EC3009

Observed Space and Time Changes in Air Temperatures and Daily Temperature Range for the Counties in the U.S. Great Plains

from 1968 to 2013

Meetpal S. Kukal, Graduate Research Assistant
Suat Irmak, Soil and Water Resources and Irrigation Engineer and Professor
Department of Biological Systems Engineering

Understanding the magnitude and direction of potential changes in climate variables is important to better understand the relationships between these changes and agricultural production, water resources, irrigation practices, and related topics. Better evaluation of the relationships between climate variables and agriculture also requires studying these relationships on large scales. This Nebraska Extension Circular presents scientific data, analyses, and interpretation using visual maps and discussion of (i) geographic variability (trends) that exists in patterns of historical air temperatures (maximum, minimum, and average) and daily temperature range across the United States Great Plains; (ii) the temporal (1968–2013) changes that have been observed in these variables; and (iii) potential consequences and significance of these changes in light of agricultural production in the Great Plains. The study region comprises nine states and 834 counties from Texas to North Dakota and from Iowa to Colorado and is about 30 percent of the surface area of the continental United States.

Global climate change and its impacts on observable climate indices have been discussed on a range of fronts. According to the Intergovernmental Panel on Climate Change (2013), the global average air temperature has risen by 1.53°F since the beginning of the 20th century, and is projected to continue to rise to 2.7°F by the end of 21st century relative to the period 1850–1900 if global emissions continue to rise at the existing rate. It has also been established that human influence, which translates to increases in greenhouse gas emissions, has been the dominant cause of the observed warming since the mid-20th century.

Widespread discussions about global climate change often provoke thoughts about the implications on local air temperature indices and the potential consequences on agricultural production and practices. While ample discussion and investigation of global climate change occur, it is imperative that individuals in local communities understand the nature and the numbers behind the observations for their particular location/region.

This interest in local-scale effects is justified because trends in air temperature observations are variable and nonuniform, even on small spatial scales. Moreover, the effects of these changes might vary with locations, even though similar temperature trends have been observed at these locations. This is especially true for large regions of agricultural production such as the Great Plains, which includes a range of climate classes ranging from arid and semiarid in the West to dry subhumid and humid in the East. Moreover, the area is home to the production of corn, cotton, wheat, soybeans, sugarbeets, beef, and swine.

Because air temperatures tend to vary with space and time, it is crucial that the trends be investigated and reported at appropriate geographic scales. This allows the user to relate the temperature trends to other available data, such as yield and production statistics. This publication is based on research conducted by Kukal and Irmak (2016a, b) and reports on the air temperature indices trends independently for all counties in the Great Plains. Using this information, policymakers and stakeholders can better understand the local and regional temperature trends, and perhaps make more informed decisions directed toward adaptation of agricultural

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practices that can help to sustain agricultural productivity against the temperature trends (warming/cooling) observed in their respective counties.

Since the Great Plains is geographically large and climatologically diverse, it is important to characterize the region in terms of the natural pattern of air temperature regimes that exist across it. The spatial pattern in air temperature is what primarily determines the agricultural suitability, prevalent cropping systems, length of growing season, crop development, crop water stress, yield potential, and crop water use of a particular region. Hence, there is a strong relationship and dependency of agricultural production on the temperature patterns for any location. This necessitates a reasonable understanding of the spatial trends and variation in maximum, minimum, and average air temperatures, as well as daily temperature range across the region, prior to delving into the temporal trends that have occurred in different parts of the region.

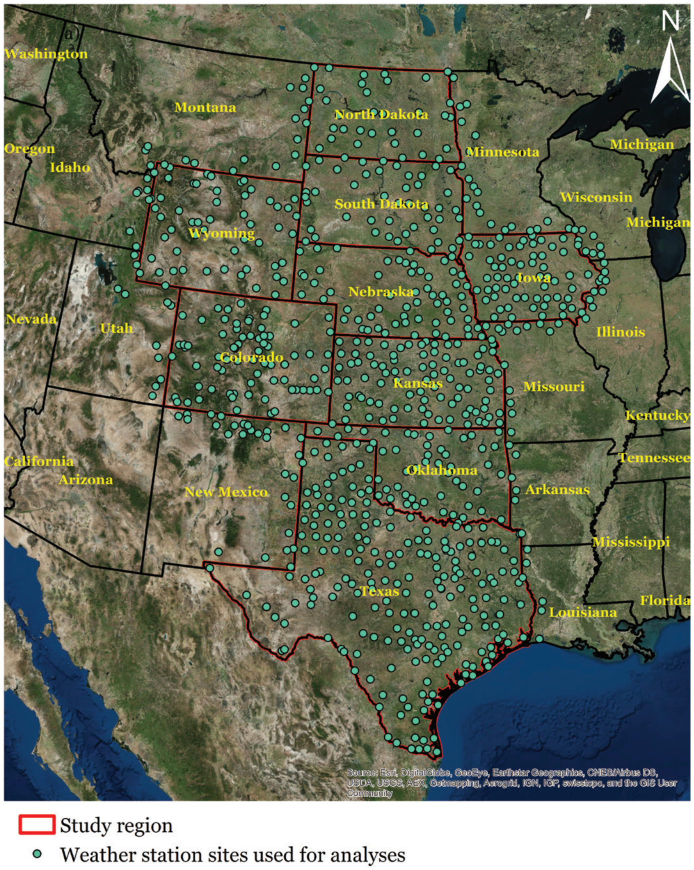
Such knowledge would aid in answering questions such as: are the areas that are warming/cooling at a greater rate the ones that naturally exist in warmer/cooler areas? Moreover, seasonal variability exists in these spatial and temporal trends; hence, it is beneficial to address these trends for different time scales, such as annually, growing season, and monthly. In this publication, the growing season is considered to be May 1 to September 30, which is a common period chosen to represent the crop growing season throughout the region.

To investigate all the previously mentioned concerns, independent analyses were conducted on 834 counties in the nine states in the Great Plains region, using observed temperature data from upwards of 800 weather stations during a 46-year period (1968–2013). Since the analyzation of the data involved in obtaining these results is both extensive and arduous, the results are best represented using visual maps. Maps allow the reader to better observe the changes (trends) in a spatio-temporal manner and increase the comprehensibility of the research. Each variable and its associated trends, both in space and time, are shown via maps for the annual growing season and monthly temporal scales in this circular. The resource at hand would be beneficial for concerned citizens to readily observe and interpret climate change impacts on air temperature and daily temperature range at their location of interest and also inter-compare these among multiple locations.

