CLIMATE CHANGE THROUGHOUT THE DAKOTAS

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ABSTRACT

How is the climate changing on a county level throughout North Dakota (ND) and South Dakota (SD)? To determine this answer, 13 different climate variables were analyzed: temperature minimums and maximums, precipitation, growing degree days (GDD), season length, first and last frost dates, standardized precipitation index (SPI), Palmer drought severity index (PDSI), evapotranspiration (ET), solar radiation, dew point and wind speed. Annual and monthly climatic trends, per decade, were developed and analyzed by county. These climatic variables show various changes throughout North Dakota and South Dakota by either increasing, decreasing or staying the same.

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DEDICATION

This document is dedicated to my family, friends and fiancé. They stood by me through all the hardships that I had to overcome throughout this project.

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LIST OF ABBREVIATIONS

ASOS..Automated Surface Observing Systems

ET..Evapotranspiration

GDD...Growing Degree Days

ND..North Dakota

NDAWN..North Dakota Agricultural Weather Network

PDSI..Palmer Drought Severity Index

PPM..Parts per Million

PRISM............................Parameter-elevation Regressions on Independent Slopes Model

SSD...Subsurface Drainage (Fields)

SD..South Dakota

SPI...Standardized Precipitation Index

Tmin...Temperature Minimum

Tmax...Temperature Maximum

UD...Un-Drained (Fields)

U.S. ....United States

HCN..Historical Climate Network

COOP...Cooperative Observing Program

CMIP...Coupled Model Intercomparison Project

in...Inch

°F..Degrees Fahrenheit

°C...Degrees Celsius

INTRODUCTION

Recent years and studies suggest that the climate is changing. In 1975, Manabe and Wetherald made the first global climate-change model calculations of warming due to an instant doubling of atmospheric CO_2. The main source of global climate change is humans (Karl & Trenberth, 2003). This study addresses how the climate is changing on a county-level, small-scale basis in North Dakota (ND) and South Dakota (SD).

Various climatic variables have changed in many ways throughout the years. The temperature has increased 0.2 degrees Celsius (°C) throughout the world (Hanson et al., 2006; Garcia-Ruiz et al., 2011). Precipitation increases that appear in the mid to high latitudes are concurrent with intense surface warming (Gu & Adler, 2015). The first and last frost dates were 1.2 and 1.5 days per decade later and earlier respectively. This acceleration of spring has led to a longer growing season (Chuine et al., 2007). The Palmer drought severity index (PDSI) calculations indicate decreased moisture, globally, since the 1970s (Sheffield et al., 2013). A study looking at the standard precipitation index (SPI) found that more extreme droughts and wet periods might occur due to global warming (Swain & Hayhoe, 2015). ET is the most important hydrological and metrological variable to reflect climate change. ET, solar radiation and wind speed have different trends throughout the world (Wild , et al., 2005) (Wang , et al., 2012; Klink, 1999). Dew-point temperatures in the United States increased during a 40-year period (1951-1990) by slightly over 1°C/100 years (Robinson, 2000).

How are temperature, precipitation, GDD, season length, first and last frost dates, SPI, PDSI, ET, solar radiation, dew point and wind speed changing on a county-level basis in North Dakota and South Dakota?

This project answers the question by combining multiple data queries and data-collection websites. This work needed to be done in order to acquire the necessary climatic variables to conduct the project's research. Each climatic variable contains different lengths and spatial characteristics. However, all the climatic variables were analyzed and summarized the same way to produce standardized results.

Overall, this project was conducted to draw conclusions about how different climatic variables are changing throughout North and South Dakota. Where are these climatic variables increasing, decreasing or staying the same at the county level? Are some climatic variables changing more than others? This project allows the public to view the findings and to gather climate data with ease.

LITERATURE REVIEW

Temperature

When looking at temperature changes throughout the world, Manabe and Wetherald made the first global climate-change model calculations of warming due to an instant doubling of atmospheric CO_2. The main driver of global climate change during the industrialization era CO_2 emitted into the atmosphere by burning fossil fuel. Other greenhouse gases also contribute to the greenhouse effect. In clear skies, the atmosphere consists of different trace gases of which, 60% is water vapor and 25% is carbon dioxide. Clouds also complicate the matter by trapping heat at night and blocking the incoming solar radiation during daytime. CO_2 has increased 31% since preindustrial times, from 280 parts per million (PPM) to 370 PPM; half of this increase has been since 1965 (Karl & Trenberth, 2003) due to burning fossil fuels which releases CO_2 particles into the atmosphere. The Goddard Institute for Space Studies has been monitoring the global surface temperature's change, which was initiated by James Hanson in 2006 using the Global Historical Climatology Network that includes about 7,000 stations. In the past 30 years, the temperature has increased 0.2 °C per decade throughout the world (Hanson et al., 2006; Garcia-Ruiz et al., 2011).

The global temperature has risen the fastest in recent decades compared to the decades prior to 1965, despite the year-to-year fluctuations associated with the El Niño-La Nina cycle. The planet is currently as warm as it was in the Holocene maximum and is also within 1 °C of the maximum temperature ever recorded during the past million years (Hanson et al., 2006). Looking at urban influences for the changes, the temperature change, as a whole, is relatively small. However, in some areas of the world, there are an insufficient number of weather stations to fully understand how much the temperature is changing everywhere (Hansen et al., 2010).

When looking at how the temperature has changed/impacted the United States, studies found that land use/land cover changes significantly affected temperature trends. Utilizing the United States Historical Climatology Network (HCN) and the North American Regional Reanalysis, 586 stations were used to document climate change on a national level from December 1983-January 1998. Both datasets showed a significant increase in trends, changing roughly 5% in most eastern and southern states. However, the differences between the two samples were significantly different (t-test, alpha = 0.05). The U.S. HCN found an average temperature increase of 0.27 °C. The North American Regional Reanalysis stations showed a temperature increase of 0.28 °C (Fall et al., 2010). Another study was completed using the Cooperative Observing Program (COOP) Network; each site needed at least 80 years of observed data. COOP stations are not given a new name or identifier unless that station has been moved more than 5 miles or 100 feet in elevation form its previous location. Urbanization around a certain station can cause artificial warming (Kunkel et al., 2013). Of the 1,219 stations in the COOP, 84 were selected. Using these stations, the overall temperature trends for the maximum and minimum temps per decade were about about 0.015 and 0.022 °C, respectively, from 1895-2007 (Menne et al., 2009). Using a pairwise algorithm, it was found that, on average, one significant, artificial shift happens for every 15-20 years of the stations' data (Menne et al,. 2009).

Research has also been conducted for North Dakota. The results show an increased annual temperature over the past 130 years; this annual change is mainly driven by warmer winters (Ojima et al., 2014). Land-use changes due to agriculture in the Great Plains region have led to decreased surface temperatures in some areas where farming is dominate (Menne et al., 2009). Temperatures above 35 °C (95°F) are quite uncommon throughout the Dakotas. However, temperatures greater than 37.78 °C (100°F) are projected to become more frequent. The warmest years on record are 1934 (dust bowl) and 2006. The second-warmest years are 1935 and 2011 (Kunkel et al., 2013). These extreme warming trends have negative consequences, such as water loss, heat stress and air-conditioning demand. With a warmer winter, fewer heating demands as well as less cold stress on humans and animals will occur, thus counteracting the negative impacts (Ojima et al., 2014). This finding is also shown through the freeze-free season which was roughly 6 days longer throughout 1991-2010 than for 1961-1990, meaning that last spring occurrence of 0 °C is earlier and that the first fall occurrence of 0 °C happens later (Kunkel et al., 2013).

Research studies have also been conducted for South Dakota. Fontaine et al. (2001) found that temperatures in the Black Hills have been increasing for the past decades. This change is due to increased CO_2 (Fontaine et al., 2001). Another study found a significant increase for the accumulated warmth-sum days between 1999 and 2012. This warmth caused more species richness in open woodlands, marsh and grasslands (Bedfold et al., 2013).

There are drawbacks with climatic data. Some temperature observations contain errors because humans read and then report the climatological observations. When the climate observations are taken has changed throughout time, leading to some inconstancies with the readings and findings. Also, thermometer changes have led to an increase or decrease for the temperature readings (Menne et al., 2009).

Precipitation

When looking at precipitation, global precipitation was suggested to increase with higher temperatures. However, the best, current precipitation data showed a negligible change in the global mean both over the land and oceans, although a significant precipitation change was seen when using shorter time intervals (Gu & Adler, 2015). The late twentieth century was warmer than the Medieval Warm Period. However; however, it was drier than the medieval warm period. The recent precipitation difference resulted from an increase in energy budgets and greenhouse-gas warming, whereas the Medieval Era's changes were due to solar-volcanic warming. The precipitation change that results from greenhouse-gas warming is about 1.3% per degree Celsius. This change is 40% less than the change due to solar-volcanic warming. As a result, there is a dryer climate today compared to the Medieval Era (Liu et al., 2013). Aerosols have been known to cause climatic variation and could be causing reduced precipitation events. However, precipitation increases that appear in the mid to high latitudes are concurrent with intense surface warming. While there is reduced precipitation in Africa's tropical portion and the northern Indian-Tibetan region, these differences are constant with the changes in monsoon strength. When looking at oceanic precipitation changes, increased precipitation was found in the equatorial Pacific region and then decreased as you moved away from that area (Gu & Adler, 2015). Precipitation-change knowledge remains quite limited because proxy data are limited and because the precipitation's spatial distribution is complex. Precipitation amounts can change on a microclimatic level. For example, one town could receive 2 inches of precipitation, and the town 5 miles away could receive zero inches of precipitation during the same storm (Liu et al., 2013).

Precipitation changes in the United States are different throughout the country. As a whole, there has been a 10% increase in precipitation across the nation. However, there are some areas, which are receiving less rainfall (Karl & Knight, 1998). In the western United States, changes in the mean precipitation are mostly dominated by the widening tropical belt and the pole-ward shift for the westerly winds. In the southwestern portion of the United States, the mean precipitation is expected to decrease. Observational records show an increase for the intense-precipitation events even if, in some cases, the mean precipitation rates are decreasing (Dominguez et al., 2012). Monsoon seasons are causing a shortage of rainfall in the southwest and in the southeast because the seasons are growing weaker over time. Also, extra-tropical cyclones may become weaker and less frequent over the western Atlantic. However, Coupled Model Intercomparison Project Phase 5 analyses suggest that increasing cyclone intensities on the East

Coast may lead to more wind and heavy precipitation extremes (Wuebbles et al., 2014).

Looking at precipitation changes throughout the Great Plains region, the precipitation amounts were greater during the 1990s compared to the years from 1901-1960. The last few years, except for 2011, have been the wettest consecutive years on record (Kunkel et al., 2013). The U.S. Geological Survey has been measuring the Devils Lake basin since 1867. Devils Lake has been fluctuating throughout the years, reaching its lowest level in 1940. Increased precipitation has caused Devils Lake to rise and, in 1999, to spill into Stump Lake. This increased surface height has caused millions of dollars in damage to surrounding areas (Kharel & Kirilenko, 2015). Badh and Aky üz (2010) tabulated the precipitation data for select North Dakota stations in order to calculate the average annual rate of change (trend) for precipitation at each station since 1874. Every station showed a unique annual-precipitation trend. For the given time period, Fargo, Bismarck, Jamestown and Williston had a negative trend for annual precipitation while Pembina, Minot, Langdon and Dickinson showed a positive trend for the annual precipitation. On average, the state's annual-precipitation trend did not deviate much from the long-term average for the study's time period (Badh & Akyüz, 2010). Looking at Morris, Minnesota, there is increased precipitation during the winter and in April, which can be beneficial for plant yields. There is also late-season precipitation which can have a negative impact on crop yields because the fields are too wet to harvest (Klink et al., 2013). Looking at the Prairie Pothole Region, precipitation fluctuates during all seasons, with the strongest variation occurring in the summer.

Growing Degree Days

Studies show that, throughout the world and due to global climate changes, GDDs could significantly alter plant phenology because temperatures influence the crops' timing and development (Chuine et al., 2007). The southern provinces of Canada, the northwestern and north-central U.S. states, northern Europe, southern portions of the former Soviet Union and China's Manchurian plains are the most sensitive to temperature changes (Ramankutty et al., 2002). The first and last frost dates were 1.2 and 1.5 days per decade earlier. This acceleration of spring led to a longer growing season. In tropical ecosystems, global warming might be less sensitive to plant species and more tuned to seasonal precipitation shifts. In Europe, fruit ripening quickened by 2.4 days per decade from 1971-2000. Throughout the Northern Hemisphere, summer CO_2 concentrations have increased, causing a change in plant phenology and increasing the production in some areas. However, these warming temperatures are creating drier summers around the globe, potentially offsetting some areas' increased terrestrial production (Chuine et al., 2007). The Canadian Atlantic Maritime Ecozone studies show that a constant 100-year offset of about 511 GDD is occurring throughout Canada. Data are based on 101 environmental climate stations in Canada (Hassan et al., 2007).

In the United States, since 1980, the frost-free season has increased by about 1 week. Linderholm (2006) found that the growing season has lengthened between 10 and 20 days in the last few decades. This change was found using satellite data. The increase had to do with the higher annual amplitude of about 40% for the seasonal CO_2 cycle (Linderholm, 2006). However, the frost-free season length increased much more in the western United States compared to the eastern United States. Climate stations in the country's western portion are very sporadic, thus it can be more difficult to determine the reliability of the season length's extreme increases (Kunkel et al., 2004). In the mountainous areas of the United States, snow and ice-free periods in the forests decreased by 15-20 days. This change could be due to the increased liquid precipitation during the winter months (Linderholm, 2006).

In the Great Plains, corn is one of the major contributors to the country's economy. With these warmer temperatures predominant throughout the United States, corn can be raised in areas where it could not be grown in before, especially in the Dakotas (Badh, 2011). While technology, climate and society are changing in the same environment where we live, it is becoming more difficult to separate the climate's influence from the other elements in order to explain the differences for crop production. The latest studies are now geared towards separating the impact of climate from the other elements. For example, Badh and Akyüz (2010) identified the average GDD trend for corn in different parts of the Northern Plains. In Fargo, North Dakota, for example, the average accumulated seasonal trend of GDDs for corn is 33.5 heat units per decade. In other words, North Dakota, on average, accumulated 335 heat units more during recent growing seasons compared to the growing seasons 100 years ago. North Dakota farmers plant a type of corn that typically matures between 85 and 90 days. Therefore, today's climate allows approximately 2,000 heat units to accumulate for this corn to mature. An average, seasonal GDD accumulation of 335 heat units today is equivalent to 17% of the necessary heat units to mature the corn that grows in North Dakota. It is, therefore, the quantity of climate impact in corn becoming a possibility in the higher latitudes (Badh and Akyüz, 2010). Today, the farmers are growing the type of corn which would have been to risky to grow then in this region.

Season Length

Looking at global changes for the season length as well as the first and last frost dates throughout the world, a study was conducted to examine the daily maximum and minimum temperature series throughout the world for more than 40 years. A total of 3,000 indicator time series were found and analyzed, illustrating that significant changes are emerging. Frost days decreased throughout the world (Frich et al., 2002). Another study found earlier thaw dates in the tundra and larch biomes over Eurasia. The earlier spring warmings mean quicker snowmelt runoff, river ice-out and lake ice-out. With the increased season length, the growing-season models show that the ET rates are also increasing (Huntington, 2006).

A study examined U.S. temperature data sets from 1948-1999, finding that frost-free days have increased throughout the United States (Easterling, 2002). This change occurs because the last spring-freeze date is significantly earlier, whereas fall-frost dates only show a small change throughout the United States. The only portion of the United States that is not showing a change is in the southeast. This increase for the spring frost-free period has occurred since the late 1970s, especially in the western portion of the United States (Cayan et al., 2010).

Palmer Drought Severity Index

The PDSI has changed globally with previous years' assessments of the historical drought changes which indicate increased evapotranspiration and decreased precipitation. Thus, the PDSI calculations indicate a decrease in moisture globally since the 1970s (Sheffield et al., 2013). The PDSI uses widely available temperature and precipitation data to estimate relative dryness; there is a set scale that ranges from -10 to +10, where negative values indicate dryness and positive values indicate wetness. This method can be used to capture the global warming's basic effect on drought. However, the model can overestimate drought for large-scale areas because it only utilizes basic characteristics, i.e., temperature and precipitation (Dai et al., 2016).

