Developing adaptation strategies using an agroecosystem indicator: Variability in crop failure temperatures

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ABSTRACT

Crop failure temperatures (CFTs) are critical temperature thresholds for plants beyond which plant tissue has a high potential of being damaged. Climatic changes resulting in fewer or more CFTs have important implications for agriculture. Examining CFT trends can provide information that will assist plant breeders and agricultural producers to develop new adaptation strategies for crop and livestock selection, and thereby safeguard the general food supply. Six CFTs temperatures [maximum temperatures ($T_{\max}$) $\geq 30^{\circ}\text{C}$, 32°C , 34°C , 35°C , 39°C and 40°C] were considered in this study. The variability frequency and intensity of CFTs were analyzed over both short-term (four time-periods; initiation of recordkeeping up to 1920, 1921–1950, 1951–1980, and 1981–2009) and long-term (100- year) time-periods, using data from 23 weather stations spread across Kansas, USA. Results indicated that ~75% of long-term trend values across all CFTs and locations decreased, one remained the same (less than 1%), and ~25% had positive trend values. About 91% of long-term trend values fell between 1 and -1 day/decade. Overall, the range in the number CFT days was greatest at 30°C and steadily decreased as CFT increased, with a 10-fold decrease in the range of the number of CFT days at 40°C CFT. However, 53% of all 30-year trend lines with absolute slope values of >6 days/decade occurred during the 1981-2009 time-period. The greatest changes in slope were also recorded during this time-period, with 9 slopes greater than 10 days/decade. Thus, the greatest changes in number of CFT days, along with the greatest number of sites experiencing decreases in CFT days occurred during the most recent time-period. Eastern Kansas had the most and largest decreases in CFT days across all CFTs.

1. Introduction

Temperature is one of the key variables affecting plant growth, development, function and photosynthesis (an important process in the plant world) – sustaining life on Earth (Centritto & Loreto, 2005). Drought and heat stress are likely to be increasingly important in determining plant productivity in many regions (Challinor et al., 2010), and recent studies have identified them as among the environmental stresses that constitute major threats to global food security in the 21st century (Wang & Frei, 2011). Plant heat stress is often defined as the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development (Wahid et al., 2007).

Temperature is a key weather component that influences the growth and yield of crops (Wheeler et al., 2000), and agronomic research indicates that higher temperatures associated with climatic change will be harmful to crop production (Adger, 2001). Duration of grain filling in cereals, for example, is determined principally by temperature (Ferris et al., 1998). The effects of short periods of exposure to high temperatures (31°C) at anthesis on wheat grain yields are thought to be equivalent to a 2 to 3°C warming in the seasonal mean temperature (Ferris, et al., 1998). Studies have found maize and soybean yields to be influenced by maximum daily temperature during certain phenological stages (Hatfield, J. L. et al., 2011). An increase in extreme temperatures events clearly will affect both crop yield and quality (Wang & Frei, 2011).

Crop failure temperatures (CFTs) are temperatures which lead to crop failure (Backlund et al., 2008). Crop failure is defined as the complete loss of crops on a farm (Mendelsohn, 2007). CFTs can be used as a powerful tool to communicate technical data from field experiments/studies in relatively simple terms. As an ecosystem indicator, CFTs portray the interrelationships between climate and plant growth. Changes in CFT can reveal evidence of the

62 already discernible impacts of climate change and can provide important insights on the factors,
63 processes and structures that promote or constrain adaptive capacity also valuable for monitoring
64 trends (Mendelsohn, 2007). CFT can be useful indicator in vulnerability studies to represent the
65 degree of climate stress arising from extreme events affecting agriculture production (Anandhi,
66 Steiner, et al., 2016). Hence, documenting the variation in frequency and duration of CFT is
67 crucial at both local and regional scales. This provides critical information for the development
68 of temperature adaptation strategies for agricultural production to such adverse environmental
69 conditions.

70 Kansas has the second-most cropland acreage in the United States and is often referred to
71 as part of the nation's bread basket (Tubiello et al., 2002). Studies have examined variations in
72 the extreme temperatures for larger regions encompassing Kansas (Alexander et al., 2006; Fodor
73 et al., 2010; Peterson et al., 2008; Tebaldi et al., 2006; Zhang et al., 2009). Studies in Kansas
74 have analyzed temperature extremes using percentile-based thresholds (Anandhi, Hutchinson, et
75 al., 2016), low temperature thresholds (Anandhi, Perumal, et al., 2013) and diurnal temperatures
76 using growing degree days (Anandhi, 2016). No studies have compared the long-term trends and
77 variability in CFTs for different time-periods within Kansas. Detailed analyses of changes in
78 CFTs will help researchers and producers develop efficient crop management practices and lead
79 to adaptive management decisions by local and regional agricultural producers. The objective of
80 this study was to quantify spatial (geographical) and temporal variations in occurrence of various
81 CFTs during four different time-periods (before 1919, 1920–1949, 1950–1979, and 1980–2009)
82 using data from 23 Centennial weather station sites across Kansas. In addition, this study
83 attempts to utilize CFT to develop quantitative adaptation strategies in a variable and changing
84 climate.