Study Region

The Great Plains region (shown in *Figure 1*) refers to what is geographically the Central USA. Its boundaries extend from the Canadian border in the north, to Texas in the south, Wyoming and Colorado on the west, and Iowa and Missouri on the east. The total land area is about 2,307,410 km^2 (891,000 miles^2) and lies between dense forests on the east and Rocky Mountains and deserts on the west. The common topographical characteristic is vast, flat-to-rolling plains. The highest elevation throughout the region is in the Rocky Mountains in Colorado and the lowest elevation is at the southern coastline of Texas.

Temperature and precipitation increase from north to south and east to west. The long-term average (1968–2013) annual precipitation ranges from 8.5 inches in the west to 57.0 inches in the southeast. Similarly, long-term average (1968–2013) growing season (May 1 to September 30) precipitation varies from 4.7 inches in the west to 27.5 inches in the southeast. Agricultural land includes rangelands, prairies, and irrigated and rainfed row crops such as corn, soybean, sorghum, alfalfa, winter wheat, sugarbeets, and cotton. In the



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 1. Study region (Great Plains and the selected weather station sites for analyses).

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eastern part of the region, rainfed crop production dominates, whereas in the western part irrigated crop production is dominant with the High Plains (Ogallala) aquifer serving as the major source of irrigation water.

Spatial Distribution of Annual, Growing Seasonal and Monthly Maximum, Minimum, and Average Air Temperatures

The long-term (1968–2013) average spatial distribution of annual and growing season maximum (T_{max}), minimum (T_{min}), and average (T_{avg}) air temperature and diurnal temperature range (DTR) are provided in *Figures 2* through *5*. The figures consist of maps representing these indices of interest, and can be used to interpret the spatial variation that occurs from east to west or north to south, which is an effective and self-explanatory way of communicating extensive information.

The long-term average of annual, growing season, and monthly (May through September) T_{max} values (*Figures 2* and *6*) shows a similar pattern of spatial distribution. The region-wide, long-term average for T_{max} was 66.0°F on an annual basis and 83.5°F on a growing season basis. T_{max} gradually increased from north to south in the region, ranging from 42.8°F to 86.0°F, when averaged annually; and from 59.0°F to 96.8°F, when averaged for the growing season. Averaged annually, the lowest T_{max} was observed in Cavalier County, North Dakota, while the highest value was observed in Starr County, Texas. When averaged over the growing season, the lowest T_{max} was observed in Lake County, Colorado, whereas the highest value was in Zapata County, Texas. *Table 2* presents the region-wide and statewide averages and other measures (including maximum, minimum, and standard deviation) for annual, growing season, and monthly average T_{max}.

The variability in T_{max} during the growing season months is also observed from the maps, with July having the highest T_{max} (89.4°F), while May had the lowest T_{max} (75.4°F), when averaged regionally. While it would be very cumbersome to observe these values for each year in the analyses period, we can study standard deviation values to infer information about temporal (annual) distributions of air temperature. Standard deviation (SD) is an indicative measure of the amount of variation from the mean air temperature values in each period. Higher SD indicates more variation or deviation of the temperature data from the mean value over a particular period, while low SD indicates that the temperature data points are relatively closer to the mean value. For the average annual T_{max}, the maximum SD was observed in North Dakota and South Dakota (2.1°F), while minimum values were observed in Oklahoma (1.3°F) and Texas (1.2°F). Generally, the SD decreased from north to south. For the growing season, the variation in the magnitudes of SD is not very large, with no clear trend in the north to south direction. Also, for most of the states, the SD in growing season T_{max} is higher than that in annual T_{max}.

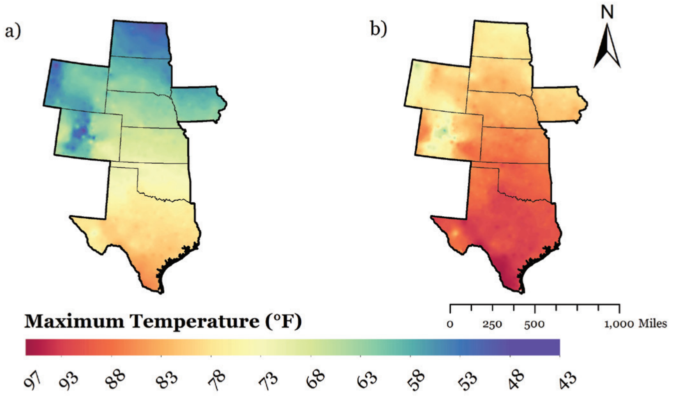

Figure 2. Spatial trends in: a) Annual, b) Growing Season maximum air temperature (T_{max}) across the Great Plains.

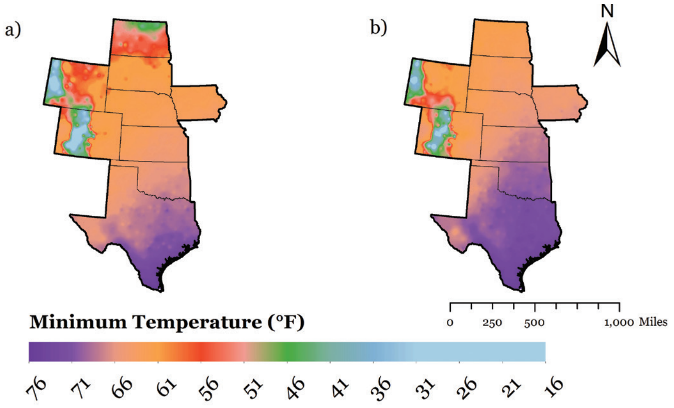

Figure 3. Spatial trends in: a) Annual, b) Growing Season minimum air temperature (T_{min}) across the Great Plains.

