OBSERVED TEMPERATURE AND PRECIPITATION RELATIONSHIP ACROSS THE UNITED STATES ANALYZED AT DIFFERENT TIMESCALES

An Undergraduate Research Scholars Thesis

by

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Approved by
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TABLE OF CONTENTS

CHAPTER

ABSTRACT

Observed Temperature and Precipitation Relationship Across the United States Analyzed at Different Timescales. (May 2015)

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Recently, the National Climatic Data Center released the nClimDiv dataset, which is the most consistent for the contiguous United States to date. The data set includes monthly averages of precipitation, maximum temperature, minimum temperature, and mean temperature data from 1895 to present. The data is available for geographic regions as well as nationally. Our research focuses on the regional dataset. We analyze the correlation and slope of average monthly maximum and minimum temperature at the inter-annual and decadal timescale in each season to determine which temperature variable has the strongest relationship with precipitation. Results from the selected regions and seasons show a warming trend in most regions of the United States at the decadal timescale, especially since the turn of the century. The "Warming Hole" in the southeast region results in net decreases in temperature from the first decadal period of the data set to the present; however, increases in temperatures over the past two decadal periods suggest this trend will reverse in the future. Precipitation levels seen in each region also affect the magnitude of warming or cooling seen in each region at the inter-annual and decadal timescale.

ACKNOWLEDGEMENTS

I would like to thank my research advisor, Dr. Nielsen-Gammon, for his wisdom and patience with me throughout the development of my thesis. You have taught me invaluable techniques and skills necessary for quality data analysis, which will be beneficial for me in my future endeavors.

CHAPTER I

INTRODUCTION

Earth has experienced a rise in surface temperature since the early 20th century, with the land surface global mean temperature increasing by 0.76°C over a 105 year period starting in 1901 (Solomon et al., 2007). From the 1970's to the early 2000's, an increase in the global mean surface temperature of 0.2°C each decade has been observed; however, these changes vary over space and time (Zhang et al., 2013). Additionally, an increase in extreme precipitation events has been observed globally in recent time, indicating that global warming may accelerate the hydrological cycle.

All aspects of temperature are not changing at the same rate. For example, in China, nighttime temperatures have experienced the most rapid rate of increase (Zhang et al., 2013). This has also been observed in the United States, with a -0.05°C decade^{-1} change between summer maximum and minimum temperatures as well as a similar decrease in the winter months (Pan et al., 2013). In the United States, studies have shown that overall the contiguous 48 states have experienced overall surface warming; however, observations of the annual mean temperature have shown that the western United States has warmed at faster rate than the eastern United States. In fact, a "warming hole" has been observed in the southeastern United States, where annual-mean surface temperatures have decreased by as much as 2°C in the twentieth century alone (Meehl et al., 2012).

In Texas, summertime average temperature has a strong negative correlation with precipitation. That is, temperature values are higher when precipitation values are lower. This is due to known physical relationships between temperature and moisture. However, apparently due to climate change, there has been an upward shift in temperature values by 1-2°C, much larger than what would normally be associated with precipitation changes during the same period (Hoerling et. al, 2013).

Since this is happening in Texas, we investigate whether these temperature increases are occurring in other regions of the United States. Our research studies the relationship between precipitation and temperature across the United States dating from 1895 to the present year. We explore whether temperature changes have been affected in regions by the relationship to precipitation and if temperature changes occur independent of this relationship. This will provide future researchers pertinent information to compare with various climate models to more accurately forecast future climate conditions for the United States as well as determine what specifically has been affecting the relationship between temperature and precipitation.

CHAPTER II

DATA AND METHODS

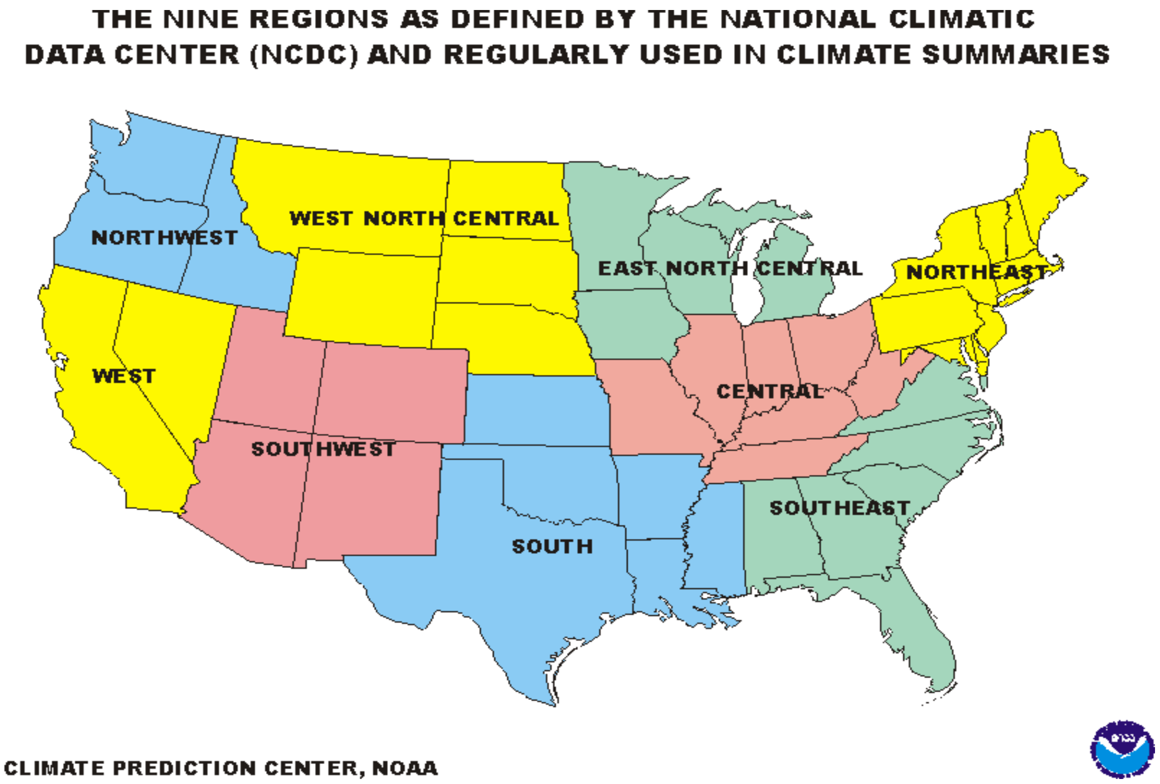

Figure 1. Map of the nine different regions we use for data collection and analysis.

This project uses the nClimDiv dataset from the The National Climatic Data Center (NCDC) as its source. The nClimDiv data set uses Global Historical Climatology Network-Daily Observations and is the most up-to-date dataset for long-term climate analysis in the United States (NOAA, 2014). The old dataset computed data for each region using the average of the data from stations within it for data past 1931, which creates a bias in the data because it does not account for under-sampled areas. For data prior to 1931, all regional values were calculated from statewide values published by the United States Department of Agriculture (Fenimore et. al, 2011). Now, the data set uses more historical temperature and precipitation data, especially dating before 1930, from more stations as well as new methods and computation techniques. (NOAA, 2014) The nClimDiv dataset transitioned from using a station-based to a grid-based approach for data calculation. (Fenimore et. al, 2011). Also, the nClimDiv dataset uses "quality control algorithms" from the NCDC (NOAA, 2014). Both of these new computation techniques improve the accuracy of the dataset used in this research paper.

First, we convert average monthly precipitation, in inches, to average daily precipitation (ADP), in millimeters. Also, we convert temperature from degrees Fahrenheit to degrees Celsius. To identify which range of months has the strongest signal in each region, we compute the correlation and slope for ADP with average monthly maximum temperature (AMMAXT) and average monthly minimum temperature (AMMINT) for every possible consecutive range of months in the calendar from a one-month period to a six-month period. The calculations include the full (inter-annual) timescale as well as the decadal time scale. Next, we identify which seasons and regions that have the relationship between temperature and precipitation closely relate to the inter-annual timescale. We then identify the departures from the inter-annual relationship of temperature and precipitation at the decadal timescale to estimate the magnitude of temperature changes that have taken place independent of the relationship from 1895 to 2014.