Looking at drought in the United States, the Department of Commerce's National Climatic Data Center has recorded 17 drought years from 1980-2012. These droughts have exceeded tens of billions of dollars in damages and costs (Ryu et al., 2014). The western portion of the United States has experienced higher ET rates and higher temperature trends throughout the twentieth century. This increase correlates with more negative PDSI values in these regions of the United States (dryer). Looking at the latter half of the twenty-first century, the PDSI values, on average, are around -5.0. This value is lower than any individual annual value in the entire observational record through 2007. However, when looking at the values from the current half century, we see values ranging from 1.0 to -1.99 (Gutzler & Robbins, 2011). With drought extending north into Minnesota, forests are starting to lose strength in the southern-middle and southern portions of Minnesota. One sign of this change is the declining tree-ring width, indicating stress. Trees at the northernmost site exhibited the most sensitivity to drought, whereas the southernmost portion of Minnesota (the wettest) showed the least sensitivity to drought (Wyckoff & Bowers, 2010). Drought significantly reduces the worldwide carbon storage, thus hindering plant growth throughout the United States (Chen et al., 2012).

Using PDSI index can be highly beneficial in estimating wetland size change in North Dakota where accurately determining snow accumulation, runoff and evaporation approximation can be difficult. In a study looking at the Cottonwood Lake area in North Dakota, the researchers found that, when the PDSI was negative, the wetlands were not small and that, when the PDSI values were positive, the wetland sizes were not large (Huang et al., 2011).

Standardized Precipitation Index

Mckee and Doesken (1993) developed the SPI to quantify dryness with respect to a given region's average precipitation and standard deviation for a defined period of time (Mckee and Doesken, 1993). Looking at the SPI in a global setting and using the University of East Anglia Climatic Research Unit global data sets, the SPI values in the southern Amazon region have decreased by .32 per decade between 1970 and 1999, thus indicating drier conditions. These droughts may delay forest turnover; severe droughts increase the flammability of the forest's floor because the leaf litter is drier (Li et al., 2008). In western Europe, the SPI values illustrate a dramatic increase for the meteorological drought frequencies in the late twenty-first century relative to the twentieth century baseline (Strzepek et al., 2010). China's SPI values show an increase in drier trends for the country's northeastern regions, whereas the northwest and central regions have a wetter trend (Zhai et al., 2010). These trends indicate the large rivers' dryness and wetness in those specific regions. Looking at Africa's SPI numbers points to a drying trend from 1900-1950. From 1950-2000, the SPI values indicate that there is no increased drought (Hoffman et al., 2009).

Looking at the southern U.S. SPI data from 1895-2007, researchers found that there was no significant change in drought conditions as a whole. However, an increased drought intensity was found in the country's southeast portion. Some areas within that region SPI values have decreased up to 40% during extreme droughts (Chen et al., 2012). Another study, based on Couple Model Intercomparison Project phase 5 simulations, found that a significant SPI increase is projected for the northern part of the United States while there were drier conditions across the southwest. Dry summer conditions were projected to increase throughout the central Great Plains. This study found that more extreme droughts and wet periods might occur due to global warming (Swain & Hayhoe, 2015).

The Great Plains region, specifically North and South Dakota, has seen the five driest summers, which were also associated with negative snowfall anomalies, during recent winters. Soil moisture is the leading factor when determining drought for the Great Plains region. Therefore, SPI calculations that only consider precipitation have weak relationships (Quiring & Kluver, 2010). However, previous research studies have found drier conditions using the SPI calculation (Swain & Hayhoe, 2015).

Evapotranspiration

ET is the most important hydrological and metrological variable that reflects climate change (Wang et al., 2012). ET is less sensitive to change than other climatic variables. Goyal (2004) suggests that, in order to obtain a large ET increase (about 14.8%), the temperature would have to increase by 20%, net solar radiation by 11% and wind speed by 7% when using the Penman-Monteith Equation. Studies found that using the Penman-Monteith Equation produces the most accurate ET rates compared with other calculations. A 10% increase for the variables mentioned above only leads to a 0.30% increase in ET (Goyal , 2004). When looking at the Yellow River Basin, which faces serious water shortages, most of the increase was due to a higher temperature (Wang et al., 2012). Wang et al. also found negative trends in other parts of the basin. However, when looking at the Tibetan Plateau as a whole, ET rates decreased for all seasons by an average of 0.52 inch per decade. The decrease in the Tibetan region was mainly influenced by the wind-speed changes (Shenbin et al., 2006). Looking at the French Mediterranean, Chaouche et al. (2010) found increases for both the annual mean temperature and annual ET throughout the entire study area. Large increases with the ET rates were found in the spring. However, these increases in ET rates were not seen in the coastal areas (Chaouche et al., 2010).

When looking at ET rates in the United States, the Columbia River region's rates have decreased. However, runoff rates have increased in the spring (Matheussen et al., 2000). Another study looked at the direct measures of annual precipitation and stream-flow discharge. These components are the largest items in the watershed's hydrological budget, finding evidence of increasing ET rates throughout large portions of the United States (Walter et al., 2004; Tian et al., 2010). ET is one of the key indicators for the plants' water availability. ET models and actual ET studies show a small error, 6% or 1.65 inch. (Zhang et al., 2001). Only in Florida and the Gulf-Coast areas of the United States and Mexico are precipitation increases likely to exceed the higher ET rate. In other southern states, the ET rates will exceed precipitation rates (Mulholland et al., 1997).

When looking at North Dakota's subsurface drainage (SSD) and undrained fields (UD), Rijal et al. (2012) found that, for July and August, ET rates in the SSD field were 31% greater for corn in 2009 and 14% greater for soybeans in 2010 than the rates for the UD crop fields. This increase holds true for the entire growing season; ET for the SSD corn field was 16% in 2009, and the ET was 7% higher in 2010 compared with the UD field (Rijal et al., 2012). Mean daily ET rates are linearly related to the mean air temperature when looking at soybean growth rates (Allan et al., 2003). However, accurately quantifying the ET rates is hard due to many other variables, such as soil moisture and changing CO_2 amounts (Lautz, 2008).

Solar Radiation

Solar-radiation changes can have a large effect on the human and terrestrial environment. Solar radiation is decreasing near land surfaces, a trend which has become apparent in many parts of the world when looking at records from 1990 and earlier. This decrease is known as global dimming. However, in the northern hemisphere, widespread brightening has been observed (Wild et al., 2005). Monitoring began 25 years ago. Solar-radiation changes can affect the stratosphere and troposphere (Lean et al., 2005). Plants and animals have ways to cope with additional UV light. However, these mechanisms can cause other stressors within the plant or animal (Hader et al., 2007).

In most of the United States, the enhanced CO_2 simulation showed a decreased trend for the seasonal-mean daily global radiation availability, ranging from 0-20%. The most noticeable decrease was in the western United States. In some parts of the southern and northwestern United States, there was increased solar radiation (Pan et al., 2004). In a study looking at sunshine durations from 106 sites and spanning 70 or more years, Stanhill and Cohen (2005) found that, at 27 sites, the sunshine increased significantly with time; at 21 sites, sunshine significantly decreased. The remaining sites remained about the same. However, a larger portion of data that showed a sunshine decrease was found for the northeastern, western and southern United States (Stanhill & Cohen, 2005).

Wind Speeds

The majority of the world's oceans have seen increased wind speeds by at least 0.25 -0.5% per year at the 90^{th} percentile. This trend is stronger over land. At the 99^{th} percentile, wind speeds tend to become more positive, indicating that extreme wind speeds are increasing for the majority of the world's oceans by at least 0.75% per year (Young et al., 2011). Australia's average wind speeds from 1975-2006 were 2.3 m s^{-1} and 1.7 m s^{-1}, for the summer and winter respectively. The annual trends for both seasons decreased -0.009 m s^{-1} in the summer and -0.010 m s^{-1} in the winter (McVicar et al., 2008). When looking at China's wind speeds between 1956 and 2004, the annual mean wind speed, days of strong wind and maximum wind speeds all had declining trends. Only in southeastern China were the wind speeds not significantly reduced; instead, wind speeds for some areas of that region increased slightly. The reason for this decrease was the changing climate and the contrasts of sea-level pressure, and near surface temperature between the continent and the Pacific Ocean has become significantly smaller over the years. Therefore, wind speeds as well as the monsoon season were affected (Jiang et al., 2009). When looking at hurricane strength, there are no data showing a linkage between hurricane strength and climate change. The hurricanes' behavior is not changing. Because we do see increased damages, this study shows that damage increases are probably due to the increased wealth and population (Pielka et al., 2005).

Studies analyzing United States wind-speed data that were obtained from terrestrial anemometers discovered a decline in the wind speeds over the last 30-50 years. Lower wind speeds were found over the north-central United States and stretched into Canada. However, wind-speed observations are known to be poorly captured, thus having room for error (Pryor et al., 2009). Klink (1999) looked at maximum and minimum wind speeds from 187 and 176 stations, respectively. She found that the mean monthly maximum winds are increasing and that the mean monthly minimums are decreasing. The maximum winds were the largest in the summer and autumn, with decreasing wind speeds from February through May. At the same time, the minimum wind speeds decreased during all months. In all, the percentage change for the minimum wind speeds outweighed the change for the maximum wind speeds. Looking at the urbanization factor, wind speeds are affected in two ways. First, the heat-island effect influences temperatures, pressure gradients and higher urban wind speeds. Second, a higher surface roughness decreases the urban wind speeds.

North Dakota and South Dakota's minimum wind speeds are normally higher because of the flat land to gently rolling hills (Klink, 1999). According to the Wind Energy Resource Atlas, there are seven regions with sufficient wind power in North Dakota and western Minnesota. According to the Canadian Climate Center Model that predicted future wind speed for 2025, 2050, 2075 and 2095. Show a decrease in wind speeds that grows over the analysis period. Wind speeds could see a future decrease of 8-10% for all seasons except winter, where the decrease is less than 4%. This wind-speed reduction can correlate with a 30-40% wind-power generation reduction (Breslow & Sailor, 2002).

Dew Point

Dew-point temperatures in the United States increased throughout a 40-year period (1951-1990) by slightly over 1 °C/100 years (Robinson, 2000). When looking only at the time span ranging from 1961-1990 an increase was found of approximately 1-2 °C/100 years except in the fall (Robinson, 2000).

Looking at dew-point temperatures in the Great Plains, sites that were irrigated due to land-use transformations had increased dew-point temperatures (Huntington, 2006). Non-irrigated sites showed a decrease for the dew-point temperatures. Therefore, due to land-use changes near the surface has modified near surface temperatures on a microclimatological scale, thus impacting the dew-point temperatures (Mahmood et al., 2004, 2006; Mahmood et al., 2006).

METHODS

Temperature minimums and maximums, precipitation, GDD, season length, first and last frost dates, SPI, PDSI, ET, solar radiation; dew point and wind speed data were gathered using a variety of data sets; then, the information was analyzed on a yearly and monthly scale. Additional variables, including minimums, maximums and averages, were assessed for those data sets. Excel's pivot table function was used to analytically calculate and construct line graphs. These graphs indicated how different climatic variables change from one year/month to another as well as the average trend for the entire period. Each line graph also highlights the maximum, minimum and normal values.

Climatological normal calculations were calculated by taking the average of the 30-year stretch from 1981-2010 (NOAA, 2014). However, some data sets did not contain the proper length of time; therefore, the normal calculations were only done for data sets that contained the proper 30-year span. Ten-year trends were calculated by taking the slope of the trend lines and then multiplying by 10.

Temperature and precipitation data were obtained using the Applied Climate Information Systems (ACIS) Query Builder (ACIS Query Builder, 2016). The service consists of five different data types: StnMeta, StnData, MultiStnData, GridData and General. Temperature and precipitation data were gathered by utilizing GridData which uses longitude and latitude coordinates to receive the required data for a specific location. All temperature and precipitation data were measured at the county's center by using Maptechnica, a high-quality mapping service. Maptechnica provides the precise centroid longitude and latitude coordinates for each county

(MapTechnica.com, 2016). ACIS Query Builder uses all of the Cooperative Observing Network (COOP) stations that surround the entered coordinates. Once the query builder has located the stations, the query builder takes the stations' weighted means and produces the desired data based on those weights. For example, if one station was 10 miles from the site and another station was 20 miles away, the station that was 10 miles away would have twice the impact on the desired data compared to the station that was 20 miles from the site. ACIS Query Builder shown in appendix B helped gather data that spanned 64 years (1950-2014) for each county in North and South Dakota.

The GDD calculation is based on the daily minimum and maximum temperatures. Each plant needs a certain number of GDDs during a given growing season to reach full maturity. Therefore, all daily temperature sets, per county, were tabulated using the ACIS Query Builder. The GDD calculation is computed by subtracting the plant's lower-base threshold temperature from the average temperature.

Temperature averages were calculated by summing the maximum and minimum temperatures and then dividing that temperature by two as shown in equation 1. The lower-base and upper-base thresholds are the minimum and maximum temperatures where plant growth ceases. For this study, corn was used; the lower-base threshold for corn is 50 °F, and 86 °F is the upper threshold. The thresholds to obtain the GDD for that given day shown in equation 2 were then subtracted from the average temperature.

Equation 1.

The Daily Average Temp (°F) = (Daily Max Temp °F + Daily Min Temp °F) / 2 (1)

Equation 2.

Daily Corn GDD (°F) = Daily Average Temperature °F - 50 °F (lower threshold for corn) (2)

Once the calculation was completed for every county in each state, Excel was used to create pivot tables to obtain a useable form for the website.

Data for both season length as well as the first and last freeze dates were computed using the xmACIS2 query builder that was created at Cornell University in 2016 (xmACIS2, 2016). This query builder is city based, i.e., where the COOP station is located, instead of using longitude and latitude. Therefore, for this data set, the data were taken at the COOP station which had the most data instead of being obtained from the county's center. For example, in Cass County, North Dakota, Fargo's Hector International Airport station contained the most data. Each data set applied this same principle. Using the station with the most data allowed for more accurate trend lines. Once the data were collected from every site, the same analysis was done for each county to acquire the desired information.

The West Wide Drought Tracker (WWDT) was used to gather the PDSI and SPI records. The WWDT uses a Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate-mapping program. PRISM is an analytical tool that utilizes point data, digital elevation models and other spatial data sets to generate fine-scale, grid-based estimates. All data sets contained 119 years of data, spanning from 1895-2014, and were taken in the center of each North and South Dakota county. The PDSI uses temperature and precipitation data to determine the accumulated water excess or deficit for a given area. This index ranges from -10 (dry) to +10 (wet) (Palmer, 1985). This method is effective for determining long-term drought, especially over the low and middle latitudes, by taking prior-month conditions into account (Palmer, 1985). However, the PDSI does not account for snow and ice runoff; instead, the technique assumes that precipitation is immediately available. This method is not as comparable across different regions when compared to SPI because the PDSI lacks multi-timescale features. The SPI only utilizes monthly precipitation for its calculation. The SPI uses negative values for drought and positive values for wet conditions. A couple strengths with using SPI are that it only uses precipitation data and that it can characterize drought or abnormal wetness at different time scales (Mckee and Doesken, 1993; Palmer , 1985). SPI is more comparable across regions with different climates than PDSI. The SPI is less complex to calculate. However, the SPI does not account for evapotranspiration, limiting the ability to capture the increased temperature's effect. Also, the SPI does not consider the precipitation's intensity and the potential impacts on runoff (Palmer, 1985). All the collected PDSI and SPI data were transformed into the desired format.

Evapotranspiration and solar-radiation records for North Dakota were found by using the North Dakota Agricultural Weather Network (NDAWN). Some counties did not have the desired NDAWN site. Therefore, not all counties were analyzed. The ET rates were calculated using the Penman Monteith equation (NDAWN, 2016). This computation was supplied by NDAWN at each site with the necessary data to calculate the ET rates using this equation. The ET and solar-radiation data could not be found for South Dakota because the data sets were not long enough for inclusion. Therefore, the data were neither gathered nor interpreted.