Minimum air temperature (T_{min}) had a northwest to southeast increasing trend, with a region-wide average of 40.4°F on an annual basis and 56.8°F on a growing season basis across the study region. T_{min} varied from 15.8°F to 66.2°F when averaged annually; and from 32.0°F to 77.0°F when averaged across the growing season *(Figure 3)*. Unlike annual average T_{max} where the lowest temperatures were observed in North Dakota, both the annual and growing season average lowest T_{min} values were observed in Lake County, Colorado. The highest annual and growing season average T_{min} values were observed in Cameron County, Texas. The region-wide and statewide averages, along with other distribution measures for annual, growing season, and monthly average T_{min}, are presented in *Table 3*. The monthly variability in T_{min} was

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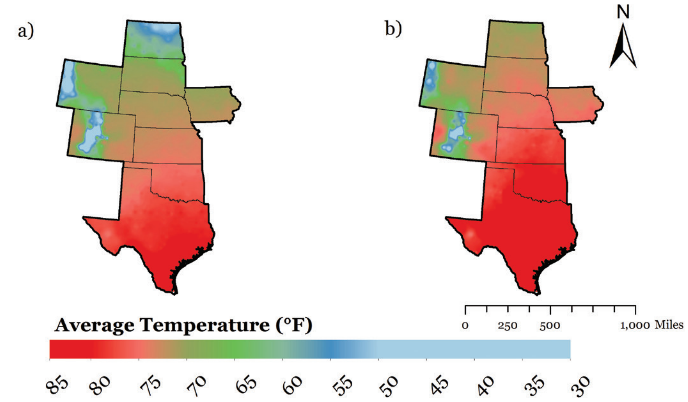

Figure 4. Spatial trends in: a) Annual, b) Growing Season average air temperature (T_{avg}) across the Great Plains.

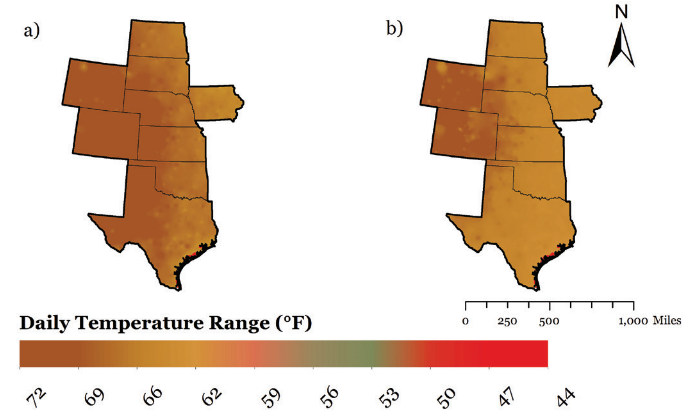

Figure 5. Spatial trends in: a) Annual, b) Growing Season daily temperature range (DTR) across the Great Plains.

similar to T_{max}, where July had the highest T_{min}, (62.8°F), while May had the minimum T_{min} (49.5°F), when averaged regionally *(Table 3)*. The SD in annual average T_{min} follows a decreasing trend in the north to south direction similar to T_{max}, which was not the case for growing season average T_{min}.

Since average air temperature (T_{avg}) is derived from T_{max} and T_{min}, both of which had similar north-south increasing trends, T_{avg} also had a north to south increasing trend *(Figure 4),* ranging from-30.2° F to 75.4° F when averaged annually, and 46.4° F to 86° C when averaged over the growing season. The region-wide annual and growing season average T_{avg} was 53.2°F and 70.1°F, respectively. The growing season monthly T_{avg} peaked in July and was at its lowest value in May. The county showing highest annual T_{avg} was Hidalgo County, Texas, whereas the county with the lowest annual T_{avg} was Lake County, Colorado. Likewise, the highest growing season T_{avg} was observed in Starr County, Texas, and the minimum was observed in Lake County, Colorado. The standard deviation of statewide annual T_{avg} was comparable to that of T_{max} and T_{min}, and also had a decreasing tendency in the north-south direction. This trend was lacking in the standard deviation for the growing season T_{avg}, which is also true for T_{max} and $T_{min.}$ Moreover, the standard deviation in growing season T_{avg} was much greater than those for T_{max} and T_{min}.

The blue colored areas *(Figure 4)* of Colorado and Wyoming, which are in the vicinity of the Rocky Mountain ranges, show extremes in air temperatures, which means that they show lower values of T_{max}, T_{min}, and T_{avg} than the rest of the region, and are an exception to the otherwise north to south increasing trend. This behavior is a result of the lower air pressure present in the mountain ranges at higher elevations, which causes the air to cool by expansion (i.e., when the air expands, its volume increases and the frequency of atomic collisions decreases, hence cooling the gas.

Daily Temperature Range (DTR)

Daily Temperature Range (DTR) is the difference in daily daytime temperature (T_{max}) and nighttime temperature (T_{min}). The annual and growing season average DTR values for the region are 25.7 °F and 26.6 °F *(Table 5)*. The DTR has strong spatial variability, with the western part showing higher values of DTR, which gradually decrease moving east. Generally, the states of Colorado and Wyoming show the highest values of DTR in the region, while the lowest magnitudes were observed in Iowa. The north-south trend that existed in T_{max} and T_{min} was eliminated in DTR as it was calculated as the difference of the two air temperatures. Also, high DTR magnitudes were found in the Rocky Mountain ranges. During the growing season months, the highest value for DTR in the region was observed in September (27.4°F) and the lowest was observed in May (25.9°F). Also, the SD in growing season DTR was higher than the annual DTR, with a clear north to south decreasing trend.

Apart from the maps representing annual and growing season air temperatures (T_{max}, T_{min}, T_{avg}) and DTR, the spatial variation in these indices during the May through September growing season months is shown in *Figures 6–9*, respectively.

Temporal Changes in Annual, Growing Season, and Monthly Maximum, Minimum, and Average Air Temperatures

The changes that have occurred in annual, growing season, and monthly T_{max}, T_{min}, T_{avg}, and DTR during the period 1968–2013 have been investigated and reported for all 834 counties over the nine states. The trends in these counties are presented in *Figures 10–13,* using maps that show the nature of the trends (whether increasing or decreasing) and their

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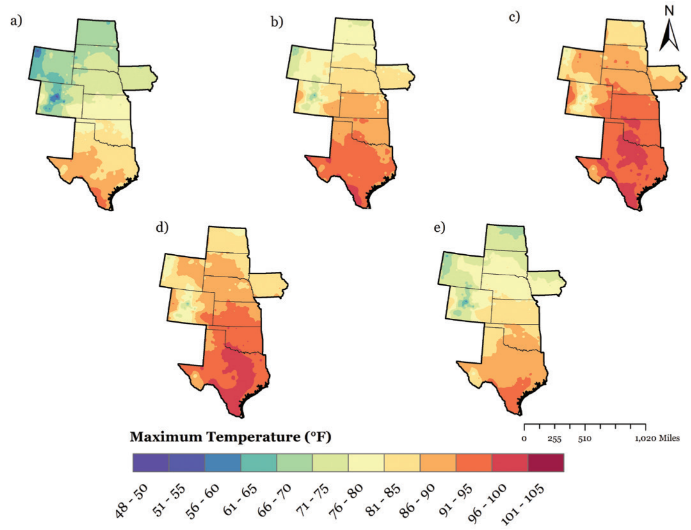

