1 Growing Degree Days – Ecosystem Indicator
2 for changing diurnal temperatures and their
3 impact on corn growth stages in Kansas
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1 **Abstract**

2 Understanding how climate change will affect plant phenology (shifts in the timing of plant
3 activity) is central to many ecological and biogeochemical studies. This aspect of plant ecology
4 often has been overlooked, but addressing the consequences of climate change for
5 adaptive/mitigative management is now high on the list of priorities for funding agencies. This
6 study is innovative because it uses growing degree days (GDD), which has existed since the
7 1730s, as an ecosystem indicator to study changing diurnal temperatures; their effects on
8 different plant growth stages in the last century; and as a basis for development of future
9 adaptive management strategies. Our results show the most recent time period (1980–2009) had
10 the earliest emergence and the least variability among stations in the day at which the crop stage
11 occurred for most stages except emergence and physiological maturity. 100 year linear trends in
12 the stations indicated all seven crop stages except tassel initiation occurred earlier by one day per
13 decade during the study period. The number of stations with significant decreases varied from 11
14 to 17 stations out of 23 stations in Kansas. Tassel initiation stage occurred later by one day per
15 decade during the study period. The most recent time period (1980–2009) had the highest
16 variability among stations and 30 year time periods. The variability in trends are higher in
17 western Kansas when compared to eastern Kansas. This knowledge has transformative potential
18 to improve our understanding of the occurrence and duration of the different plant growth stages,
19 add local precision to earlier findings for changes in overall GDD that encompassed larger areas,
20 and help explain the differences in trends from some earlier studies. These shifts in the
21 phenology of agricultural plants as a result of climate change have implications for required
22 increases in food production to feed the growing population.

Keywords: Corn growth stages: emergence, tassel initiation, tassel emergence, silking, dough stage, dent stage, and physiological maturity, Kansas centennial stations, heat units, growing degree days, climate change, adaptation

1 Introduction

Measuring “heat units” started with the concept that growth and development of plants are related to temperature and do not occur beyond a threshold temperature [Esparza *et al.*, 2007], an idea that has been used in studies relating to growth and development during the growing season [Kadioğlu and Şaylan, 2001]. The “heat units approach” or “remainder index method” has been used since about 1730 [Wang, 1960] and is known by a number of expressions, including “thermal time” , “degree-days,” “heat units,” “growth units,” or “growing degree days” [Feng and Hu, 2004; Wang, 1960]. Growing degree days (GDD) is used widely in many applications: (1) as a phenoclimatic measurement to represent changes in temperature that are relevant to different phases of plant development [Cleland *et al.*, 2007]; (2) as a hybrid maturity descriptor by the seed industry to help make late planting decisions (e.g. choosing early maturity varieties) because delayed planting and replanting shorten the effective growing season and GDD can characterize the growing season [Nielsen *et al.*, 2002; Thomison and Nielson, 2002]; (3) as a measurement to study the effects of planting dates on crop yield [Bollero *et al.*, 1996]; (4) as an indicator useful in the practice of sustainable management and development of forests and agriculture through plant functions such as evapotranspiration, photosynthesis, plant respiration, and plant water and nutrient movement [Hassan *et al.*, 2007]; (5) as a way to predict N release from crop residues and other amendments [Griffin and Honeycutt, 2000]; and (6) as an explanation of seasonal variation in the linear increase of the

1 harvest index, which increases crop yield [Lu *et al.*, 2001]. Variations in GDD also can be an
2 important indicator of climatic change effects on plants that may not be represented in mean
3 conditions.

4 As temperatures increase during the next century, shifts may occur in crop production
5 areas because temperatures will no longer occur within the range or during the critical time
6 period for optimal growth and yield of grain or fruit [Walthall, 2012]. The challenge of
7 increasing food production to meet the needs of the increasing population has become more
8 urgent than ever [Tscharnkte *et al.*, 2012] even as climate change variations and events threaten
9 both land and water resources [Horlings and Marsden, 2011]. In addition, numerous studies
10 examining frost dates and growing season length have found changes that are consistent with
11 climate warming [Anandhi *et al.*, 2013a; Anandhi *et al.*, 2013b]. Increasing temperature could
12 significantly alter plant phenology because temperature influences the timing of development,
13 both alone and through interactions with other factors (e.g., photoperiod). These are often-
14 overlooked aspects of plant ecology [Cleland *et al.*, 2007] and have important implications for
15 agricultural production.