The temperature and precipitation relationships tend to show several common patterns at the decadal and inter-annual timescales. To investigate these differences, we select and analyze five separate cases from various regions of the United States. This serves as a suitable number to show how various differences in the data characterize the temperature and precipitation relationship. Also, the use of five cases permits the analysis of multiple regions to show how temperature and precipitation relationships vary across the contiguous United States. The first case shows high correlations at the inter-annual and decadal timescale, as well as a large absolute slope difference. The second case possesses a high correlation at the inter-annual timescale, but a low correlation at the decadal time-scale. The third case shows a large slope difference between the inter-annual and the decadal timescales. The fourth case displays high correlations at the inter-annual and decadal time scale, but the slopes of the inter-annual and decadal timescales are similar. In other words, their slope difference is close to zero. The fifth case holds a negative inter-annual slope and a positive decadal slope.

Then, we implement a first order control for precipitation for each chosen case region and its range of months across the full timescale, using equation (1). P' is the difference between the year of observation's precipitation value and the average over the full timescale. T stands for the year of observation's temperature and **Δ**T and **Δ**P stand for the change of temperature and precipitation from year to year. The ratio is averaged over the period of record. We remove **Δ**P values that are close to zero from year to year from the calculation to eliminate values that skew the data results for the first order control. We use this as supplemental information for the selections of the five cases.

$$T - \left(\overline{\frac{\Delta T}{\Delta P}}\right) P' = T_{no\ P} \ (1)$$

To confirm the existence of the “warming hole” in the Southeastern United States, we then select a time frame and analyze the temperature and precipitation relationship in this region at the decadal and inter-annual time scale. We also perform the same analysis in two states, Alabama and Georgia, within the region. The existence of a consistent pattern between the regional and state level at the decadal time scale will confirm that the conclusions apply locally as well as regionally.

CHAPTER III

RESULTS

A. Overview

We choose five separate regional periods that best fit each case to analyze where a strong signal for departures from the inter-annual relationship of temperature and precipitation exist. All of the regions selections compare AMMAXT with ADP.

Inter-annual	Region	JJA correlation	JJA slope	DJF correlation	DJF slope
	Southwest	-0.6	-1.96	0.16	0.69
	West	-0.57	-3.2	0.4	0.62
	Central	-0.66	-1.34	0.37	1.19
	Northeast	-0.37	-0.58	0.19	0.70
	Southeast	-0.64	-0.63	0.08	0.17
Decadal	Region	JJA correlation	JJA slope	DJF correlation	DJF slope
	Southwest	-0.47	-3.00	0.37	2.05
	West	-0.47	-4.72	0.36	0.61
	Central	-0.52	-2.77	0.58	2.95
	Northeast	0.27	0.41	0.13	0.87
	Southeast	-0.03	-0.05	-0.62	-2.72

Table 1. Summertime June, July, and August (JJA) and wintertime December, January, and February (DJF) correlations and slopes for selected regions. Summertime ADP is correlated with AMMAXT and Wintertime ADP is correlated with AMMINT.

Table 1 illustrates the negative relationship between temperature and precipitation in all case selections at the inter-annual timescale. That is, if ADP increases, then AMMAXT decreases. However, the Northeast is the only one of the selected regions that possesses a positive relationship at the decadal timescale in the summer months. Additionally, all of the wintertime correlations and slopes are positive at the inter-annual timescale; however, the strength of the correlation is weaker than during the summer months. At the decadal timescale, the Southeast region is the only region that deviates from the positive relationship between temperature and precipitation in wintertime. That is, temperatures increase as precipitation increases at the inter-annual timescale; however, temperatures increase as precipitation decreases at the decadal timescale. The following selections look at monthly time frames during the warm half of the year. The selected regional periods possess similar relationships to the correlation and slope values observed for the summer months.

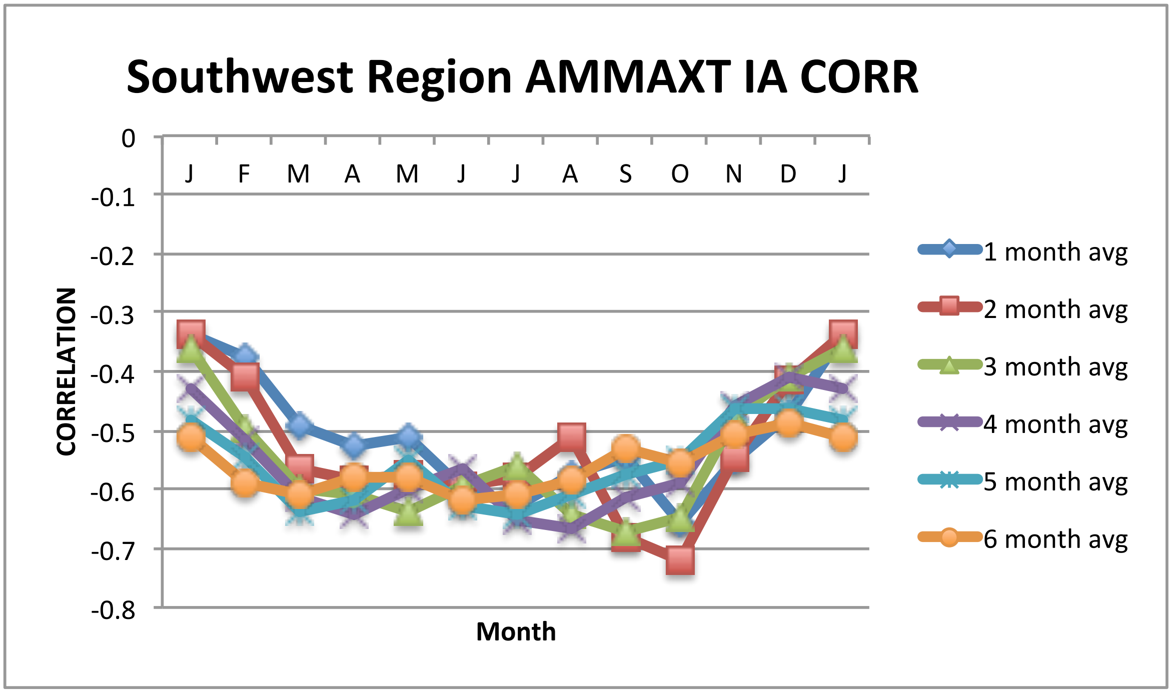

Figure 3. Southwest Region AMMAXT and ADP correlation at the inter-annual timescale. Months are labeled with their respective beginning letter and go in chronological order. Data points beginning at each month for each series represent the beginning month for the calculation. For example, the green triangle for May, with a correlation of roughly -0.65, calculates the correlation for the time period of May, June, and July.

Figure 3 displays the computation technique used to make our regional case selections. This calculation was done for each region of the contiguous United States at the inter-annual and decadal timescale.

