COMPARISON OF THERMAL UNITS DERIVED FROM DAILY AND HOURLY TEMPERATURES

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Abstract

Crop development as a function of thermal time has important applications in crop management and crop modeling. Several reports have indicated that calculation of thermal units on an hourly basis, and averaging these values over 24 h, was superior to calculations of thermal units using the average of maximum (T_{max}) and minimum (T_{min}) temperatures. In this report, daily and hourly calculations of thermal-unit accumulation were compared for two sets of cardinal temperatures for representative warm-season crops. Daily (DTU) and hourly thermal units (HTU) agreed closely except when average temperatures were above 34°C or when close to the base temperature (T_b). Simulations across 43 yr of weather data comparing the time required to cumulate 200°C d were nearly identical for calculations based on DTU and HTU for two sets of cardinal temperatures. For warm-season crops with similar cardinal temperatures, there is no advantage in hourly calculations of thermal units over daily values.

Phenological development of photoperiod-insensitive processes in crops is often described as occurring at a rate proportional to the average daily temperature (ADT) minus a lower temperature limit (T_b), below which crop development does not occur (Fig. 1). Average daily temperature is the mean of the T_{max} and T_{min} temperatures, and DTU for a given day are calculated as the ADT minus T_b (Ritchie and NeSmith, 1991). A major advantage of using thermal units to describe crop development is that the number of thermal units required to reach an ontogenetic phase is relatively constant, whereas the time required (or number of days) to reach an ontogenetic stage varies considerably across environments.

Thermal unit requirements to reach specific ontogenetic stages are usually determined in controlled environments by regressing development rate (inverse of time required to reach ontogenetic phase) against ADT (Olivier and Annandale, 1998; Baker and Reddy, 2001). The linear relationship between development rate and ADT is extrapolated to the *x* axis to define T_b, the lower temperature limit at which development ceases, and the optimum temperature (T_{Opt}) is defined as the temperature at which development rate is maximal (Olivier and Annandale, 1998; Baker and Reddy, 2001). At temperatures above T_{Opt}, the linear decline in development rate may also be extrapolated to the *x* axis to define T_c, the upper temperature limit at which development ceases. A further modification some thermal-development models include is a temperature plateau in which maximal development occurs between a lower optimum temperature (T_{Opt1}) and an upper-optimum temperature (T_{Opt2}) (Boote et al., 1998; Ritchie and NeSmith, 1991). An example of a thermal development model from muskmelon (*Cucumis melo* L.; Baker and Reddy, 2001) with a single temperature optimum is illustrated in Fig. 1. Also illustrated in Fig. 1 is an example of thermal development for vegetative soybean [*Glycine max* (L.) Merr., Boote et al., 1998] that has upper and lower temperature optima. The cardinal temperatures illustrated in Fig. 1 are representative of many warm-season crops, and these two models are evaluated in detail in this report.

Although thermal units have generally been calculated from the ADT, several authors (Grimm et al., 1993; Snyder et al., 1999; Cesaraccio et al., 2001) have suggested that instead of DTU, thermal units should be calculated on an hourly basis. The use of hourly temperature data is considered important because diurnal temperature curves are not symmetrical (Parton and Logan, 1981; Cesaraccio et al., 2001), which may cause DTU to differ from HTU. To reflect the diurnal changes in temperature, thermal units are calculated on an hourly basis by subtracting T_b from the temperature (T) for each hour of the diurnal cycle, the temperature values are summed, and the summation is divided by 24 so that HTU (°C h) are expressed on a daily basis (°C d, Grimm et al., 1993; Cesaraccio et al., 2001), as shown in Eq. [1]:

$$\mathrm{HTU} = \left(\sum_{h=1}^{24} T - T_b\right)/24. \quad [1]$$

Long-term weather data, however, do not typically include hourly temperature data, and several methods have been used to estimate hourly temperatures based on T_{max}, T_{min}, and daylength (Parton and Logan, 1981; for a review of several methods see Cesaraccio et al., 2001). By estimating hourly temperatures, thermal units for each day may be calculated on an hourly basis as shown in Eq. [1].

