11-2012

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Skaggs, Kari E. and Irmak, Suat, "Long-Term Trends in Air Temperature Distribution and Extremes, Growing Degree-Days, and Spring and Fall Frosts for Climate Impact Assessments on Agricultural Practices in Nebraska" (2012). *Biological Systems Engineering: Papers and Publications*. 331.

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Long-Term Trends in Air Temperature Distribution and Extremes, Growing Degree-Days, and Spring and Fall Frosts for Climate Impact Assessments on Agricultural Practices in Nebraska

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(Manuscript received 19 July 2011, in final form 26 June 2012)

ABSTRACT

Air temperature influences agricultural practices and production outcomes, making detailed quantifications of temperature changes necessary for potential positive and negative effects on agricultural management practices to be exploited or mitigated. Temperature trends of long-term data for five agricultural locations, ranging from the subhumid eastern to the semiarid western parts of Nebraska, were studied to determine local temperature changes and their potential effects on agricultural practices. The study quantified trends in annual and monthly average maximum and minimum air temperature ($T_{\max}$ and $T_{\min}$), daily temperature range (DTR), total growing degree-days, extreme temperatures, growing-season dates and lengths, and temperature distributions for five heavily agricultural areas of Nebraska: Alliance, Central City, Culbertson, Fremont, and Hastings. July and August were the months with the greatest decreases in $T_{\max}$ for the central part of Nebraska—Culbertson, Hastings, and Central City. Alliance, Culbertson, and Fremont had year-round decreases in DTR. Central City and Hastings experienced growing-season decreases in DTR. Increases in growing-season length occurred at rates of 14.3, 16.7, and 11.9 days century⁻¹ for Alliance, Central City, and Fremont, respectively. At Hastings, moderately earlier last spring frost (LS) at a rate of 6.6 days century⁻¹ was offset by an earlier (2.7 days century⁻¹) first fall frost (FF), resulting in only a 3.8 days century⁻¹ longer growing season. There were only slight changes in LS and FF dates of around 2 days earlier and 1 day later per century, respectively, for Culbertson.

1. Introduction

The impacts of climate change on agriculture are dependent on the magnitude and type of climate change and the mitigation and adaptation practices undertaken by agricultural producers and managers (Parry 1989; Easterling et al. 1993; Southworth et al. 2000). By considering the observed trends, adjustments and adaptations will need to be made in order to exploit favorable agricultural conditions and to mitigate negative effects in maintaining optimal agricultural productivity (Easterling et al. 1993). In order for beneficial agricultural management strategies to be developed and sustained, trends in climate variables must be quantified in agriculturally relevant terms. Since agriculture is highly sensitive to weather and climate change, agricultural resource management practices and policy decisions

require detailed information of trends in temperature, precipitation, and other variables, such as carbon dioxide concentration and cloudiness, on relevant spatial and temporal scales.

Temperature is one of the most widely used predictors of crop development, yield potential, and crop water use due to the dependency and interrelation of crop production to temperature. However, quantifications of average temperatures and average temperature changes are not adequate in determining the effects of weather/climate and climate change on agriculture. Since the sensitivity of agriculture to air temperature varies with crop type and physiology during the growing season, important factors for agriculture are the timing of the temperatures changes, the changes in temperature distribution, and the duration of the changes. Moreover, a great deal of the vulnerability of agriculture and most other sectors to climate change lies in the changes of temperature extremes, which may have nonlinear associations with average temperature changes and have yet to be extensively studied (Mearns et al. 1984; Easterling

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et al. 2000; Wheeler et al. 2000). The least certain climate changes are those that most impact agricultural management practices, decision making, and risk assessment. These uncertainties include the annual timing of temperature change, changes in extreme temperatures, changes in the variance of temperature, and interactions with other weather–climate variables (Katz and Brown 1992). In a simulation study, Challinor et al. (2007) found that changes in extreme temperatures impacted groundnut yield more in the future, warmer climate scenario than in the current climate, and increases in the actual crop-growing season decreased the negative impact of the temperature extremes. The interdependencies of temperature with agriculture, irrigation management practices, and other land-use forcings complicate quantification of trends (Bonan 2001; Mahmood et al. 2006). In a study conducted with a climate dataset from 1895 to 1998, Hu and Buyanovsky (2003) found that within-season precipitation and temperature variations explained differences in central Missouri maize yield. Ferris et al. (1998) found declines in spring wheat yield when plants were exposed to extreme maximum temperatures during the anthesis stage. Hu et al. (2005) found that earlier winter wheat heading dates were associated with warmer spring minimum temperatures. Matsui et al. (2001) found that variety selection was crucial to minimizing the effects of extreme heat stress on japonica rice during flowering on grain yield. There have also been strong relationships developed between temperature and crop water use [evapotranspiration (ET)]. Many ET estimation equations use temperature as the primary driver of ET or in combination with radiation factors (Penman 1948; McCloud 1955; Turc 1961; Monteith 1965; McGuinness and Bordne 1972; Doorenbos and Pruitt 1977; Mather 1978).

