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CHARACTERISTICS OF THE 2011-2016 CALIFORNIA DROUGHT

A THESIS APPROVED FOR THE
SCHOOL OF METEOROLOGY

BY

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Abstract

The recent California drought persisted for five years from 2011-2016 and was the worst drought in recent memory. Previous studies have established that this drought was marked by low but not unprecedented rainfall coupled with extremely warm temperatures that acted to exacerbate the effects of reduced precipitation. Other studies analyzed how snow-water equivalent during the drought compares with California's historical records and the role teleconnections (El Niño Southern Oscillation and the Pacific Decadal Oscillation) may have had to influence precipitation patterns across the state. This study analyzes maximum temperature, minimum temperature, and precipitation to compare with the findings of previous studies while specifically focusing on understanding how snowfall in the Sierra Nevada Mountains during the five years of drought from November through April compares with other five-year groups since 1950. It was found that 2011-2016 was the warmest five years for maximum temperature in California as well as the lowest snowfall in the mountains, which was significantly different from all other five-year groups since 1950. Snowfall exhibited strong oscillatory behavior significant for a cycle of 16 years with a secondary maximum between 2 and 4 years. These periods for snowfall were compared against ENSO and the PDO, where significant coherence was found with both teleconnections at periods between 3-4 years. It can be concluded that the California drought of 2011-2016 had the warmest maximum temperature on record since 1950 as well as the lowest snowfall in the Sierra Nevada Mountains and that the periodicity of ENSO and the PDO is coherent at short time scales with snowfall. Understanding how snowfall differed during

the drought when compared to climatology will help to explain why runoff during these years was so low and why reservoir capacity was well below the historical average.

Chapter 1

Introduction and Background

Starting in 2011, the drought in California persisted for more than five years, reaching a peak severity in 2013-2014 (Griffin and Anchukaitis, 2014; Williams et al., 2015; Swain et al., 2014; AghaKouchak et al., 2014). The drought had major effects on the economy and agriculture of the state, as well as effects on people's everyday lifestyles. California is home to over 12% of the United States population, totaling 39 million people (United States Census Bureau, 2016) and has the sixth highest Gross Domestic Product of the world (Holony, 2016). Valued at $2.46 trillion, the GDP of California surpasses other countries such as France, Russia, and Brazil. Since the drought placed severe stress on the economy, agriculture, and water resources of the state, it is important to understand how this drought compares to other drought periods in California's past.

The importance of this drought may be understood by examining the job and monetary losses that have resulted from years of low precipitation. The drought was at its worst in 2014, which is clearly reflected in the economic impact of that year: crop revenue losses were valued at $810 million, with a total economic impact of $1.5 billion and 17,100 job losses in total (Howitt et al., 2014). In 2016, crop revenue losses were estimated to have amounted to $247 million, with a total economic impact of $603 million (Medellín-Azuara et al., 2016) leading to the direst loss of 1,815 jobs. Economically, 2016 was relatively better for California than 2014, but the compilation of several years of drought and a stunted economy left many wondering if there would be any end in sight. Analyzing this drought within the context of other memorable droughts can help to understand if this was a normal or unprecedented event, and may also lead to questions if droughts of this magnitude may become more normal with a warming climate.

California's climate is variable in space with seven climate divisions. The borders of each division were largely determined by having a common drainage basin or common crops (Guttman and Quayle, 1996). While each division is not completely homogeneous with respect to its climate, these divisions provide a general representation of the variation of temperature and precipitation across a state. Coastal locations tend to be fairly moderate with little seasonality while the Sierra Nevada Mountains may receive several meters of snow each year. Death Valley and a hot, dry desert climate dominate much of the southeastern portion of the state. Overall, much of the state has a distinct wet season (November through April) and dry season (May through October), the magnitudes of which vary across the entire state. Average annual precipitation patterns are shown in Figure 1.1, where the desert (less than 10 inches of rain per year) and Central Valley (10-20 inches of rain per year) are relatively dry and the coast (15-60 inches per year) and mountains (up to 120 inches per year) are relatively wet (Spatial Climate Analysis Service, Oregon State University, 2000). Average annual snow depth patterns are shown in Figure 1.1. In general, the southern Sierra Nevada Mountains are higher in elevation than to the north, so snow depth tends to be greater in the south (72+ inches per year) where the higher elevations (up to 48 inches) remain cooler such that little snowfall melts (Sierra Nevada Photos, 2012). During the recent California drought, however, these patterns looked drastically different, such that in January 2014, there was little to no snow depth throughout the entirety of the Sierra Nevadas (NASA Earth Observatory, 2014).

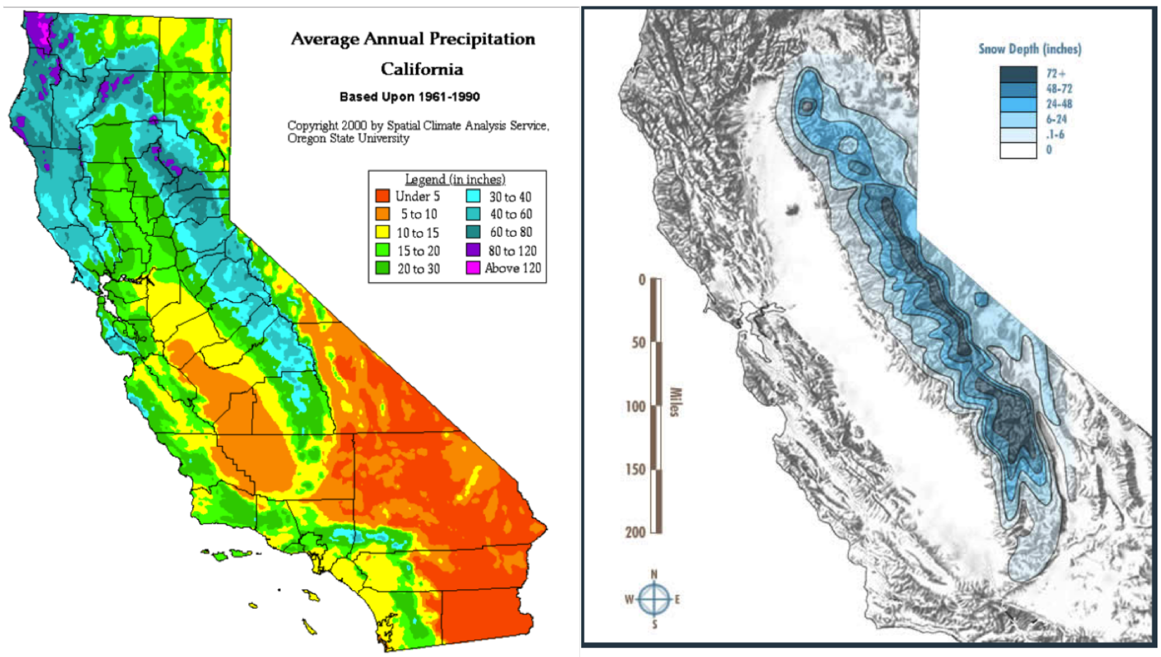


Figure 1.1: (left) Average annual precipitation (1961-1990), courtesy of Oregon State University. (right) Average snow depth (1966-1996), courtesy of Sierra Nevada Photos.

1.1 Role of Precipitation in Drought

By analyzing observations available since 1895, any single year of the recent drought (up to 2015) is not considered to be to be the worst on record (AghaKouchak et al., 2014; Diaz and Wahl, 2015; Mao et al., 2015). According to Williams et al. (2015), Water Year (WY) 2014 had the third lowest annual precipitation since 1901. A water year is defined as beginning on October 1 and ending on September 30 of the following year and is defined by the year in which the WY ends (United States Geological Survey, 2016). AghaKouchak et al. (2014) show that November 2013-April 2014 had the fifth lowest winter precipitation on record since 1895 while 1977 was the worst single year on record for low precipitation (Figure 1.2). Additionally, according to Mao et al. (2015), WY2014 was the fifth driest year as measured by several moisture variables, including winter precipitation, April 1 snow water equivalent (SWE), and springtime snowmelt runoff. Using other variables to measure the intensity of the drought in 2014, Williams et al. (2015) found that the Palmer Drought Severity Index (PDSI) for June, July, and August (JJA) 2014 was the lowest ever for a three-month average and that the highest proportion of the state of California was classified under record-breaking drought since 1901 during this time.

While one year of the drought does not break many records, the combined effect of multiple years of drought, namely 2012-2014, are record breaking for some drought measures. According to Mao et al. (2015), WY2012-2014 are the worst three years in the observational record in terms of average April 1 SWE, but the average JJA PDSI for 2012-2014 was not the worst for a three-year period (2007-2009 had the lowest average three-year PDSI for the summer months) (Williams et al., 2015). The difference between these two time frames, however, is that the drought of 2007-2009 started off extremely severe and eased with time while the 2012-2014 drought became more severe with time. Williams et al. (2015)

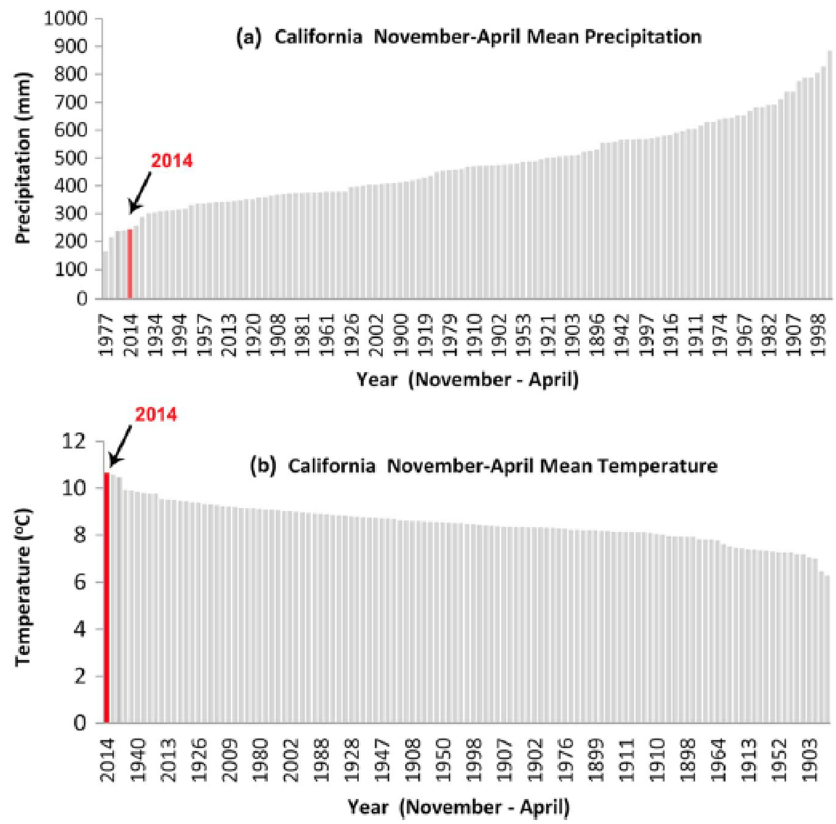


Figure 1. Ranked historical average November–April (a) precipitation and (b) temperature data for California.

Figure 1.2: (top) Ranking for Nov-April mean precipitation from 1896-2014, where the years are ranked from low to high values. (bottom) Ranking for Nov-April mean temperature from 1896-2014, where the years are ranked from high to low. 2014 is marked by the red bar in each plot (AghaKouchak et al., 2014)

noted that in the agriculturally-important area of Central Valley, PDSI was record-breaking for 2012-2014. Similarly, Richman and Leslie (2015) concluded that the four years of 2011/2012-2014/2015 was the only time from 1895-present to have had drought persisting for four years in a row, where drought is defined as seasonal precipitation at or below the 25$^{\text{th}}$ percentile. However, this only considers the low precipitation and other atmospheric variables, specifically temperature, need to also be considered to provide a multivariate framework for describing drought frequency.

1.2 Role of Temperature in Drought

As discussed, while 2012 -2014 in California was fairly dry, many studies show that this drought was not the worst on record when precipitation is the only variable considered. In most cases, 1977 is regarded as having experienced the lowest annual precipitation. There are two additional metrics to account for when considering the severity of the drought. The first is that the population of California has increased approximately 72% since the drought of 1976-1977 (Diffenbaugh et al., 2015). Although this increase in population has not drastically changed water demand due to increased efficiency, when water resources are scarce, however, there are now more people to feel the stress of reducing their water consumption.

The second factor that has changed since 1977 is increased temperature. While warming alone cannot cause a drought to occur, warmer temperatures can amplify the effects of reduced precipitation by increasing evapotranspiration. Reduced precipitation during drought can be exacerbated by warming temperatures and increased evaporation. According to Williams et al. (2015), the three years of WY2012-2014 had the highest potential evapotranspiration on record WY1949-2014 experienced a positive, significant trend in potential evapotranspiration, of which 10-13% of this trend is due to anthropogenic warming. When the effects of decreased precipitation and warming temperatures are combined, the current drought appears much worse than when precipitation is only considered. Using a multivariate framework of determining drought severity in terms of both precipitation and temperature, the most recent California drought set many records.

According to Mao et al. (2015), daily minimum temperature has a statistically significant increasing trend during the winter and non-winter months between 1920-2014, but there was no significant trend found in daily maximum temperature. Additionally, LaDochy et al. (2007) found that minimum temperature is increasing faster than maximum temperature throughout all of California for 1950-2000. The winter of 2013-2014 was the warmest winter on record (AghaKouchak et al., 2014), and WY2012-2014 were the warmest three years on record (Seager et al., 2015). Additionally, from 1895-2015, Richman and Leslie (2015) found that only eight years were characterized by having precipitation less than 25% of the annual average as well as temperature greater than 75% of the annual average. Of these eight extremely warm and dry years, 2012/2013-2014/2015 was the only period when these conditions persisted for more than one year. The drought could therefore be described as an unprecedented four years of dryness in tandem with three years of warmth (as of 2015).

AghaKouchak et al. (2014) considered the combined effects of decreased precipitation and warming temperatures on the return period of a drought like the drought of 2014, and showed that the return period was 200 years versus 24 years when only precipitation was considered (Figure 1.3). This clearly demonstrates the extreme effect warm temperatures have on exacerbating low rainfall. For the drought of 1977, the return period considering precipitation only was 120 years, but when combining the effects of low precipitation and warm temperature, the return period was reduced 50 years. In this case, relatively lower temperatures may have helped to mitigate some of the effects from reduced precipitation whereas the

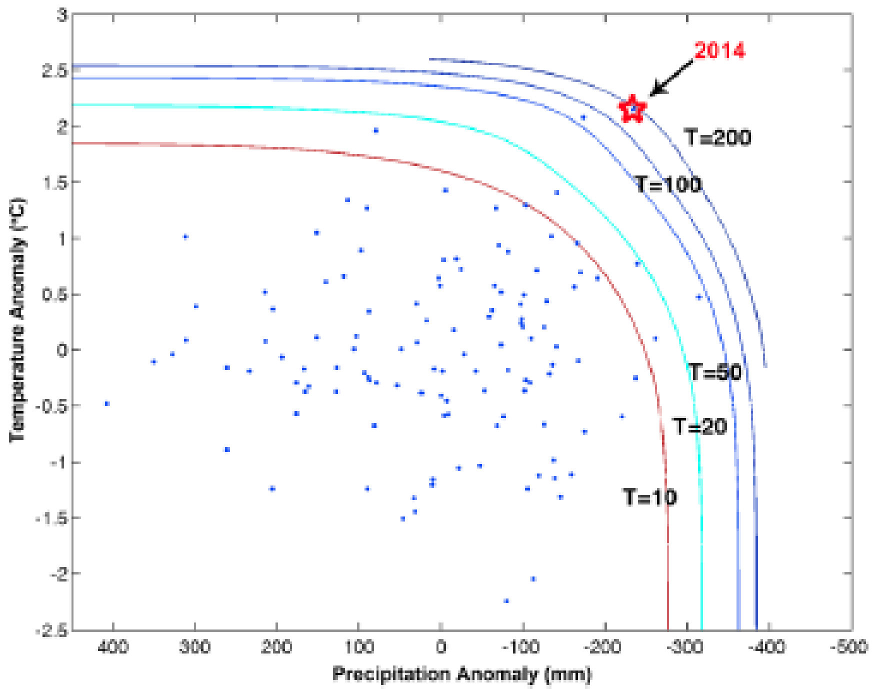


Figure 1.3: Return period for droughts based on precipitation and temperature anomalies. The curved lines represent the return periods. Each point is a different year in California's observational record. 2014 is marked by the star (AghaKouchak et al., 2014).

most recent drought has been worsened due to warming temperatures. With a return period of 200 years, the drought conditions of 2014 arising from low, but not record breaking, precipitation coupled with record-warm temperatures result in California's most recent drought being the worst in the observational history of the state (since 1895). One limitation of this study is that it assumes the temperature signal is stationary, but average temperatures have been increasing for several decades due to anthropogenic warming and therefore, this study may be overestimating the return period of these events.

1.3 Snowfall

While drought is often thought of within the context of low rainfall, snowfall is a crucial water resource to many communities. In California, nearly all of the snowfall occurs during the wet season (Nov-April). During a normal or plentiful year, this snowfall will build up as a dense snowpack in the mountains that will begin to melt in the springtime, filling the reservoirs throughout the state. The months of May through October are the state's dry season and the water contained within the reservoirs helps to sustain the state and provide water during the dry months. Without this water from snowfall and snowpack, severe restrictions are put in place to reduce water use and consumption. This especially affects the agricultural sector, which consumes up to 77% of California's water (Diffenbaugh et al., 2015). For the California drought of 2011-2016, not only were there reduced rainfall and warm temperatures, but there was also a snow drought.