16 Temperature changes present unprecedented challenges to the adaptive capacity of
17 agriculture by influencing crop distribution and production and by increasing the economic and
18 environmental risks associated with a multitude of agricultural systems [Walthall, 2012]. Many
19 adaptation programs and strategies do not yet sufficiently connect with regional and local
20 planning and management programs because much academic research is not being conducted
21 with the objective of meeting specific decision-makers' information needs [Bolson *et al.*, 2013;
22 Moser and Luers, 2008]. Improving the link between climate impacts and adaptation research
23 and public and private planning and management decisions is a critical challenge in supporting

climate change adaptation [Mastrandrea et al., 2010]. GDD can be considered a climate impact index that helps translate academic climate change research and makes it useful in making planning and management decisions.

Detailed information on geographical and temporal variations of GDD can be beneficial for updating management decisions and recommendations (e.g., timing of sowing and harvesting and effective timing for irrigation, fertilizer, and pesticides) for local and regional agricultural production, supporting agricultural research and education (e.g., phenology of hybrid varieties), and providing compelling evidence that species and ecosystems are being influenced by global environmental change (e.g., shifts in the timing of plant activity). A few studies have examined variations in GDD for larger regions encompassing Kansas, but no studies have compared the 100 year trends in GDD for different time periods and crop growth stages in Kansas. Therefore, the main objective of this study was to examine 100 year and 30 year variation and trends in Kansas GDD for seven crop growth stages of corn in four different time periods using 23 Centennial Weather Stations. The secondary objective of this study was using GDD to translate academic climate change research to information that can help make management decisions in food production systems.

2 Definition of GDD

The canonical form of calculating *GDD* is provided in equation 1.

$$GDD = [T_{max} - T_{min}]/2 - T_{base} \quad 1$$

$$T_{max} = \begin{cases} T_{max} & 30^{\circ}\text{C} > T_{max} > T_{base} \\ 30^{\circ}\text{C} & T_{max} \geq 30^{\circ}\text{C} \\ T_{base} & T_{max} \leq T_{base} \end{cases} \quad 2$$

$$T_{\min} = \begin{cases} T_{\min} & 30^{\circ}\text{C} > T_{\min} > T_{\text{base}} \\ 30^{\circ}\text{C} & T_{\min} \geq 30^{\circ}\text{C} \\ T_{\text{base}} & T_{\min} \leq T_{\text{base}} \end{cases} \quad 3$$

where $T_{\max}$ and $T_{\min}$ are daily maximum and minimum air temperature in degrees Centigrade and T_{base} is the base threshold temperature in degrees below which the process of growth does not progress. T_{base} varies among species and possibly cultivars and likely varies with growth stage being considered. In this study, T_{base} is 10°C (50°F). 30°C (86°F) is the upper threshold temperature because plant roots have greater difficulty taking in water fast enough to keep the plant growing at full speed [Duncan *et al.*, 2010]. More details such as modifications of equation 1 and implications of the various definitions can be found in McMaster and Wilhelm [1997]. This study assumes that the GDD required to complete a given growth stage is constant for a hybrid regardless of the temperatures experienced; however, GDD have been found to vary with soil temperature [Bollero *et al.*, 1996].

Equation 1 describes the heat energy received by the crop over a given time period by integrating the area under the diurnal temperature curve, summing the daily heat energy over an interval of time and then relating the accumulation of heat energy to progress in development or growth processes [McMaster and Wilhelm, 1997].

3 Data and statistical techniques used in the study

3.1 Study Region and Data

Kansas is the study region. It is important to study Kansas because it lies between 37° and 47° N latitude, where Manabe and Wetherald [1980] have predicted that, due to climate change an increase in CO_2 , a decrease in precipitation, an increase in evaporation, and a decrease in excess of precipitation over evaporation will occur. Further, the corn production regions in Kansas

largely overlies the High Plains (Ogallala) aquifer. This region is considered one of the most productive agricultural regions and are referred to as the "breadbasket of the world." [Sanderson and Frey, 2014] or the "grain basket of United States" [Scanlon *et al.*, 2012]. The Kansas portion in High Plains aquifer supports the congressional district with one of the highest market value for agriculture in the nation; and declining water levels in the aquifer would cut agricultural production [Steward *et al.*, 2013]. Exposure of the agricultural production in this region to changing climate such as longer growing season and changing developmental stage can further increase the vulnerability of ecological and hydrological systems in this region. This creates a need for adapting the corn production to utilize the benefits of changes while reducing the impacts of change.