Wind-speed and dew point data were collected using Climate Information for Management and Operational Decisions (CLIMOD), which is powered by ACIS. Wind-speed and dew-point data could only be collected from the Automated Surface Observing System (ASOS) stations; North Dakota and South Dakota have 9 and 15 stations, respectively. These stations are designed to serve meteorological and aviation needs. These systems generally report in hourly intervals, but they also report special observations if weather conditions change rapidly. The CLIMOD website is not free for the public. A $25 fee is required to obtain the data. After the dues were paid, hourly wind-speed and dew-point data were retrieved using. These data were transformed into daily and annual intervals and then analyzed.

Once all the data were collected and analyzed, a website was constructed (www.ndsu.edu/climate) to display the data. The website contains annual and monthly line graphs, per county, that display the maximum, minimum, normal and trends for all climatic variables that were collected and analyzed. The website allows the public to access and to obtain the required information for a specific county. Another way of displaying and analyzing the data is to take all of the trends, by county per climatic variable, and to transform that information into maps that show these trends with different colors separating the negative and positive trends for easy interpretation using Global Information Systems (GIS) software. In order to make these maps, the kriging interpolation method within the GIS software program was used. Each map utilizes different kriging methods to obtain a map that best fits that climatic variable. This interpolation was accomplished by looking at the Normal QQ Plots and the Semivariogram models to find a model of best fit for each climatic variable. These methods are shown in Appendix A. The maps display the trends of different climatic variables with a scale located at the bottom, left-hand corner. These maps indicate, the magnitude and the direction of change, trend, by decade geographically for each climate variable.

RESULTS AND DISCUSSION

Temperature Trends

A thorough investigation shows that every climatic variable changes differently in each state. Figure 1 shows how the temperature maximums are changing throughout North Dakota. Looking at the western portion of North Dakota, the temperature maximums are increasing faster than they are for the rest of the state, ranging from 0.125 to 0.407 °F/decade. Looking at the eastern portion of North Dakota, the temperature maximums are actually decreasing, ranging as much as -0.149 °F/decade. Looking at the center of North Dakota, there is a portion where temperature maximums are not changing much at all, per decade, ranging from -0.092 to -0.013 °F/decade.

Figure 2 illustrates the spatial variation for the decadal minimum-temperature trends in North Dakota. Looking at Figure 4, we see that there is no pattern for the results as we saw with the temperature maximum's change per decade in Figure 2. The temperature minimums are decreasing in the northwest, southeast-west, north-central and northeastern portions of the state, as much as -0.007 °F/decade. The remaining portions of the state are seeing increased minimum temperature trends, especially near Eddy and Foster Counties and in the central portion of the state. Additionally, we see the same trend in Golden Valley County, which is located in the southwest portion of the state, with increases ranging from 0.400 to 0.669 °F/decade.

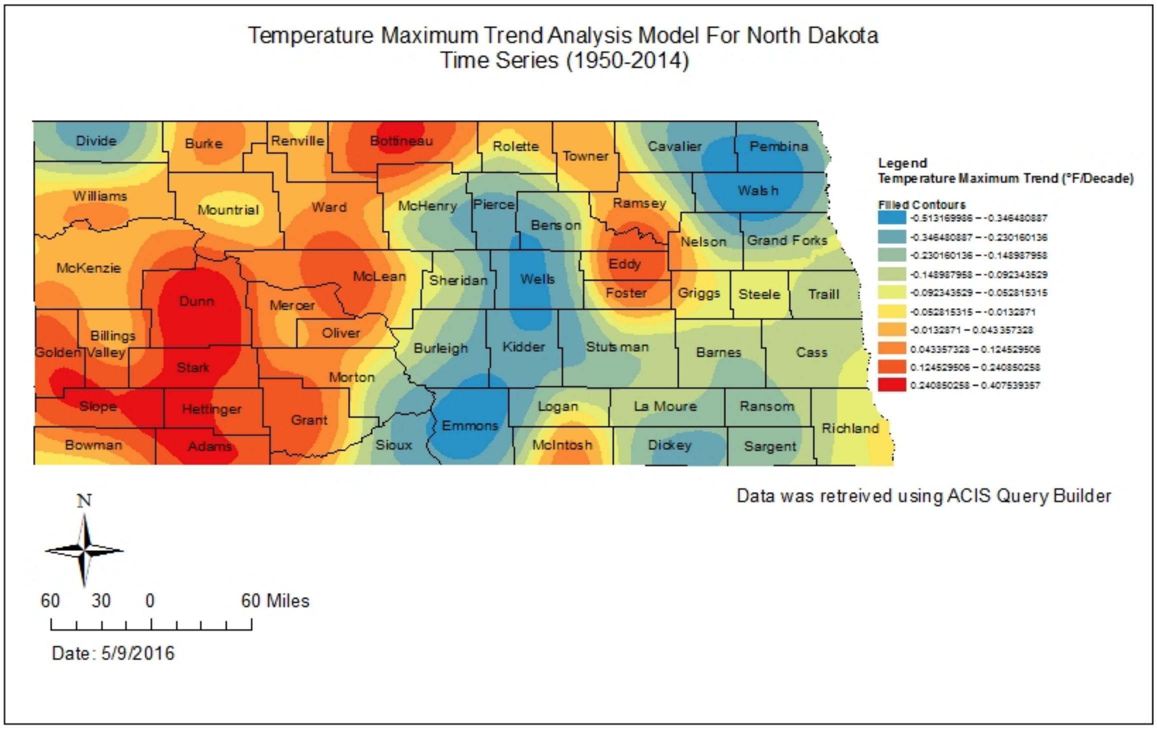

Figure 1. Temperature maximum trends for North Dakota

Figure 3 demonstrates how temperature maximums have changed throughout South Dakota over the past 64 years; there is a rise in the temperature maximums per decade in western South Dakota, ranging from 0.265 to 0.482 °F/decade. This rise is roughly the same as the one seen for western North Dakota in Figure 3. Looking at eastern South Dakota, there is also a decrease, ranging from -0.151 °F to -0.453/decade, in temperature maximums per decade. This is also similar to North Dakota. No change occurs at the center of South Dakota where the values range from -0.091- 0.1072 °F per decade. This change is also similar to North Dakota.

Figure 4 shows how South Dakota's temperature minimums are changing by decade. Unlike Figure 2, looking at ND change in temperature minimums per decade, South Dakota's change in the temperature minimum per decade shows a pattern. This pattern is roughly the same as the change in temperature maximums, i.e., Figures 2 and 3. In the western portion of the state, the temperature minimums are increasing from 0.107 to 0.482 °F/decade, whereas for the state's eastern portions, the temperature minimums are decreasing from -0.255 to -.15. In the central portion of South Dakota, the temperature minimums stay roughly the same per decade, ranging from -0.090 to -0.007.

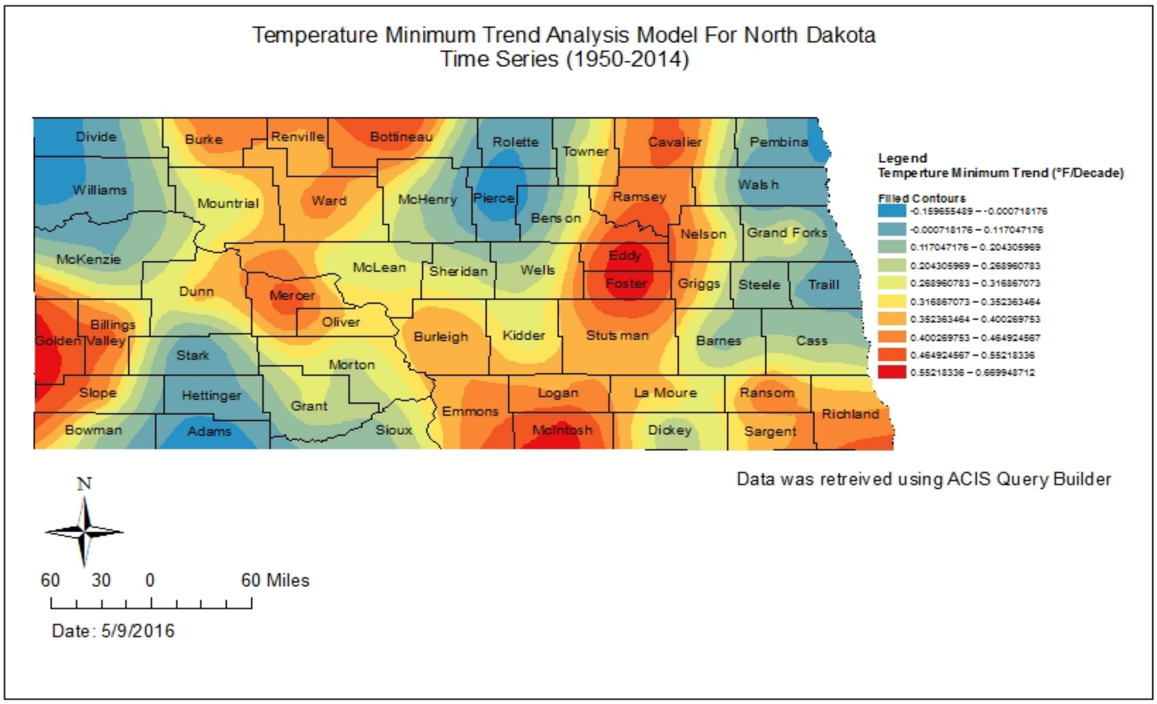

Figure 2. Temperature minimum trends for North Dakota

As a whole, this study found that North and South Dakota showed warming trends per decade. These findings were also true in previous studies. Ojima et al. (2014) found that North Dakota had an increasing annual temperature over the past 130 years (Ojima et al., 2014). Temperatures above 35 °C (90 °F) are quite uncommon throughout the Dakotas. However, temperatures that are greater than 37.78 °C (100 °F) are projected to become more frequent (Kunkel et al., 2013).

These higher temperatures are portrayed in the previous figures. The maps show that the maximum temperatures are increasing, directly correlating with Kunkel et al.'s (2013) study.

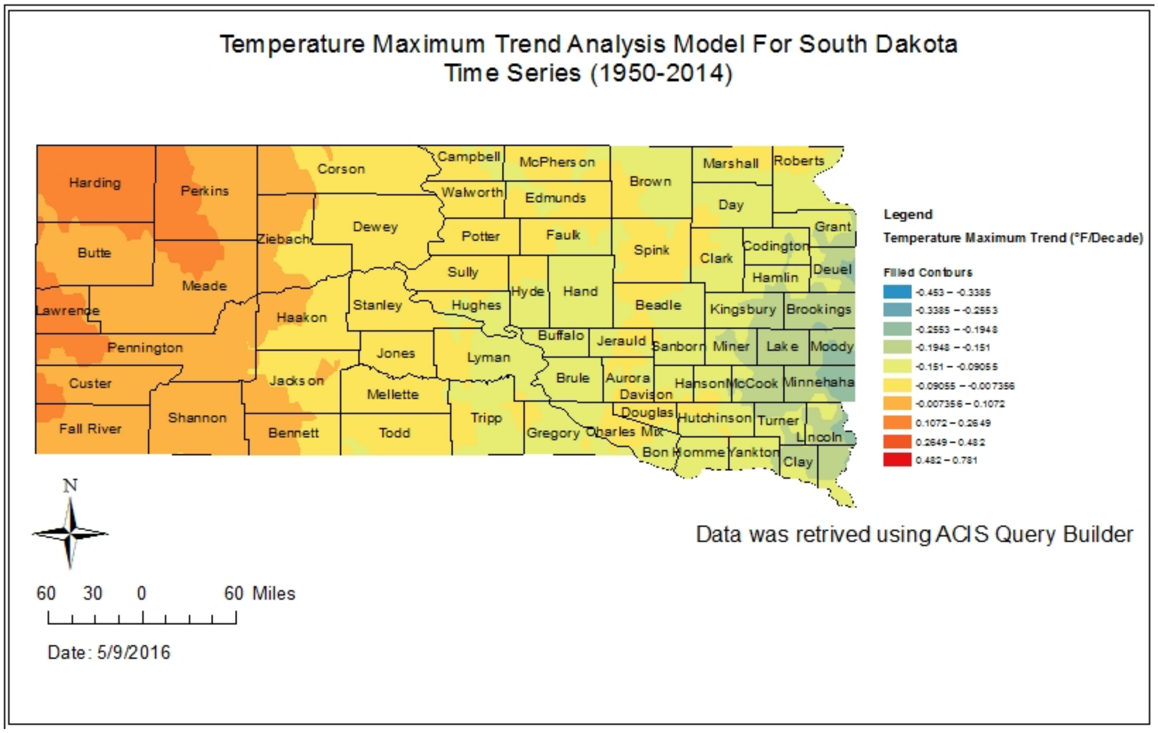

Figure 3. Temperature maximum trends for South Dakota

Looking at South Dakota, the temperature trends per decade are increasing in the state's western portion. This result is the same as Fontaine et al. (2001) who found that temperatures in the Black Hills have been increasing. However, this study could have inconsistent climate observations with the same drawbacks that were found in Menne et al.'s (2009) study. The time when readings are taken, as well as the landscapes surrounding the COOP stations, has changed, thus leading to warmer or cooler recordings, depending on the landscape change. Concrete surfaces tend to have warmer readings than grass surfaces (Menne et al., 2009).

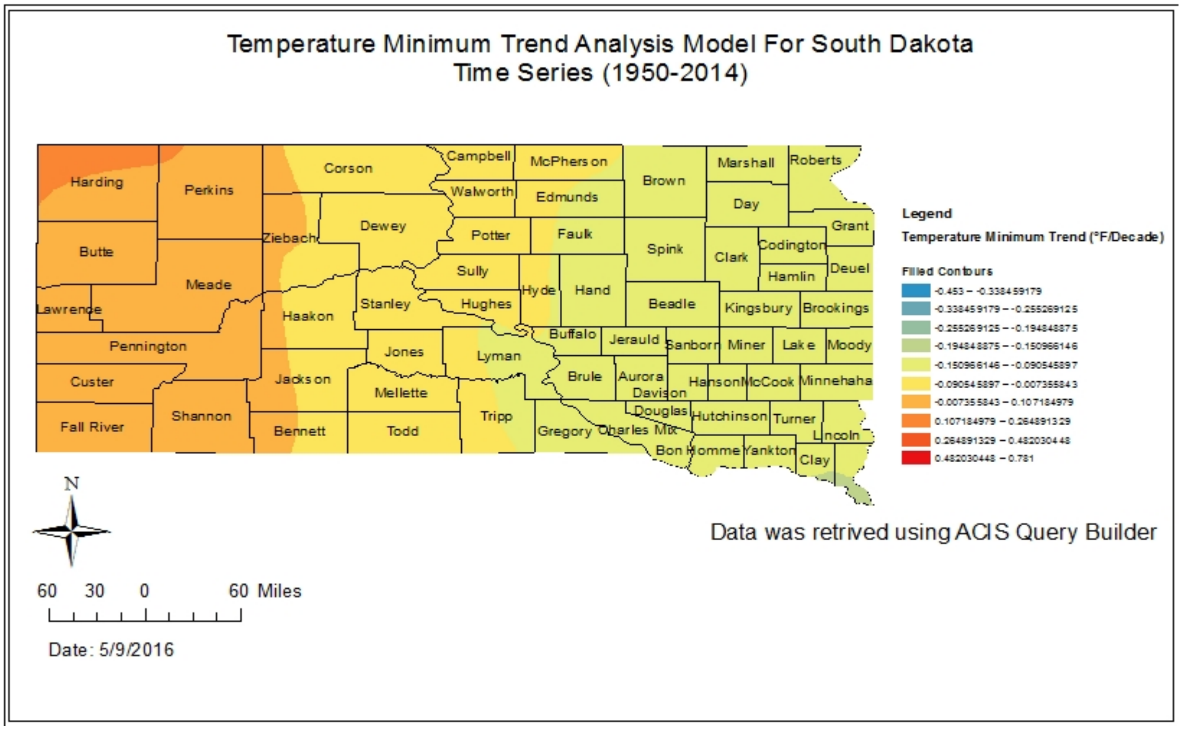

Figure 4. Temperature minimum trends for South Dakota

Precipitation Trends

Figure 5 shows the spatial distribution of North Dakota's decadal precipitation trends. The same non-distinguishable pattern seen in Figure 2, which looked at minimum temperature trends, is shown here. For every county, there is some sort of increased precipitation trend. Looking at western North Dakota, we see that the lowest increased precipitation ranges from 0.0532 to 0.172 in/decade. Looking at the state's eastern portion, we see that the highest increased precipitation ranges from 1.291 to 0.721 in/decade. For the remaining areas, i.e., the central portion of the state, the precipitation change ranges from 0.577 to 0.650 in/decade.

