Observational Analysis of Twentieth Century Summer Climate over North America

by

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Bachelor of Science in Engineering
Duke University, 2013

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of

Master of Engineering in Civil and Environmental Engineering at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2016

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Abstract

How did the climate of the central United States change over the course of the twentieth century? In this study, multiple complementary statistical analyses were carried out on weather and agricultural production data in order to determine the spatiotemporal nature of changes. Variables considered included: precipitation, air temperature, air pressure, humidity, and evapotranspiration, as well as acreage, yield, and production of major crops. The study focused primarily on changes in July and August climate in the Midwest and Great Plains, home to the majority of agricultural production in the U.S.

Statistically significant and sustained increases in summer precipitation and decreases in summer temperature were observed in the Midwest, with the changes centered on the period 1950-1970. Evidence was also observed for increases in specific humidity and evapotranspiration over the century. These changes were collated in space and time with rapid increases in photosynthetic activity through increased crop production and yield. The study thus lays the ground for future research in attributing the causes of regional climate change, especially through the interactions of climate and land use.

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Title: Associate Department Head, Professor of Civil and Environmental Engineering

ACKNOWLEDGMENTS

This research was made possible by support from the MIT-SUTD Dual Masters' Programme. I would like to thank all the people at MIT and SUTD who run this programme that afforded me the incredible opportunity to study at two amazing universities.

My thanks go out especially to Professor Elfatih Eltahir, who has been my guide through this study. His vision, insight, and encouragement have helped me develop skills that will prove hugely helpful in my future career. I've really enjoyed being a part of his group. Thanks, also, to Postdoctoral Researcher Ross Alter, with whom I have collaborated closely in this work. Ross' experience, patience, and guidance have been invaluable to me in conducting all of the work in this thesis.

Many others have helped me get to this point, not least including: The Robertson Scholars Leadership Program, my former colleagues at Geosyntec Consultants in Austin, and my friends both here and abroad. Finally, I would like to thank my family in New Zealand. My parents and brothers have supported me totally in this grand adventure despite the huge distances and times between seeing each other. I couldn't do it without you.

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1. INTRODUCTION

1.1. BACKGROUND

The twentieth century in North America was one of great change. Cities rose, agriculture exploded, and technology became dominant. The climate also changed. When your grandmother claims that the weather sure was different when she was a girl, she might actually be telling the truth. Changes in climate can have huge consequences for people and businesses, and nowhere is that more true than for agriculture. The Great Plains and Midwest regions of the U.S. provide food for hundreds of millions of people, and the staple crops grown there depend on good weather. Understanding what drives changes in climate in this region is vitally important for the future food security of the U.S. The first step in determining those drivers is understanding how climate has changed in the past.

This study set out to determine what changes in climate and land use have occurred across the United States during the twentieth century. What happened to climate? Where and when did things change? By how much? Through statistical analyses, the regions and time periods over which these changes were most pronounced were determined. Land use was considered along with climate because the two are inextricably linked. Feedback between soil, crops, and the atmosphere is well established, but extremely complex (Eltahir, 1998) (Alter et al., 2015). The results of this study are intended to serve as a basis upon which future research can be built. Determining the causes of changes in climate requires a robust understanding of what these changes are, and this study attempts to provide that understanding.

1.2. OVERVIEW

The study focuses only on changes in weather during the summer months of July and August. These two months are when the greatest amount of irrigation and agricultural growth occurs over the region of interest (USDA, 2010), and so the effects of agricultural land use change on weather are likely to be most pronounced during this time. The study considers data from the twentieth century, but also the first decade of the 21st century in order to help determine the persistence of observed changes.

All analyses and figures in this study were produced using NCAR Command Language (NCL), from the National Center for Atmospheric Research (NCAR, 2016).

1.2.1. Region of Interest

This study focuses on the Midwest and Great Plains regions of the United States. The Great Plains is an area roughly bounded by the Rocky Mountains to the west and the Mississippi River to the east. The Midwest is commonly defined as including the following twelve states:

Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.

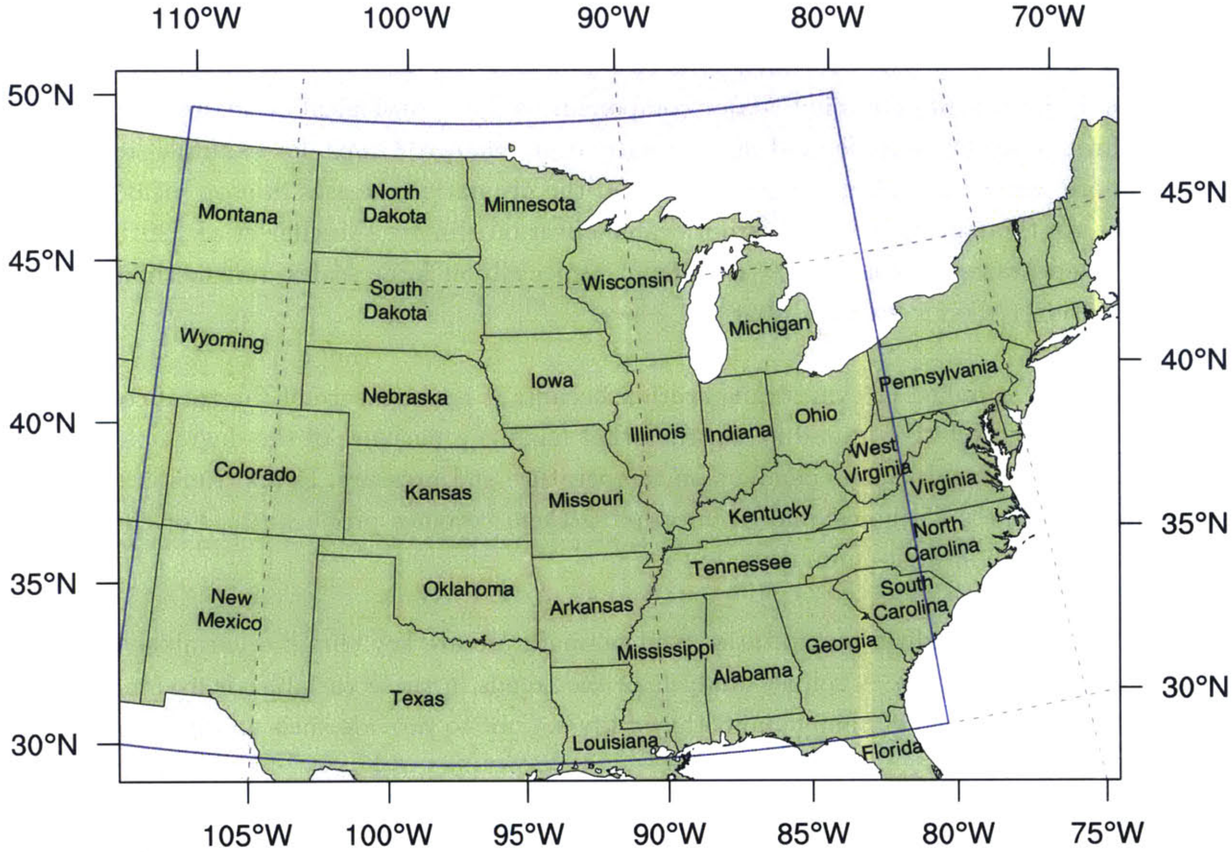


Figure 1: Reference Map with State Names

Notes:

1) Blue lines indicate the analysis domain.

2) The unlabeled green area north of Wisconsin is also part of Michigan.

The analysis domain, outlined in blue in Figure 1, is a 20° by 30° area between latitudes 30°N and 50°N and longitudes 80°W and 110°W. The domain extends beyond the Midwest and Great Plains, including southeastern states and part of southern Canada. This extension of the domain was intended to capture weather effects in neighboring states that may have been caused by land use change in Midwestern or Great Plains states, while trying to avoid coastal or mountainous states, which have complicating orographic effects on the weather.

1.2.2. Variables Considered

This study analyzed a number of key climatic variables, including: precipitation, air temperature, air pressure, specific humidity, and evapotranspiration (ET). These variables were selected because they are affected by land use, and so any trends observed will help inform future studies analyzing the effects of land use change on climate.

Evapotranspiration from plants is a major component of the hydrological cycle, and it is modified through anthropogenic land use and land cover change. Crops, for example, tend to transpire more water than natural vegetation, and the dramatic increases in crop yield over the last century are thought to have had a noticeable effect on climate (Mueller et al., 2015). Measuring evapotranspiration directly is difficult, especially at large scales, but methods exist for its estimation (Allen & Pereira, 1998).

Specific humidity is linked to evapotranspiration because it is a measure of the total content of moisture in the air. Relative humidity, on the other hand is a measure of the degree of saturation of the air, and so is dependent on temperature and pressure. Evapotranspiration, in turn, is linked to these variables, and so uncoupling them becomes problematic. For this reason, the study focused on specific humidity.

Along with specific humidity, precipitation and temperature are key climatic variables that are affected by land use change. A robust analysis of the trends in these variables is a valuable tool in determining the drivers of change, and this study set out to provide such an analysis.

1.2.3. Outline

Five complementary analyses of historical weather and agricultural data were carried out:

- Gridded Weather Data
- Weather Stations
- Gridded Pressure Data & Reanalysis Products
- Crop Production Data
- Water Balance Estimation of Evapotranspiration

A chapter is devoted to each of these analyses, with the methods used, the results, and discussion of the results included in each chapter. Conclusions based on the findings of all of the analyses taken together follow these chapters.

1.3. LITERATURE REVIEW

Several studies were reviewed to determine what changes, if any, have been observed in the climate of the U.S. during the twentieth century. Many of these studies also sought to link the observed trends to changes in land use, something beyond the scope of this study.

1.3.1. Trends in Precipitation

Pryor et al. (2009) analyzed twentieth-century precipitation records from stations across the continental United States in order to identify trends in precipitation characteristics, and to test the robustness of these identified trends. Daily data were analyzed using both the more conservative "nonparametric Kendall's tau-based slope estimator" and "bootstrap resampling of the residuals from OLSR [ordinary least squares regression] analysis", with relatively consistent results from both. The study also analyzed each station (those that had passed data completeness criteria) individually, in an attempt to isolate regional and local effects.

The authors identified trends of increasing total precipitation amount, increasing frequency of precipitation events, and increasing proportions of precipitation from extreme events at many stations across the US. These trends were especially apparent in the central Great Plains and the Midwest. While the study did not attempt to explain the causes of this increase, it did note that the central Great Plains were subject to some of the greatest changes in land use in the country over the course of the century through increases in irrigation. The authors also found that the trends of increasing precipitation (especially from extreme events) appear to be primarily due to changes in the latter third of the century. (Though they cautioned that this is less certain than the prior conclusions, due to the higher influence of interannual variability on the shortened timescale.)

Alter et al. (2015) hypothesized that the competing effects of increased soil moisture on energy fluxes in the near-surface atmosphere may result in reduced precipitation over irrigated areas and enhanced precipitation downwind. The study examined historical rainfall station observations across the Midwestern United States, especially Nebraska, and compared patterns prior to and after large-scale increases in irrigation. The study focused specifically on the impacts in two downwind "target regions": Upper Midwest and Midwest, and also separated data for rainfall intensity, frequency, and total amounts in order to attribute causes.

Alter et al. found increases in summer precipitation intensity, frequency and total amounts over the latter half of the twentieth century in the Midwest and Upper Midwest that were robust under statistical analyses. Data for several different combinations of pre- and post-irrigation sets of years were compared. The study found that frequency increases were not unique to summer months, and so were not likely due solely to irrigation. Rainfall intensity increases, however, while predominant in the summer, were not found to be unique to the Midwestern US. Other potential drivers of increasing precipitation, including climate change, were considered, but are found to be less likely drivers than land use change. On balance, the study concluded that the significant increases in overall summer precipitation in the Midwest and Upper Midwest indicated increased atmospheric moisture and/or moisture convergence.

DeAngelis et al. (2010) presented the case for large-scale, predominantly downwind effects of irrigation on rainfall, based on both an analysis of observational data and vapor tracking analysis using a dynamic recycling model. The authors also outlined the potential shortcomings of prior observational studies that considered short or inappropriate time periods and/or small data sets. The study broke the central US into three large, multi-state regions: Region 1, where the bulk of irrigation occurs; Region 2, immediately northeast (i.e. downwind) of Region 1; and Region 3, immediately east of Region 2.

In their observation of historical data, DeAngelis et al. took the arithmetic average of precipitation at all stations in a region. Both Regions 2 and 3 demonstrated an increase in summer precipitation around the late 1940s. Comparing data from 1900-1950 with data from 1950-2000, Region 3 saw a 20.9% increase in July precipitation, significant at the 95% level. Region 2 saw a 14.1% increase in July precipitation, though this was not found to be statistically significant. Using a Pettit test, 1947 was found to be a statistically significant (at the 95% level) change point in Region 3 July precipitation.

1.3.2. Trends in Temperature and Humidity

Mueller et al. (2015) conducted an analysis of historical data and found trends of decreased summer temperature extremes in the US Midwest during the twentieth century. The study found strong correlations between areas experiencing cooling and areas where crop productivity had increased. Statistically significant cooling trends were particularly strong in areas where irrigation had increased, though also apparent in rainfed agricultural areas. In the rainfed areas, this trend was not apparent during times of drought, and so the authors conclude that sufficient soil moisture is required for cooling to occur. They proposed that the mechanism for cooling is through enhanced soil moisture and evapotranspiration, which then also leads to increased precipitation. The implication is that improving the yields of crops in the Midwest U.S. has had the effect of bringing about better conditions for plant growth: lower summer temperatures and higher precipitation.

Historical records of temperature were also analyzed by Mahmood et al. with the intention of investigating the effects of irrigation (Mahmood et al., 2006). The study considered trends during the twentieth century in the Midwestern United States, especially Nebraska. The authors selected five irrigated and five non-irrigated sites, and carried out statistical analyses on their mean historical monthly maximum, minimum, and mean air temperatures. Their results show that mean temperatures decreased during the growing season (when water is applied) at irrigated sites, due primarily to lowering of the mean maximum temperatures. Meanwhile, mean temperatures increased at non-irrigated sites (a trend that they attributed to global climate change). Mean minimum temperatures actually increased at irrigated sites, which they attributed to the increased heat capacity of the moister soil.

Brown and DeGaetano (2013) analyzed observational data from stations across the U.S. in the Integrated Surface Database (a database also used in this study) and other sources to determine trends in surface humidity. Over the period 1930 to 2010, they found general increases in temperature, with decreases observed in the Great Lakes region. No significant changes were observed in dew point temperature, relative humidity, or specific humidity across the country as a whole. However, regional areas displayed significant trends. One such trend was that the Midwest and Great Plains exhibited statistically significant increases in annual specific humidity. This "Midwest moistening" was observed over the period of 1947-2010. The authors mention a possible link to agricultural land use change noted in other studies. They point out that specific humidity peaks during the summer, when irrigation use is at its highest.

1.3.3. Summary

In multiple analyses of observational weather data, the weight of evidence points to a trend of increasing precipitation in the central U.S. during the twentieth century. Over the same time period, some regions exhibited decreases in temperature, despite overall increases in global temperatures. There is also evidence towards increases in specific humidity, which is linked to crop evapotranspiration. These trends appear to be strongest in the summer, which is also the period of greatest crop growth in this region. Crop production and irrigation increased markedly during the twentieth century. This change in land use may have contributed to the observed trends.

2. GRIDDED WEATHER DATA

2.1. ANALYTICAL METHODS

2.1.1. Dataset

Analyses were carried out using the *Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series (V3.01)* dataset from Willmott and Matsuura at the University of Delaware, herein referred to as the "UDel dataset" (Matsuura & Willmott, 2012). This quality-controlled, gridded dataset is built from land-based observations at weather stations. It provides monthly values for average air temperature and total precipitation from 1901 to 2010 at a resolution of 0.5° latitude by 0.5° longitude across the entire globe.

Two other comparable gridded weather datasets were also investigated: the *Full Data Reanalysis Version 5* from the Global Precipitation Climatology Center (Schneider et al., 2011), and *CRU TS3.23* from the Climatic Research Unit (Harris et al., 2014). In a preliminary analysis, both datasets yielded weather records very comparable to the UDel dataset across the region of interest (see Appendix A – Alternative Gridded Weather Data Results). Accordingly, it was deemed sufficient to carry out the analyses using the UDel dataset only.

Data from prior to 1910 were not considered, as the reliability of data from this early period is not as great as that of the later data. The UDel dataset draws heavily on data from the Global Historical Climatology Network (GHCN), which incorporates readings from land-based weather station observations. Figure 2 shows the number of stations in the GHCN network. The number of stations in the US, and especially in the analysis domain, increased rapidly just prior to 1910, when the number reached a level maintained through the twentieth century. Readings from before 1910 thus rely on relatively few sources.

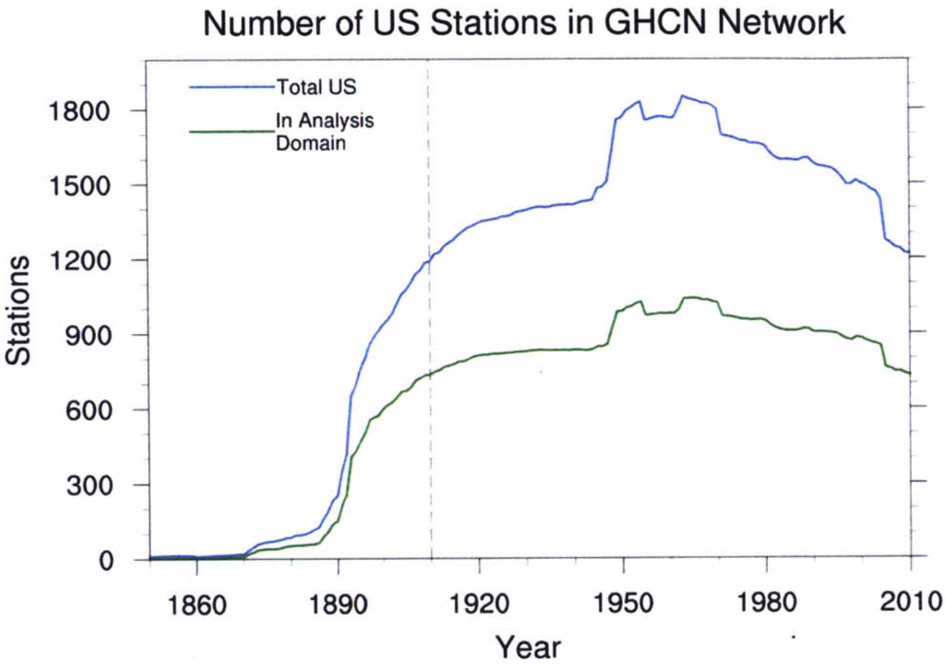


Figure 2: Number of U.S. Stations in GHCN Network

Notes:
1) Analysis Domain is defined in Figure 1.

2.1.2. Definitions of Terms

- *Grid cell*: one of many data points in the UDel dataset covering an area of 0.5° latitude by 0.5° longitude. Each grid cell contains one temperature and one precipitation value for each month.
- *Region of Interest*: The geographical area of the statistical analysis, encompassing the Great Plains and Midwest. Defined in Figure 1.
- *Subgrid*: A particular way of dividing the region of interest into multiple subregions. Defined in Figure 3 and Figure 4.
- *Subregion*: A numbered subset of the region of interest whose dimensions depend on the subgrid considered.
- *Climate*: The average weather for a particular region over a 30-year period.

2.1.3. Tests of Statistical Significance

Statistical significance was determined using a two-sample Kolmogorov-Smirnov test (K-S test). The K-S test is used to determine how likely it is that two samples of data arise from the same distribution function. It is based on the maximum difference between the empirical cumulative distributions of the two samples, and identifies both shifts in the means of the data and changes in their variance (Sheskin, 2007), (Smirnov, 1939). The K-S test is also nonparametric (i.e. it makes no assumptions about the distributions of the data). Because of these factors, it is an appropriate test to use for comparing distinct samples of unknown distribution, such as weather data (Sheskin, 2007), (Lehmann, 1951). The K-S test was chosen over the Student's t test because meteorological data are not necessarily normally distributed, and the t test assumes normality. (This is especially true for precipitation, which tends to have a one-tailed distribution with many near-zero values and a few very large values.)

In fact, the K-S test is less powerful than other commonly used tests in identifying shifts in means (Sheskin, 2007), (Dudley, 2015), and so using it to identify increases or decreases in average precipitation (for example) is a conservative technique. The test does assume that the data are continuous and that each point within the data sample is independent and identically distributed. However, these are appropriate assumptions for weather data suitably separated in time. (One wet summer is unlikely to have a large effect on the wetness of the following summer.) The p-values output by the K-S test indicate the likelihood that the two samples come from the same distribution. A low p-value, in this study, then represents a low likelihood that the characteristics of the two climates share the same distribution, given the sample. In this study, statistical significance was defined at the 95% level, i.e. p-values of 0.05 or less.

2.1.4. Statistical Analysis Methods

To determine where and when the greatest changes in precipitation patterns had occurred in the historical records, the following procedure was followed:

- Divide the region of interest into subregions,
- divide the weather record into two "before" and "after" 30-year climates,
- test the statistical significance of the difference between corresponding grid cells in these climates using Kolmogorov-Smirnov tests, and
- vary the starting date of these climates and the separation between them in order to find the time(s) for each subregion where the greatest proportion of grid cells exhibit statistically significant change.

The region of interest was divided into subregions in order to spatially distinguish time periods of significant change. For example, an area around the Great Lakes might show significant change over a different time period than an area in the southwest. For the initial analysis, the region of interest was divided into Subgrid A: 24 equally-sized, 5° latitude by 5° longitude boxes, as shown in Figure 3 below:

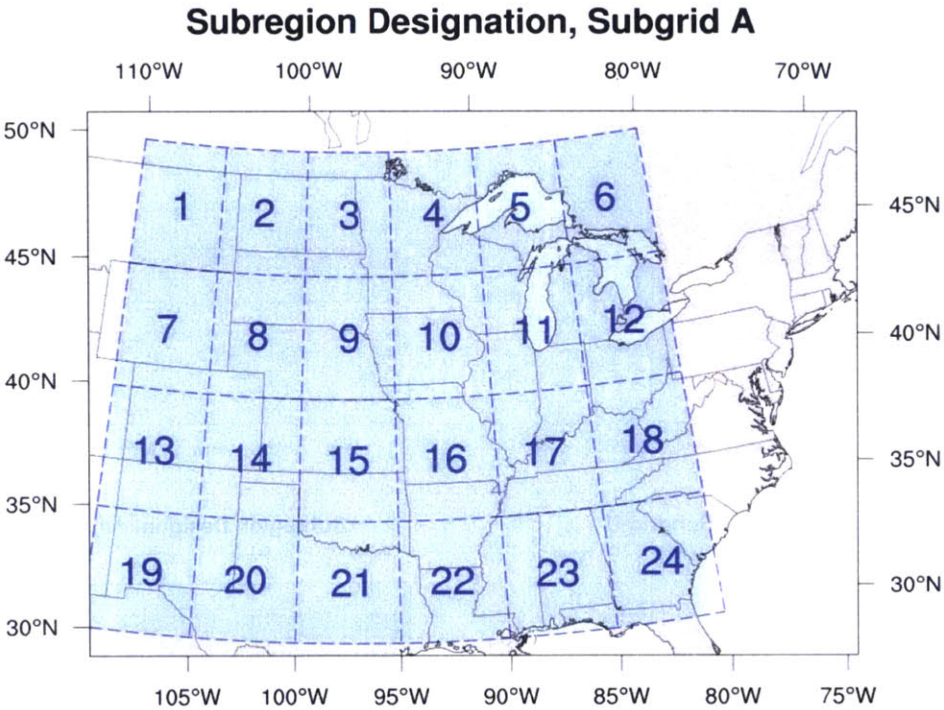


Figure 3: Subregion Designation, Subgrid A

Each subregion in Subgrid A, then, contained 100 grid cells. In order to ensure that the results were not overly dependent on the subgrid definition, the analysis was repeated using 4 alternative divisions:

- Subgrid B: As Subgrid A, but with each subregion shifted 2.5° northeast,
- Subgrid C: fifteen 6° latitude by 6° longitude subregions,
- Subgrid D: twelve 7° latitude by 7° longitude subregions, and
- Subgrid E: six 10° latitude by 10° longitude subregions.

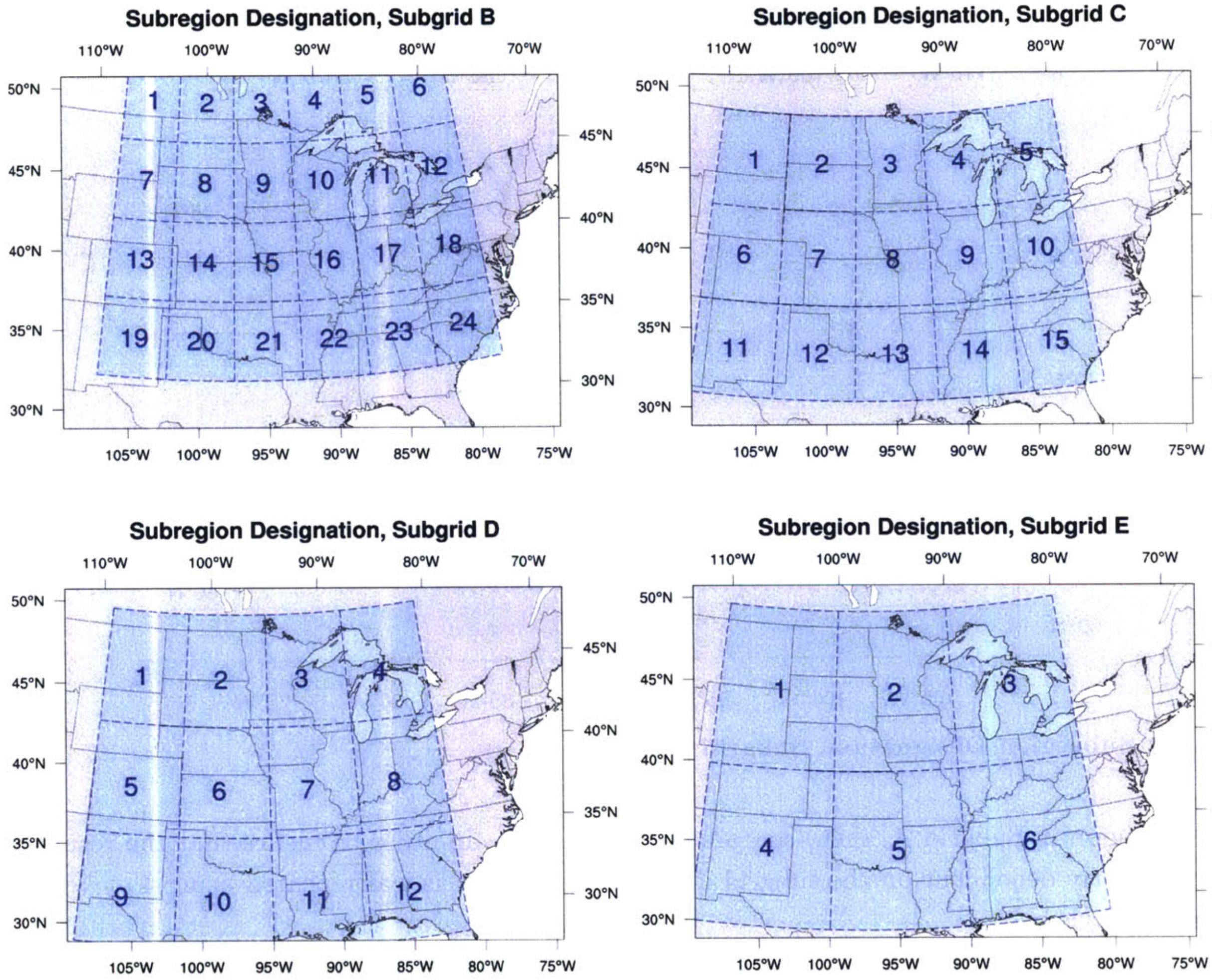


Figure 4: Subregion Designation, Subgrids B, C, D, and E

The historical precipitation data from the UDel dataset were then divided into two "before" and "after" 30-year climates. 30 years is a standard length of time for defining climate normals in a region, as defined by the World Meteorological Organization (WMO, 2011). The data considered were mean monthly precipitation values across both July and August for each year in the record since 1920.

In the statistical analysis, the start times for the "before" and "after" climates were varied in 5-year increments, as were the times separating the two climates. 5-year precision was chosen in order to better compare results between different subgrids and the subregions within them, so that agreement in identified periods of change would be more apparent. The period of most significant change was then defined as the years between the "before" and "after" climates where the greatest proportion of grid cells in a subregion exhibited statistically significant difference between the two climates. The results of the statistical analysis are summarized in section 2.2. Results below.

The overall period of most significant change for the region of interest was determined by inspecting the periods of greatest change for all subregions across each of the subgrids. Weighted averages of the start and end years of the periods of change were used to define the overall period. The greater the percentage of grid cells exhibiting statistically significant change, the greater weighting that subregion had in determining the overall period of most significant change. This period and the resulting changes in precipitation are shown in the Results section below (Figure 5). The change in monthly average air temperatures over the same region and time was also then plotted (Figure 6).

Based on the findings of this analysis, a "Region of Significant Change" (ROSC) was defined that encompassed the majority of grid cells exhibiting statistically significant change. A spatial average for the climate of this region was then determined at each year, and the resulting time series was plotted. The time series plot also shows average precipitation and temperature for the "before" and "after" climates, and the results of testing these for statistically significant change.

Following the determination of the period of most significant change in precipitation, the analysis was repeated while shifting the "after" climate to 1981-2010, the latest period of available data. This approach tests the persistence of the identified change in precipitation. The absolute and percentagewise changes in mean monthly July and August precipitation over the same time period were also determined.

Additionally, a sensitivity check was conducted wherein the two climate periods were extended to 40 years, with 10 earlier years added to the "before" climate, 10 later years added to the "after" climate. The motivation for this was to further reduce the effect of anomalously dry and/or wet individual years on the results. For example, the "Dust Bowl" years of the 1930s (1934, 1936, and 1939), where low rainfall and high temperatures were experienced in the Great Plains, would have affected the mean values of the 30-year "early" climate.

2.2. RESULTS

2.2.1. Period of Most Significant Change

The aim of the statistical analysis on the gridded precipitation data was to determine where and when the greatest changes in precipitation patterns had occurred. Varying the start times of the "before" and "after" climates and the times between them gave different periods of change. The "period of most significant change" was defined as that time during which the greatest proportion of grid cells exhibited statistically significant change. These periods for Subgrid A are given in Table 1 below. The same results for all subgrids are included in Appendix B – Periods of Most Significant Change, Subgrids B-E.

Subregion	Period of Most Significant Change	Percent Change in Monthly Precipitation	% of Grid Cells Exhibiting Statistically Significant Change
1	1965-1970	7.7	7
2			4
3	1940-1970	12.5	12
4	**1950-1970**	**14.1**	**21**
5	1945-1970	10.1	10
6	**1940-1970**	**10.9**	**27**
7	1970-1975	15.7	15
8	1965-1970	16.6	12
9	1950-1975	15.0	18
10	**1950-1980**	**21.5**	**27**
11	**1950-1975**	**29.0**	**73**
12	**1955-1980**	**16.2**	**22**
13	1965-1970	5.1	8
14	1940-1945	11.7	13
15	1960-1965	7	8
16	1940-1980	2.6	7
17	1955-1965	14.9	18
18	1945-1975	-4.7	15
19	1965-1970	14.0	18
20	**1960-1965**	**22.3**	**29**
21			5
22	1940-1980	-8.8	8
23			5
24	**1945-1975**	**-9.8**	**21**

Table 1: Results from Period of Most Significant Change Analysis, Subgrid A

Notes:

1) Results where 5% or less of grid cells exhibited statistically significant change were not included because the significance level of the test was 5%; i.e. results of up to around 5% could be expected simply from random variations in the data.

2) Subregions where more than 20% of grid cells exhibited statistically significant change are bolded for emphasis.

With few exceptions, the periods of most significant change centered on the middle of the century. The results did not appear to be very multimodal (i.e. having more than one peak). This allowed for a single weighted average to be taken in order to determine the overall period of most significant change.

The weighted averages of the start and end years for the overall period of most significant change for each of the subgrids are shown in Table 2, below.

Subgrid	Start Year Weighted Average	End Year Weighted Average
A	1951.66	1971.83
B	1951.27	1969.46
C	1952.88	1970.76
D	1952.71	1970.09
E	1951.36	1969.69

Table 2: Weighted Averages for Start and End Years of Period of Most Significant Change

Notes:

1) The greater the percentage of grid cells in a subregion exhibiting statistically significant change, the greater weighting that subregion had in determining the overall period of most significant change.

Based on these results, the period of most significant change for the region of interest was defined as 1950-1970.

2.2.2. Region of Most Significant Change

As is shown in the results in Table 1 above, Subregions 4, 6, 10, 11, 12, 20, and 24 exhibited the most significant changes in precipitation across the analysis period. This suggests much significant change around the Great Lakes region in the northeast of the region of interest, as well as significant change in smaller areas in the southwest and southeast. Similar results are found when the results from alternative Subgrids are analyzed (see Appendix A – Alternative Gridded Weather Data Results).

Perhaps the most revealing illustration of the changes in precipitation is when these differences are plotted for the period of most significant change as defined above.

