values of up to two previous seasons.



Linear Trend 1895-present		+ 1.54 ± 0.51°F/100yr		
Linear Trend 1949-present		+ 2.45 ± 1.26°F/100yr		
Linear Trend 1975-present		+ 3.10 ± 2.88°F/100yr		
Warmest Year		58.4 °F (+ 2.3 °F) in 1934	MEAN	56.1°F
Coldest Year		52.7 °F (- 3.4 °F) in 1917	STDEV	0.98 °F
Jul-Jun	2010	55.9 °F (- 0.2 °F)	RANK	67 of 115

Linear Trend 1895-present		+ 1.05 ± 0.62°F/100yr		
Linear Trend 1949-present		+ 1.41 ± 1.63°F/100yr		
Linear Trend 1975-present		+ 2.43 ± 3.80°F/100yr		
Warmest Year		72.4 °F (+ 3.4 °F) in 1934	MEAN	69.0 °F
Coldest Year		66.3 °F (- 2.7 °F) in 1917	STDEV	1.16 °F
Jul-Jun	2010	68.3 °F (- 0.7 °F)	RANK	41 of 115

Linear Trend 1895-present		+ 2.03 ± 0.51°F/100yr		
Linear Trend 1949-present		+ 3.48 ± 1.11°F/100yr		
Linear Trend 1975-present		+ 3.77 ± 2.66°F/100yr		
Warmest Year		45.2 °F (+ 2.1°F) in 2004	MEAN	43.1°F
Coldest Year		39.2 °F (- 4.0 °F) in 1917	STDEV	1.00 °F
Jul-Jun	2010	43.5 °F (+ 0.3 °F)	RANK	91 of 115

Fig. 2. California temperature trends for mean, max, min annual (water years) data, 1895-present.

A. Mean temperature Linear trends/ 100 yrs	Annual	Winter	Spring	Summer	Fall
1895-present	+0.87	+0.66	+0.95	+0.94	+0.85
1949-present	+1.45	+1.08	+1.98	+1.68	-0.56
1975-present	+2.06	-0.58	+2.86	+3.59	+1.97
B. Max temperatures 1895-present	+0.61	+-.51	+0.88	+0.42	+0.51
1949-present	+0.89	+0.43	+1.67	+1.04	-0.09
1975-present	+1.77	-2.17	+3.20	+3.31	+2.19
C. Min temperatures 1895-present	+1.14	+0.81	+1.01	+1.46	+1.19
1949-present	+2.01	+1.73	+2.31	+2.32	+1.22
1975-present	+2.34	+1.01	+2.51	+3.88	+1.71

Table 1. California annual (water year) temperatures, 1895-present, for mean, max and min linear trends in ^{o}C/100 years. Source: NOAA,WRCC.

Killam et al. (2011) indicated that the mean annual precipitation trend for the state shows a 14% increase for the long term record (since 1895), but a 17% decrease since 1975 (see Table 2A). Regionally, central and northern California show precipitation gains throughout the record, while southern California shows large decreases since the 1970s.

Interestingly, since about 1950, the northern regions record decreases in precipitation, while records of the southern regions show increases. Many climate studies use the more complete data record from the 1950-2000 period to document warming and increasing precipitation. This period marks a distinct shift in Pacific Ocean conditions from the cold phase to the warm phase of the PDO.

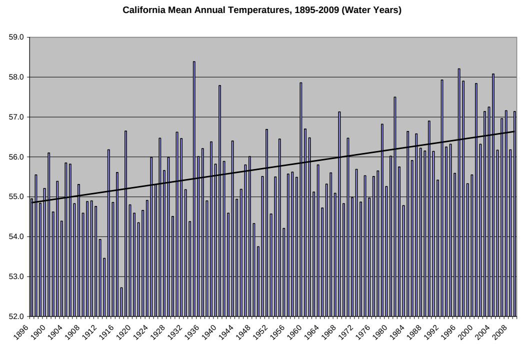


Fig. 3. California annual temperature trend, 1895-2009.

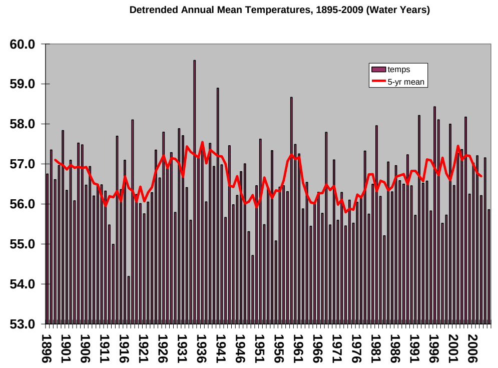


Fig. 4. California annual temperature detrended, 1895-2009.