Figure 6. Spatial trends in maximum air temperature (T_{max}) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

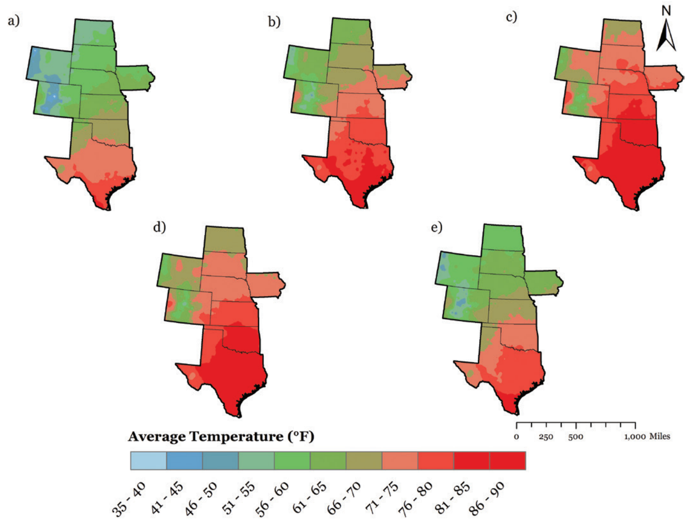

Figure 8. Spatial trends in average air temperature (T_{avg}) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

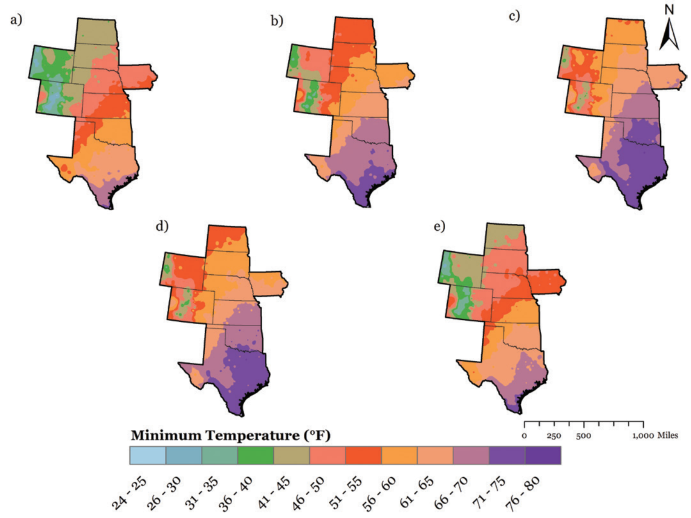

Figure 7. Spatial trends in minimum air temperature (T_{min}) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

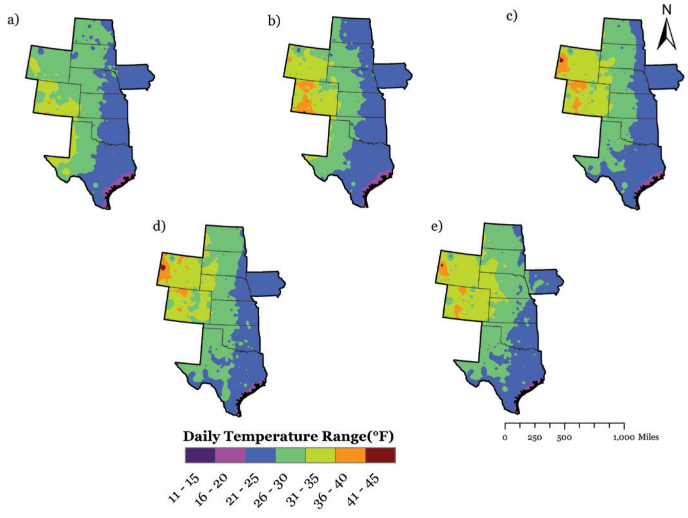

Figure 9. Spatial trends in daily temperature range (DTR) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

significance (whether a trend is large enough to be qualified as a trend by statistical definition).

In these maps, the blue upright arrows represent increasing (positive) trends, while the red inverted arrows indicate decreasing (negative) trends. Counties with a green background indicate that the trend for the county is statistically significant at α = 0.05, which distinguishes them from the counties with insignificant trends (counties with a white background). Nevertheless, non-significant trends can be crucial because they have potential implications for agricultural crop production by affecting yields, irrigation, risk of diseases/pests, etc., although they are not qualified in terms of statistical theory.

For annual T_{max}, 71 percent of the counties showed increasing trends in annual T_{max} in the region. Most of these significantly increasing trends were observed in Texas, along with a few counties in Colorado. Although they were insignificant, most of the Great Plains region showed increasing trends in T_{max}. Some areas showed insignificant decreasing trends, including southeast North Dakota, eastern South Dakota, western Iowa, central Nebraska, eastern Kansas, and central Oklahoma. The regional average increasing and de-

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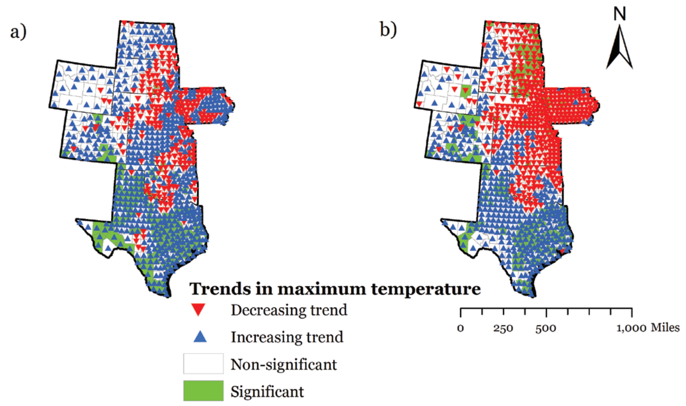

Figure 10. Temporal trends in: a) Annual and b) Growing Season maximum air temperature (T_{max}) across the Great Plains.