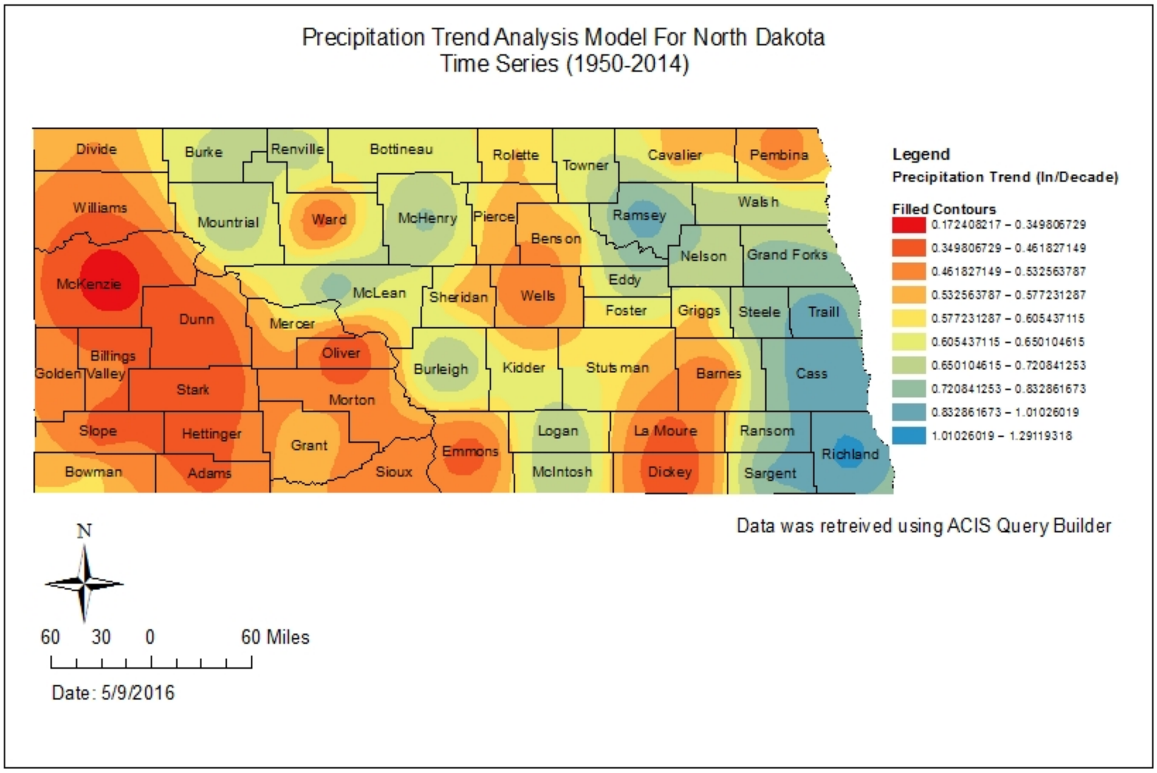

Figure 5. Precipitation trends for North Dakota

Figure 6 shows the spatial distribution for South Dakota's decadal precipitation trends. Just like the North Dakota precipitation, there is no distinguishable pattern. However, there are segments of the state with roughly the same change in precipitation. Once again, the entire state shows increased precipitation. Looking at the western portion of South Dakota, starting in the northwest corner of Harding County and heading south to Fall River County, we see a small increase for the precipitation trend, ranging from 0.0185 to 0.459 in/decade. Moving east into Perkins County and heading south to Shannon County, we see a higher precipitation change, ranging from 0.662 to 0.937 in/decade. Heading east into Corson County and heading south to Bon Homme County, there is a small increase precipitation, ranging from 0.0185 to 0.459 in/decade. For the remainder of the state heading east, besides a small portion in the state's far western portion, we see a larger increase for the precipitation, ranging from 0.662 to 0.937 in/decade.

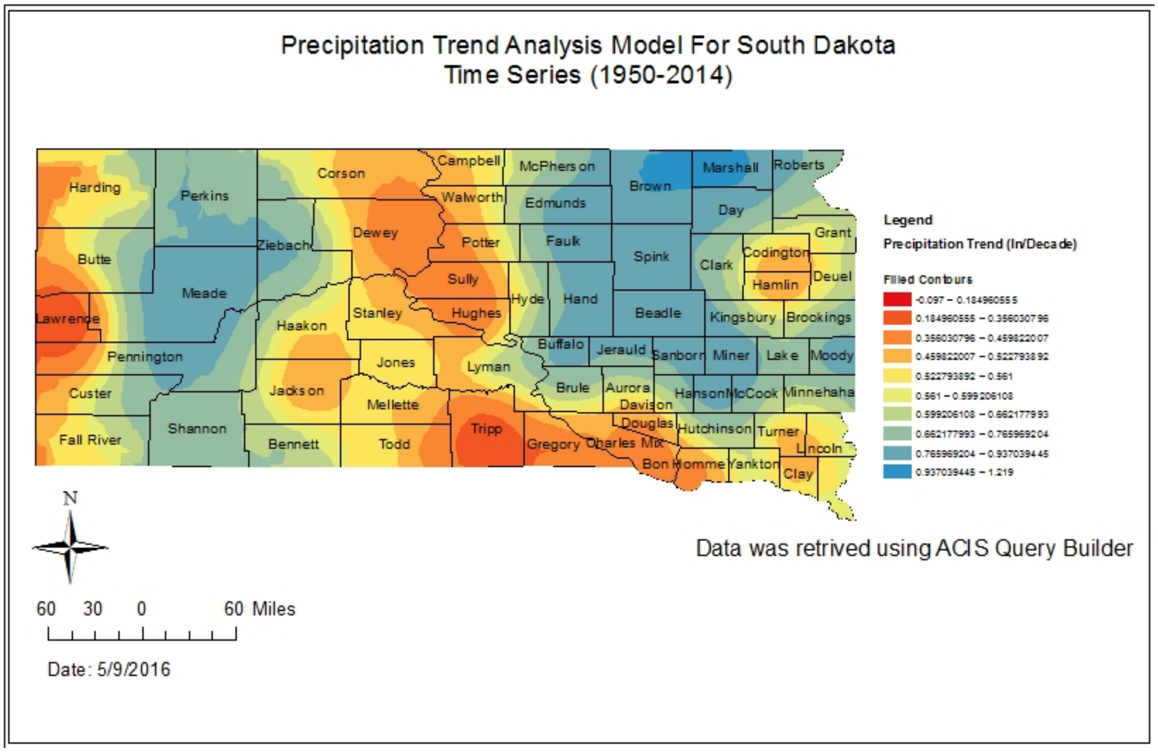

Figure 6. Precipitation trends for South Dakota

Precipitation, as a whole, increased by 10% (Karl & Knight, 1998). This increase was seen throughout North and South Dakota when looking at the previous precipitation-trend figures. Kunkel et al. (2013) found the same patterns; the precipitation amounts were greater during the 1990s compared to the precipitation amounts from 1901-1960. The last few years, except for 2011, were the wettest consecutive years on record (Kunkel et al., 2013).

Badh and Akyuz (2010) tabulated precipitation data; each station showed a unique annual-precipitation trend. Fargo, Bismarck, Jamestown and Williston showed a negative trend for annual precipitation while Pembina, Minot, Langdon and Dickinson had a positive trend for the given time period (Badh & Akyüz, 2010). These results were different than the results found for this thesis. All trends were increasing throughout North Dakota for Badh and Akyüz's research while this thesis found that some trends were decreasing. However, the data were taken from different parts of the county. Badh and Akyüz's study used data that were collected from major cities while this study examined precipitation rates at the county's center. Comparing these two studies, we determined that precipitation quantities could differ on a micro scale.

Growing-Degree-Day (GDD) Trends

Figure 7 shows the spatial distribution for the decadal GDD trends throughout North Dakota. Looking at the image, there are no unique trends. Looking at the state as a whole, most counties show a decrease in GDDs, ranging from -3.469 to -59.270 days/decade, except for a few small portions in the state's southwest corner, southeast corner, and near Eddy/Foster County where there are increased GDDs, ranging from 2.052 to 23.237 days/decade.

South Dakota, on the other hand, has a unique trend across the state when looking at the GDDs' change per decade (Figure 8). Starting in the state's western portion, we see a positive GDD trend, ranging from 47.8 to 22.11 days/decade. Heading east, the GDD change becomes negative, ranging from -7.482 to -45.5 days/decade. This negative trend becomes more prominent when moving east throughout the state. As a whole, most of South Dakota also shows a negative trend for GDDs. This trend is also seen throughout North Dakota (Figure 7).

Linderholm (2006) found that the U.S. growing season has lengthened 10-20 days in the last few decades. In the Great Plains region, Badh and Akyüz (2010) identified the average GDD trend for corn in different parts of the Northern Plains. In Fargo, North Dakota, for example, the average, accumulated seasonal GDD trend for corn is 33.5 heat units per decade. North Dakota farmers plant a type of corn that matures, on average, between 85 and 90 days (Badh and Akyüz, 2010).

Badh et al. (2010) results differ from the thesis findings where GDD was shown to be declining in parts of North and South Dakota. The GDD values directly relate to the temperature data, therefore we did not intend to compute average temperature from daily maximum and minimum temperatures. Instead, we analyzed maximum and minimum temperatures separately. Also we need to keep on mind that we are aggregating the data at county level instead of a point value.

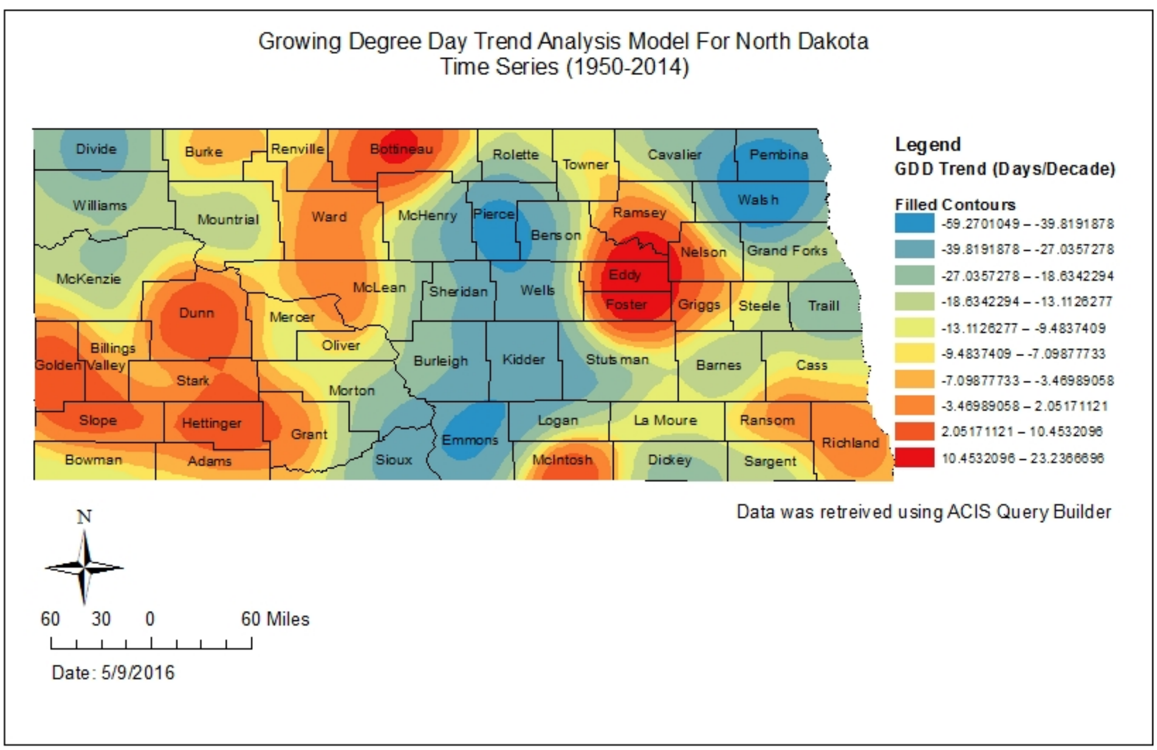

Figure 7. Growing degree days trends in North Dakota

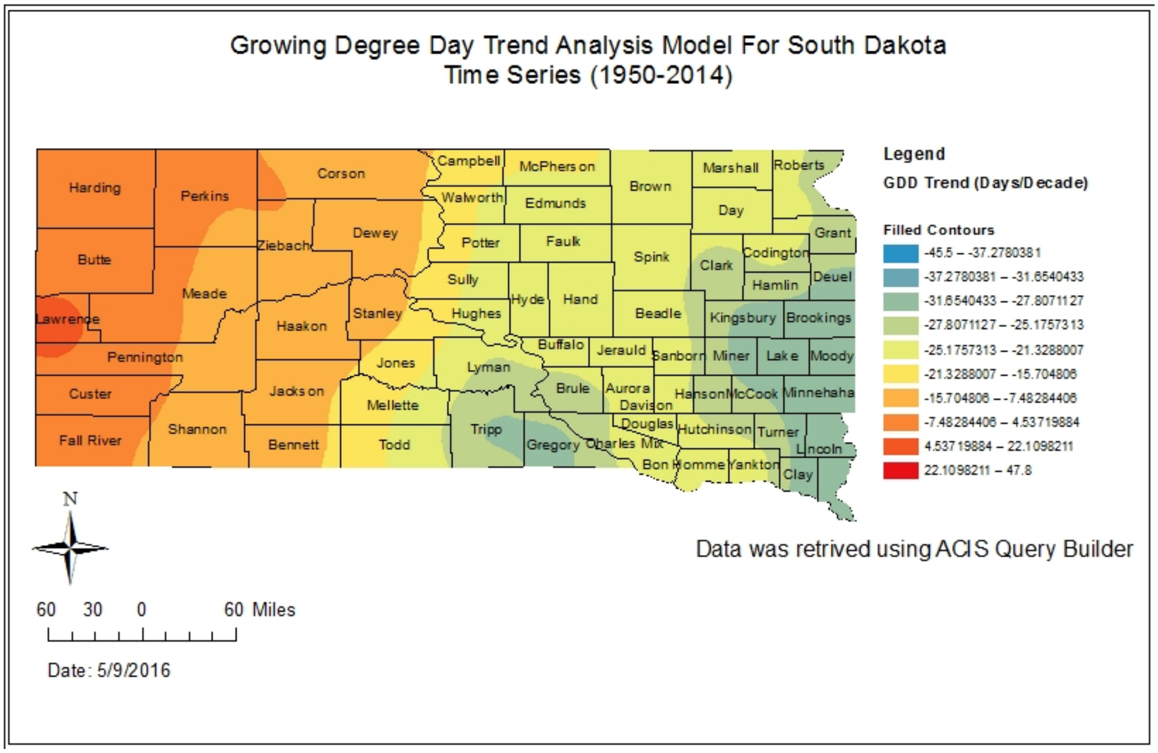

Figure 8. Growing degree day trends for South Dakota

Season-Length Trend

Figure 9 portrays North Dakota's changing season length. This figure shows a distinctive pattern. Starting in the state's southwestern area shows a slight negative trend, just less than -1.324 days/decade. Elsewhere, lengthening growing season that is at least 0.5 days per decade occurred. Moving east, even higher season-length changes occur, ranging from 3.172 to 9.366 days/decade. The highest change in the season length occurs across a diagonal line that starts in the northeast corner of Pembina County and heads southwest to Logan County. These changes range from 6.102 to 9.366 days/decade.

Instead of the trends changing from west to east throughout the state as seen in the previous figures, South Dakota's changes for the season length occur from north to south as shown in Figure 10. Starting in the state's northeast corner, we see the highest season-length trends, ranging from 3.134 to 4.539 days/decade. Heading south through the state, decreasing trends are seen, ranging from 1.460 to 2.331 days/decade. Finally, the lowest trend change is seen for the state's southernmost point, with values ranging from -0.643 to 0.739 days/decade. This area of the state showed the latest increase, or no increase per decade.