B. The Southwest Region

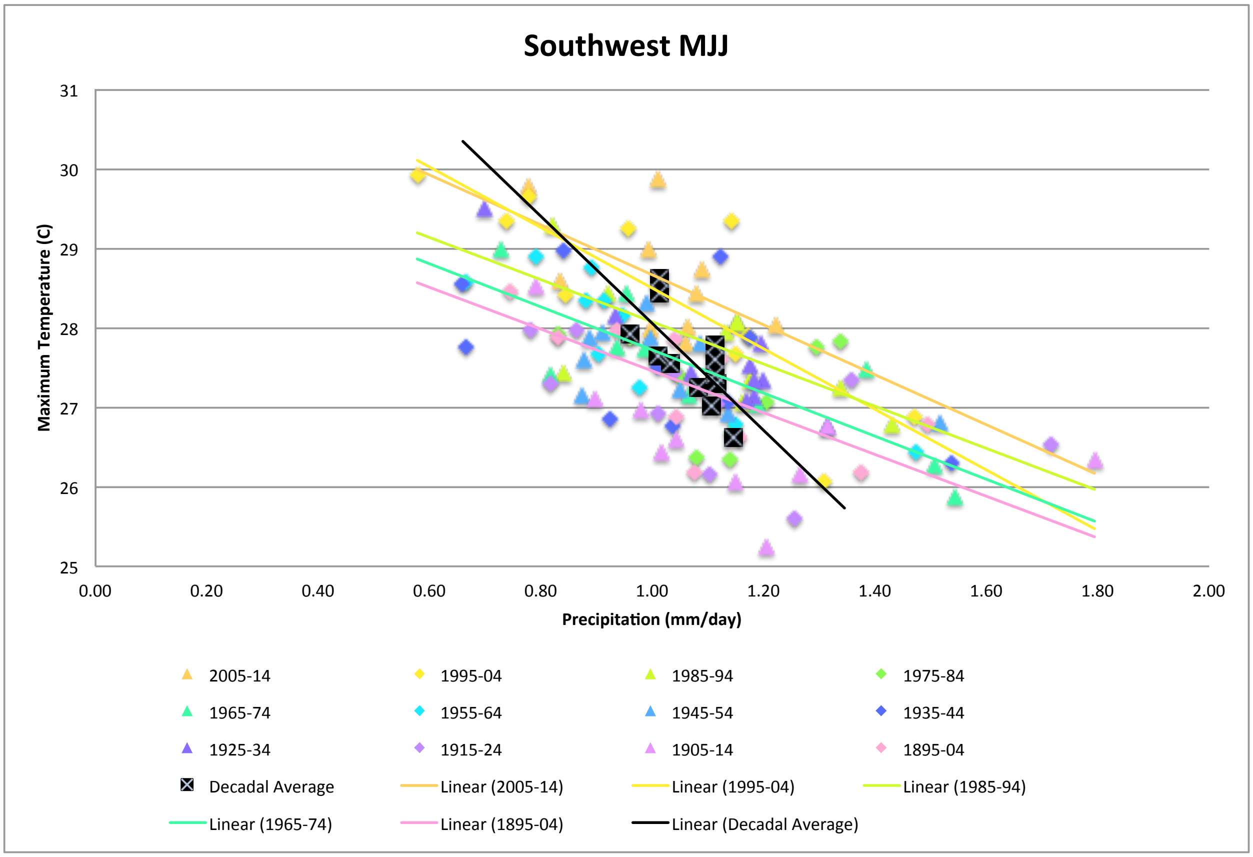

Figure 3. Case one AMMAXT data and ADP data for the period of May, June, and July for the Southwest Region. The color scheme for the decadal periods goes from pink, to purple, to blue, to green, and then to yellow across the full time period for the dataset. The regression lines place the best-fit linear relationship for each respective decadal period as well as the decadal averages using the least squares method.

For case one, we choose the May, June, and July (MJJ) months for the Southwest Region. This region possesses strong inter-annual and decadal correlations, with values of -0.636, as seen in figure 2, and -0.706 respectively. Also, the slope difference between the inter-annual and decadal timescale is large, with a value of 4.03. According to figure 3, temperatures have gradually risen about a degree and a half Celsius since the decadal period of 1895, with the largest increase occurring between the decadal periods beginning in 1985 and ending in 2004. Between these decadal periods, temperatures rise by over a half of a degree Celsius. Precipitation slightly decreases in the two most recent decadal periods, which amplifies the rate of warming in this regional period.

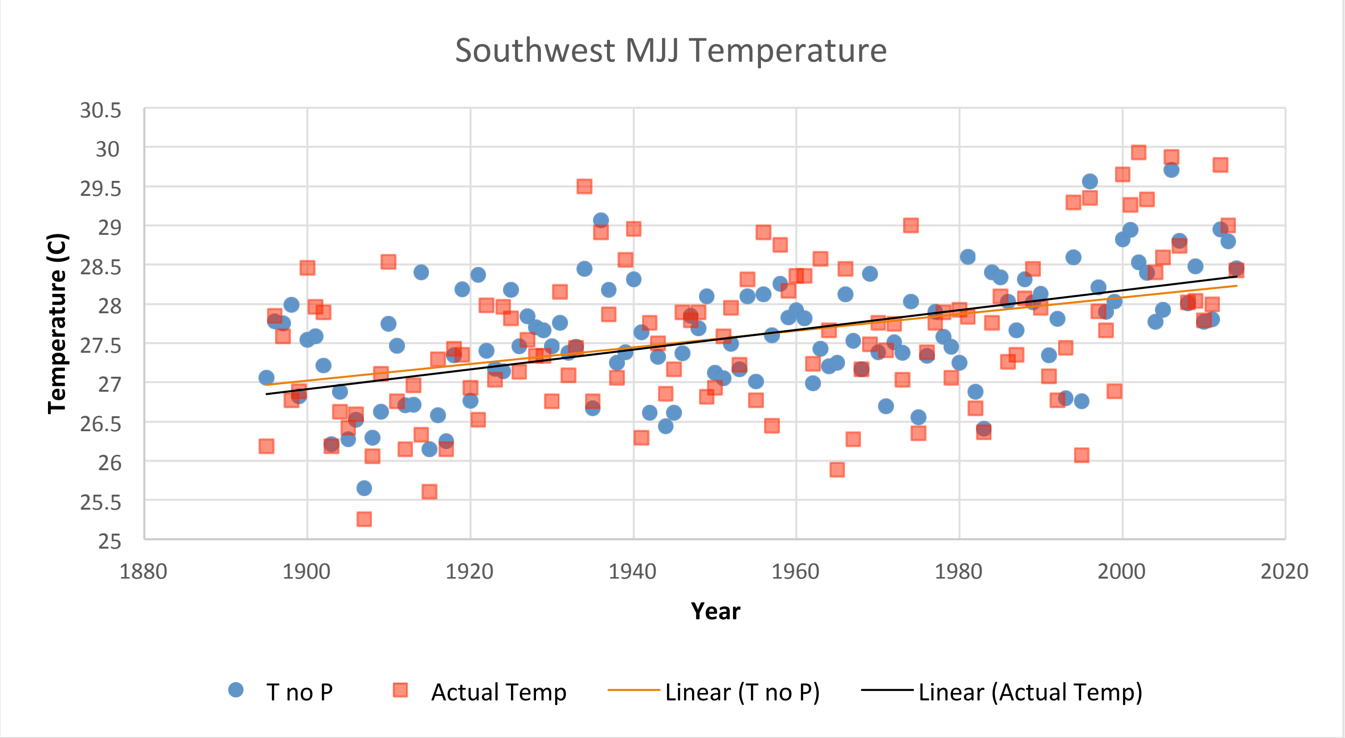

Figure 4. Southwest Regions May, June, and July AMMAXT (in degrees Celsius), using a first-order control for precipitation for the time period of 1895 to 2014 (T no P) and actual temperature values for the same time period (Actual Temp).

Figure 4 illustrates the purpose of implementing a first order control for precipitation. The R^2 value of the first-order control temperature data is 0.25, while the value is 0.21 for actual temperature data. The higher R^2 value for the first order control illustrates that this computation technique slightly reduces the noise caused by precipitations relationship with actual temperature data. Consistent with figure 3, figure 4 confirms a gradual increase in temperatures since 1895, with the most significant increase occurring since the turn of the century. Since 2000, first-order control temperatures exceed 28.5 degrees Celsius seven times, while this occurs three times between 1980 and 2000 and only twice prior to 1980. Additionally, since the turn of the twenty-first century, first-order control temperatures do not drop below 27.5 degrees Celsius. First-order control temperatures below 27.5 degrees Celsius occur frequently in each decade prior to 2000. This shows that the recent rise in temperatures is not caused solely be a decrease in precipitation.