Evidence strongly suggests that global average surface temperature increased by $0.74^{\circ} \pm 0.18^{\circ}\text{C}$ from 1906 to 2005, a large portion of which occurred at a rate of $0.13^{\circ} \pm 0.03^{\circ}\text{C decade}^{-1}$ during the latter half of the century (Solomon et al. 2007). Global surface temperature is expected to continue to increase by 0.4°C by 2025 (Solomon et al. 2007). Solomon et al. (2007) suggest, with the increase in average temperature, that cold days and nights and frosts have become less frequent, while hot days and nights and heat waves have become more frequent. Predicted regional and local temperature changes are less certain because of the greater impact of local land-use/land-cover changes on the land surface and coarse modeling resolutions, which makes the detailed quantification of observed trends essential. Gaffen and Ross (1999) found increases of over $0.4^{\circ}\text{C decade}^{-1}$ in the high plains nighttime, daytime,

and daily temperatures from 1961 to 1995 along with 1% decade $^{-1}$ increases in daily and nighttime relative humidity. Irmak et al. (2012) found increases of 3.8° and 1.9°C in daily minimum and average air temperatures, respectively, from 1893 to 2008 at Central City in central Nebraska. Widespread decreases in daily temperature range have also been observed (Karl et al. 1984; Easterling et al. 1997; Bonan 2001). Several studies have quantified the variation in the length of the frost-free season, also known as the climatological growing season. Kunkel et al. (2004) found an average of a 2-week increase in the frost-free season (0°C inclusive threshold) for the United States from 1895 to 2000 with a greater increase observed in the western part than in the eastern part of the country. Christidis et al. (2007) found an increase in growing-season length, defined by local temperature thresholds, by an average of around 1 day decade $^{-1}$ from 1950 to 1999 in the United States, mostly due to earlier spring onset. Similarly, Marino et al. (2011) found earlier last hard freezes (-2.2°C inclusive threshold) for the northern and western regions of their study encompassing the majority of the southeast and southern midwestern United States, which decreased the probability of early growth damaging frosts. Most studies on the trends in growing-season length have found increasing trends, in conjunction with earlier spring onsets, for various regions of North America during all or part of the twentieth century, including Skaggs and Baker (1985), Robeson (2002), and Easterling (2002).

In this study, we quantify long-term air temperature trends that have had, and are expected to have, the greatest impact on highly agricultural areas of Nebraska. To quantify trends in average temperature and changes in temperature variability and extremes, this study provides an in-depth analysis of long-term temperature data for five Nebraska locations that have substantially different climatic characteristics. The next section describes the Nebraska station locations, followed by the data and definitions of temperature change used in this study. In the fourth section, we provide the results and discussion of the temperature trends. Finally, temperature changes for each location are summarized, and potential agricultural impacts are discussed.

2. Study locations

Daily maximum and minimum air temperature data from five Nebraska sites are used in the study. The sites are all part of the National Weather Service Cooperative Observer Network (<http://www.nws.noaa.gov/om/coop/>) and were chosen on the basis of their long periods of record (greater than 115 yr) and their location in the

FIG. 1. Map of the five stations discussed in this study and their counties, including information on National Weather Service cooperative weather station identifier, latitude, longitude, elevation, and years of historical data studied.

state. The five sites, from east to west, are Fremont, Central City, Hastings, Culbertson, and Alliance (Fig. 1). Nebraska is located on the leeward side of the Rocky Mountains with no mountain ranges on the eastern, northern, or southern sides and has an elevation increase of approximately 2 m km^{-1} from the east to west. The location of Nebraska leads to the east–west gradients in temperature and precipitation. The weather in Nebraska is influenced by extremely cold and dry continental air masses passing through Canada and the Rocky Mountains during winter, and warm and humid turbulent air moving from the Gulf of Mexico during summer (Irmak 2010). The weather stations represent a wide range of climatic zones within Nebraska ranging from the study's most humid location in the eastern part of the state, Fremont; to subhumid locations in Central City and Hastings; and transitioning to semiarid at Culbertson and Alliance in western Nebraska. The elevation ranges from only 360 m above mean sea level in Fremont to as high as 1217 m in Alliance. All stations have been historically located in small towns or more rural settings; thus, the urban development impact on the weather station site and its potential impact on weather data are minimal. The annual average temperature ranges from approximately 11°C in southeast Nebraska to 7°C in the panhandle of northwestern Nebraska. Precipitation averages greater than 850 mm in the southeast corner to less than 400 mm in the western panhandle (1961–90 climatology). The rainy season is typically from late spring until early fall. The majority of spring precipitation is frontal, while precipitation occurring in summer is dominantly convective.