Daily maximum ($T_{\max}$) and minimum air temperature ($T_{\min}$) data were downloaded from the High Plains Regional Climate Center's website for 23 Centennial Weather Stations across Kansas. The locations and periods of record are provided in Figure 1a and Table 1. The records began from 1890 to 1908; consequently, the start dates of the records are different, but the end dates are the same (2009). The records were selected to cover non-overlapping 30-year timespans backward from 2009. The four time periods were through 1919, 1920–1949, 1950–1979, and 1980–2009. Weather stations were selected for their long-term quality, based on criteria such as consistent observation times, low potential for heat-island bias [Robeson, 2002]. The other quality checks were: statistical outliers were identified and checked against original records; so was the minimum temperature less than maximum temperature.

3.2 Steps and statistical techniques used

The steps involved in estimating GDD are provided in Figure 1b for the seven growth stages of corn: emergence, tassel initiation, tassel emergence, silking, dough stage, dent stage, and physiological maturity.

Step 1: Calculate GDD: For each station and day of the year, GDD was calculated using equation 1 in Centigrade scale using the station's daily $T_{\max}$ and $T_{\min}$.

Step 2: Calculate cumulative GDD: The daily GDD was accumulated from March 1 of each year for each station and day of the year.

Step 3: Determine plant growth stage: The approximate accumulated GDD from the time of planting was used to estimate the plant growth stage. The GDD for the seven growth stages considered in this study was obtained from *Duncan et al.* [2010] in a mid-season maturity corn hybrid (Table 2).

Step 4: Estimate the day of year to reach each growth stage: This is the day when the approximate cumulative GDD is reached for each of the seven growth stages in a mid-season maturity corn hybrid. Estimate the duration of each growth stage: The number of days between two growth stages.

Step 5: Calculate the averages for each of the four time periods: The averages were calculated for the day of the year and duration of each growth stage for the four time periods (through 1919, 1920–1949, 1950–1979, and 1980–2009) as well as for the entire study period (through 2009). Averages are presented in boxplots (Figures 1c–e).

Step 6: Estimate trends: Fitted least squares linear trends to the day of the year and duration of each growth stage using linear regression. Test significance of trends: A variant of the t-test calculated the significance of the trend and accounted for the serial auto-correlation in the time series. The methods are described briefly in the supplementary material, and detailed information

can be obtained from supplementary material in *Anandhi et al.* [2013b], Wigley et al. [2006], and Santer et al. [2000].

4 Results

In sections 4.1 to 4.7 the results of 100 year and multiple 30 year variations; and trends of GDD for seven crop growth stages of corn in Kansas using 23 centennial weather stations are provided. The trends in the duration of the seven crop stages are in section 4.8. The usefulness of these results for making management decisions and for adaptive management are discussed in sections 5.1 and 5.2 respectively.

4.1 GDD in emergence stage

In general, emergence (69 GDD) occurred across the state from March 23 through April 4, with March 29 as the median date during the study period (Figure 1c). The range and median dates varied, however, among 30 year time periods. The earliest median emergence date was March 27, which occurred through 1919 and during the most recent period, which had different ranges (March 20 through April 4 and March 24 through April 1, respectively). The 1920–1949 period, which included the Dust Bowl, had a median date of March 28 with a range very similar to the most recent period; 1950–1979 had the latest median date of March 30 (March 24 through April 6) (Figure 1c).

Fourteen stations in the state show a 100 year decrease of 0.03 to 0.47 days/decade (Horton had the highest decrease), and seven stations show a significant increase of 0.05 to 0.45 days/decade (Colby had the highest increase) (Figure 2a). The decrease indicates earlier emergence and is more consistent in eastern Kansas, but variability is higher in western Kansas.