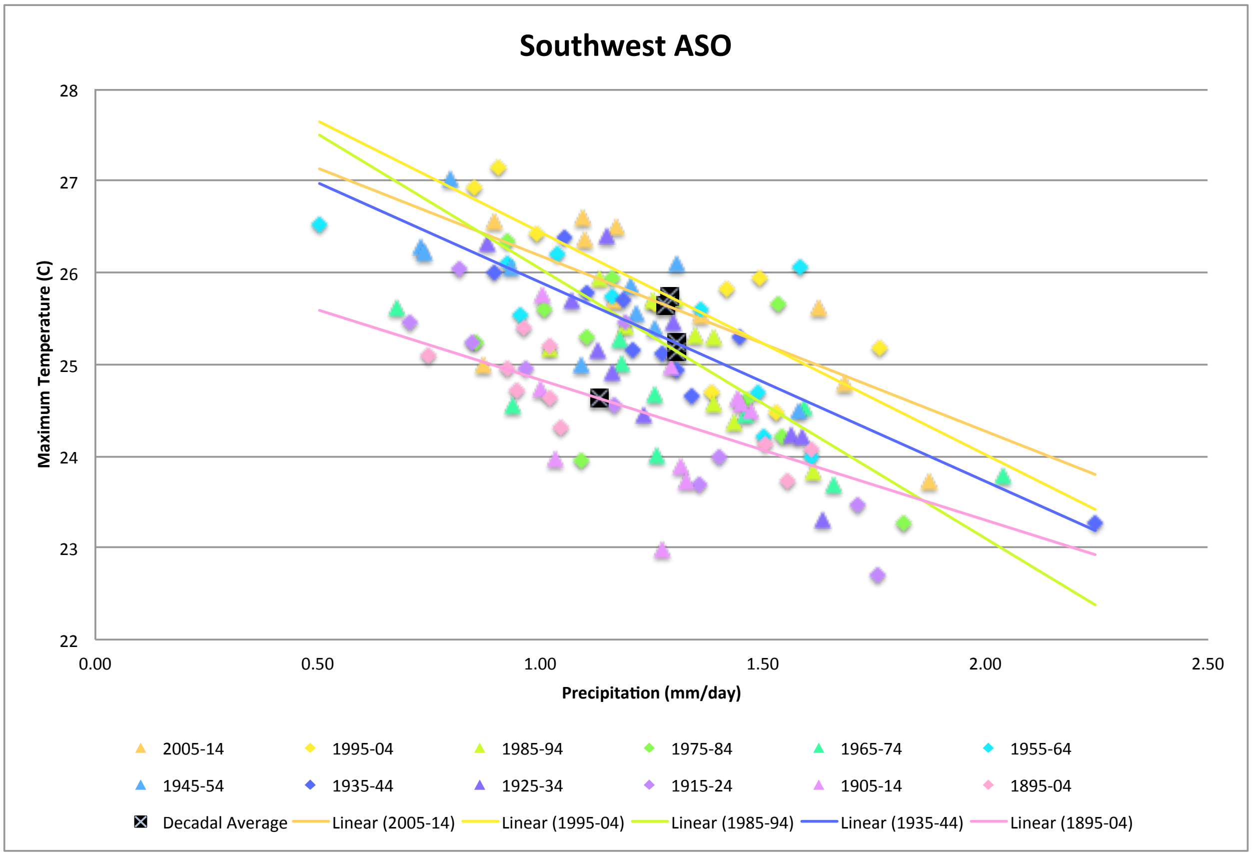

Figure 5. Case two AMMAXT and ADP data for the period of August, September, and October for the Southwest Region.

For case two, we choose the ASO months for the same region as case one, with a high inter-annual correlation of negative 0.641 and a low decadal correlation of negative 0.1. Both case one and case two display strong signals for rising maximum temperatures at the decadal time scale. From 1895 to the most recent decadal period, temperatures rise by about a degree Celsius. However, the slight increase in rainfall between these decadal periods has suppressed the rate of warming that has occurred in this region. Like the May, June, and July period for case one, the August, September, and October period shows the largest increase in temperature between the decadal periods beginning in 1985 to the one ending in 2004. During this timeframe, temperatures rise by a half of a degree Celsius, independent of the relationship to precipitation.

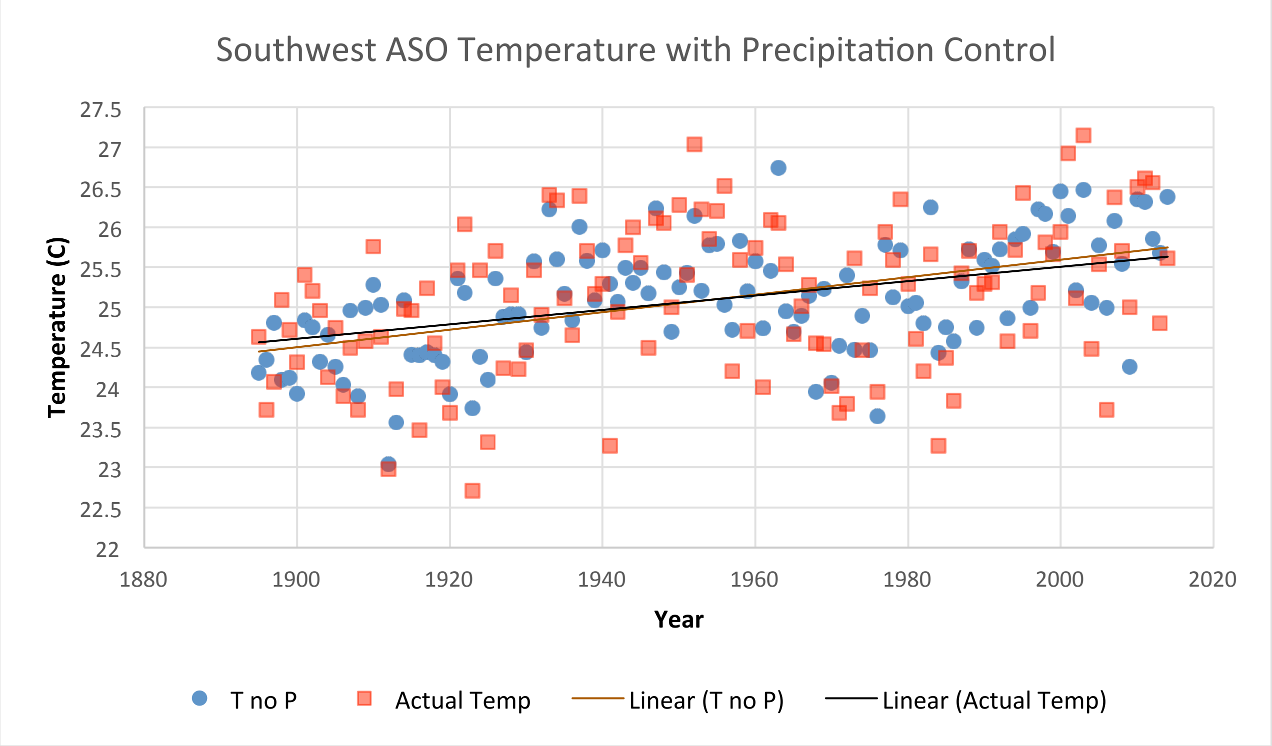

Figure 6. Southwest Regions August, September, and October AMMAXT, using a first-order control for precipitation for the time period of 1895 to 2014 (T no P) and actual temperature values for the same time period (Actual Temp).

The R^2 value for the first-order control temperature data is 0.28, while the value is 0.11 for the actual temperature data. For the ASO months, the first order control temperature calculation does a better job reducing the noise caused by precipitation than for the MJJ months. The gradual increase in temperature in this time frame since 1895 is evident in figure 6, similar to figure four. Consistent with figure 4, first-order control temperature increases have been most significant in the past twenty years. After 2000, seven years have first-order temperature values above 26 degrees Celsius, where for the time period of 1895 to 1980 this occurs a maximum of three times per twenty year period. Additionally, since 2000, first-order temperature values fall below 25 degrees Celsius only twice, whereas before the turn of the twenty-first century this occurs frequently.

C. The West Region

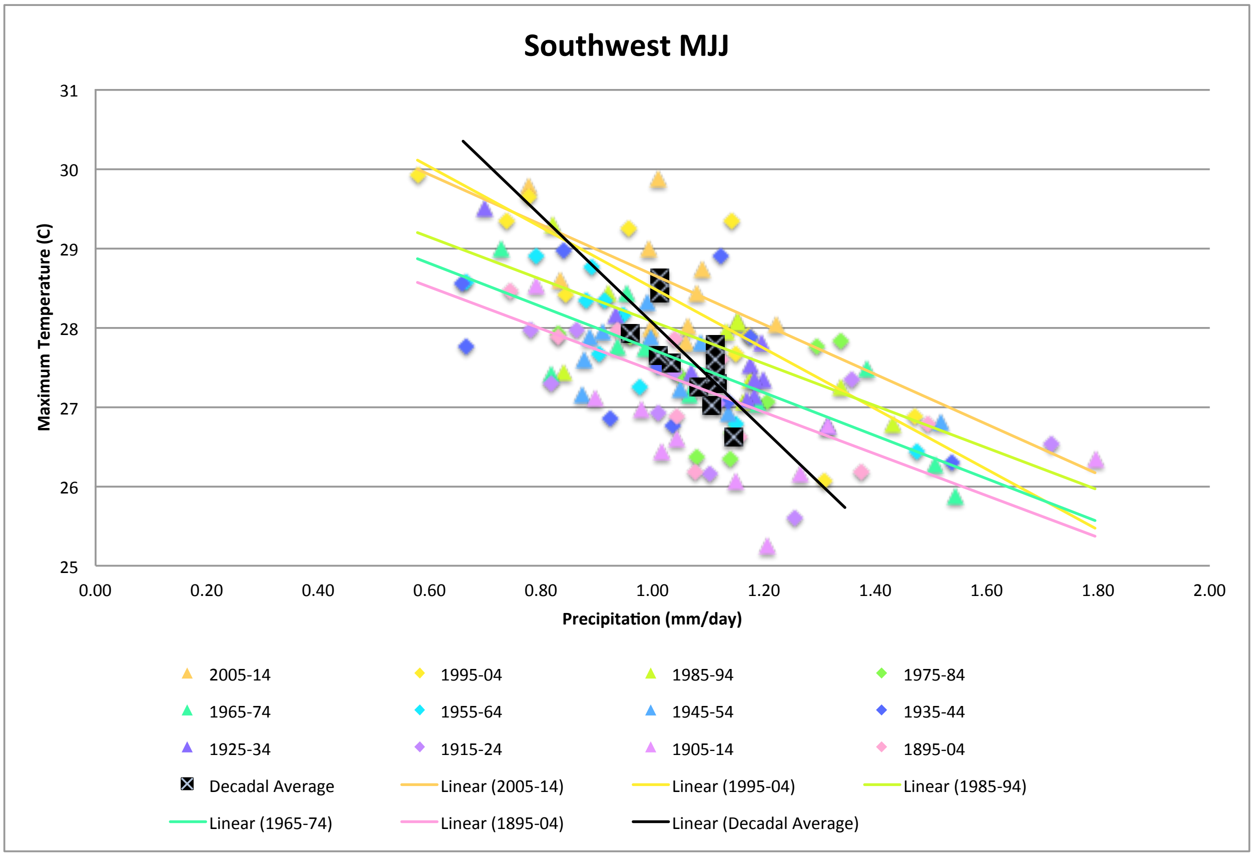

Figure 7. Case three AMMAXT and ADP data for the period of May, June, July and August for the West Region.