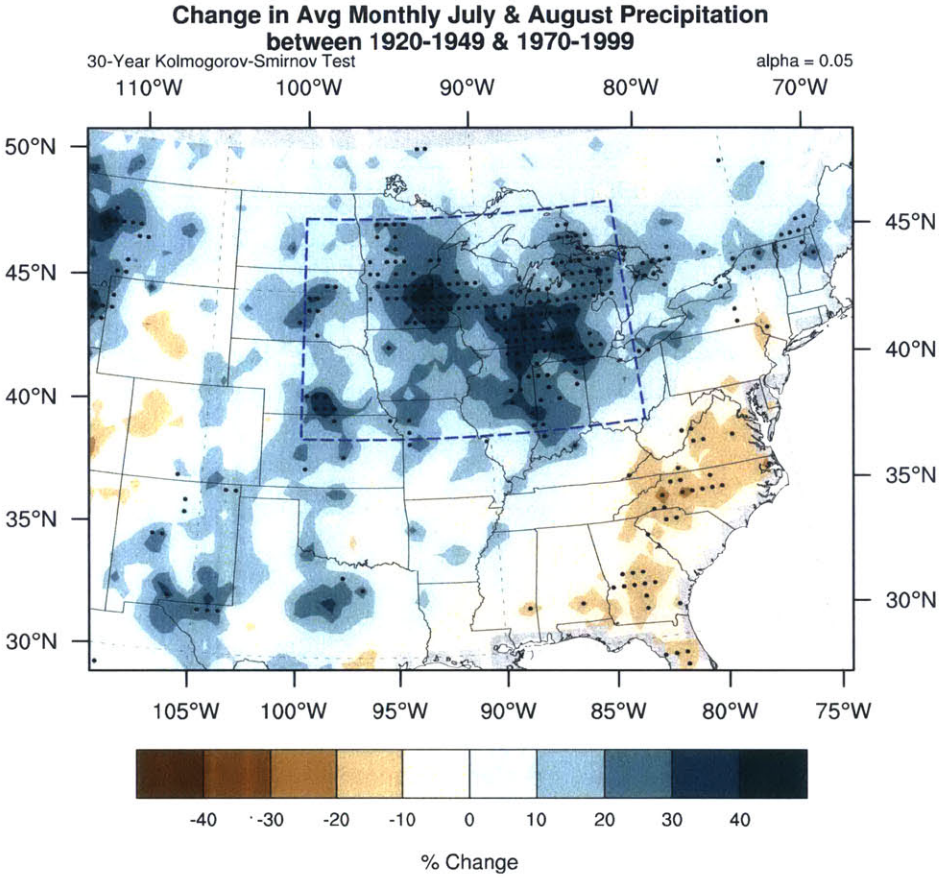


Figure 5: Change in Average Monthly July & August Precipitation between 1920-1949 & 1970-1999

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 95% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the Region of Significant Change (ROSC), defined below.

We can see that between the 30-year climates either side of the period 1950-1970, precipitation increased by over 20% in a large area over Minnesota, Wisconsin, Michigan, Illinois, and Indiana, with increases of over 40% in some areas. Smaller regions in central South Dakota, southern Nebraska, and near the Texas-New Mexico border also exhibited large, statistically significant increases in precipitation. Meanwhile, southeastern coastal states from Virginia to Florida all exhibited decreases in precipitation of up to ~30%. For the equivalent figures using the CRU and GPCC datasets, see Appendix A – Alternative Gridded Weather Data Results.

Based on these results, a "Region of Significant Change" (ROSC) was identified. The ROSC is a 9° latitude by 18° longitude subregion that encompasses the majority of areas that exhibited significant increases in precipitation. The ROSC extends from 39°N to 48°N and 82°W to 100°W.

The average precipitation levels for the region during the "before" and "after" climates are shown in Figure 6, below.

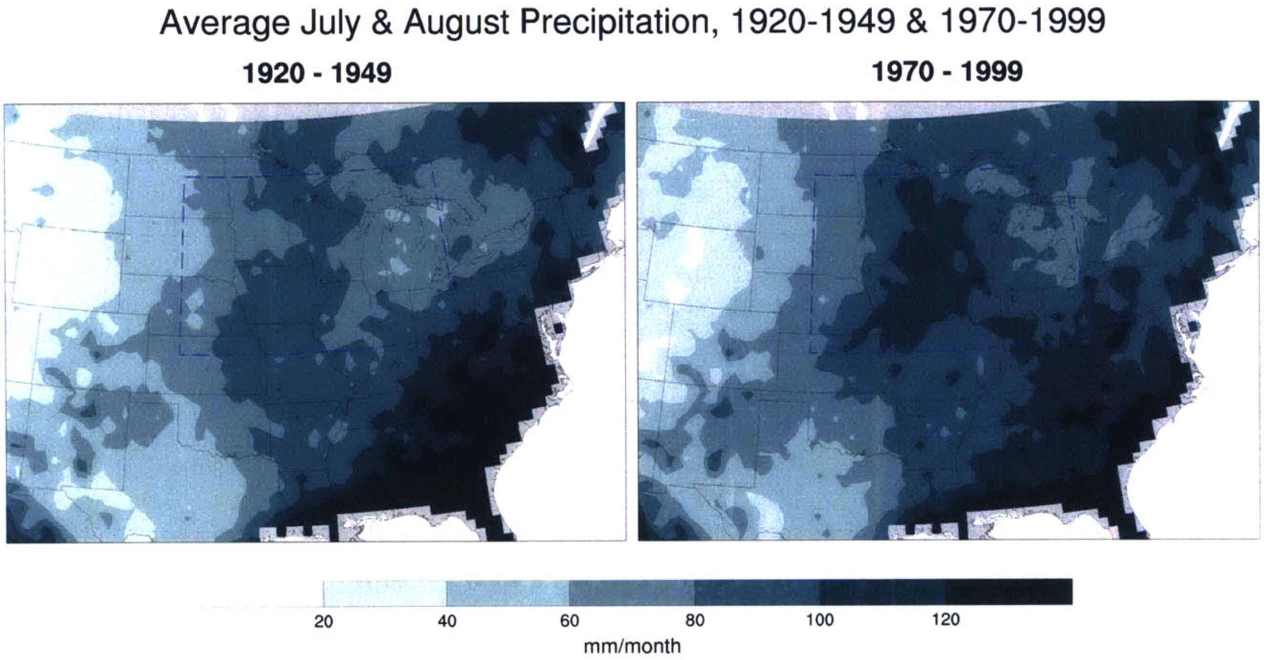


Figure 6: Average July & August Precipitation, 1920-1949 & 1970-1999

The increases in July & August precipitation in the ROSC are apparent in this figure. Large parts of the region increased from an average precipitation rate of 60-80mm/month to 80-100mm/month or from 80-100mm/month to 100-120mm/month. The decreases in precipitation in the Southeast are also apparent with a shrinking of the proportion of the region with over 120mm/month of precipitation.

2.2.3. Temperature

The same region was also analyzed for changes in temperature, over the same period.

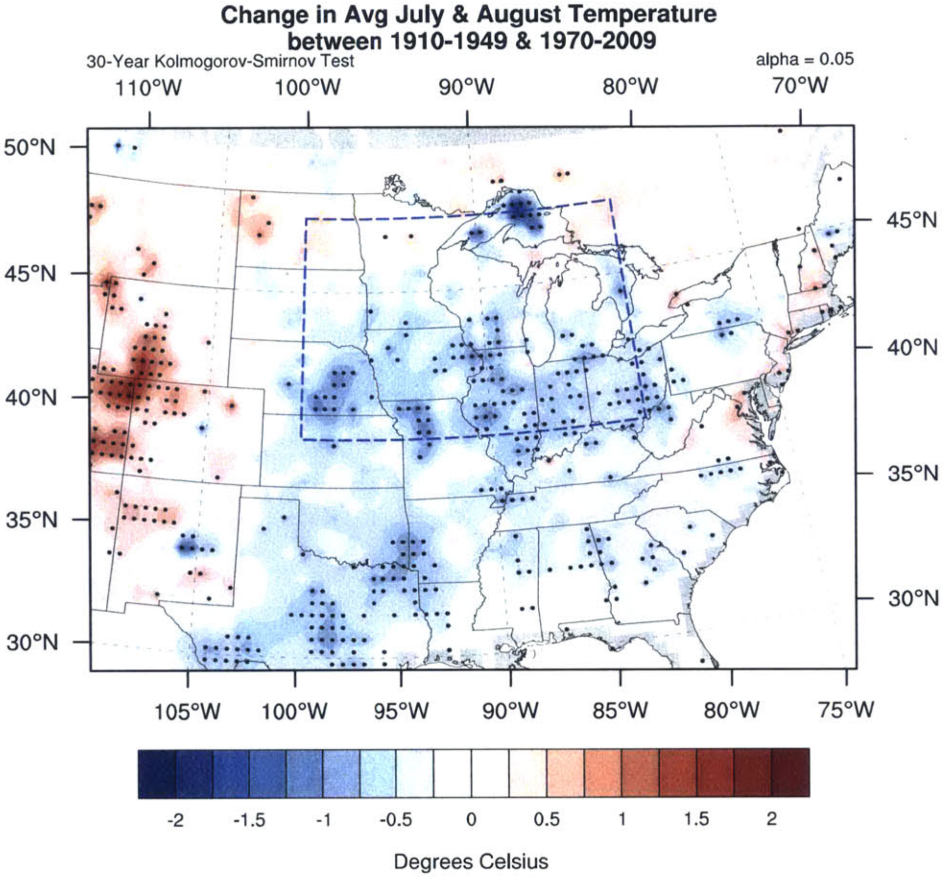


Figure 7: Change in Average July & August Temperature between 1920-1949 & 1970-1999

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the ROSC.

Comparing Figure 5 and Figure 7, we can see that the region generally southwest of the Great Lakes where precipitation increased also experienced significant decreases in temperature over the period of 1950-1970. Significant decreases in temperature were also observed in South Dakota and Nebraska, where precipitation increased. The magnitude of these changes was typically around -0.5°C to -1.0°C.

Significant decreases in temperature were also observed in Texas, though they did not necessarily correlate with those areas that experienced increases in precipitation. The coastal southeastern states where precipitation decreased did not exhibit robust changes in temperature.

Temperatures increased significantly in the western mountainous sections of Wyoming, Colorado, and New Mexico. As is discussed further in the Discussion section below, it is important to note that these observed changes in temperature are against a background of global warming, with general worldwide increases in global July and August temperatures.

2.2.4. Time Series

To illustrate more clearly the temporal nature of changes in precipitation and temperature, both of these weather parameters were averaged over the ROSC and then plotted in a time series.

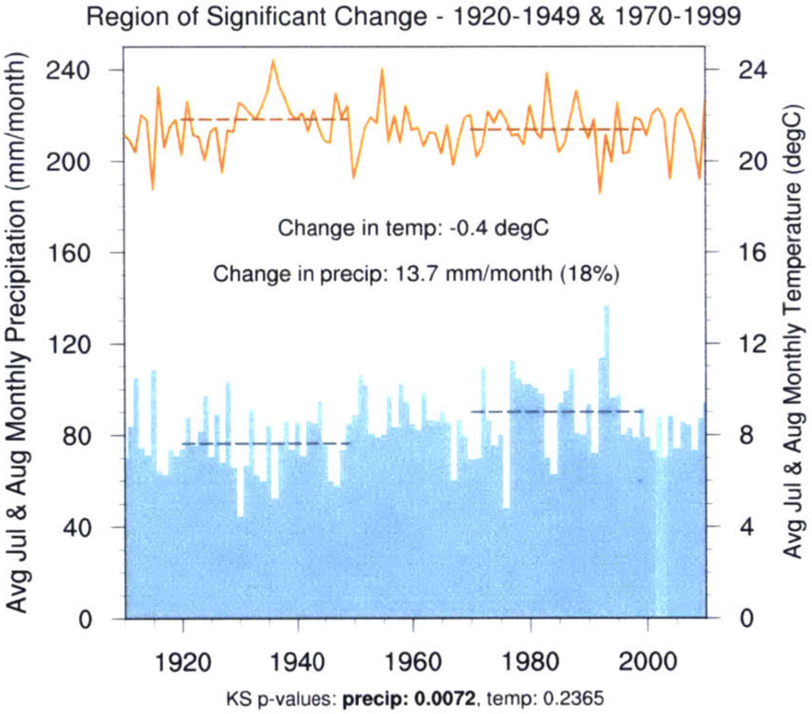


Figure 8: Time Series of ROSC, Comparing 1920-1949 & 1970-1999

Notes:

1) P-values less than 0.05 are bolded to indicate statistical significance as defined in "Tests of Statistical Significance" in "Analytical Methods", above.

The observed change in average total monthly precipitation was an average of 13.7mm across the ROSC, representing an 18% increase. This change was statistically significant. Average July and August temperatures also decreased, though this decrease was not found to be statistically significant. This is perhaps to be expected, as a smaller proportion of grid cells in the ROSC exhibited statistically significant change for temperature than for precipitation.

2.2.5. Determining Persistence of Change

In order to determine whether the observed changes in climate were transient or whether they represented a more long-term shift, the "after" climate was redefined as 1981-2010, the latest 30-year period included in the UDel dataset. The aim of this was to mediate the influence of anomalous years, which may have exaggerated the magnitude of the observed changes. However, there is considerable overlap between the periods of 1970-1999 and 1981-2010, so this effect cannot be ruled out entirely.

The analyses were carried out using the same "before" climate and both the original and later "after" climate:

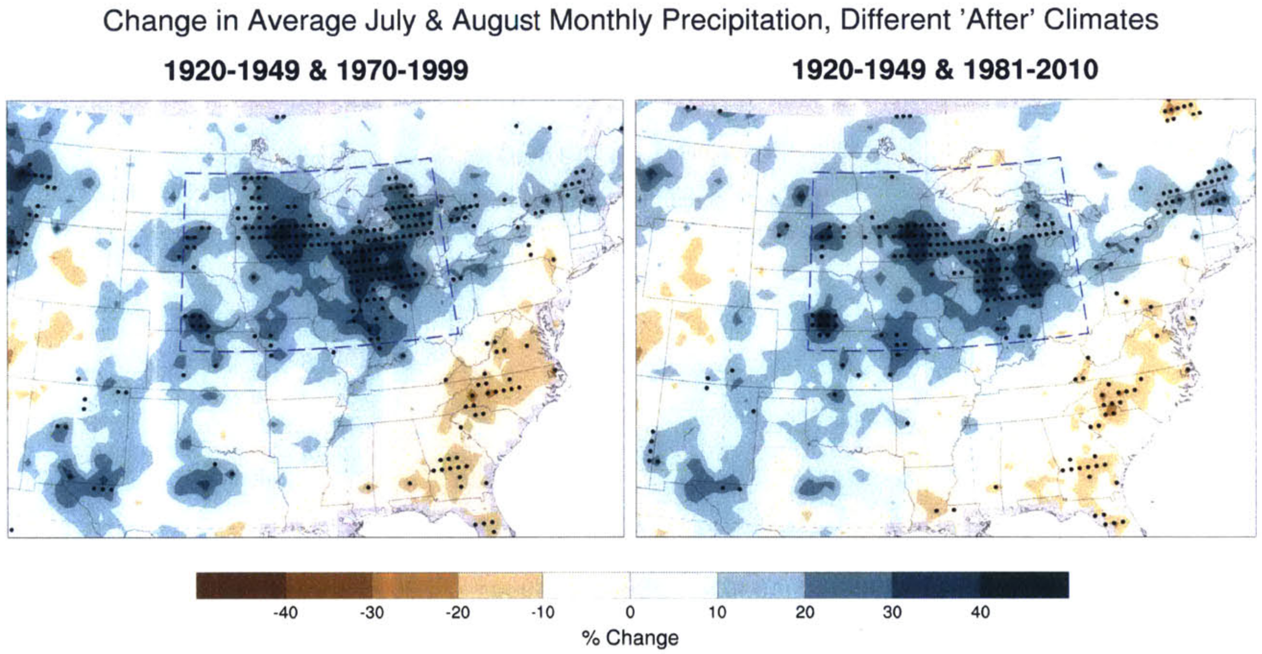


Figure 9: Change in Average July & August Monthly Precipitation using Different "After" Climates

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the ROSC.

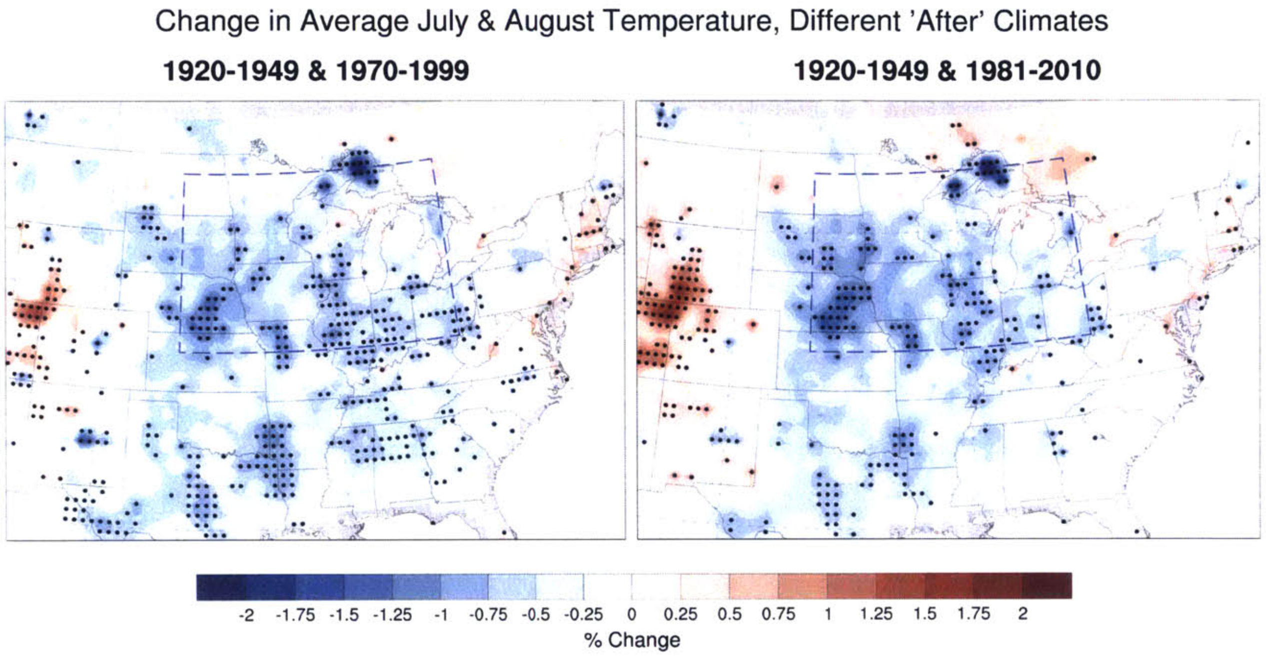


Figure 10: Change in Average July & August Monthly Temperature using Different "After" Climates

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the ROSC.

The trends observed for precipitation in the first analysis persist, though the magnitude of change appears to slightly decrease in most areas. The broad decrease in temperature observed in the first analysis is lowered in magnitude, though it is relatively persistent within the ROSC. Eastern Nebraska exhibits a greater decrease in temperature with the later "after" climate. The observed increase in temperature over the mountainous West becomes even greater.

A time series analysis similar to Figure 8 was also produced for the later "after" climate.

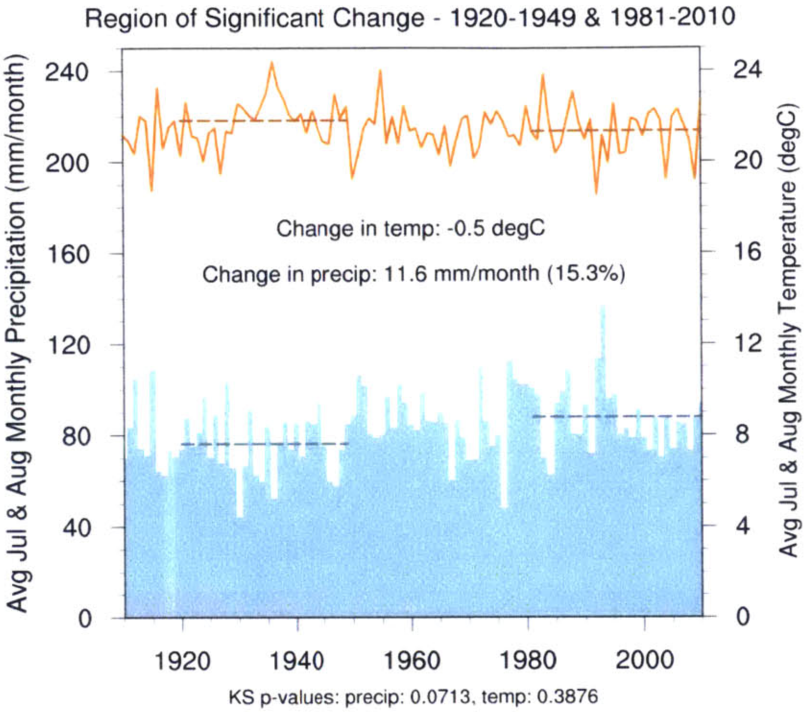


Figure 11: Time Series of ROSC, Comparing 1920-1949 & 1981-2010

Shifting the "after" climate out to 2010, precipitation was still seen to increase, though by a lesser amount. While the trend is still apparent, it is no longer statistically significant at the 95% level when averaged over the entire ROSC. Temperature decreased by slightly more in this analysis than previously, though the trend is still not statistically significant.

The climate characteristics across the ROSC are tabulated for each of the 30-year climates in Table 3, below.

		Climate Period		
		1920-1949	**1970-1999**	**1981-2010**
Precipitation (mm/month)	**Mean**	76.3	90.0	87.9
	σ	29.2	36.2	34.5
	% Significant	-	27.2%	20.8%
Temperature (°C)	**Mean**	21.8	21.4	21.4
	σ	2.84	2.73	2.73
	% Significant	-	19.3%	15.9%

Table 3: Summary of Climate Characteristics across Region of Significant Change

Notes:

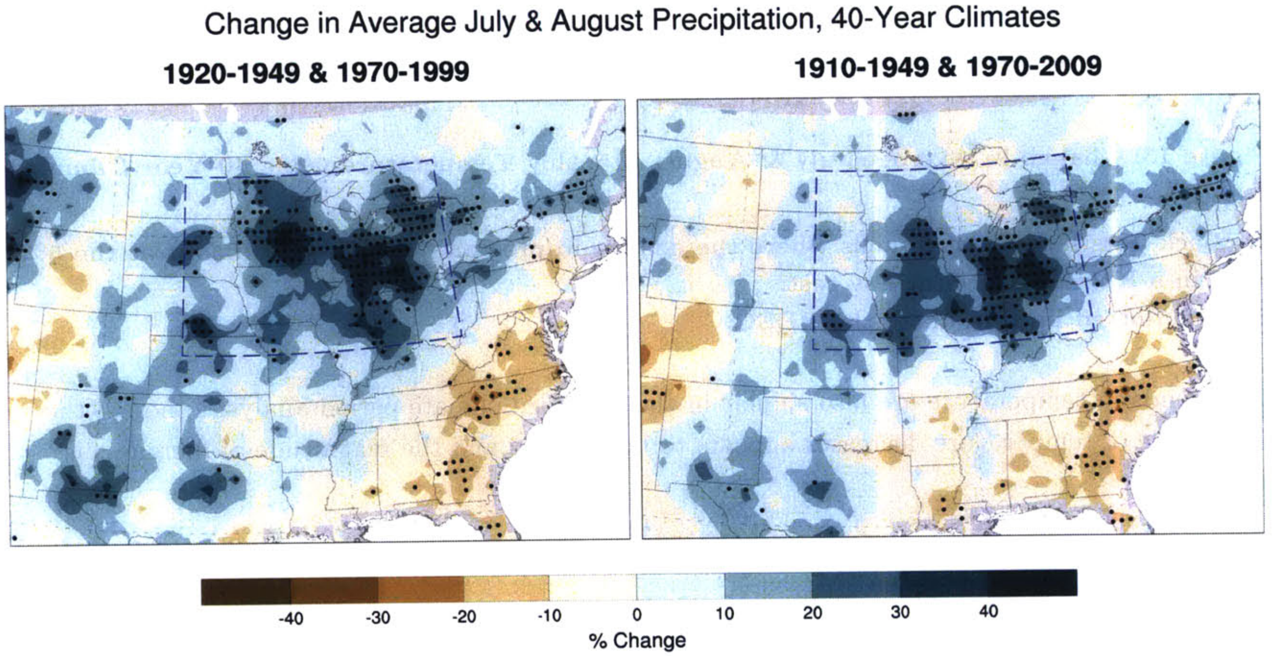
1) σ = Standard Deviation

2) % Significant = the percentage of grid cells within the ROSC exhibiting statistically significant change

It is notable that for precipitation, both the mean and standard deviation increased, i.e. there were changes in both central tendency and variance. Both of these changes in the empirical distribution are captured using the K-S test. Both the mean and the standard deviation decreased for temperature, though to a lesser degree than for precipitation. As is expected from the earlier figures, a greater proportion of grid cells change significantly for precipitation than for temperature and for 1970-1999 than for 1981-2010.

2.2.6. Additional Sensitivity Check

To test the sensitivity of the results to anomalous years, the "before" and "after" climates were extended 10 years earlier and later, respectively. Both precipitation and temperature were analyzed.


Change in Average July & August Precipitation, 40-Year Climates

1920-1949 & 1970-1999

1910-1949 & 1970-2009

Figure 12: Change in Average July & August Monthly Precipitation using 40-Year Climates

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the ROSC.

The trends in precipitation are very similar when the climate periods are extended to be 40 years long, while maintaining the same separation period (1950-1970). The magnitude of change is slightly less in most areas, but significant increases are still observed within the ROSC. The decreases in the Southeast and relatively modest increases in Texas are also still apparent.

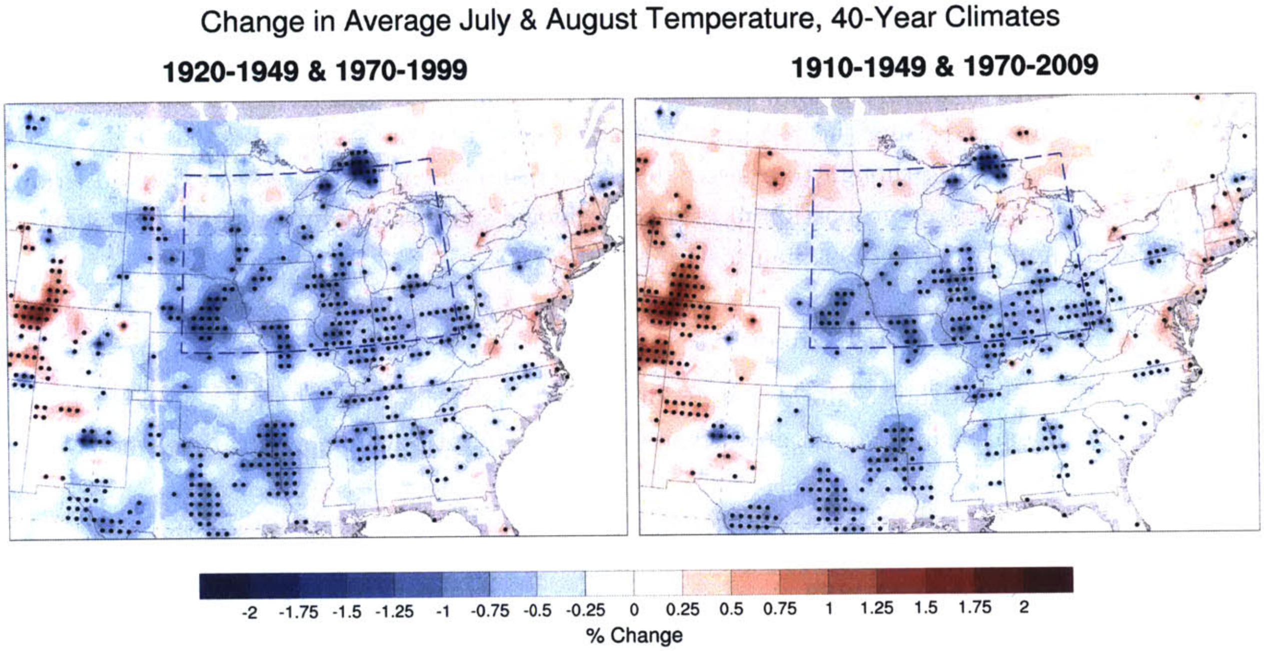


Figure 13: Change in Average July & August Monthly Temperature using 40-Year Climates

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

2) Blue dotted lines indicate the ROSC.

The trends in temperature are also similar in the extended climate period analysis, though the magnitude of temperature decreases appears to be lessened and the magnitude of increases is greater.

2.3. DISCUSSION

The evidence for changes in both precipitation and temperature in the region of interest is very strong. Precipitation increased significantly over a large area covering much of the Midwest and decreased in the Southeast. Meanwhile, the Midwest, Great Plains, and parts of Texas all experienced decreases in temperature. These changes in climate occurred primarily between 1950 and 1970 between 39°N & 48°N and 82°W & 100°W.

The changes in precipitation are persistent; the increases have been sustained through to recent years. The decreases in temperature exhibit less persistence, but appear to be better sustained in the Midwest than elsewhere. The proportion of grid cells exhibiting statistically significant change in both precipitation and temperature decreases when the analysis is shifted to more recent years, though large areas within the region maintain this significance.

One notable location is Eastern Nebraska, where the temperature decrease was even greater when a later comparison climate period was considered. The prominent increase in irrigation in this area (see Figure 24) may have contributed to this. The decreases in Nebraska may account for the overall continued decrease in temperature when the analysis was extended out to 2010.

Based on the time series, the increase in precipitation appears to remain somewhat steady after the period of change, while temperature appears to continue to decrease. It is thus somewhat unclear whether the nature of the change in climate is more of a step change that occurred in the past or more of a gradual trend that is ongoing.

The overall trends of precipitation increases and temperature decreases in the Midwest are in agreement with prior observational analyses.

It is also important to note that the observed decreases in temperature are against a background of global warming during the same time period. Average July and August temperature decreased by around 0.4°C in the ROSC between 1920-1949 and 1970-1999. However, when the same analysis is applied to all land surfaces across the globe using the UDel dataset, average July and August temperature increased by around 0.3°C over the same time. This suggests that some mechanism other than global climate change is responsible for the observed decrease in temperature and that without global warming, the decreases might be even greater.

These results do not appear to be particularly influenced by anomalously dry and/or wet years. Extending both climate periods to be 40 years long, but separated by the same 1950-1970 period reveals that the observed trends are still clearly apparent. This suggests that there was indeed a shift in the climate characteristics of the region in the middle of the century.

The UDel dataset is a rich source of data that has been through many quality control procedures and the findings from analyzing it appear clear. However, it is always prudent to subject such findings to verification. The following chapters look for additional evidence for changes in precipitation and temperature, as well as other climate variables, to further investigate possible changes in climate. The period of greatest change and ROSC identified in this analysis are carried through into the following chapters to allow for direct comparisons of the findings.

3. WEATHER STATION DATA

3.1. ANALYTICAL METHODS

Data from weather stations were used for two primary purposes: 1) to verify the results from the UDel dataset, and 2) to analyze variables that were not included in the UDel dataset, including humidity and air pressure.

3.1.1. Verifying Findings from the UDel Dataset

In order to verify the results obtained from analyzing the UDel dataset, independent records of precipitation and temperature were required. Stations from the GHCN network and accessed via the National Oceanic and Atmospheric Administration (NOAA) website were chosen for this purpose (Menne et al., 2012). While it is important to note that data from these stations may have been included in the UDel dataset, comparing the individual station data against the gridded dataset can be seen as a check against the interpolation and sanitization methods used in preparing the UDel dataset.

25 stations were chosen that had at least 95% data coverage over the time period 1920-2010. Stations were chosen to, as close as possible, be collocated with areas exhibiting significant change in precipitation in the UDel dataset (Figure 14). The variables analyzed were monthly mean temperature and monthly precipitation. Average values including both July and August for each year were calculated and plotted as a time series for each station.

Also shown on the time series plots are two 30-year average values for temperature and pressure. These 30-year periods align with the time periods identified through the statistical analysis of the UDel dataset. The changes in both temperature and pressure were calculated, and the statistical significance of these changes was calculated using the K-S test.

3.1.2. Humidity and Air Pressure

Humidity and air pressure are important variables to consider in ascertaining whether or not changes in agricultural land use are partly responsible for observed changes in climate. Directly measuring evapotranspiration (ET) from crops is difficult, though techniques exist for estimating ET from other variables (Allen & Pereira, 1998). General increases in humidity and air pressure should be observed if there was an increase in ET, though the exact relationship is highly dependent on other weather conditions. (e.g. high relative humidity can, in turn, limit ET.)

A second set of station data, the Integrated Surface Database (ISD), was also accessed through NOAA (NOAA Federal Climate Complex, 2006). Stations in this database record parameters including: air temperature, dew point temperature, and air pressure. Of the stations collocated with areas exhibiting significant change in precipitation in the UDel dataset, only those that had data going back to before 1950 and with over 80% data coverage were selected. 12 stations were identified that met these criteria (see Figure 16 in "Results" below). No stations with complete records dating to before 1938 were identified.