Seasonally for the state, according to Killam et al. (2011), showed increases over the long term in winter precipitation from 1895-2009, particularly since the 1970s. During the same period, fall, spring and summer precipitations showed modest gains , but large decreases since the 1970s. Regionally, all regions showed winter increases for all time periods, but large decreases in spring, fall and summer since the 1970s (see Table 2B).

As discussed in the previous section, to evaluate precipitation characteristics more closely, daily precipitation data was collected for 16 met stations having complete records from 1925 to present (Killam et al. 2011). These stations cover most of the climatic regions of the state. The trend in annual precipitation totals, when ordered by latitude, indicates an increase in the north and a slight decrease or no change in the south (Figure 5). The trend in the number of rainfall days closely followed annual totals (not shown). Seasonal trends follow closely those of the climatic regions, with largest increases in winter, followed by fall for most stations (Killam et al. 2011).

Mean precipitation Linear trends in inches/ 100 years	Annual	Winter	Spring	Summer	Fall
1895-present	+82.3	+49.0	+9.7	+5.6	+19.3
1949-present	+6.6	+42.7	+14.0	-4.8	-42.4
1975-present	-104.1	+194.1	-103.9	-29.2	-151.9

Mean precipitation Linear trends in inches/ 100 years	Annual	Winter	Spring	Summer	Fall
1895-present	+82.3	+49.0	+9.7	+5.6	+19.3
1949-present	+6.6	+42.7	+14.0	-4.8	-42.4
1975-present	-104.1	+194.1	-103.9	-29.2	-151.9

Mean precipitation Linear trends/ 100 yrs	N Central	N Coast	NE	Sierra	Sac Delta	Central Coast
1895-present	+247.9	-21.1	+52.1	+114.6	+128.8	+77.7
1949-present	-75.9	-219.7	-67.3	-8.1	+61.0	+82.3
1975-present	+98.8	+479.6	-31.5	-74.2	+26.9	+71.6
	San Joaquin	S. Coast	S. Interior	Mojave	Sonora	
1895-present	+36.6	+88.1	-10.2	+39.9	+24.1	
1949-present	+50.3	+75.7	+28.4	+57.9	+43.4	
1975-present	-135.4	-340.4	-642.4	-205.2	-245.1	

Table 2A. California annual (water trend in mm/ 100 years. B. Annual precipitation linear trend in mm/ 100 years. B. Annual precipitation linear trends by climatic regions

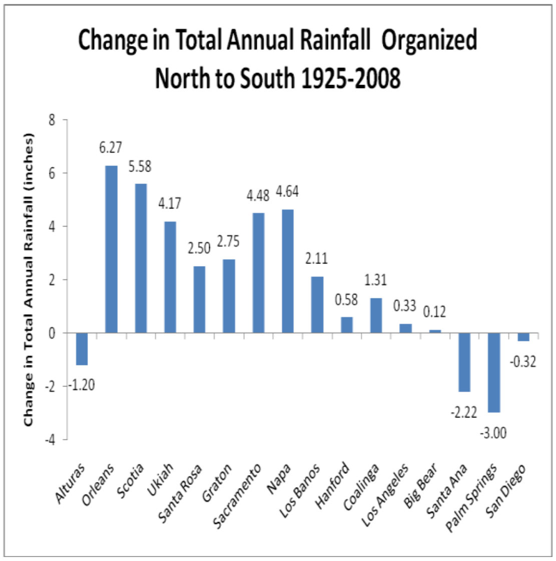


Fig. 5. Rainfall trends from north to south California, 1925-2009. Northern and central California wetter, southern California drier.

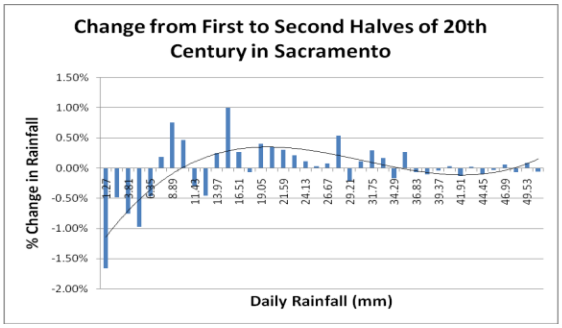


Fig. 6. Rainfall intensity shows increased moderate, heavy rains in Sacramento in second half of record.