The 30 year trends across the three time periods also indicate earlier emergence during the 1980–2009 period with higher variability of trends among stations (Figure 1e).

4.2 GDD in tassel initiation stage

In Kansas, the tassel initiation stage (264 GDD) occurred April 26 through May 11, with May 2 as the median date during the study period (Figure 1c). Variation in these dates among 30 year time periods include: 1) the earliest median tassel initiation stage date was May 1 during the 1920–1949 period, but for the rest of the periods it was May 3; 2) the 1950–1979 period had the highest range (April 24 through May 15), followed by the earliest period (April 23 through May 12); and 3) the least variability (16-day range) among stations was observed during the Dust Bowl and recent periods from April 22 through May 8 and April 28 through May 12, respectively (Figure 1c).

Most stations (17 had significant change) in the state show an increase of one day per decade during the study period, indicating tassel initiation occurred later (Figure 2b). All the decreases (0.07 to 0.66 days/decade) were at stations in northeast Kansas. Colby had the highest increase, and Horton had the highest decrease. Among the three time periods, the trends during the 1980–2009 period were slightly higher, whereas those during 1950–1979 were the lowest (Figure 1e).

4.3 GDD in tassel emergence stage

During the study period, based on the station average, the tassel emergence stage (639 GDD) occurred sometime from June 5 through June 23, with June 11 as the median date (Figure 1c). Variation in these dates among 30 year time periods included: 1) the median tassel emergence

stage date was June 11 to 13; 2) the 1950–1979 period had the highest variability of 24 days (June 2 through June 25), followed by the 1920–1949 period, with 20 days (June 2 through June 21); and 3) The earliest and recent periods had the least variability of 19 days among stations during June 4 through June 22 and June 6 through June 24, respectively (Figure 1c).

Similar to emergence, the days to tassel emergence decreased significantly (0.04 to 0.73 days/decade) in 11 stations, with the highest decrease in Horton (eastern Kansas) (Figure S1). Eight stations had significant increases, with Colby and Lakin (western Kansas) having the highest increase (0.37 days/decade). The variability in the trends in the 23 stations increased among the three time periods, with the current period having the highest variability (Figure 1e).

4.4 GDD in silking stage

Among stations across the state, the silking stage (778 GDD) generally occurred sometime from June 15 through July 4, with June 22 as the median date during the entire time period (Figure 1c). The range and median dates varied in the 30 year periods. The earliest median date for the silking stage was June 21 in 1950–1979, followed by June 22, June 23, and June 25 during the 1920–1949, through-1919, and recent periods, respectively. The 1950–1979 period had the highest variability of 24 days (similar to the entire time period), and the recent period had the lowest variability of 19 days (June 17 and July 23) among stations. The first two periods (through 1950) had 20 days of variability, June 15 through July 4 and June 13 through July 2, respectively (Figure 1c).

Fourteen stations had a decrease in days to silking (0.04 to 0.74 days/decade), indicating that silking is occurring earlier in the year (Figure S2). Seven stations showed an increase (0.05 to 0.35 days/decade). Horton had the highest decrease, and Ashland had the highest increase. The

variability in the 30 year trends among stations is increasing, with the current period having the highest variability (Figure 1e).

4.5 GDD in dough stage

In Kansas, the dough stage (1069 GDD) occurred in July on average. The dates were July 6 through July 27, with July 13 as the median date during the entire period among all stations (Figure 1c). These dates were different in the 30 year time periods. The earliest median date for the dough stage was July 11 during 1950–1979, followed by July 13 during 1920–1949 and recent periods and July 17 in the through-1919 period. Similar to the silking stage, the 1950–1979 period had the highest variability of 26 days (July 4 and July 25), and the recent period had the least variability of 21 days (July 7 and July 27) among stations. The first two periods (through 1949) had 23 and 22 days of variability during July 5 through July 27 and July 4 through July 25, respectively (Figure 1c).

Fourteen stations out of 23 stations in the state showed a significant decrease of 0.07 to 0.78 days/decade (Figure-S3) during the study period, indicating that the dough stage is occurring earlier in the year. Seven stations show an increase (0.05 to 0.35 days/decade) in northwest Kansas. Among stations, Horton had the highest decrease, and Ashland had the highest increase.