Specific humidity was calculated from dew point temperature and air pressure using the following formulae, derived from (Alduchov & Eskridge, 1996) and (Vaisala Oyj, 2013):

$$SH = a\frac{P_w}{P}$$

$$P_w = 6.1094e^{\left(17.625T_d/(243.04+T_d)\right)}$$

Where:

SH = specific humidity

a = ratio of molecular weight of water to that of dry air = 0.622

P_w = vapour pressure of water at a given dew point temperature

P = atmospheric pressure

T_d = dew point temperature

Because very little data was available for the period of the earlier 30-year climate, using the K-S test for determining statistically significant change was not considered appropriate. Instead, a simple linear least squares regression was applied to the specific humidity and air pressure data and the sign of the trend (positive or negative) was observed.

3.2.1. Verifying Findings from the UDel Dataset

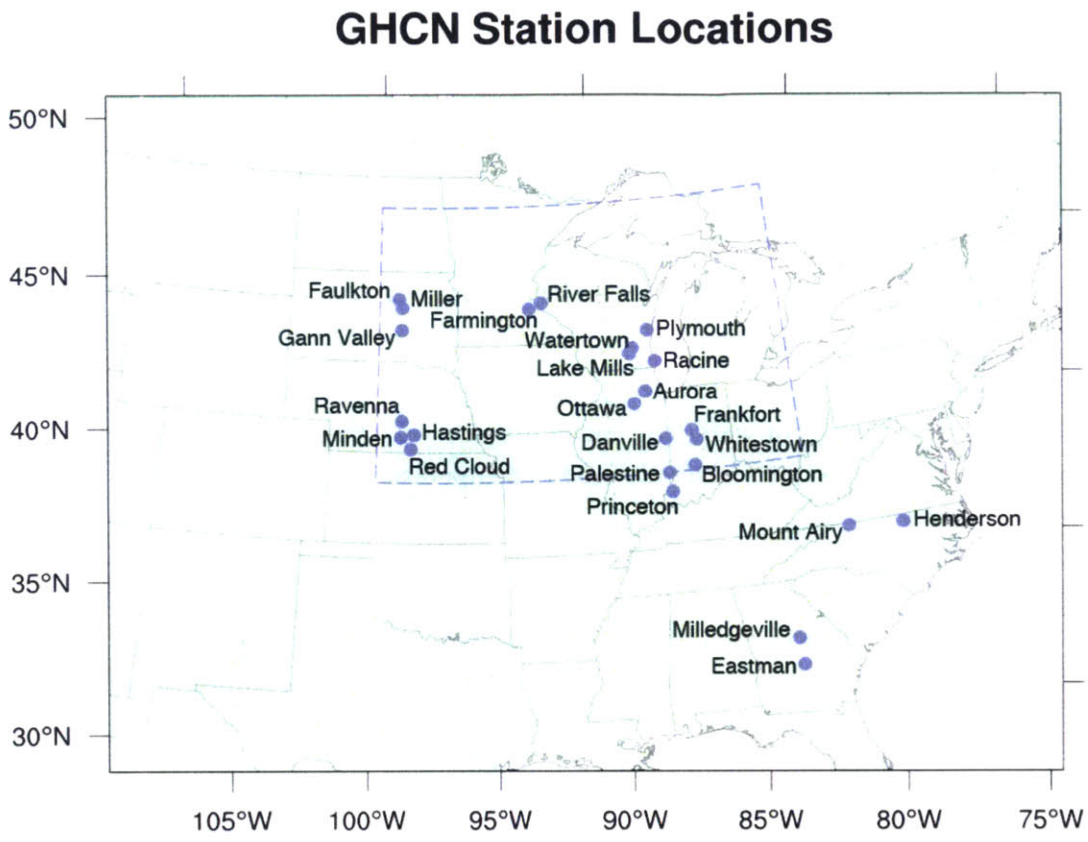


Figure 14: Map of GHCN Station Locations

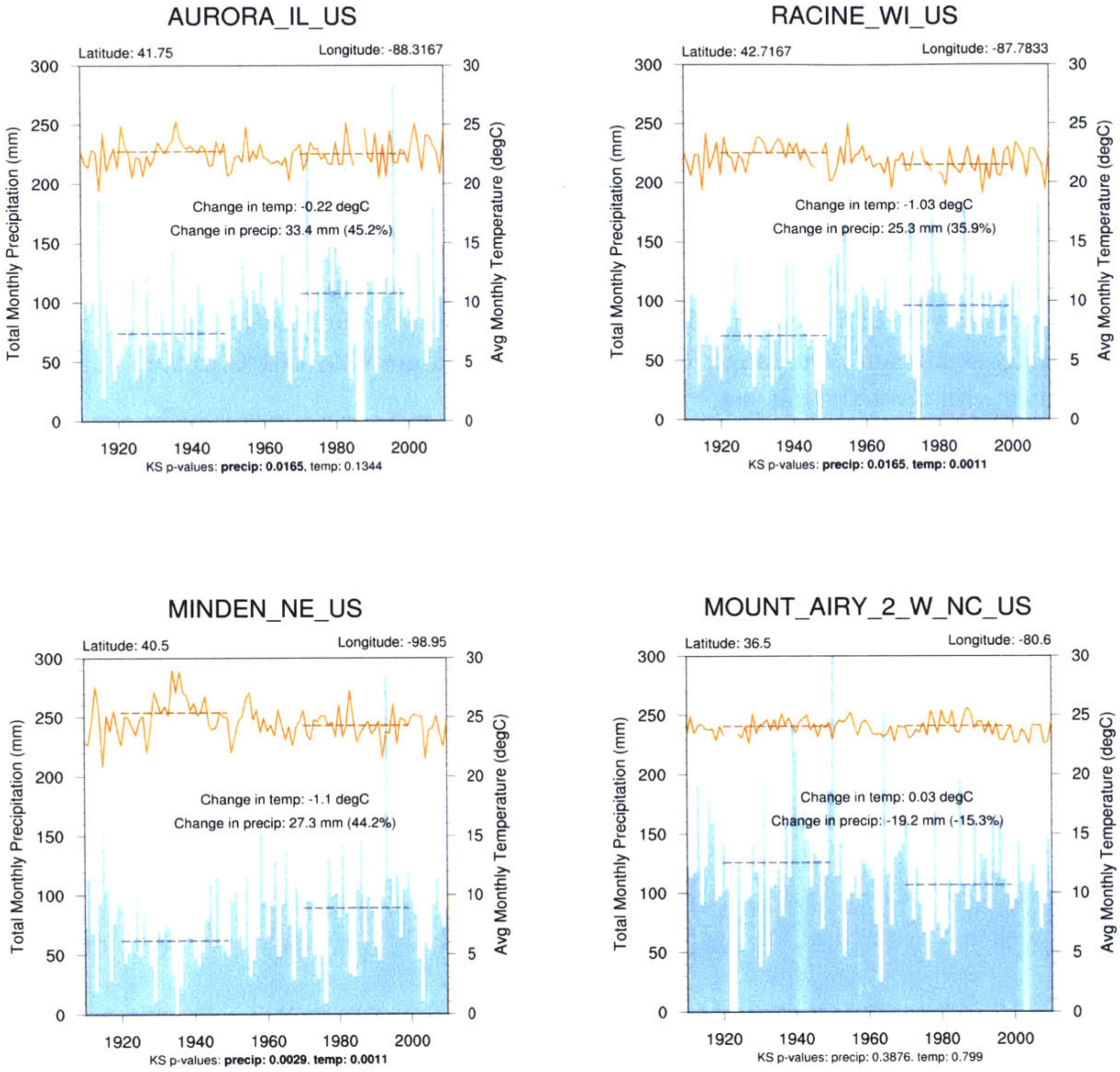


Figure 15: Examples of Time Series Plots of Precipitation and Temperature for GHCN Stations

Notes:

1) P-values less than 0.05 are bolded to indicate statistical significance.

Equivalent plots for all 25 stations are included in Appendix D – Time Series for GHCN Stations.

Of the 25 stations analyzed, all exhibited changes in precipitation in the same direction as the corresponding regions in the UDel dataset between the "before" and "after" climates. Stations in North Carolina and Georgia exhibited decreases in precipitation, while the other stations exhibited increases. 12 out of 25 changes were found to be statistically significant. The range of changes in precipitation was -23.9% to 54%, which is in general accordance with the UDel dataset.

For temperature, 23 of 25 stations exhibited changes in temperature in the same direction as the corresponding regions in the UDel dataset between the "before" and "after" climates. 22 of these 23 changes were decreases, with one station in North Carolina showing a very slight increase in temperature, in accordance with the UDel data. 13 out of 25 changes were found to be statistically significant. Both stations that exhibited increases in temperature where UDel showed decreases were in Wisconsin. Both increases were very slight, and neither was found to be statistically significant. The range of changes in temperature was -1.61°C to 0.06°C, which is in accordance with the UDel dataset.

3.2.2. Humidity and Air Pressure

Plots of average July and August specific humidity over time for the twelve ISD stations analyzed are included in Figure 16, while average July and August sea level pressure values for the same stations are shown in Figure 17. Specific humidity is reported in kg/kg, while sea level pressure is reported in hectopascals, hPa. The start dates ranged from 1938 to 1955. Some stations suffered from considerable gaps in the data record. Individual plots for all stations are included in Appendix E – Time Series for ISD Stations.

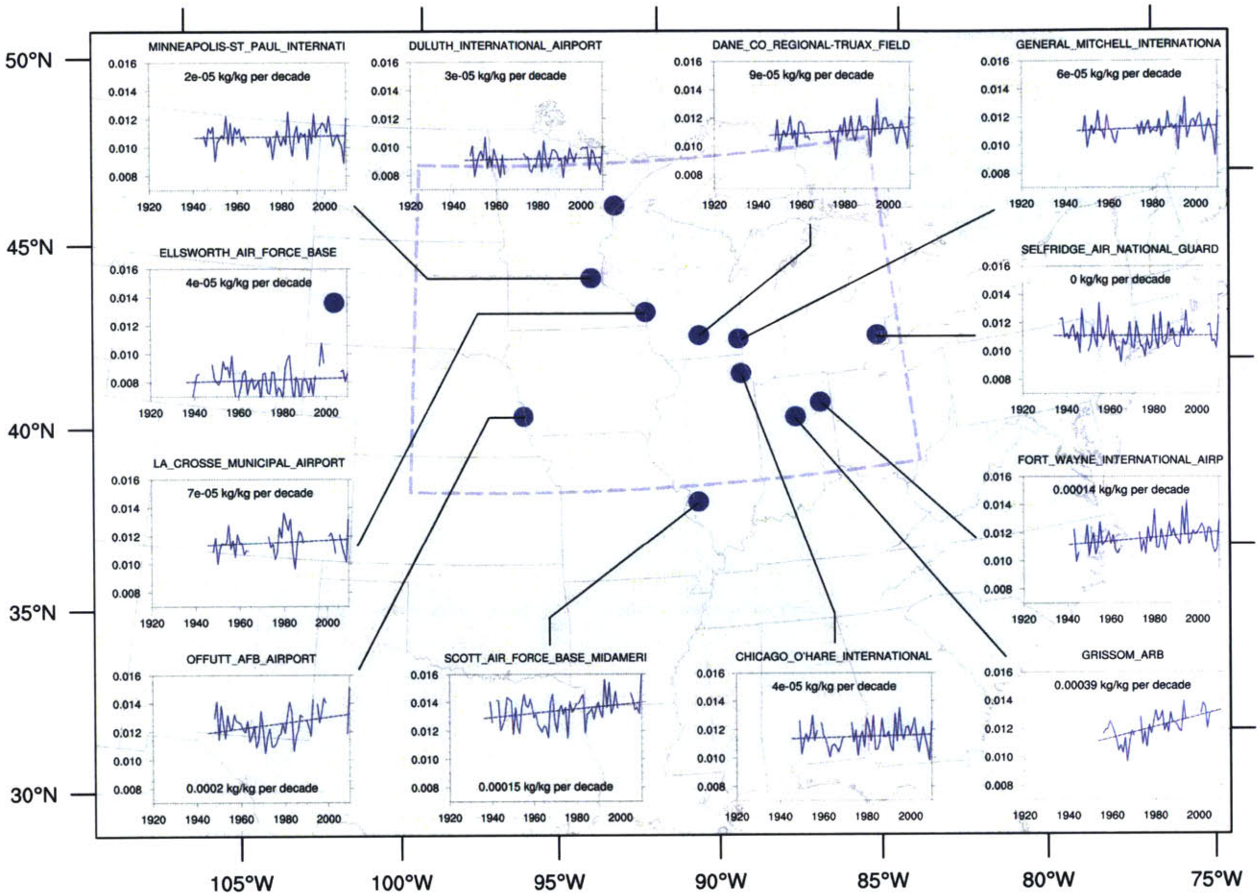


Figure 16: Map of ISD Stations with Time Series of Specific Humidity

Notes:

1) Specific humidity is reported in kg/kg.

All except one of the stations exhibited increases in specific humidity across their periods of record, with one station exhibiting no trend.

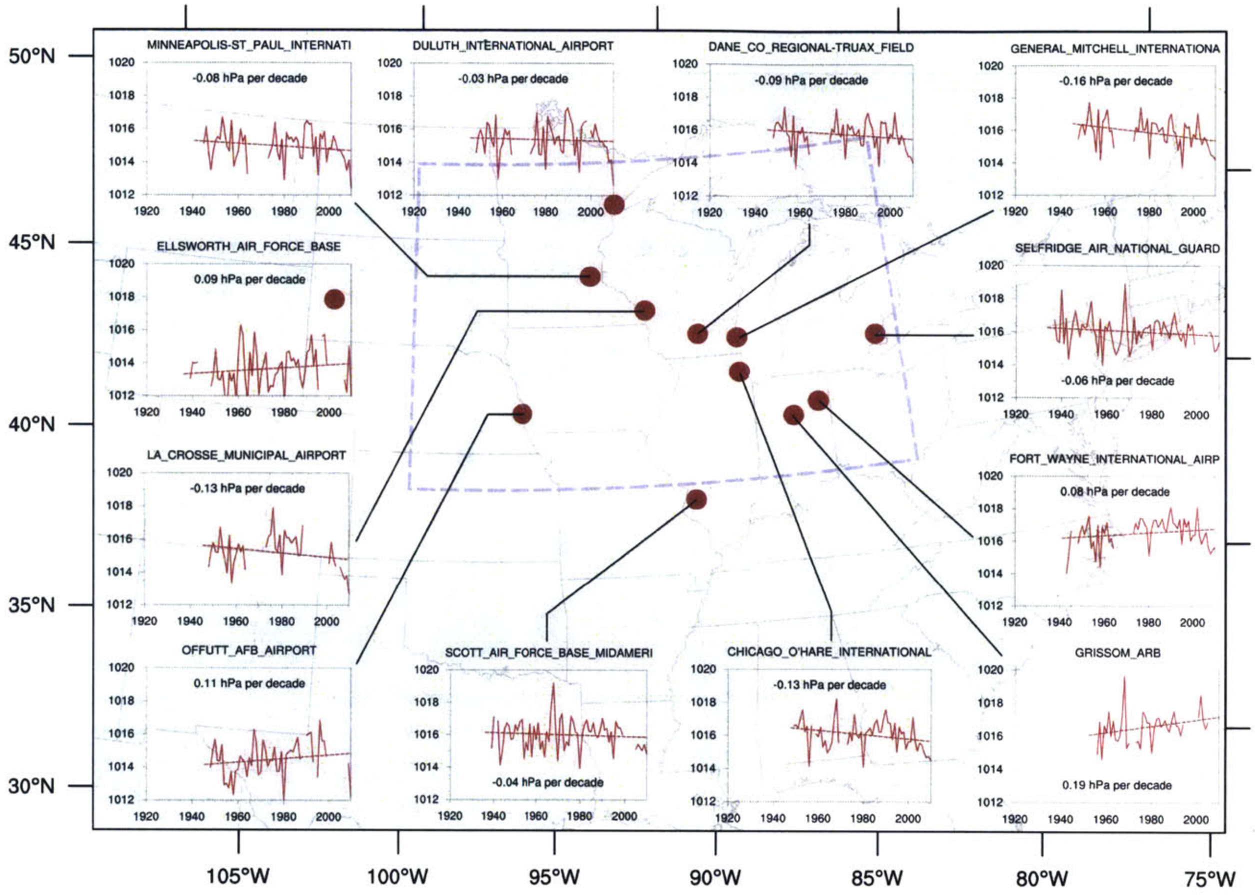


Figure 17: Map of ISD Stations with Time Series of Sea Level Pressure

Notes:

1) Sea level pressure is reported in hPa.

No consistent trend emerged from the sea level pressure data, with 8 of the 12 stations exhibiting negative trends in pressure and 4 exhibiting positive trends. There also appears to be no regional pattern as to whether a station exhibited an increasing or decreasing trend.

3.3. DISCUSSION

3.3.1. Verifying Findings from the UDel Dataset

The GHCN stations showed very good correspondence with results from the UDel dataset. Both precipitation and temperature were observed to change between the "before" and "after" climates with similar magnitudes to the corresponding areas in the UDel dataset. Changes at approximately half of the stations were found to be statistically significant.

While the range of changes in precipitation were slightly higher than for the UDel dataset, this is unsurprising, as the interpolation methods used in creating the gridded UDel dataset likely smoothed out the influence of extreme values to some extent. The stations exhibiting the greatest increases in precipitation correspond exactly with local maxima on the plot of UDel data.

Similar to the time series for the ROSC, most stations appear to show more of a step increase in precipitation either side of 1950-1970 and more of a gradual decline in temperature.

Because the UDel dataset is, in part, based off of data from GHCN stations, good correspondence between the stations and the gridded dataset is unsurprising. This finding does, however, demonstrate that the trends observed from the UDel dataset alone are not artefacts of the data interpolation and processing methods used to generate the dataset.

3.3.2. Humidity and Air Pressure

Because the range of the available data for ISD stations did not allow for a "before" and "after" pairwise comparison of climates, a simple linear least squares regression was used to test for trends in specific humidity. All except one of the stations exhibited increases in specific humidity. The periods of record for most stations included the time between the "before" and "after" climates, and so the trend observed can help inform what the change in specific humidity was likely to be. It would be somewhat spurious to conclude solely from these results that specific humidity definitely increased between 1920-1949 and 1970-1999 in the region of interest, but these results present a compelling argument in support of this conclusion. This increase in specific humidity is evidence in favor of a corresponding increase in evapotranspiration over the same time and region.

The results from analyzing air pressure were less conclusive. There may have been a slight trend towards decreasing sea level air pressure, but this was not consistent across the stations analyzed. A station's location appeared to have little bearing on whether air pressure increased or decreased. However, this was not the only source of data for analyzing variables besides precipitation and temperature. The next chapter looks at the results from analyzing additional gridded datasets.

4. GRIDDED PRESSURE DATA & REANALYSIS PRODUCTS

4.1. ANALYTICAL METHODS

Two additional datasets of gridded weather data were analyzed in order to determine the changes in climate variables not covered in the UDel dataset. Descriptions of these datasets follow. The methods used very closely followed those for the UDel dataset once the period and region of most significant change had been determined. The results show changes in variables between the "before" climate of 1920-1949 and the "after" climate of 1970-1999.

4.1.1. Hadley Data Center

The Hadley Centre Sea Level Pressure dataset (HadSLP2) from the United Kingdom's Met Office is a database of mean sea level atmospheric pressure (Allan & Ansell, 2006). It provides monthly values from 1850 to 2004 at a resolution of 5° latitude by 5° longitude across the entire globe. Its resolution is thus 100 times coarser than the UDel dataset, but it has complete coverage over the time period analyzed (1920-1999). The dataset is built from observations at 2228 stations, with relatively good coverage in the United States.

4.1.2. NOAA-CIRES Twentieth Century Reanalysis

The Twentieth Century Reanalysis (Version 2c) is produced by the Earth System Research Laboratory Physical Sciences Division from NOAA and the University of Colorado Cooperative Institute for Research in Environmental Sciences (Compo et al., 2015). The dataset is produced using a global climate model that assimilates historical surface observations of atmospheric pressure at a synoptic level. Data from 1851 to the present are provided at a resolution of 2° latitude by 2° longitude across the entire globe. The variables considered in this analysis are: precipitation rate, surface-level air temperature, sea level pressure, surface-level specific humidity, and canopy water evaporation.

4.2. RESULTS

4.2.1. Hadley Data Center

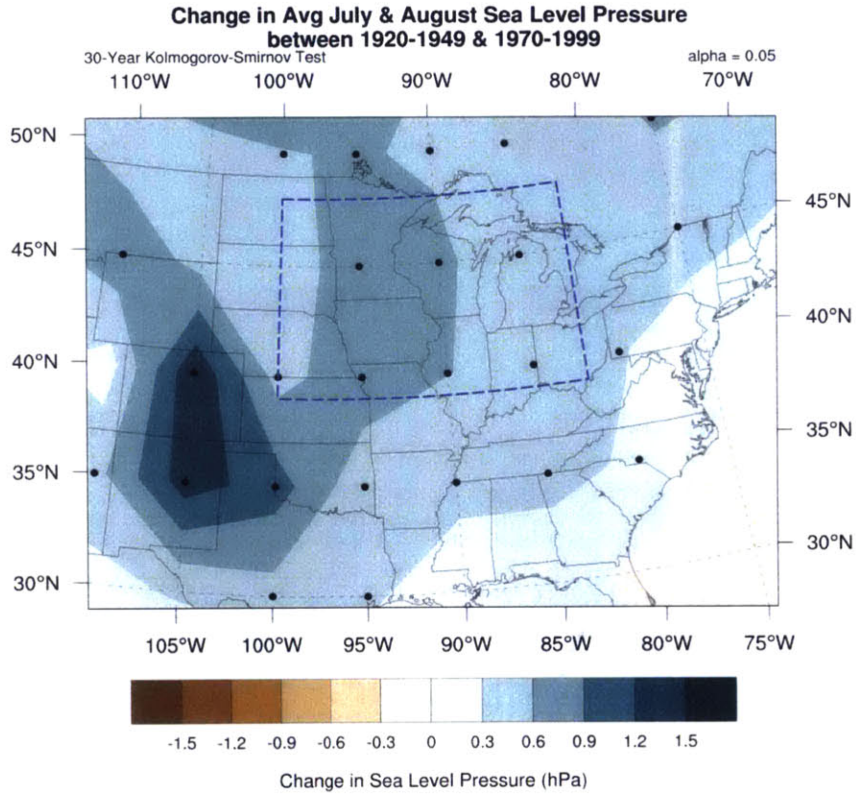


Figure 18: Change in Average July & August Sea Level Pressure between 1920-1949 & 1970-1999 (HadSLP2)

Notes:

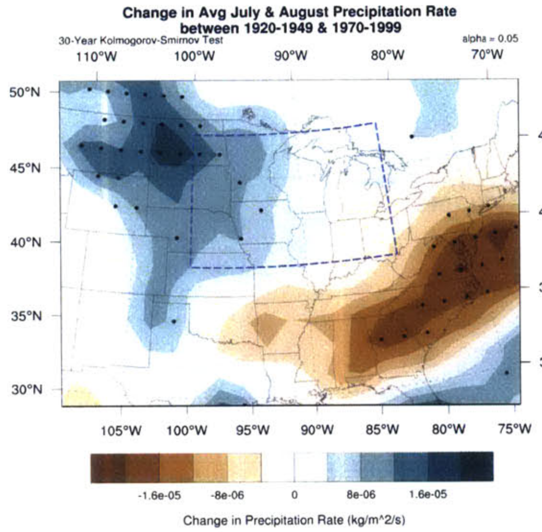
1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

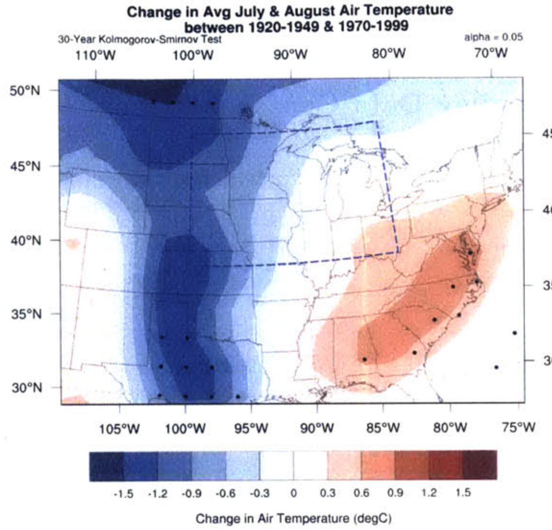
2) Blue dotted lines indicate the ROSC.

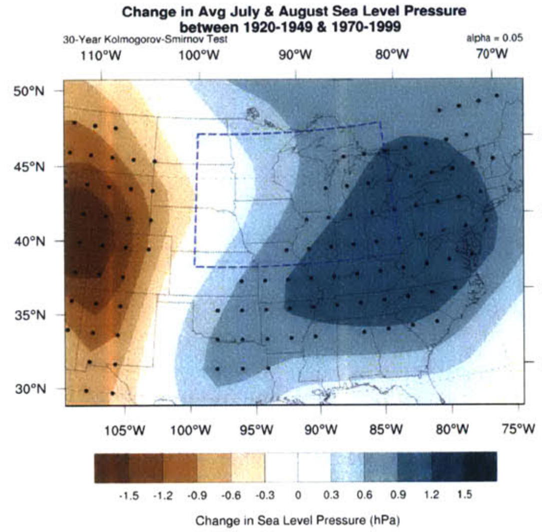
The Hadley results show an increase in sea level pressure across the eastern United States, including the ROSC. Inside the ROSC, pressure increased by 0.3-0.9hPa.

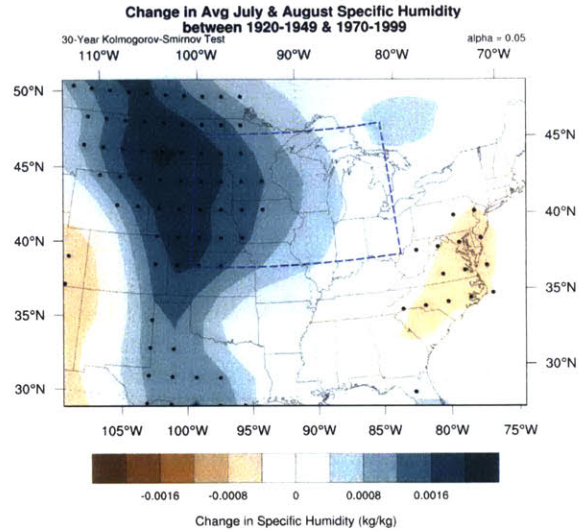
4.2.2. NOAA-CIRES Twentieth Century Reanalysis

The NOAA-CIRES results show increases in precipitation in the northwest of the ROSC and decreases to the southeast in a pattern similar to the UDel dataset (Figure 19, below). The results also capture some of the observed decreases in temperature, though not as well. Increases in sea level pressure, canopy water evaporation, and specific humidity were also observed within the ROSC. Sea level pressure within the ROSC generally increased by up to 1.2hPa.


Change in Avg July & August Precipitation Rate between 1920-1949 & 1970-1999
30-Year Kolmogorov-Smirnov Test
alpha = 0.05
110°W
100°W
90°W
80°W
70°W
50°N
45°N
40°N
35°N
30°N
105°W
100°W
95°W
90°W
85°W
80°W
75°W
-1.6e-05
-8e-06
0
8e-06
1.6e-05
Change in Precipitation Rate (kg/m^2/s)


Change in Avg July & August Air Temperature between 1920-1949 & 1970-1999
30-Year Kolmogorov-Smirnov Test
alpha = 0.05
110°W
100°W
90°W
80°W
70°W
50°N
45°N
40°N
35°N
30°N
105°W
100°W
95°W
90°W
85°W
80°W
75°W
-1.5
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
1.5
Change in Air Temperature (degC)


Change in Avg July & August Sea Level Pressure between 1920-1949 & 1970-1999
30-Year Kolmogorov-Smirnov Test
alpha = 0.05
110°W
100°W
90°W
80°W
70°W
50°N
45°N
40°N
35°N
30°N
105°W
100°W
95°W
90°W
85°W
80°W
75°W
-1.5
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
1.5
Change in Sea Level Pressure (hPa)


Change in Avg July & August Specific Humidity between 1920-1949 & 1970-1999
30-Year Kolmogorov-Smirnov Test
alpha = 0.05
110°W
100°W
90°W
80°W
70°W
50°N
45°N
40°N
35°N
30°N
105°W
100°W
95°W
90°W
85°W
80°W
75°W
-0.0016
-0.0008
0
0.0008
0.0016
Change in Specific Humidity (kg/kg)

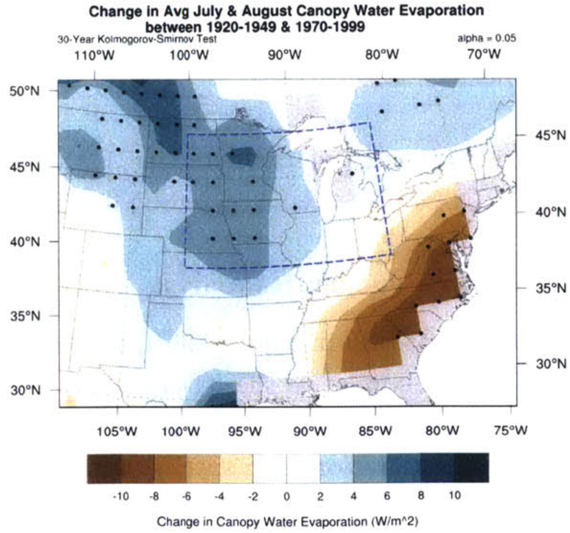

Change in Avg July & August Canopy Water Evaporation between 1920-1949 & 1970-1999
30-Year Kolmogorov-Smirnov Test
alpha = 0.05
110°W
100°W
90°W
80°W
70°W
50°N
45°N
40°N
35°N
30°N
105°W
100°W
95°W
90°W
85°W
80°W
75°W
-10
-8
-6
-4
-2
0
2
4
6
8
10
Change in Canopy Water Evaporation (W/m^2)

Figure 19 (preceding page): Changes in Precipitation Rate, Surface-Level Air Temperature, Sea Level Pressure, Surface-Level Specific Humidity, and Canopy Water Evaporation between 1920-1949 & 1970-1999 (NOAA-CIRES)

4.3. DISCUSSION

It is important to acknowledge that the data in the NOAA-CIRES dataset are not direct historical observations. Findings based off of this dataset should thus, for the purposes of this study, be viewed only as additional evidence towards other findings. Any conclusions based solely on findings from this dataset are heavily subject to the biases of the model, and may not accurately represent true historical conditions.

The Hadley dataset, while it is built directly off of historical observations, includes data at a relatively coarse resolution. The ROSC defined using the UDel dataset only includes 8 grid cells in the Hadley dataset (compared to 648 grid cells in the UDel dataset). Findings from this dataset should thus similarly be considered only as supporting evidence.

The ISD station data analyzed in "Station Data" above did not reveal a clear trend in air pressure data over time, so there is little with which to compare the findings from the Hadley dataset. However, increases in air pressure were observed in both the Hadley and NOAA-CIRES datasets. Such an increase in air pressure is also consistent with the increase in ET suggested by other analyses in this study.

The NOAA-CIRES data show an increase in specific humidity in the western part of the ROSC, with a peak just to the west of the ROSC. This result is broadly consistent with the increases in humidity observed across the majority of ISD stations analyzed above. The increases sea level pressure, humidity, and canopy water evaporation observed in the ROSC all point towards an increase in ET during the period analyzed. Such an increase in ET may be due to increased photosynthetic activity, and the next chapter focuses on measuring this through analyzing agricultural crops.

5. CROP PRODUCTION DATA

5.1. ANALYTICAL METHODS

5.1.1. County-Level Spatiotemporal Analysis

The U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) maintains rich archives of the nation's historical crop production data. This service was used to obtain records of crop production, yield, and harvested acreage for key summer crops (USDA, 2016). Two crops were selected, corn and soybeans, as these represent the vast majority of summertime agricultural production in the region of interest. In the USDA's 2012 Survey of Agriculture, corn represented 44% of the reported field crops by acreage (excluding winter wheat) while soybeans represented 35% (USDA, 2014). The predominance of these two crops (representing around 80% of total summertime agricultural production) means that trends in their yield and production should together capture a good picture of trends in US agriculture generally.

Total crop production and average yield across corn and soybeans were calculated for the "before" and "after" climate periods, and then the differences between the two periods were taken. Production and yield were reported in bushels and bushels per acre, respectively, and so to get normalized results, the values were multiplied by 70 pounds per bushel for corn and 60 pounds per bushel for soybeans (Murphy, 1993). Production and yield are thus reported below in pounds and pounds per acre. The resulting plots are show in Figure 20 and Figure 21, below. Plots of production and yield for corn and soybeans separately are included in Appendix F – Change in Production and Yield for Corn and Soybeans.

5.1.2. State-Level Temporal Analysis

Time series plots for statewide total production and average yield were produced. Data for this analysis also came from NASS. These were similarly normalized across corn and soybeans to gain results in pounds and pounds per acre. 30-year averages for the two climate periods were calculated and tested for statistically significant change. Additionally, time series plots of harvested acreage for corn and soybeans were produced.

5.1.3. Irrigated Area Analysis

The amount of land that was irrigated during the "before" and "after" climates was analyzed. Data on the extent of irrigated land came from the Historical Irrigation Dataset (HID) (Siebert et al., 2015). The HID is a global gridded dataset at 5 arcmin (1/12°) × 5 arcmin spatial resolution. Data are available at 10-year steps from 1900 to 1980, and at 5-year steps thereafter. 30-year averages for the two climate periods were calculated, and then the difference between these two averages was taken. Because of the temporal resolution of the data, the "before" and "after" climates were defined as 1920-1950 and 1970-2000, instead of 1920-1949 and 1970-1999.