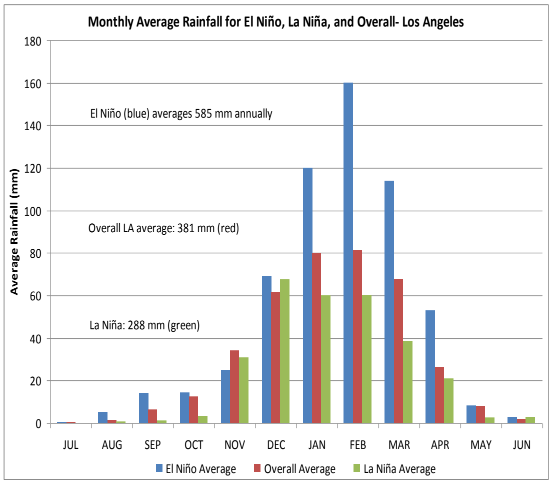


Fig. 7. Monthly average rainfall in Los Angeles by ENSO phases.

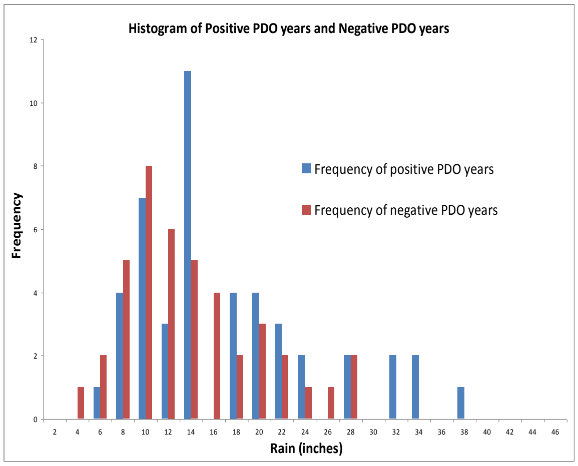


Fig. 8. Los Angeles rainfall vs. PDO phases.

Daily precipitation data was also analyzed by Killam et al. (2011) for trends in intensity, with histograms of varying precipitation amounts compared between the two halves of the century. The second half of the century at Sacramento displays less light rainfall and more moderate and heavy rainfall (Figure 6). The change in intensity is mostly focused in Northern California, though some Southern California stations such as Los Angeles show similar changes.

Annual precipitation totals were compared for positive and negative phases of ENSO and PDO. Although the variability is high, wetter years do occur during negative phases of SOI and positive phases of the PDO. For the 1925-2009 period, Los Angeles annual (water years) average precipitation was 605.79 mm (23.85”) during El Nino years, but only 263.65 mm (10.38”) for La Nina years (Figure 7). For positive phases of PDO, the Los Angeles average was 423.42 mm (16.67”), while only 335.53 mm (13.21”) for the negative phases (Killam et al. 2011). The SOI accounted for more of the precipitation variability for southern stations than for northern ones. For the 1946-2005 water years, SOI explained over 51% of the variability in the south coast climate division while only about 36% for the central coast and about 13% for the north coast. The relationships are stronger when SOI and PDO are in the same phase (negative SOI with positive PDO or positive SOI with negative PDO, see Figure 8). When analyzing just the heaviest rainfall events, a majority of them occurred in neutral ENSO years. While El Niño years generally have more days with precipitation and more intense rains than non-El Niño years, flooding associated with extreme precipitation events can also take place in La Niña or neutral ENSO years (Figure 9).

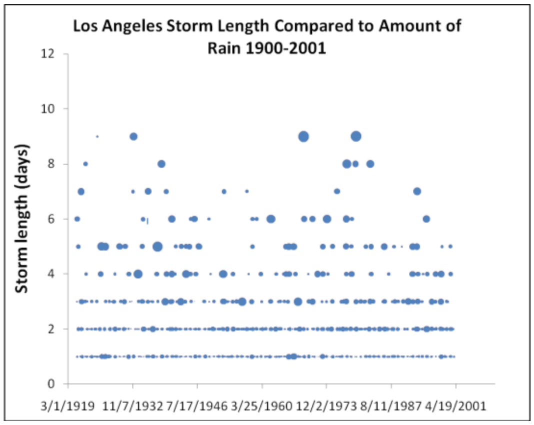


Fig. 9. Shows storm length, amounts for LA over study period. ENSO pattern is not apparent.