4.6 GDD in dent stage

During the entire time period, based on station averages, the dent stage (1361 GDD) occurred sometime from July 25 through August 19, with August 2 as the median date (Figure 1c). Variation in these dates among 30 year time periods include: The latest median tassel emergence stage date was August 7 during the period through 1919 and earliest during the recent period (August 1), but for the rest of the periods it was August 2. The 1950–1979 period had the highest

variability of 31 days (July 23 through August 21), followed by the earliest and recent periods, with 27 days of variability from July 25 through August 19 and July 26 through August 20, respectively (Figure 1c).

Most stations (out of which 14 had significant change) in the state showed a decrease of 0.08 to 0.88 days/decade (Figure S4). The decrease indicates the dent stage is occurring earlier in the year. Seven stations show an increase (0.07 to 0.41 days/decade) at stations in northwest Kansas. Among stations, Horton had the highest decrease, and Colby had the highest increase.

4.7 GDD in physiological maturity stage

Among stations across the state, the physiological maturity stage (1500 GDD) generally occurred sometime during August 3 through 31, with August 11 as the median date during the entire time period (Figure 1c). The range and median dates varied in the 30 year time periods. The earliest median date for the maturity stage was August 10 during 1950–1979, followed by August 11 during 1920–1949 and recent periods and August 17 in the through-1919 period, respectively. The 1950–1979 period had the highest variability of 35 days (July 31– September 2), and the 1920–1949 period had the least variability of 28 days (August 2 and August 29) among stations. The through-1919 and the most recent period had 30 days of variability, August 4 through September 2 (Figure 1c).

Fourteen stations showed a significant decrease (0.06 to 0.95 days/decade; Figure 2c), with the highest decrease in Horton (eastern Kansas). Five stations had an increase, with Colby having the highest increase (0.54 days/decade). The variability in the 30 year trends among stations increases in the three time periods, with the current period having the highest variability during tassel emergence, silking, and dough stage (Figure 1e). Among the three time periods, the Dust Bowl period had the least variability and highest decreasing trends (Figure 1e).

1 In all stages except emergence, among 23 stations in Kansas, 1950–1979 had the highest
2 variability (Figure 1d). This variability for all seven stages are 13, 18, 20, 21, 23, 27, and 30
3 days, respectively. Generally, the stations in western Kansas had higher variability in the 100
4 year trends when compared to those in the eastern Kansas for the date at which the stage was
5 reached (Figure 3a). The long term trends are summarized in Table 3.

6 7 8 **4.8 Duration between stages**

9 The 30 year trends in the in the duration between crop stages are shown in Figure 1f. The most
10 recent period (1980–2009) had higher trends in the duration between emergence and tassel
11 initiation; silking and dough stage; and dough and dent stage. Higher variability trends were
12 observed during most of these durations and in the duration between tassel emergence and
13 silking.

14 The 100 year trends in the duration between emergence and tassel initiation are
15 increasing significantly in 19 stations, with the highest increase in Lakin (0.42 days/decade)
16 (Figure-S5); however, in general the 100 year trends were decreasing in the duration between
17 other stages (Figure-1f). All stations (except Manhattan) had a decrease of up to 0.36
18 days/decade in the time between tassel initiation and tassel emergence (Figure-S6). A significant
19 decrease of up to 0.12 days/decade in 17 stations (Lakin had the highest decrease) was observed
20 in the duration between tassel emergence and silking, but stations in the lower latitudes in
21 southeastern Kansas showed either an increase or no change (Figure S7). The decrease in the
22 duration between silking and dough stage was up to 0.18 days/decade at 19 stations (Lakin had
23 the highest decrease) (Figure S8). A decrease of up to 0.16 days/decade in 18 stations (Ottawa

had the highest decrease) was observed in the duration between dough and dent stage (Figure S9). In the duration between dent and physiological maturity stage, only 11 stations showed a significant decrease (Figure S10). Among 30 year periods, the trends in the duration between crop stages: emergence and tassel initiation; between silking and dough stages in the recent periods are higher compared to the earlier study periods (Figure 1f). Generally, the stations in western Kansas have higher variability in the 100 year trends when compared to those in the eastern Kansas for the duration between stages (Figure 3b).