2. Data used

Daily maximum air temperature ($T_{\max}$) data from 23 weather stations across Kansas were downloaded from High Plains Regional Climate Center (HPRCC). The location and station history details are provided in **Figure 1a** and Table 1, respectively. The records extended to the late 1800s for a few stations, but many began recording observations in the early 1900s; consequently, the start dates of the records were different, but the end dates were the same (2009). The criteria to select stations were stations with consistent observation times, low potential for heat-island bias, and other quality assessments (Easterling, D. R. et al., 1999; Robeson, 2002). More information about these stations can be obtained from (Anandhi, et al., 2013).

3. Methodology

The various terms CFT, cardinal temperatures, optimum temperatures, maximum temperatures, base temperatures are used in meteorology and agriculture literature (Backlund, et al., 2008; Glickman & Zenk, 2000). Plant growth ceases when the temperature drops below a certain minimum value (also referred as base temperature) or exceeds a certain maximum value (also referred as CFT). Between these limits, there is an optimum temperature at which growth proceeds with greatest rapidity. These three points are known as cardinal temperatures.

The steps used in the study are provided in **Figure 1b** and explained below.

Monthly analyses:

Step 1: The six CFTs used for analysis in this study were selected after perusal of already determined CFTs for crops commonly grown in Kansas (Table 2, adapted from Hatfield,

J. et al. (2008) and Herrero and Johnson (1980)). CFTs for additional crops can be obtained from Table 2.3 in Hatfield, J., et al. (2008).

Step 2: The daily $T_{\max}$ records were obtained from historical weather station records (see “Data Used” section for more details). The mean monthly $T_{\max}$ was estimated for each station and plotted in both boxplots and empirical **probability density function (PDF)** plots (Figure 2). The **cumulative distribution function (CDF)**, $F(x)$ was calculated using **equation 1**.

$$F(x) = \begin{cases} 0 & -\infty < x < x_i \\ \frac{i}{n} & x_i \leq x < x_{(n)} \\ 1 & x_n \leq x < \infty \end{cases} \quad (1)$$

where x is the value of the predicted CFT or $T_{\max}$ for each of four time-periods. Short term sample size was 30 years ($n=30$); for the long term sample size, size varied ($n=100$ to 120 years) depending on how long weather data had been recorded at an individual site. **~30 year trends are referred to as short term-trends in this study. There are four short term periods used in this study namely: before 1920, 1921-1950, 1951-1980, and 1981-2009).**

The boxplots in this manuscript provide a visual representation of the variability in the predicted CFT or $T_{\max}$ values.

Step 3: For each weather station and year, the number of days in a month with $T_{\max} \geq$ a CFT was counted. The counting was repeated for each of the six CFTs. Counting was carried out using Matlab programs developed for this purpose (Matlab, 2010). In this study, the counts are referred to as frequency of CFTs and are defined as the number of days in a time-period with $T_{\max} \geq$ CFT. Thus for a station with a 100 years of daily $T_{\max}$ data, a

time-series of 1200 (100×12) monthly frequency values was generated for each of 6 CFTs.

Step 4: Similar frequency estimations were carried out using the Matlab program for all the 23 centennial stations.

Step 5: For each of the 23 weather stations, for each year and month, the temperatures on the days when temperatures exceeded the selected CFT were averaged in a time-series as described above. For this study, this averaged value is referred to as the intensity of CFTs. For example if the frequency of 34°C CFTs for year 2009 and month July is 25, then the $T_{\max}$ from those 25 days were averaged to obtain the intensity of 34°C CFT. Unlike the frequency times-series, the intensity time-series are temperature values. Intensity of CFT was also estimated using Matlab programs developed for this purpose.

Annual analyses:

Step 6: Annual time-series of frequency and intensity of CFTs were estimated for each of the 23 stations. For each station and year, the monthly frequencies were summed up to obtain the annual frequency, while the monthly intensity values were averaged to obtain the annual intensity. Thus for a station with a 100 year daily $T_{\max}$ we would have a time-series of 100 annual frequency and intensity values for each CFT and a total of six time-series of 100 annual frequency values for all the CFTs.

Step 7: The long-term trends were estimated for the entire time-period examined and short-term trends were calculated for each of 4 four time-periods (initiation of recordkeeping up to 1920, 1921–1950, 1951–1980, and 1981–2009). Averages were estimated on annual and four seasonal scales for $T_{\max}$. Seasonal data was at: Winter [December January, February (DJF)], Spring [March April May (MAM)], Summer [June, July, August (JJA)], and

Autumn [September, October, November (SON)]. Analysis for CFTs were only for three seasons namely: Spring, Summer and Autumn. No CFTs were observed in winter season.