The measurements in the dataset were given in units of hectares irrigated per grid cell. In order to normalize the measurements to percentage of land irrigated, the areas of each grid cell were calculated using the following approximation:

$$A \approx \left[2\pi R/\left({}^{360}\!/_{d\theta}\right)\right]^2 \cos\theta_{lat}$$

Where:

A = area of grid cell (km^2)

R = radius of Earth = 6371 km

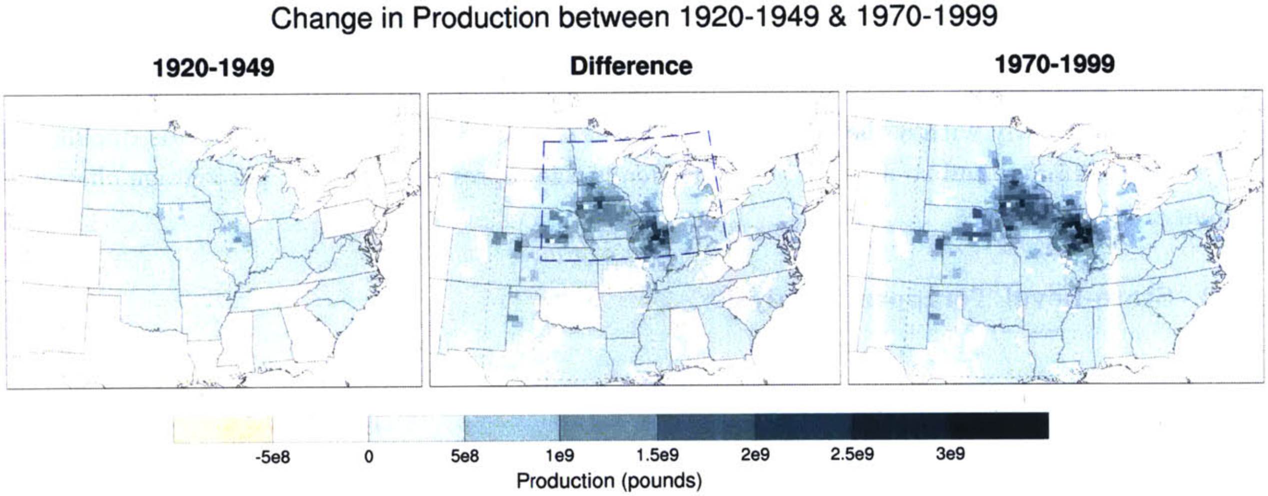
$d\theta$ = angular height of grid cell in degrees = 5 arcmin = (1/12°)

θ_{lat} = latitude in degrees

This approximation assumes a spherical Earth, which is a reasonable assumption for the scale and precision at which this study operated.

5.2. RESULTS

5.2.1. County-Level Spatiotemporal Analysis


Change in Production between 1920-1949 & 1970-1999

1920-1949

Difference

1970-1999

Figure 20: Change in Crop Production between 1920-1949 and 1970-1999

Notes:

1) Counties where data is missing appear in white

Agricultural crop production increased greatly between the two climate periods. Production increases were greatest in Illinois, Iowa, Eastern Nebraska, and Southern Minnesota. In these areas and some other isolated counties, production more than doubled in magnitude. The greatest increases in production were mainly located within the ROSC.

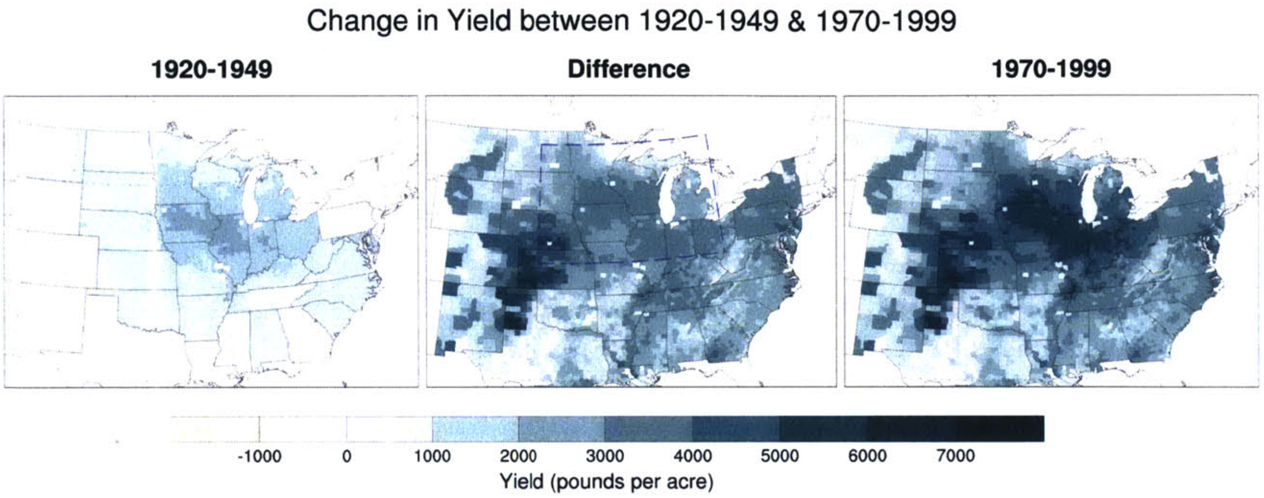


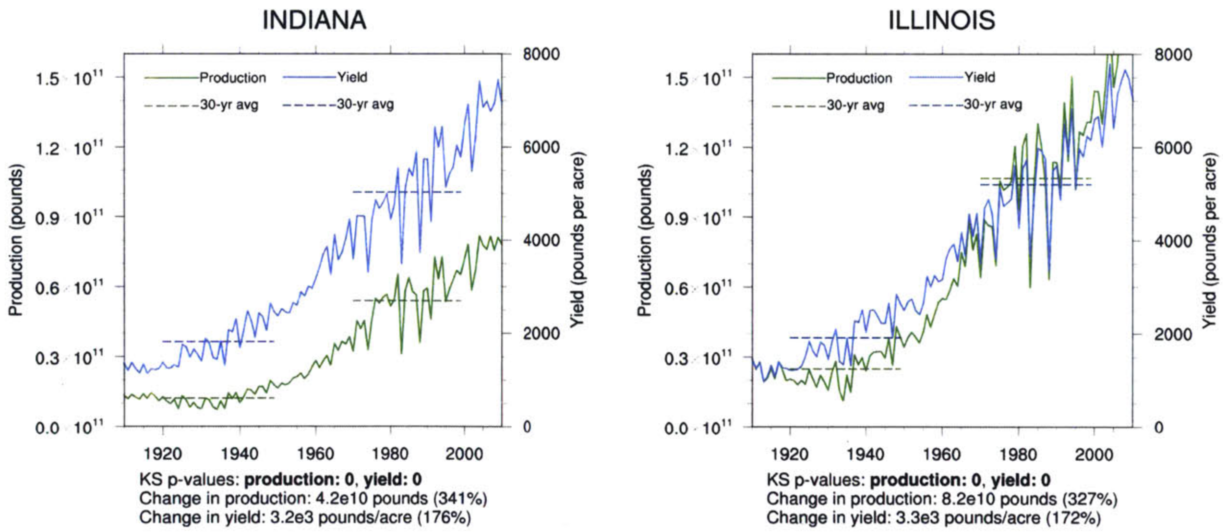
Figure 21: Change in Crop Yield between 1920-1949 & 1970-1999

Notes:

1) Counties where data is missing appear in white

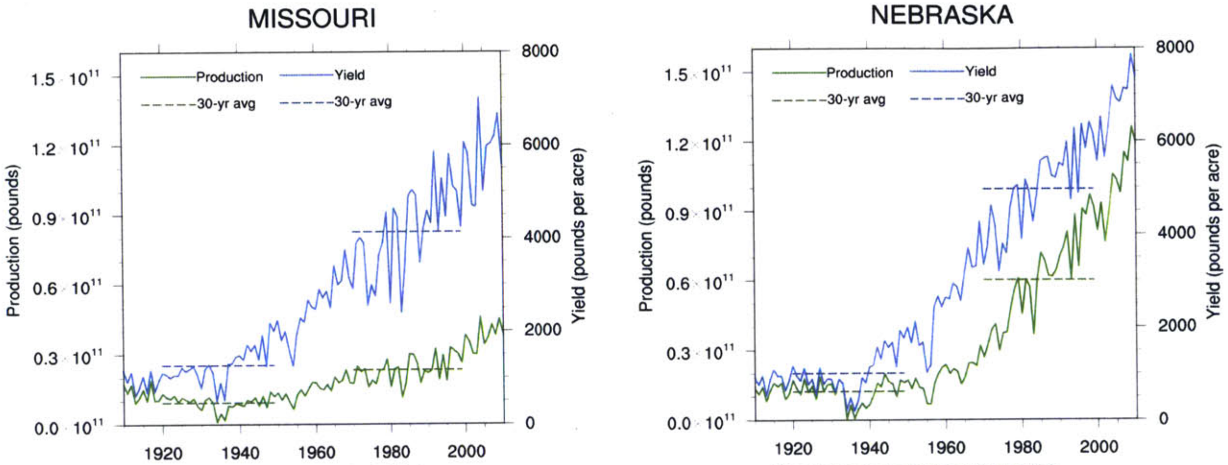
Yield also exhibited large increases between the two climate periods. Yield increased over almost the entire analysis domain, though the magnitude of these increases was highly variable. Yield increased the most in Northern Texas, Kansas, Eastern Colorado, and Nebraska – areas where irrigation has increased dramatically over the same time period (see Figure 24, below). Yield also increased greatly within the ROSC. Counties in this region had the highest yields during the "before" climate, and so a similar magnitude change represented a lower percentage change compared to other areas.

5.2.2. State-Level Temporal Analysis



KS p-values: **production: 0, yield: 0**
Change in production: 4.2e10 pounds (341%)
Change in yield: 3.2e3 pounds/acre (176%)

KS p-values: **production: 0, yield: 0**
Change in production: 8.2e10 pounds (327%)
Change in yield: 3.3e3 pounds/acre (172%)



MISSOURI

KS p-values: **production: 0, yield: 0**
Change in production: 1.4e10 pounds (150%)
Change in yield: 2.9e3 pounds/acre (226%)

NEBRASKA

KS p-values: **production: 0, yield: 0**
Change in production: 4.8e10 pounds (392%)
Change in yield: 4e3 pounds/acre (395%)

Figure 22: Examples of Time Series for State-Level Crop Production and Yield, Comparing 1920-1949 & 1970-1999

Notes:
1) P-values less than 0.05 are bolded to indicate statistical significance.

Equivalent plots for all 33 states are included in Appendix G – Time Series of Production and Yield for All States.

33 states were identified within the region of interest that had data available across both of the climate periods. Across all of these states, yield increased consistently through the twentieth century. The rate of increase grew sharply in the post-World War II period for most states. Production also increased in all but two states. Many states exhibited close correlation between the shapes of the production and yield curves. This indicates that harvested acreage was relatively constant during the twentieth century, i.e. the increases in production were more due to increased yield than to new areas being turned over to farming.

In all states analyzed, the changes in production and yield were found to be statistically significant, and in most cases the increases were very large in magnitude. Changes in production ranged from -51% to 703%, with an average increase of 247%. Changes in yield ranged from 113% to 785%, with an average increase of 279%. Total production and average yield of corn and soybeans thus more than tripled in most states between the two climate periods.

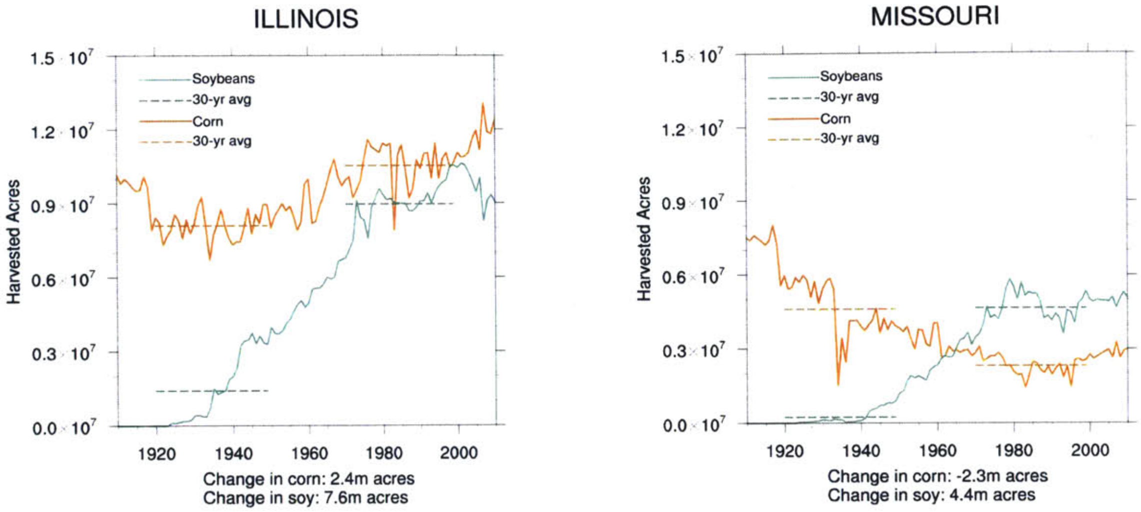


Figure 23: Examples of Time Series for State-Level Harvested Acreage for Corn and Soybeans, Comparing 1920-1949 & 1970-1999

There was no consistent trend for the harvested acreage of corn across the states analyzed. Some states exhibited increases, some decreases, and some relatively constant levels. Soybeans, on the other hand, tended to either increase in acreage in the post-World War II period or were hardly grown at all. In some states, soybeans appear to have displaced corn, with one rising while the other falls. Equivalent plots for all states are included in Appendix H.

5.2.3. Irrigated Area Analysis

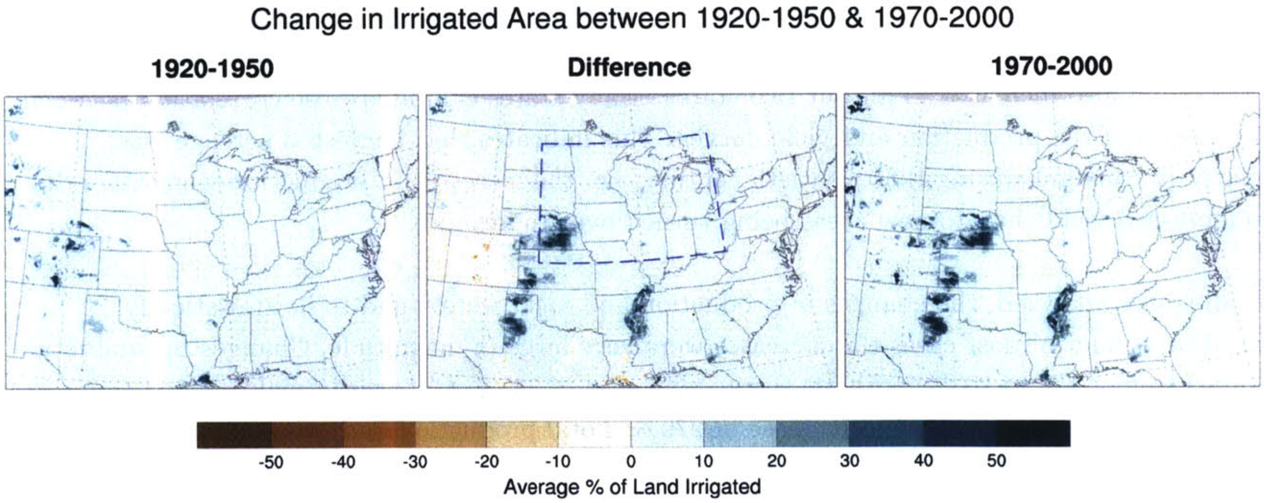


Figure 24: Change in Irrigated Area between 1920-1950 & 1970-2000

Notes:

1) The earlier period contains data at 1920, 1930, and 1950, while the later period contains data at 1970, 1980, 1985, 1990, 1995, and 2000.

Irrigated area increased dramatically in four major areas: Northern Texas, Western Oklahoma, Eastern Nebraska (within the ROSC), and the Mississippi River along the Arkansas border. Note that the "Difference" part of the figure does not represent percent change, but the number of percentage points between the two averages. Discussing the increases in irrigation in terms of percent change makes little sense as many of these areas started with no irrigation in the earlier climate period. There were modest decreases in irrigated area in some western states and Louisiana, and little to no change in all other areas. Over 50% of the area was irrigated in the most heavily irrigated grid cells.

5.3. DISCUSSION

The dramatic increase in crop yields across the US in the twentieth century is well documented, and is confirmed in this analysis. Many factors led to the observed increases, including: increased fertilizer and pesticide use, increased mechanization, development of higher-yielding cultivars, and increased use of irrigation (Tilman, Cassman, Matson, Naylor, & Polasky, 2002). In the highly irrigated areas, the observed increases in yield and production are likely due primarily to the increase in irrigation. The figures shown above also indicate, though, that production also increased dramatically in areas where agriculture is primarily rain-fed. As was shown in the "Gridded Weather Data" chapter above, precipitation increased significantly in many of these states. We can reasonably conclude that the increase in precipitation likely helped increase production in the ROSC. Whether or not increased production in turn helped to enhance precipitation is beyond the scope of this study.

However, the results in the Southeastern coastal states suggest that the increases in production were not due solely to increased precipitation. Of these states, Georgia is the only one with any notable use of irrigation, and yet while precipitation decreased significantly across the entire region, crop production remained relatively constant and yield increased. If water were the limiting factor, we would expect production and yield decreases.

It is important to note that the increases in production and yield may be due in part to underreporting of production in earlier years. For some county and crop combinations, the available data did not go back as early as 1920. It was unclear whether this was because the crop in question was not grown at this point in time, or whether production was simply not reported. As such, those counties lacking data for particular crops could not simply be discounted in the analysis. Where no data existed for a particular crop and county, production and yield were assumed to be zero. However, the state-level data, which often had better temporal coverage than the county-level data, show in the time series plots that these increases are indeed highly significant.

In those states within the ROSC, there appears to be a general increase in the harvested acreage when corn and soybeans are considered together. However, the close correlation between the yield and production plots suggests that the increases in production were in fact driven primarily by increases in yield. Overall harvested acres in those regions that were not irrigated are unlikely to have changed much because these regions had been farmed for a long time prior to the twentieth century. Instead, what is being shown is more likely the substitution of other crops with corn and soybeans. The work of Alter et al. confirms these suggestions for Nebraska (Alter et al., 2015). Mueller et al. also note that the majority of new land being turned over to cropland in the Midwest occurred in the late 1800's (Mueller et al., 2015).

Agricultural production can be thought of as a proxy for total photosynthetic activity. The more crop produced, the more photosynthesis that had to occur to feed that crop. This is an imperfect estimation; agricultural crops often supplant natural vegetation, and the loss of these plants' photosynthetic activity is not accounted for. Additionally, this analysis only looked at the two most prevalent crops, and did not take into account replacement of some other crop with corn and/or soybeans. However, even if one assumes that the preceding crop or natural vegetation was equally productive at the time it was replaced by corn or soybeans, the later increases in yield are so dramatic that total production must have increased. One can then view the increase in production in these two crops as a rough estimate of an increase in total photosynthetic activity between the two climate periods considered. Such an increase in plant growth must be accompanied by an increase in evapotranspiration. Attempting to measure this increase in ET is the focus of the following chapter.

6. WATER BALANCE ESTIMATION OF EVAPOTRANSPIRATION

6.1. ANALYTICAL METHODS

6.1.1. Background

As is mentioned above, directly measuring ET is difficult. However, one method for estimating ET is through a simple water balance analysis:

$$ET = P - Q$$

Where:
ET = Evapotranspiration
P = Precipitation
Q = Runoff

Measuring runoff can also be difficult as the term includes both surface runoff and groundwater infiltration. Taking long-term average values helps overcome this difficulty by minimizing the influence of anomalously low or high values and allowing sufficient time for most water to migrate to the point of measurement.

6.1.2. Methods

Runoff was calculated using streamflow measurements for 4 different stream gauges in the Mississippi River Basin (MRB). The MRB has considerable overlap with the region of interest in this study, as is indicated in Figure 25, below. Measurements were obtained from the Global Runoff Data Centre's *Long-Term Mean Monthly Discharges and Annual Characteristics of GRDC Stations* (GRDC, 2015). Annual mean flows (computed from monthly mean values) were used in the analysis. The GRDC data also include the catchment area for each stream gauge. Areal-average runoff values were calculated for each year by dividing the streamflow (in m^3/s) by the catchment area (in m^2) and multiplying by a unit conversion constant to obtain runoff in mm/year. The four chosen stream gauges were: Vicksburg, MS; St. Louis, MO; Hermann, MO, and Metropolis, IL. The Vicksburg and St. Louis gauges are located on the Mississippi River, while the Hermann gauge is located on the Missouri River and the Metropolis on the Ohio River. Both the Missouri and Ohio Rivers are tributaries to the Mississippi River.

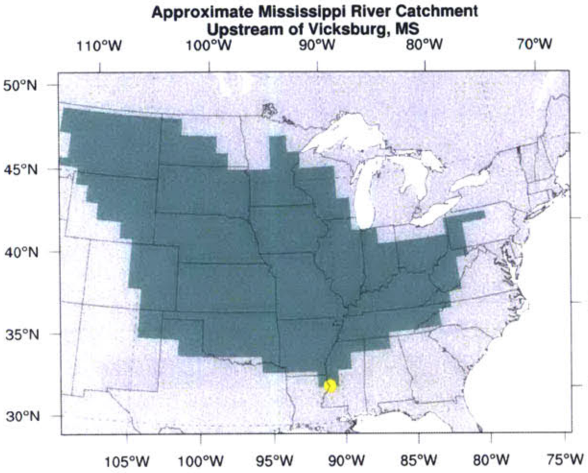
Precipitation over the same catchment area was estimated using the UDel dataset. Those grid cells which fell into the approximate catchment area were identified and isolated for each stream gauge, as indicated in Figure 25 in "Results", below. The bounds of the MRB were determined from the Mississippi River hydrologic region defined by the U.S. Geological Survey (Buell & Markewich, 2004). Unlike in the previous chapters' analyses, the entire year's precipitation data were included, not just those for July and August. This is because when water infiltrates into the ground, there can be a lag of months or even years between rain falling at one point in a catchment area and it reaching the stream in question (Michel, 1992). Accordingly, July and August precipitation does not necessarily correspond to July and August streamflow.

ET values for each year were then estimated for the entire catchment area by subtracting the areal average runoff from the average precipitation. Average values for the "before" and "after" climates were calculated and compared, as for the precipitation and temperature data in the previous analyses. For those stations where data for 1920 was unavailable, the "before" climate was moved forward to the earliest 30-year period with available data.

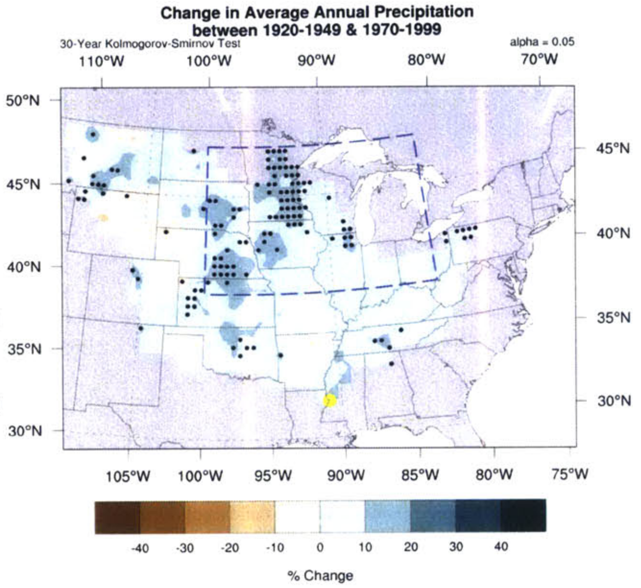
This analysis was carried out for the four stream gauges identified above, and then again for the differences between two stations. By subtracting the streamflow at the St. Louis, MO stream gauge from that at the Vicksburg, MS gauge (the station furthest downstream), an estimate of the runoff between these two stations was obtained. Similarly, precipitation was calculated over the Vicksburg catchment area minus the St. Louis catchment area, resulting in runoff and precipitation estimates for a virtual stream gauge. This process was repeated for the sets of Vicksburg & Hermann, Vicksburg & Metropolis, and St. Louis and Hermann.

6.2. RESULTS

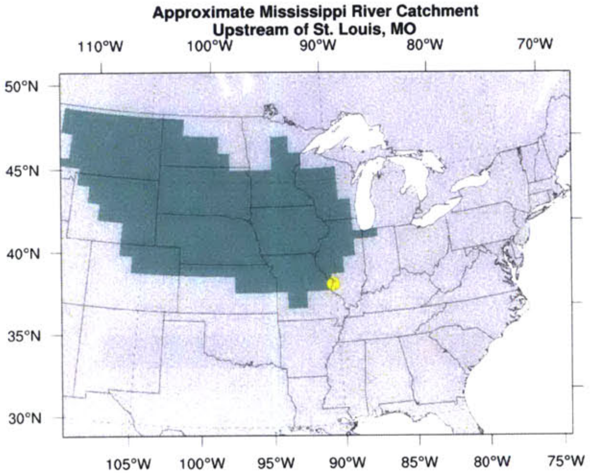
6.2.1. Gauges, Catchment Areas, and Precipitation Change



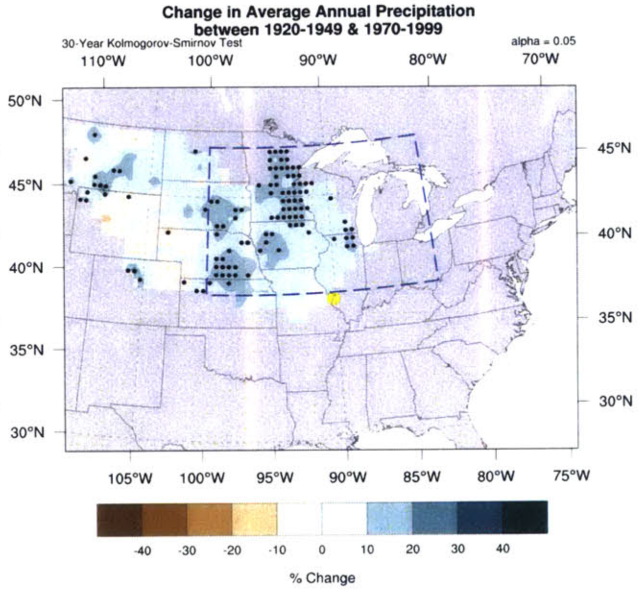
Approximate Mississippi River Catchment
Upstream of Vicksburg, MS



Change in Average Annual Precipitation
between 1920-1949 & 1970-1999

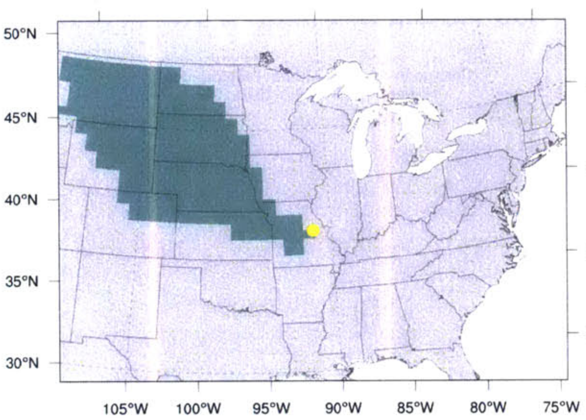


Approximate Mississippi River Catchment
Upstream of St. Louis, MO

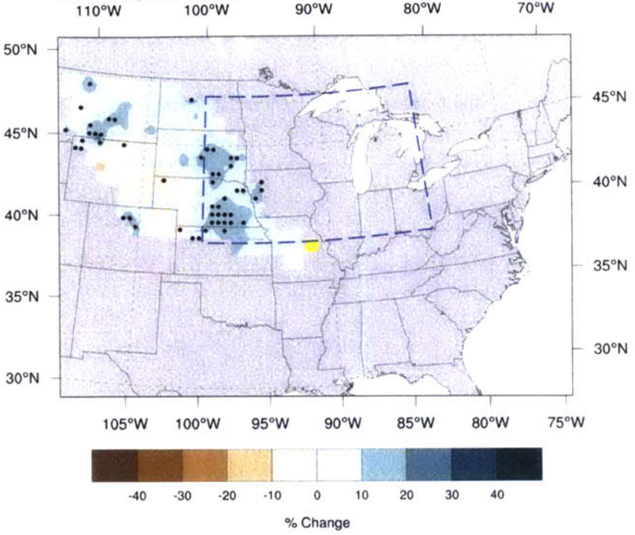


Change in Average Annual Precipitation
between 1920-1949 & 1970-1999

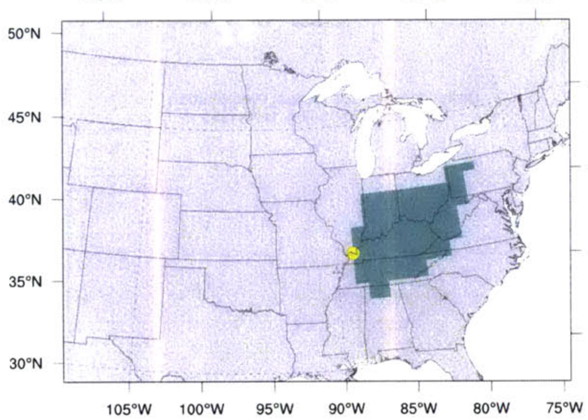
Approximate Mississippi River Catchment
Upstream of Hermann, MO



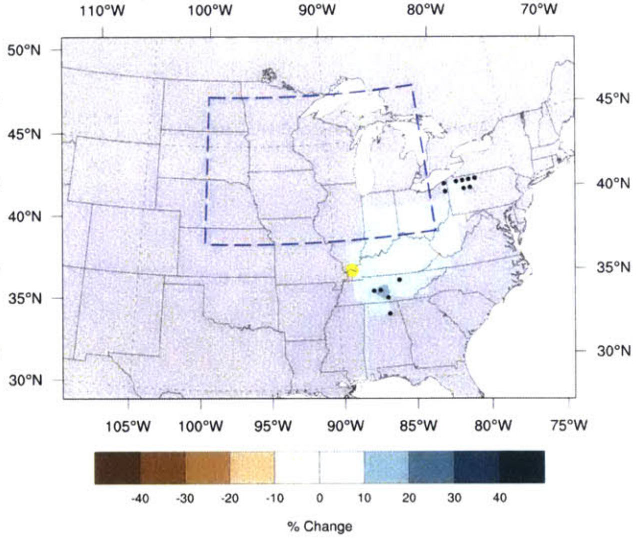
Change in Average Annual Precipitation
between 1920-1949 & 1970-1999

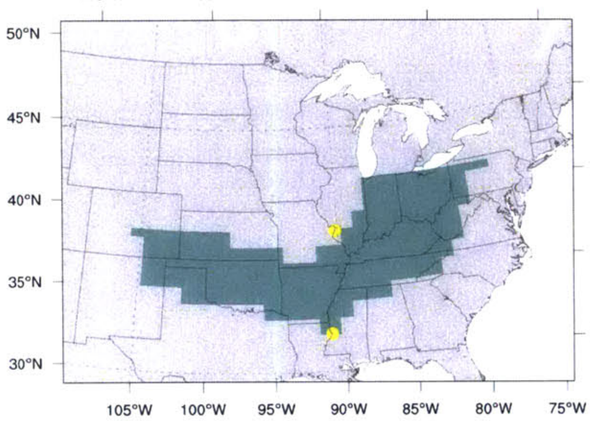


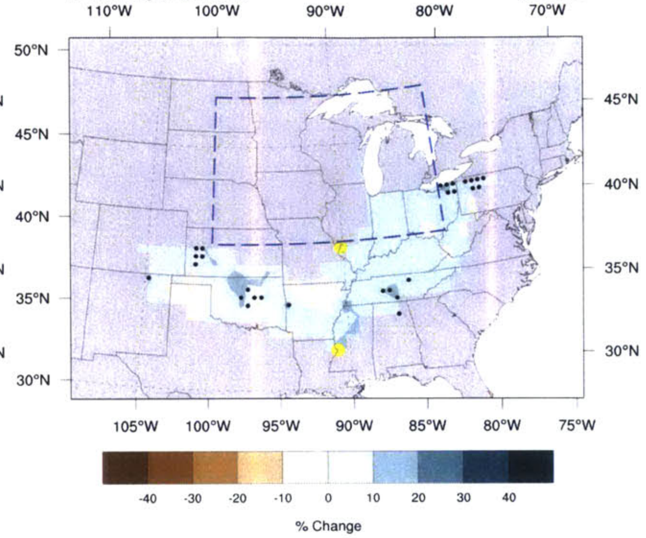
Approximate Ohio River Catchment
Upstream of Metropolis, IL