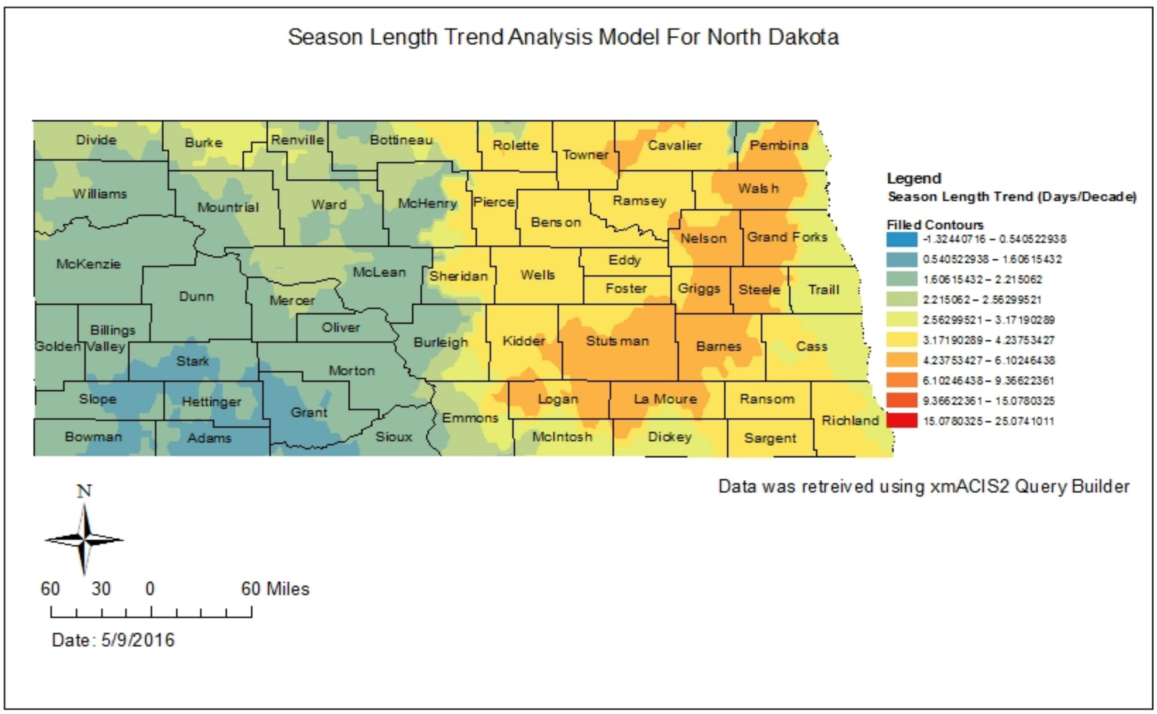

Figure 9. Season length trends for North Dakota

Recent analyses assessed U.S. temperature data sets ranging from 1948-1999, finding that frost-free days had increased throughout the United States (Easterling, 2002). Outside a small area of North and South Dakota, season lengths were increasing. Another study discovered that these increases for the frost-free days were found since the late 1970s, particularly in the western portion of the United States (Cayan et al., 2010).

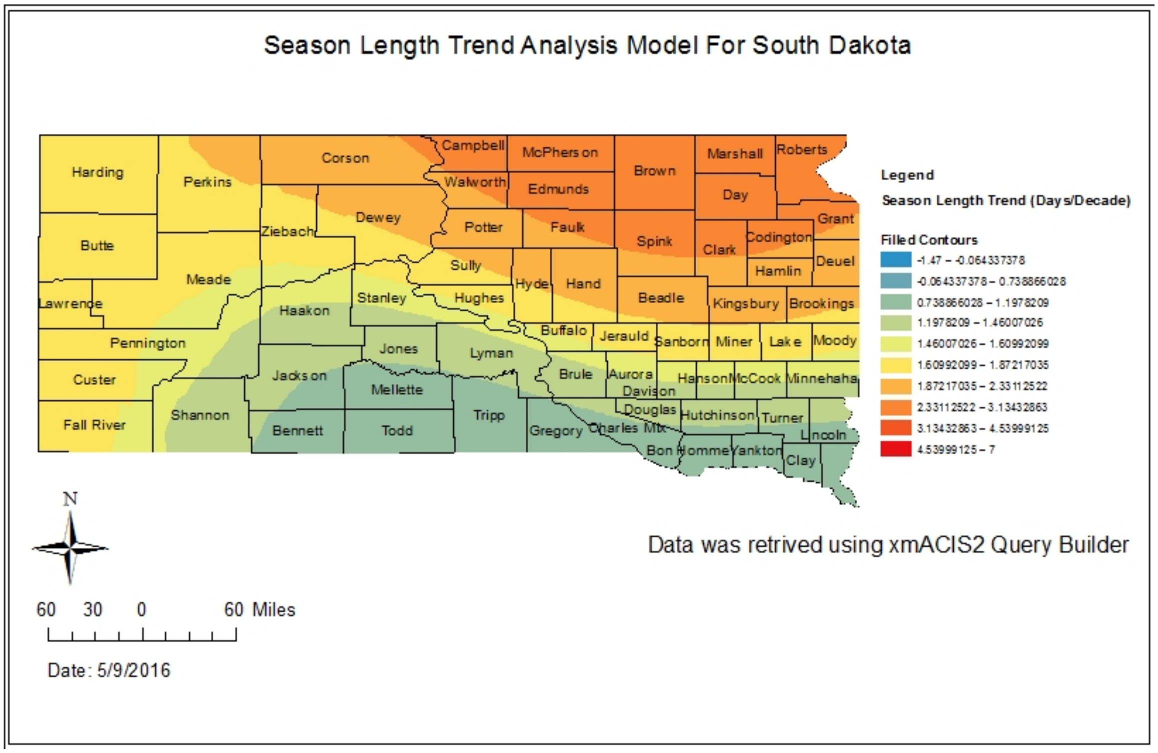

Figure 10. Season length trends for South Dakota

Trend for the First and Last Thaw Dates

Figure 11 depicts the spatial distribution for the decadal trend of North Dakota's last spring-frost dates. These trends correlate with the season-length trends depicted in Figure 9. Starting in the west, we see that the last spring-frost dates are increasing (occurring at later calendar days), ranging from 2.33 to 0.462 days/decade. This change is also seen in Figure 9 where the season length is decreasing, thus indicating that the last spring-frost date could have changed in the positive direction, which it did. Just like in Figure 9, moving east throughout the state, the trend change becomes more negative, meaning that the last frost days occur at earlier calendar days. These trend changes range from -0.585 to -8.848.

Even though Figures 9 and 11 are not exactly the same, they show similar trends moving across the state from west to east.

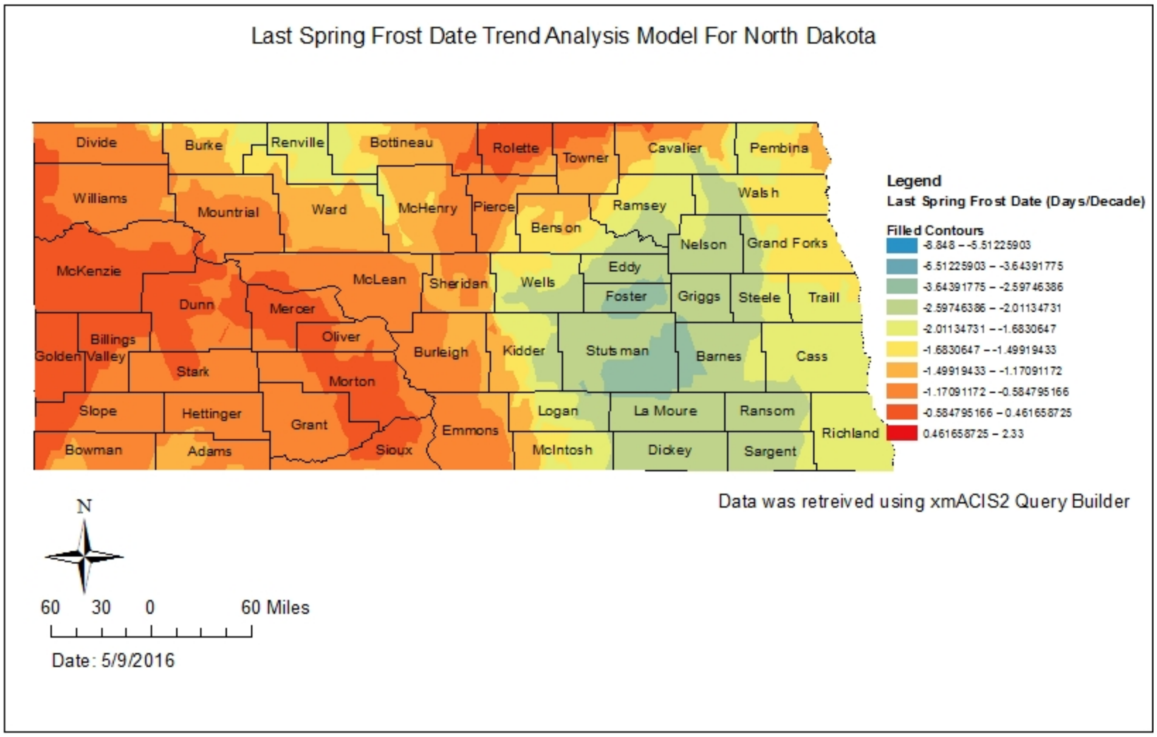

Figure 11. Last spring frost dates trends for North Dakota

Figure 12 shows the trend for North Dakota's first day of fall frost. Also it is important to note that a larger portion of the state displays a negative trend that means in general, the state showed an earlier last day of spring frost in time. It is also important to note that figure 12 displays that the majority of the state experienced a positive trend indicating later onset of freeze in time which yields longer growing seasons. Therefore, we can conclude that the increased season length is caused by both the early finish of freeze in the spring and later start of freeze in fall. Neither the first nor the last frost dates are changing at a higher rate than the other one. Therefore, both variables affect the change in the season length per decade equally.

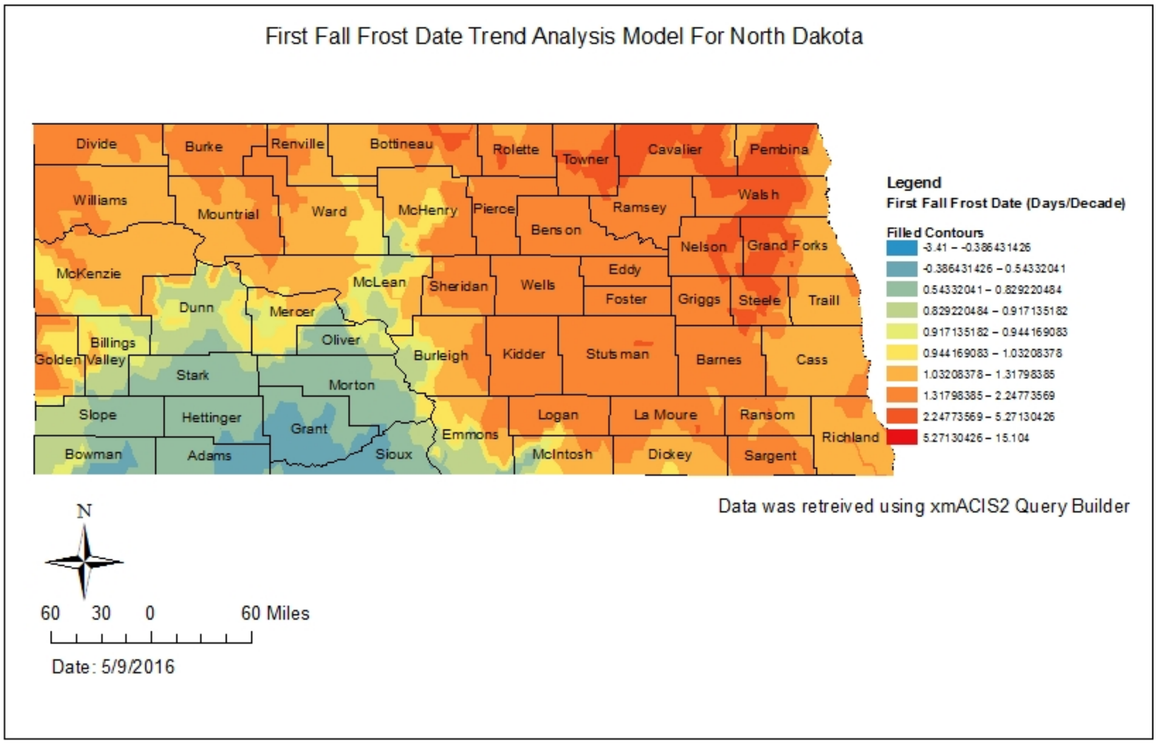

Figure 12. First fall frost dates trends for North Dakota

Looking at South Dakota's last spring-frost date trend per decade in Figure 13, this map closely resembles South Dakota's season-length map that is shown in Figure 10. Once again, in the state's northern portion, a negative trend change is found, ranging from -3.592 to -1.194 days/decade. This result goes in concert with the increasing season length which is mentioned in Figure 10. Looking at the state's southern portion, we see that the last spring-frost dates have increased, ranging from 0.154-1.205 days/decade. This change also closely resembles what is depicted in Figure 10. It is however, important to note that the majority of the state displayed a negative trend, indicating the end of freeze days occurred earlier in time.

Figure 14 illustrates the trend for South Dakota's first fall-frost date. This graphic varies slightly from Figures 10 and 12 Instead of changing very systematically from north to south, Figure 14 shows some areas where the changes occur sporadically, instead of fluently, i.e., the dark-orange color, throughout the state. We still see that most increases occur in the state's northern section and then decrease as you move south, as high as -2.088 days/decade. This, once again, is roughly the same as we saw for the last spring-frost dates. It is important to note that the majority of the state experiencing a positive trend, indicating the first day of fall frost occurred later in time. Therefore, we can conclude that changes with both the last and first frost dates have an effect on the season length in South Dakota.

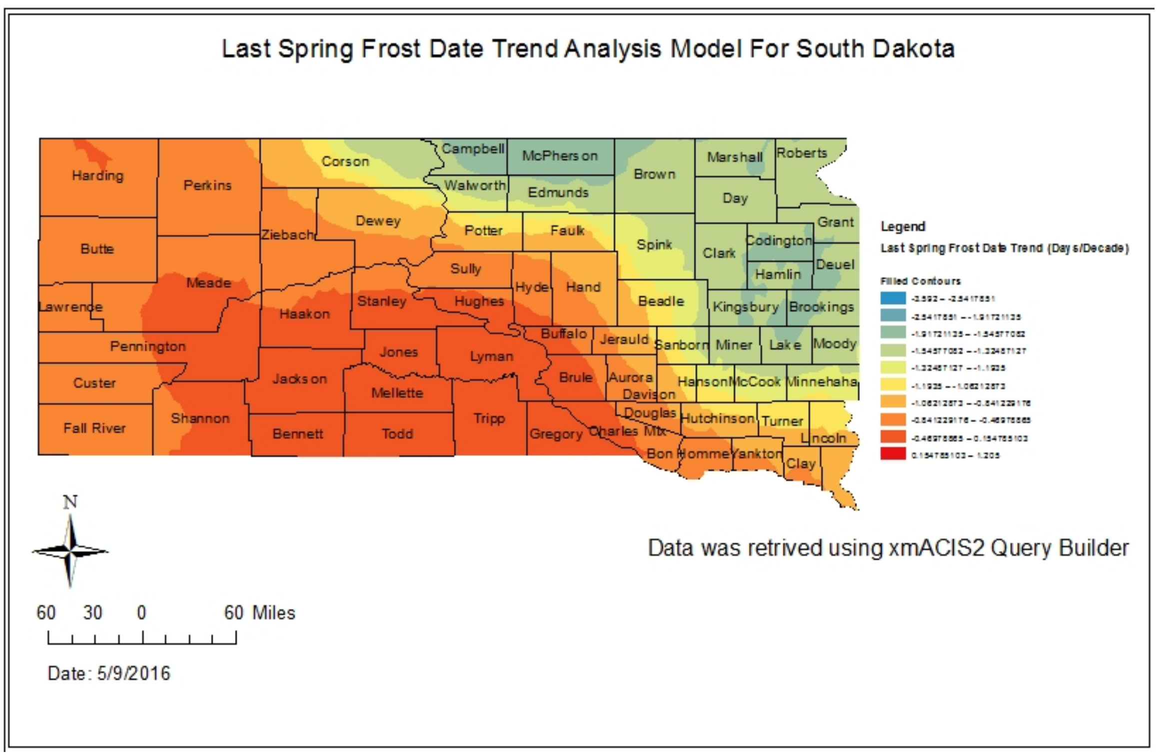

Figure 13. Last Spring frost dates trends for South Dakota

The first fall-frost and last spring-frost dates are directly correlated with the season length. Therefore, the studies done by Easterling (2002) and Cayan et al. (2010) are also directly correlated with the first and last frost dates. Therefore, all these studies lead to one conclusion: season length as well as the first fall- and last spring-frost dates are increasing throughout the United States, North Dakota and South Dakota.