5 Discussion

5.1 Application of GDD for management decisions

The usefulness of GDD for various applications was stated in the introduction section and the results such as: the occurrence dates, its trend for the seven crop stages, and the trends in the duration of the crop stages obtained from GDD were presented in the previous eight sub-sections (4.1-4.8). In this sub-section a discussion on selected management decisions such as plant water use; fertilizer application and choosing hybrids appropriate for each management situation is initially discussed followed by the general usefulness of this study. The results from individual station data can be useful for planning and management decisions at a local level, while the changes in 23 stations can provide more useful information at the county or state level.

Water supply for crop use is the primary factor controlling corn yield in this region of the central Great Plains [Thorp *et al.*, 2007]. The High Plains (Ogallala) aquifer is the main source of irrigation water supply for corn production. Recent studies have shown that among the states overlying the aquifer, Kansas has one the most steep water level declines [Sanderson and Frey, 2014]. In addition to the declining water levels in the aquifer, and longer growing season

1 observed in the region [*Anandhi et al.*, 2013b] brings out a need for better water management.

2 These results in GDD can be useful for better crop water management in the following ways: (1)

3 The dates and duration of corn growth stages identified in this study can be used in estimating

4 crop water requirement predicted using the information on likely duration of each development

5 stage and potential evapotranspiration. Combining information on water availability and GDD

6 helps optimize available water by improving water use, especially under water scarcity

7 conditions during critical development stages. One day of moisture stress within a week after

8 silking can result in up to 8% yield losses, whereas a period of 3 to 4 days of severe moisture

9 stress at this time can easily reduce final grain yields by 30% [*Duncan et al.*, 2010]. Water stress

10 occurring during different development stages of corn may reduce final grain yield at varying

11 degrees, and the extent of yield reduction depends on the severity of the stress and the stage of

12 plant development [*Agehara and Warncke*, 2005]. (2) The longer duration of crop development

13 stage observed in the study (earlier emergence and physiological maturity) can be combined with

14 projected available water in the aquifer. This can be useful in the estimation of the potential

15 changes in crop water requirement, identify periods with water stress and their potential impact

16 on crop yield. **These results are also useful in selecting hybrids that produce** optimum yield in the

17 anticipated water environment [*Thorp et al.*, 2007].

18 Choosing an appropriate hybrid is essential for successful corn production. The corn

19 producer's challenge is to choose hybrids appropriate for each management situation, keeping in

20 mind risks associated with potential weather extremes [*Rickards and Howden*, 2012]. Although

21 factors other than temperature enter into determining rate of growth, seed producers use the

22 temperature based GDD concept to express hybrid maturity [*Duncan et al.*, 2010]. The hybrid

23 maturity descriptor used in seed industry describes the duration of the hybrid, using GDD

[Nielsen *et al.*, 2002] to characterize the growing season. Combining the descriptor details with the spatio-temporal variability of the date of emergence and physiological maturity, identified in this study (Figures 1c and d, 2a and c) can provide the optimum timeframe for planning and managing the planting and harvesting operations useful to producers. This is important, because delayed planting can shorten the effective growing season, and earlier planting can cause spring frost damage in corn plants. Also, fields planted during the optimum time frame occasionally require replanting at later dates after weather stresses or pests cause excessive plant mortality. Replanting shortens the effective growing season, so producers often must decide whether to switch to earlier-maturity hybrids to ensure that physiological grain maturity occurs before a killing fall frost.

Among many factors, temperature is important for making appropriate N recommendations especially while using natural organic materials because increasing temperature increases N release [Agehara and Warncke, 2005]. GDD have be used to predict the availability of N from these materials [Griffin and Honeycutt, 2000]. Also, Nitrogen uptake by corn is quite rapid in a period starting about 25 days after emergence and by the time of silking, with 60 percent of the total nitrogen is taken up [Duncan *et al.*, 2010]. Better N fertilizer management practices are developed by combining the knowledge of N fertility and GDD. These results in GDD can be useful in the following ways: (1) to plan fertilizer management and provide the approximate growing season midpoint. The fertilizer applications should be timed so that nutrients are available when needed for this rapid growth [Duncan *et al.*, 2010]. (2) to predict the final corn grain yield for the year and adjust N application recommendations accordingly. These management practices are crucial for both economic and environmental reasons because inadequate N fertility results in lower yields and lower economic returns,

1 whereas over fertilization affects water resources, reduces net economic returns, and results in
2 higher emissions of nitrous oxide, an important greenhouse gas [Thorp *et al.*, 2007].