The general trend in snow pack has been steadily decreasing for many decades, even prior to the latest California drought of 2011-2016 (Mote, 2006). Mote et al. (2016) analyzed the causes of the extremely low snow pack in the western United States for 2015. Using stations located in the mountains in California, Oregon, and Washington, it was found that at 81% of the locations (454 stations), snow-water equivalent (SWE) in 2015 was the lowest ever record, breaking records set during the winter of 1977. Additionally in 2015, 111 stations recorded 1 April SWE of zero for the first time in observations. Usually, 1 April SWE is used as an indicator for the amount of snow pack left in the mountains and also the amount of runoff that has yet to occur. This serves as a proxy for understanding the amount of water that will melt to fill the reservoirs. For the case of 2015, 1 April SWE of zero indicates that there will be no more runoff to fill the reservoirs, which means that there will be little water available for the dry season.

Prior to the start of the California drought in 2011, Mote et al. (2005) analyzed SWE changes that were occurring in the western U.S. due to a warming climate. From 1950-1997, it was found that SWE has decreased up to 75% in the northern Sierra Nevada Mountains. In general, nearly all of the mountain ranges in the western U.S. experienced SWE losses of 20%-80% during this time (Figure 1.4. The southern Sierra Nevada Mountains, however, are an exception. Since the southern region is higher in elevation than the northern region, it was shown that the former had increased SWE up to 30%. While higher elevation mountains may fair well in a warming climate as compared to lower elevation mountains, the greatest changes will occur in low and mid-elevations as it becomes too warm for snow pack to build.

Temperature has a large role in affecting snow pack, SWE, and runoff. Barnett et al. (2008) found that from 1950-1999, up to 60% of the climatic trend in wintertime air temperature as well as the amount of snow pack is human induced. Additionally, it was noted that warmer temperatures result in decreased SWE as well as affecting the timing of springtime runoff. Temperature is the dominant factor that controls the timing of runoff and over the last half century, the 1-2°C of warming over the western United States has resulted in runoff occurring 1-4 weeks earlier in the low to mid-elevation mountains, when compared to the first half of the 20th century (Rauscher et al., 2008). While decreased precipitation may affect the amount of runoff that occurs, by controlling the amount of snow pack that is built up over the winter, it does not have as strong of an effect on the actual timing that runoff occurs. As the climate continues to warm, Rauscher et al. (2008) determined that snowmelt-driven runoff may begin to occur up to 70 days earlier than present in the Sierra Nevada Mountains as well as the mountains experiencing up to 60 fewer days a year below freezing.

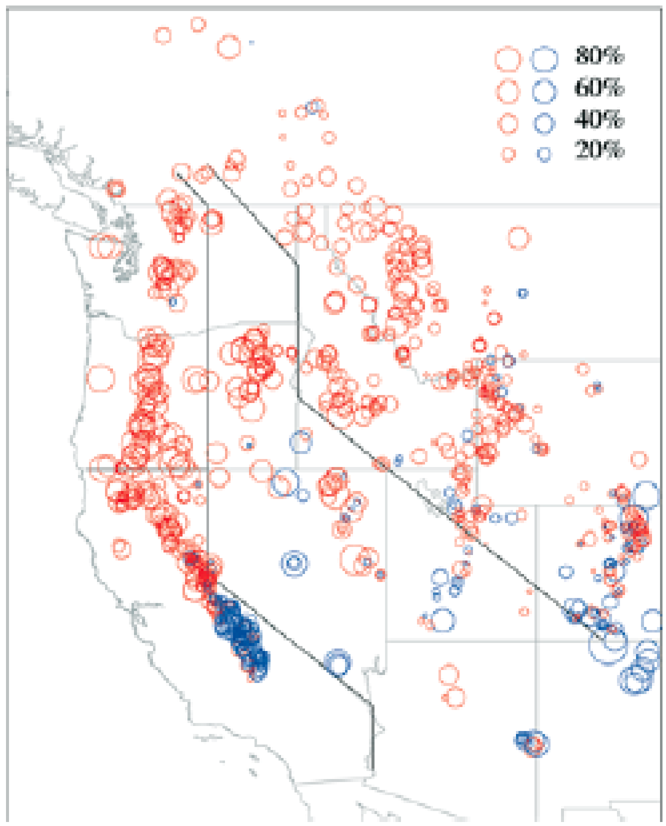


Figure 1.4: Changes to snow water equivalent from 1950-1997. (Mote et al., 2005). The red circles represent decreases in SWE while blue circles represent increases. The size of the circle is significances the percent increase.

While many studies have analyzed how temperature and precipitation, and even snow pack, during the drought compare to the observational record of the state, no study has yet to directly compare the low snowfall of the drought with California's history and contextualize if the snowfall during this period was record setting. Previous studies have all focused on understanding how snowpack and SWE during the drought compare to the state's history, but no study has specifically analyzed the amount of snowfall during the drought. Since snowfall is the is needed to build up snowpack and determine SWE, this study will emphasize how snowfall during the drought of 2011-2016 compares to the state's historical observations.

1.4 Teleconnection Patterns

In addition to long-term changes related to anthropogenic warming, temperature and precipitation in California can be impacted by remote teleconnections via changes in the global circulation. Perhaps the most well-known of these teleconnection patterns that influence California (and the U.S.) is the El Niño Southern Oscillation (ENSO) e.g. (Schonher and Nicholson, 1989; Hoerling and Kumar, 1997; Capotondi et al., 2015).

Hoell et al. (2016) recognized that a strong El Niño, which is marked by sea surface temperature (SST) anomalies in the equatorial Pacific of at least 1.5°C, on average results in increased precipitation California-wide (Figure 1.5). El Niño tends to cause the greatest relative change in the southern regions of the state, but increased precipitation to the north is also important to build snow pack in the Sierra Nevada Mountains, if the precipitation is in the form of snow.

Heading into winter 2016-2017, it was expected that weak La Nina conditions would persist over the equatorial Pacific (Climate Prediction Center, 2016), suggesting that precipitation was likely to be below normal for southern California while temperature would be above average for nearly all of the state (Halpert,

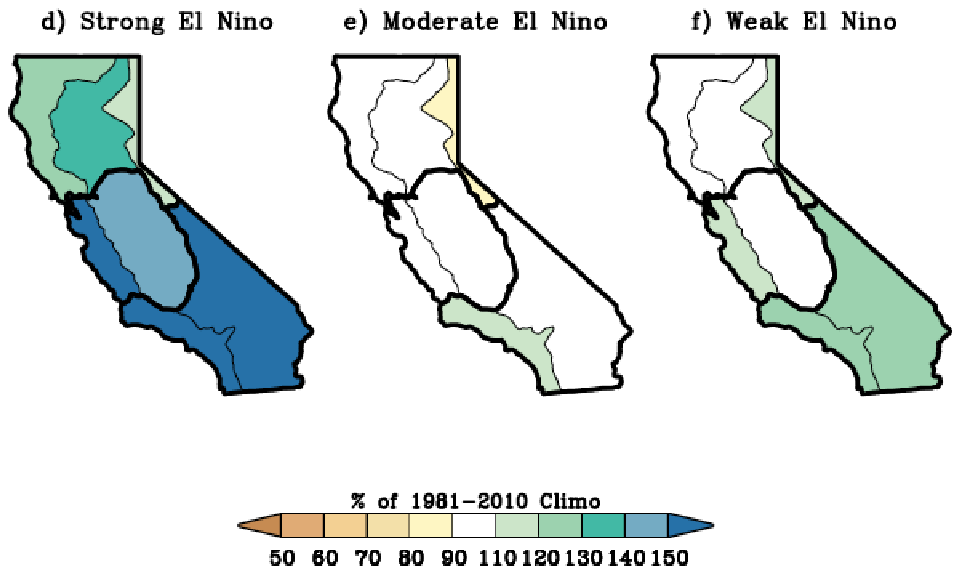


Figure 1.5: The influence of strong, moderate, and weak El Niño on precipitation in California. The color bar shows the relative change of precipitation for each climate division compared to climatology. (Hoell et al., 2016)

2016). However, the winter of 2016-2017 had above-average precipitation and snowfall (National Weather Service Sacramento, 2017) and as of 21 March 2017, the Sierra Nevada Mountains have SWE of 158% of normal (California Department of Water Resources, 2017). Even though it was a weak La Nina through the winter, the expected effects on precipitation did not occur and California experienced one of its most plentiful years of rainfall and snowfall in quite some time.

In addition to ENSO, Fierro (2014) analyzed the relationship between California rainfall variability and other teleconnections, including the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), North Pacific Index (NPI), Atlantic Multidecadal Oscillation (AMO) and Arctic Oscillation (AO), and found that the leading modes of variability differed between northern and southern California. In southern California, the influence of ENSO was stronger than in northern California, and both regions had a stronger correlation during the wet season when compared to the dry season. Additionally, southern California correlated well with the SOI, NPI and the PDO while the most northern portions of California had a strong correlation with the PDO. All of these teleconnection patterns, however, interact with one another such that there is a combination of teleconnections that lead to the highest drought risk for California. Kam et al. (2014) found that California is most at risk for drought when the AMO is in a positive phase, the PDO has a negative phase, and SOI is positive. While ENSO is considered to be the leading teleconnection affecting drought in California, the other teleconnection patterns also play an important role in determining the atmospheric setup driving precipitation.

In particular, the relationship between the climate the western United States and the PDO has been heavily studied (Hidalgo and Dracup, 2003; Cañón et al., 2007; Pavia et al., 2016; McCabe and Dettinger, 1999; Goodrich, 2007). The PDO is a mode of climate variability over the midlatitude Pacific Ocean Basin (north of 20°N) marked by long-term SST anomalies that change polarity between warm and cool phases approximately every 20-30 years (Hare, 1996). This is in contrast with ENSO, which has a much shorter period of approximately 2-7 years and fluctuates between warm and cold phases. According to MacDonald and Case (2005) who used wavelet analysis to identify which frequencies have significant power for the PDO, two periods ranging from 50-70 years as well as 4-7 years had significant power in the frequency of the PDO.

To best determine the influence that the PDO may have on precipitation over the western U.S., Goodrich (2007) analyzed the effect of the warm and cool phases of the PDO during ENSO-neutral years from 1925-1998 and found a widespread drought signal during the cool phase at over 80% of the climate divisions in the western U.S. During an ENSO-neutral year with a warm-phase PDO, 82% of the climate divisions were wetter than normal. In addition to the relation between the PDO and precipitation, LaDochy et al. (2007) analyzed correlation between mean temperature, maximum temperature, and minimum temperature for 1950-2000 across California for over 200 stations. It was found that 76% of stations for mean temperature have a significant, positive correlation with the PDO while only 44% of station have a positive, significant correlation between maximum temperature and the PDO whereas 83% of stations had a significant correlation for minimum temperature and the PDO. As LaDochy et al. (2007) mentions, one of the limitations of analyzing the PDO when the PDO has a period of 20-30 years, is that there are not many cycles that occur over the time of analysis. This limitation applies to nearly all studies, including this one, that use data only for 50-100 years.

1.5 Research Question

Snow pack and SWE have decreased in the 20th century in California and many years within the most recent California drought saw low, but not record breaking precipitation, while temperature was the warmest on record. However, the entire five years of the drought (2011-2016) have not been analyzed and it has yet to be determined specifically how snowfall from 2011-2016 compares to climatology and if snowfall was at a record low during this time. Due to the importance of snowfall for building snow pack for water resources during the dry season, this study will address how temperature, precipitation, and snowfall during the California drought of 2011-2016 compare to climatology for the state and what influence teleconnection patterns have had on snowfall. Having a better understanding of the role that snowfall has played during this drought will provide added knowledge to the conditions that gripped California during these five years of drought.

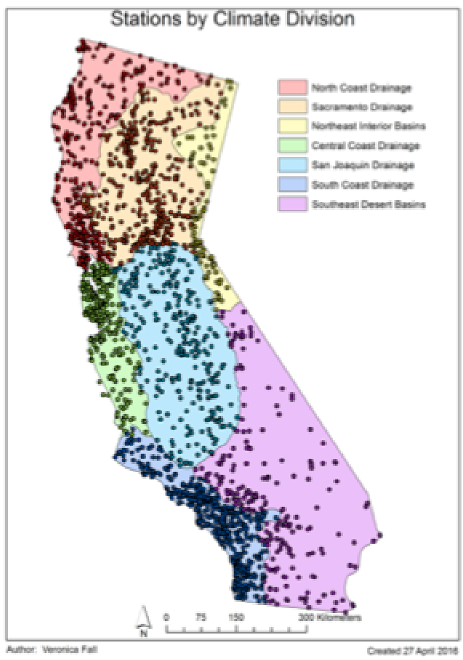
Chapter 2

Data and Methodology

2.1 Data

Daily data from the Global Historical Climatology Network (GHCN) was retrieved for: maximum temperature (tmax, °C), minimum temperature (tmin, °C), precipitation (prcp, mm), and snowfall (snow, mm), from the National Center for Environmental Information (NCEI). The snowfall measurements are made for the actual amount of snowfall and not liquid water equivalent (although this data is available from NCEI). The daily data from NCEI was chosen over other data sets because there was greater temporal coverage, specifically for snowfall, for this data over other observation networks. For several other data sets, snowfall measurements began to be collected in the 1970s or 1980s. From the daily data, monthly averages were computed for maximum and minimum temperature while monthly totals were computed for precipitation and snowfall, with the seasonal cycle removed from the data. The data represent 2512 stations across California from 1 January 1895 until 30 April 2016 (Figure 2.1, subset by climate division). A majority of the stations do not have complete records throughout the entire period and few stations have a complete record for all four variables for the entire period.

Monthly teleconnection indices were obtained for the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) from NCEI for 1950-present. The PDO is defined as the leading principle component of monthly SST anomalies that occur north of 20°N in the Pacific Ocean. Positive anomalies correspond with the warm phase of the PDO while negative anomalies correspond to the cool phase of the PDO. The monthly anomalies for Niño3.4 from the Climate Prediction Center were acquired to determine the phase of ENSO. The Niño3.4 region encompasses 5°N-5°S and 170°W-120°W. Positive anomalies correspond to the warm phase of ENSO (El Niño) while negative anomalies correspond to the cool phase (La Nina).



Climate Division	No. Stations
North Coast	419
Sacramento	491
Northeast	95
Central Coast	344
San Joaquin	350
South Coast	568
Southeast	240

Figure 2.1: Location of all NCEI GHCN stations in California as well as the number of stations per climate division.

2.2 Methodology

In order to compare the characteristics of the entirety of the drought (2011-2016), the five-year period was compared against other periods of the same length in California's history to determine how various characteristics of the drought are different from other time periods. For these five-year periods, only the wet season months (November-April) were considered. The wet season is defined by when most of the snowfall occurs, as well as the month of April when snowmelt-driven runoff is notable ((AghaKouchak et al., 2014; Hoell et al., 2016). Additionally, although maximum temperature, minimum temperature, and precipitation have reasonably complete records from 1895 until present, there is very little snowfall data dating back this far. Because of this, the complete analysis began on 1 January 1950 and ended on 30 April 2016. To compare 2011-2016 against other five-year periods beginning in 1950, the first group is Nov 1950-April 1955, the second five-year group is Nov 1951-April 1956, the third group is Nov 1952-April 1957 etc. and the last five-year group is the time of the California drought, Nov 2011-April 2016. In total, 62 five-year groups were created for analysis.

Since a majority of the stations do not have complete records for the entire period of interest, only stations with complete records were chosen. Additionally, in order for the data to be considered independent, only one station was selected per climate division to provide a statewide perspective on changes. This resulted in each five-year group having data from seven stations for six months of each year (Nov-April) for five years, so that each group had 210 values. The chosen station varied for each variable (due to the completeness of the record) and the station chosen from each climate division and for each variable is shown in Figure 2.2. When multiple stations were available within each climate division with a complete record, the station nearest to the geographic center of each division was chosen.

In addition, seven stations located in the Sierra Nevada Mountains were selected in order to analyze snowfall changes in the higher elevations. Approximately 250 stations were located in the mountains and only one-tenth offered complete records. The seven stations that were chosen have a wide elevation range as well as being located in both the northern and southern regions of the mountains. Seven

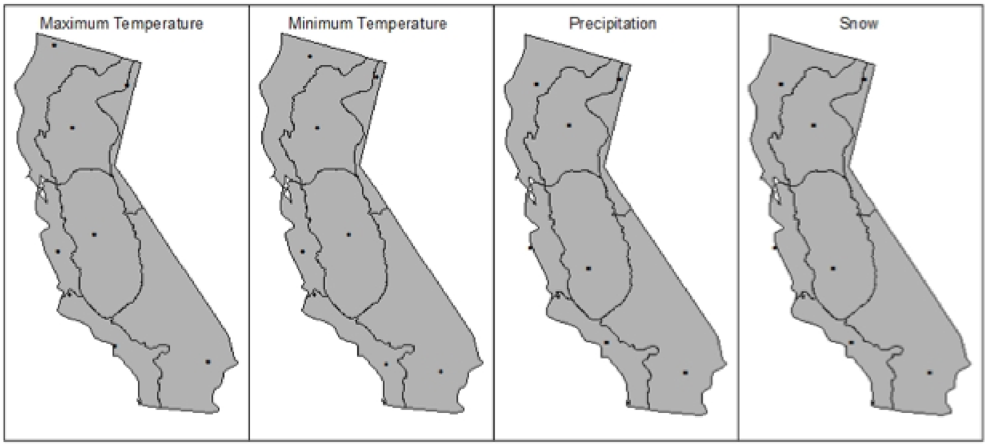


Figure 2.2: Location of the chosen stations (complete record for 1950-present) for each climate division and variable.

stations were chosen to match the number of stations chosen for the statewide analysis. These stations have an elevation range of 847.6-2011.7m, with an average elevation of 1389.9m. These stations were only used in the analysis of snowfall since understanding changes to California's snowfall was the focus of this study. These stations are shown in Figure 2.3. Locations in the mountains were not chosen for the other variables since the changes for temperature and precipitation have been well documented in other studies (Griffin and Anchukaitis, 2014; Richman and Leslie, 2015; Mao et al., 2015; Williams et al., 2015; Swain et al., 2014; AghaKouchak et al., 2014; Diffenbaugh et al., 2015; Diaz and Wahl, 2015).