An analysis of global warming effects on precipitation appears to indicate an increase in both the intensity and amounts of precipitation for the central and northern portions of the state. However, this trend only explains less than 2% of the total variability in annual precipitation for the state. ENSO and PDO are much more useful in predicting precipitation in California. Minimizing the impacts of global warming on state precipitation trends would be short-sighted. Climate models and observational studies are showing that warming is leading to the emission of more water vapor into the atmosphere which subsequently leads to more and heavier rains in some regions, while others are becoming drier (IPCC 2009). This may be the case in California as well.

Discussion

In describing temperature and precipitation trends in California, regional differences must be accounted for. This is especially true for precipitation. Temperatures have increased throughout the state for the last century or more, with the warming rates increasing in the last few decades (Table 1). Minimum temperatures show greater warming than maximum temperatures, decreasing the diurnal temperature range. Seasonally, the state has warmed faster in spring and summer, particularly since the mid-1970s. Heat waves have also increased in the state, which does not bode well for health concerns. Regionally, the fastest temperature increases occur in the areas of greater urbanization, which are concentrated mostly in southern California, but more recently urbanization has also increased in the interior of the southeast region and the Central Valley. Since the 1970s, the fastest warming occurred in the interior regions, while the slowest occurred along the coast. This difference in warming between interior and coastal regions may reflect a marine influence as the California coastal waters have warmed slower than the state average, or only 1.3 ^{o}C for 1950-1999 (DiLorenzo et al. 2005). The coastal-interior heating differential also tends to enhance the marine influence as Tmax is reduced along the coast (Thomas et al. 2011). The Pacific also influences the temperature variability recorded by California stations. The PDO correlates well with annual average temperatures for all regions of the state (LaDochy et al. 2007). As PDO shifts from the warm phase to the cool phase, temperatures tend to decline. Since 1998, the PDO has been mostly negative, except for

2003-2007 and during the 2009-10 El Niño. The outlook based on a more negative phase of the PDO would be a decrease in state temperatures to below the trendline established and previously discussed.

temperatures. While the state as a whole has been getting wetter over the last last century, the northern regions have shown steady increases, while the southern regions show little increases and in some even decreases since the year) precipitation, 1895-2010, linear early 1900s. The southern regions especially show large decreases in precipitation since the mid-1970s (Table 2). Seasonally, all regions show increased winter precipitation throughout the 1895-present period, especially since the 1970s. In this last period, the northern regions experienced increased precipitation while precipitation decreased in southern regions. These regional differences in precipitation seem to be connected to the Pacific SSTs. El Niño events are associated with both greater precipitation amounts and days with measurable precipitation. La Niña events generally correspond with drier conditions. However the relationship of state precipitation and El Niño/La Niña events is stronger to the south than the north. The PDO either enhances or weakens these relationships depending on whether the El Niño/La Niña events are in phase with the PDO.. Recent rainfall patterns have shown decreased amounts statewide, especially in the southern regions. PDO values have been tending negative since 1998, although short positive years occur during 2002-2007 and 2009-early 2010. Interestingly, Los Angeles had a record rainfall year during the 2002-2007 period (Patzert et al. 2007) A moderate El Niño with wetter than normal rainfall occurred during the 2009-2010 period. Los Angeles had a record dry year at the end of the 2002-2007 period, when the PDO was switching back to a negative phase. Since then, the PDO and ENSO are in phase. Both are in cool phases. Unusually cool waters off the southern California coast in 2010 favor drier conditions.

The question of how much global warming effect California temperature and precipitation trends is difficult to answer. While non-urban stations have shown warming similar to global averages, land use changes have accelerated warming, especially in urban areas. Pacific SSTs also influence California temperatures, particularly the PDO, which accounts for the annual variability quite well. Warming may also be leading to rising precipitation trends, although more to the northern sections of the state than the south. A northward shift in storm track position has been detected in the West in the late winter and early spring (McAfee and Russell 2008). This may account for the wetter conditions to the north and the drying to the south of the state, as the subtropical anticyclone belt also may be shifting northward. In general, Pacific SSTs, especially ENSO and PDO, explain much of the annual variability in precipitation, although the relationships are stronger to the south.

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California precipitation over several decades.

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