3 Climate change studies have estimated cumulative GDD and their trends across regions.
4 For example, *Feng and Hu [2004]* observed a decrease of 10 to 20 GDD/decade in Kansas
5 during the 1950–2000 time period for corn production using threshold temperatures similar to
6 those in this study; thus, our study adds local precision to earlier GDD findings that encompassed
7 larger areas and helps explain the differences in trends from some earlier studies. This study also
8 provide detailed analysis of how maximum and minimum temperature changes have affected the
9 seven stages of corn growth (emergence, tassel initiation, tassel emergence, silking, dough stage,
10 dent stage, and physiological maturity) using GDD. These details are useful for adaptive
11 management of corn production to changing climate (discussed in more detail in next section).

12 In general, these results indicate an earlier emergence and maturity which are useful for
13 planning the planting and harvesting operations. These provide evidence that can support
14 education of our producers, and decision-makers about some of the implications of global
15 environmental change on corn production. Similarly, the periods of other crop stages, its duration
16 and trends are useful for planning the timing for irrigation, fertilizer and pesticide application for
17 optimum activity, efficacy, and control; updating management decisions and recommendations;
18 supporting agricultural research and education, and providing compelling evidence that species
19 and ecosystems are being influenced by global environmental change.

20 **5.2 Application of GDD for linking climate-impacts research with adaptation planning and** 21 **management**

22 Stakeholders (e.g., decision-makers, producers) are becoming more interested in obtaining
23 understandable information about climate change risks in ecological and hydrological systems.

1 They are expressing the need for climate information that can support adaptation-related
2 decision-making, provide straightforward estimations of variability, and be tailored to specific
3 user groups [*Mastrandrea et al.*, 2010]. Informed decisions can lead to economic development.
4 This study has attempted to improve the linkage between climate-impacts and adaptation
5 research, by providing quantitative information for developing adaptation strategies at different
6 levels namely: incremental, systems and/or transformational adaptation. Incremental adaptation
7 changes are practices and technologies within an existing system. Systems adaptation are
8 changes to an existing system, such as new crop types which are mapped against an increasing
9 degree of change. Transformational adaptation refer to the more radical end of a spectrum of
10 change such as a change in land use [*Rickards and Howden*, 2012]. The results from this study
11 (duration and trend information on the seven crop stages in Kansas), can provide quantitative
12 information for crop breeder/researchers to developing new corn varieties (systems adaptation)
13 that are conducive to these changes. Managers/crop advisors/producers can use this information
14 for selecting hybrids from existing crop varieties (e.g. early or late maturing varieties;
15 incremental adaptation) or they can decide to go for a different land use (transformational
16 adaptation).

18 **6 Conclusion**

19 This study is innovative because growing degree days (GDD) that has existed since the 1730s for
20 modeling plant development stage is used: (1) as an ecosystem indicator to study changing
21 diurnal temperatures and their effects on different plant growth stages in the last century. (2) as a
22 basis for development of future adaptive management strategies and insights for updating
23 management decisions and recommendations. The earlier emergence and physiological maturity

and changes in the other five stages are useful to quantify future adaptive management strategies. (3) to improve the linkage between climate-impacts and adaptation research and public and private planning and management decisions. The detailed documentation of changes in the seven plant development stages are useful for incremental, systems and/or transformational adaptation.

These are explained using our 100 year and 30 year analysis of GDD on 23 Centennial Stations in Kansas for the seven growth stages for corn: emergence, tassel initiation, tassel emergence, silking, dough stage, dent stage, and physiological maturity. Also this study added local precision to earlier findings for changes in GDD that encompassed larger areas, help explain the differences in trends from some earlier studies, Future work can build on this research by exploring the implications of these changes on crop yield and quality and comparing the changes with model simulations (past and future) for sustainable agricultural production.