2.3 Permutation Tests

To compare the drought years against other time periods, permutation tests were used to determine whether or not two groups are from the same distribution. Stated another way, a permutation test determines if the difference between the mean of group A (with a size n_A) and the mean of group B (with a size n_B) is significant. For all analyses, group B will be the five-years of the California drought

Figure 2.3: Location of the chosen stations (complete record from 1950 until present) in the Sierra Nevada Mountains to analyze snowfall.

(2011-2016) while group A will be all other five-year groups that the drought is compared against for a given variable, e.g. 1950-1955, 1951-1956...and so on. For this study, both groups will have 210 data points. One of the advantages of using permutation tests is that there is no assumption made about the underlying distribution of the data. Temperature, for instance, tends to have a Gaussian distribution while precipitation and snowfall tend to have Gamma distributions. There are many types of tests that would not be available to use for data with a gamma distribution, so permutation tests were chosen since the same test can be used for all atmospheric variables, independent of distribution.

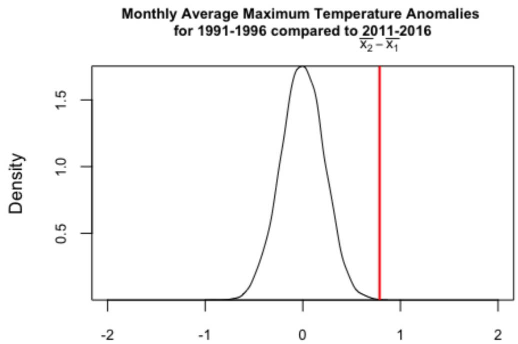
The procedure for a permutation test is as follows. First, each data point is labeled as either belonging to group A or group B. Then, all possible permutations of the labels are performed, such that group A always has a size $\mathrm{n_A}$ and group B always has a size of $\mathrm{n_B}$. The mean of each group is calculated for each permutation, as well as the difference of the means for each permutation of the data ($\bar{x}_{\mathrm{b}} - \bar{x}_{\mathrm{a}}$). The difference of the means of the original data must also be calculated ($\bar{\mu}_{\mathrm{b}} - \bar{\mu}_{\mathrm{a}}$). Next, the set of values obtained from the permutation tests ($\bar{x}_{\mathrm{b}} - \bar{x}_{\mathrm{a}}$) is compared against ($\bar{\mu}_{\mathrm{b}} - \bar{\mu}_{\mathrm{a}}$). If the difference between the set of values and the original data is statistically significant at $\alpha = 0.05$, the null hypothesis is rejected and it can be stated that group A and group B are from different distributions. If the difference between group A and group B is not statistically significant, the null hypothesis is accepted and groups A and B are likely to have come from the same distribution.

In addition to using permutation tests to compare the entire wet season of each five-year group, the same test was performed for each month of the wet season within each five-year group to determine if significant changes were occurring in a given month. For this analysis, each five-year group contained the same seven stations but for only one month of a year. This resulted in each group containing 35 data points for the monthly analyses.

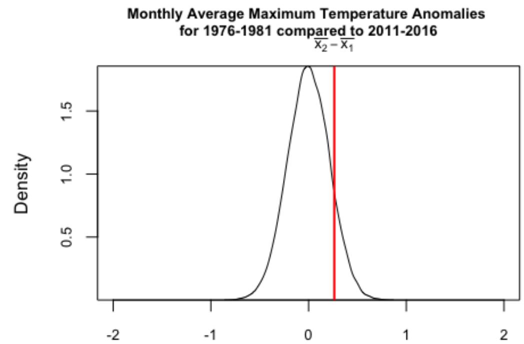
An example of the result generated from a permutation test can be seen in Figure 2.4 for statewide maximum temperature. Figure 2.4a is an example of a period which was significantly different from 2011-2016 at $\alpha = 0.05$. Compared to 1991-1996, the recent drought years were significantly warmer. In Figure 2.4a, the vertical red line indicates the difference of the means of the two periods ($\bar{\mu}_{\mathrm{b}} - \bar{\mu}_{\mathrm{a}}$) while the black, bell-shaped curve represents the difference of the means from the permutations of the data. The red line falls at the very tail end of the curve on the right side, so 2011-2016 was much warmer than 1991-1996. This result was expected since the climate has steadily been warming for several decades. The mean maximum temperature anomaly for 1991-1996 is 0.2 °C while the mean maximum temperature anomaly for 2011-2016 is 1.0°C. The p-value from the comparison of these two groups is 0.0006, which is well below the 0.05 threshold. This years 1991-1996 are an example of a period that was significantly different from 2011-2016 and many other five-year groups had similar plots to this one. Figure 2.4b, however, shows an example where a five-year group was not significantly different from 2011-2016 for statewide maximum temperature. It can therefore be stated that 1976-1981 and 2011-2016 are not significantly different from one another and that the five-year mean maximum temperature of 2011-2016 was not significantly warmer than 1976-1981. The mean maximum temperature anomaly from 1976-1981 is 0.7°C. This is not a large difference from the mean anomaly of 2011-2016, so this five-year period is not considered significantly different from 2011-2016. The comparison of these periods results in a p-value of 0.226. For all variables, the plots generated from the permutation tests closely resemble those shown for maximum temperature. In Appendix A, additional examples from the permutation tests can be found for all other variables.

2.4 Wavelet Analysis

Based on prior works (Fierro, 2014; Hoell et al., 2016), a periodicity is expected in the data. To determine the frequency, intensity, and time evolution of the periodicity, a wavelet analysis was performed, following the recommendation of Torrence and Compo (1998). Wavelet analyses were carried out for one-year anomalies rather than the five-year anomalies of snowfall. For certain teleconnection patterns, such as ENSO, using the five-year groups would have washed out some of the strong ENSO signal, since this teleconnection can change significantly from year to year. The data was linearly detrended prior to analysis. The series of mean anomalies was then padded with twenty years of zeroes anomalies at the



(a) 1991-1996 is significantly different from 2011-2016



(b) 1976-1981 is not significantly different from 2011-2016

Figure 2.4: Examples from the permutation tests of statewide maximum temperature. The vertical red line indicates the difference of the means of the two periods while the black, bell-shaped curve represents the difference of the means from the permutations of the data

beginning and ending of the time series in order to achieve a better estimate of the periodicity at longer time scales. The wavelet analysis for snowfall was also compared against the wavelets of the wet-season average of the PDO and ENSO. Wavelet coherence was also utilized to determine the relationship between snowfall and the PDO as well as snowfall and ENSO.

Chapter 3

Results

3.1 Statewide Characteristics

3.1.1 Maximum Temperature

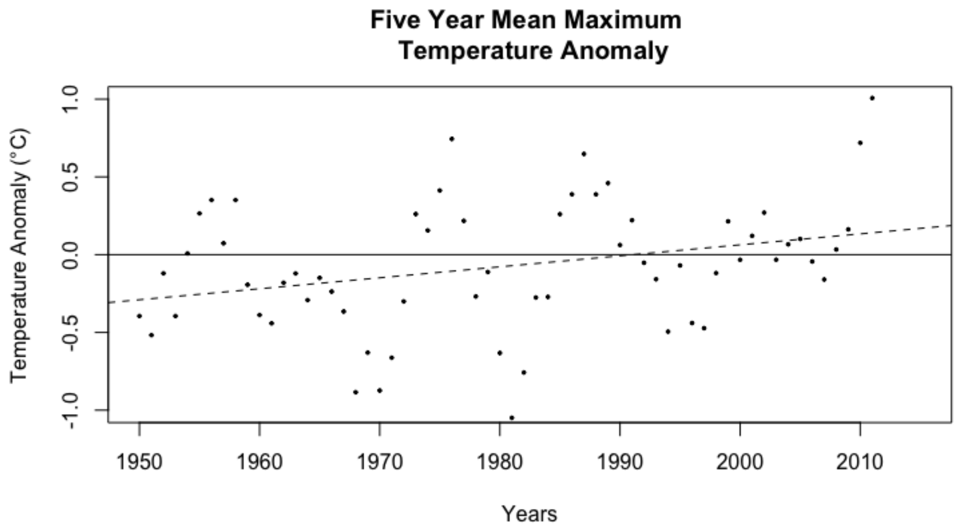
To best compare the results of each five-year group against 2011-2016, the mean maximum temperature anomalies and p-value from the permutation tests were calculated and are shown in Figure 3.1. In Figure 3.1a, the mean maximum temperature anomalies of the five-year groups show a significant amount of periodicity, as well as an increasing trend. The trend in the mean maximum temperature (given by the dashed line) is +0.07 °C per decade of five-year groups and is significant at $\alpha = 0.05$ using a t-test. This result is in contrast with that found by Mao et al. (2015) where maximum temperature did not have a significant increasing trend, although this study was performed for 1920-2014 in and around the Sierra Nevada mountains, which may explain the discrepancy between the results since this study includes data from stations closer to the coast as well as in the desert. In general since about the year 2000, the mean anomalies are either positive or slightly negative, while prior to 2000 there are many periods with a mean anomaly of at least -0.5°C. After performing a wavelet analysis, temperature has a periodicity that is significant at 95% for all periods between 8 and 12 years (Appendix B, Figure B.1), with the most power occurring at a period of approximately 10 years, or rather a period of 10 years of five-year mean maximum temperature anomalies.

The mean maximum temperature anomaly for 2011-2016 stands out as being the warmest on record, with an anomaly of 1.0°C. In Figure 3.1b, only three of the five-year groups were not significantly different from 2011-2016 (1976-1981, 1987-1992, and 2010-2015). and the mean maximum temperature anomalies for these periods are 0.7°C, 0.6°C, and 0.7°C, respectively. The corresponding p-values for these years are 0.226, 0.125, and 0.183. Aside from these three five-year groups, all of the other periods since 1950 are significantly different from 2011-2016 and all of these groups are cooler as well.

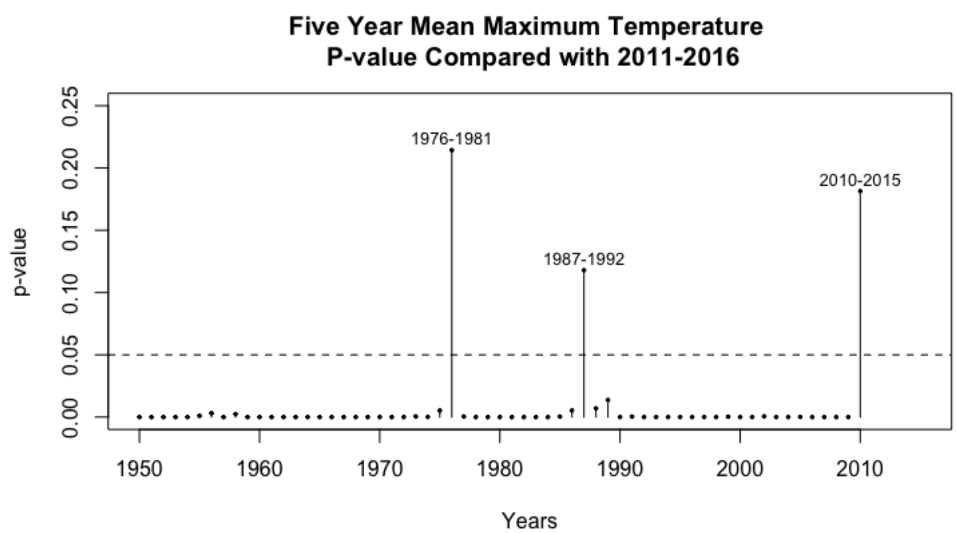
In total, 58 of 61 five-year groups were significantly different from and cooler than 2011-2016. This shows that the drought that recently engulfed California was affected by warmer than normal maximum temperature. Although there were three periods that were not significantly different from 2011-2016, the mean maximum temperature anomaly for this time was the warmest on record (1.0°C).

3.1.2 Minimum Temperature

Similar to the analysis performed for statewide maximum temperature, permutation tests were used to compare statewide minimum temperature as well. Examples of the permutation test comparing two five-year groups may be found in Appendix A, Figure A.1. Figure 3.2 shows the mean minimum temperature anomalies and p-values for all of the five-year periods. Similar to maximum temperature, there is a considerable oscillation to the mean anomalies with approximate decadal variability. While the range of temperature anomalies varied between approximately +0.5°C and -0.25°C through the mid 1960s, this range has increased considerably since to a range of +1.0°C to -0.5°C since the 1960s. After conducting a wavelet analysis for minimum temperature, it was found that at 95% confidence, no period



(a) Mean maximum temperature anomaly for all five-year groups

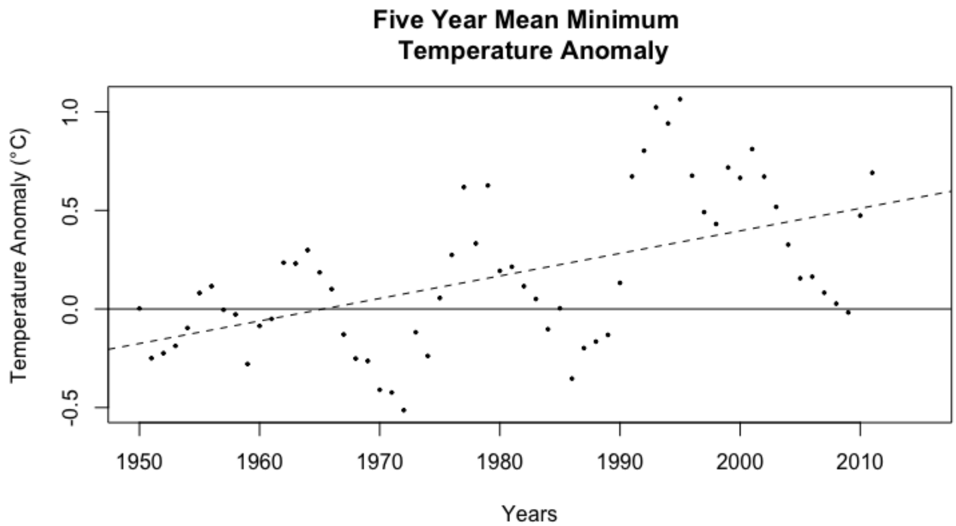


(b) P-value for all five-year groups compared to 2011-2016

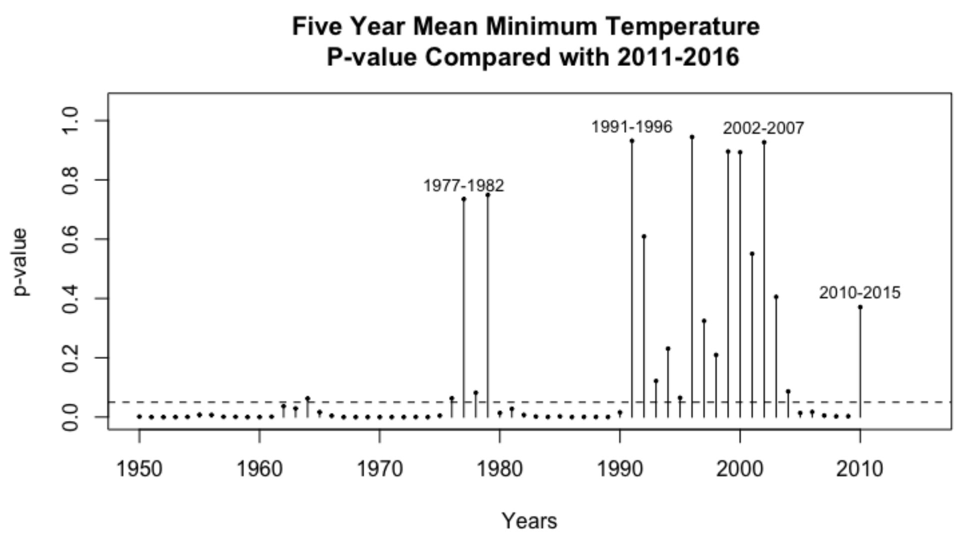
Figure 3.1: (a) Mean maximum temperature anomaly (°C) and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

was significant. However, at 90% confidence, the periods of approximately 12-16 years were significant (Appendix B, Figure B.2). The correlation between maximum and minimum temperature is fairly weak (0.187), but the average wavelet coherence between these two variables is fairly high (approximately 0.9) (Appendix B, Figure B.3). The coherence describes the relation between two variables at a given time and space, so maximum and minimum temperature have a strong coherence in the time-frequency domain.

In Figure 3.2a, it can be seen that 2011-2016 was not the warmest five-year period. The temperature anomaly for 2011-2016 is 0.7°C. Several periods in the 1990s and early 2000s have higher anomalies. The period of 1995-2000 has the highest anomaly of 1.1°C. This period encompasses the very strong El Niño of 1997-1998. The five-year group of 2011-2016 is the seventh warmest period for minimum temperature. There are more five-year periods that are not significantly different for minimum than maximum temperature (58 of 61 groups were significantly different for maximum temperature compared with 41 groups for minimum temperature, Figure 3.2b. However for minimum temperature, a majority of the times that are not significantly different are relatively recent (15 of the 20 non-significant periods have occurred since 1991). For all groups that are significantly different from 2011-2016, these groups were all cooler than the years of the drought. Similar to maximum temperature, there is a significant increasing trend in minimum temperature of +0.1°C per decade of five-year groups, which is about 1.5 times as large as the trend of maximum temperature. This finding agrees with that of LaDochy et al. (2007) in that minimum temperature is increasing faster than maximum temperature and that the trend in minimum temperature is significant, which was also found by Mao et al. (2015). Additionally, with the exception of 2009-2014, minimum temperature anomalies have been positive since 1990.