For case three, we choose the months of May, June, July, and August (MJJA) from the West Division. We use the four-month period for this region to survey a longer time period since precipitation during the summer months is low. This period possesses a large slope difference of 5.7 between the inter-annual and decadal timescale. Also, the correlations for the inter-annual and decadal timescale are moderately strong, with values of negative 0.522 and negative 0.541 respectively. The decadal period of 2005 to 2014 displays an increase of almost a degree and a half Celsius from the decadal period of 1895 to 1904, independent of the relationship to precipitation. Additionally, the two most recent decadal periods show a large temperature increase of half of a degree Celsius compared to the prior decadal period of 1985 to 1994. However, the reduction in rainfall has magnified the temperature increase in the two most recent decadal periods.

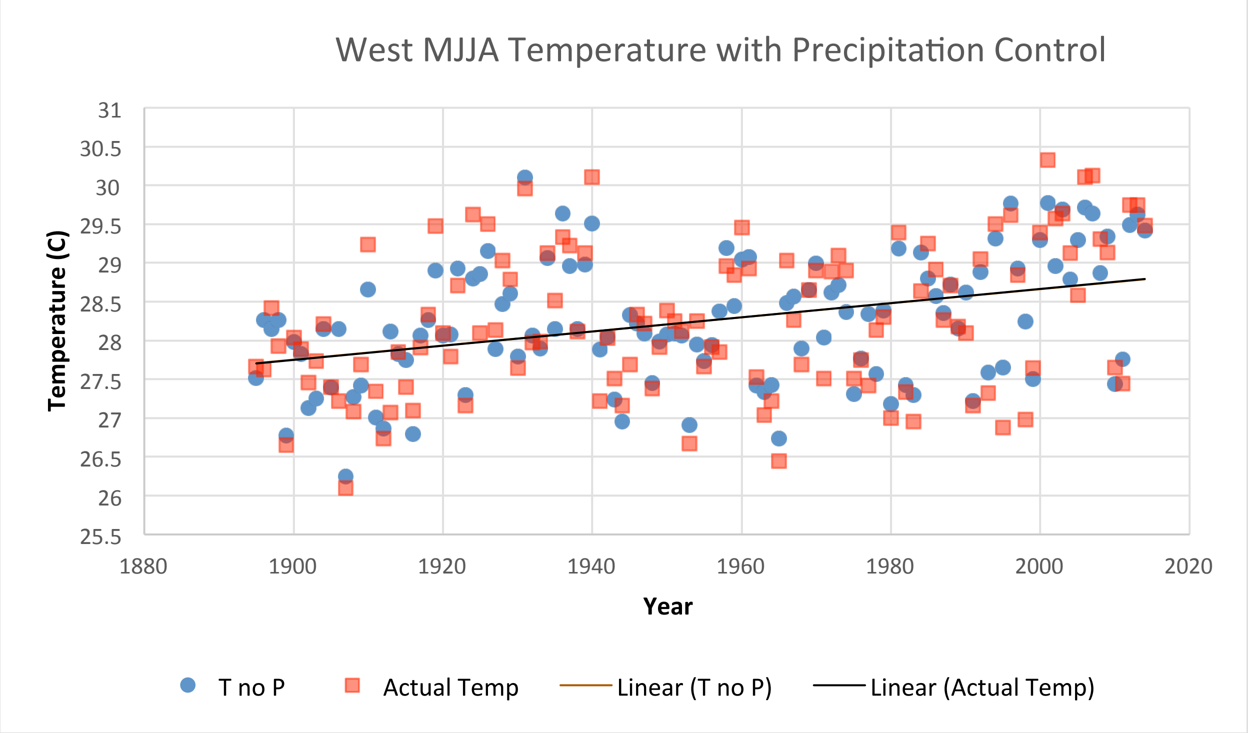

Figure 8. West Regions May, June, July, and August summer AMMAXT, using a first-order control for precipitation for the time period of 1895 to 2014 (T no P) and actual temperature values for the same time period (Actual Temp).

The R^2 value for the first order control temperature data is 0.15, while the actual temperature data value is 0.12. Thus, the first-order control slightly reduced the noise of the actual temperature data. Evidence of gradual temperature increases in the West region is depicted in figure 8, especially since the turn of the century. An anomalously warm period occurs between

1920 and 1940, which is also illustrated in figure six. This is likely due to a prolonged period of drought during this time period. Prior to 2000, first-order control temperature values drop below 28.5 degrees Celsius consistently; however, since the turn of the century, values drop below 28.5 degrees Celsius only twice. Additionally, first-order control temperature values above 29.5 degrees Celsius occur six times since the turn of twenty-first century, while it only occurs three times in the past century.

D. The Central Region

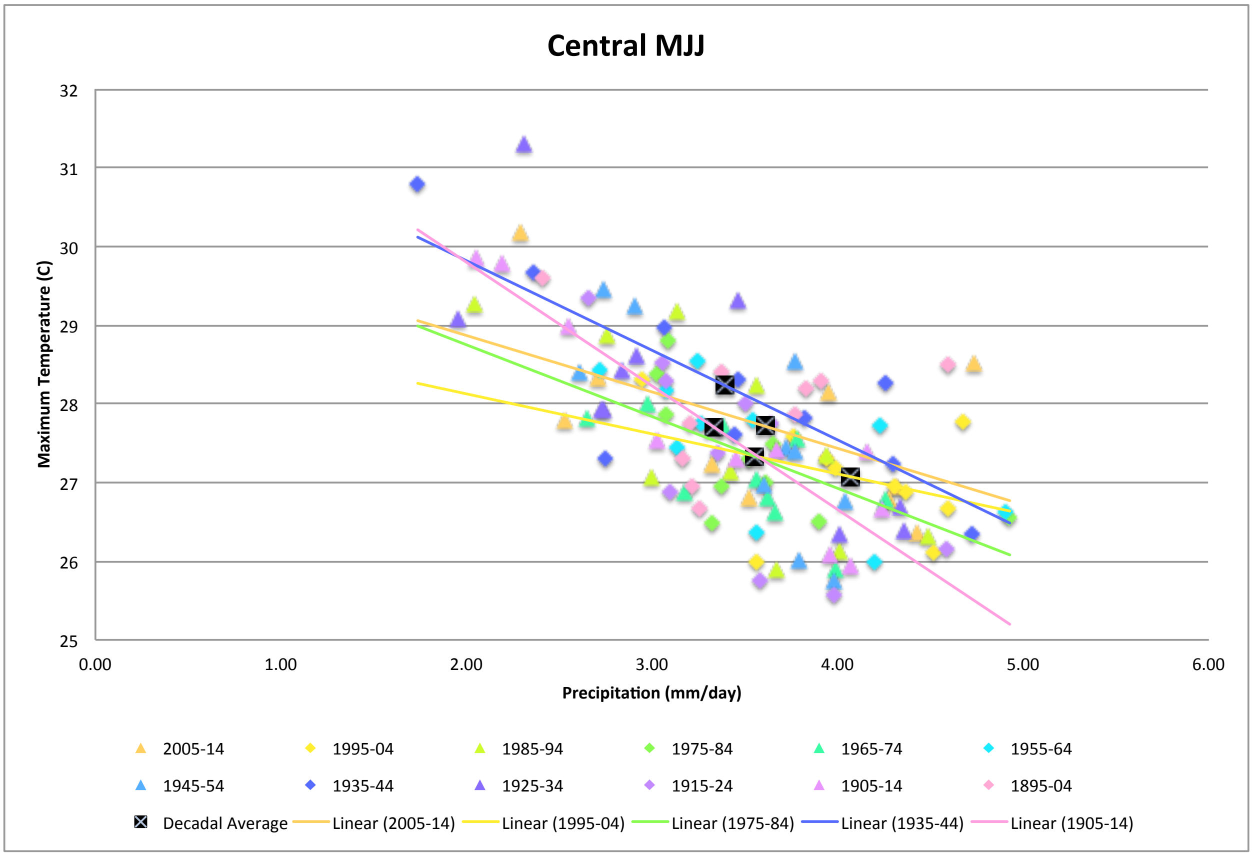

Figure 9. Case four AMMAXT and ADP data for the May, June, and July period for the Central Region.