Cropland, particularly field maize and soybean for grain, dominates eastern and central Nebraska agricultural acreage, while prairie and pasture land dominate western Nebraska. Box Butte County, wherein Alliance is located, lies in the northwest panhandle of the state (Fig. 1). According to the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) 2007 Census of Agriculture (USDA/NASS 2007), of the over 270 000 ha of farmland in Box Butte County 41% was dedicated to pasture, 33% of the remaining farmland was under winter wheat, and 17% was under maize for grain. Dry edible beans, sugar beets, and hay and other forage crops also cover a significant amount of cropland in northwest Nebraska. Farmland was similarly distributed to cropland (55%) and pasture (43%) on the nearly 141 000 ha of farmland in Hitchcock County (Culbertson) in the southwestern part of the state (Fig. 1) in 2007. Near-equal parts of Hitchcock County cropland were under winter wheat, maize for grain, and other crops including hay, grain sorghum, and soybean. In 2007, 80%–90% of the over 100 000 ha of farmland in each of Adams (in which Hastings is located), Merrick (Central City), and Dodge (Fremont) Counties was cropland. From 50% to 60% of the cropland in these counties was under maize for grain while the majority of the remaining acreage was soybean. Hay and other forage crops, winter wheat, and popcorn are other significant crops in the central and eastern parts of the state. Historically, winter wheat acreage exceeded soybean acreage in much of the central part of the state prior to the expansion of irrigation development during the 1950s–60s. Total land area under irrigation in Nebraska has increased from about 1.7 million ha in 1970 to

over 3.5 million ha in 2007, more than in any other state, with maize for grain being the primary crop grown under irrigation. Currently, approximately 80% of the 3.5 million ha is under center pivot (sprinkler) irrigation, and 20% is under surface (primarily furrow) irrigation. There are approximately 65 000 center pivot irrigation systems and around 110 000 active irrigation wells in the state, and about 65% of the total of center pivot irrigation systems in the state is located in south-central Nebraska (Irmak 2010).

3. Data and analysis methods

Daily minimum and maximum temperature data were obtained from the High Plains Regional Climate Center (HPRCC 2011). Data were available for all locations beginning in the late 1800s. The HPRCC rigorously checks data quality and maintains a high standard for data-gap filling, so no further data quality maintenance/data quality analyses were performed. Data homogeneity is always a concern when quantifying long-term trends from a single station's data. To obtain the greatest amount of data homogeneity, we used station metadata, as a recommended method toward homogenization in Peterson et al. (1998), from the National Climatic Data Center (NCDC 2011) to only include the minimum and maximum temperatures that were recorded using self-registering minimum and maximum temperature instrumentation. Prior to utilization of this technology, recorded minimum and maximum temperatures were actually early morning and afternoon temperatures, read at the same times each day. Each location installed this self-registering technology on different dates. The initial year of study for each location is the first full year that the self-registering minimum and maximum temperature instrumentation was used. Each station had modifications in instrumentation as well as several moves during its period of record. Influences of these station modifications and moves are not differentiated in this study and are left as part of future investigation of the causes of temperature change, which may include land-use/land-cover change, widespread irrigation expansion, and circulation variations.

We used minimum and maximum temperature to calculate the daily average temperature [$T_{\text{avg}}: (T_{\text{max}} + T_{\text{min}})/2$], daily temperature range (DTR: $T_{\text{max}} - T_{\text{min}}$), and daily growing degree-days (GDDs). GDDs were calculated as the accumulation of T_{avg} exceeding 10°C (a commonly used base temperature for maize and soybean) as $\text{GDD} = (T_{\text{avg}}/2) - 10^\circ\text{C}$. Two annual dates were identified for analysis: last spring frost (LS) and first fall frost (FF). Annual LS date was defined as the latest day of the year before 15 July with $T_{\text{min}} \leq 0^\circ\text{C}$.

Similarly, annual FF date was the earliest date after 15 July with $T_{\text{min}} \leq 0^\circ\text{C}$. We also discuss the trends in the length of the climatological growing season—the period from LS to FF. Changes in the annual magnitude of the bottom and top five-percentile thresholds of T_{min} and T_{max} were quantified. Theoretically, the bottom and top five percentiles of T_{min} represent the extremely cold winter nighttime and extremely warm summer nighttime temperatures, respectively. Similarly, the bottom and top five percentiles of T_{max} represent the extremely cold winter and the extremely warm summer daytime temperatures, respectively. The linear regressions of these variables on annual or monthly time scales were quantified, and statistically significant trends were identified at the 5% significance level ($P < 0.05$).

While quantification of trends and magnitudes of air temperatures provides important information for a variety of purposes, quantifying in which temperature ranges these changes occur can provide crucial information for better assessment of agricultural productivity and better evaluation of potential crop response to the temperature changes. During the growing season, each crop has different levels of sensitivity to different temperature ranges. Extreme (very high and very low) temperatures can result in various degrees of yield quantity and quality impacts, depending on the crop's genetic characteristics and management practices. To quantify the change in the distribution of temperatures, trends in the relative frequencies of days with T_{avg} observed in a 2° or 3°C range during subperiods were quantified for each location by season. Depending on the length of each stations record, there were 10 or 11 subperiods of lengths between 9 and 11 yr. For the months of September–November (SON), December–February (DJF), and March–May (MAM), 3°C temperature ranges were used, while 2°C temperature ranges were used for June–August (JJA) due to less temperature variability during the summer season. For each season in each subperiod, the relative frequency for a given temperature range is the number of days that had T_{avg} in the given range divided by the total number of days in the subperiod as