(a) Mean minimum temperature anomaly for all five-year groups



(b) P-value for all five-year groups compared to 2011-2016

Figure 3.2: (a) Mean minimum temperature anomaly (°C) and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.5 threshold.

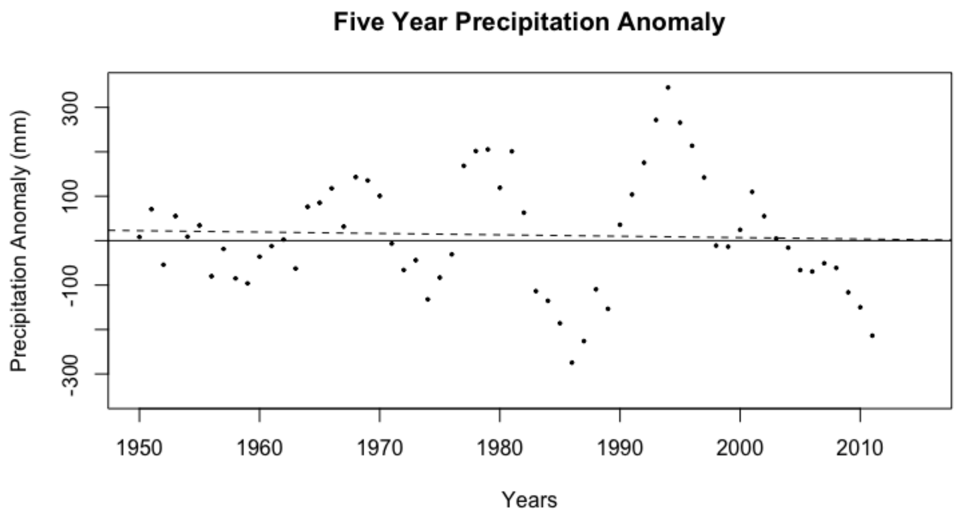
3.1.3 Precipitation

Permutation tests were also used to analyze how precipitation during the drought compares to past years since 1950 (see Appendix A, Figure A.2 for examples). Figure 3.3 shows the mean precipitation anomalies and p-values for all of the five-year groups. Figure 3.3a, which shows the mean anomaly, also shows a general oscillation from negative to positive anomalies throughout the entire time of analysis. Although there is a decreasing trend in precipitation of -3 mm per decade, this trend was not found to be significant. There is a clear decadal oscillation in the data and the amplitude of this oscillation has been increasing. From 1950 until 1970, the low precipitation anomaly was approximately -100 mm while the high anomaly was approximately 150 mm, for a difference of 250 mm between wet and dry periods over an approximate ten year period. Between the mid 1980s and mid 1990s, however, the low anomaly was around -300 mm while the high anomaly was near +300 mm. Over ten years, this difference of approximately 600 mm is much greater than the difference found a few decades before.

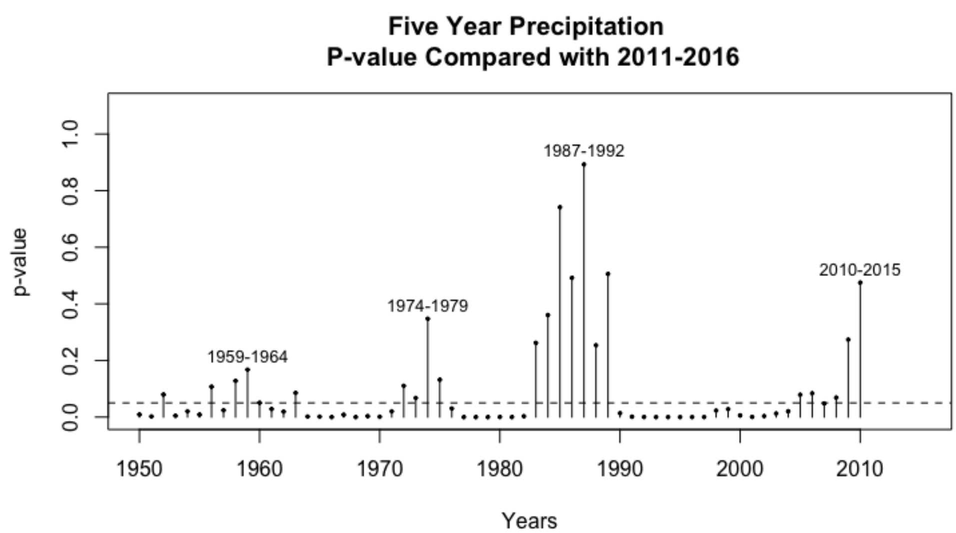
After performing a wavelet analysis, the periods that were statistically significant at $\alpha = 0.05$ range from approximately 10-12 years (Appendix B, Figure B.4). To better understand how maximum temperature, minimum temperature, and precipitation are related, wavelet coherence was also analyzed. The correlation between maximum temperature and precipitation is -0.567 while the correlation between minimum temperature and precipitation is 0.529. With these moderate correlation values, the degrees of freedom are reduced, so the range of periods that appear significant for wavelet coherence are reduced. With 62 five-year groups and a moderate correlation between maximum temperature and precipitation, the degrees of freedom are reduced to 17 while the degrees of freedom between minimum temperature and precipitation are reduced to 19. From wavelet coherence, the average coherence between maximum temperature and precipitation is approximately 0.9 (Appendix B, Figure B.5), but with the reduced degrees of freedom, a statistically significant coherency only exists at a short period of approximately 3 years. The average coherence between minimum temperature and precipitation is greater than 0.9 (Appendix B, Figure B.6) but due to the reduced degrees of freedom, the coherency is not significant at any period. While precipitation is strongly coherent with the time series for temperature, it is not statistically significant at many periods.

The period of 2011-2016 had low, but not a record-setting precipitation anomaly (-214 mm). The years of 1986-1991 and 1987-1992 had lower anomalies (-275 mm and -226 mm, respectively). The recent drought was therefore the third-lowest, five-year period for statewide precipitation since 1950. Of the 61 groups compared to 2011-2016, 39 groups were significant different. Several periods in the 1950s and 1980s were not significantly different, so it does not appear that there has been a trend towards more recent years being drier. For all of the groups that were different from 2011-2016, these groups had significantly more precipitation than the drought.

One of the interesting findings is that none of the five-year groups that contain the worst single drought year of 1976-1977 have remarkably low precipitation. While the precipitation anomaly for the five-year groups in the mid 1970s, as seen in Figure 3.3a, is below average, it is not exceptionally low when compared against several periods in the mid 1980s and the drought. The period of 1974-1979 has an anomaly of -132 mm, and while this is the seventh lowest anomaly for a five-year period, this difference in the magnitude of the anomalies between this group and the drought is 82 mm. As shown by Mao et al. (2015), the two years of 1976 and 1977 are the worst two years of drought, but at a longer period of 3 years, the recent drought is the worst. Low precipitation during 1976 and 1977 is balanced



(a) Precipitation anomaly for all five-year groups



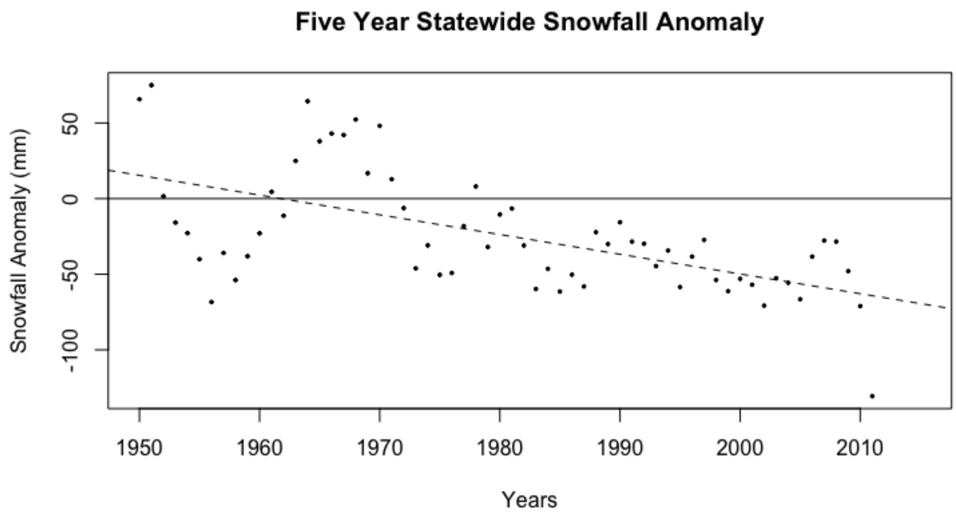
(b) P-value for all five-year groups compared to 2011-2016

Figure 3.3: (a) Mean precipitation anomaly (mm) and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

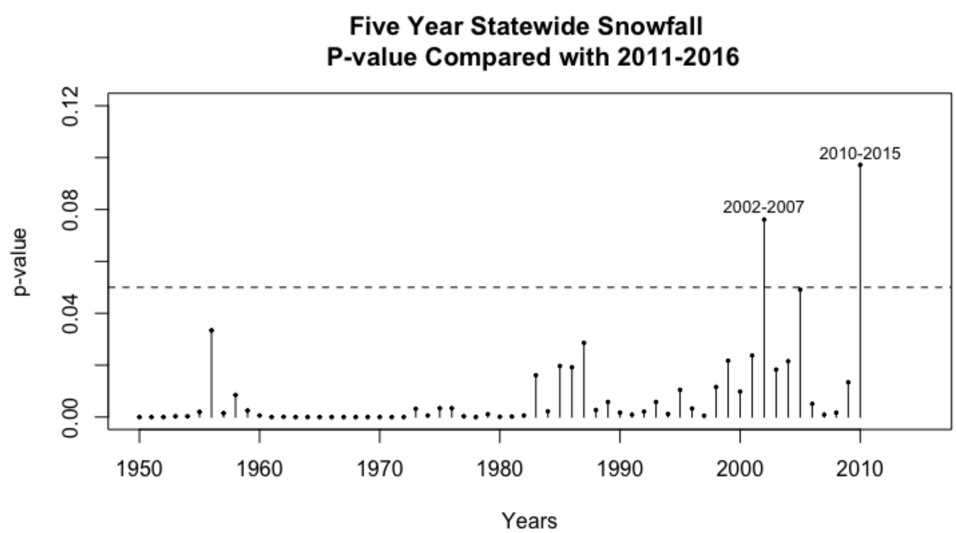
by wetter years contained within the five-year group so that the strong, relatively short-term drought of 1976-1977 does not appear as bad in the five-year analysis.

3.1.4 Snowfall

Using the selected stations from each climate division for snowfall, permutation tests were also utilized to compare snowfall during the drought across the entire state with other periods since 1950 (examples of which may be found in Appendix A, Figure A.3). Figure 3.4 shows the mean snowfall anomalies and p-values during the entire wet season for all of the five-year groups. The mean snowfall anomaly during 2011-2016 is -131 mm, which is the lowest anomaly for any group. This anomaly is approximately twice as low as any other group. The second lowest group had an anomaly of -71 mm (2010-2015) while the third lowest group also had an anomaly of -71 mm (2002-2007). These two five-year groups are also the only groups that were not significantly different from 2011-2016 (Figure 3.4b). The mean snowfall anomalies also show a strong oscillation at a frequency of approximately 10 years and with a large amplitude from 1950-1980, but the oscillation becomes quite dampened after 1980, such that until 2011-2016, the amplitude was quite small from 1980-2010. Additionally, the last five-year group that had a positive snowfall anomaly was 1978-1983 (+8 mm). Since this time, snowfall has been steadily decreasing until reaching a record low in 2011-2016. This clear trend decreased at 13 mm per decade, which is significant at $\alpha = 0.05$. The first two five-year groups (1950-1955 and 1951-1956) had the highest snowfall anomalies while 2011-2016 had the lowest snowfall anomaly, which has affected the magnitude of this trend. Even without considering these three groups, a decreasing trend and change in amplitude is still very evident in the data. By removing the groups of 1950-1955, 1951-1956, and 2011-2016, the trend was found to be a decrease of -10 mm per decade, which is still considered significant at $\alpha = 0.05$.



(a) Statewide snowfall anomaly for all five-year groups

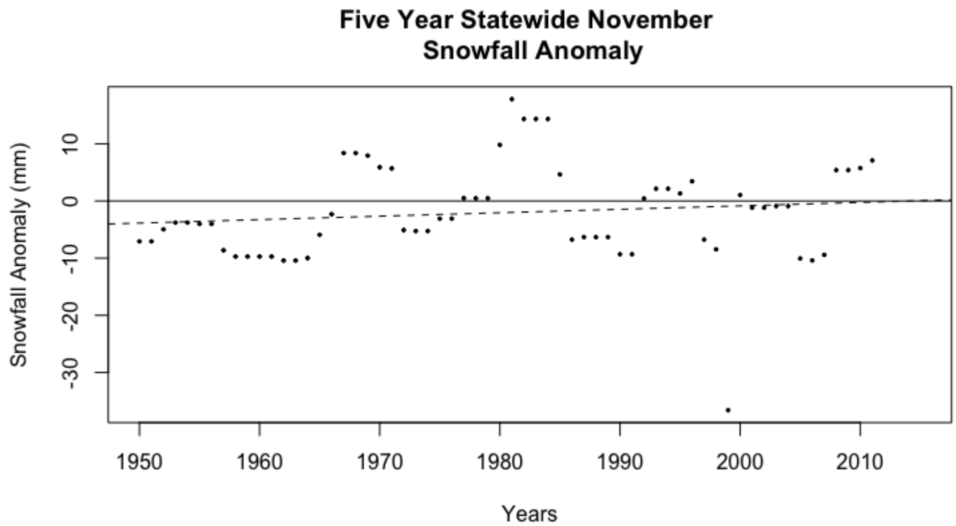


(b) P-value for all five-year groups compared to 2011-2016

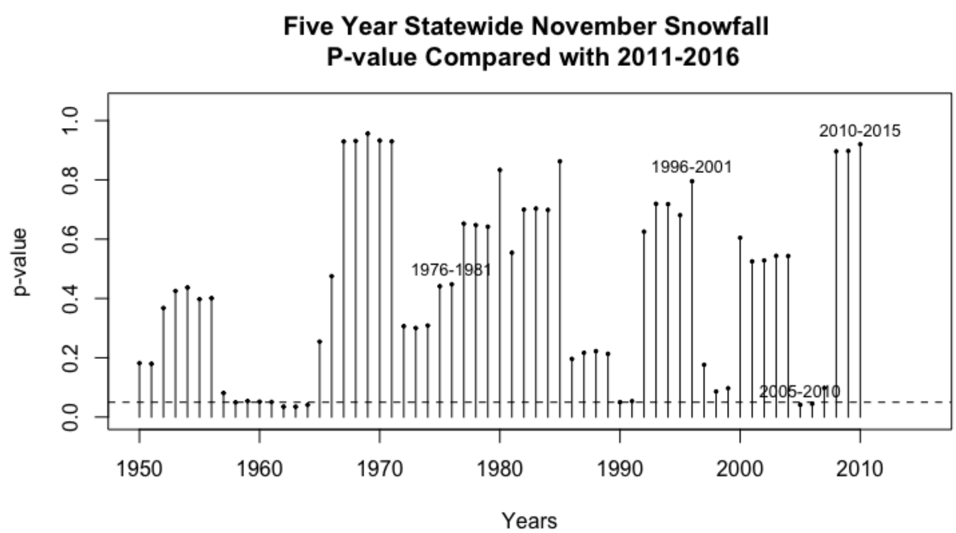
Figure 3.4: (a) Statewide mean snowfall anomaly (mm) and (b) p-value for all five-year groups during the entire wet season. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

Since previous studies have focused on snow pack and SWE, the trends in the snowfall data cannot be easily compared to previous works. Specifically, it is unclear what may be causing the amplitude of the snowfall oscillation to become dampened around 1980 and remained dampened until the years of the drought. When the mean value is lower, however, the variability and amplitude of the variability must decrease since there are not any positive values contributing to the amount of variability. While determining the cause of this dampening is beyond of the scope of this study, it is curious to see this same pattern appear not just in the analysis for statewide snowfall, but in further analyses for snowfall anomalies broken down by month as well as snowfall in the mountains. Additionally, although snowfall and SWE are different measures, Mote et al. (2005) found that SWE had decreased throughout the mountains of the western U.S. up to 20-80% from 1950-1997. In this analysis in snowfall, the significant decreasing trend in snowfall would contribute to these findings in that reduced snowfall will not allow for as dense of a snow pack to build, reducing SWE. However as Mote et al. (2005) notes, the decrease in SWE is also a consequence of warming temperatures in the mountains.

In addition to analyzing snowfall across the entire wet season, individual months of the wet season were analyzed to see what trends may be occurring in each month. With November marking the beginning of the wet season, is the decreasing snowfall occurring early in the season, or could snowfall be decreasing at the end of the season in April? January is typically the month in which the most snow falls (Knowles et al., 2006), so is it the middle of the season that is seeing the greatest changes to snowfall? The same permutation tests were used to answer these questions, but the dataset was smaller since the monthly analysis only included one-sixth of the amount of data as the analysis performed for the total wet season.