For case four, we choose the months of May, June and July from the Central Region. The inter-annual and decadal timescale correlations are high, with values of negative 0.68 and negative 0.66 respectively; however, the slope difference between the inter-annual and the decadal timescale is a very low 0.05. The data for this region is inconclusive in determining an increase in maximum temperatures. The temperature data at the decadal timescale varies with precipitation. Thus, no distinct signal exists that indicates a departure from the inter-annual timescale at the decadal timescale. This justifies the small slope difference and the similar correlation values at the inter-annual and decadal timescale for this regional period.

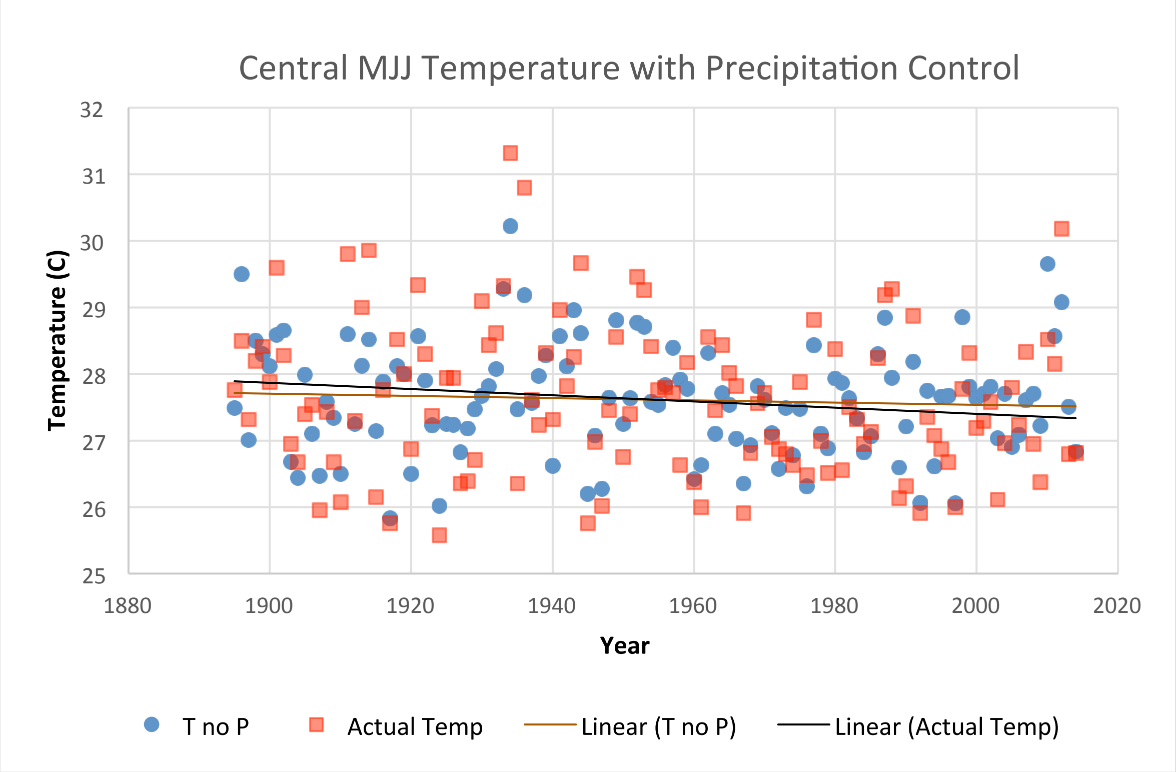

Figure 10. This shows the Central Regions May, June and July AMMAXT, using a first-order control for precipitation for the time period of 1895 to 2014 (T no P) and actual temperature values for the same time period (Actual Temp).

The R^2 value for the first-order control temperature data is 0.005, while the actual temperature data value is 0.02. Since the slope of the trend lines are negative, the smaller R^2 value for first order control reduces the noise of temperature data caused by precipitation In figure 10, the slightly negative slope of first order control temperature values over the full time scale indicates that temperatures remain relatively similar to variances at the inter-annual timescale. Also it is of significance that increased precipitation, especially in the past two decadal periods, is responsible for most of the temperature decline, as seen in figure 9.

E. The Northeast Region

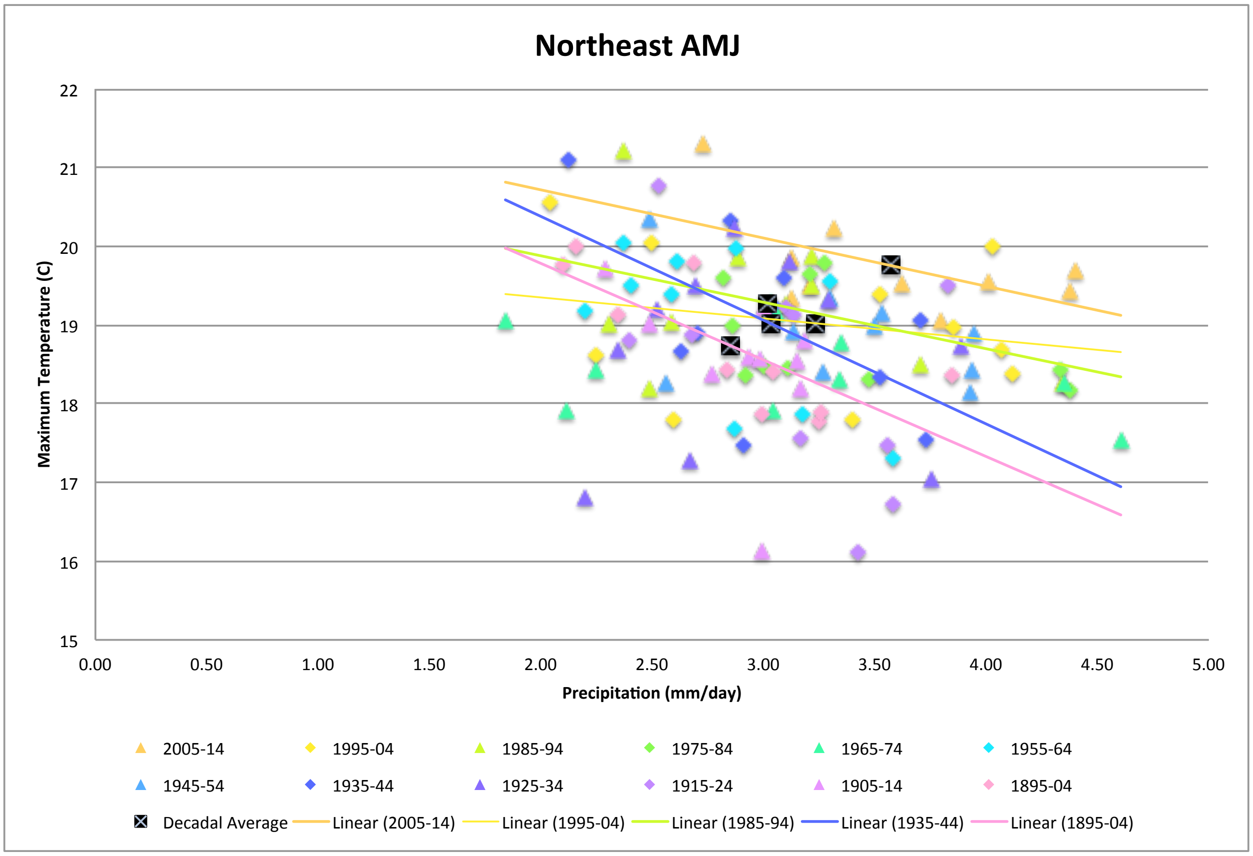

Figure 11. This displays the case five AMMAXT and ADP data for the April, May, and June period for the Northeast Region.

For case five, we choose the April, May, and June months from the Northeast region. The slope for the decadal time period is 0.77; however, the slope for the inter-annual time period is negative 0.42. The correlations for the inter-annual and decadal time period are negative 0.265 and 0.47 respectively. The most recent decadal period displays the most significant increases in temperature, where temperatures have risen close to a degree Celsius from the decadal period beginning in 1995. Additionally, from 1895 to the most recent decadal period, temperatures have increased over a degree Celsius; however, the increase in rainfall has suppressed the magnitude of warming in this region.