Although there has been considerable interest in different methods of calculating diurnal temperatures and HTU, there has been little research illustrating if prediction of phenological events changes with the use of DTU or HTU. Roltsch et al. (1999) and Cesaraccio et al. (2001) evaluated several different methods of predicting DTU and compared these against HTU for several sites in California, but these evaluations were cumulative monthly estimates of thermal units and were not specific for warm-season annual crops. If calculation procedures for DTU and HTU give similar results for warm-season crops, then there would be no benefit in the more complicated procedure of calculating thermal units on an hourly basis compared with simple daily calculations.

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Abbreviations: ADT, average daily temperature; DOY, day of year; DTU, daily thermal units; HTU, hourly thermal units; T_b, base temperature; T_{Opt}, peak optimum temperature; T_{Opt1}, lower optimum temperature; T_{Opt2}, upper optimum temperature; T_c, upper temperature limit; T_{max}, maximum temperature; T_{min}, minimum temperature.

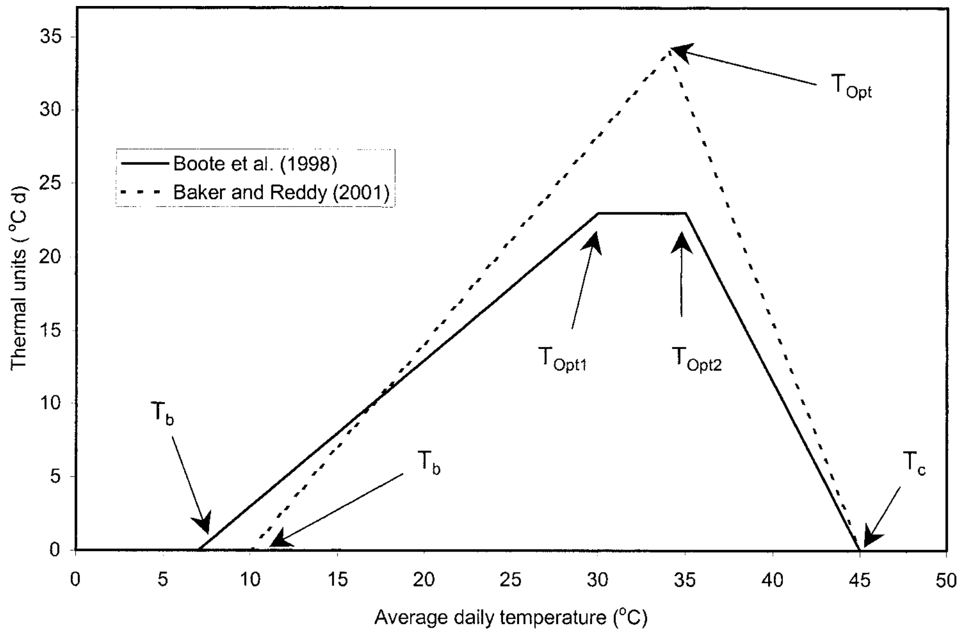

Fig. 1. Thermal units vs. average daily temperatures for cardinal temperature values presented by Boote et al. (1998) and Baker and Reddy (2001). The Baker and Reddy (2001) model has a base temperature (T_b) of 10°C, an optimum temperature (T_{Opt}) of 34°C, and an upper limit (T_c) of 45°C. The Boote et al. (1998) model has a T_b = 7°C, a lower temperature optimum (T_{Opt1}) of 30°C, an upper temperature optimum (T_{Opt2}) of 35°C, and a T_c = 45°C.

The purpose of this report was to determine (a) under what conditions calculations of DTU and HTU differed for two representative thermal-unit models for warm season crops (Boote et al., 1998; Baker and Reddy, 2001) and (b) if the conditions which result in differences between DTU and HTU would affect simulated time for phenological development for a warm-season crop when using long-term weather data.