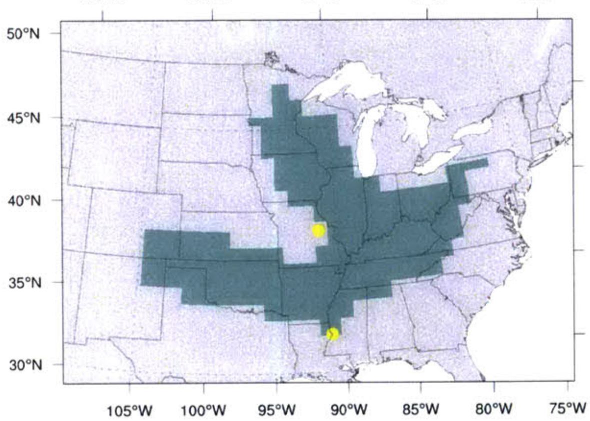


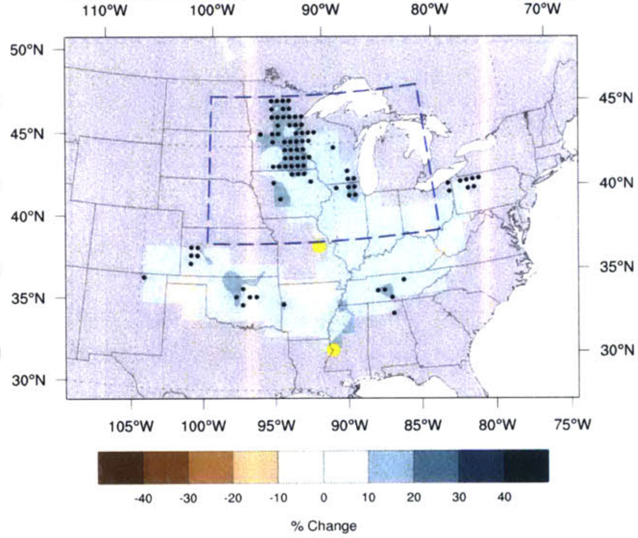
Change in Average Annual Precipitation
between 1920-1949 & 1970-1999




Approximate Mississippi River Catchment
Vicksburg, MS - St. Louis, MO


Change in Average Annual Precipitation
between 1920-1949 & 1970-1999


Approximate Mississippi River Catchment
Vicksburg, MS - Hermann, MO


Change in Average Annual Precipitation
between 1920-1949 & 1970-1999

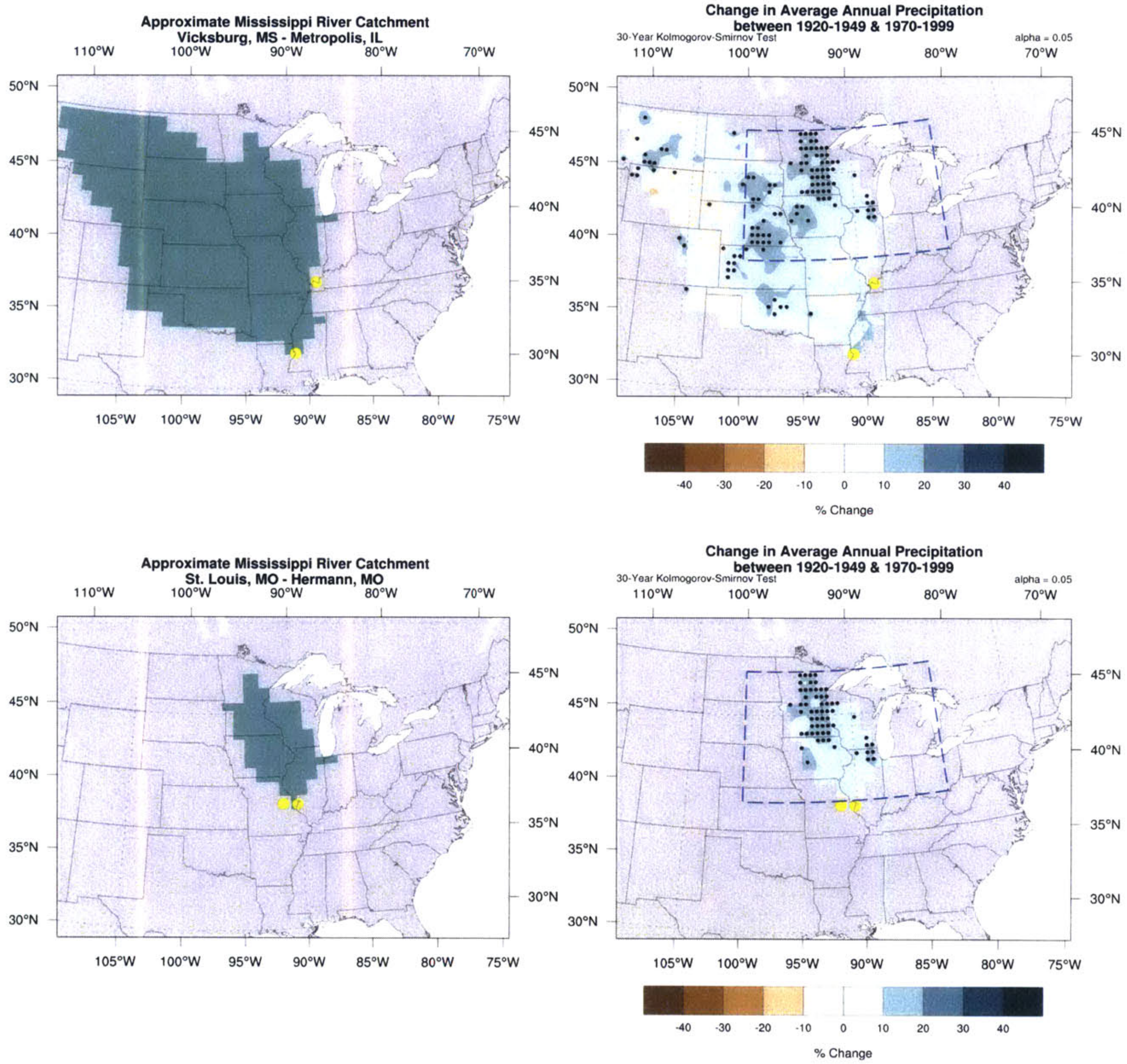


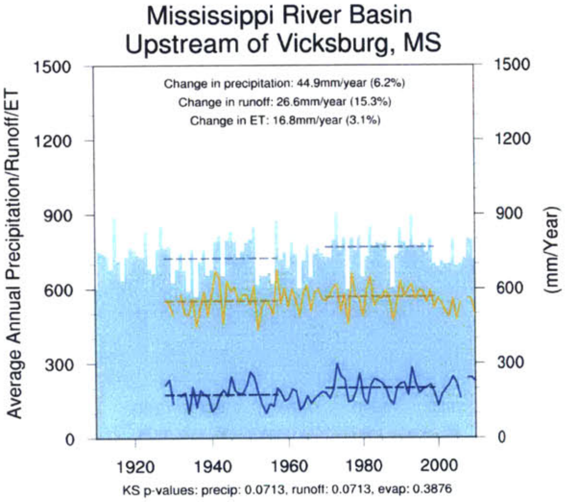
Figure 25: Catchment Areas, Station Locations, and Change in Average Annual Precipitation between 1920-1949 & 1970-1999 for 4 Stream Gauges & 4 Virtual Gauges

Notes:

1) Black dots indicate grid cells where the change in precipitation was significant at the 5% level in a Kolmogorov-Smirnov test.

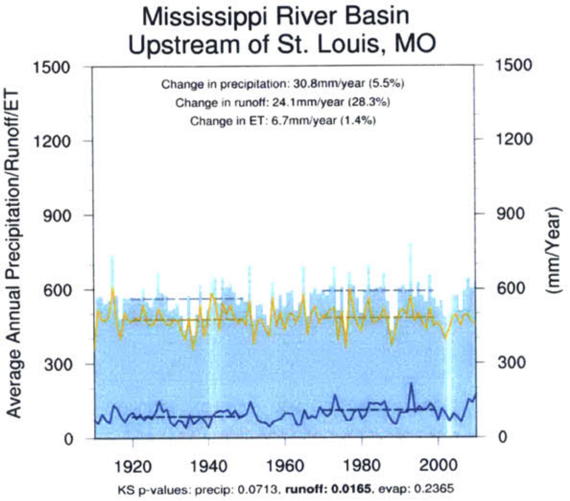
2) Blue dotted lines indicate the ROSC.

6.2.2. Time Series


Mississippi River Basin
Upstream of Vicksburg, MS

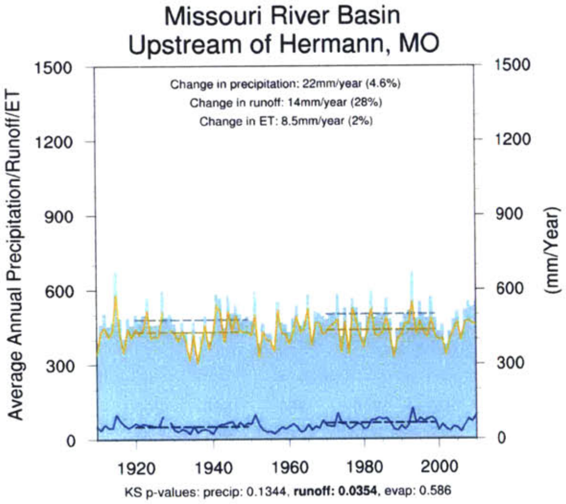
Change in precipitation: 44.9mm/year (6.2%)
Change in runoff: 26.6mm/year (15.3%)
Change in ET: 16.8mm/year (3.1%)

KS p-values: precip: 0.0713, runoff: 0.0713, evap: 0.3876


Mississippi River Basin
Upstream of St. Louis, MO

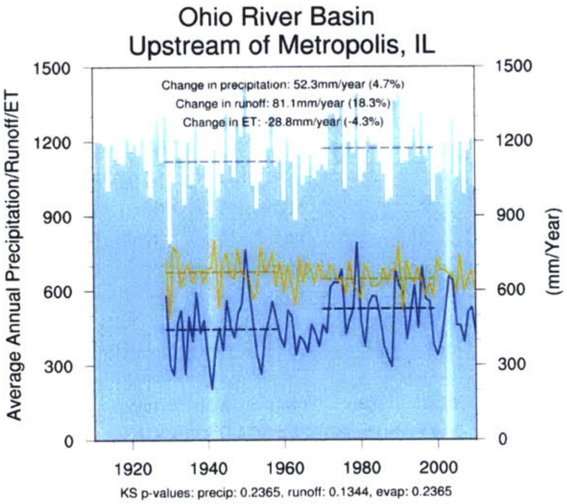
Change in precipitation: 30.8mm/year (5.5%)
Change in runoff: 24.1mm/year (28.3%)
Change in ET: 6.7mm/year (1.4%)

KS p-values: precip: 0.0713, **runoff: 0.0165**, evap: 0.2365


Missouri River Basin
Upstream of Hermann, MO

Change in precipitation: 22mm/year (4.6%)
Change in runoff: 14mm/year (28%)
Change in ET: 8.5mm/year (2%)

KS p-values: precip: 0.1344, **runoff: 0.0354**, evap: 0.586


Ohio River Basin
Upstream of Metropolis, IL

Change in precipitation: 52.3mm/year (4.7%)
Change in runoff: 81.1mm/year (18.3%)
Change in ET: -28.8mm/year (-4.3%)

KS p-values: precip: 0.2365, runoff: 0.1344, evap: 0.2365

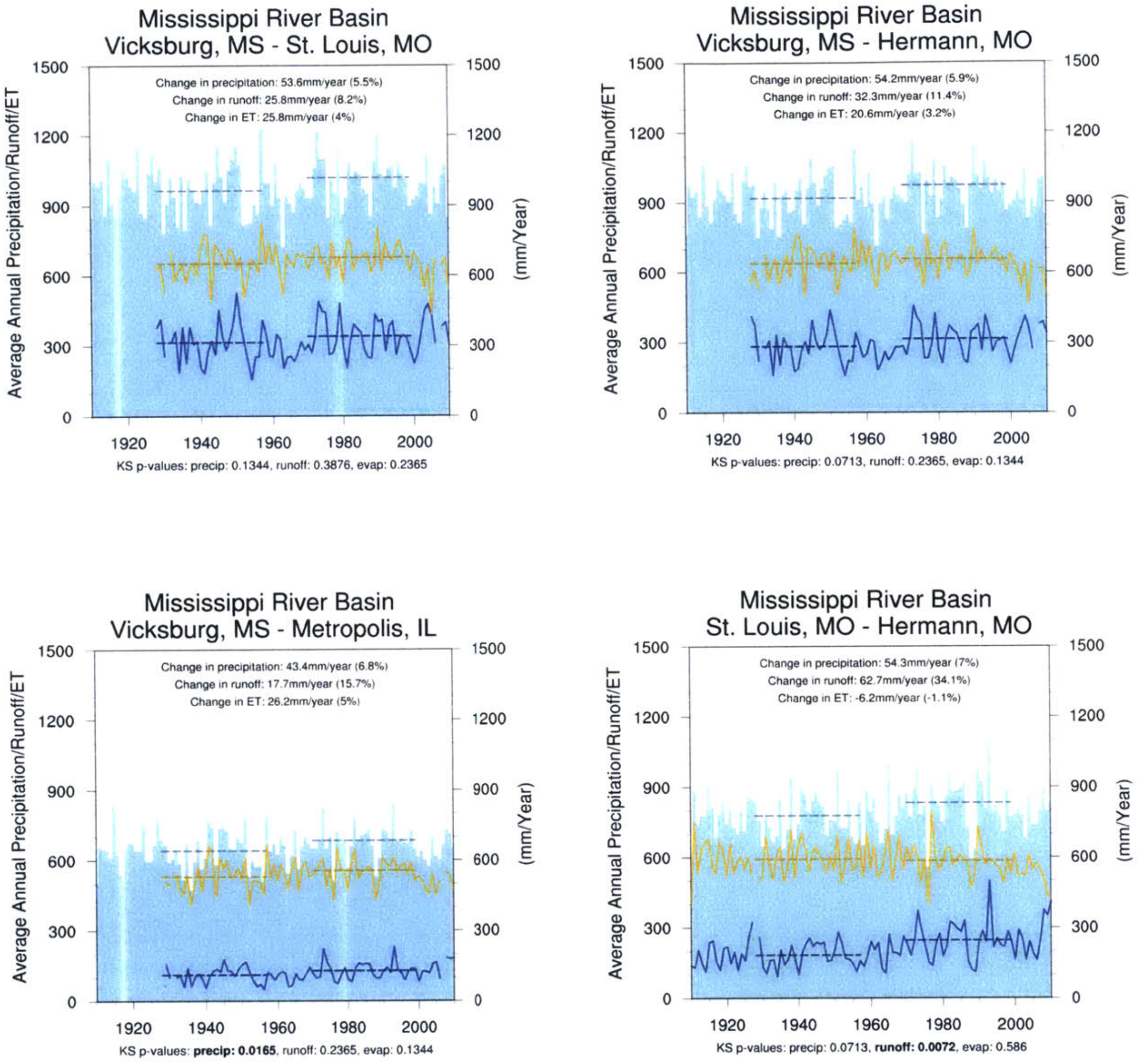


Figure 26: Time Series of Average Annual Precipitation, Streamflow, and ET, Comparing "Before" & "After" Climates for 4 Stream Gauges & 4 Virtual Gauges

Notes:

1) P-values less than 0.05 are bolded to indicate statistical significance as defined in "Tests of Statistical Significance" in "Analytical Methods", above.

Of the four gauges analyzed, three exhibited increases in ET and one (Metropolis, IL) exhibited a decrease. The range of changes was -4.3% to 3.1%. Similarly, of the four virtual gauges, three exhibited increases in ET and one exhibited a decrease. The range of changes was -1.1% to 5%. None of the observed changes in ET were found to be statistically significant.

All four gauges and four virtual gauges exhibited increases in both precipitation and runoff. In one case, the increase in precipitation was found to be statistically significant, and in three cases the increases in runoff were found to be statistically significant.

6.3. DISCUSSION

This analysis, a water balance estimation, revealed that evapotranspiration tended to increase across the region of interest between the two climate periods. However, this trend was not found to be statistically significant. The analysis had the tangential benefit of showing that annual precipitation increased across the region of interest, which is likely to be driven largely by the July and August precipitation increases described in previous chapters. The increases in runoff are notable and probably linked to a variety of factors, including increased precipitation and increases in impervious cover due to urbanization.

While the estimates appear to be inconclusive about establishing a trend of how ET has changed over time, it is important to note that these estimates likely represent a lower bound on the actual change in ET. The calculation does not take into account drawdown of aquifers, a process that adds water to the system. Aquifer drawdown is caused by both increased extraction (e.g. pumping for irrigation) and reduced recharge (e.g. due to increases in impervious cover). Accounting for aquifer drawdown would result in higher estimates of ET. The drawdown of aquifers in the region of interest, most notably the Ogallala Aquifer, is well documented and more pronounced in the later half of the twentieth century (Konikow, 2013). Accordingly, we can expect that ET actually increased by more than the figures above suggest.

The one gauge and one virtual gauge that showed decreases in ET (Metropolis and St. Louis – Hermann) were the two smallest catchment areas analyzed. They were thus the most susceptible to bias due to random variations in the data. With these considerations in mind, it is likely that ET increased over the region of interest in the time period considered, though we cannot say so conclusively based solely on this analysis.

7. CONCLUSIONS

Significant and sustained changes occurred in the climate of the Midwest during the twentieth century. The greatest changes were observed in an area extending from the Great Lakes southwest to Northern Kansas. These changes included increases in both the amount and the variability of precipitation, decreases in air temperature, and likely increases in specific humidity and evapotranspiration.

The period of most significant change was found to be 1950-1970. The 30-year climates either side of this period were those that exhibited the greatest degrees of statistically significant difference. The change in precipitation appears to be more of a step increase around this time than an ongoing increase. Temperature, on the other hand, appears to have decreased more monotonically.

Confidence in these findings is bolstered through confirmation by multiple complementary analyses. Precipitation and temperature were analyzed using multiple sets of gridded weather data and individual weather station data. Humidity was analyzed using weather station data and gridded weather data from a model reanalysis. Evaporation was analyzed using the same model reanalysis and by conducting a water balance on precipitation and stream flow, as well as being supported by the analysis of crop production data. Furthermore, the observed changes are consistent with the findings from similar, prior studies.

The observed changes in climate variables are consistent with changes due to increased plant transpiration, namely: increased humidity, increased precipitation, and lowered temperatures. This points towards land use change in the form of increased photosynthetic activity as being a possible driver of these climate changes.

Very significant changes in agricultural land use occurred during this same period; yield and total production increased dramatically across the U.S., but especially so in the Midwest. These changes correlate spatially and temporally with the aforementioned changes in climate. Using these measures as a proxy, we can conclude that overall photosynthetic activity increased over the twentieth century in the Midwest. This would have resulted in a corresponding increase in evapotranspiration due to increased transpiration from plants.

8. FURTHER RESEARCH RECOMMENDATIONS

This study used multiple complementary analyses in order to determine where and when changes in twentieth-century climate occurred. The analysis domain was limited to the United States east of the Rocky Mountains for a variety of reasons. One potentially useful extension to this study would be to conduct similar analyses on other parts of the globe where comparable changes in land use have occurred. Such an approach would help establish the universality of trends identified herein, to provide an even more solid foundation for attribution studies.

While the findings of this study illustrate correlation between climate changes and land use change, they do not demonstrate any causative effects. The most powerful application of this research will be to feed into attribution studies that attempt to determine what drives climate change. This will allow for predictions of future climate change based on trends in the drivers.

It is likely that there is no simple answer to isolating these drivers, as climate and land use are interwoven with multiple feedbacks. As such, one of the most promising avenues for exploring the question of causation is through climate modeling. Modeling allows for inputs to the climate system to be varied individually and the outputs measured. The models that researchers use in these analyses need to be calibrated against real-world data, and that is where this study comes in. Calibrating inputs to the land use trends identified in this study and checking the outputs against the climate variables analyzed herein will aid in the calibration process.

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APPENDIX A – ALTERNATIVE GRIDDED WEATHER DATA RESULTS

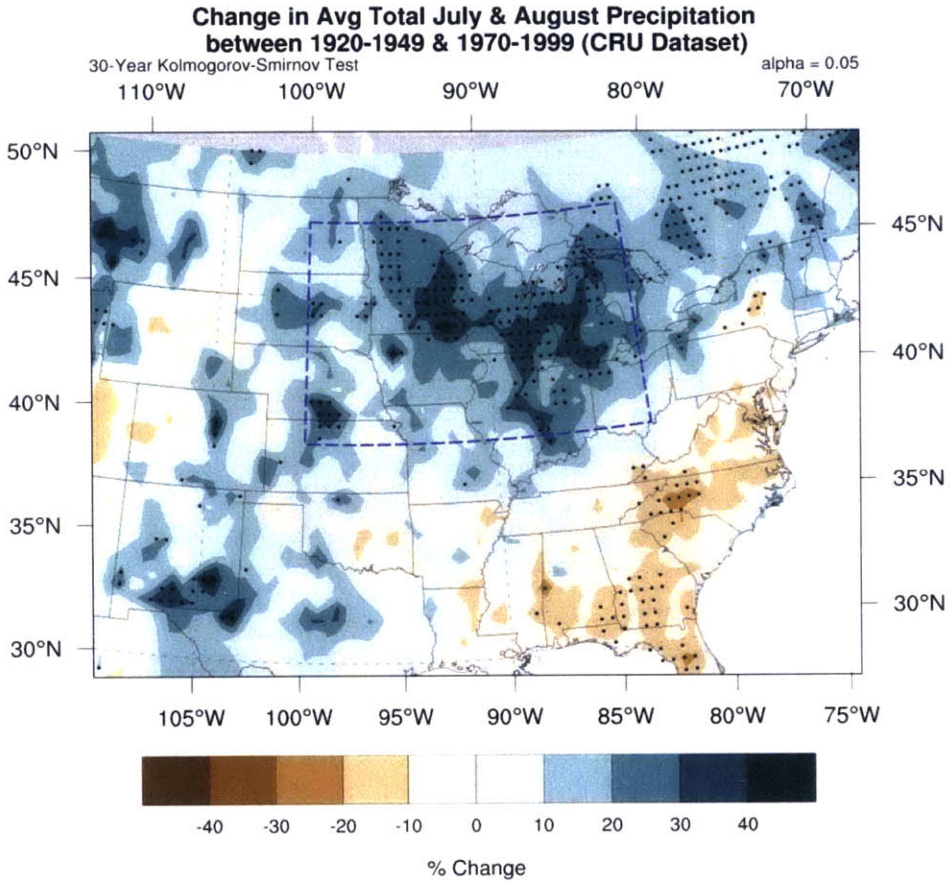

Change in Avg Total July & August Precipitation between 1920-1949 & 1970-1999 (CRU Dataset)

Figure 27: Change in Average Monthly July & August Precipitation between 1920-1949 & 1970-1999 (CRU Dataset)

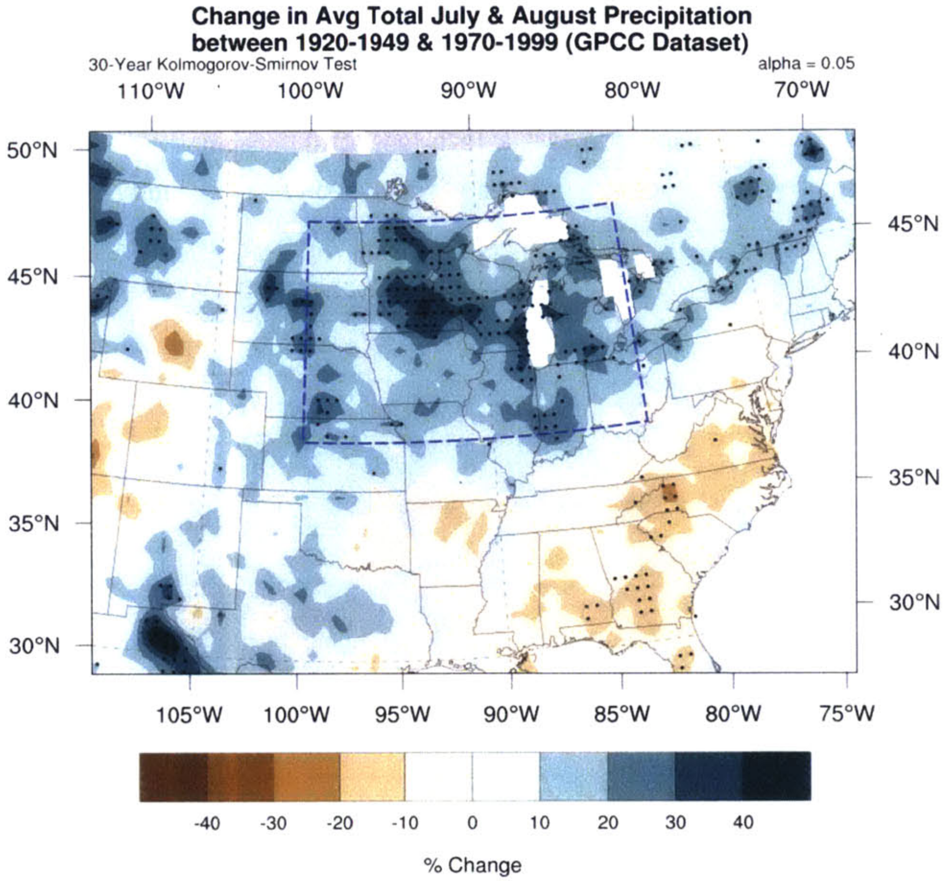


Figure 28: Change in Average Monthly July & August Precipitation between 1920-1949 & 1970-1999 (GPCC Dataset)

APPENDIX B – PERIODS OF MOST SIGNIFICANT CHANGE, SUBGRIDS B-E

Subgrid B

Subregion	Period of Most Significant Change	Percent Change in Monthly Precipitation	% of Grid Cells Exhibiting Statistically Significant Change
1			4
2			5
3	1955-1980	10.9	17
4			4
5			4
6	1960-1965	8.7	13
7	1965-1970	7.8	9
8	1955-1975	16.4	16
9	**1950-1970**	**19.8**	**35**
10	**1950-1975**	**18.8**	**39**
11	**1950-1970**	**21.2**	**52**
12	1940-1970	11.2	16
13	1940-1945	12.1	7
14	1950-1980	13.6	10
15	1940-1950	16.8	15
16	1950-1975	17.3	19
17	**1955-1975**	**19.5**	**34**
18	1940-1945	5.2	9
19	**1965-1970**	**14.8**	**22**
20	1960-1975	13.6	16
21			5
22			2
23	1945-1975	-9.2	11
24	**1945-1975**	**-9.9**	**21**

Subgrid C

Subregion	Period of Most Significant Change	Percent Change in Monthly Precipitation	% of Grid Cells Exhibiting Statistically Significant Change
1	1965-1970	10.0	11.1
2	1955-1975	12.8	11.1
3	**1950-1970**	**17.2**	**29.9**
4	**1950-1970**	**15.9**	**27.8**
5	**1950-1970**	**13.8**	**28.5**
6	1965-1975	10.8	6.9
7	1960-1965	11.9	9.0
8	1940-1950	15.3	11.1
9	**1950-1975**	**19.3**	**30.6**
10	1955-1980	11.0	17.4
11	1965-1970	12.9	17.4
12	1960-1965	17.7	19.4
13			3.5
14			4.2
15	**1945-1975**	**-11.3**	**27.1**

Subgrid D

Subregion	Period of Most Significant Change	Percent Change in Monthly Precipitation	% of Grid Cells Exhibiting Statistically Significant Change
1	1965-1970	6.3	6.6
2	1950-1970	16.7	10.2
3	**1950-1970**	**16.7**	**28.6**
4	**1955-1970**	**13.9**	**28.1**
5	1965-1980	10.4	6.6
6	1960-1965	10.0	7.1
7	1940-1975	14.5	13.8
8	**1955-1965**	**15.0**	**25.0**
9	**1960-1965**	**18.2**	**21.4**
10			4.6
11	1940-1980	-6.9	5.6
12	1945-1975	-9.7	18.4

Subgrid E

Subregion	Period of Most Significant Change	Percent Change in Monthly Precipitation	% of Grid Cells Exhibiting Statistically Significant Change
1			4.7
2	1950-1970	15.0	12.0
3	1950-1970	15.3	18.8
4	1960-1965	13.0	10.1
5			2.4
6	1945-1975	-3.9	7.1

APPENDIX C – SOURCES OF DATA

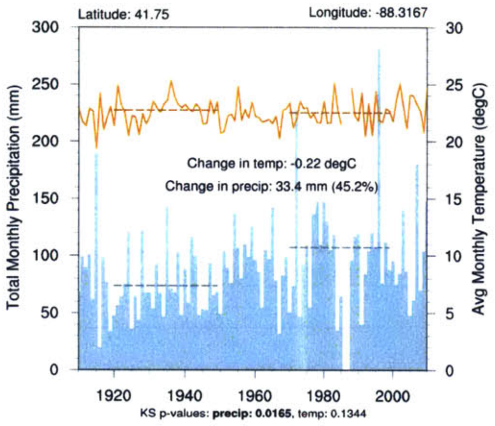
The sources of all of the sets of data used in this analysis are cited throughout and included in "Works Cited". However, for ease of access, the download pages for all of these datasets are provided below.