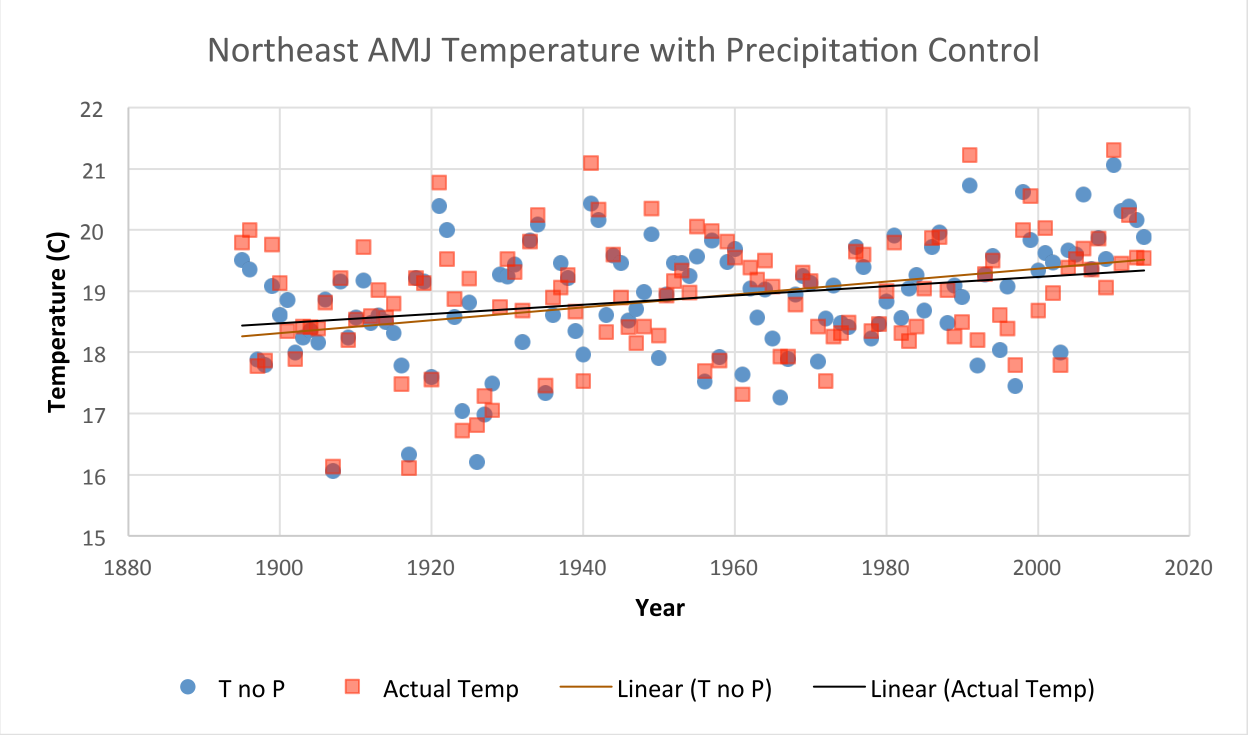

Figure 12. This shows the Northeast Regions April, May and June AMMAXT, using a first-order control for precipitation for the time period of 1895 to 2014 (T no P) and actual temperature values for the same time period (Actual Temp).

The R^2 value for first-order control for temperature is 0.15, while the value for actual temperature data is 0.07. Thus, the first-order control reduces the noise of actual temperature data caused by precipitation. In figure 12, the first order control temperature trend line indicates that temperatures have gradually been on the rise since 1895. Similar to figure 11, figure 12 depicts that the most significant increases in temperature occur since 2000. Since 2000, first-order temperature values reach above twenty degrees Celsius five times while in the twentieth century this only occurs a maximum of two times per twenty year period. Furthermore, first-order temperature values drop below nineteen degrees Celsius once since the turn of the century, while they drop below this value frequently in each twenty-year period prior to 2000. However, the increased rainfall has suppressed the magnitude of these changes since the turn of the century.

F. The "Warming Hole"

In the southeastern United States, models and historical data indicate that a "warming hole" exists in the southeastern United States, where annual-mean surface temperatures decrease by as much as 2°C in the twentieth century alone. (Meehl et al., 2012) Figure 13 indicates that temperature values drop by over a half of a degree Celsius from the decadal period of 1935-1944 to the period of 1975-1984. However, in the most recent two decadal periods, temperatures have steadily risen, and an increase of a half of a degree Celsius occurs from 1975 to the most recent decadal period. In Alabama, temperatures decrease by over a degree Celsius from the decadal period of 1895 to the decadal period beginning in 1975; however, temperatures increase by just under a half of a degree Celsius from 1975 to the most recent decadal period. However, the decreased rainfall has magnified the temperature rise from 1975 to the present. Similar to Alabama and the Southeast Region, temperatures decrease by close to a degree Celsius in Georgia from 1895 to the decadal period beginning in 1975; however, temperatures increases by almost a half of a degree Celsius from the decadal period of 1975 to the most recent decadal period have been amplified by the reduction in rainfall.

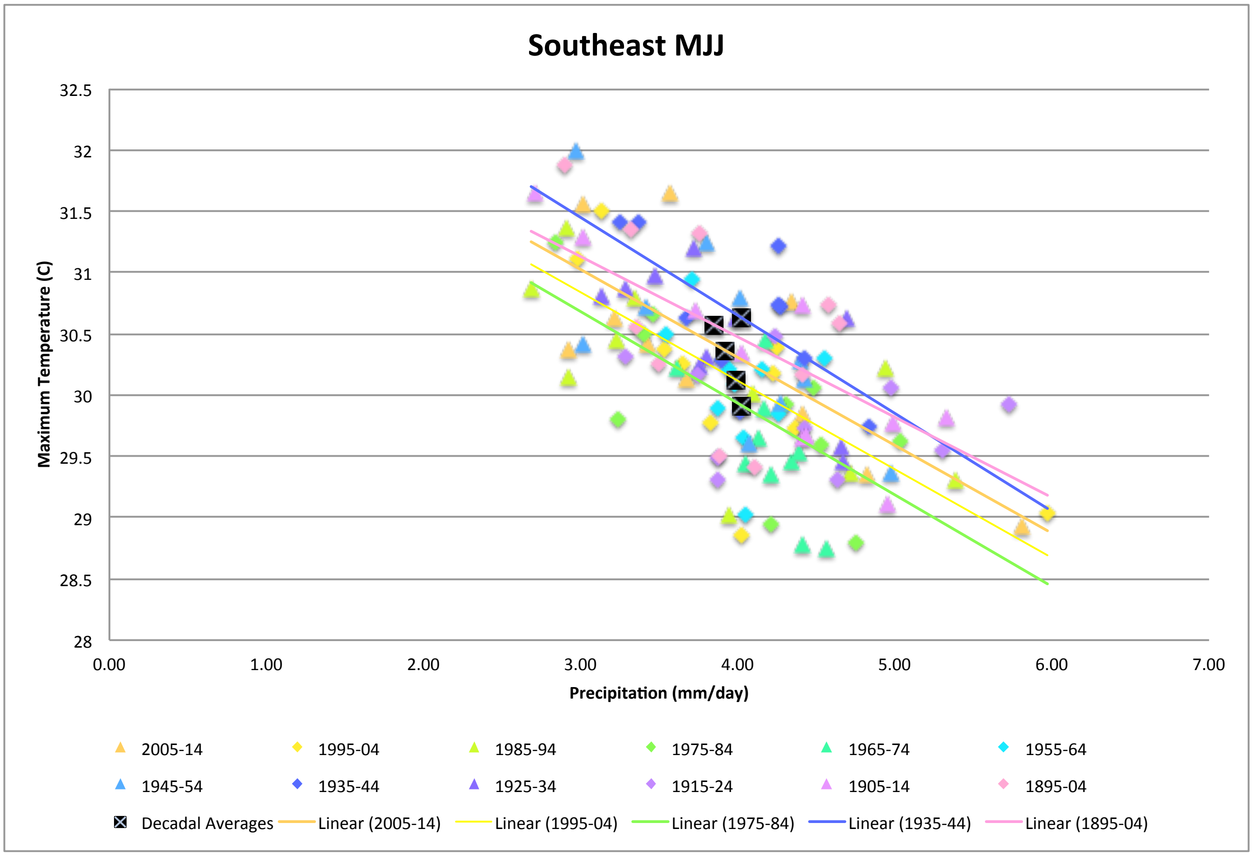

Figure 13. AMMAXT and ADP data for the May, June, and July period for the Southeast Region.