(a) Statewide November snowfall anomaly for all five-year groups



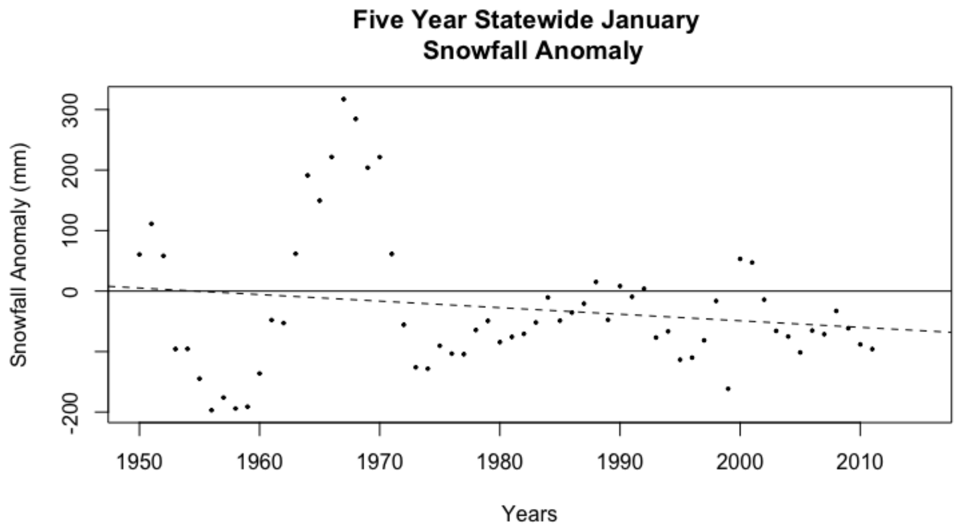
(b) P-value for all five-year groups compared to 2011-2016

Figure 3.5: (a) Mean statewide November snowfall anomaly (mm) and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

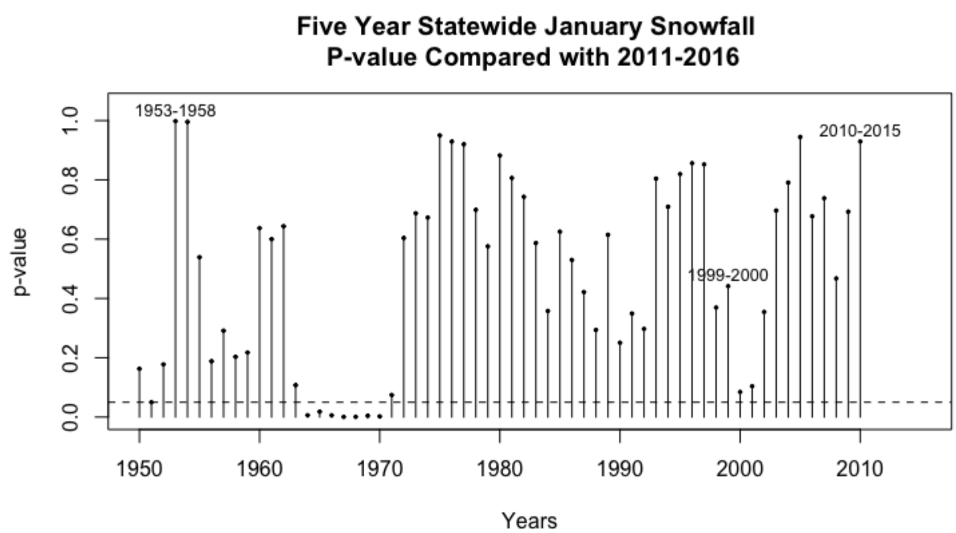
When comparing snowfall for the month of November during 2011-2016 and using each station chosen per climate division, very few years were significantly different from the recent drought (an example of a non-significant difference may be found in Appendix A, Figure A.4). Snowfall in November for years 2011-2016 was actually above average (Figure 3.5a), so snowfall does not appear to be worse at the start of the wet season for the drought and therefore may not be a good indicator of the snowfall anomaly over the entire wet season. From 1950 until 2016, the range of November snowfall anomalies is from approximately -10 mm to +15 mm (with the exception of 1999-2004 which has an anomaly of -36 mm) and the positive and negative anomalies are well-dispersed throughout the entire time of analysis.

As shown in Figure 3.5, many of the five-year groups were not significantly different from 2011-2016. Most of the years that were different had significantly less snowfall than 2011-2016. Of the 61 groups compared against the drought, only six were significant (1958-1965,1962-1967,1963-1968,1964-1969,2005-2010,2006-2011). Also, the mean November snowfall anomalies do not have a clear increasing or decreasing trend. Although the trend line has a slope of +0.602mm per decade, this slope was not found to be significant.

Snowfall during January was also compared. Similar to November, very few five-year groups were significantly different from the January months during the drought (Figure 3.6). Only seven of the 61 five year groups were significantly different from the drought. The anomaly for 2011-2016 is -96 mm (Figure 3.6a). Several five-year groups have snowfall anomalies below this value (especially in the late 1950s). The general pattern of January snowfall anomalies follows the pattern for statewide snowfall during the entire wet season. Until about 1980, there is a strong oscillation with a period of approximately ten years that has a large amplitude. After 1980, the oscillation is dampened and the period is harder



(a) Statewide January snowfall anomaly for all five-year groups

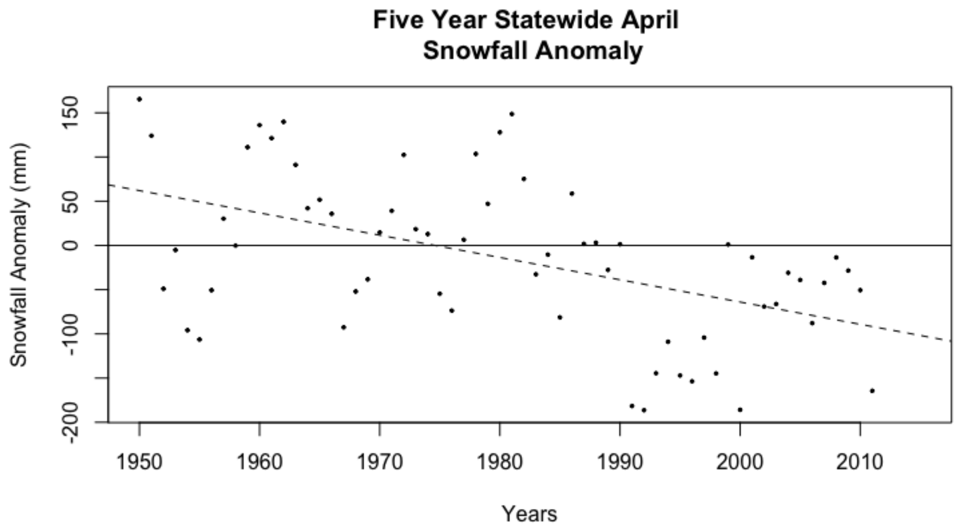


(b) P-value for all five-year groups compared to 2011-2016

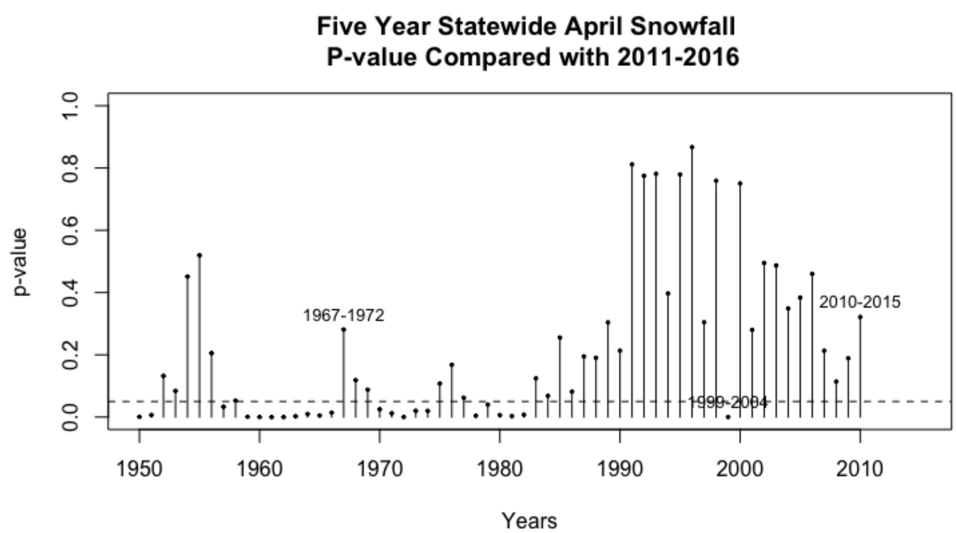
Figure 3.6: (a) Mean statewide January snowfall (mm) and (b) p-value (top) for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

to discern. There is also a general decreasing trend in January snowfall anomalies with a slope of -11 mm per decade, but this was not significant. Although January snowfall was lower than average during the drought, it was not the lowest on record and January snowfall has generally been below average since the mid 1970s.

April marks the end of the wet season for California. Figure 3.7 shows the p-values and mean snowfall anomalies for April. While there are more five-year periods significantly different from the April months of the drought than there were for November or January, there are not as many when compared against the entire state. There are 21 five-year groups significantly different from 2011-2016 for the month of April. Other than 1999-2004, all of the five-year groups that are different from the drought years occurred before 1982-1987. The anomaly for 2011-2016 is -164.435mm. This is the fourth lowest anomaly on record (1991-1996 had an anomaly of -182 mm, 1992-1997 had an anomaly of -186 mm, and 2000-2005 had an anomaly of -186 mm). So snowfall for 2011-2016 was among one of the lowest five-year periods for the month of April. The oscillation that was quite clear for the entire wet season and for January is not as apparent for April, especially after 1980. The trend for snowfall in April is stronger than for any other month, with a slope of -25 mm per decade, that was found to be significant. While significant changes in snowfall do not appear to be occurring at the beginning of the wet season (November) or in the middle of the wet season (January), snowfall is decreasing at the end of the wet season in April. The April snowfall for 2011-2016 was not the lowest on record, so the low snowfall observed over the entire wet season may be part of a general trend rather than a record-setting event for one particular month.



(a) Statewide April snowfall anomaly for all five-year groups



(b) P-value for all five-year groups compared to 2011-2016

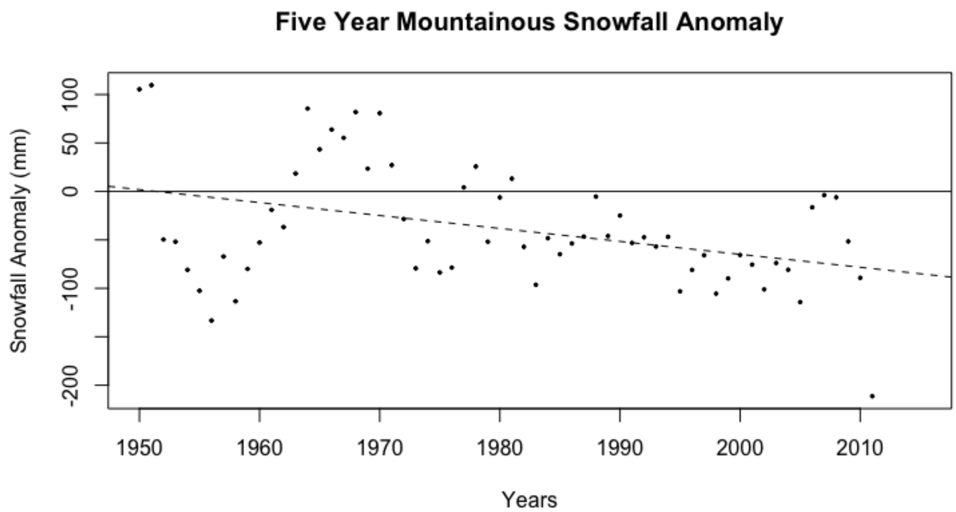
Figure 3.7: (a) Mean statewide April snowfall anomaly (mm) and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

3.2 Mountainous Snowfall

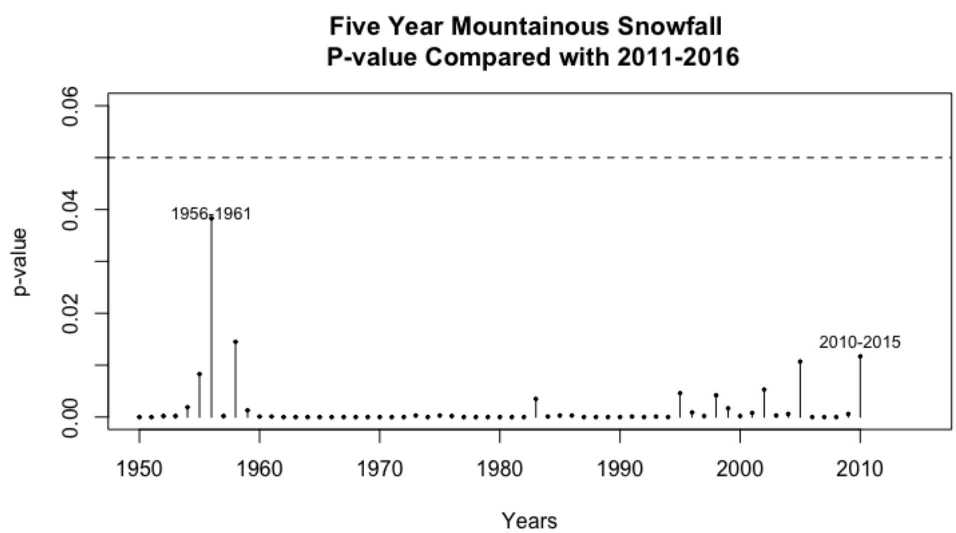
The same permutation analysis was performed for stations in the mountains. Since snowfall and the resulting snow pack are crucial to California's water resources, the snowfall in the mountains is more important to analyze than the snowfall that occurs over the entire state.

Permutation tests for the entire wet season in the mountains reveal slightly different results from the statewide analysis in that all five-year groups were significantly different from 2011-2016. In Figure 3.8a, the mean snowfall anomaly for 2011-2016 is -211 mm. The second lowest anomaly (-133 mm) was for the period of 1956-1961, but this five-year group was still significantly different from 2011-2016 (p-value of 0.042). Every other five-year group therefore had significantly more snowfall than the five years of the drought (Figure 3.8b). An example of the five-year group that was significantly different from 2011-2016 may be found at Figure A.5 in Appendix A . The mean mountainous snowfall anomalies also have a similar pattern in oscillation to that of statewide snowfall. Prior to 1980, there is a clear decadal period as well as a large amplitude that ranges from approximately -125mm to 100mm, a range of about 225mm. After 1980, the period of the oscillation is more difficult to distinguish and the amplitude has decreased to only about 100mm. Similar to statewide snowfall, there is a decreasing trend of 13 mm per decade, which is significant. This trend is nearly identical to the trend from the statewide analysis (also -13 mm per decade). Therefore, most of the statewide trend was being influenced by the trend in the mountains.

Monthly analyses for the start and end of the wet season were also performed for the mountainous locations. Figure 3.9 shows the mean snowfall anomalies and p-values during November. In November, the snowfall anomalies do not have as wide of a range as later in the season. For the month of November, the drought years actually had the highest snowfall anomaly (31 mm). Other years with relatively

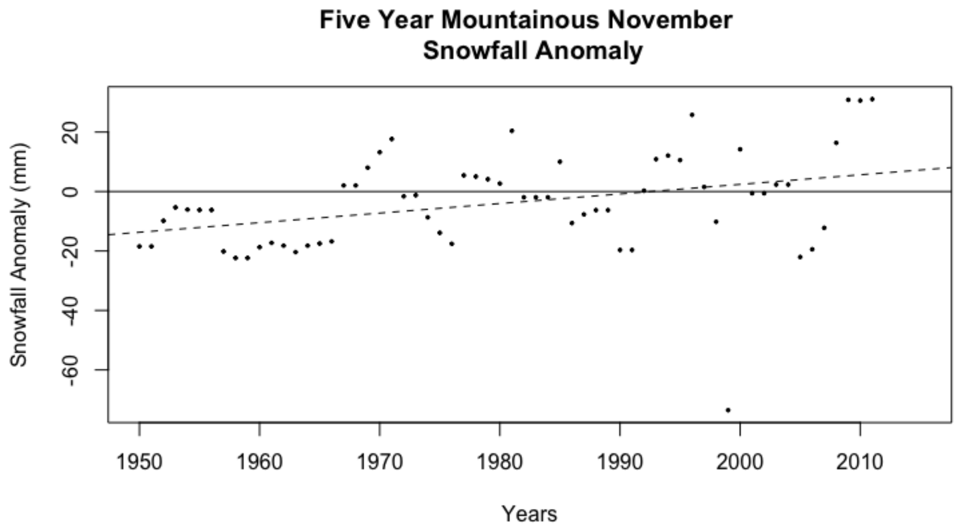


(a) Mountainous snowfall anomaly for all five-year groups

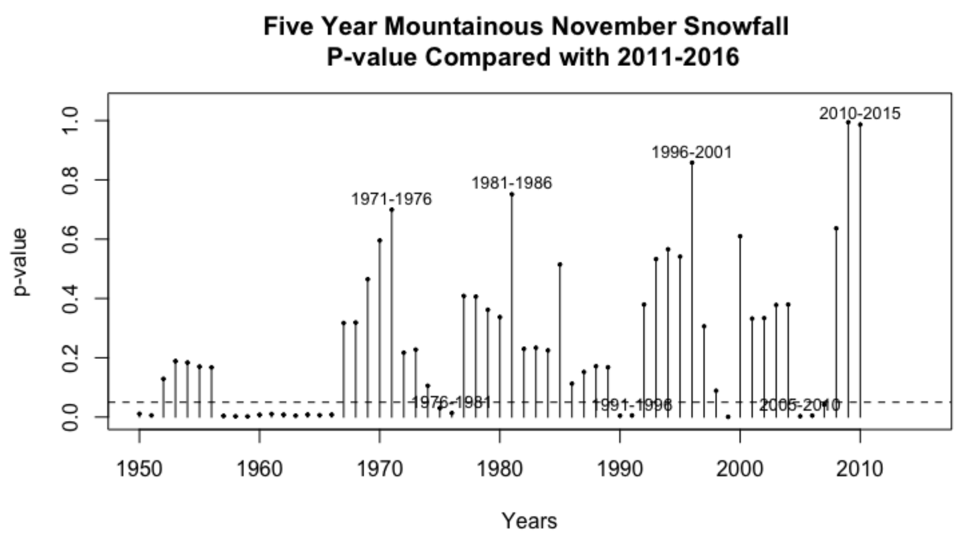


(b) P-value for all five-year groups compared to 2011-2016

Figure 3.8: (a) Mean Mountainous snowfall anomaly (mm) and (b) p-value for all five-year groups for the entire wet season. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.