The long- and short-term averages were presented as boxplots showing means and variation (Figures 2-4). Numbers of days for long-term trend values were rounded to the nearest 5 for ease of interpretation. Linear regression lines are fitted to each of these time series to estimate trends. The slope of the fitted line (b) or the linear trend value is in equation 2.

$$b = \frac{\sum (t - \bar{t}) T_t}{\sum (t - \bar{t})^2} \quad (2)$$

Where, T_t are the predictands. In this study the predictands are $T_{\max}$ and the CFTs. Evenly spaced time index $\{t (t=1,2,3,\dots,n)\}$ is month to month, year to year, etc..

Step 8: A variant of the t-test was used to calculate the significance of each trend and accounted for the serial auto-correlation in the time series. In this study each time series has one value for each year. So the denominator in equation 2 is estimated using equation 3. In equation 3, n represent the number of data points (e.g. $n=30$; for the 30 year time-period, say 1920-1949).

$$\sum (t - \bar{t})^2 = n(n^2 - 1)/12 \quad (3)$$

For large samples ($n \geq 30$), the calculated t ratio (t') followed the t-distribution (Brown & Kipfmüller, 2011) and was compared a t-table with critical t values (t_{crit}) at a significance level with $(n-2)$ degrees of freedom.

To test if the trend in T_t is significantly different from zero, the ratio between the estimated trend and its standard error [S_b] is calculated (equation 4):

$$t' = \frac{b}{S_b} \quad (4)$$

In equation 4, S_b is calculated using equations 5-6 representing the variance of the residuals, with equivalent sample size (n_e) to account for lag 1 serial autocorrelation (r_1) in the time series

$$S_b = \frac{1}{n_e - 2} \sum (T_t - \hat{T}_t)^2 \quad (5)$$

$$n_e \approx n \frac{1 - r_1}{1 + r_1} \quad (6)$$

The detailed information can be obtained from (Anandhi, et al., 2013), Anandhi, Zion, et al. (2013), Wigley et al. (2006), and Santer et al. (2000). In this paper, a trend is considered to be statistically significant if it is significant at the 5% level.

Step 9: The proportion of increasing, neutral, and decreasing trend lines, both short and long-term, were determined for each weather station for three seasons (spring, summer, and autumn), six temperatures (CFT 30°C, 32°C, 34°C, 35°C, 39°C, 40°C), and by both longitudinal (east, central, west) and latitudinal (north, central, south) sections of the state. Only three seasons for CFTs because no CFTs were observed in winter season. The proposition is calculated by counting the number of trends in each of the stations with increasing (>0), neutral ($=0$), and decreasing (<0) in each of the short time-periods divided by the total number in the longer time-periods. For example, the absolute trend values of more than 6 days/decade divided ($= 9$ numbers during the 1981-2009 time-

period) divided by the total number in longer time-periods (=17 during the 1921-2009 time-period) resulting in 53% (calculations are shown in Table S1 in supplementary material). Weather reporting stations were assigned to longitudinal divisions as follows: East (Winfield, Horton, Atchison, Manhattan, Ottawa, Independence, Fort Scott, Sedan, and Columbus); Central (Phillipsburg, Hays, Minneapolis, Larned, McPerson, and Medicine Lodge); and West (Saint Francis, Colby, Tribune, Wekeeeney, Lakin, Elkhart, Ashland, and Oberlin). Latitudinal divisions were as follows: North (Saint Francis, Colby, Oberlin, Phillipsburg, Horton, Atchison, and Manhattan); Central (Tribune, Wakeeney, Hays, Minneapolis, Larned, McPherson, and Ottawa); and South (Lakin, Elkhart, Ashland, Medicine Lodge, Winfield, Independence, Fort Scott, Sedan, and Columbus. Strong trends (<-1 , >1) were identified.

4. Results

4.1. Maximum air temperature ($T_{\max}$ °C)

Monthly mean climatology and distribution of daily $T_{\max}$ for the 23 selected stations in Kansas was plotted in Figure 2 for the four time-periods. July and August had the highest mean daily $T_{\max}$, and January had the lowest. The western Kansas stations recorded higher $T_{\max}$ than those in eastern Kansas. Variation in $T_{\max}$ among the stations for all four time-periods was higher during winter than in summer (Figure 2). No significant differences were observed among PDFs for the four time series.

4.2. Changes in frequency and intensity of CFT

The monthly frequency of $T_{\max} \geq$ CFTs (30°C, 32°C, 34°C, 35°C, 39°C, and 40°C) were plotted in Figure 3. Generally across all the locations in Kansas, $T_{\max} \geq 30^\circ\text{C}$ and 32°C occurred

April through October. Higher CFTs occurred in fewer months: $T_{\max} \geq 34^{\circ}\text{C}$ and 35°C occurred May through September, and $T_{\max} \geq 39^{\circ}\text{C}$ and 40°C occurred June through September. For all six CFTs, the frequency of days with above-threshold temperatures increased in 1920–1949 time-period (red), remained stable or dropped in 1950–1989 time-period (blue), and then dropped again during the latest time-period, 1980–2009 (gray). The monthly frequency of $T_{\max} \geq 39^{\circ}\text{C}$ and 40°C was highest in 1920–49 compared with other time-periods.