Materials and Methods

As a first step in comparing the importance of daily temperature calculation on thermal units and crop development, hourly air temperatures were estimated from T_{max}, T_{min}, and daylength using the procedure of Parton and Logan (1981). Three coefficients are required for this method that describe the occurrence of T_{max} and T_{min} and how rapidly temperature decreases after sundown. The coefficients used were those currently in use by the Cropgro simulation model (Boote et al., 1998). The first coefficient (c) defines that T_{min} occurs 1 h after sunrise (c = 1, from Table 1 of Parton and Logan, 1981). The second coefficient (a) defines that T_{max} occurs 2 h after solar noon plus the value of coefficient c (a = 2, Table 1 of Parton and Logan, 1981), and the third coefficient (b) describes how rapidly temperature declines after sundown (b = 2.2, Table 1 of Parton and Logan, 1981). Using this method, from 1 h after sunrise until sundown, hourly temperature follows a sine curve (Fig. 2A), and from sundown until 1 h after sunrise, temperature follows an exponential decay. Predicted hourly temperature values were compared with observed hourly temperature values for data collected from Fayetteville, AR (36°06′ N) in 2002 from Day of Year (DOY) 100 to 214.

To determine conditions in which thermal units on a daily (DTU) and an hourly (HTU) basis differed, simulations were made comparing DTU and HTU using computer programs written in GWBASIC. Two sets of cardinal temperatures were evaluated, both of which are illustrated in Fig. 1. The first set of cardinal temperatures evaluated have been described for vegetative development in soybean (Boote et al., 1998). This model uses a T_b of 7°C, a maximum rate of development between 30 and 35°C (T_{Opt1} and T_{Opt2}, respectively), and a linear decline in development rate above 35°C to 0 at 45°C (T_c). The second set of cardinal temperature values evaluated are those described for muskmelon development (Baker and Reddy, 2001), and unlike the Boote et al. (1998) model, the Baker and Reddy (2001) model has a single T_{Opt}. Although Baker and Reddy (2001) expressed thermal units on an hourly basis (°C h), these units have been converted to a daily basis (°C d) in this report, for both DTU and HTU. Although the cardinal temperature values evaluated in this report have been specifically described for vegetative soybean (Boote et al., 1998) and muskmelon (Baker and Reddy, 2001) development, these values are typical of cardinal temperature values for other warm-season crops.

An initial series of simulations compared DTU and HTU for both the Boote et al. (1998) and Baker and Reddy (2001) cardinal values. Simulations were made in 1°C increments for ADT values from 5 to 45°C. In these simulations, daylength remained constant at 14 h and T_{min} values were always 10°C < T_{max}. Differences between T_{max} and T_{min} average between 10 and 12°C for humid, temperate climates (L.C. Purcell, T.R. Sinclair, and R.W. McNew, 2003, unpublished data).

A second series of simulations were made using weather data collected at Fayetteville, AR, from 1959 to 2001. Weather data were obtained from the National Climatic Data Center (http://lwf.ncdc.noaa.gov/oa/ncdc.html) and contained daily values for T_{max}, T_{min}, and precipitation. Observations that had values flagged as questionable or missing were eliminated. Month-and-day format were replaced with DOY format. Daylength for each DOY at this latitude was calculated as described by Goudriaan (1982) and used as an input variable for the GWBASIC programs. For each of the 43 yr in the data set, DTU and HTU accumulation, using both sets of cardinal values illustrated in Fig. 1, was begun on DOY 100, 150, and 200 to determine the number of days required to accumulate 200°C d.