Product	**Download Page**
Gridded Weather Data	
UDel V3.01	http://climate.geog.udel.edu/~climate/html_pages/download.html
CRU TS3.23	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.23/
GPCC Full Data Reanalysis Version 5	ftp://ftp-anon.dwd.de/pub/data/gpcc/html/fulldata_download.html
GHCN	http://www.ncdc.noaa.gov/ghcnm/v3.php
Weather Station Data	
GHCN Stations	https://gis.ncdc.noaa.gov/maps/ncei/summaries/monthly
ISD	https://www.ncdc.noaa.gov/isd/products
Additional Gridded Datasets	
HadSLP2	http://www.esrl.noaa.gov/psd/gcos_wgsp/Gridded/data.hadslp2.html
NOAA-CIRES 20th Century Reanalysis V2c	http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.monolevel.mm.html
Crop Production Data	
NASS	https://quickstats.nass.usda.gov/
HID	https://mygeohub.org/publications/8/2
Water Balance Estimation	
Long-Term Mean Monthly Discharges and Annual Characteristics of GRDC Stations	http://www.bafg.de/GRDC/EN/03_dtprdcts/32_LTMM/longtermmonthly_node.html

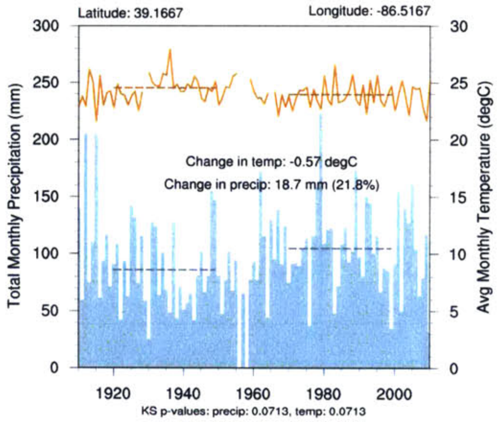
Table 4: Download Pages for Sources of Data

APPENDIX D – TIME SERIES FOR GHCN STATIONS

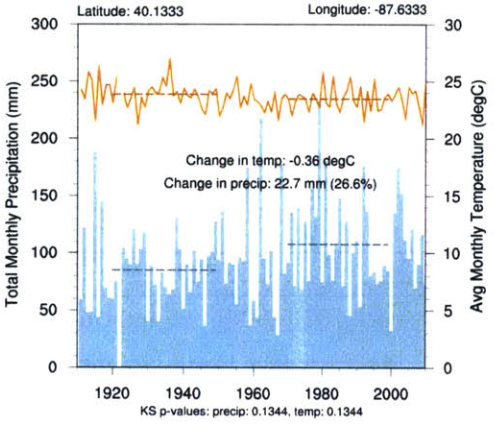
AURORA_IL_US



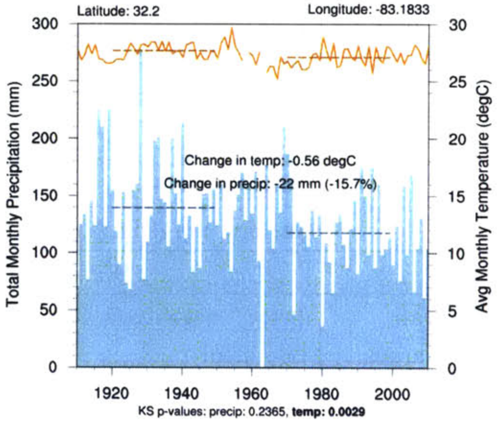
BLOOMINGTON_INDIANA_UNIVERSITY_IN_US

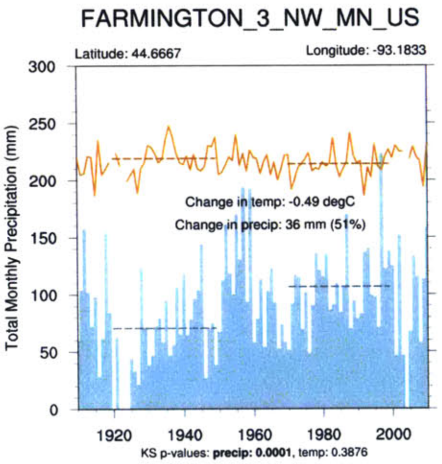


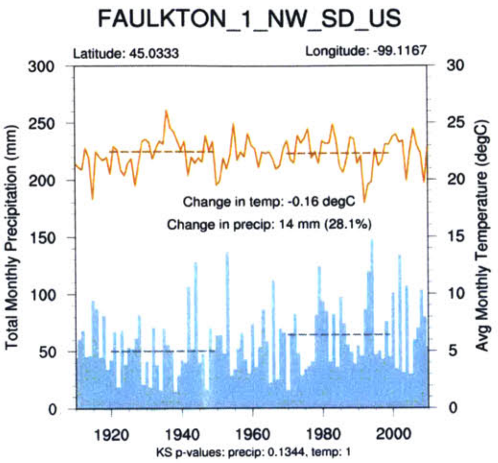
DANVILLE_IL_US

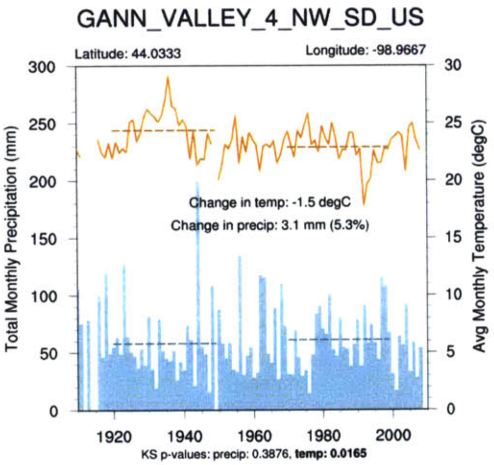


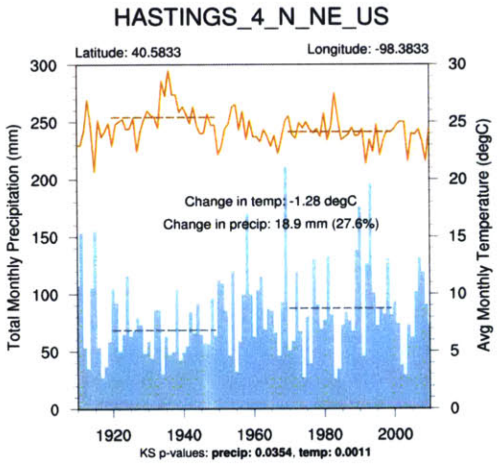
EASTMAN_1_W_GA_US

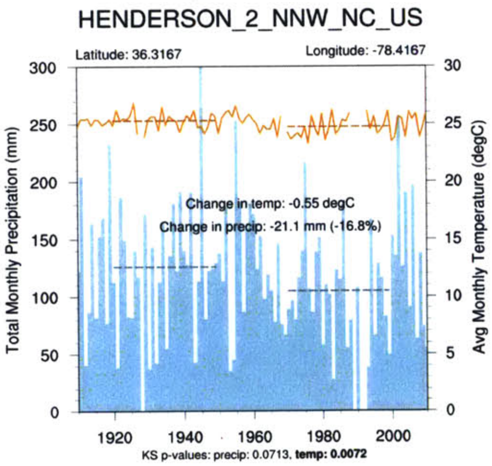


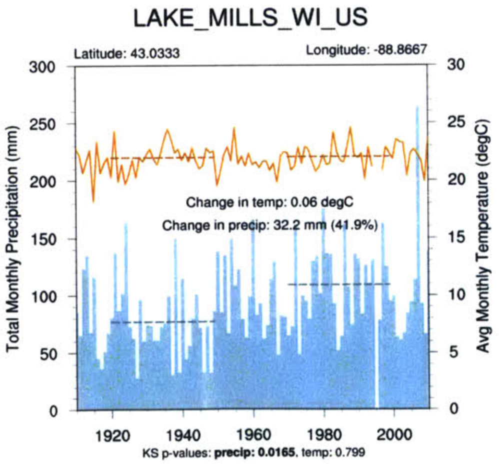

FARMINGTON_3_NW_MN_US
Latitude: 44.6667
Longitude: -93.1833
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: -0.49 degC
Change in precip: 36 mm (51%)
KS p-values: precip: 0.0001, temp: 0.3876
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

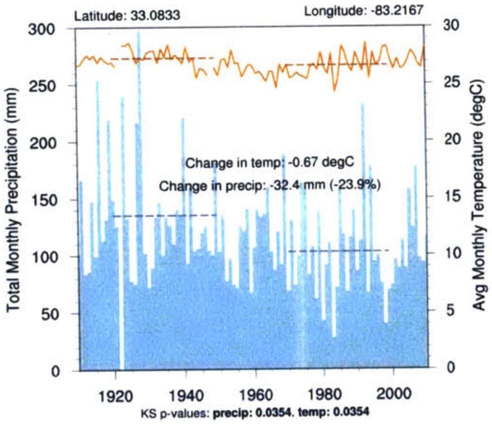

FAULKTON_1_NW_SD_US
Latitude: 45.0333
Longitude: -99.1167
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: -0.16 degC
Change in precip: 14 mm (28.1%)
KS p-values: precip: 0.1344, temp: 1
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

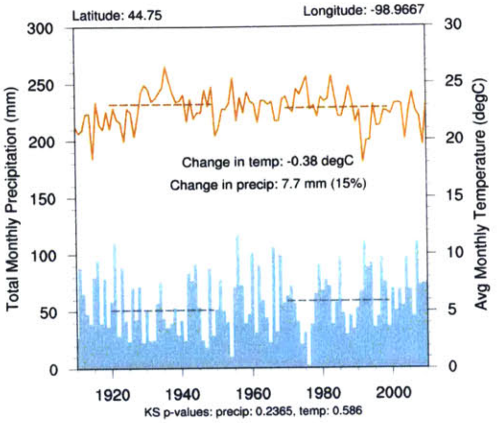

GANN_VALLEY_4_NW_SD_US
Latitude: 44.0333
Longitude: -98.9667
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: -1.5 degC
Change in precip: 3.1 mm (5.3%)
KS p-values: precip: 0.3876, temp: 0.0165
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

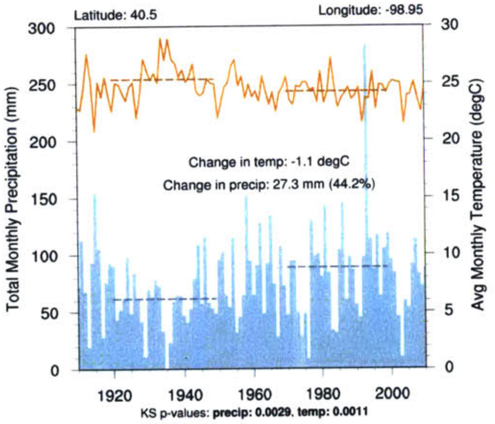

HASTINGS_4_N_NE_US
Latitude: 40.5833
Longitude: -98.3833
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: -1.28 degC
Change in precip: 18.9 mm (27.6%)
KS p-values: precip: 0.0354, temp: 0.0011
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

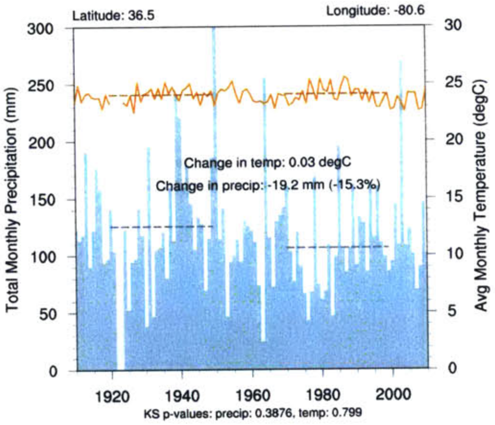

HENDERSON_2_NNW_NC_US
Latitude: 36.3167
Longitude: -78.4167
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: -0.55 degC
Change in precip: -21.1 mm (-16.8%)
KS p-values: precip: 0.0713, temp: 0.0072
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

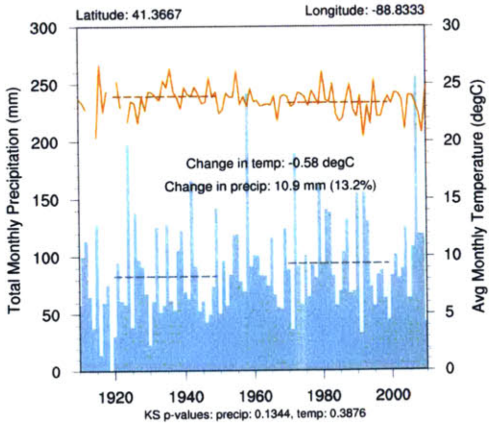

LAKE_MILLS_WI_US
Latitude: 43.0333
Longitude: -88.8667
Total Monthly Precipitation (mm)
Avg Monthly Temperature (degC)
Change in temp: 0.06 degC
Change in precip: 32.2 mm (41.9%)
KS p-values: precip: 0.0165, temp: 0.799
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1920
1940
1960
1980
2000

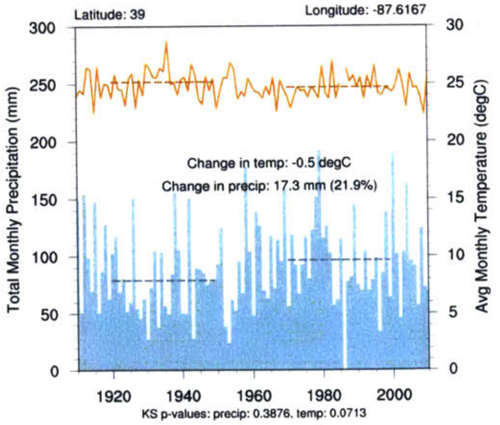

MILLEDGEVILLE_GA_US

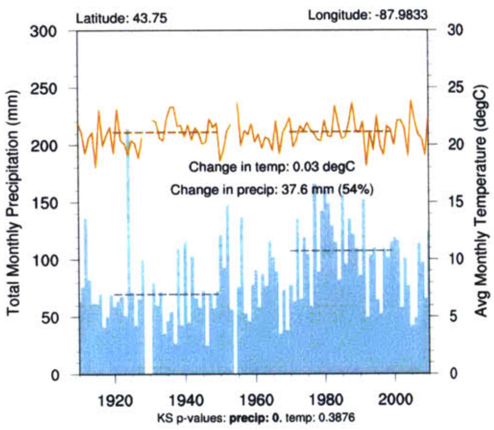

MILLER_SD_US

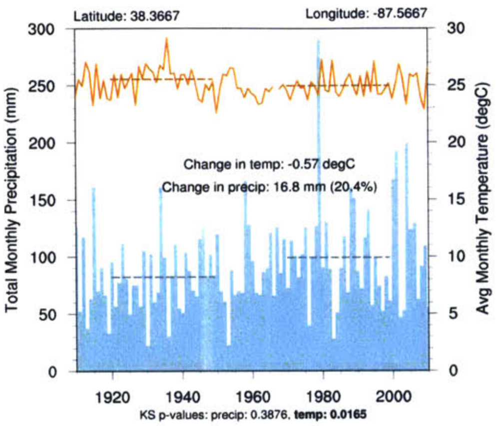

MINDEN_NE_US

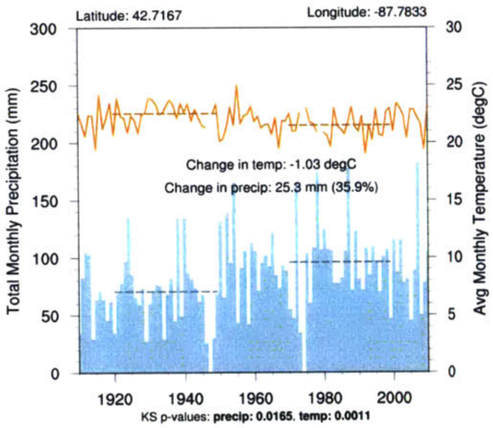

MOUNT_AIRY_2_W_NC_US

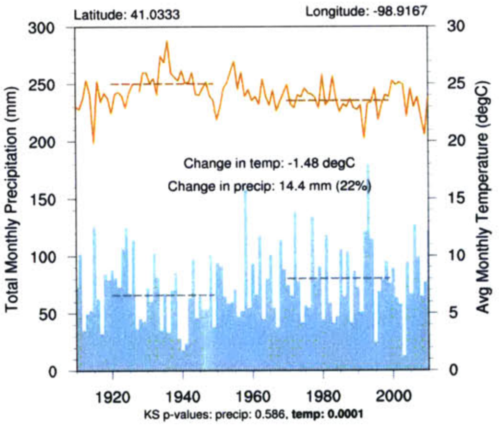

OTTAWA_5_SW_IL_US

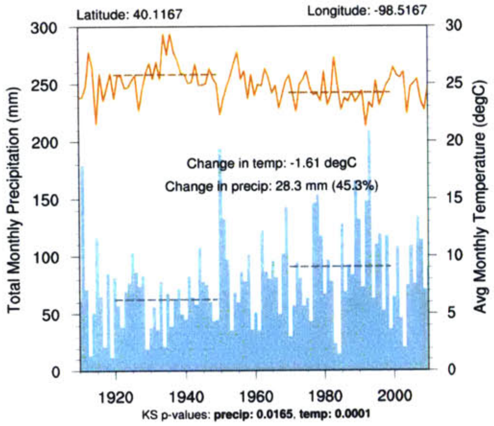

PALESTINE_2_W_IL_US

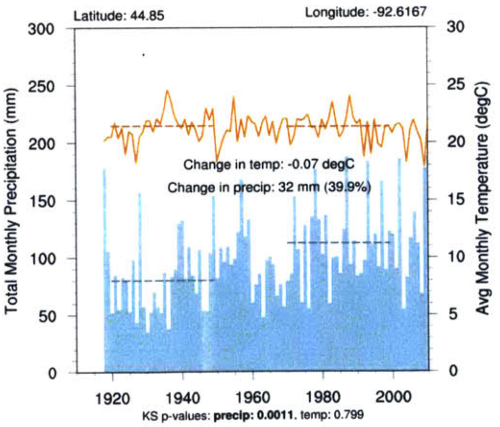

PLYMOUTH_WI_US

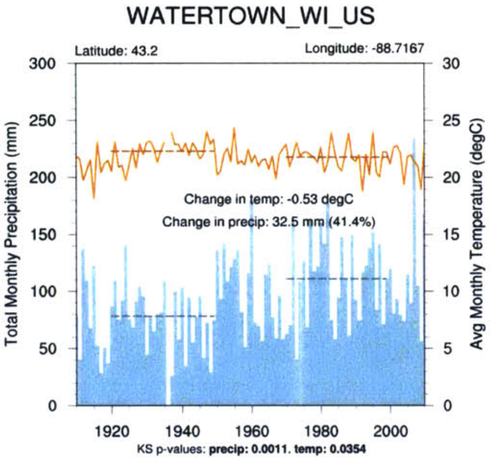

PRINCETON_1_W_IN_US

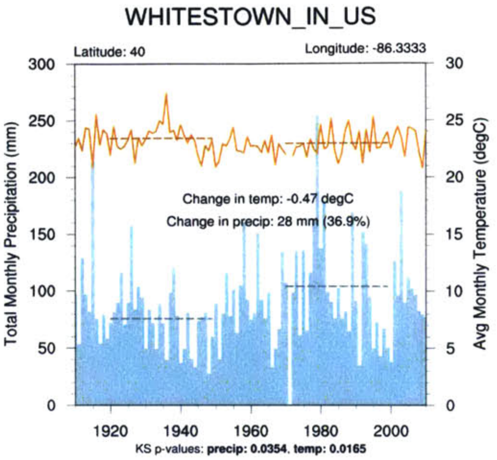

RACINE_WI_US


RAVENNA_NE_US

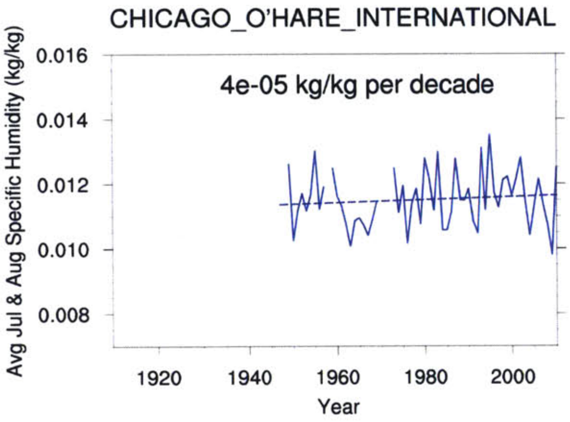

RED_CLOUD_NE_US

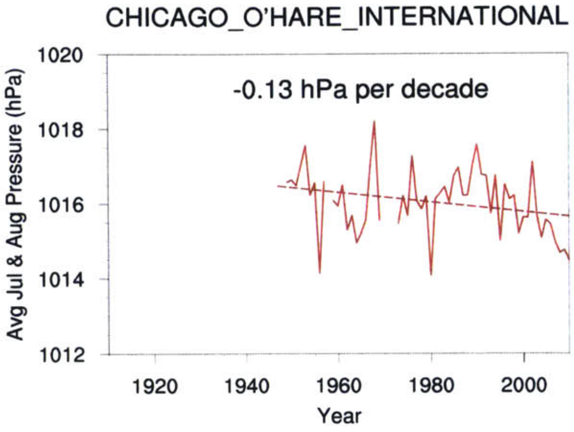

RIVER_FALLS_WI_US

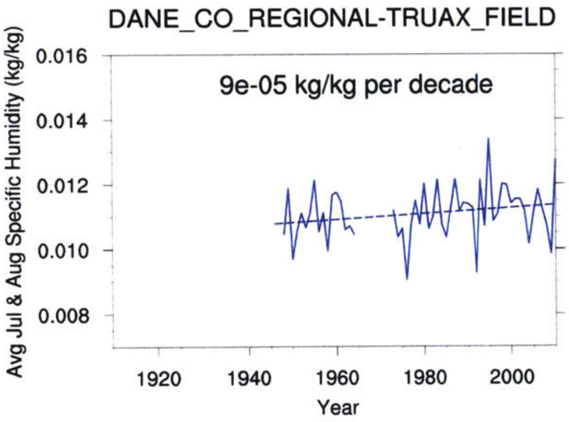

WATERTOWN_WI_US
Latitude: 43.2
Longitude: -88.7167
300
250
200
150
100
50
0
Total Monthly Precipitation (mm)
30
25
20
15
10
5
0
Avg Monthly Temperature (degC)
Change in temp: -0.53 degC
Change in precip: 32.5 mm (41.4%)
1920
1940
1960
1980
2000
KS p-values: precip: 0.0011. temp: 0.0354

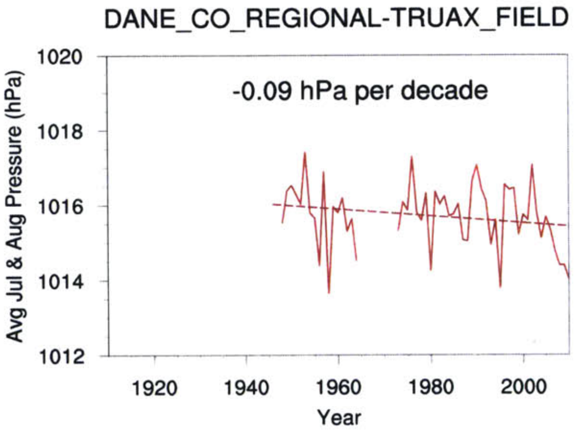

WHITESTOWN_IN_US
Latitude: 40
Longitude: -86.3333
300
250
200
150
100
50
0
Total Monthly Precipitation (mm)
30
25
20
15
10
5
0
Avg Monthly Temperature (degC)
Change in temp: -0.47 degC
Change in precip: 28 mm (36.9%)
1920
1940
1960
1980
2000
KS p-values: precip: 0.0354. temp: 0.0165

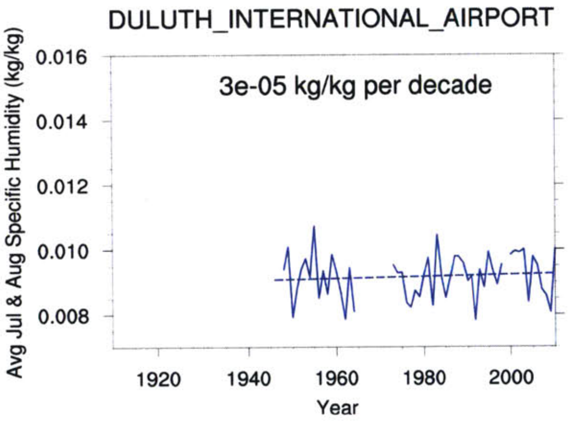
APPENDIX E – TIME SERIES FOR ISD STATIONS

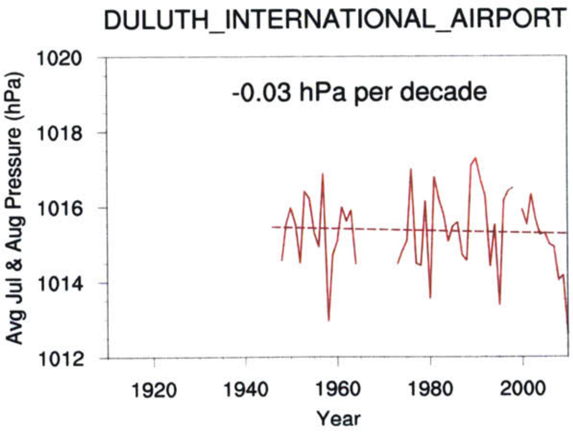


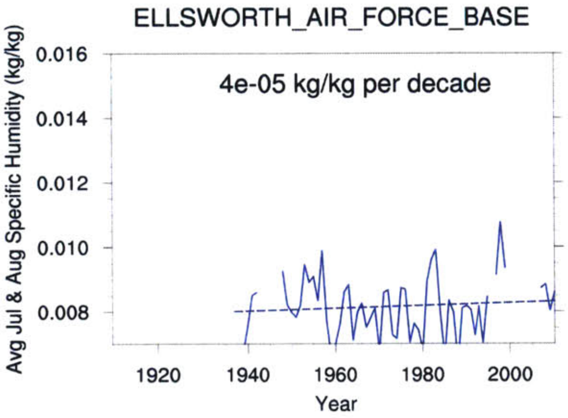


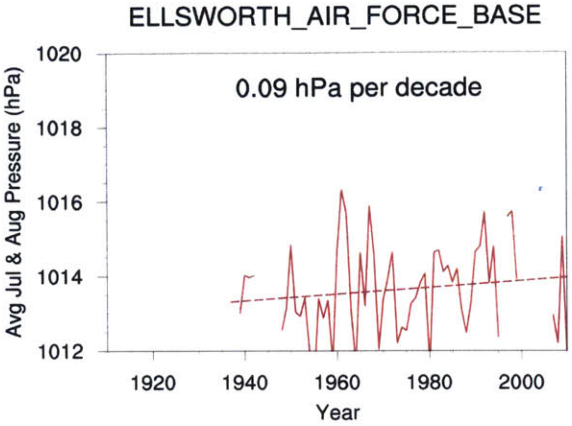


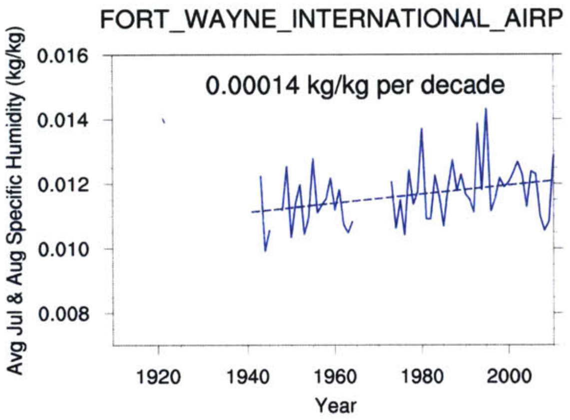


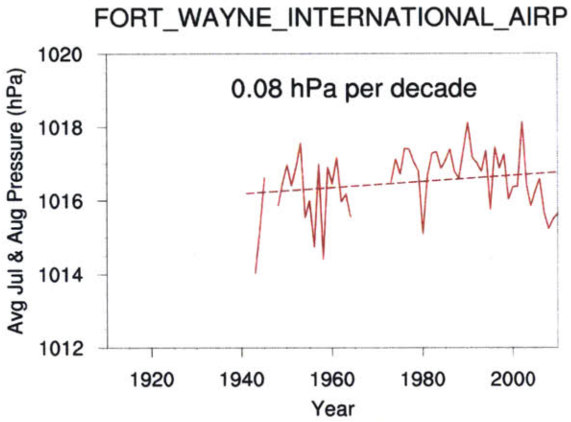


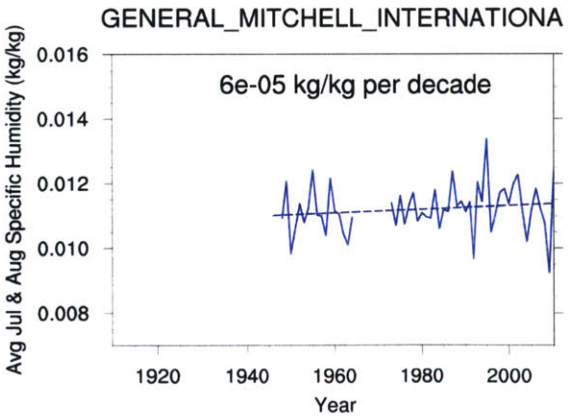


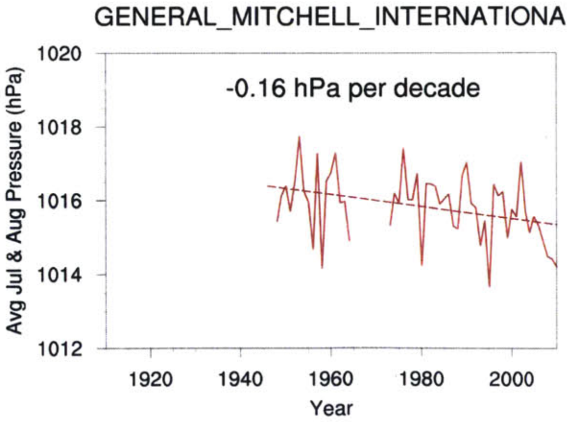

ELLSWORTH_AIR_FORCE_BASE

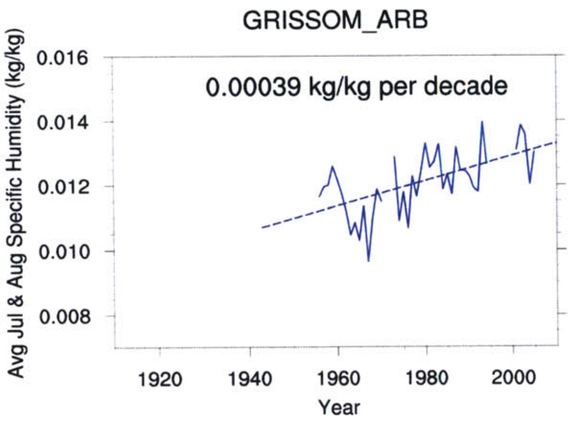

ELLSWORTH_AIR_FORCE_BASE

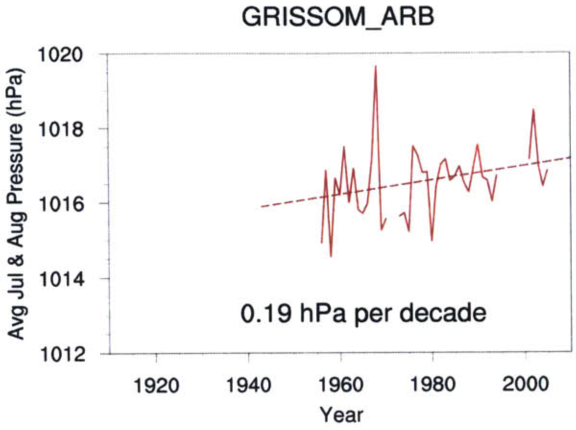

FORT_WAYNE_INTERNATIONAL_AIRP

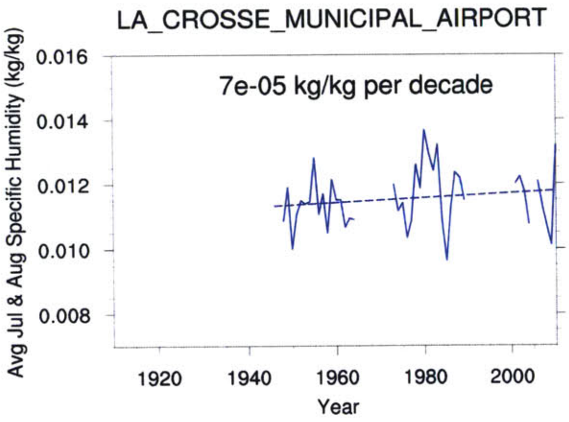

FORT_WAYNE_INTERNATIONAL_AIRP

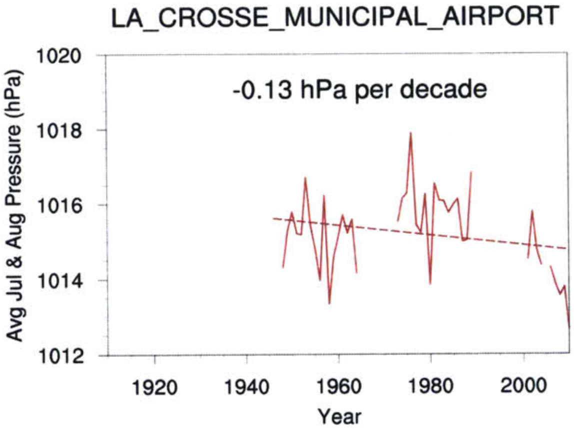

GENERAL_MITCHELL_INTERNATIONA

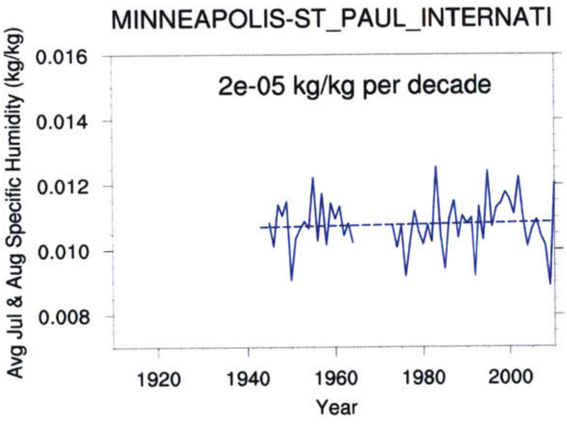

GENERAL_MITCHELL_INTERNATIONA

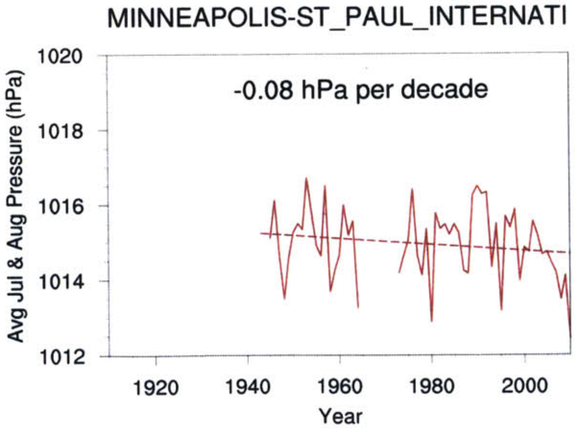

GRISSOM_ARB

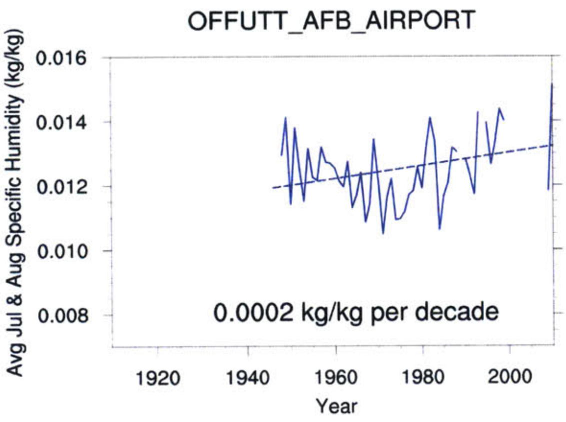

GRISSOM_ARB

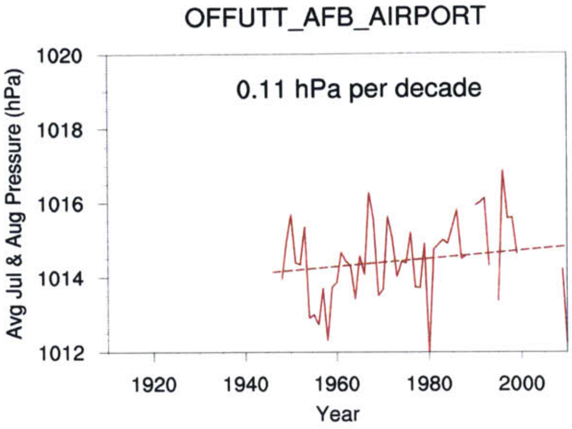

LA_CROSSE_MUNICIPAL_AIRPORT

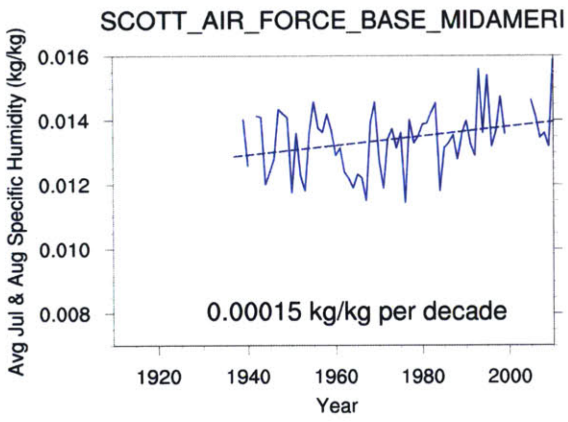

LA_CROSSE_MUNICIPAL_AIRPORT

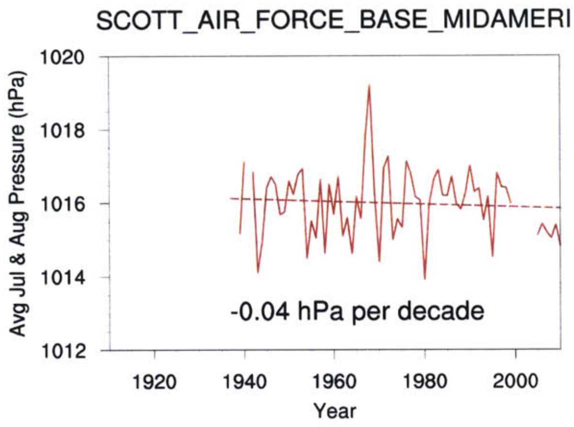

MINNEAPOLIS-ST_PAUL_INTERNATI

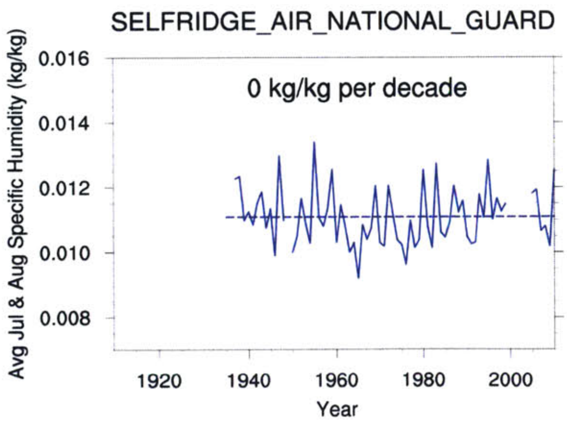

MINNEAPOLIS-ST_PAUL_INTERNATI

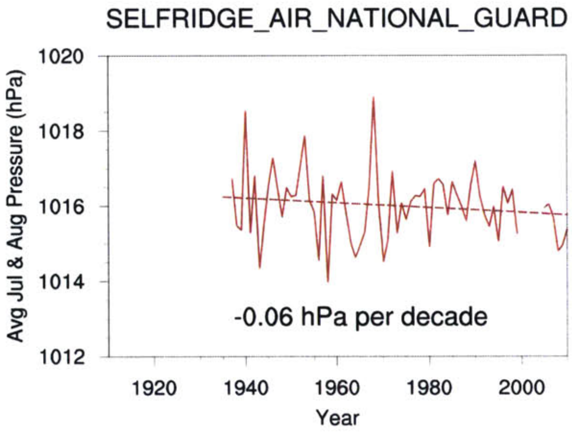

OFFUTT_AFB_AIRPORT
Avg Jul & Aug Specific Humidity (kg/kg)
0.016
0.014
0.012
0.010
0.008
0.0002 kg/kg per decade
1920
1940
1960
1980
2000
Year