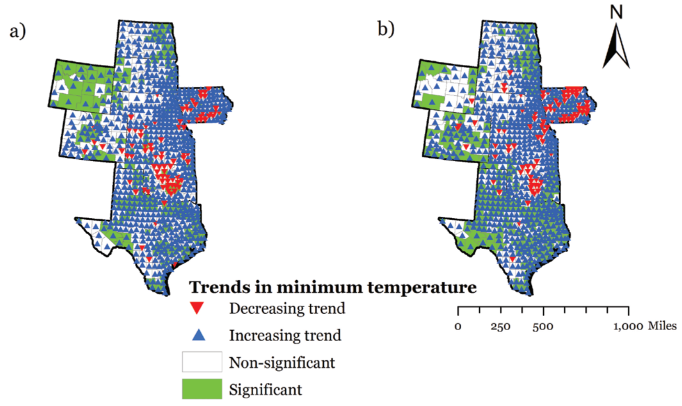

Figure 11. Temporal trends in: a) Annual and b) Growing Season minimum air temperature (T_{min}) across the Great Plains.

creasing trends in annual T_{max} are 0.27°F/decade and 0.14°F/decade, respectively.

On the other hand, the proportion of the counties that showed positive and negative trends in growing season T_{max} was 48 percent and 52 percent, respectively. The regional average increasing and decreasing trends in growing season T_{max} were 0.32°F/decade and 0.37°F/decade, respectively. Primarily, the northern, eastern, and central parts of the region showed decreasing trends, and several counties in eastern North Dakota and South Dakota show significantly decreasing trends. On the contrary, the western and southern parts of the region show an increase in T_{max}. Similar to what was observed for annual T_{max}, several counties in Texas show significantly increasing trends for growing season T_{max} along with some counties in Colorado. On the other hand, unlike the more dominant northern positive trends in annual T_{max}, the growing season mean maximum air temperatures show negative trends in the northern region, with the eastern parts of North Dakota and South Dakota showing significantly negative trends.

These differences in trends between annual and growing season average T_{max} show that when studying the potential impacts of climate change on agricultural production, annual trends can be misleading, and thus, the analysis of growing season trends is crucial. The decreasing trends in growing season T_{max} can potentially be due to the cooling effect of irrigation, especially in counties with large acreages of irrigated summer crops such as those in south-central Nebraska. This is because soil water affects surface reflective properties (albedo) and evaporation, and also has been shown to influence regional temperature.

The trends for the growing season months *(Figure 14)* were similar to the growing season average trends explained above, with the counties in the northern and eastern regions showing decreasing trends, and the southern and western regions showing increasing trends. There is considerable variability in the nature of these trends for every month. It is extremely difficult to explain the variability that occurs in the trends observed for each county and state, which signifies the importance of the self-explanatory maps that can be used to extract invaluable information.

T_{min} had highly dominant positive trends in almost all counties, with a substantial number of counties showing significant trends. Roughly 90 percent of the counties in the region showed positive trends. The regional average positive and negative trends in annual T_{min} were 0.36°F/decade and 0.13°F/decade, respectively. Moreover, the proportion of counties showing significant positive trends was roughly the same (90 percent) for growing season T_{min} as the annual time scale. The regional average positive and negative trends in growing season T_{min} were found to be 0.34°F/decade and 0.11°F/decade, respectively. Focusing on the monthly T_{min} trends *(Figure 15),* it was found that almost all significant trends are increasing trends, and the only significant decreasing trends are observed in some counties in Oklahoma for September. Most of the significant increasing trends were observed in the growing season months.

As the average air temperatures are derived from maximum and minimum air temperatures, it is expected that the trends in T_{max} and T_{min} would be inherited in T_{avg}. As discussed before, the trends in both annual and growing season T_{min} were dominantly positive, but trends in T_{max} exhibited different trends across the region. This resulted in increasing trends in annual T_{avg} in the counties where annual T_{max} was increasing, since the annual T_{min} had uniform increasing trends in the area.

Some examples of these areas are Texas, Colorado, and Wyoming. Also, we observed earlier that annual T_{max} had

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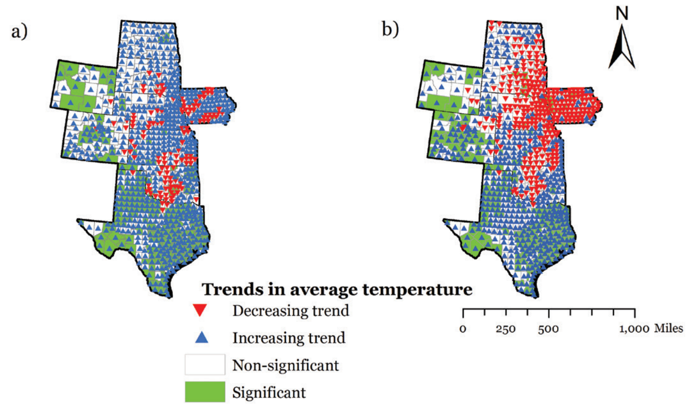

Figure 12. Temporal trends in: a) Annual and b) Growing Season average air temperature (T_{avg}) across the Great Plains.

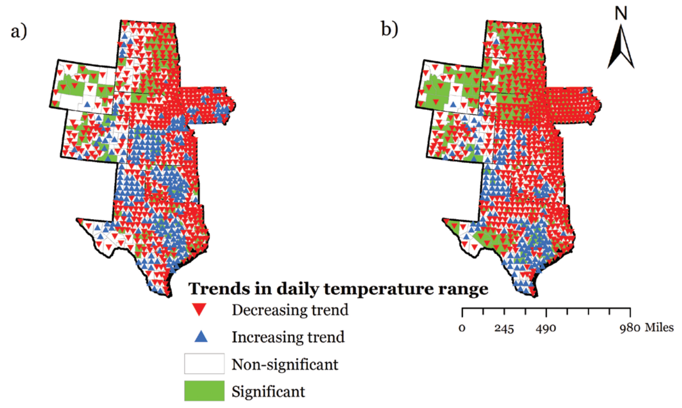

Figure 13. Temporal trends in: a) Annual and b) Growing Season daily temperature range (DTR) across the Great Plains.

decreasing trends in certain counties in northern, central, and eastern states, and growing season T_{max} had very uniform decreasing trends in these parts. As a result, similar decreasing trends were found in T_{avg}, although some weaker T_{max} decreasing trends were converted to positive T_{avg} trends because of significant T_{min} trends. The proportion of counties that had positive trends in annual and growing season T_{avg} is 85 percent and 62 percent, respectively. The regional average positive and negative trends in annual T_{avg} are 0.28°F/decade and 0.11°F/decade, respectively. Similarly, the region averages for the positive and negative trends in growing season T_{avg} are 0.31°F/decade and 0.16°F/decade, respectively.