The monthly changes in intensity of $T_{\max} \geq$ CFT were also plotted in Figure 3. The general trend showed higher intensity of $\text{CFT} \geq (34^{\circ}\text{C}, 35^{\circ}\text{C}, 39^{\circ}\text{C}, \text{ and } 40^{\circ}\text{C})$ in May through September and of $\text{CFT} \geq 30^{\circ}\text{C}$ and 32°C in April through October. The time-period 1920–1949 (red) had highest intensity of $T_{\max}$ greater than the threshold temperatures, except in May for $\text{CFT} \geq 30^{\circ}\text{C}$ and in June, when $\text{CFT} \geq 39^{\circ}\text{C}$ and 40°C .

4.3. Overall trends in frequency of CFT

The overall trends in the annual and seasonal frequency of CFT were observed from boxplots (Figure 4). Annual variation in CFT increased with later time-periods. Variation in number of CFT days was greatest during the 1980–2009 time-period for $\text{CFT} \geq 30^{\circ}\text{C}$, 32°C , 34°C , and 35°C , and during 1940–1979 for $\text{CFT} \geq 39^{\circ}\text{C}$ and 40°C . At all CFTs, the median number of CFT days was greatest and the variation was least during the 1920–1949 time-period. Variation across all sampled time-periods was lowest at the higher CFT (39°C and 40°C). Although median values remained similar during 1950–2009, variation increased greatly in 1980–2009 for $\text{CFT} \geq 30^{\circ}\text{C}$, 32°C , 34°C , and 35°C , with the greatest variation in the lower end of the range.

From the seasonal trends, we observed that the greatest median number of CFT days did not consistently occur within any season. Seasonal variation in the range of the number of CFT

days was greatest overall during the 1980–2009 time-period. CFTs were most tightly grouped around the median during the spring (MAM), and this was most pronounced at 39°C and 40°C CFT.

For $\text{CFT} \geq 30^\circ\text{C}$, 32°C , 34°C and 35°C , the highest median number of CFT days was greatest during summer (JJA) except in 1980–2009, when spring had a higher median number of CFT days. There was virtually no change in the median of the number of CFT days during spring for the entire time-period sampled for 39°C and 40°C .

For $\text{CFT} \geq 30^\circ\text{C}$ and 32°C , the median number of CFT days trended downward during the summer over the entire time-period sampled, with the highest median values during the 1920–1949 time-period (Figure 4, rows 1-2). Variation in the number of CFT days was greatest in the summer during the most recent (1980–2009) sampling period, and the extent of the variation was greatest in the lower part of the range. The median of the number of CFT days was lowest in 1950–1979 for both spring and fall (SON).

For $\text{CFT} \geq 34^\circ\text{C}$ and 35°C (Figure 4, rows 3-4), the median number of CFT days fell slightly in the spring during the 1950–1979 time-period and were greatest during the most recent time-period (1980–2009). Variation in the number of CFT days was least during the spring across all time-periods, and greatest in the summer in 1980–2009. The medians of the number of CFT days in summer and fall were greatest during the 1920–1949 time-period. There was little change in the median value of the number of CFT days in summer and fall in 1950–2009.

For $\text{CFT} \geq 39^\circ\text{C}$ and 40°C , there was virtually no change in the median of the number of CFT days during spring for the entire time-period sampled (Figure 4, rows 5-6). The median fell at the lower end of the range of variation during the most recent time-period (1980–2009). The median of the number of CFT days in the fall were equal to or greater than the median number of

CFT days in spring and summer for each time-period. The median of the number of CFT days remained similar for spring across all time-periods and during 1950–2009 for summer. The median number of CFT days was greatest for summer and fall during the 1920–1949 time-period. The median number of CFT days increased in the fall in 1980-2009.

4.4. Trends in frequency of CFTs in individual stations

Annual trends in the frequency for all 23 stations can be observed for individual station time-series plots (Figures 5, 6; [Figures, S-1, S-2 and S3 in supplementary material](#)). The figures showed that 75% of long-term trend values across all temperatures and locations decreased, one remained the same (less than 1% variation), and 25% had positive trend values. Ninety-one percent of long-term trend values fell between 1 and -1 CFT days. The greatest long-term trend change was -2.16 in Independence at 32°C CFT.

Short-term trends showed that both the greatest changes in the number of CFT days, along with the greatest number of sites experiencing decreases in CFT days, occurred during the most recent period sampled (1981–2009). Eastern Kansas had the most and largest decreases in CFT days across all temperatures. These decreases were most pronounced in southeast Kansas. Western and south-central Kansas consistently exhibited the least variation in the range of the number of CFT days at all temperatures.