OFFUTT_AFB_AIRPORT
Avg Jul & Aug Pressure (hPa)
1020
1018
1016
1014
1012
0.11 hPa per decade
1920
1940
1960
1980
2000
Year

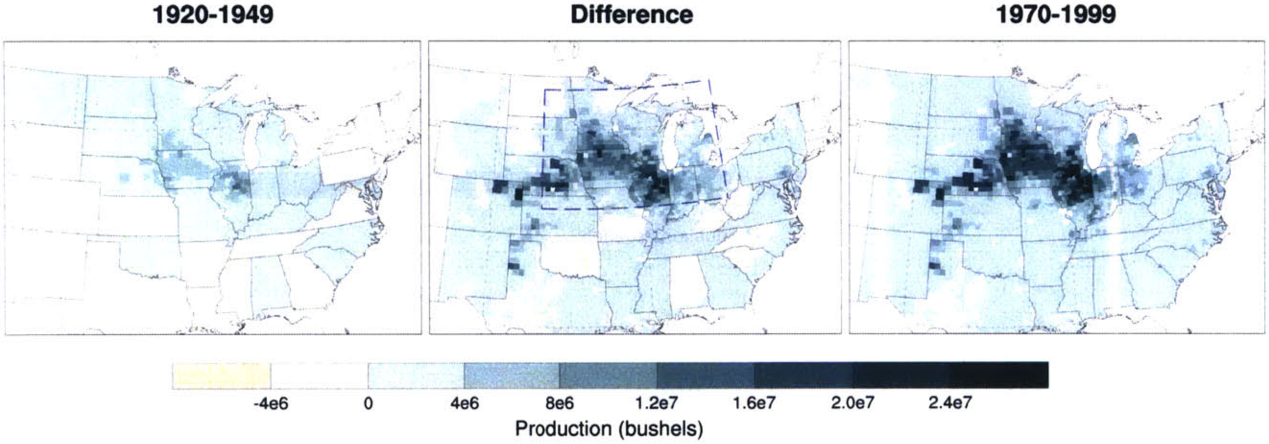

SCOTT_AIR_FORCE_BASE_MIDAMERI
Avg Jul & Aug Specific Humidity (kg/kg)
0.016
0.014
0.012
0.010
0.008
0.00015 kg/kg per decade
1920
1940
1960
1980
2000
Year


SCOTT_AIR_FORCE_BASE_MIDAMERI
Avg Jul & Aug Pressure (hPa)
1020
1018
1016
1014
1012
-0.04 hPa per decade
1920
1940
1960
1980
2000
Year


SELFRIDGE_AIR_NATIONAL_GUARD
Avg Jul & Aug Specific Humidity (kg/kg)
0.016
0.014
0.012
0.010
0.008
0 kg/kg per decade
1920
1940
1960
1980
2000
Year

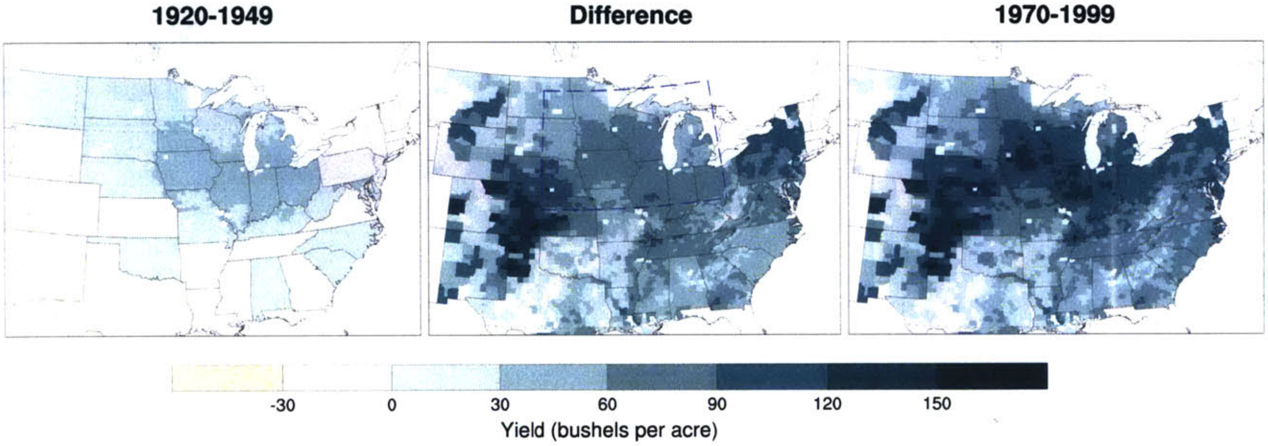

SELFRIDGE_AIR_NATIONAL_GUARD
Avg Jul & Aug Pressure (hPa)
1020
1018
1016
1014
1012
-0.06 hPa per decade
1920
1940
1960
1980
2000
Year

APPENDIX F – CHANGE IN PRODUCTION AND YIELD FOR CORN AND SOYBEANS



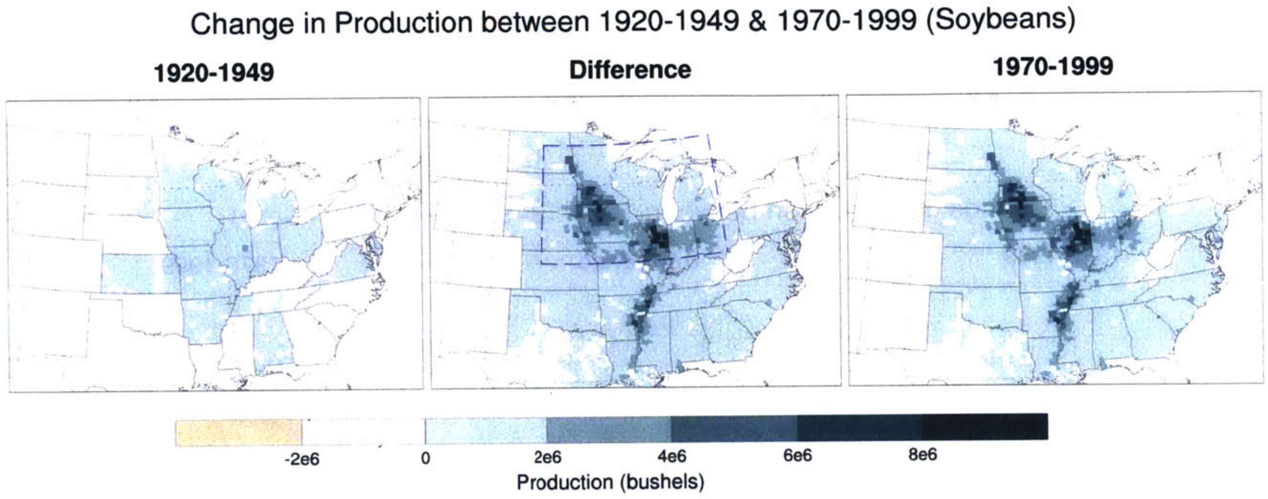
Change in Production between 1920-1949 & 1970-1999 (Corn)

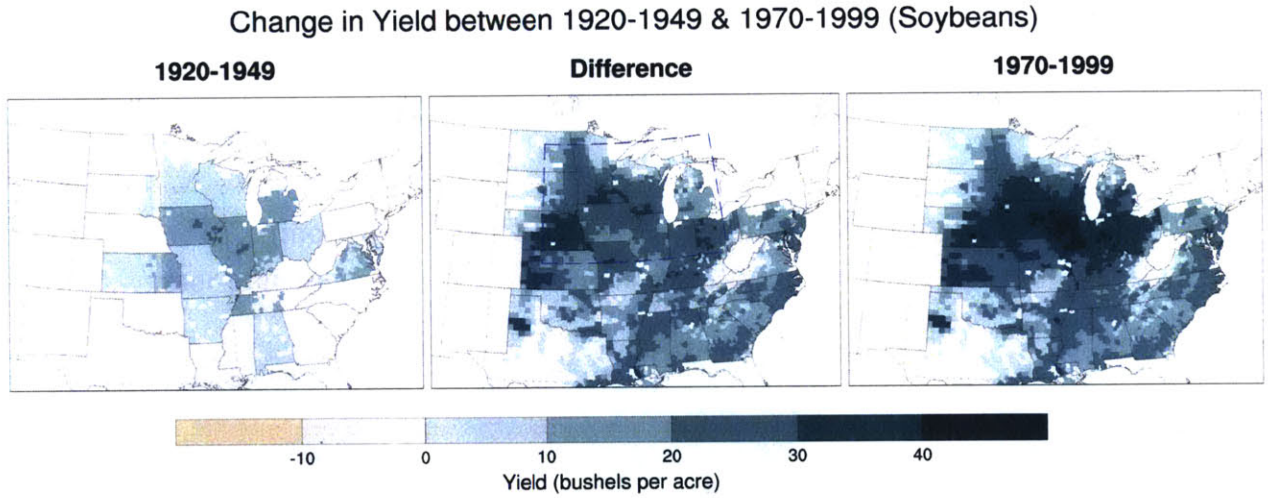
1920-1949 **Difference** **1970-1999**



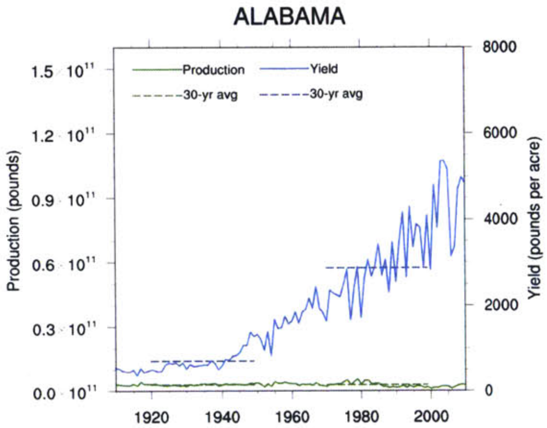
Change in Yield between 1920-1949 & 1970-1999 (Corn)

1920-1949 **Difference** **1970-1999**

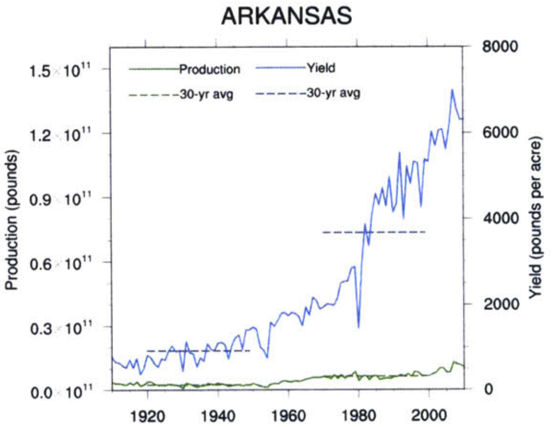

Change in Production between 1920-1949 & 1970-1999 (Soybeans)
1920-1949
Difference
1970-1999
-2e6
0
2e6
4e6
6e6
8e6
Production (bushels)


Change in Yield between 1920-1949 & 1970-1999 (Soybeans)
1920-1949
Difference
1970-1999
-10
0
10
20
30
40
Yield (bushels per acre)

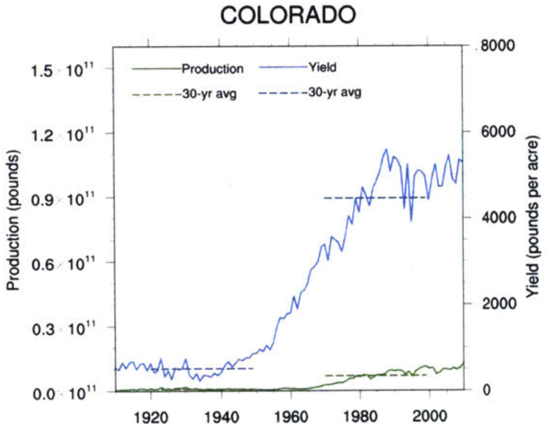
APPENDIX G – TIME SERIES OF PRODUCTION AND YIELD FOR ALL STATES



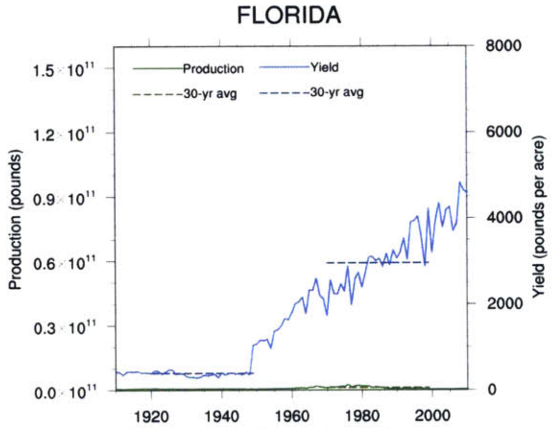
KS p-values: **production: 0.0165, yield: 0**
Change in production: -0e10 pounds (-4%)
Change in yield: 2.2e3 pounds/acre (304%)



KS p-values: **production: 0, yield: 0**
Change in production: 0.4e10 pounds (166%)
Change in yield: 2.8e3 pounds/acre (300%)

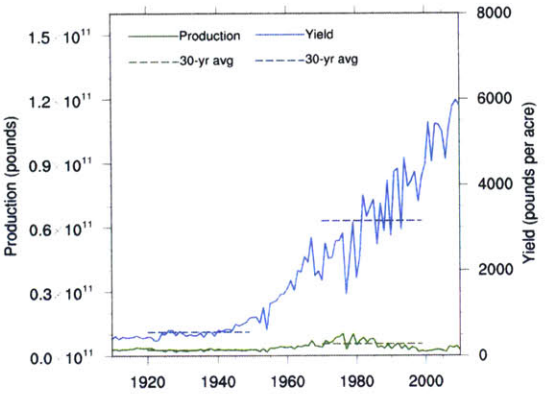


KS p-values: **production: 0, yield: 0**
Change in production: 0.6e10 pounds (689%)
Change in yield: 3.9e3 pounds/acre (760%)



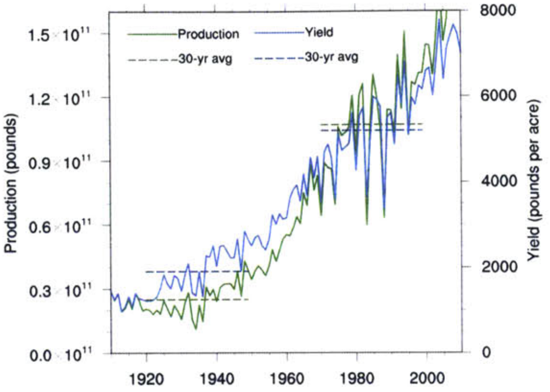
KS p-values: **production: 0, yield: 0**
Change in production: 0.1e10 pounds (132%)
Change in yield: 2.6e3 pounds/acre (651%)

GEORGIA



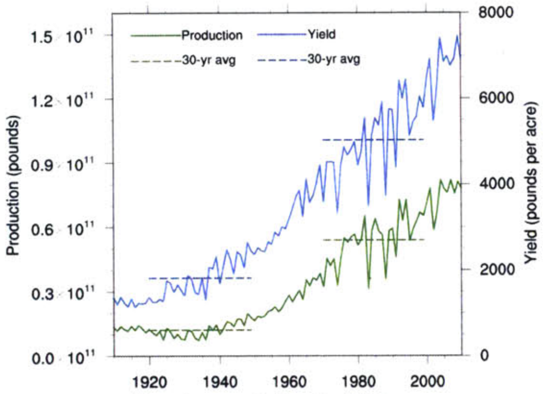
KS p-values: **production: 0, yield: 0**
Change in production: 0.3e10 pounds (98%)
Change in yield: 2.6e3 pounds/acre (456%)

ILLINOIS



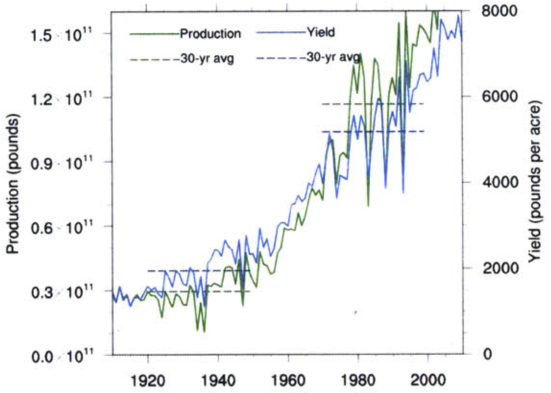
KS p-values: **production: 0, yield: 0**
Change in production: 8.2e10 pounds (327%)
Change in yield: 3.3e3 pounds/acre (172%)

INDIANA



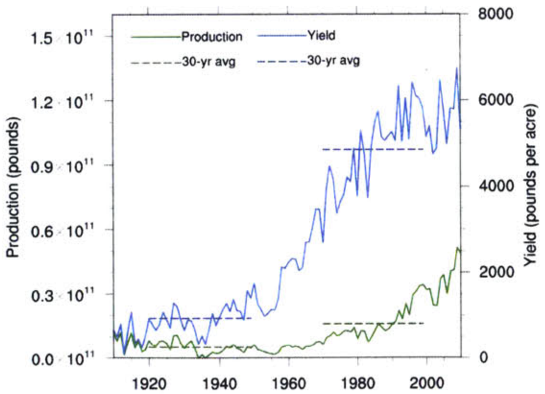
KS p-values: **production: 0, yield: 0**
Change in production: 4.2e10 pounds (341%)
Change in yield: 3.2e3 pounds/acre (176%)

IOWA



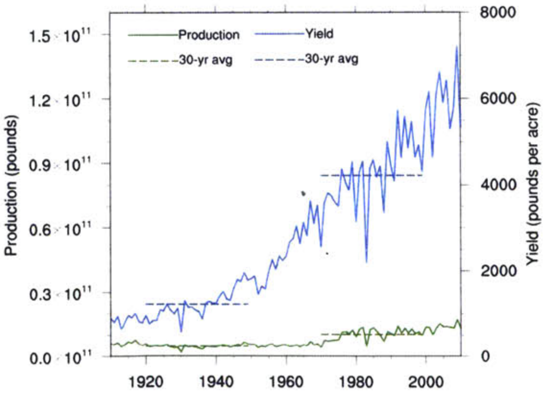
KS p-values: **production: 0, yield: 0**
Change in production: 8.7e10 pounds (295%)
Change in yield: 3.2e3 pounds/acre (164%)

KANSAS



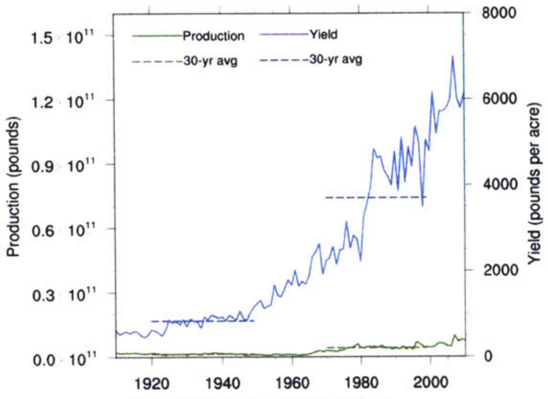
KS p-values: **production: 0, yield: 0**
Change in production: 1.1e10 pounds (212%)
Change in yield: 3.9e3 pounds/acre (418%)

KENTUCKY



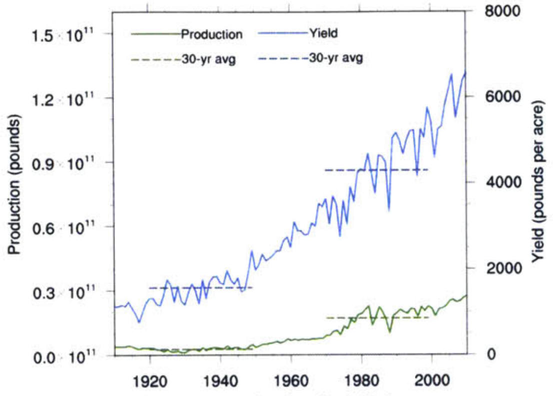
KS p-values: **production: 0, yield: 0**
Change in production: 0.6e10 pounds (120%)
Change in yield: 3e3 pounds/acre (245%)

LOUISIANA



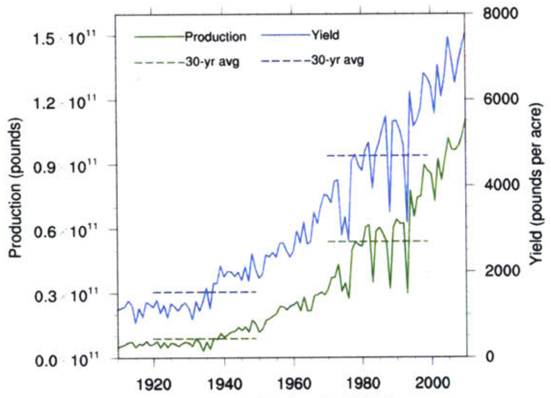
KS p-values: **production: 0, yield: 0**
Change in production: 0.3e10 pounds (198%)
Change in yield: 2.9e3 pounds/acre (344%)

MICHIGAN



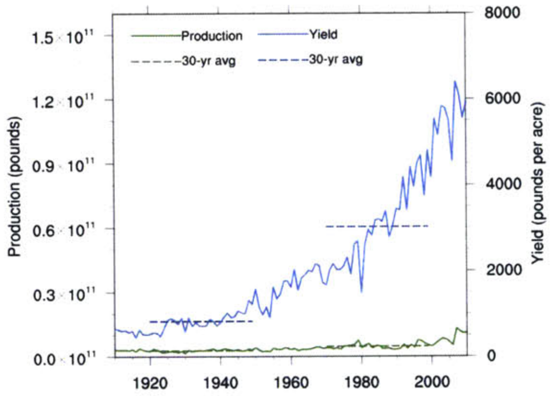
KS p-values: **production: 0, yield: 0**
Change in production: 1.4e10 pounds (548%)
Change in yield: 2.7e3 pounds/acre (175%)

MINNESOTA



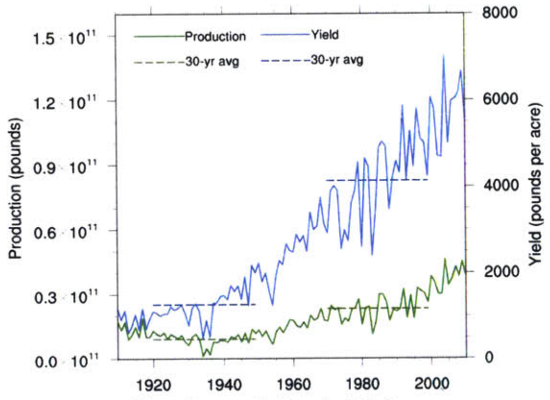
KS p-values: **production: 0, yield: 0**
Change in production: 4.5e10 pounds (503%)
Change in yield: 3.2e3 pounds/acre (207%)

MISSISSIPPI



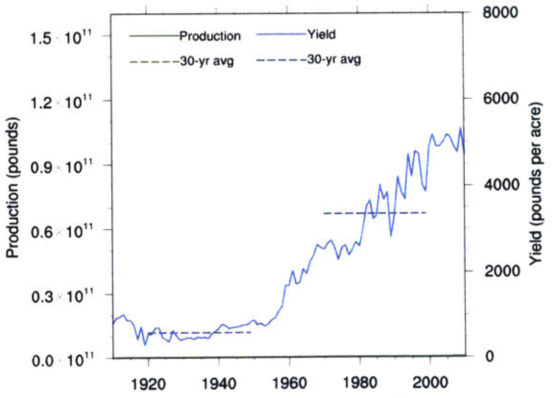
KS p-values: **production: 0, yield: 0**
Change in production: 0.2e10 pounds (69%)
Change in yield: 2.2e3 pounds/acre (267%)

MISSOURI

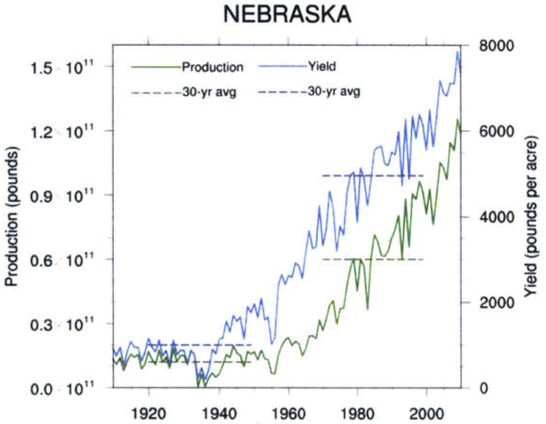


KS p-values: **production: 0, yield: 0**
Change in production: 1.4e10 pounds (150%)
Change in yield: 2.9e3 pounds/acre (226%)

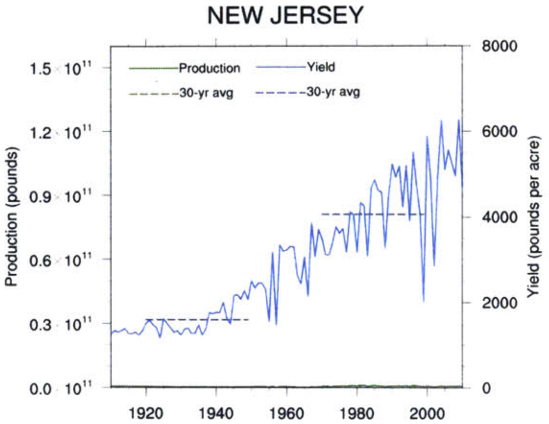
MONTANA



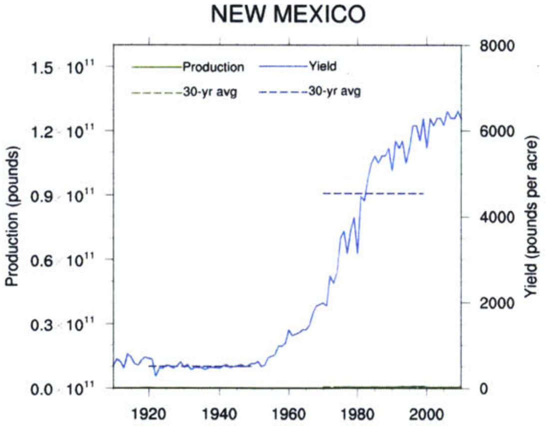
KS p-values: **production: 0.0011, yield: 0**
Change in production: 0e10 pounds (100%)
Change in yield: 2.8e3 pounds/acre (465%)



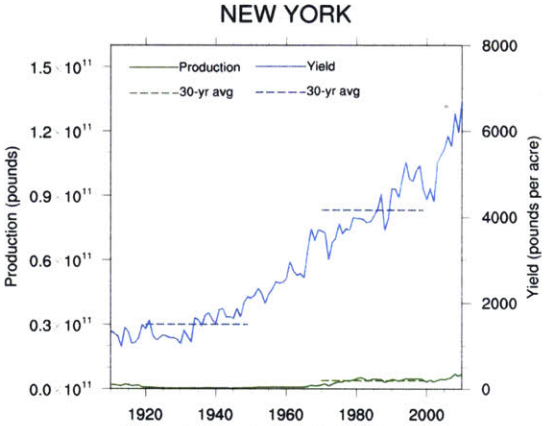
KS p-values: **production: 0, yield: 0**
Change in production: 4.8e10 pounds (392%)
Change in yield: 4e3 pounds/acre (395%)



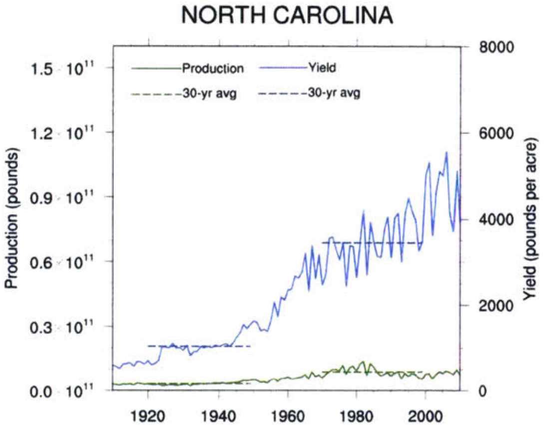
KS p-values: **production: 0, yield: 0**
Change in production: 0e10 pounds (92%)
Change in yield: 2.5e3 pounds/acre (156%)



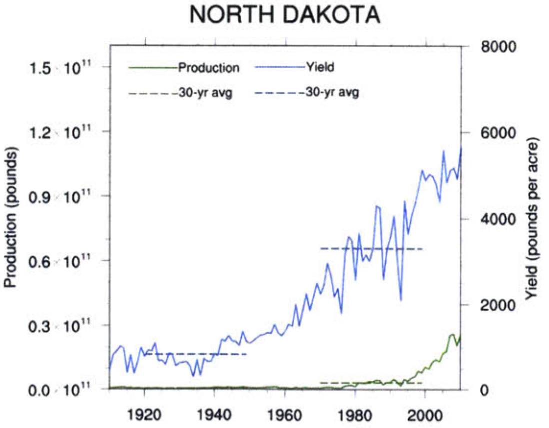
KS p-values: **production: 0, yield: 0**
Change in production: 0e10 pounds (269%)
Change in yield: 4e3 pounds/acre (785%)



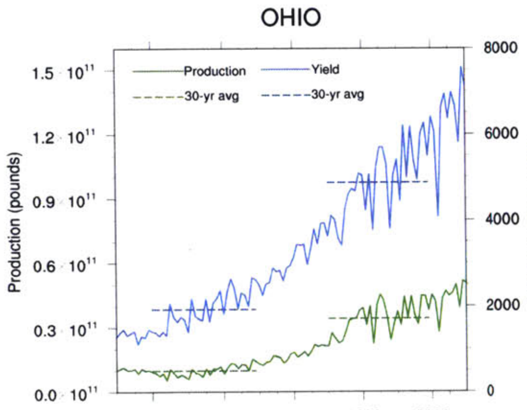
KS p-values: **production: 0, yield: 0**
Change in production: 0.4e10 pounds (821%)
Change in yield: 2.7e3 pounds/acre (177%)