$$n_{jk} = \frac{\text{count}(\text{day}_i \in \text{day}_{jk}: \text{lower}_k \leq T_{\text{avg}_i} < \text{upper}_k)}{\text{count}(\text{day}_{jk})},$$

where i is the day index; j is the subperiod index; k is the temperature range index; upper_k and lower_k are the upper and lower bounds of temperature range k , respectively; T_{avg_i} is the average temperature on day i ; and n_{jk} is the relative frequency for range k in subperiod j . Each location has different upper and lower T_{avg} bounds

TABLE 1. Linear trend slopes over the periods of record of monthly average $T_{\max}$, $T_{\min}$, and DTR ($^{\circ}\text{C century}^{-1}$); monthly total GDD ($^{\circ}\text{C month}^{-1} \text{ century}^{-1}$); annual average $T_{\max}$, $T_{\min}$, and DTR ($^{\circ}\text{C century}^{-1}$); and annual total GDD ($^{\circ}\text{C yr}^{-1} \text{ century}^{-1}$) for Alliance, Central City, Culbertson, Fremont, and Hastings. Statistically significant ($P < 0.05$) trends are set in boldface and italics.

Alliance													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$T_{\max}$	0.49	1.80	0.08	-0.89	0.20	0.04	0.56	-0.06	-0.48	-1.56	-1.68	0.13	-0.12
$T_{\min}$	1.40	2.16	0.82	0.19	1.11	0.47	0.98	0.65	0.68	0.17	0.47	0.77	0.81
DTR	-0.91	-0.36	-0.74	-1.08	-0.91	-0.43	-0.42	-0.71	-1.17	-1.73	-2.15	-0.64	-0.93
GDD	0.08	-0.05	1.51	-0.32	16.65	6.84	23.94	9.22	4.78	-8.02	3.02	-0.05	57.60
Central City													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$T_{\max}$	2.95	2.99	3.11	2.50	1.07	0.05	-3.10	-2.45	-0.33	-0.44	1.79	1.01	0.74
$T_{\min}$	2.98	2.34	2.15	1.80	2.46	1.54	1.22	1.16	1.10	0.70	1.94	1.10	1.70
DTR	-0.03	0.65	0.95	0.70	-1.39	-1.48	-4.32	-3.61	-1.44	-1.14	-0.15	-0.09	-0.96
GDD	-0.05	1.60	14.98	39.21	46.81	23.65	-29.11	-20.11	9.10	-6.70	14.58	0.05	94.01
Culbertson													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$T_{\max}$	-0.60	-0.54	-1.19	-1.90	-1.11	-0.97	-1.36	-1.31	-1.63	-1.78	-2.20	-0.57	-1.26
$T_{\min}$	0.25	0.07	-0.04	-0.97	0.05	-0.60	0.23	0.27	-0.23	-0.34	-0.08	0.16	-0.10
DTR	-0.85	-0.60	-1.15	-0.93	-1.16	-0.37	-1.59	-1.58	-1.40	-1.45	-2.12	-0.73	-1.16
GDD	0.04	0.02	-2.35	-13.86	-16.58	-23.10	-17.50	-15.97	-25.65	-20.84	1.59	0.12	-134.10
Fremont													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$T_{\max}$	0.23	2.08	0.72	0.88	0.81	0.77	-1.11	-1.05	-0.89	-1.10	-0.48	0.52	0.10
$T_{\min}$	0.28	2.52	1.16	1.07	1.58	1.57	1.61	1.13	0.34	0.15	0.92	1.01	1.10
DTR	-0.05	-0.44	-0.44	-0.18	-0.77	-0.81	-2.72	-2.19	-1.23	-1.25	-1.39	-0.49	-1.00
GDD	-0.05	0.74	5.40	17.21	32.87	35.07	7.84	1.23	-10.10	-15.72	6.21	0.43	81.13
Hastings													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$T_{\max}$	0.62	0.76	0.48	0.45	0.44	-0.09	-2.27	-2.28	-1.12	-1.23	-0.85	0.11	-0.42
$T_{\min}$	0.66	0.96	0.90	0.02	1.39	0.53	0.08	-0.28	-0.95	-0.31	-0.28	-0.21	0.21
DTR	-0.04	-0.20	-0.42	0.43	-0.95	-0.62	-2.34	-2.00	-0.17	-0.92	-0.57	0.32	-0.63
GDD	0.23	0.99	2.88	6.15	20.80	6.61	-33.96	-39.74	-31.42	-28.08	3.25	-0.18	-92.49

for the lowest and highest temperature ranges, respectively. The bounds were defined by the 2° or 3°C increment in temperature such that at least half of the subperiods had at least 1% of days with T_{avg} in this range. The nonparametric Mann-Kendall trend test (Mann 1945; Kendall 1955; Lettenmaier et al. 1994) was used to detect significant changes in the relative frequencies of temperature ranges across the subperiods (trends in n_{jk}) at the 5% significance level ($P < 0.05$).