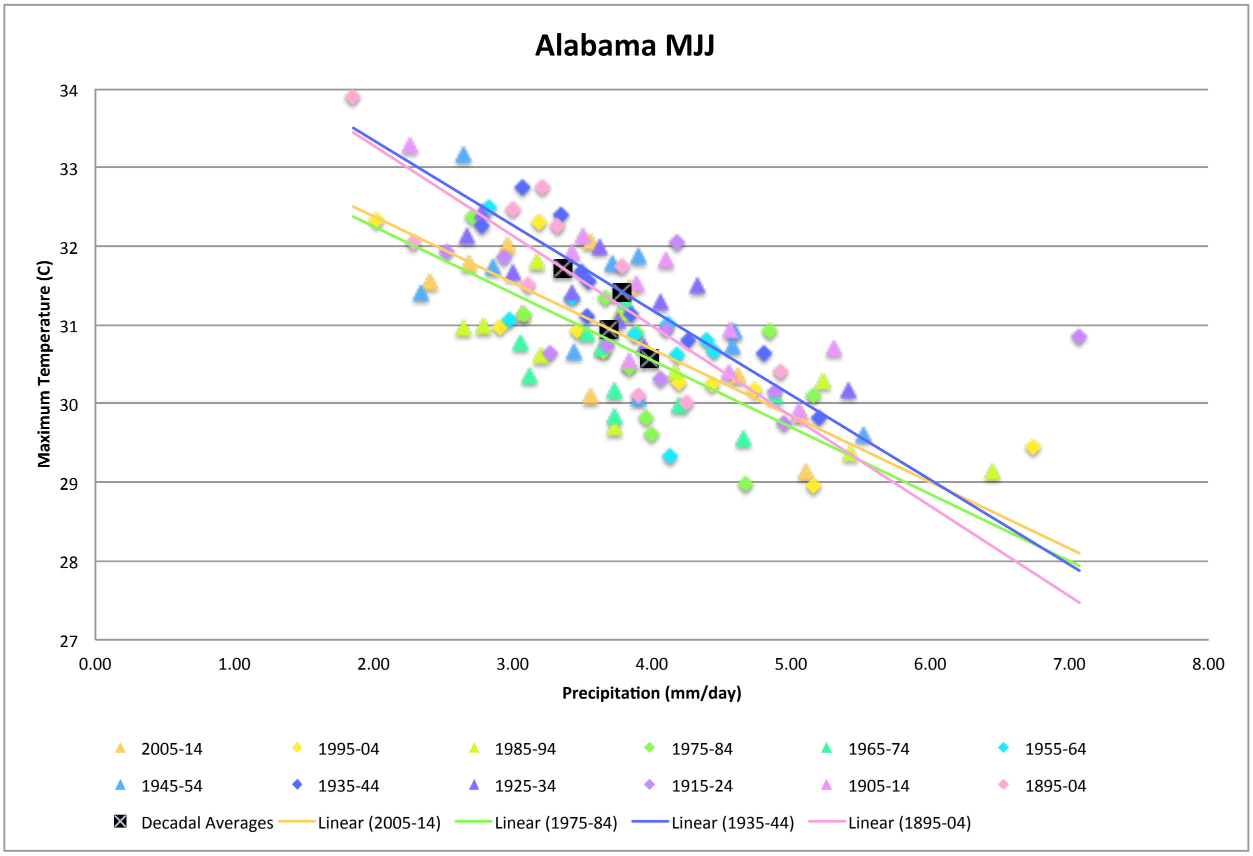

Figure 14. AMMAXT and ADP data for the May, June, and July period for the state of Alabama at the decadal time scale.

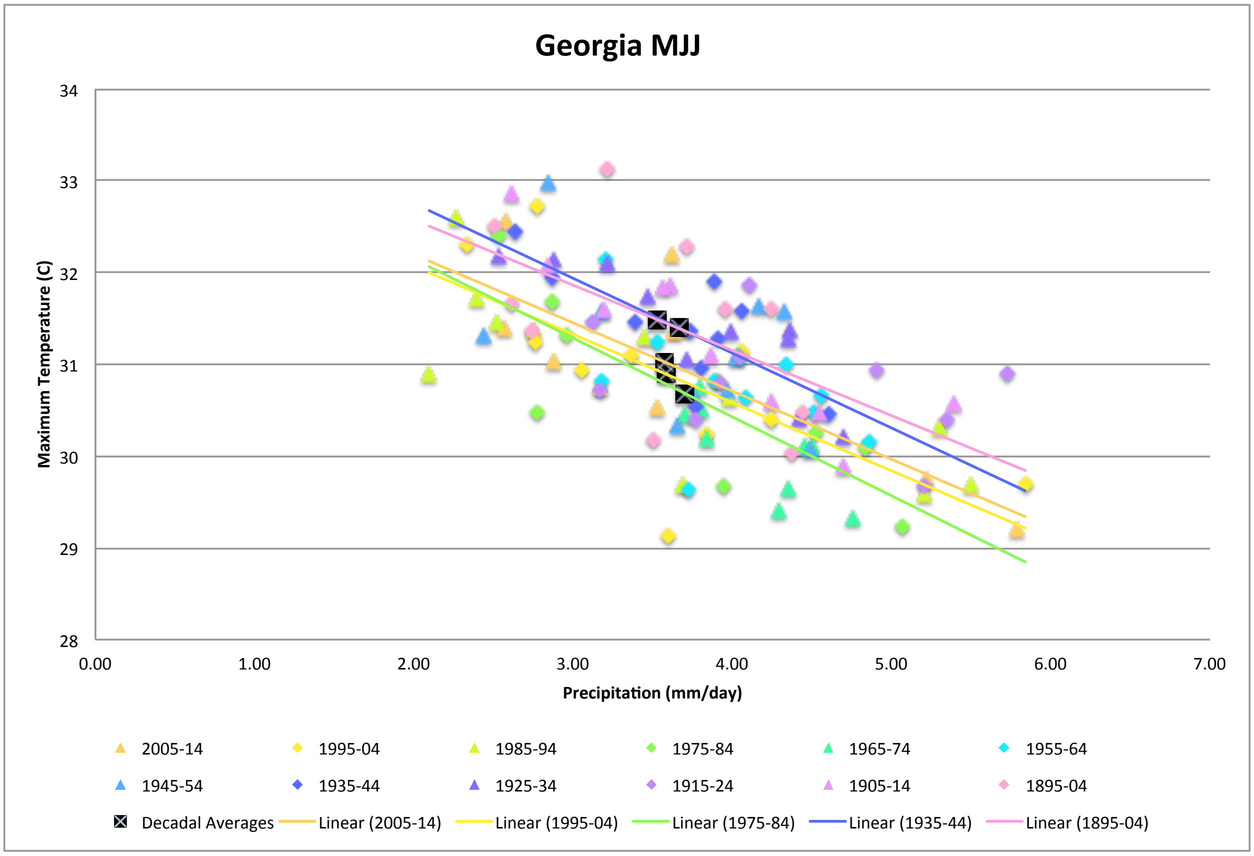

Figure 15. AMMAXT and ADP data for the May, June, and July period for the state of Georgia at the decadal timescale.

CONCLUSION

With the exception of the Central region and the Southeast warming hole, significant warming has occurred in the selected regions and seasons since the turn of the century. The Northeast, Southwest, and West regions have seen the most significant temperature increases, with temperature departures of a degree to a degree and a half Celsius from 1895 to the most recent decadal period. The most significant increase of temperature has occurred in the past two decades, with a rise of between a half to almost a full degree Celsius in each region. The Southeast region experiences a more modest temperature increase of around a half of a degree Celsius in the past two decades. Even though the Southwest has a net decrease in temperature values from the decadal period of 1895 to the most recent decadal period, the gradual warming in the past two decades at the regional and state levels indicates that the net cooling trend will reverse in the coming decades. Additionally, the lack of difference between the trend lines for raw temperature and the first order control temperature values shows that the relationship between temperature and precipitation plays a minimal role in long-term temperature changes. Thus, something other than the relationship of precipitation to temperature has been resulting in the rise of temperature since the turn of the century. This could be due to the greenhouse effect, which reflects outgoing infrared radiation back to the surface, leading to more thermal energy in our atmosphere. More investigation needs to be done in different regions of the United States to determine the full extent of temperature changes across the United States; however, the data suggests that the warming trend since the turn of the century will be evident in the other regions of the United States and will continue in the future.

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