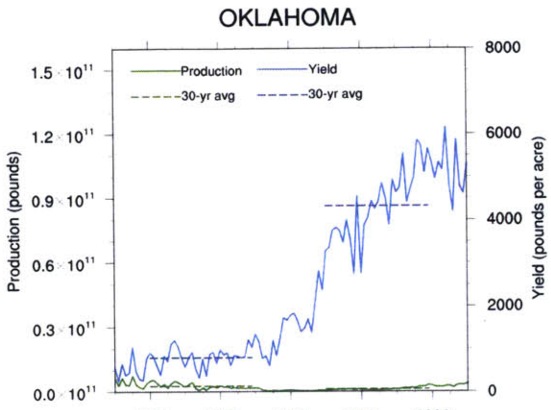
KS p-values: **production: 0, yield: 0**
Change in production: 0.6e10 pounds (173%)
Change in yield: 2.4e3 pounds/acre (231%)



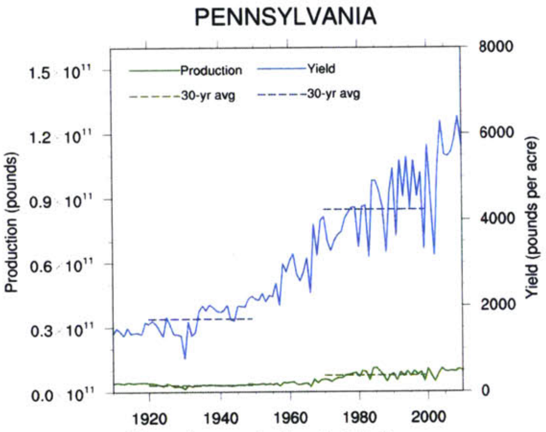
KS p-values: **production: 0, yield: 0**
Change in production: 0.3e10 pounds (561%)
Change in yield: 2.5e3 pounds/acre (298%)



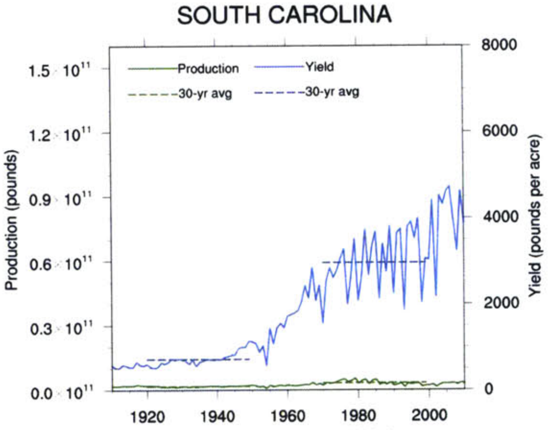
KS p-values: **production: 0, yield: 0**
Change in production: 2.4e10 pounds (246%)
Change in yield: 2.9e3 pounds/acre (153%)



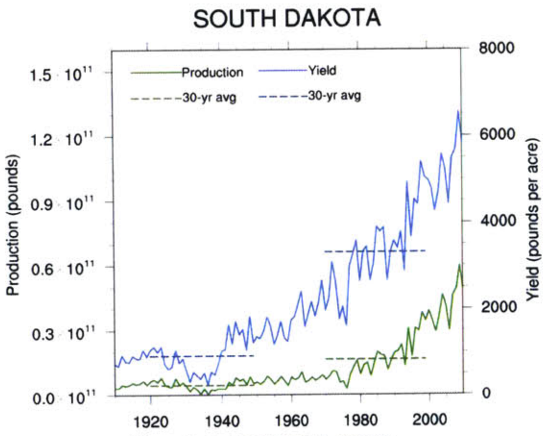
KS p-values: **production: 0, yield: 0**
Change in production: -0.1e10 pounds (-56%)
Change in yield: 3.5e3 pounds/acre (442%)



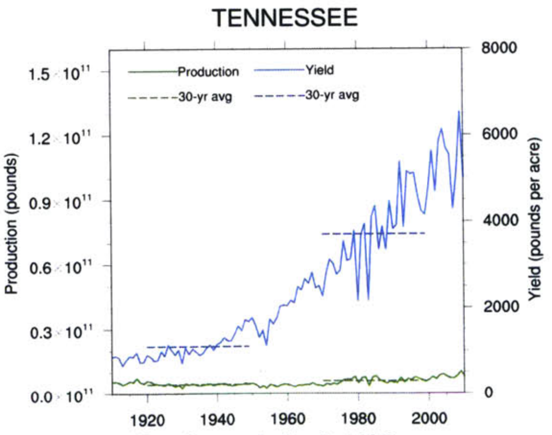
KS p-values: **production: 0, yield: 0**
Change in production: 0.4e10 pounds (147%)
Change in yield: 2.5e3 pounds/acre (150%)



KS p-values: **production: 0, yield: 0**
Change in production: 0.2e10 pounds (94%)
Change in yield: 2.2e3 pounds/acre (315%)

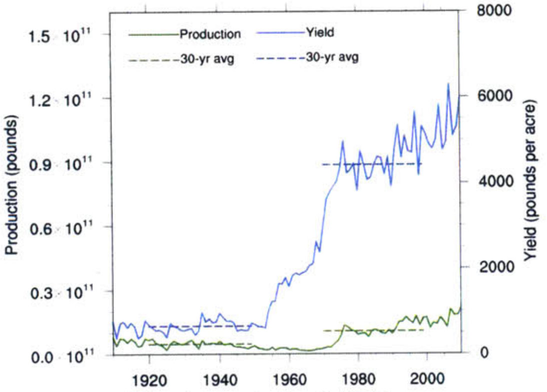


KS p-values: **production: 0, yield: 0**
Change in production: 1.2e10 pounds (253%)
Change in yield: 2.4e3 pounds/acre (263%)



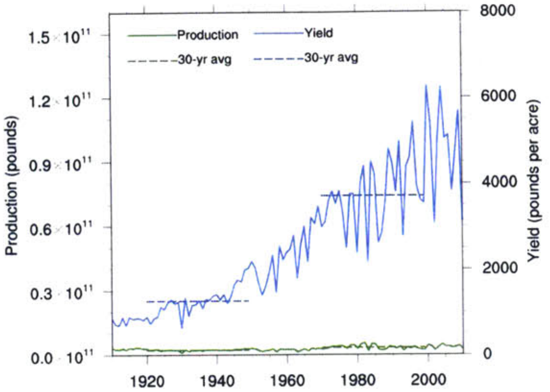
KS p-values: **production: 0, yield: 0**
Change in production: 0.1e10 pounds (33%)
Change in yield: 2.6e3 pounds/acre (237%)

TEXAS



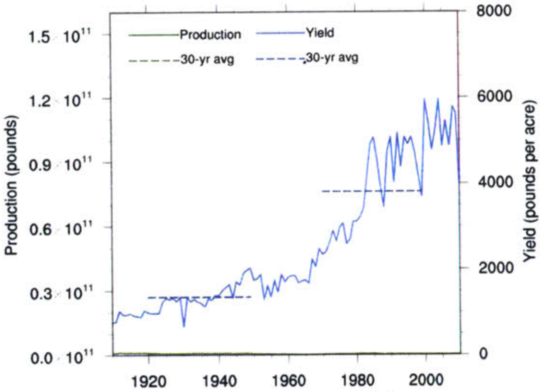
KS p-values: **production: 0, yield: 0**
Change in production: 0.6e10 pounds (124%)
Change in yield: 3.8e3 pounds/acre (565%)

VIRGINIA



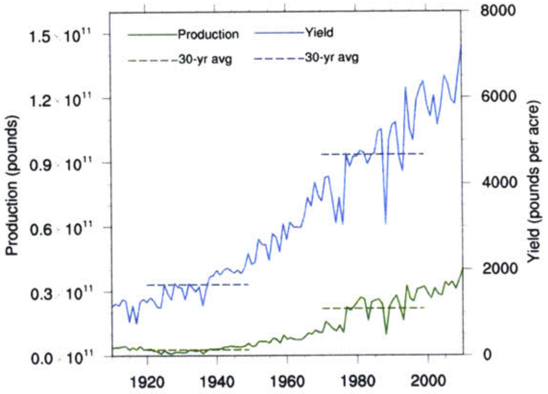
KS p-values: **production: 0, yield: 0**
Change in production: 0.1e10 pounds (44%)
Change in yield: 2.4e3 pounds/acre (194%)

WEST VIRGINIA



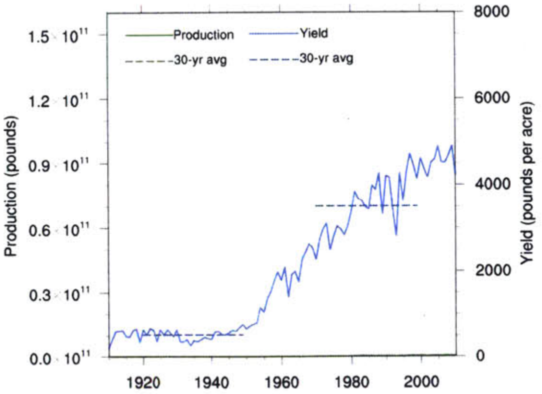
KS p-values: **production: 0, yield: 0**
Change in production: -0e10 pounds (-57%)
Change in yield: 2.5e3 pounds/acre (181%)

WISCONSIN



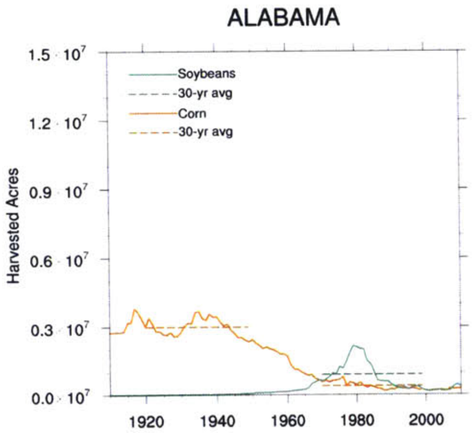
KS p-values: **production: 0, yield: 0**
Change in production: 1.9e10 pounds (656%)
Change in yield: 3e3 pounds/acre (181%)

WYOMING

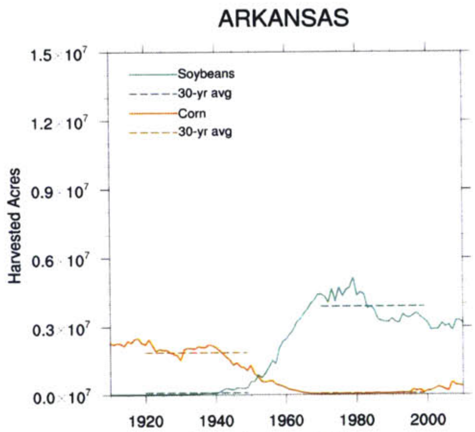


KS p-values: **production: 0, yield: 0**
Change in production: 0e10 pounds (371%)
Change in yield: 3e3 pounds/acre (564%)

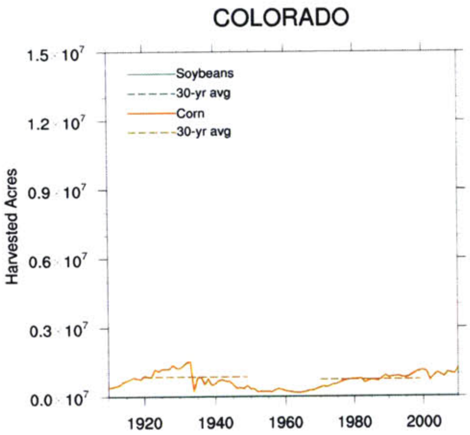
APPENDIX H – TIME SERIES OF HARVESTED ACREAGE FOR CORN AND SOYBEANS, ALL STATES



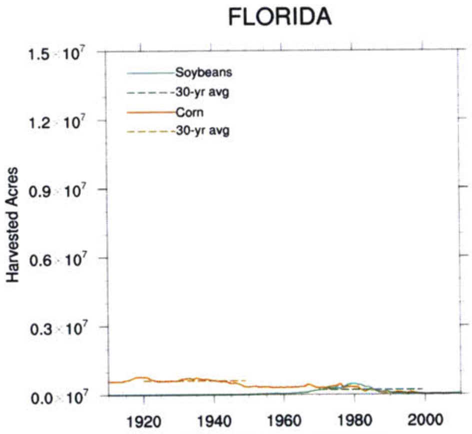
Change in corn: -2.6M acres
Change in soy: 0.9M acres



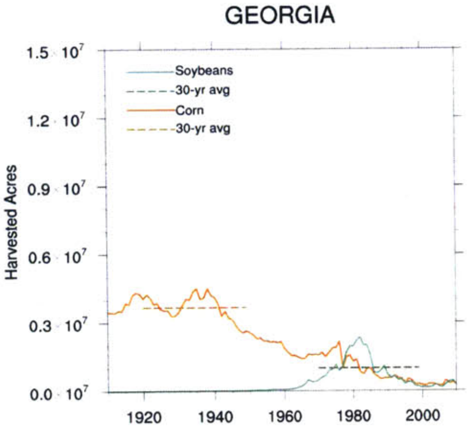
Change in corn: -1.8M acres
Change in soy: 3.8M acres



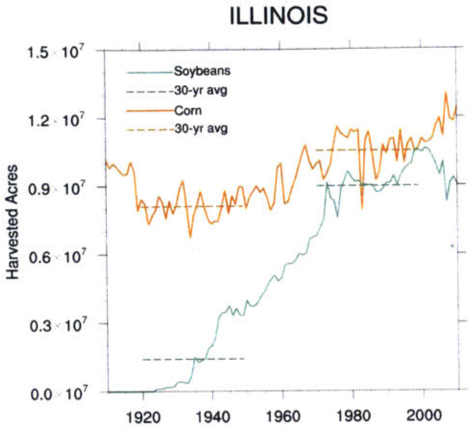
Change in corn: -0.1M acres
Change in soy: 0M acres



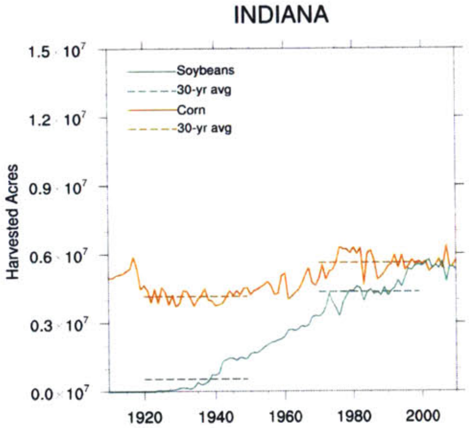
Change in corn: -0.4M acres
Change in soy: 0.2M acres


GEORGIA

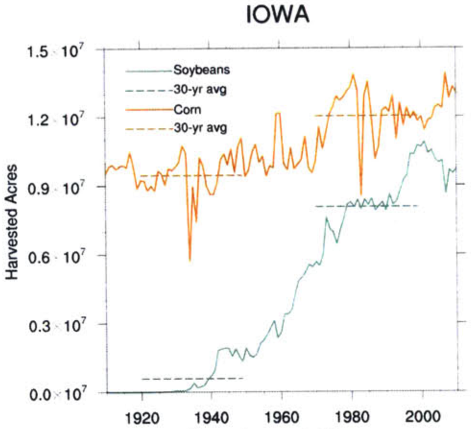
Change in corn: -2.7M acres
Change in soy: 1M acres


ILLINOIS

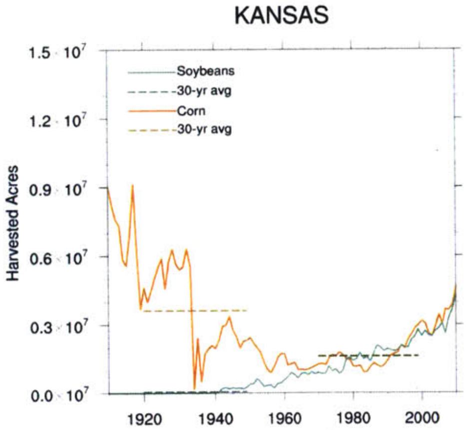
Change in corn: 2.4M acres
Change in soy: 7.6M acres


INDIANA

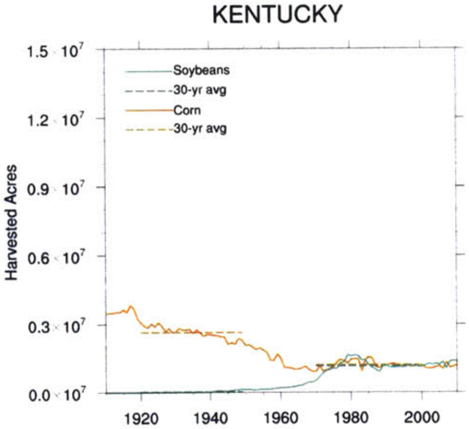
Change in corn: 1.5M acres
Change in soy: 3.8M acres


IOWA

Change in corn: 2.6M acres
Change in soy: 7.5M acres

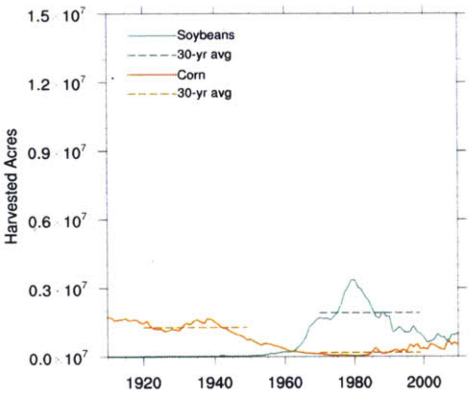

KANSAS

Change in corn: -2M acres
Change in soy: 1.6M acres


KENTUCKY

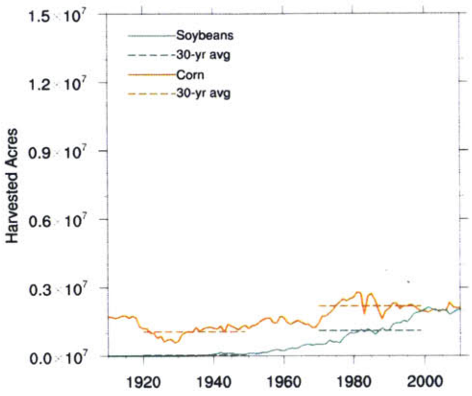
Change in corn: -1.4M acres
Change in soy: 1.2M acres

LOUISIANA



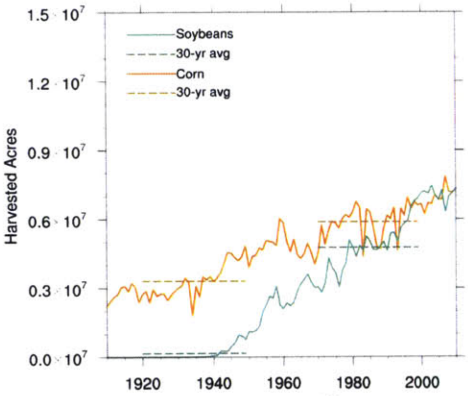
Change in corn: -1.1M acres
Change in soy: 1.9M acres

MICHIGAN



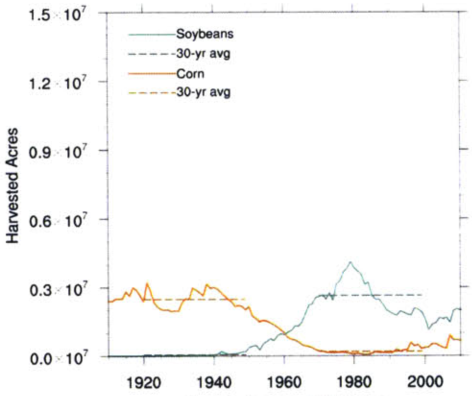
Change in corn: 1.1M acres
Change in soy: 1.1M acres

MINNESOTA



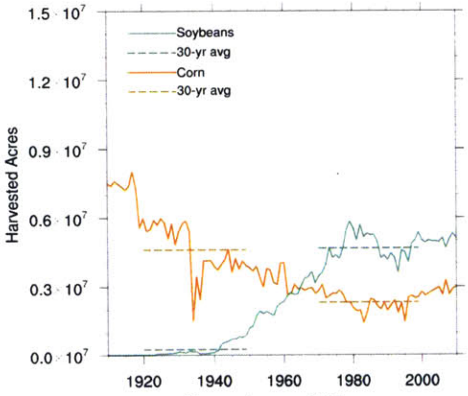
Change in corn: 2.6M acres
Change in soy: 4.6M acres

MISSISSIPPI



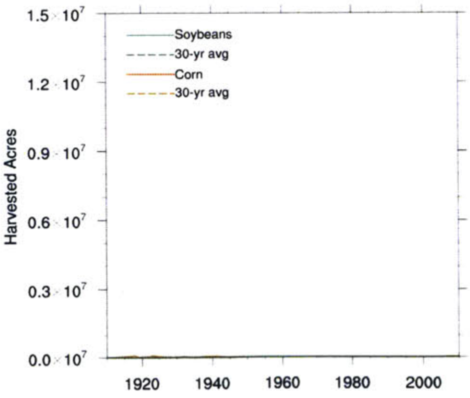
Change in corn: -2.3M acres
Change in soy: 2.6M acres

MISSOURI

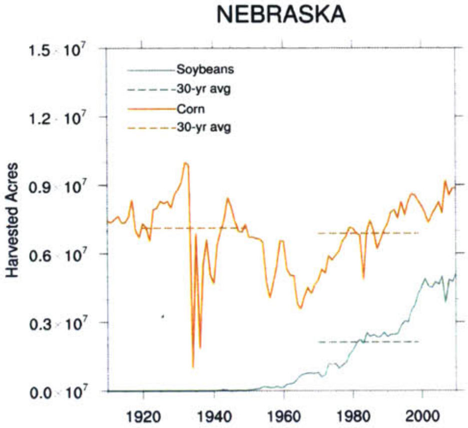


Change in corn: -2.3M acres
Change in soy: 4.4M acres

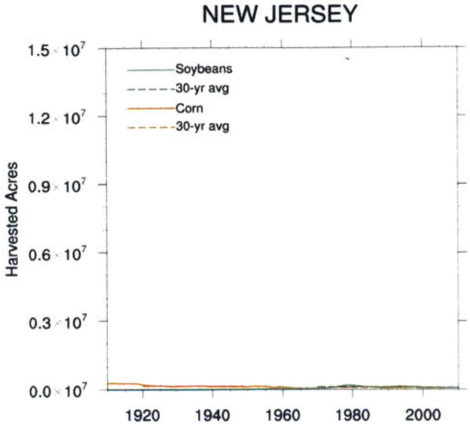
MONTANA



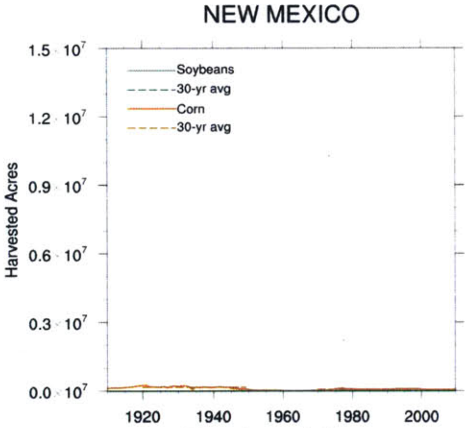
Change in corn: -0M acres
Change in soy: 0M acres


NEBRASKA

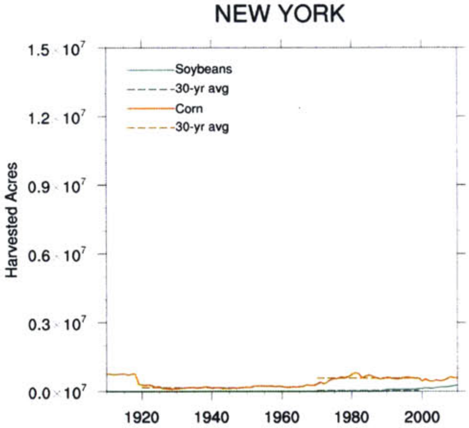
Change in corn: -0.2M acres
Change in soy: 2.1M acres


NEW JERSEY

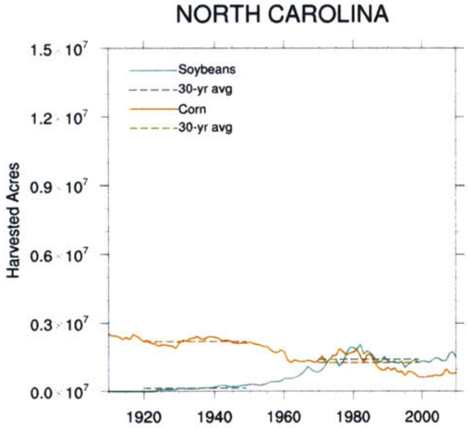
Change in corn: -0.1M acres
Change in soy: 0.1M acres


NEW MEXICO

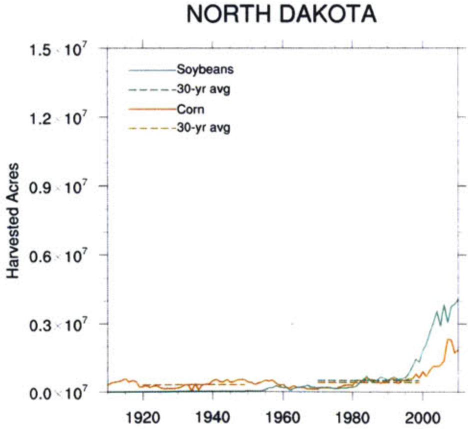
Change in corn: -0.1M acres
Change in soy: 0M acres


NEW YORK

Change in corn: 0.4M acres
Change in soy: 0M acres

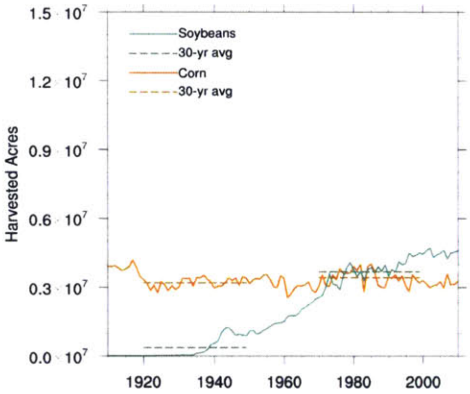

NORTH CAROLINA

Change in corn: -0.9M acres
Change in soy: 1.3M acres


NORTH DAKOTA

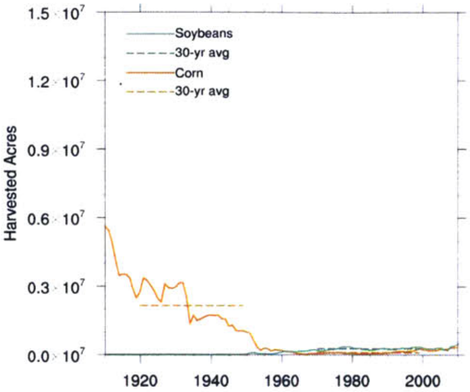
Change in corn: 0.1M acres
Change in soy: 0.5M acres

OHIO



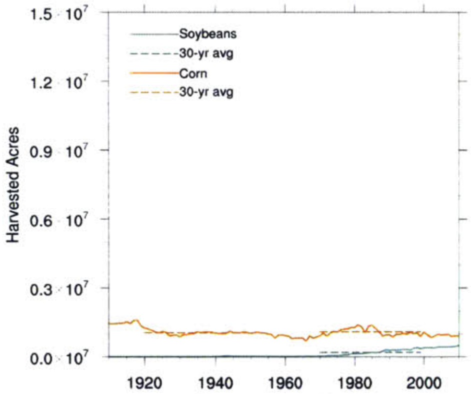
Change in corn: 0.2M acres
Change in soy: 3.3M acres

OKLAHOMA



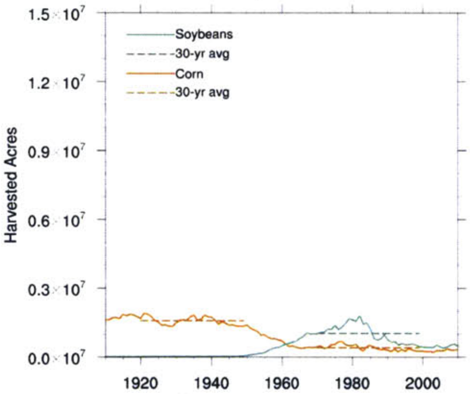
Change in corn: -2M acres
Change in soy: 0.3M acres

PENNSYLVANIA



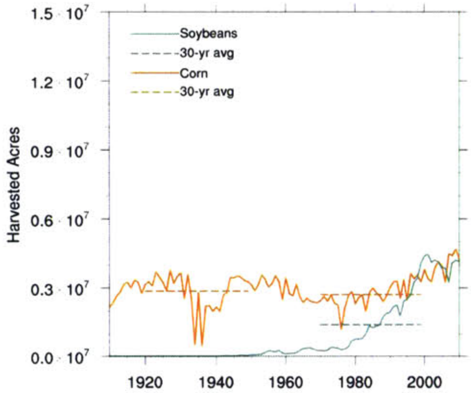
Change in corn: 0M acres
Change in soy: 0.2M acres

SOUTH CAROLINA



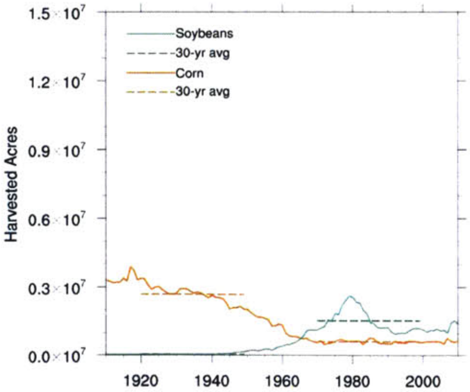
Change in corn: -1.2M acres
Change in soy: 1M acres

SOUTH DAKOTA

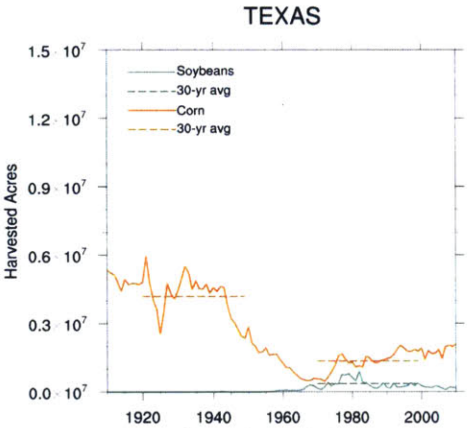


Change in corn: -0.2M acres
Change in soy: 1.4M acres

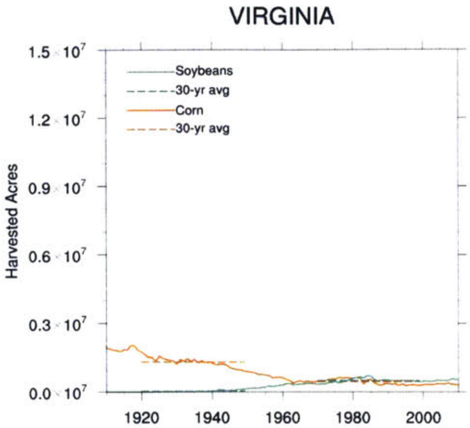
TENNESSEE



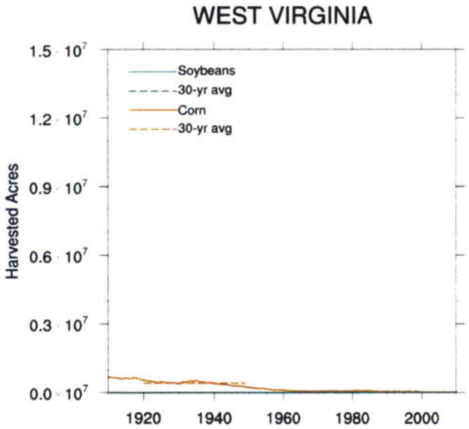
Change in corn: -2.1M acres
Change in soy: 1.5M acres



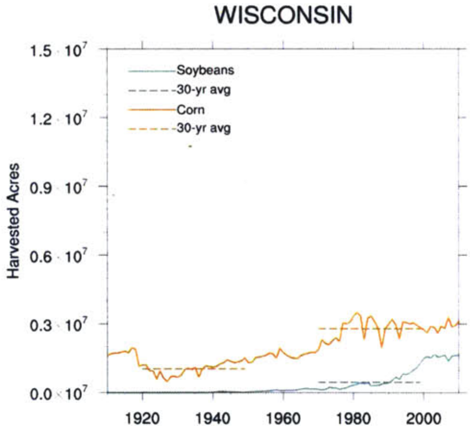
Change in corn: -2.8M acres
Change in soy: 0.4M acres



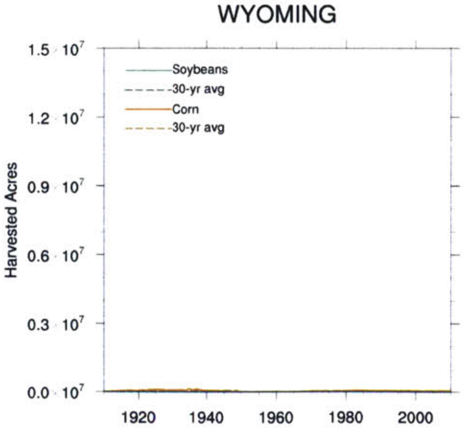
Change in corn: -0.9M acres
Change in soy: 0.5M acres



Change in corn: -0.4M acres
Change in soy: 0M acres



Change in corn: 1.8M acres
Change in soy: 0.4M acres



Change in corn: -0M acres
Change in soy: 0M acres