4. Results and discussion

a. Annual average trends

The most dominant changes among annual average $T_{\max}$, $T_{\min}$, and DTR and annual total GDD over the entire periods of records were decreases in DTR (Table 1),

as has been observed in much of the United States and Canada (Bonan 2001; Karl et al. 1984). Statistically significant trends of -0.93° , -0.96° , -1.16° , and $-1.00^{\circ}\text{C century}^{-1}$ in DTR occurred for Alliance, Central City, Culbertson, and Fremont, respectively. Hastings also had a decrease in annual average DTR at a rate of $0.63^{\circ}\text{C century}^{-1}$. Decreases in DTR are often associated with increases in atmospheric moisture and cloudiness. This is supported by the increases in precipitation (0.87 mm yr^{-1}) and significant reductions in incoming shortwave radiation at a rate of $-0.0223 \text{ MJ m}^{-2} \text{ yr}^{-1}$ and net radiation at a rate of $-0.0032 \text{ MJ m}^{-2} \text{ yr}^{-1}$ from 1893 to 2008 at central Nebraska found by Irmak et al. (2012). For Alliance, Central City, and Fremont, these decreases in DTR echoed increases in $T_{\min}$, which occurred at rates of 0.81° , 1.70° , and $1.10^{\circ}\text{C century}^{-1}$, respectively. At Culbertson, the decrease in DTR was

FIG. 2. Time series and linear trend lines of (top to bottom) seasonal average $T_{\max}$ (circles), $T_{\min}$ (squares), DTR (diamonds), and seasonal total GDD (triangles) by (left to right) season for Alliance.

primarily due to a significant decrease in $T_{\max}$ at a rate of $1.26^{\circ}\text{C century}^{-1}$. There was also a significant decrease in annual total GDD at Culbertson at a rate of $134.10^{\circ}\text{C yr}^{-1} \text{ century}^{-1}$. There were strong trends in $T_{\min}$ at Culbertson on periods shorter than the entire record; annual average $T_{\min}$ significantly increased at a rate of $3.88^{\circ}\text{C century}^{-1}$ from 1920 to 1949 and $4.50^{\circ}\text{C century}^{-1}$ from 1970 to 2009, with a statistically significant decrease of $8.84^{\circ}\text{C century}^{-1}$ between those periods. No trends in annual averages were statistically significant for Hastings over the period of record. However, there was a slight decrease in $T_{\max}$, increase in $T_{\min}$, decrease in DTR, and increase in GDD, which are consistent with irrigation expansion, so we expect the seasonal trends at Hastings to have greater magnitudes.

b. Trends in $T_{\max}$, $T_{\min}$, DTR, and GDD by month

Table 1 provides the linear trend values of monthly average $T_{\max}$, $T_{\min}$, DTR, and monthly total GDD. Figures 2–6 provide time series plots of seasonal average $T_{\max}$, $T_{\min}$, DTR, and seasonal total GDD for observation of shorter-period fluctuations. All locations had decreases in $T_{\max}$ during the mid- to late growing season. July and August were months with the greatest decreases in $T_{\max}$ across central Nebraska. Culbertson, Hastings, and Central City had decreases in $T_{\max}$ during July and August at average rates of 1.33° , 2.28° , and $2.78^{\circ}\text{C century}^{-1}$. Irrigation expansion has been the

greatest for the central part of the state, which may have contributed to increased atmospheric moisture and cloudiness during these active irrigation months, resulting in a decrease in $T_{\max}$. Significant decreases in $T_{\max}$ were greater at Culbertson in the fall, with an average decrease of $1.87^{\circ}\text{C century}^{-1}$ for September–November. From July through November, there were slight decreases in $T_{\max}$ for Fremont at an average rate of $0.92^{\circ}\text{C century}^{-1}$. At Alliance, decreases in $T_{\max}$ occurred from August through November at an average rate of $0.95^{\circ}\text{C century}^{-1}$. Since the duration of grain development in cereals is primarily determined by temperature, decreases in $T_{\max}$ during this time can prolong the maturity of the crops, resulting in improved crop yields. Therefore, decreases in $T_{\max}$ can result in positive impacts on crop physiological development, dry matter accumulation, and grain yield, especially during silking and grain-fill growth stages for maize and during pod formation and pod-filling stages for soybean. Additionally, decreases in $T_{\max}$ can reduce evaporative losses and crop water stress, reducing the water requirements for crop production.