Annual DTR trends were found to be negative for the majority of the region, which is evident from the fact that the proportion of counties that showed negative annual DTR trends was 69 percent. These negative trends were observed in all counties of North Dakota, South Dakota, and Wyoming. The Nebraska counties—except for some counties in the southeast and east-central regions—also showed negative (decreasing) trends. In Iowa, the majority of the counties showed negative trends, with the exception of some counties in the southwest and southeast parts. Western Colorado showed negative trends, while eastern Colorado showed positive trends. Similarly, Kansas showed positive trends in the western counties, whereas eastern Kansas counties showed negative trends. In Oklahoma, counties in the central part of the state showed positive trends. In Texas, counties in the High Plains, Trans Pecos, north-central, and south-central regions showed positive trends.

The negative trends found in some counties of North Dakota, South Dakota, Wyoming, Colorado, Oklahoma, and Texas were statistically significant. On the other hand, some significant positive trends were found in Colorado. The regional average positive and negative annual DTR trends were 0.14°F/decade and 0.25°F/decade, respectively.

The negative (decreasing) trends in growing season DTR are more dominant in the region in comparison with annual DTR. The proportion of the counties that showed negative trends in growing season DTR is 80 percent, which is 11 percent more than what was found for annual DTR. North Dakota, South Dakota, Iowa, Nebraska, and Wyoming showed dominant negative trends, with most of them being significant. The distribution of positive and negative trends in the rest of the states is similar to that of annual DTR. The regional average positive and negative growing season DTR trends were 0.16°F/decade and 0.4°F/decade, respectively.

In our study, a decrease in DTR across the region, which is one of the major findings, may be due to an increase in atmospheric moisture and a decrease in incoming shortwave radiation. One of the likely explanations for the decreases found in growing season DTR values is the significant expansion of irrigation in the region, leading to an increase in atmospheric moisture. The temporal trends in T_{max}, T_{min}, T_{avg}, and DTR during the growing season months, i.e., May through September, are also shown in *Figures 14–17*, respectively.

As an example, we chose one county, Clay County, Nebraska, from the 834 counties in the region to extract and tabulate all the temporal trends during the 1968–2013 period. Detailed information for the observed T_{max}, T_{min}, T_{avg}, and DTR trends in Clay County, Nebraska, is listed in *Table 1*. The trends in T_{max} in Clay County were negative for all the growing season months and the growing season average T_{max}. However, the annual T_{max} trend was positive. For T_{min}, all periods showed positive trends except May. The T_{avg} trends were the same in nature as T_{max} trends. DTR showed negative trends for all the periods throughout. Interestingly, the DTR trends during June and July (marked in bold red) were significantly decreasing.

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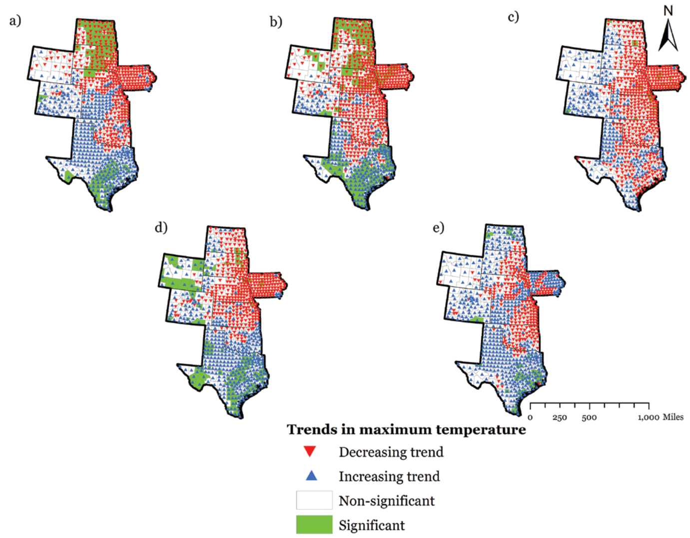

Figure 14. Temporal trends in maximum air temperature (T_{max}) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

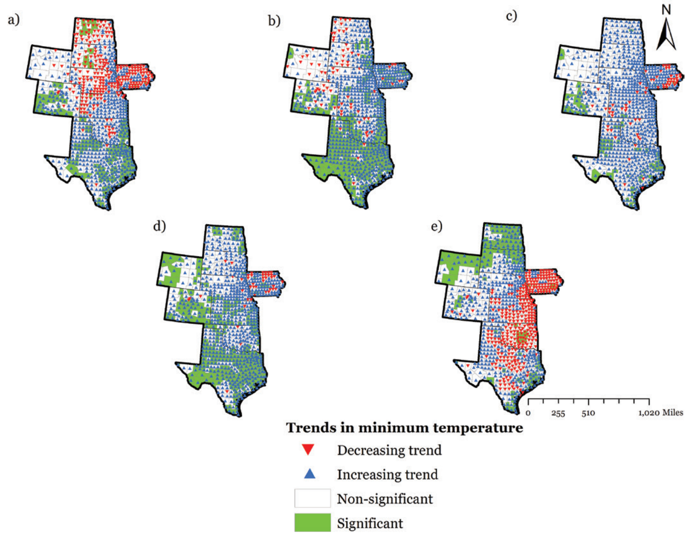

Figure 15. Temporal trends in minimum air temperature (T_{min}) during: a) May, b) June, c) July, d) August, and e) September across the Great Plains.

Table 1. Temporal trends in T_{max}, T_{min}, T_{avg}, and DTR observed for Clay County, Nebraska. The values marked in red bold letters mean that the corresponding trend is significant.

Period	*Trend (°F/decade)*			
	T_{max}	*T_{min}*	*T_{avg}*	*DTR*
May	-0.11	-0.01	-0.08	-0.05
June	-0.63	0.21	-0.23	**-0.70**
July	-0.63	0.15	-0.24	**-0.74**
August	-0.52	0.18	-0.14	-0.52
September	-0.02	0.07	-0.02	-0.14
Growing Season	-0.37	0.10	-0.12	-0.42
Annual	0.07	0.21	0.15	-0.13

Region-Wide and Statewide Averages of Air Temperatures and DTR

The following tables show the region-wide and statewide averages for annual, growing season, and monthly T_{max} *(Table 2)*, T_{min} *(Table 3)*, T_{avg} *(Table 4)*, and DTR *(Table 5)* to aid the interpretation of the discussed results based on political units.

Table 2. Region-wide and statewide average annual, growing season, and monthly T_{max}.