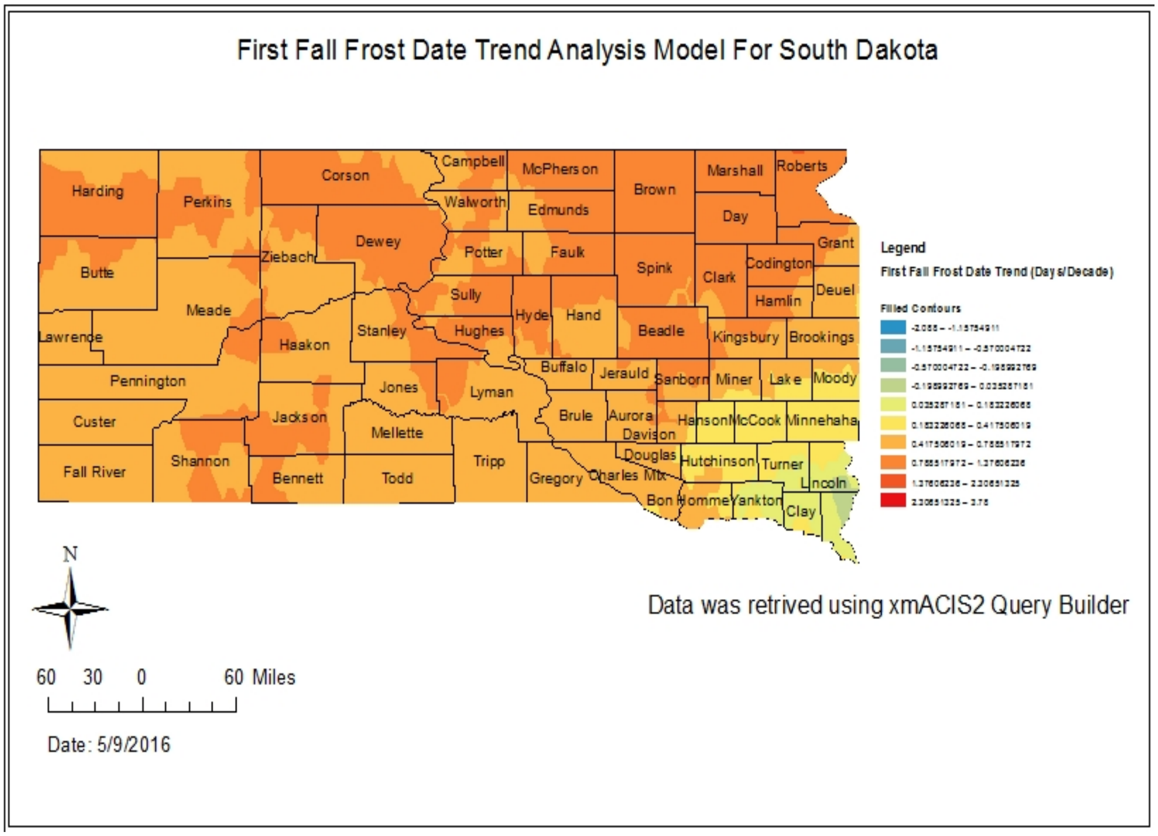

Figure 14. First fall frost dates trends for South Dakota

Palmer Drought Severity Index (PDSI) Trend

The highest positive PDSI trends were observed in the center and the northcentral parts of North Dakota as shown in Figure 15. The red and dark-orange colors indicate that these areas are getting wetter, ranging from 0.266 to 0.167/decade. Moving from the center of the state, this wetting effect is becoming less severe and is even negative in a few spots, indicating that areas are becoming dryer. The magnitude of these trends are as much as -0.003 /decade.

We see a similar pattern in South Dakota with a slight difference, as shown in Figure 16. The state's center shows the highest PDSI rates, ranging from 0.227 to 0.153 trend/decade. This wetting effect becomes less severe the farther you move from the state's center. Besides for two counties, Lawrence and Brookings Counties, these counties are also becoming wetter. The remainder of the state PDSI trend values range from 0.131 to -0.068/decade. Fall River County in the southwest corner of the state is actually becoming dryer. This area is the only place in South Dakota where the PDSI rates indicate a negative trend, indicating the fastest drying county in the state.

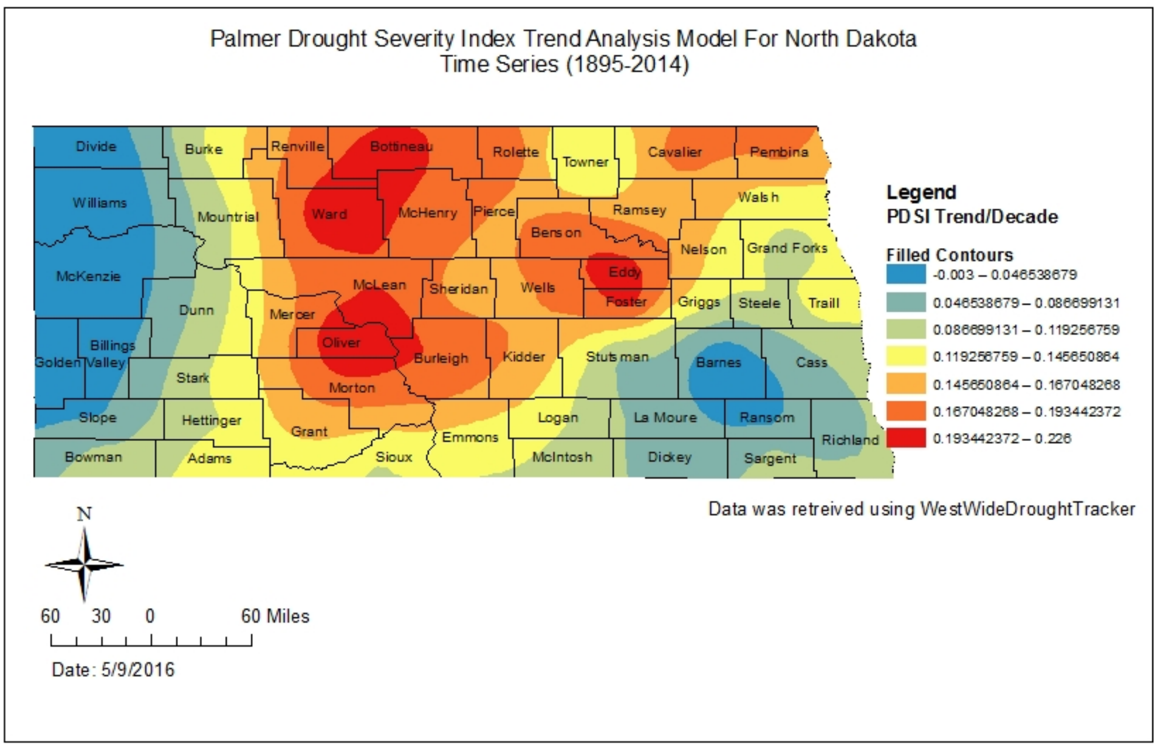

Figure 15. Palmer drought severity index trends for North Dakota

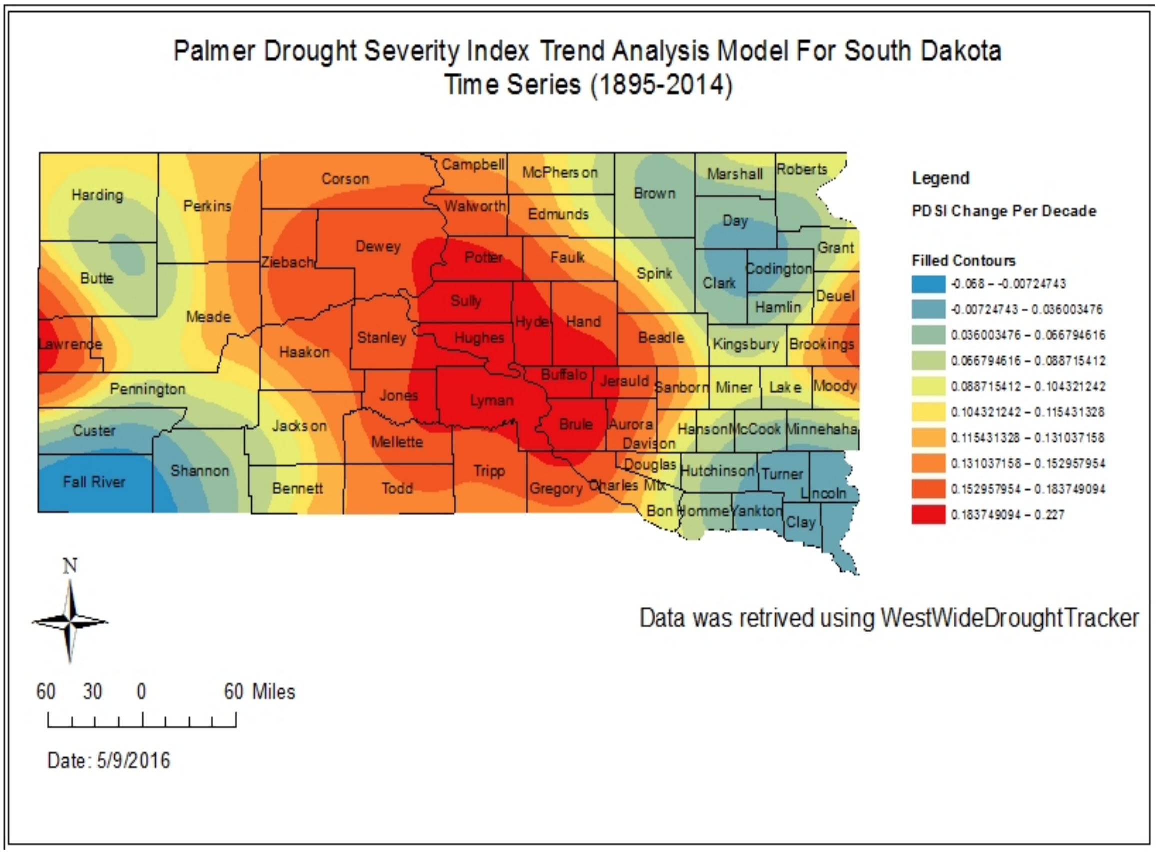

Figure 16. Palmer drought severity index trends for South Dakota

Throughout the United States, the Department of Commerce's National Climatic Data Center has recorded 17 drought years from 1980-2012. These droughts have exceeded tens of billions of dollars in damages and costs (Ryu et al., 2014). The PDSI trends in North and South Dakota are increasing at the states' center. Application of more drought resistant crops in areas where drought is becoming more intense can be a smart climate change adaptation strategy to mitigate the economic loss due to the drought.

Standardized Precipitation Index (SPI) Trend

Figure 17 shows the SPI trends' variation for North Dakota. This graphic is smoother than Figure 15, which showed North Dakota's PDSI changes per decade.

However, they portray complementary information. The north-central parts of North Dakota are becoming wetter at a higher rate than the rest of the state with the SPI trends ranging from 0.01 to 0.02 per decade. The SPI trends become weaker elsewhere. Some negative trends are even found in western North Dakota, indicating that the drought intensity is getting slightly stronger or has no trend in these regions; the SPI trend values range from -0.06 to -0.0004 per decade. It is; however, important to note that the majority of the state displays positive SPI trends, indicating wetter trends.

This correlation also holds true for South Dakota, as shown in Figure 18. Once again, the SPI trend values indicate a positive SPI trend in the center of the state, with lesser trends northward and southward. Lawrence County has an exceptional positive trend, ranging from 0.02 to 0.03 per decade, that indicates the most accelerated wetness in the state.

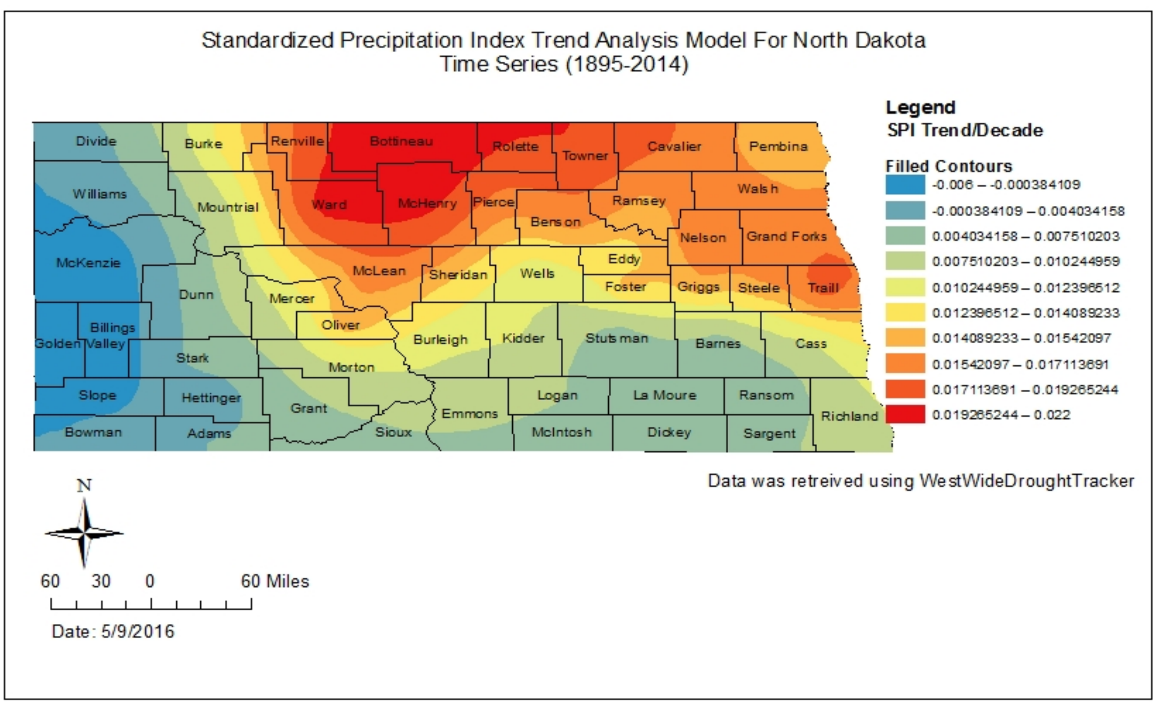

Figure 17. Standard precipitation index trends for North Dakota

Chen et al. (2012) used the Couple Model Intercomparison Project phase 5 simulations and found that a significant SPI increase is projected for the northern United States with drier conditions across the southwest. Dry summer conditions are also projected to increase throughout the central Great Plains (Chen et al., 2012). These simulation findings are seen at the center of North and South Dakota.