Statistically significant increases in $T_{\max}$ were observed during spring months at Central City with increases at an average rate of $2.80^{\circ}\text{C century}^{-1}$ during March and April. In general, there were slight increases in $T_{\max}$ from December through March for Alliance. Increases in $T_{\max}$ for extended periods can reduce the

FIG. 3. As in Fig. 2, but for Central City.

number of kernels per ear in maize and number of grains per pod in soybean, resulting in reduced yields. However, the impacts of high temperatures appear to be most severe around anthesis. High $T_{\max}$ during the period from the onset of the meiosis in the male generative

tissue to the completion of anthesis can affect the pollination process by reducing the grain set for cereals (Smika and Shawcroft 1980). Furthermore, seed set for maximum crop productivity requires successful production and transfer of viable pollen grains to the

FIG. 4. As in Fig. 2, but for Culbertson.

FIG. 5. As in Fig. 2, but for Fremont.

stigma, germination of the pollen grains and growth of the pollen tubes down the style, and fertilization and development of the zygote, all of which are sensitive to temperature extremes (Ferris et al. 1998). Also, during extreme $T_{\max}$ conditions, plant water stress may occur due to greater atmospheric evaporative demand [vapor

pressure difference between the atmosphere and evaporating surface (i.e., soil surface/plant canopy)]. Plant stomata may not be able to maintain the increased rate of plant water uptake demand. As a reaction to this stress, plants may close their stoma, which reduces the transpiration rate and dry matter accumulation.

FIG. 6. As in Fig. 2, but for Hastings.

Increases in $T_{\min}$, which usually occur during the night, may have significant implications in crop productivity. Nighttime increases in temperature can result in greater plant respiration, which is a physiological process opposite to transpiration. Transpiration is mainly driven by sunlight, air temperature, and soil/plant water availability during the daytime and results in dry matter production and accumulation by the plant. Since $T_{\min}$ is the main driver of respiration during nighttime, increases in $T_{\min}$ can accelerate respiration, increase dry matter consumption by the plants at night, and result in reduction in crop yields. The greatest changes in $T_{\min}$ occurred during the early to midgrowing season for all locations except for the southernmost location of Culbertson. There were only slight changes in $T_{\min}$ over the entire period of record at Culbertson, with average changes in either direction of less than $0.2^{\circ}\text{C century}^{-1}$.

At Hastings, $T_{\min}$ increases occurred from January through July, with a statistically significant increase of $1.39^{\circ}\text{C century}^{-1}$ during May, followed by slight decreases in $T_{\min}$ from August through December. At Central City, Fremont, and Alliance, there were increases in $T_{\min}$ during every month. At Central City, $T_{\min}$ had its greatest increases from late fall through midsummer with $T_{\min}$ increasing at maximum rates of 2.98° and $2.46^{\circ}\text{C century}^{-1}$ during January and May, respectively. Continuing northward, the greatest $T_{\min}$ increases occurred at Fremont between February and August, with a maximum increase of $2.52^{\circ}\text{C century}^{-1}$ in February and significant increases between 1.13° and $1.61^{\circ}\text{C century}^{-1}$ from April to August. At Alliance, significant increases in $T_{\min}$ occurred for the months of February (with the maximum increase of $2.16^{\circ}\text{C century}^{-1}$), May, and July.

The greatest changes in DTR occur during months when there are opposite-signed changes in $T_{\min}$ and $T_{\max}$. At Alliance, slight increases in $T_{\min}$ and slight decreases in $T_{\max}$ resulted in significant decreases in DTR during September–November at rates of 1.17° , 1.73° , and $2.15^{\circ}\text{C century}^{-1}$. At Culbertson, the greatest changes in DTR occurred in summer and fall. From July to November, the average DTR decrease at Culbertson was $1.63^{\circ}\text{C century}^{-1}$. These two locations and Fremont had year-round decreases in DTR. Fremont had the most months with significant decreases in DTR; they occurred from June to November with rates ranging from -0.81° to $-2.72^{\circ}\text{C century}^{-1}$. At Central City and Hastings, DTR decreases were greatest during the growing season. Significant decreases in DTR occurred from May to September for Central City and in July and August for Hastings. The maximum decreases in DTR for Central City were 4.32° and $3.61^{\circ}\text{C century}^{-1}$ during July and August and were 2.34° and $2.00^{\circ}\text{C century}^{-1}$ during the same months for Hastings.

FIG. 7. Time series and linear trends of last spring frost date (LS; green diamond) and first fall frost date (FF; brown triangle) for Alliance. Trends are reported as the change in days per century.

Although statistically significant changes in GDD can occur during any month, the greatest absolute changes occur during the months with greatest average GDD, which are during the summer. Alliance had no significant changes in GDD during the growing season (May–September) with the greatest absolute change of a GDD increase at a rate of $23.94^{\circ}\text{C century}^{-1}$ in July. Culbertson had no significant GDD changes during any month, but the majority of the decreasing trend in annual total occurred during the growing season at an average rate of $19.76^{\circ}\text{C century}^{-1}$. There were also decreases in monthly total GDD at Hastings during the latter part of the growing season and into early fall with a maximum decrease of $39.74^{\circ}\text{C century}^{-1}$ during August. At Central City, there were slight decreases in GDD in the range of $20^{\circ}\text{C century}^{-1}$ during July and August due to decreases in $T_{\max}$. However, in April and May there were significant increases in GDD of 39.21° and $46.81^{\circ}\text{C century}^{-1}$ at Central City. Similarly, in Fremont, there were slight decreases in GDD during September and October, but significant increases in GDD of 32.87° and $35.07^{\circ}\text{C century}^{-1}$ during May and June.