4.5 Seasonal trends in Crop Failure Temperatures

4.5.1 Long term trends.

Long-term trends for the period 1909-2009 were mixed. Spring CFT trends in Central Kansas increased for mid-range CFTs. Summer CFT trends in Eastern and Southern Kansas declined, especially at higher temperatures, while CFT trends for central Kansas increased at

lower temperatures. Autumn trends generally showed declining CFTs across the state at the lower CFT temperatures.

4.5.2 Short term trends.

Latitudinal trends for the most recent time-period.

Spring CFT trends increased at the lower temperatures. Summer CFT trends generally decreased or remained neutral, except for slightly higher CFT trends in northern Kansas. Autumn CFT trends decreased at lower temperatures, but showed some increase at higher temperatures.

Longitudinal trends for the most recent time-period.

Spring CFT trends increased (100%) in Central and Western Kansas at lower temperatures, with Western Kansas also showing a strong increasing trend at a higher temperature. Summer CFT trends decreased (100%) at higher temperatures in Eastern and Central Kansas. By contrast, Autumn CFT trends decreased at lower temperatures for Eastern and Central Kansas, and increased at higher temperatures for Eastern Kansas. During the 100 years studied, only four 20-year CFT trends were greater or less than 1. Three of these (two at Larned and one at Ottawa) were during the era that included the 1930's dust bowl years at locations in South and East Kansas (Larned and Ottawa) at 34°C and 35°C CFT. In the most recent era, Winfield had a trend of -1.0178 at 40°C CFT.

5. Discussion

Countermeasures for incremental adaptation to climate change are marginal management changes (production and policy) applied within an existing agricultural production system, while those for systems adaptation are more major changes applied to modifying an existing system (Anandhi, 2016). Transformational adaptations refer to the more radical end of a spectrum of

changes that can be applied (Rickards & Howden, 2012) and these countermeasures can replace the existing agricultural production system with a different one.

In the models that control the crop growth and development processes in order to optimize yields under the climate changes (Easterling, W. E. et al., 2003), countermeasures are typically applied by adjusting the model parameter values for key model output variables (e.g. crop yield, biomass, evapotranspiration). In our review of climatological data, we obtained information from PFT (an example of an agroecosystem indicator) to develop countermeasures. These countermeasures may be for incremental, systems and/or transformational adaptation.

5.1 Application of CFT for developing countermeasures for adaptive management

The CFT agro-ecosystem indicator provides information on high temperatures that can reduce crop yields in two ways, either through frequent acute heat stress or through chronic effects of higher average temperatures. This information will be useful in developing agronomic countermeasures for incremental, systems and/or transformational. In this research, we reviewed the changes in CFT to derive potential agronomic countermeasures for use by producers, breeders and decision makers to combat negative impacts of climate changes or to take advantage of positive ones.

Acute and chronic heat stress affects crop production through different processes and can occur in any season or location. Acute heat stress generally has a threshold response with damage increasing rapidly over a small range of temperature, whereas most chronic effects have temperature response curves that may be modeled as a product of an exponentially increasing rate function and an exponential decay function (Peng et al., 2004).

Acute effects of high temperature are most striking when heat stress occurs during anthesis. Critical stages for high temperature injury include germination in most crops, silking

and tasseling in corn (Shaw, 1983), flowering and grain filling in wheat (Johnson & Kanemasu, 1983), flowering in sorghum (Prasad et al., 2008), and flowering in soybean (Raper Jr & Kramer, 1983). The occurrence of a mild heat wave (13 days above normal (2-3°C) temperatures) in early spring at the reproductive stage caused a 28% reduction in the grain yield of wheat, as reported in Rasul et al. (2011).

The plant process most sensitive to high temperature during the reproductive stage is anthesis/flowering, identified by the appearance of the anthers (Nakagawa et al., 2003; Satake & Yoshida, 1978). High temperatures of 30°C for 3 days significantly decrease pollen viability (Saini & Aspinall, 1982). Only a few days of extreme temperature (greater than 32.8°C) at the flowering stage can drastically reduce yield of many crops (Wheeler, et al., 2000). Wollenweber et al. (2003) reported that plants experience warming periods as independent events, and critical temperatures of 35.8°C around anthesis for even a short-period had severe yield-reducing effects. Heat stress during anthesis leads to an irreversible effect with the stagnation of panicle dry weight, even with subsequent improvement in the environment (Oh-E et al., 2007).