(a) Mountainous November snowfall anomaly for all five-year groups



(b) P-value for all five-year groups compared to 2011-2016

Figure 3.9: (a) Mean mountainous November snowfall anomaly and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.

large snowfall values include 1971-1976, 1981-1986, 1996-2001, and 2010-2015. The first three of these five-year groups contain a very strong El Niño year (1972-1973, 1982-1983, and 1997-1998, respectively). These five-year groups are all relative maxima in the plot of mean snowfall anomalies. Overall there is a slight oscillation to the data that has a weak increasing trend of +3 mm per decade that was found to be significant. The trend in the mountains throughout the entire wet season of decreasing snowfall is not seen in the month of November; November snowfall has been generally increasing since 1950 with a statistically significant trend, with peak November snowfall occurring in the drought years of 2011-2016. Of the 61 five-year groups, twenty were significantly different from 2011-2016. These twenty groups are distributed throughout all years since 1950, with the most recent time that was significantly different from 2011-2016 occurring in 2006-2011, which had an anomaly of -19 mm. All of the years that are significantly different from 2011-2016 had lower snowfall than the years of the drought. November snowfall may therefore not be a good indicator of snowfall for the entire wet season. As shown in Figure 3.10, November snowfall is not a good indicator for the snowfall over the entire wet season. There is a very weak relationship among all of the data (R-squared value of 0.01) with a regression line of -3 mm/mm, which is not significant. For the years of 2011-2016, although November snowfall was plentiful and the highest on record, this was no indication of what was to occur over the entire wet-season, which had the lowest snowfall anomaly ever recorded.

Figure 3.11 shows the mean snowfall anomaly and p-value in the mountains in April. The snowfall anomaly for 2011-2016 is -283 mm, which is not the lowest for a five-year group. For instance, the snowfall anomaly from 1995-2000 is -286 mm, 1996-2001 is -301 mm, 1998-2003 is -275 mm, and 2000-2005 is -303 mm. The snowfall, however, is low when compared to the five-year groups 2007-2012 through 2010-2015, which all had positive snowfall anomalies. In general since

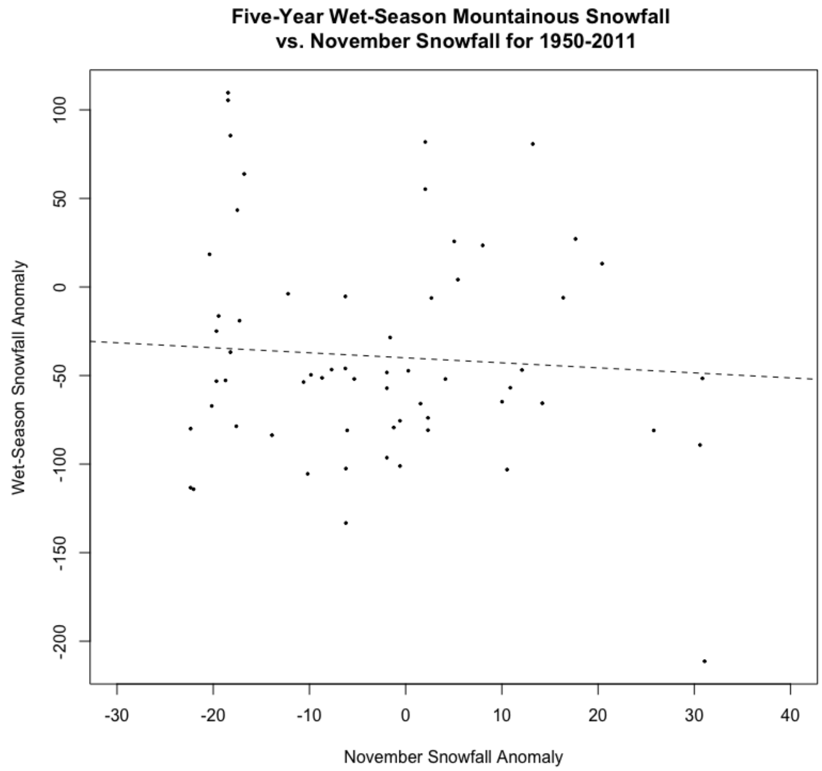


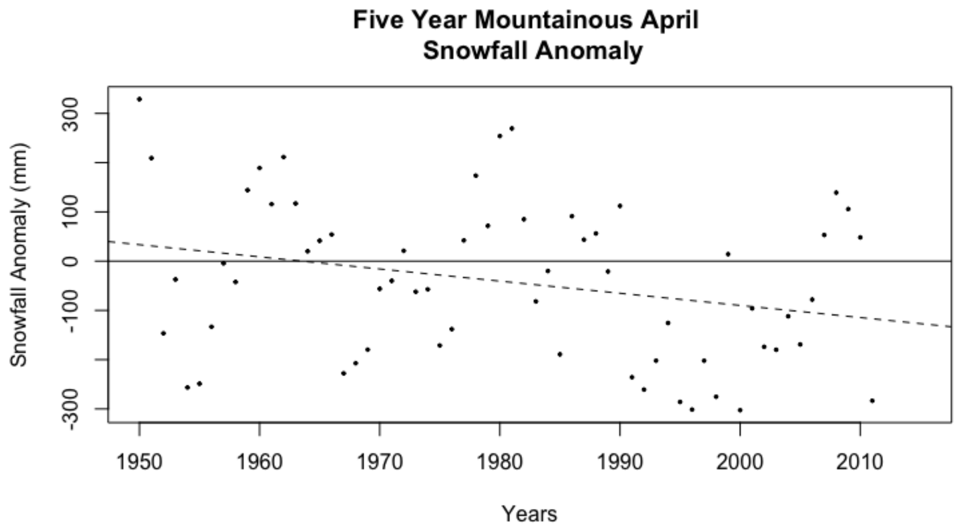
Figure 3.10: Five-year wet-season mountainous snowfall anomalies as a function of five-year November mountainous snowfall anomalies for 1950-2011. Each marker represents the anomalies for a certain five-year group. The dashed line represents the linear trend.

1950, snowfall has been decreasing in April at a rate of -25 mm per decade, which was found to be significant. The distinctive oscillation exhibited in the analysis for the mountains of the entire wet season is not very apparent in the plot for April only. Prior to 1990 though, there appears to be an even dispersal of years with positive and negative snowfall anomalies, but after 1990, only five of the five-year groups have positive anomalies. Overall, Figure 3.11b shows that 25 of the 61 five-year groups were significantly different from 2011-2016. The most recent period significantly different from the drought is 2009-2014, which had a snowfall anomaly of 106 mm. The 25 periods that are significantly different from the years of the drought are well-dispersed throughout the time series beginning in 1950.

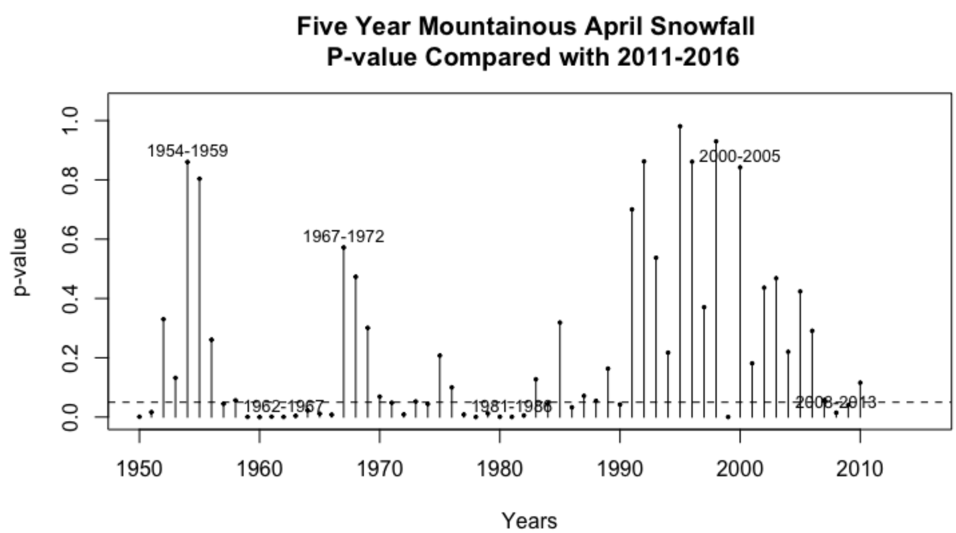
In all of the snowfall analyses, there appears to be a change in the pattern and oscillation of snowfall frequency and intensity that begins around around 1980-1990. Using wavelet analysis, the amplitude and periodicity of oscillations can be determined. Since snowfall in the mountains is the primary variable of interest, wavelet analysis was performed for this data only. All following wavelet analyses use one-year, wet-season mean anomalies rather than the five-year groups. This will offer a better comparison with various teleconnections since the periodicity for teleconnections, especially ENSO, is maximized over one year, so comparison are better made using the mean mountainous snowfall anomaly for one year.

Figure 3.12 shows the wavelet analysis for mountainous snowfall. Figure 3.12a shows the wavelet power averaged across the entire time of analysis (1950-2015). When the entire time series from 1950-2015 is considered, the periods that were found to be significant have a wide range from approximately 2-6 years.

Figure 3.12b shows how the wavelet power changes in both time and frequency from 1950-2015. Throughout most of the time of analysis, the band from 2-6 years is statistically significant while beyond 6 years, there is very little wavelet power. Although the significant region near a period of 8 years from 2015-2015 is outside of the cone of influence, there may be some change in the periodicity occurring at the end of the time series that requires additional investigation. For the 6 year period, this is only significant between 1970-1980 and after 1980, the significant periods exist between 2-4 years. Looking back to Figure 3.8a, the change in the periodicity that occurs around 1980 stands out. Prior to 1980, there is a distinctive relatively long-term, decadal period while after about 1990, it is harder to distinguish a clear dominant period. Although this wavelet analysis is useful in distinguishing the actual periodicity of the mountainous snowfall data as well as the changes in the

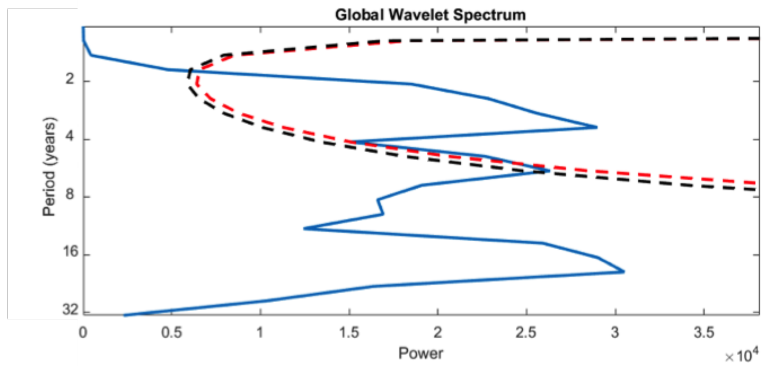


(a) Mountainous April snowfall anomaly for all five-year groups

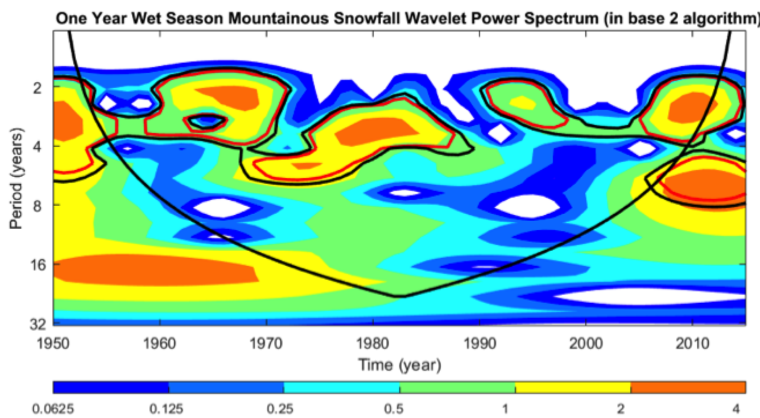


(b) P-value for all five-year groups compared to 2011-2016

Figure 3.11: (a) Mean mountainous April snowfall anomaly and (b) p-value for all five-year groups. The dashed line in (a) represents the linear trend. The dashed line in (b) represents the 0.05 threshold.



(a) The red dash is significant at $\alpha = 0.05$ and the black dash is significant at $\alpha = 0.10$.



(b) The red outline represents the 95% confidence interval and the black outline represents the 90% confidence interval. The shading within the cone outlined by the black line represents the region of interest. Warm colors correspond to high power while cool colors correspond to low power.

Figure 3.12: (a) Average wavelet power from 1950 until 2016 and (b) wavelet analysis for 1950 until 2015 for mountainous snowfall.

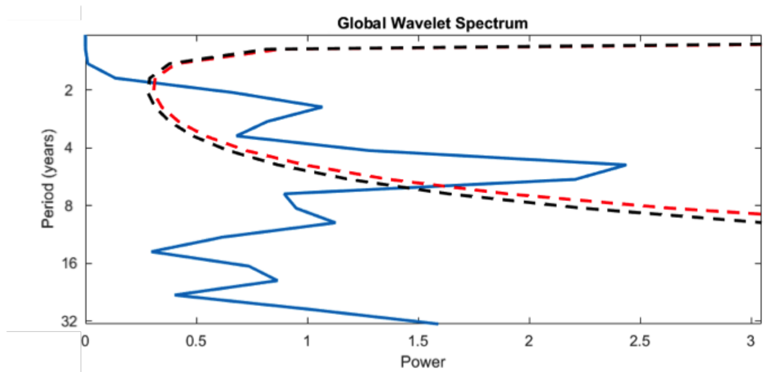
periodicity throughout time, this does not offer any explanation of what may be causing this periodicity. Wavelet coherence with the PDO and ENSO (discussed later) may offer some additional insight into the causes of this periodicity.

3.3 Teleconnection Patterns

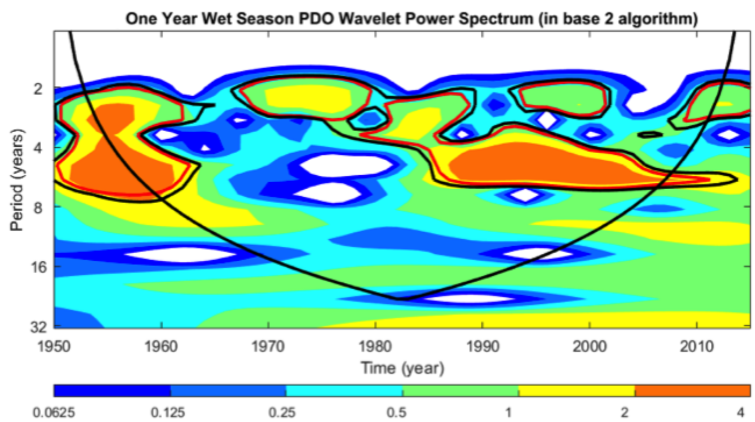
To see how oscillation and periodicity in the snowfall analysis compares to well-known teleconnection patterns, such as the PDO and ENSO, further wavelet analyses were performed. Figure 3.13 shows a similar wavelet analysis for the PDO index as was performed for snowfall. The average annual PDO was calculated for the months of the wet season only so that the same months and time periods are considered to compare with snowfall. Figure 3.13a shows the average power for the PDO averaged across all time. The period of 2-7 years has an average wavelet power ranging from 0.5-2.5, which is significant at $\alpha = 0.05$. The period at which the PDO was found to be significant closely match the results of MacDonald and Case (2005) for the shorter period, who found significant power from 50-70 years as well as 4-7 years.

Figure 3.13b shows how the wavelet power varies over time and at different frequencies. For the time period of interest, the strongest signal between 1950-2015 has a period of 2-7 years. Between 1960-1980, the shorter periods of approximately 2-3 years are significant while after 1980, longer periods, namely 4-7 years, become significant. This switch that occurs around 1980 also appears in the snowfall analysis.

ENSO was also analyzed to see how this teleconnection compares with the snowfall periodicity. Similar to the PDO, indices were only used from November through April and the average was calculated for each wet season. Figure 3.14a shows that on average, a period of approximately 2-6 years is significant with an average power of 0.4-1.4. While a secondary maximum in power occurs around 12



(a) The red dash is significant at $\alpha = 0.05$ and the black dash is significant at $\alpha = 0.10$.



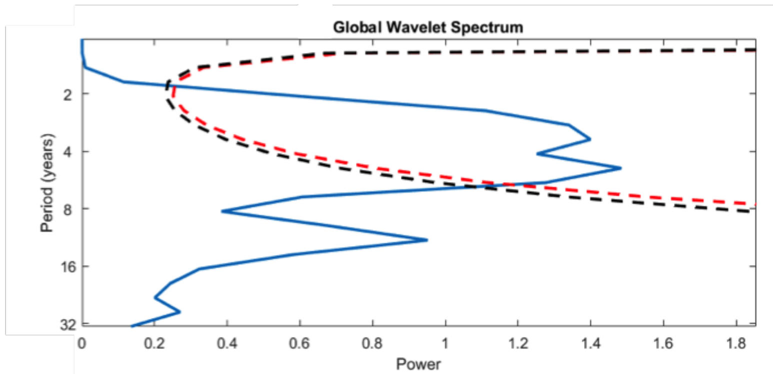
(b) The red outline represents the 95% confidence interval and the black outline represents the 90% confidence interval. The shading within the cone outlined by the black line represents the region of interest. Warm colors correspond to high power while cool colors correspond to low power.

Figure 3.13: (a) Average wavelet power from 1950 until 2016 and (b) wavelet analysis for 1950 until 2015 for the PDO.