Months	*Regional*	*ND*	*SD*	*NE*	*KS*	*CO*	*WY*	*IA*	*OK*	*TX*
Monthly Means										
May	75.4	67.5	70.0	72.5	76.5	69.6	65.5	72.0	80.2	85.1
June	84.4	76.3	79.5	82.8	86.7	80.4	76.3	81.1	88.9	91.6
July	89.4	82.8	86.9	88.5	92.3	85.8	85.1	85.1	94.3	94.1
August	88.2	81.9	85.5	86.7	90.5	83.3	83.3	82.9	93.7	93.9
September	80.1	71.1	75.9	78.3	82.0	75.6	72.9	75.6	85.3	87.8
Annual Statistics										
Mean	66.0	52.7	58.3	62.6	67.5	61.7	57.4	58.8	72.3	77.5
Max	69.8	57.2	63.0	67.5	72.0	65.1	61.3	63.7	75.9	80.6
Min	63.3	48.2	53.4	58.1	63.5	59.0	53.6	55.2	70.2	75.6

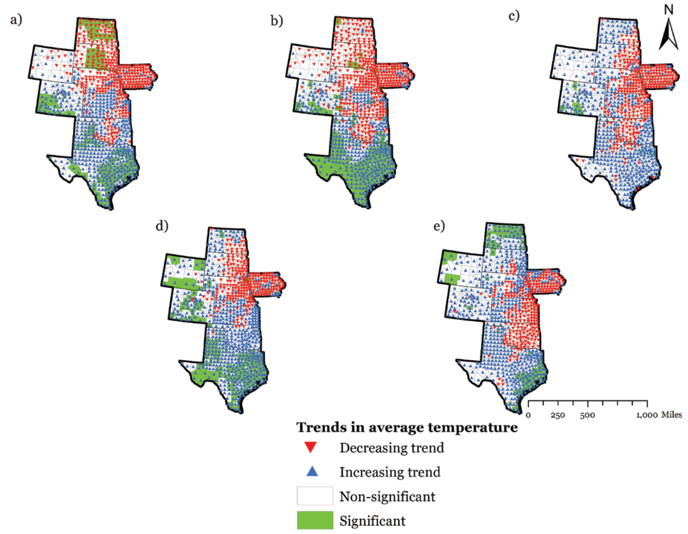

Figure 16. Temporal trends in average air temperature (T_{avg}) during a) May, b) June, c) July, d) August, and e) September across the Great Plains.

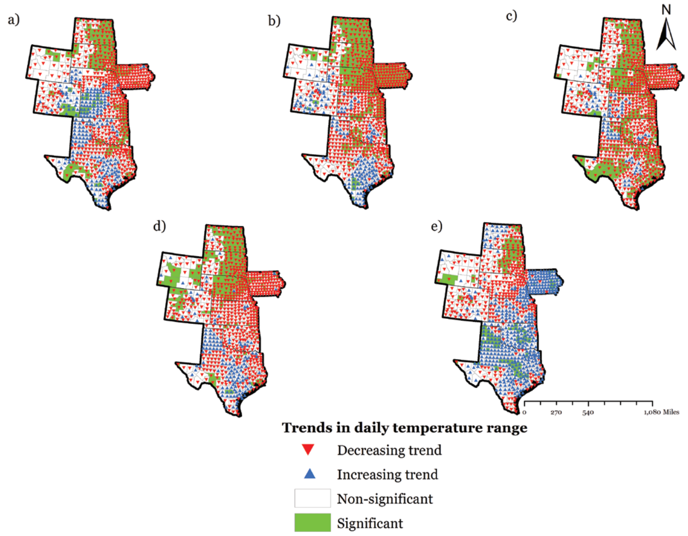

Figure 17. Temporal trends in daily temperature range (DTR) during a) May, b) June, c) July, d) August, and e) September across the Great Plains.

Months	*Regional*	*ND*	*SD*	*NE*	*KS*	*CO*	*WY*	*IA*	*OK*	*TX*
Monthly Means										
SD	33.3	34.2	34.2	33.8	33.6	33.3	33.4	33.8	33.3	33.3
Growing Season Statistics										
Mean	83.5	75.9	79.5	81.7	85.6	79.0	76.6	79.3	88.5	90.5
Max	86.7	81.1	84.0	86.5	89.8	82.6	80.8	84.9	93.0	95.9
Min	80.8	70.9	73.9	77.5	81.7	76.1	72.3	75.4	84.4	87.8
SD	33.3	34.0	34.2	33.8	33.8	33.4	33.8	33.8	34.0	33.6

Table 3. Region-wide and statewide average annual, growing season, and monthly T_{min}.

Months	*Regional*	*ND*	*SD*	*NE*	*KS*	*CO*	*WY*	*IA*	*OK*	*TX*
Monthly Means										
May	49.5	42.1	44.2	46.4	51.4	39.0	37.0	48.9	56.5	60.4
June	58.1	51.8	54.0	56.3	61.3	47.5	45.5	58.6	65.5	67.6
July	62.8	56.7	59.9	61.9	66.6	53.4	51.6	63.1	69.8	70.3
August	61.2	54.5	57.6	59.7	64.8	51.8	49.6	60.6	68.5	69.6
September	52.7	44.2	47.3	49.5	55.2	43.3	40.1	51.4	60.4	63.5
Annual Statistics										
Mean	40.5	29.7	33.6	36.5	42.1	31.5	29.5	37.6	47.8	52.3
Max	42.8	34.2	36.7	39.0	44.4	33.6	32.0	41.4	50.2	54.5
Min	38.3	26.1	30.7	34.2	39.9	29.5	26.8	35.1	45.7	49.8
SD	33.1	33.8	33.6	33.3	33.1	33.1	33.3	33.4	32.9	33.1
Growing Season Statistics										
Mean	56.8	49.8	52.7	54.9	59.9	47.1	44.8	56.5	64.2	66.2
Max	59.0	52.7	55.4	57.2	62.1	49.1	47.8	59.0	67.1	69.1
Min	55.0	47.1	49.8	52.3	57.6	44.8	42.4	53.6	61.3	63.5
SD	32.9	33.4	33.3	33.1	33.1	33.1	33.3	33.3	33.3	33.3

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Table 4. Region-wide and statewide average annual, growing season, and monthly T_{avg}.