Chronic stress occurs due to prolonged exposure to temperatures above 32°C and can reduce pollen germination of many maize genotypes to levels near zero (Herrero & Johnson, 1980). High temperatures impact plant physiology, affecting both crop yield and quality. Various physiological injuries have been observed under elevated temperatures, such as scorching of leaves and stems, leaf abscission and senescence, and shoot and root growth inhibition or fruit damage, all of which lead to decreased plant productivity (Vollenweider & Günthardt-Goerg, 2005). High temperatures (2–4°C warmer than normal) accelerate plant development because the required heat units were met (Anandhi, 2016). Wheat grains could not gain proper size and weight; rather, they shriveled and resulted in reduced yield (Rasul, et al., 2011).

For any particular crop, the effect of increased temperature will depend on the crop's optimal temperature for growth and reproduction; however, high temperatures, in general, decrease plant growth by affecting the net assimilation rates and thus the total dry weight of the plant (Wahid, et al., 2007). For some crops (such as grains), faster growth decreases the amount of time that seeds have to grow and mature, resulting in lower grain yields (Prasad, et al., 2008). Little attention has been paid to changes in CFT, which can have both positive and negative effects on crop quality (Wang & Frei, 2011).

Observing the frequency of CFT during periods of critical crop stages and predicting how they might change in the future can provide useful information for developing production countermeasures to combat the negative impacts of acute and chronic stress. For example, the increasing trends in 32°C CFT in spring (MAM) season in this study suggest that countermeasures might be identified in order to help producers maintain crop yields under changing climatic conditions. Appropriate countermeasures at this CFT temperature that might be explored for their usefulness include earlier planting dates, new crops or crop varieties that utilize warmer spring temperatures and a longer growing season, and a complete reevaluation of the application timing and need for pesticides given a longer growing season and earlier germination/reproduction of pests, including more generations of insects in each growing season. Other countermeasures include crop varieties that have greater water-use efficiency to sustain growth through the longer growing season. Earlier growth in the spring result in earlier wheat harvesting and expand the opportunity to double crop. In some cases, producers will need to consider changes in land use that better conform to new climatological conditions. Land use changes may be most critical for irrigated acres where a longer growing season may require additional irrigation due to warmer spring temperature and the associated increases in

evapotranspiration. Where irrigation water availability is already limited, an increase in CFT in MAM may drive land use change.

Although cold stress can also affect the crop yield and quality, clear CFT thresholds are not well documented for the crops grown in Kansas. Hence, in this study we have not focused on low CFT. Based on earlier study the number of days below freezing (minimum temperature $<0^{\circ}\text{C}$) decreased in Kansas. This study also found northwest Kansas recorded the greatest number of days whereas southeast Kansas had the lowest number of days below freezing. In Kansas, the last spring freeze occurred earlier by 0.1–1.9 days/decade, first fall freeze occurred later by 0.2–0.9 day/decade, and growing season length was longer by 0.1– 2.5 day/decade. These changes in low temperature can provide useful information for developing countermeasures to such as earlier planting or late harvesting (incremental adaptation) and/or develop cultivar traits with longer growing length (systems adaptation).

5.2. Application of CFT for linking climate-impacts research with adaptation planning and management

Despite decades of work on developing various decision support tools for water managers, crop breeders, producers there still remains a disconnect between the supply of and demand for climate information and a need for tailoring the information for decision making (Anandhi, 2016; Bolson et al., 2013; Kirchhoff et al., 2015). This study has attempted to improve the linkage between climate-impacts and adaptation research and planning and management decisions by providing objective information to stakeholders whose activities require them to manage climate risks and opportunities. This information can be used in the following ways:

(1) Using CFT as a powerful tool to communicate technical data (plant failure) in relatively simple terms. Detailed changes in various CFT information communicates to stakeholders the

approximate timeframe in the last 100 years (temporal variability) and the changes in the timeframe across locations in Kansas (spatial variability). These trends and spatio-temporal variability demonstrate uncertainty in the occurrence and duration of CFTs.

(2) Supporting adaptation-related decision-making by quantifying the changes in the plant failure threshold temperatures and then translating this information into incremental, systems and/or transformational adaptive practices that are tailored to specific user group needs using countermeasures (described in section 5.1). If long-term trends (e.g. 1890-2009) indicate there has been no change in CFTs, **producers could continue using the management procedures that they have used the past provided other climate or production variables have also remained nearly constant.** Knowledge of changes in CFT provides the quantitative information that can be used by decision makers to introduce farm program incentives that encourage the adoption of adaptive production practices, incorporation of new “plant by” dates into crop insurance policies, and revision of crop yield estimation dates. This study is a specific example of using CFT trends for developing quantitative adaptation countermeasures. The results presented here are specific to the Kansas region and for high temperatures only, and would not be directly useable by others outside of Kansas. Our study period ends in 2009 and the high temperature years since then, if included, might have influenced the overall trends. We concluded that overall decreases in the annual CFT trends in this study may be due to the following reasons:

(1) The overall trend was affected by a period of high temperature during the Dust Bowl period (1930’s), followed by a period of cooling (the so-called “warming hole”, referring to the large area of cooling in the central US during 1950-2010) [Fig. 2 in Terando et al. (2012)]. Studies suggest that US anthropogenic aerosols may be the drivers of changes in circulation causing central US cooling (Leibensperger et al., 2012).