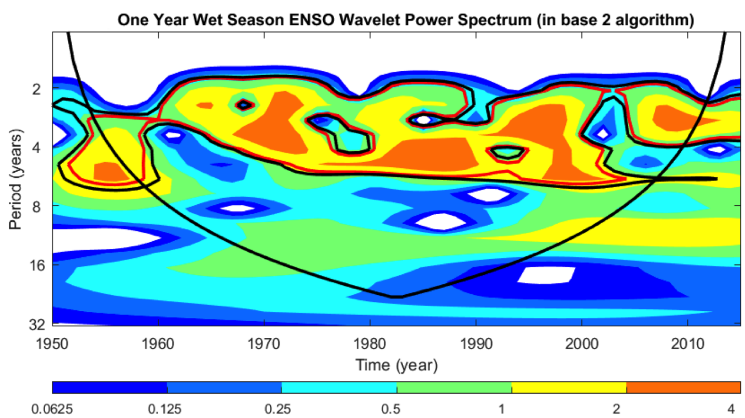
years, it is not significant when averaged over the entire time period. Figure 3.14b shows the wavelet analysis for the entire time series and at all frequencies. From 1950-2015 , there is strong power within the range of 2-6 years for all times.

In order to really grasp how the time series of mountainous snowfall is related to the PDO and ENSO, wavelet coherence was analyzed. Contemporaneous correlation between snowfall and the PDO (-0.146), and snowfall and ENSO (-0.032) are both weak. Coherence, however, is better utilized in wavelet analyses to describe the relationship between two variables at different periods and times in the analysis. A coherence value of 1.0 implies a strong relationship while a value of 0 implies no relationship. Since the correlation between these variables is so weak, the degrees of freedom was not reduced and the figures for coherence that show what periods are statistically significant do not need to be adjusted by changing the degrees of freedom. For instance, the coherence between one-year wet-season mountainous snowfall anomalies and the PDO is shown in Figure 3.15. Averaging across all times, Figure 3.15a shows that at the 95% confidence interval, the coherence is significant at four different periods: 3-4 years, 6 years, 20-25 years, and 30 years. The average coherence at all periods is greater than 0.9, which implies a strong relationship between mountainous snowfall and the PDO. Figure 3.15b shows how the coherence varies with time and frequency. Between years 1950 and 1970, there is strong coherence with a value of 1.0 at a period of approximately 20-30 years. Near the end of the time of analysis (Year 2015, time 85), the two time series have strong coherence at multiple periods (4-8 years, 16 years, and 32 years). Overall, the coherence is very strong for all years and periods, but only small pockets are considered significant.

Additionally, Figure 3.15b can be used to determine when snowfall and the PDO are and are not in phase, as well as which variable is leading. Within the 95% confidence interval that is outlined by the white line, the black arrows show



(a) The red dash is significant at $\alpha = 0.05$ and the black dash is significant at $\alpha = 0.10$.

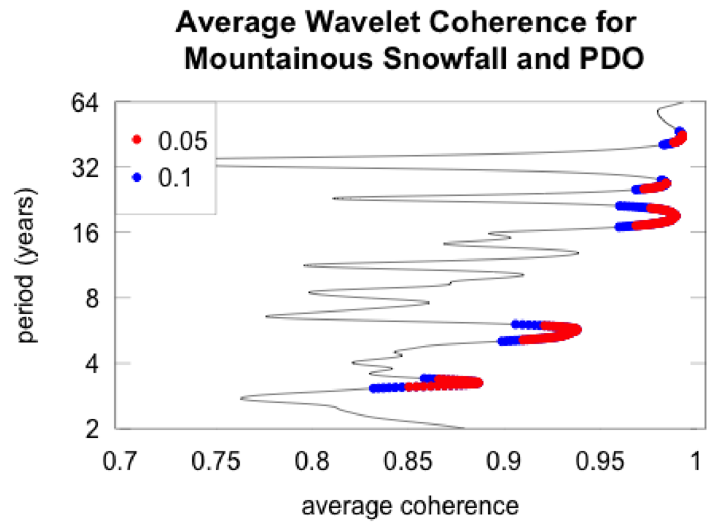


(b) The red outline represents the 95% confidence interval and the black outline represents the 90% confidence interval. The shading within the cone outlined by the black line represents the region of interest. Warm colors correspond to high power while cool colors correspond to low power..

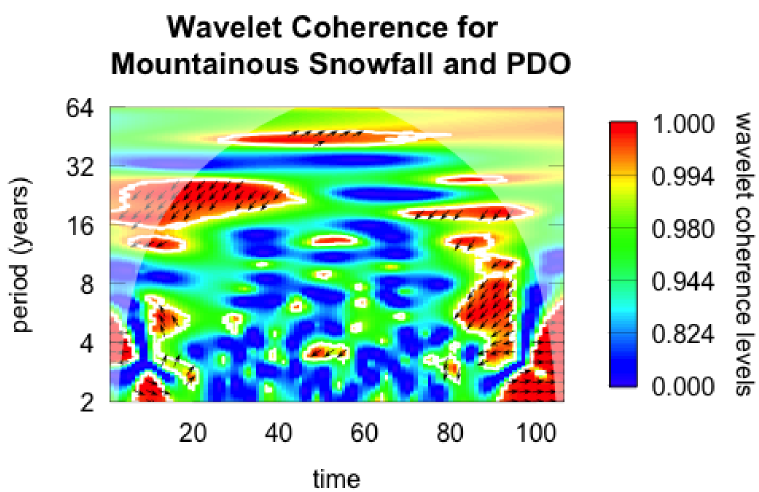
Figure 3.14: (a) Average wavelet power from 1950 until 2016 and (b) wavelet analysis for 1950 until 2015 for ENSO.

phase. When the arrows point to the right, the two variables are in phase and when the arrows point to the left, the variables are out of phase (antiphase). Also, when the arrows point to the right-up or left-down, snowfall leads. When the arrows point to the right-down or left-up, PDO leads. For the coherence analysis between snowfall and the PDO, the arrows are nearly always pointing to the left-down in all the areas of significance. This means that snowfall leads the PDO in its phase and since the arrows are to the left, the two variables are antiphase.

The same coherence analysis was performed for one-year wet-season snowfall and ENSO, as shown in Figure 3.16. Overall, the coherence values are above 0.9 for most of the time of analysis. The average coherence across all times is significant at many different periods, especially between 2-4 years, 6 years, and a majority of the range from 12-32 years (Figure 3.16a). These periods are not significant at all times in the analysis, as shown by Figure 3.16b. While there are several small pockets of significance between periods of 2 and 8 years for the entire time of analysis, the larger areas of significance occur at longer periods, specifically periods between 16 and 32 years. Near the very end of the time of analysis around year 2015 (time 85), nearly all periods between 6 and 32 year are significant. Also, the arrows in Figure 3.16b are primarily pointed downward and slightly to the left, implying that snowfall is the lead variable and snowfall and ENSO are antiphase.

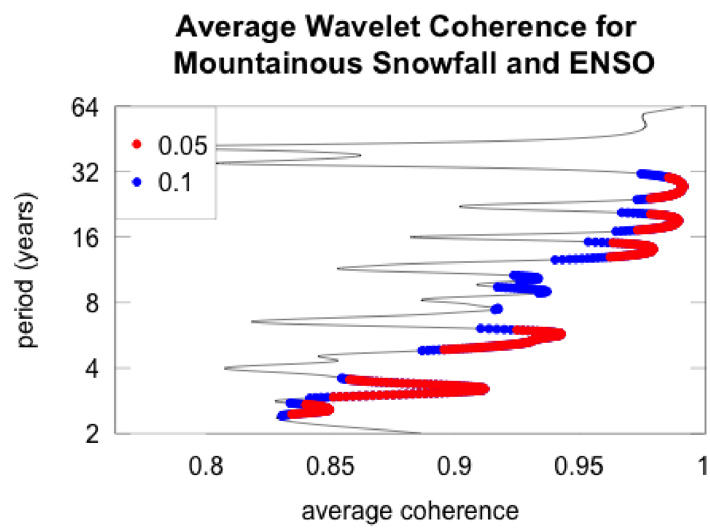


(a) The red shading is significant at $\alpha = 0.05$ and the blue shading is significant at $\alpha = 0.10$.

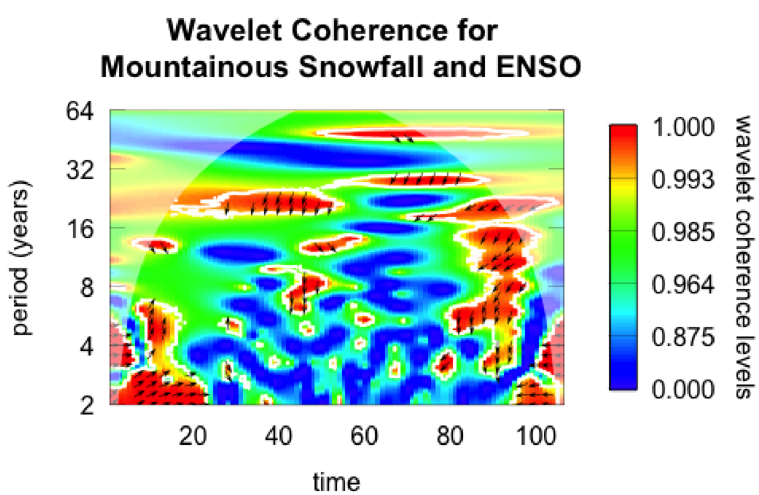


(b) The white outline represents the 95% confidence interval. Warm colors correspond to high coherence while cool colors correspond to low coherence. The muted, cone-shaped area shows where edge effects become important. The arrows describe which variable is leading.

Figure 3.15: (a) Average coherence for one-year snowfall and the PDO from 1950-2015 and (b) coherence analysis from 1950 (time 20) until 2015 (time 85).



(a) The red shading is significant at $\alpha = 0.05$ and the blue shading is significant at $\alpha = 0.10$.



(b) The white outline represents the 95% confidence interval. Warm colors correspond to high coherence while cool colors correspond to low coherence. The muted, cone-shaped area shows where edge effects become important. The arrows describe which variable is leading.

Figure 3.16: (a) Average coherence for one-year snowfall and ENSO from 1950-2015 and (b) coherence analysis from 1950 (time 20) until 2015 (time 85).

Chapter 4

Conclusions

Several of the results discussed above agree with and enhance findings of previously research. During the California drought of 2011-2016, precipitation was the the third lowest five-year group since 1950. The drought can therefore be characterized by low, but not record-breaking, precipitation across a five-year period during the months of November through April. As several other studies mention, the California drought may be termed a heat drought, meaning that relatively low precipitation is exacerbated by warm temperatures. The five-year mean maximum temperature during the California drought was the warmest on record and significantly different from all but two other five-year groups. These findings are in agreement with many other studies that found precipitation was near record low for one year or a range of years during the drought, but temperature was a record high. The results posed in this study expand the analysis and understanding of the drought through through 2016. It was also found that there is an increasing trend in statewide mean maximum temperature of +0.07°C per decade while mean minimum temperature has been increasing at a rate of +0.1°C per decade, both of which are significant. Statewide minimum temperature has therefore been increasing approximately 1.5 times as quickly as the maximum temperature. This result is different from the results found by Mao et al. (2015) in that they only found minimum temperature to have a statistically significant increasing trend for 1920-2014. For the results of this study, both maximum and minimum temperature have significant increasing trends from 1950-2016, but the rate at which minimum temperature has been increasing is greater than maximum temperature, which agrees with patterns found in previous studies.

The most unique finding of this study is that the five years of 2011-2016 has significantly less snowfall in the Sierra Nevada mountains that is nearly twice as low as any other five-year period since 1950. As mentioned in Section 1.3, snowfall and the associated building of snowpack that melts in the springtime fills the state's reservoirs to be used during the dry months of May through October. Without enough snowfall and the associated runoff, California had to put drastic, restrictive measures in place on the little water available during the drought. However when the snowfall data in the mountains was separated by month, neither November or April exhibited the same drastic decrease in snowfall for 2011-2016 when compared to all other five-year groups. Particularly in November for 2011-2016, the snowfall anomaly in the mountains was the highest recorded since 1950, so November snowfall cannot be used as a good predictor of snowfall for the entire wet season in the Sierra Nevada mountains of California.

The analysis for snowfall also exhibited a clear oscillation that appeared to have an approximate decadal frequency. Through the use of wavelet analysis, it was found that one-year mountainous snowfall has a statistically significant frequency of approximately 16 years and also exhibits high power in the range of 2-4 years. It was suspected that the higher frequency may be due to ENSO, but to begin to understand the potential cause of the long-term period, a wavelet analysis was also performed for the one-year, wet-season average of the PDO from 1950-2016. The PDO was found to have significant periods of 5-7 years as well as a longer term period of 32+ years. While this is not the same significant period found in the snowfall data, the PDO does have a local maximum in wavelet power around

16 years. To understand the relation between the two time series of snowfall and the PDO, wavelet coherence was also performed and determined that the average coherence is quite high, greater than 0.9, and several periods have a statistically significant coherence, including the 16 year period. These results indicate that the relation between snowfall and the PDO is very strong and that the two variables are out of phase.

Since snowfall also had a significant period of 2-4 years, it was expected that this could be attributed to ENSO, so wavelet analysis for the average one-year ENSO index for wet season was calculated to compare with snowfall. ENSO had the most power in the range of 3-4 years, which was also statistically significant. After performing a wavelet coherence analysis between one-year, wet-season mountainous snowfall and ENSO, the average coherence was greater than 0.9 and the period of 2-4 was significant between these two time series, as expected. Other periods, however, were also found to be significant between these variables (6 years and 12-32 years). Other studies have shown that ENSO has a period of 2-7 years, but the strong relation between snowfall and ENSO at longer periods was unexpected for this shorter-term teleconnection. Since the coherence between snowfall and the PDO was also significant for a period of 3-4 years, it remains to be seen what the combined effect of these two teleconnections may have on the periodicity of snowfall in the Sierra Nevada Mountains.

This study highlights many of the important features of the 2011-2016 California drought with respect to changes in statewide maximum and minimum temperature, precipitation, and snowfall, as well as snowfall in the mountains and the relation of snowfall with ENSO and the PDO. It remains to be determined what the primary causes are of these extreme anomalies in temperature and specifically mountainous snowfall during these five years. Previous studies have analyzed geopotential height anomalies during the drought and the effect the presence of an intense and prolonged ridge situated over the Pacific has had on the drought (Swain et al., 2014; Wang et al., 2014; Seager et al., 2015). Additionally, many studies have hypothesized how normal droughts of this magnitude may become with a warming climate and important role of temperature in the future (Neelin et al., 2013; Cayan et al., 2010; Rauscher et al., 2008; Barnett et al., 2005). Expanding on the work in this study to better understand the mechanisms determining plentiful versus low snowfall years needs to be investigated. These mechanisms may include specific interactions of teleconnection patterns, the presence of ridges and troughs, or the prevalence of atmospheric rivers (Dettinger, 2013).

Some of the limitations for the data used include a limited time of analysis due to data (especially snowfall) sparsity prior to 1950 as well as numerous large gaps from 1950-present. There are other datasets available that may help to fill in these gaps in the more recent decades (such as the Snow Telemetry (SNOTEL) network). These stations are also located around the mountain watersheds and may therefore be more useful in assessing the impact of snowfall on the snowpack that builds and subsequently melts into nearby reservoirs. As mentioned by LaDochy et al. (2007), since the PDO has a relatively long period, there are not many cycles completed for the time period of interest. While this is a shortcoming in using the PDO, little can be done to obtain more data. Additionally, while snowfall provides one look at the amount of winter precipitation falling, analyzing other variables such as snow depth and snow-water equivalent would offer a more direct comparison to other studies regarding wintertime precipitation in the Sierra Nevada Mountains. For instance, NCEI has data for snow depth as well as snow-water equivalent, so the next step would be to analyze these variables to see how the five years of drought compare to other periods in California's history.