Months	*Regional*	*ND*	*SD*	*NE*	*KS*	*CO*	*WY*	*IA*	*OK*	*TX*
Monthly Means										
May	62.4	54.9	57.0	59.4	63.9	54.3	51.3	60.4	68.4	72.7
June	71.2	64.0	66.7	69.6	73.9	63.9	60.8	70.0	77.2	79.5
July	76.1	69.8	73.4	75.2	79.3	69.6	68.4	74.1	82.0	82.2
August	74.7	68.2	71.6	73.2	77.5	67.6	66.6	71.8	81.1	81.9
September	66.4	57.7	61.7	63.7	68.5	59.5	56.5	63.5	72.9	75.6
Annual Statistics										
Mean	53.2	41.2	45.9	49.5	54.9	46.6	43.3	48.2	60.1	64.9
Max	56.1	45.7	49.5	52.7	57.9	49.3	46.8	51.8	62.6	67.3
Min	51.3	37.2	42.1	46.6	52.2	44.6	40.3	45.3	58.1	63.0
SD	33.1	34.0	33.8	33.4	33.3	33.1	33.3	33.4	32.9	33.1
Growing Season Statistics										
Mean	70.2	63.0	66.0	68.2	72.7	63.0	60.6	68.0	76.3	78.4
Max	72.3	66.9	69.4	70.9	75.7	65.8	63.9	71.6	79.9	82.0
Min	55.0	47.1	49.8	52.3	57.6	45.5	42.6	53.6	62.1	64.9
SD	37.4	37.4	37.8	37.6	37.4	38.7	38.5	36.9	37.0	36.9

Table 5. Region-wide and statewide average annual, growing season, and monthly DTR.

Months	*Regional*	*ND*	*SD*	*NE*	*KS*	*CO*	*WY*	*IA*	*OK*	*TX*
Monthly Means										
May	25.9	25.6	25.7	25.9	25.0	30.4	28.4	23.0	23.8	24.7
June	26.1	24.5	25.6	26.5	25.4	33.1	31.0	22.5	23.4	23.9
July	26.6	26.1	27.0	26.6	25.9	32.4	33.3	22.0	24.5	23.8
August	27.0	27.5	27.9	26.8	25.7	31.5	33.7	22.1	25.0	24.5
September	27.4	26.8	28.4	28.8	26.6	32.4	32.8	24.1	24.8	24.3
Annual Statistics										
Mean	25.7	23.2	24.5	25.9	25.4	30.2	28.1	21.2	24.5	25.2
Max	27.7	26.5	27.9	29.7	28.3	32.0	29.9	24.7	27.0	27.5
Min	24.1	21.1	22.1	23.0	22.7	28.4	26.1	18.2	22.7	22.9
SD	0.9	1.3	1.4	1.3	1.3	0.9	0.9	1.3	1.1	0.9
Growing Season Statistics										
Mean	26.6	26.1	27.0	27.0	25.7	31.9	31.9	22.7	24.3	24.3
Max	28.6	30.1	31.3	31.5	29.3	34.6	34.7	26.6	27.2	27.5
Min	25.0	22.9	23.8	23.4	23.2	29.9	29.2	19.1	20.9	21.2
SD	0.9	1.4	1.8	1.6	1.4	1.1	1.3	1.4	1.3	0.9

Potential Consequences and Significance of the Observed Air Temperature Trends

Observed trends, whether increasing or decreasing, have the potential to impact agricultural production positively or negatively. The changes/shifts in air temperatures can affect various processes as they relate to plant growth. For instance, air temperature governs the grain development period in cereals, so if T_{max} gets negatively affected (decreases) during this period, the result can be an extension of crop maturity and eventually, improved crop yields. Moreover, declines in T_{max} positively impact

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crop physiological development, biomass accumulation, and grain yield, especially during silking and grain-filling stages for corn and during pod formation and pod-filling stages for soybean. Additionally, decreases in T_{max} can reduce evaporative losses and may reduce crop water stress, reducing crop water requirements. Our analyses show that trends in T_{max} are negative for a majority of the region during the growing season, especially in July, which could potentially translate to greater yields or lower crop water requirements in these regions.

It should be noted that trends in T_{max} could also negatively affect crop production in certain instances. If T_{max} is high for prolonged periods, the number of kernels per ear in corn and number of beans per pod in soybeans could be reduced, resulting in reduced yields. If T_{max} near anthesis, i.e., flowering, is extremely high, even more severe impacts can be expected, as this would potentially affect the pollination process, thereby reducing the grain set for cereals (Smika and Shawcroft, 1980).

Several other processes, such as successful production and transfer of viable pollen grains to the stigma; germination of the pollen grains; growth of the pollen tubes below the style; and the fertilization and development of the zygote, are both crucial to maximize productivity and temperature sensitive (Ferris et al., 1998). Also, during higher T_{max} conditions, greater atmospheric evaporative demand results in plant water stress and increased crop water requirements. In such cases, plant stomata may not be able to maintain the high rate of plant water uptake demand and plants may close their stoma, causing reduction in the transpiration rate and dry matter accumulation, which results in yield reduction.

Increasing trends in T_{min}, which are evident in most of the counties during the growing season, may have significant implications in crop productivity. Higher T_{min} can accelerate plant respiration, which causes an increase in dry matter consumption (decrease in dry matter production) by the plants at night, potentially resulting in a reduction in crop yields. A response of crop yields to DTR changes is expected since many plant processes are non-linearly related to temperature, and the effects of increased temperature may be different during day and night. For example, increased DTR for a given T_{avg} may cause a reduction in yields, because the accompanying increase in T_{max} causes increased water stress or reduced photosynthesis rate (Dhakwa and Campbell, 1998).

In regions where freezing temperatures can result in crop injury or death, reductions in T_{min} associated with increased DTR can be harmful (Rosenzweig and Tubiello et al., 2002). Alternatively, increased DTR may benefit yields in cases where development or grain filling rates are more sensitive to T_{min} than T_{max} (Wilkens and Singh, 2001), with crops able to grow longer and produce more grain with lower nighttime temperatures. Increases in DTR can positively impact crops such as fruit and nuts, which benefit from increased chilling hour accumulation (Lobell et al., 2006). Increased DTR is usually associated with increased solar radiation (Bristow and Campbell, 1984) that can result in higher crop yields, primarily for well-fertilized and irrigated fields (Monteith, 1972; Fischer, 1985).

All of these potential impacts depend on the process that gets most affected, as it is extremely difficult to study the dynamics of interactions between the change in climate variables, and plant physiology and productivity, especially when these can vary on local scales. Skaggs and Irmak (2012), Irmak et al. (2012), EC715, *Climate Change Impact on Air Temperature, Daily Temperature Range, Growing Degree Days and Spring and Fall Frost Dates in Nebraska*, and EC716, *Long-Term (1892–2012) Change in Air Temperature, Relative Humidity and Vapor Pressure Deficit (Atmospheric Evaporative Demand) in Central Nebraska* are some of the other useful resources that can be explored for further information on this topic.

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