(2) In regions with heavily irrigated areas, long-term surface climate data analyses indicate a steadily decreasing trend in diurnal and maximum air temperatures. An increase in irrigation or surface wetness reduces sensible heat flux while increasing evaporation and transpiration. In the Midwestern United States, there is evidence of an irrigation-induced cooling effect that can be related to the conversion of the natural prairie vegetation in these region to irrigated cropland (Adegoke et al., 2003).

(3) Our study period ends in 2009 and the high temperature years since then may influence the overall trends.

However, the results presented here are specific to the Kansas region and for high temperatures only. The general methodology developed in this research project should be valuable to others contemplating similar work on developing adaptive management strategies in other locations, especially where greater changes in CFT, high or low, are clearly documented.

6. Summary and Conclusions

Changes in the frequency and intensity of temperatures beyond the CFT as a result of climate change can be devastating for crop production in terms of crop yield and crop quality and hence CFT can be an useful agroecosystem indicator. Maximum temperatures ($T_{\max}$) $\geq 30^{\circ}\text{C}$, 32°C , 34°C , 35°C , 39°C , and 40°C were considered in this study as CFTs that affect crop yield and can cause it to fail. Both short-term and long-term analysis (100- and 30-year time-periods) of frequency of CFT in Kansas were carried out from 23 Centennial Stations. Results indicated that 75% of long-term trend values across all temperatures and locations decreased, one remained the same (less than 1%), and 25% had positive trend values. Ninety-one percent of long-term trend values fell between 1 and -1 CFT days. Overall, the range in the number CFT days was greatest at 30°C CFT and steadily decreased as CFT temperatures increased, with a 10-

fold decrease in the range of the number of CFT days at 40°C CFT. However, short-term trends show that 53% of all 30-year trend lines with absolute slopes >6°C/decade occurred during the 1981–2009 time-period (Table S1 in supplementary material). The greatest changes in slope were also recorded during this time-period, with 4 slopes greater than 10 days/decade. Thus, the greatest changes in number of CFT days, along with the greatest number of sites experiencing decreases in CFT days, occurred during the most recent time-period. Eastern Kansas had the most and largest decreases in CFT days across all temperatures. **The dust bowl years of the 1930s remain the hottest on record in Kansas.**

This study provides a methodology to utilize CFTs for developing countermeasures for incremental, systems and transformational adaptive management. It improves our current understanding of the spatio-temporal changes in CFT in Kansas. This understanding will lead to better identification of crop production response to extreme weather events, adaptation of agricultural production through countermeasures such as improved agronomic management and breeding novel crop genotypes adapted to stress environments, and mitigating both quantitative yield losses and crop quality caused by such adverse environmental conditions. Detailed analyses of the duration in CFTs will further improve crop management practices and help update management decisions and enable future research.

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Table 1: Details of the 23 meteorological stations used in Kansas.

SN	COOPID ¹	Station Name	County	Latitude N (deg:min)	Longitude W (deg:min)	Elevation (MSL)	Record Period
1	140365	Ashland	Clark	37:11	-99:45	600	1900–2009
2	140405	Atchison	Atchison	39:34	-95:06	288	1893–2009
3	141699	Colby 1 Sw	Thomas	39:23	-101:04	966	1900–2009
4	141740	Columbus	Cherokee	37:10	-94:50	276	1890–2009
5	142432	Elkhart	Morton	37:00	-101:53	1097	1900–2009
6	142835	Ft Scott	Bourbon	37:50	-94:42	258	1895–2009
7	143527	Hays 1 S	Ellis	38:51	-99:20	613	1892–2009
8	143810	Horton	Brown	39:40	-95:31	314	1890–2009
9	143954	Independence	Montgomery	37:14	-95:42	245	1893–2009
10	144464	Lakin	Kearny	37:56	-101:14	914	1893–2009
11	144531	Larned No. 2	Pawnee	38:11	-99:05	614	1903–2009
12	144972	Manhattan	Riley	39:11	-96:34	325	1890–2009
13	145152	McPherson	McPherson	38:22	-97:36	463	1890–2009
14	145175	Medicine Lodge	Barber	37:17	-98:33	468	1891–2009
15	145363	Minneapolis	Ottawa	39:07	-97:42	403	1892–2009
16	145906	Oberlin	Decatur	39:49	-100:31	796	1893–2009
17	146128	Ottawa	Franklin	38:36	-95:16	280	1900–2009
18	146378	Phillipsburg #2	Phillips	39:44	-99:18	576	1891–2009
19	147093	Saint Francis	Cheyenne	39:46	-101:48	1025	1908–2009
20	147305	Sedan	Chautauqua	37:07	-96:11	274	1890–2009
21	148235	Tribune 1 W	Greeley	38:27	-101:46	1108	1900–2009
22	148495	Wakeeney	Trego	39:01	-99:52	750	1893–2009
23	148964	Winfield 3 Ne	Cowley	37:17	-96:56	376	1900–2009

¹ Station identification number. The first two digits designate a US state code, and the last four digits are assigned to stations within a state in general accordance with the alphabetical order of the station name.