c. Climatological growing-season length trends

Figures 7–11 present the time series and trends of LS and FF dates for each location. The most salient results from the growing-season analyses are the longer climatological growing seasons and earlier last spring frost. Statistically significant changes in both of these were recorded for Alliance, Central City, and Fremont, the most northern locations. Increases in climatological growing season were 14.3 , 16.7 , and 11.9 days century^{-1} for Alliance, Central City, and Fremont, respectively. For Alliance, the increase in growing-season length had

FIG. 8. As in Fig. 7, but for Central City.

FIG. 10. As in Fig. 7, but for Fremont.

equal contributions from earlier LS and later FF. At Central City and Fremont, the majority of the lengthening of the growing season resulted from earlier LS dates at rates of 12.2 and 8.3 days century⁻¹, respectively. There were only slight changes in LS and FF dates of around 2 days earlier and 1 day later per century, respectively, for Culbertson. At Hastings, moderately earlier LS at a rate of 6.6 days century⁻¹ was offset by an earlier (2.7 days century⁻¹) FF, resulting in only a 3.8 days century⁻¹ longer growing season.

d. Extreme temperature trends

Table 2 summarizes the trends in extreme temperatures at all locations. The northern locations experienced the greatest increases in the magnitude of the bottom and top fifth-percentile $T_{\min}$ threshold values, which represent the extremely cold winter nighttime and extremely warm summer nighttime temperature thresholds. Extremely cold winter nighttime temperatures increased significantly by 2.36°, 2.58°, and 1.78°C century⁻¹ for Alliance, Central City, and Fremont,

respectively. Extremely warm summer nighttime temperatures had statistically significant increases for Alliance and Fremont at 0.74° and 0.91°C century⁻¹, respectively, and increased by 0.78°C century⁻¹ for Central City. Extremely cold winter nighttime temperatures also increased for Culbertson and Hastings; yet extremely warm summer nighttime temperatures decreased by 0.3°C century⁻¹ for both locations. The decrease in extremely warm summer nighttime temperatures for Culbertson and Hastings could be due to an increase in atmospheric humidity (Irmak et al. 2012), which could also have dampened a potentially significant increase at Central City—another central Nebraska location. The southern and eastern locations (all except Alliance) had significant decreases in extremely warm summer daytime temperatures (top fifth-percentile $T_{\max}$ threshold) with the two central locations, Hastings and Central City, having the greatest decreases of 2.34° and 2.67°C century⁻¹. There were no statistically significant changes in the bottom fifth-percentile $T_{\max}$ threshold temperature—extremely cold winter daytime temperatures.

FIG. 9. As in Fig. 7, but for Culbertson.

FIG. 11. As in Fig. 7, but for Hastings.

TABLE 2. Trends in magnitudes of the bottom and top percentiles of $T_{\min}$ and $T_{\max}$ for Alliance, Central City, Culbertson, Fremont, and Hastings. Statistically significant ($P < 0.05$) trends are set in boldface and italics.

Location	Top 5% $T_{\max}$ (°C century ⁻¹)	Top 5% $T_{\min}$ (°C century ⁻¹)	Bottom 5% $T_{\max}$ (°C century ⁻¹)	Bottom 5% $T_{\min}$ (°C century ⁻¹)
Alliance	0.35	<i>0.74</i>	0.12	<i>2.36</i>
Central City	<i>-2.67</i>	0.78	1.94	<i>2.58</i>
Culbertson	<i>-1.13</i>	-0.33	-1.32	1.05
Fremont	<i>-1.78</i>	<i>0.91</i>	0.66	<i>1.78</i>
Hastings	<i>-2.34</i>	-0.30	0.18	0.56

e. Changes in temperature distribution by season

Figure 12 summarizes the trends in temperature ranges by season for each location and trends for each season are presented separately.

1) MARCH–MAY

A general shift from cool temperatures to warmer temperatures ($>15^{\circ}\text{C}$) occurred for Central City and Fremont, with significant changes in the more extreme temperatures for Fremont and significant changes in the midrange temperatures for Central City. At Culbertson, temperatures greater than 3°C , especially in the 15° – 18°C range, became less frequent, and colder temperatures, particularly in the 0° – 3°C range, became more frequent. The changes in temperature distribution were more mixed at Alliance and Hastings. Both locations had increases in the frequency of the 12° – 24°C range similar to Fremont and Central City. However, the frequency of temperatures in the range from -6° to -3°C also increased at Alliance.