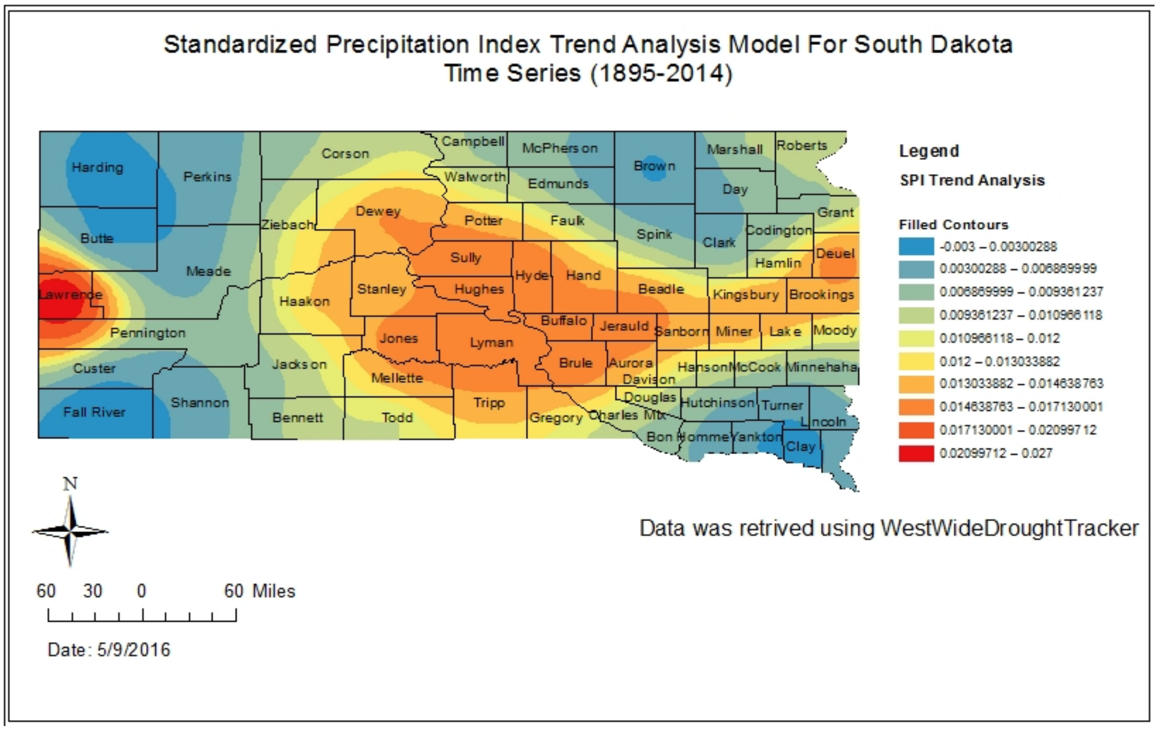

Figure 18. Standard precipitation index trends for South Dakota

Evapotranspiration and the Solar-Radiation Trend

Figure 19 shows the geographical variation of the ET trends. Starting at Mountrail County and extending north and south, evapotranspiration rates decrease, as indicated by the blue colors, ranging from -0.004 to -0.0317 in per decade. This decrease is also seen in the state's northeastern portion, specifically in Pembina, Cavalier, Walsh and Grand Forks Counties. This decrease might result from a combination of air temperature, solar radiation and wind speed. The remaining areas of the state have increased evapotranspiration that is portrayed by the orange and yellow colors, ranging from 0.028 to 0.003; this increase might lead these portions of the state to become dryer, which was evident in both drought indicators, SPI and PDSI.

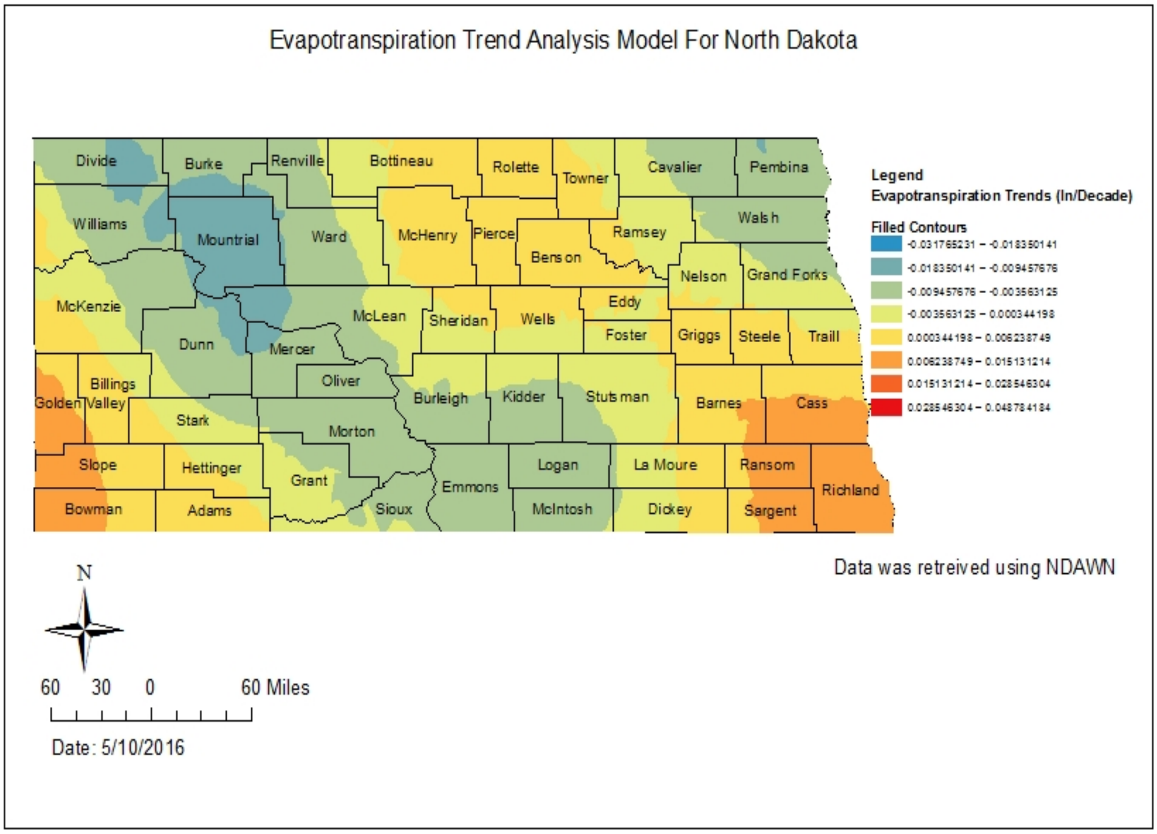

Figure 19. Evapotranspiration rates trends for North Dakota

Looking at how solar radiation has changed per decade throughout North Dakota, Figure 20 indicates that the highest increase occurred at the state's center and in the southeast corner, ranging from 29.259 to 3.817 Lys/decade, as indicated by the red and orange colors. Increased solar radiation means that more sunlight is arriving at the earth's surface than during previous decades, causing an increased evapotranspiration rate. The remainder of the state is characterized by yellow and a light-green colors; these areas range from -17.37 to -3.956 Lys/decade, meaning that less sunlight is arriving at the earth’s surface than during previous decades. Solar radiation information is an important variable not only to estimate the ET rate but also it is an important variable to estimate the growth stage and maturity dates of certain plants such as soybean (Akyuz et al., 2016)

Rijal et al. (2012) found that, in 2009, ET rates in the SSD field were 31% greater for corn and 14% greater in 2010 for soybean than the values for the UD crop fields. This holds true for the entire growing season; in 2009, ET for the SSD field was 16% for corn and 7% higher in 2010 compared with the UD field (Rijal et al., 2012). Looking at Figure 19, the ET rates are increasing throughout most of the state except for a band in the state’s center; therefore, this research is concurrent with Rijal et al. (2012). The ET rates are increasing throughout most of North Dakota.

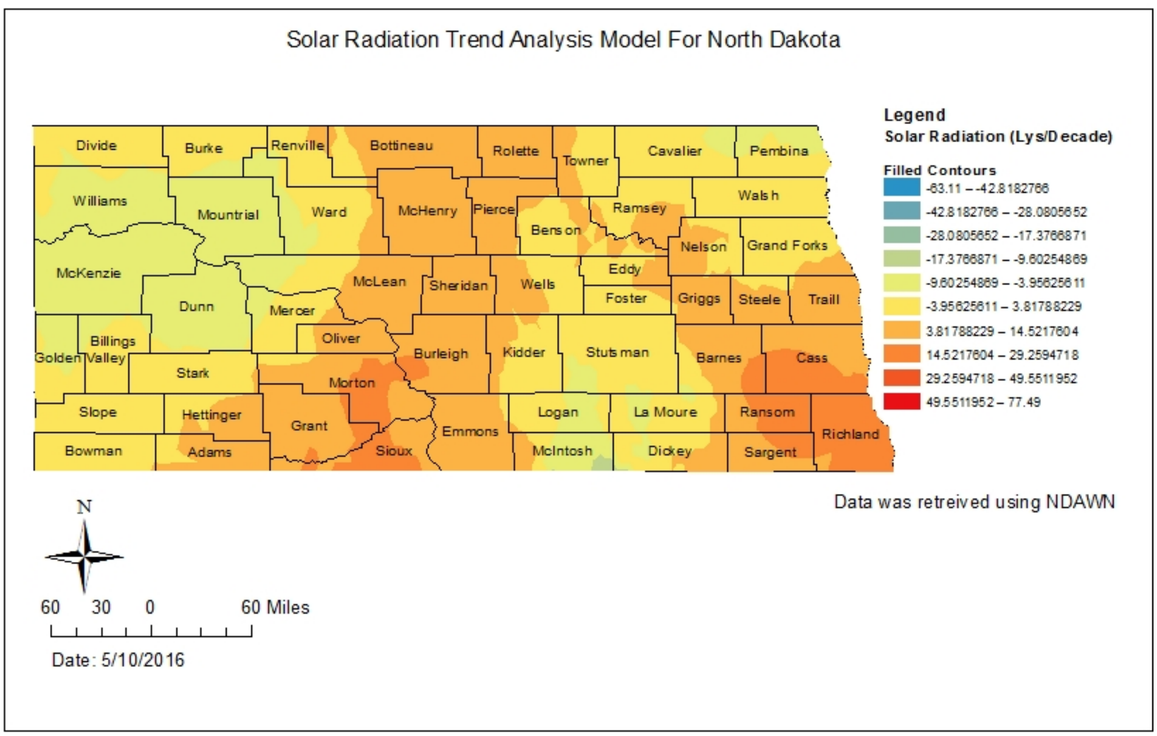

Figure 20. Solar radiation trends for North Dakota

In recent studies, the solar radiation decreased throughout the United States. Pan et al. (2014) found that solar-radiation simulations showed a decreased trend for the seasonal-mean daily global radiation availability, ranging from 0-20%. The most noticeable decrease was in the western United States (Pan et al., 2004). In contrast, Stanhill and Cohen (2005) looked at 106 sites throughout the United States. Stanhill and Cohen found that one-third of the sites were increasing, that one-third decreased and that one-third showed no change. Looking at Figure 20, solar radiation increased throughout the entire state, displaying similarities to Stanhill and Cohen's research. Pan et al. (2004), Stanhill and Cohen (2005).

Wind-Speed Trend

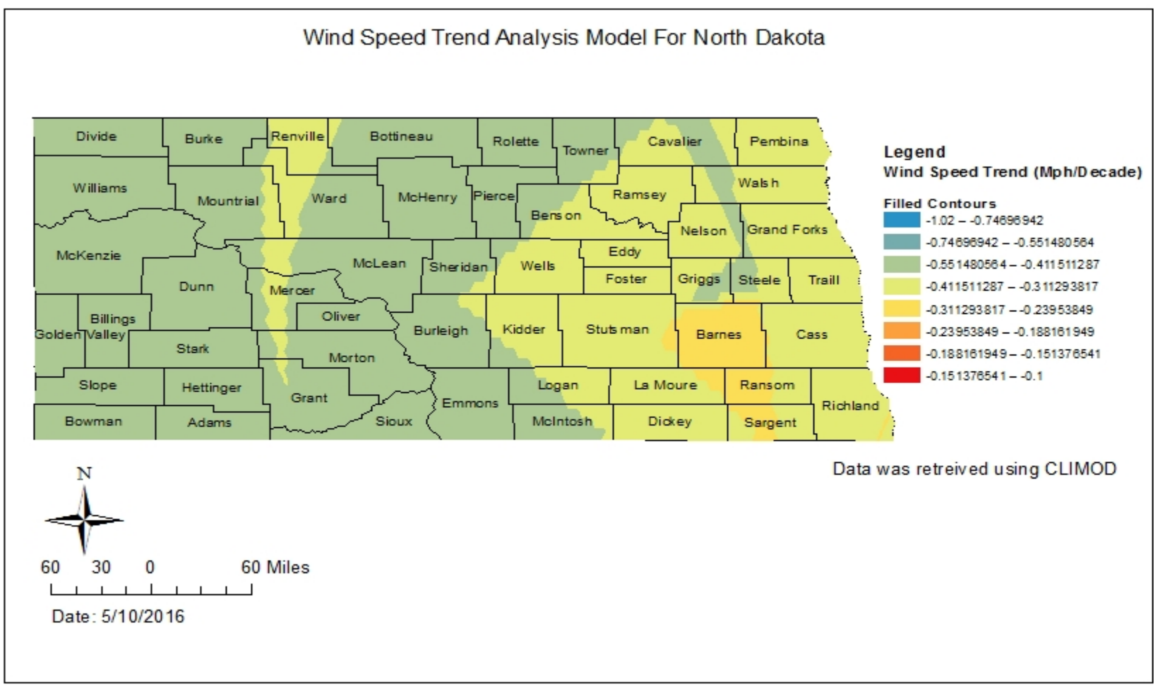

Figure 21. Wind speed trends for North Dakota

Figure 21 shows the variation for the wind-speed trends in North Dakota. In general, the wind speed decreased since 1948 in all locations included in this study.

The largest decreases, ranging from -0.551 to -0.412 mph/decade, can be seen in western North Dakota and are indicated by the green color. The decreased wind speeds become less eastward throughout the state, ranging from -0.412 to -0.239/decade, as indicated by the light-green and yellow colors. The decreasing wind-speed trends mean that, on average, the wind speeds are diminishing throughout the state.

Figure 22 illustrates how wind-speed trends are changing in South Dakota. The wind-speed trends are positive in the state's northwest corner and central area, ranging from 0.131 to 0.495 mph/decade, indicating the increased wind speeds with time. In the state's southwest and northeast corners, wind-speed trends have a negative value, ranging from -0.057 to -0.105 mph/decade, indicating the decreased wind speeds with time.

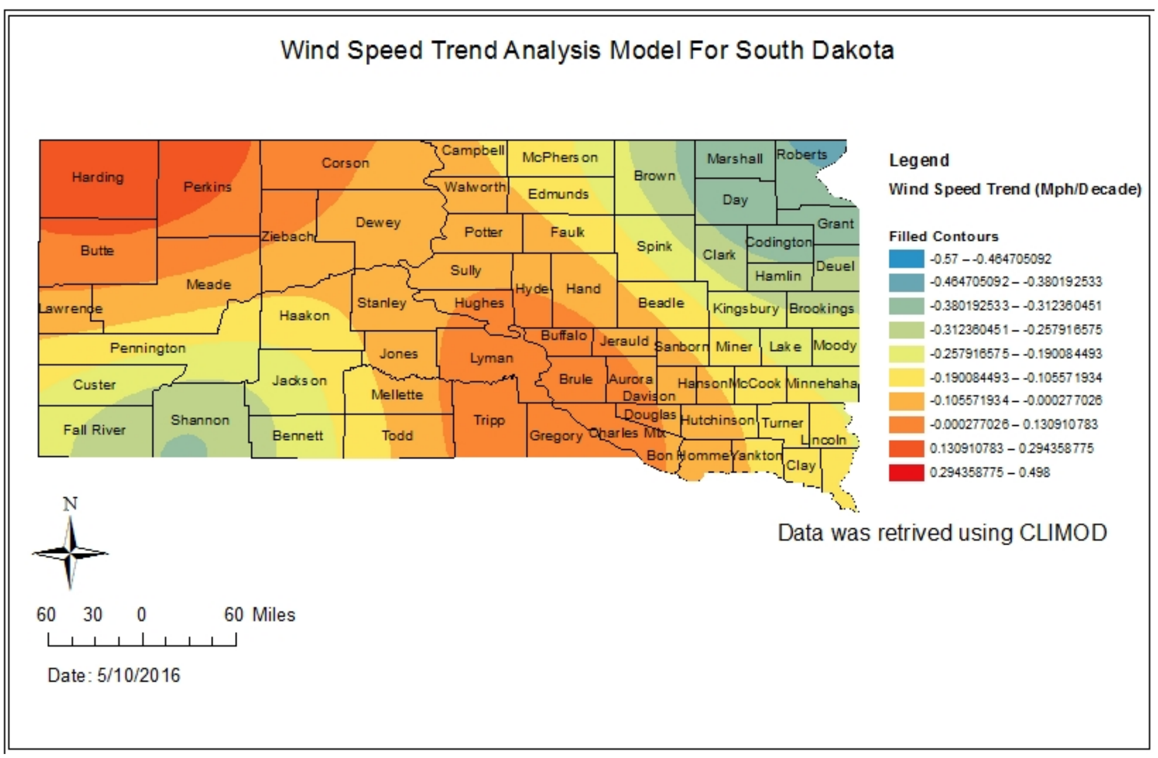

Figure 22. Wind speed trends for South Dakota

Throughout the United States, terrestrial anemometers measured declining wind speeds over the last 30-50 years (Pryor et al., 2009). The decreasing trends were seen throughout North Dakota in this study as shown in Figure 21. Klink (1999) found that the mean monthly maximum winds were increasing and that the mean monthly minimums were decreasing. The maximum winds were the highest in the summer and autumn, with decreasing wind speeds occurring from February through May. However, the minimum wind speeds decreased for all months. In all, the percentage change for the minimum wind speeds outweighed the maximum wind speeds' change (Klink, 1999). These variations are prevalent in South Dakota as shown in Figure 22.