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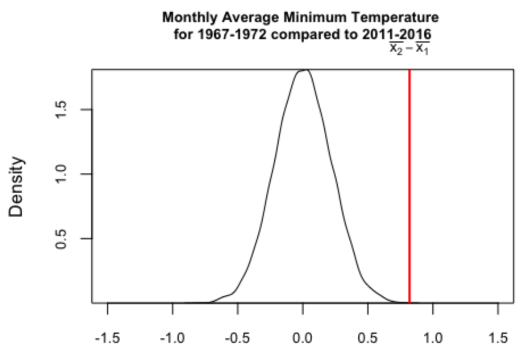
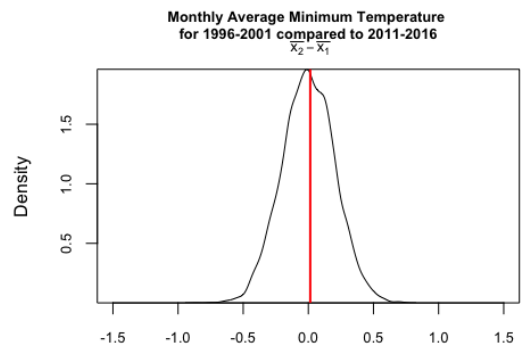
Appendices

Appendix A

Further Examples of Permutation Tests

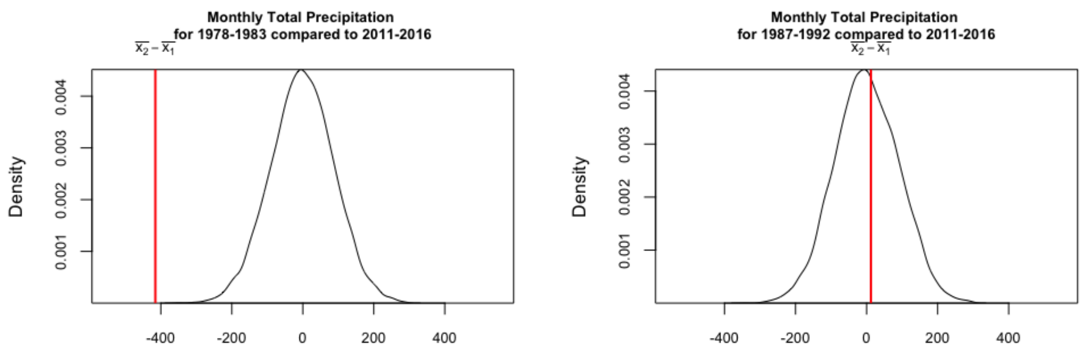


(a) 1967-1972 is significantly different from 2011-2016



(b) 1996-2001 is not significantly different from 2011-2016

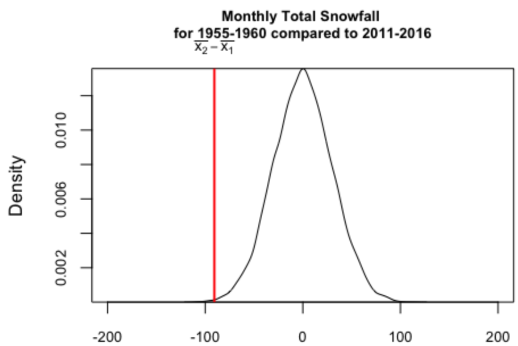
Figure A.1: Examples from the permutation tests of statewide minimum temperature. The vertical red line indicates the difference of the means of the two periods while the black, bell-shaped curve represents the difference of the means from the permutations of the data



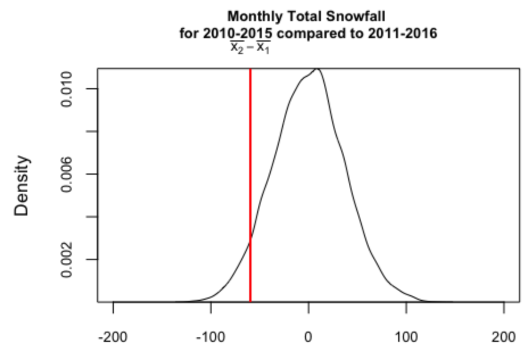
(a) 1978-1983 is significantly different from 2011-2016

(b) 1987-1992 is not significantly different from 2011-2016

Figure A.2: Examples from the permutation tests of statewide precipitation. The vertical red line indicates the difference of the means of the two periods while the black, bell-shaped curve represents the difference of the means from the permutations of the data



(a) 1955-1960 is significantly different from 2011-2016



(b) 2010-2015 is not significantly different from 2011-2016

Figure A.3: Examples from the permutation tests of statewide snowfall. The vertical red line indicates the difference of the means of the two periods while the black, bell-shaped curve represents the difference of the means from the permutations of the data

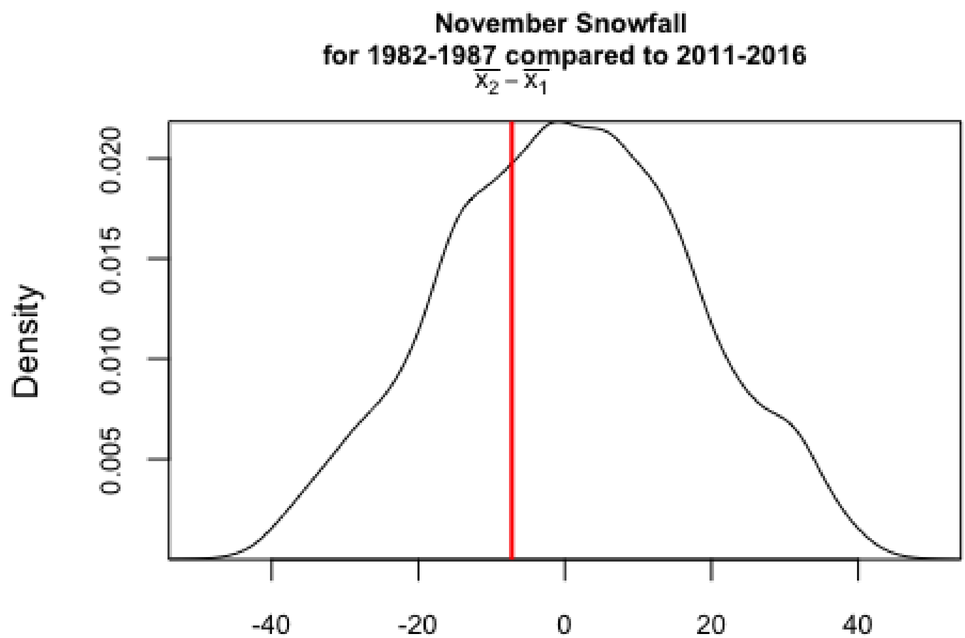


Figure A.4: Example from the permutation tests of statewide November snowfall. The years 1982-1987 were not significantly different from 2011-2016.

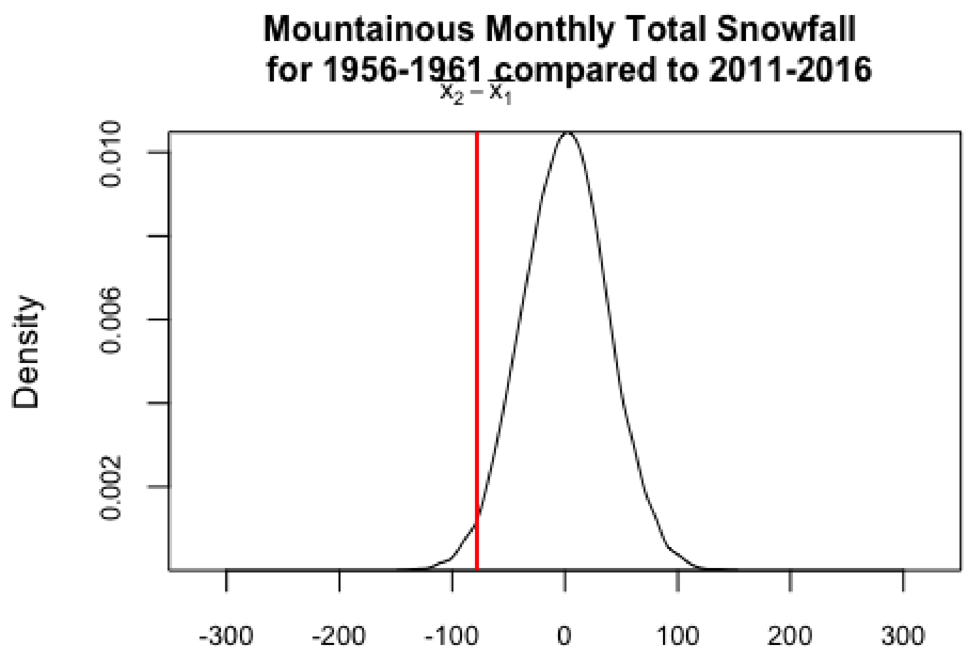


Figure A.5: Example from the permutation tests of mountainous snowfall during the wet season. The years 1956-1961 were significantly different from 2011-2016. All five-year groups were significantly different from 2011-2016. The vertical red line indicates the difference of the means of the two periods while the black, bell-shaped curve represents the difference of the means from the permutations of the data

Appendix B

Wavelet Analysis for Temperature and Precipitation

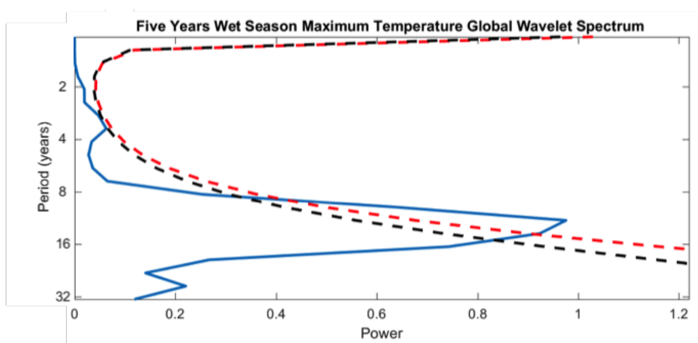


Figure B.1: Average wavelet power for the five-year groups of statewide maximum temperature. The red dash is significant at alpha=0.05 and the black dash is significant at alpha=0.10

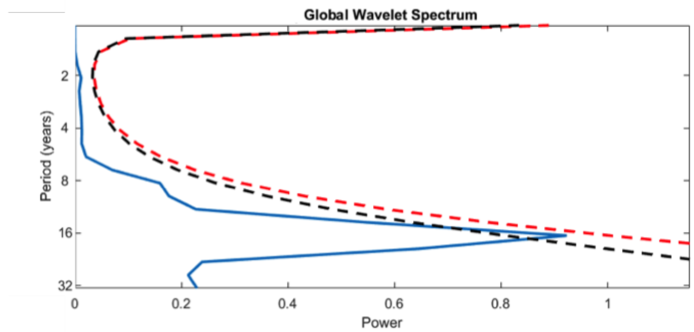


Figure B.2: Average wavelet power for the five-year groups of statewide minimum temperature. The red dash is significant at alpha=0.05 and the black dash is significant at alpha=0.10

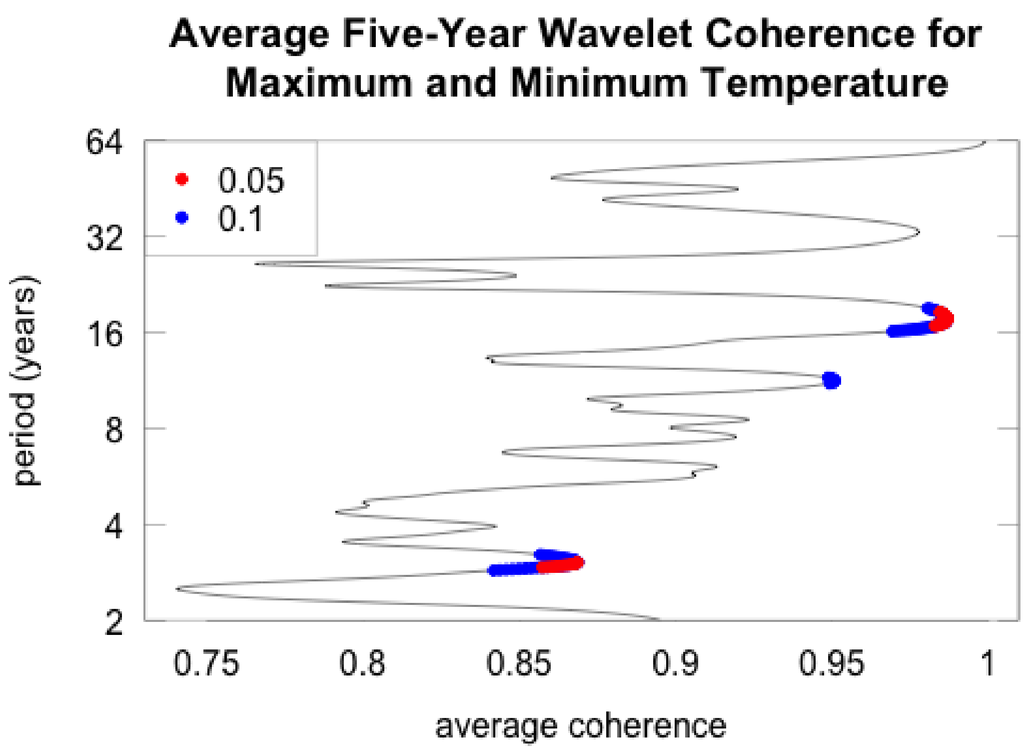


Figure B.3: Average wavelet coherence for the five-year groups of statewide maximum temperature and minimum temperature. The red shading is significant at alpha=0.05 and the blue shading is significant at alpha=0.10.

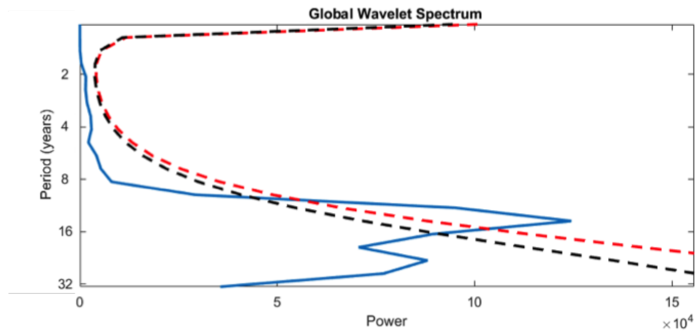


Figure B.4: Average wavelet power for the five-year groups of statewide precipitation. The red dash is significant at alpha=0.05 and the black dash is significant at alpha=0.10

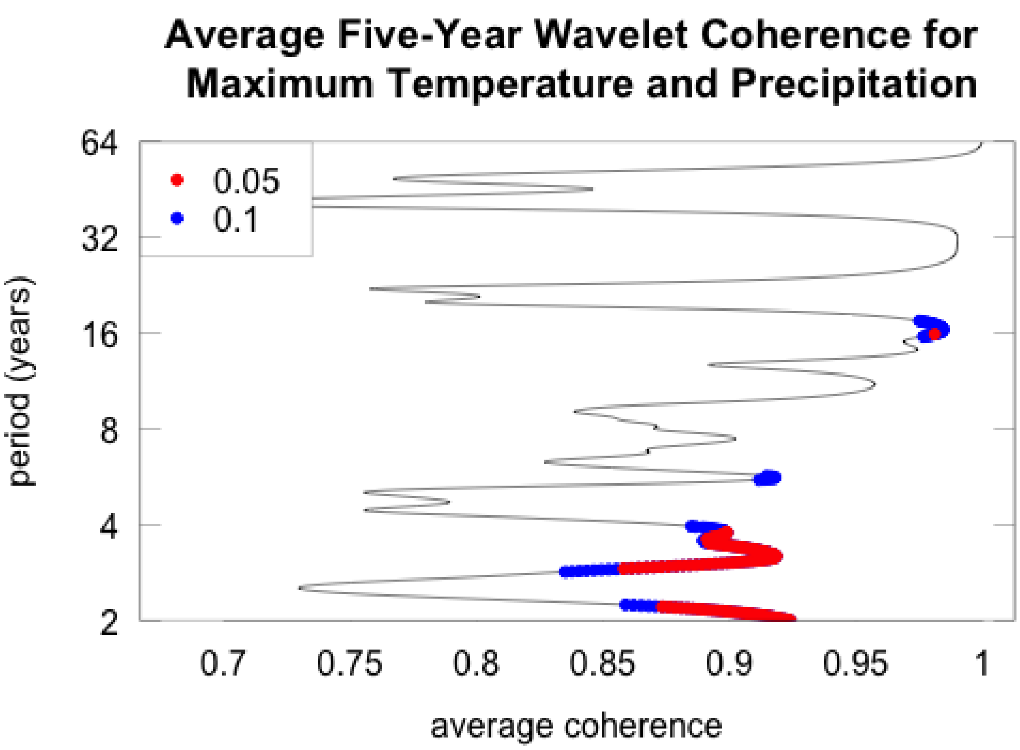


Figure B.5: Average wavelet coherence for the five-year groups of statewide maximum temperature and precipitation. The red shading is significant at alpha=0.05 and the blue shading is significant at alpha=0.10.

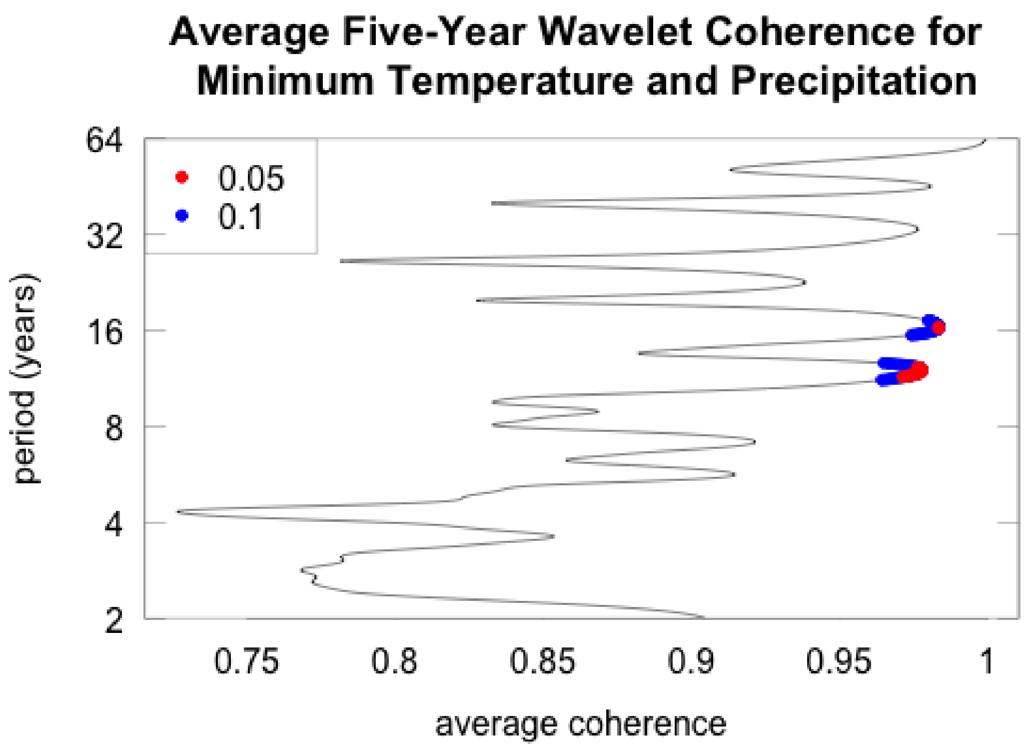


Figure B.6: Average wavelet coherence for the five-year groups of statewide minimum temperature and precipitation. The red shading is significant at alpha=0.05 and the blue shading is significant at alpha=0.10.