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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. Approximate accumulated growing degree days (GDD) in Celsius (°C) and Fahrenheit (°F) scale required for a mid-season maturity corn hybrid to reach different growth stages from the time of planting (March 1)¹.

Stage	GDD (°C scale)	GDD (°F scale)
Emergence	69	125
Tassel initiation	264	475
Tassel emergence	639	1,150
Silking	778	1,400
R4-Dough stage	1069	1,925
R5-Dent stage	1361	2,450
R6-Physiological maturity	1500	2,700

¹ Adapted from *Duncan et al.* [2010].

Table 3. List of number of stations and their range with increasing/decreasing long term linear trends in the seven crop developmental stages and six duration between stages, in the 23 Centennial Stations in Kansas are provided. These values summarize the Figure 2 and figures in supplementary material.

Crop development stage	Number of stations with long term significant increasing trend (range in days/decade)	Number of stations with long term significant decreasing trend (range in days/decade)	Number of stations with long term not significant trend (range in days/decade)
Emergence (E)	7 (0.05 to 0.45)	14 (0.03 to 0.47)	1 (0.03)
Tassel initiation (TI)	17 (0.04 to 0.73)	5 (0.07 to 0.66)	1 (0.03)
Tassel emergence (TE)	8 (0.04 to 0.37)	11 (0.04 to 0.73)	4 (0.01 to 0.02)
Silking (S)	7 (0.05 to 0.35)	14 (0.04 to 0.74)	2 (0.01 to 0.02)
Dough stage (D)	7 (0.05 to 0.35)	14 (0.07 to 0.78)	2 (0.02 to 0.06)
Dent stage (D)	4 (0.07 to 0.41)	14 (0.08 to 0.88)	5 (0.02 to 0.04)
Physiological maturity (PM)	5 (0.07 to 0.54)	14 (0.06 to 0.95)	2 (0.03)
Duration: E, TI	19 (0.04 to 0.42)	3 (0.09 to 0.2)	1 (0.02)
Duration: TI, TE	1 (0.02)	22 (0.02 to 0.36)	-
Duration: TE, S	5 (0.01 to 0.09)	17 (0.01 to 0.12)	-
Duration: S, D	1 (0.01)	19 (0.02 to 0.18)	-
Duration: D, D	3 (0.02 to 0.14)	18 (0.02 to 0.16)	1 (0.02)
Duration: D, PM	7 (0.02 to 0.13)	11 (0.01 to 0.06)	1 (0.01)

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Figure 1. (a) Map of the meteorological stations in Kansas used in the study. Elevation is provided in the background. (b) Flowchart of the methodology used in the study. DOY in step 4 represents the day of year. (c) Variability in the date the different crop stages studied occurred among 23 stations across 5 time periods: 4-short time periods (through 1919, 1920–1949, 1950–1979, 1980–2009) and through 2009 (entire record). (d) Variability in days among stations different crop stages studied occurred. The numbers 1–5 in x-axis in (c) and (d) represents the long and short time periods: through 1919, 1920–1949, 1950–1979, 1980–2009, and through-2009, respectively. (e) boxplots to depict the variability in linear trends in the date the different crop stages studied occurred across three time periods (1920–1949, 1950–1979, 1980–2009). and 23 stations in Kansas. (f) boxplots to depict the variability in linear trends in the duration between the different crop stages studied across three time periods (1920–1949, 1950–1979, 1980–2009), and across the 23 stations in Kansas. In all 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. The red dots in the boxplots represent values that are greater than 1.5 times the box width. Each boxplot is for a time period and comprises 23 values from each station.

Figure 2. Ten-year moving averages (thin blue lines) and linear trends in the day of year the crop stage at (a) emergence, (b) tassel initiation, and (c) physiological maturity estimated from GDD 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 (1920–1949, 1950–1979, 1980–2009). (short black lines). The subplots are arranged in their approximate geographical locations. There is an empty space above Ashland because that region has fewer centennial stations. 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 30 year trends for the three time periods.

Figure 3. Variability in the long-term trends among the 23 meteorological stations in Kansas used in the study (a) the date at which the stage was reached (b) the duration between the stages in days.

In the figure the three axis represents the latitude, longitude and the trend value. The geographical north is shown by the north arrow (top right corner).