Table 2: Crop failure temperatures for reproductive growth (yield) of selected crops adapted from Hatfield, J., et al. (2008).

Plant name	Plant Failure Temperatures
Vegetables (Tomato)	30°C
Vegetables (Bean)	32°C
Wheat	34°C
Maize	35°C
Soybean, Sorghum, Cotton	39°C
Grass	40°C

Figure 1. (a) Map of the meteorological stations in Kansas used in the study with elevation provided in the background; and (b) flowchart of the methodology used in the study. In the figure (b) CFT refer to crop failure temperature; CDF refer to cumulative distribution function.

Figure 2. Mean monthly Tmax across the 23 Centennial Stations in Kansas for four short time-periods (through 1919, 1920–1949, 1950–1979, and 1980–2009) and monthly probability density functions (PDFs) of daily Tmax across the same 23 stations and periods. Mean values for entire time-period of record are plotted as dotted vertical lines. Each boxplot comprises 23 monthly mean values. For this and all subsequent boxplots, the bounds of the box represent the 25th percentile (Q1 quartile) and 75th percentile (Q3 quartile), and the lower whiskers extend from 25th percentile to the minimum value, whereas the upper whisker extends from 75th percentile to the maximum value. Each PDF for a month represents the distribution of the monthly values across the 23 stations for a time-period. For example, the PDF in January for the 30-year time-period (1980–2009) is the distribution of 690 values (30 Tmax in January $\times$ 23 stations). The four colors represent four short time-periods (green: through 1919; red: 1920–1949; blue: 1950–1989; gray: 1980–2009). The boxplots in each figure represent the variability in the values.

Figure 3. The boxplots show the changes in frequency and intensity of events greater than or equal to different crop threshold temperatures in different time-periods with colors representing the four time-periods (green: through 1919; red: 1920–1949; blue: 1950–1989; gray: 1980–2009). For this and all subsequent boxplots, the bounds of the box represent the 25th percentile (Q1 quartile) and 75th percentile (Q3 quartile), and the lower whiskers extend from 25th percentile to the minimum value, whereas the upper whisker extends from 75th percentile to the maximum value. Each boxplot comprises 23 monthly mean values. Freq. and Int. in the y-axis label in the figure refer to frequency and intensity, respectively. There were no values for April and October at CFTs above 32°C. The September distribution frequency of CFTs at 30°C and 34°C for period 4 was significantly different from periods 1, 2 and 3. The October distribution frequency of CFTs at 30°C for period 4 was significantly different from periods 1, 2 and 3.

There was no significant difference between periods 3 and 4 at the highest CFTs (35°C, 39°C and 40°C) except during July at 40°C .

Figure 4. Distribution of linear trends in the frequency of days maximum temperature $\geq$ thresholds across three time-periods (1921–1950, 1951–1980, 1981–2009) and 23 stations in Kansas. Each boxplot is for a time-period and comprises of 23 trends in days/decade from each station. The different thresholds are 30°C, 32°C, 34°C, 35°C, 39°C, and 40°C. The annual averages are in column 1. The three seasonal trends (spring, MAM; summer, JJA; and fall, SON) are in columns 2 through 4. **Only three seasons for CFTs because no CFTs were observed in winter season.**

Figure 5. Ten-year moving averages (thin blue lines) and linear trends in number of days with plant failure temperature (CFT) (a) 30 and (b) 35°C estimated from daily maximum temperature in the 23 Centennial Stations in Kansas are shown. A single trend was calculated for the entire period of record (red line), and multiple trend lines were calculated for three time-periods (1921–1950, 1951–1980, and 1981–2009) (short black lines). The subplots are arranged in their approximate geographical locations. The numbers in the subplots represent the trend in days/decade, and significant trends are in italics and bold. The long-term trend value is in red (top), and the three values in black (bottom) are the short-term trends for the three time-periods.

Figure 6. Ten-year moving averages (thin blue lines) and linear trends in number of days with plant failure temperature (CFT) (a) 39 and (b) 40°C estimated from daily maximum temperature in the 23 Centennial Stations in Kansas are shown. A single trend was calculated for the entire period of record (red line), and multiple trend lines were calculated for three time-periods (1921–1950, 1951–1980, 1981–2009) (short black lines). The subplots are arranged in their approximate geographical locations. The numbers in the subplots represent the trend in days/decade, and significant trends are in italics and bold. The long-term trend value is in red (top), and the three values in black (bottom) are the short-term trends for the three time-periods.