Dew-Point Trend

Dew point temperatures account for the amount of moisture in the atmosphere. Dew-point trends throughout North Dakota vary geographically as shown in Figure 23. Throughout the entire state, the dew point decreases, ranging from -1.676 to -0.060/decade. This decrease means that less moisture is stored in the atmosphere than in previous decades.

South Dakota's dew-point change is shown in Figure 24. Once again, the state's dew-point trends are decreasing. Looking at the state's western portion, dew-point trends have the greatest negative values, ranging from -1.235 to -0.763 °F/decade, as indicated by the turquoise color. Moving east throughout the state, the dew-point trends are still decreasing. However, the dew-point trends have less or negative values, ranging from -0.399 to -0.118 °F/decade, as indicated by the green and yellow colors.

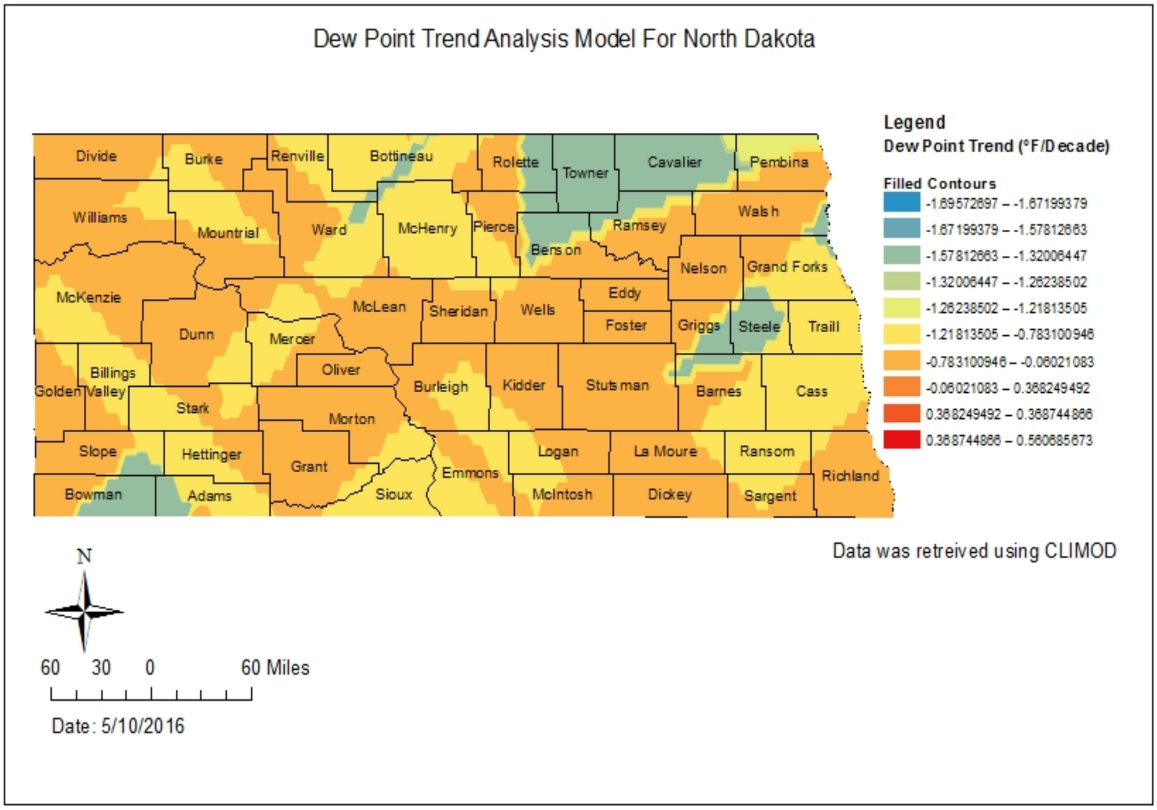

Figure 23. Dew point trends for North Dakota

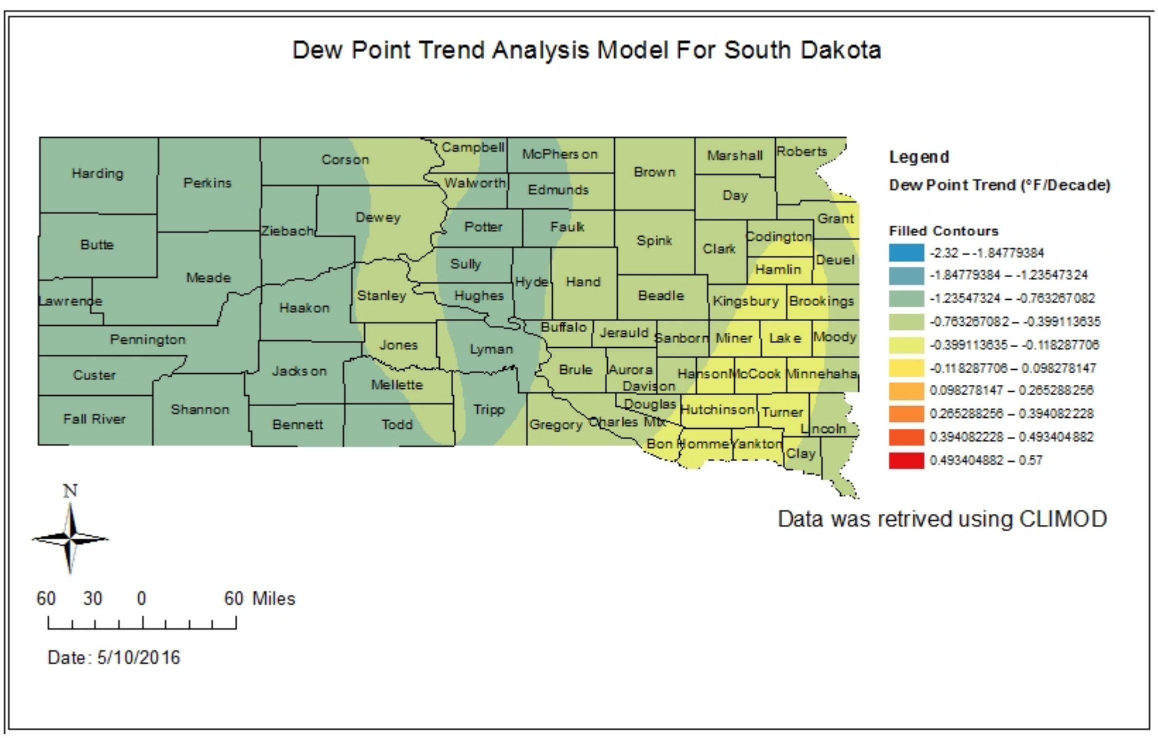

Figure 24. Dew point trends for South Dakota

Robinson (2000) and Huntington (2006) found that dew-point temperatures were decreasing throughout the United States and the Great Plains region. Robinson (2000) illustrated that U.S. dew-point temperatures decreased by approximately 1-2 °C/100 years (Robinson, 2000; Huntington, 2006). Findings from Robinson, Huntington and this thesis research produced comparable results. The dew-point temperatures were decreasing throughout the United States, including North and South Dakota.

SUMMARY

Looking at North Dakota's daily maximum and minimum temperature change, in general the greatest increases were evident in minimum temperatures. Furthermore, maximum temperatures even showed negative trends in most areas except for the southwestern parts of the state.

The maximum and minimum temperature trends in South Dakota were positive in the state's western portion, thus indicating a temperature rise. Moving eastward throughout the state, we see a drop for both the minimum and maximum trends while they maintained their positive nature. These trends become negative in the extreme east-central locations. This change concludes that temperatures have decreased in the state's extreme east-central areas during the last century. Therefore, the western portions of South Dakota have become warmer and the eastern portions have become colder, based on temperature minimums and maximums, during the last century.

During this period, both, North and South Dakota has become wetter. On average, each state has seen increased precipitation of about 0.5 in/decade. The steepest precipitation increase was observed in the eastern parts of both states. This may explain why the Red River of the North experiences increased frequency of major floods during the past 15 years in eastern North Dakota.

The GDDs roughly follow the same trends as the temperature minimums. In the southwest portion of North Dakota, there is an increase for the GDDs as shown in Figure 7. In the northwest section of North Dakota, where there is a decrease for the minimum temperatures, there is also a decrease for the GDDs. Looking at the rest of the state; we see that the GDD trends correlate almost perfectly with the temperature-minimum trends that are illustrated in Figure 3. This relationship among the temperature minimums (Figure 4) can also be seen when looking at South Dakota's GDD trends (Figure 8). In the western portion of South Dakota, we see a rise for both the temperature minimums and GDDs. Moving east throughout the state, there are decreased temperatures and GDDs. Both of these trends become negative, eventually moving further eastward though the state. In conclusion, GDDs correlate well with the state's minimum temperatures in such that higher the minimum temperatures are, the higher the GDDs are; the lower the minimum temperatures the lower the GDDs become.

Looking at Figure 9, we see that North Dakota's season length has increased when moving eastward throughout the state, even though the temperature minimums and maximums have decreased in the same direction. This indicates that, even though temperature minimums and maximums have decreased for the state's eastern areas, the minimums have stayed above 32 degrees longer. This shows us that the summer minimums have decreased while the spring and fall temperature minimums have increased during the last century.

This pattern does not hold true for South Dakota as shown in Figure 10. The season length has increased for the northern portion of South Dakota and has decreased when moving southward. The temperature minimums and maximums have decreased when moving eastward. Therefore, we do not see any spatial correlation between these two variables.

Looking at last-spring and first-fall frost dates (Figures 11-14), we see that, for both North and South Dakota, the last day of spring frost has a negative trend at roughly the same rate as a positive trend of the first day of fall frost. These figures are following the season-length trends (Figures 19 and 10) where season length has increased proportionally with the changing frost dates. That means, as the last seasonal frosts are occurring earlier by the same amount as the first seasonal frosts are occurring later. Previous research found that last spring-frost dates decreased faster than first fall-frost dates, which also resulted in longer growing seasons.

Figures 15 and 16 indicate how the PDSI trends are changing throughout North and South Dakota. The PDSI trends indicate that both states have become wetter at the center of the state faster than elsewhere. Comparing this to the changing precipitation (Figures 5 and 6), we see that, for North Dakota, the central portion of the state has received a moderate increase for the precipitation amounts during the last century. The lowest increase for the precipitation amounts is located in western North Dakota. As a result, there is a positive relationship between the PDSI and precipitation changes in North Dakota. When adding the temperature factor (Figures 1-4), we see that both the temperature minimums and maximums are increasing at the center of North Dakota. Therefore, precipitation increases seem to outweigh the increased temperature. When looking at South Dakota's temperature minimums and maximums, there has not been an increase. The precipitation trends have increased. Therefore, the temperature and precipitation trends correlate with the PDSI trends at the center of the state. North and South

Dakota's SPI rates per decade (Figures 17 and 18) follow the same pattern as the PDSI.

Looking at North Dakota's ET and solar-radiation rates (Figures 19 and 20), the ET rates have decreased in the state's central portion and in the northwest corner, whereas the remaining portions of the state have seen increased ET rates. These results show no correlation with the temperature trends while one might suspect an eastward decrease for the ET rates. However, it is important to note that ET rates depends not only temperature but also a combination of wind speed and solar radiation also. The ET trend decreased from southeast to northwest corners of the state in ND. The solar radiation trend also decreased along the same line.

Wind speeds have decreased throughout North Dakota (Figure 21). The highest decrease is located in the state's western portion. Moving eastward throughout the state, negative trends become less severe. Looking at the ET rates for North Dakota (Figure 19), where portions of the ET trends are more negative, wind speed trends were also the most negative. However, ET trends were most positive where wind speed trends were least negative in the southeast parts of ND. It shows that ET rates were more sensitive to solar radiation values than wind speeds in this portion of the state. Wind speeds have increased in the central and northwest areas of South Dakota (Figure 22), whereas, for the rest of the state, i.e., the eastern and southwest areas, we see a decreased wind speed.

Dew points throughout North Dakota (Figure 23) have changed in a sporadic pattern. However, we see a decline in dew-point trends per decade across the entire state. The same can be said for South Dakota (Figure 24), where dew points are also decreasing. The decrease is greater for the western portion of South Dakota than for the state's the eastern portion.

CONCLUSION

In conclusion, all the climatic variables studied in this thesis have shown some sort of trend, on a county-level basis, throughout North and South Dakota. Some climatic variables correlate with each other while others do not. These changes with the climatic variables affect plants and animals. The changes impact farmers differently, depending on the types of crops that are grown; the effects include when to plant as well as how much water is needed to manage the risk of crop loss.

The public website that was constructed displays not only the previously presented information, but also the annual and monthly line graphs for each climatic variable. This website consisted of over 10,000 graphs that help illustrate, on a county level, how the studied variables have changed over the last century, allowing the public to easily view and gather these data for the first time. The data were converted from raw data and into forms that make it easy to see how a data set has changed in a specific county for a specific time. This project was completed to demonstrate climate change throughout North and South Dakota at the county level.

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APPENDIX A. KRIGING METHODS USED TO PRODUCE A MAP INDICATING CLIMATIC TRENDS PER DECADE THROUGHOUT ND AND SD FOR EACH CLIMATIC VARIABLE

Clamatic Variable	Method	Method Type	Output Type	Model Type	Smoothing Factor
ND Temperature Maximum	Kriging	Simple	Prediction	Gaussian	0.5
SD Temperature Maximum	Kriging	Ordinary	Prediction	K-Bessel	0
ND Temperature Minimum	Kriging	Ordinary	Prediction	K-Bessel	0.8
SD Temperature Minimum	Kriging	Ordinary	Prediction	Tetraspherical	0.2
ND Precipitation	Kriging	Simple	Prediction	K-Bessel	0.8
SD precipitation	Kriging	Ordinary	Prediction	Tetraspherical	0
ND GDD	Kriging	Simple	Prediction	K-Bessel	0.6
SD GDD	Kriging	Ordinary	Prediction	Pentaspherical	0.2
ND Season Length	Kriging	Ordinary	Prediction	Gaussian	0
SD Season Length	Kriging	Ordinary	Prediction	Gaussian	0
ND Last Spring Frost Date	Kriging	Ordinary	Prediction	Tetraspherical	0
SD Last Spring Frost Date	Kriging	Ordinary	Prediction	Tetraspherical	0
ND First Fall Frost Date	Kriging	Ordinary	Prediction	Pentaspherical	0
SD First Fall Frost Date	Kriging	Ordinary	Prediction	Tetraspherical	0
ND PDSI	Kriging	Ordinary	Prediction	Tetraspherical	0
SD PDSI	Kriging	Ordinary	Prediction	Gaussian	0.5
ND SPI	Kriging	Ordinary	Prediction	Spherical	0
SD SPI	Kriging	Ordinary	Prediction	Tetraspherical	0.7
ND ET	Kriging	Ordinary	Prediction	K-Bessel	0
ND Solar Radiation	Kriging	Ordinary	Prediction	Tetraspherical	0
ND Wind Speed	Kriging	Ordinary	Prediction	Gaussian	0
SD Wind Speed	Kriging	Ordinary	Prediction	Gaussian	0.2
ND Dew Point	Kriging	Ordinary	Prediction	Stable	0
SD Dew Point	Kriging	Ordinary	Prediction	Gaussian	0.2
Key	ND	SD			

APPENDIX B. HOW TO PROPERLY SETUP THE CLIMATE ACIS QUERY BUILDER, TO OBTAIN THE CLIMATE DATA FOUND IN THIS STUDY