2) JUNE–AUGUST

There were distinct shifts in temperatures for all locations during JJA, with a highly latitudinal signature to the changes. The northernmost location, Alliance, had a shift in the frequency of temperatures greater than 24°C to temperatures between 12° and 22°C . Continuing southward, Fremont had significant decreases in the frequency of temperatures less than 18°C with a general increase in warmer temperatures, though not in the extreme for this season. Central City had a similar change in distribution as Fremont. However, the increase in the frequency of temperatures in the 20° – 28°C range at Central City had less of a contribution from the decrease in temperatures less than 18°C , as Fremont experienced, but also had decreases in the frequencies of temperatures greater than 28°C . Increases at Hastings were in the frequencies of temperatures from 16° to 24°C , with decreases in temperatures outside of this range. The moderating trend of summer temperatures may be an indication of the impact of land cover/land use and

FIG. 12. Directional trends in the relative frequency of daily T_{avg} occurring in 2° or 3°C ranges. Negative trends are shaded green; positive trends are shaded blue. Trends that are significant at the 95% confidence level are indicated by the darker color shadings.

extensive irrigation practices on surface temperatures, as well as changes in atmospheric circulation patterns, altering moisture advection to this region. The land-use/land-cover changes impact atmospheric water vapor content through modification of surface properties and evaporation-altering surface energy balance dynamics, including air temperature (Pielke et al. 2002). The heaviest center pivot (sprinkler) irrigation is practiced during JJA in the area. In water-limited areas, increased irrigation application leads to increased evapotranspiration flux over the region. Increased latent heat flux would result in decreases in daytime surface temperatures during the summer irrigation season (June–August) supporting the moderation of temperatures that were observed in central Nebraska during June–August. Further investigation of other climate variables is necessary to isolate causes, including land-use/land-cover and circulation pattern changes, of these temperature changes. The southernmost location had the most pronounced shift to colder temperatures during this season. Temperatures less than 24°C increased in frequency at Culbertson, while greater temperatures decreased in frequency.

3) SEPTEMBER–NOVEMBER

The steadiest change in temperature distribution for this season occurred for Central City where there were widespread decreases in the frequencies of temperatures less than 9°C and increases for greater temperatures, particularly in the 12°–15°C range. At Alliance and Culbertson, there were significant increases in the frequencies of cold temperatures, in the extreme for Culbertson, and decreases in mild to warm temperature frequencies. Hastings experienced decreases in the frequency of extremely warm temperatures, which shifted to milder temperatures. Fremont also experienced a decrease in the frequencies of this season's extremely warm temperatures, but there was no significant shift toward any temperature range.

4) DECEMBER–FEBRUARY

All locations experienced increases in the warmest temperatures for this season. Alliance and Central City experienced shifts from cold and extremely cold temperatures to above 0°C temperatures. The shifts from warm temperatures at Fremont, Hastings, and Culbertson were less pronounced, but there were also decreases in the extremely cold temperature frequencies at these locations.

5. Summary and conclusions

Long-term trends in several temperature variables were quantified for five highly agricultural areas of

Nebraska: Alliance, Central City, Culbertson, Fremont, and Hastings. The study locations have substantial differences in climate characteristics, ranging from humid in Fremont to semiarid in Culbertson and arid in Alliance. In addition, the land use and agricultural management and irrigation practices vary throughout the state. For many of the quantifications of temperature, there were high spatial correlations to the trends. July and August were the months with the greatest decreases in $T_{\max}$ for the central part of Nebraska. Culbertson, Hastings, and Central City had decreases in $T_{\max}$ during July and August (months in which extensive irrigation is practiced) at average rates of 1.33°, 2.28°, and 2.78°C century⁻¹. For all locations except the southernmost, Culbertson, the greatest $T_{\min}$ increases occurred during the early to midgrowing season. Alliance, Culbertson, and Fremont had year-round decreases in DTR, while Central City and Hastings experienced decreases in DTR primarily during the growing season. The most northern locations studied, Alliance, Fremont, and Central City, had the greatest increases in growing-season length with earlier last spring frosts dates. These locations also had the greatest increases in extremely cold winter and extremely warm summer nighttime temperatures. All locations, except the northernmost and westernmost location, Alliance, had decreases in extremely warm summer daytime temperatures, with a maximum decrease of 2.67°C century⁻¹ experienced at Hastings. There were pronounced shifts in temperature distribution for each location during the summer and winter seasons.

Decreases in daily temperature range across the agricultural areas of Nebraska may be due to an increase in atmospheric moisture and decrease in incoming shortwave radiation. In particular, decreases in daily temperature range during the mid- to late growing season could be due to significant irrigation expansion in central Nebraska. Of importance to changes in agricultural management practices are the trends in the length of the growing season and the seasonal accumulation of GDDs. The northern locations had the greatest increase in growing-season length with earlier last spring frosts dates. In conjunction with early growing-season increases in accumulated GDDs, as have been observed at Fremont, Central City, and Hastings, locations should be, and have been, taking advantage of earlier planting and use of longer-season, higher-yielding hybrids/varieties, with current seasonal forecasts and water availability considered as determining factors. Conditions should continue to be monitored at the more southern sites, Culbertson and Hastings, as trends in growing-season length and

GDDs have changed from earlier to more recent decades.

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