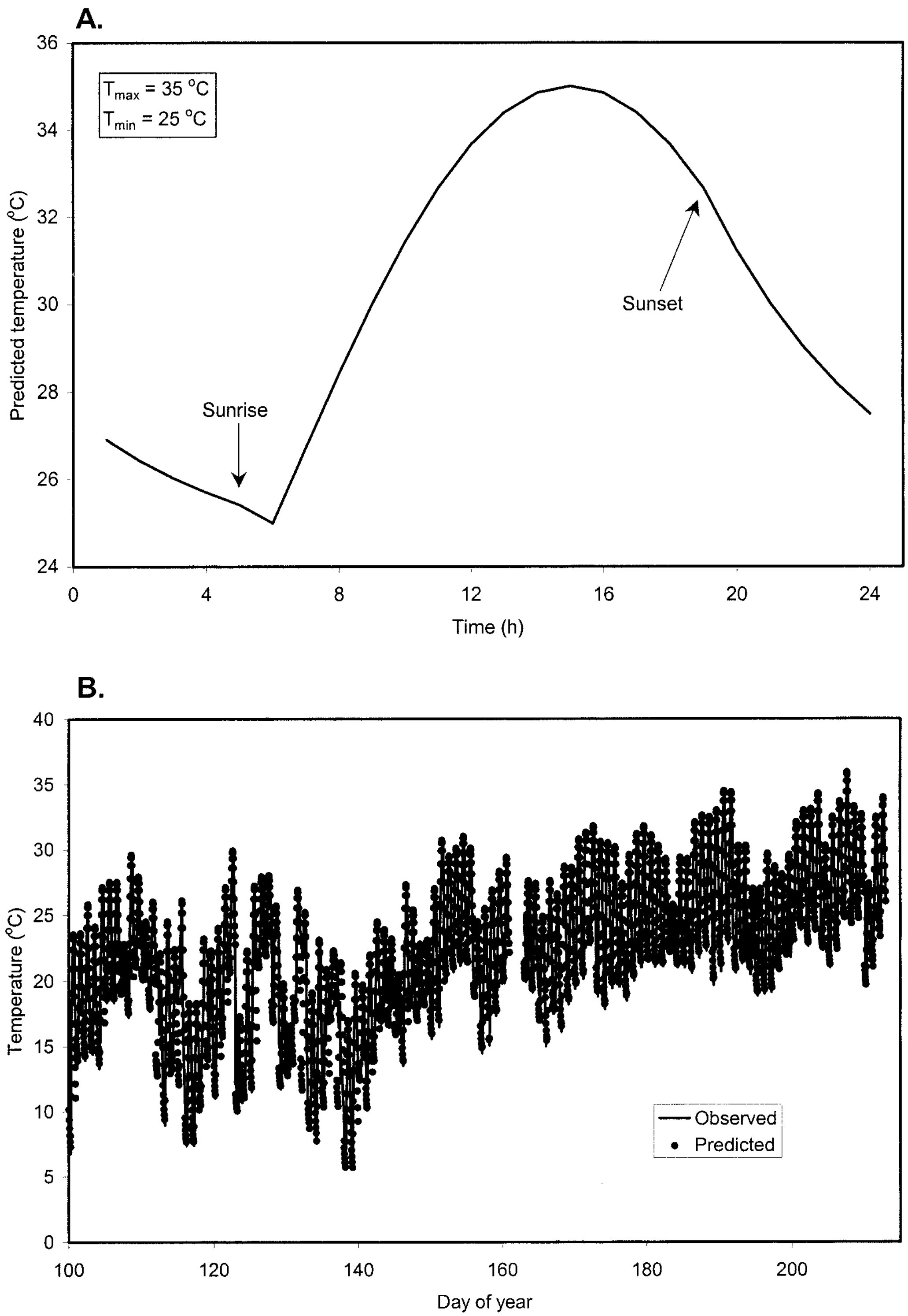

Fig. 2. (A) Predicted hourly temperature profile for a maximum temperature (T_{max}) of 35°C, a minimum temperature (T_{min}) of 25°C, and a daylength of 14 h using the model of Parton and Logan (1981). Predicted and observed hour temperatures at Fayetteville, AR, in 2002 vs. day of year. (B) Hourly temperature values were predicted from maximum and minimum temperatures and daylength using the procedure of Parton and Logan (1981). Data were not available for days of Year 161 and 162.

Results and Discussion

Predicted hourly temperatures, using the method of Parton and Logan (1981), generally agreed well with observed hourly temperatures from DOY 100 to 214 at Fayetteville, AR, in 2002 (Fig. 2B). Overall, the regression of predicted hourly temperature values with observed hourly temperature values for data shown in Fig. 2B had a slope of 0.96, an intercept of 0.97, and an r^2 = 0.90. The predictive ability of this model was decreased (r^2 = 0.78) slightly in early spring (DOY 100 to 140) when rapid movement of weather fronts occasionally caused T_{max} to occur at night or when T_{min} values

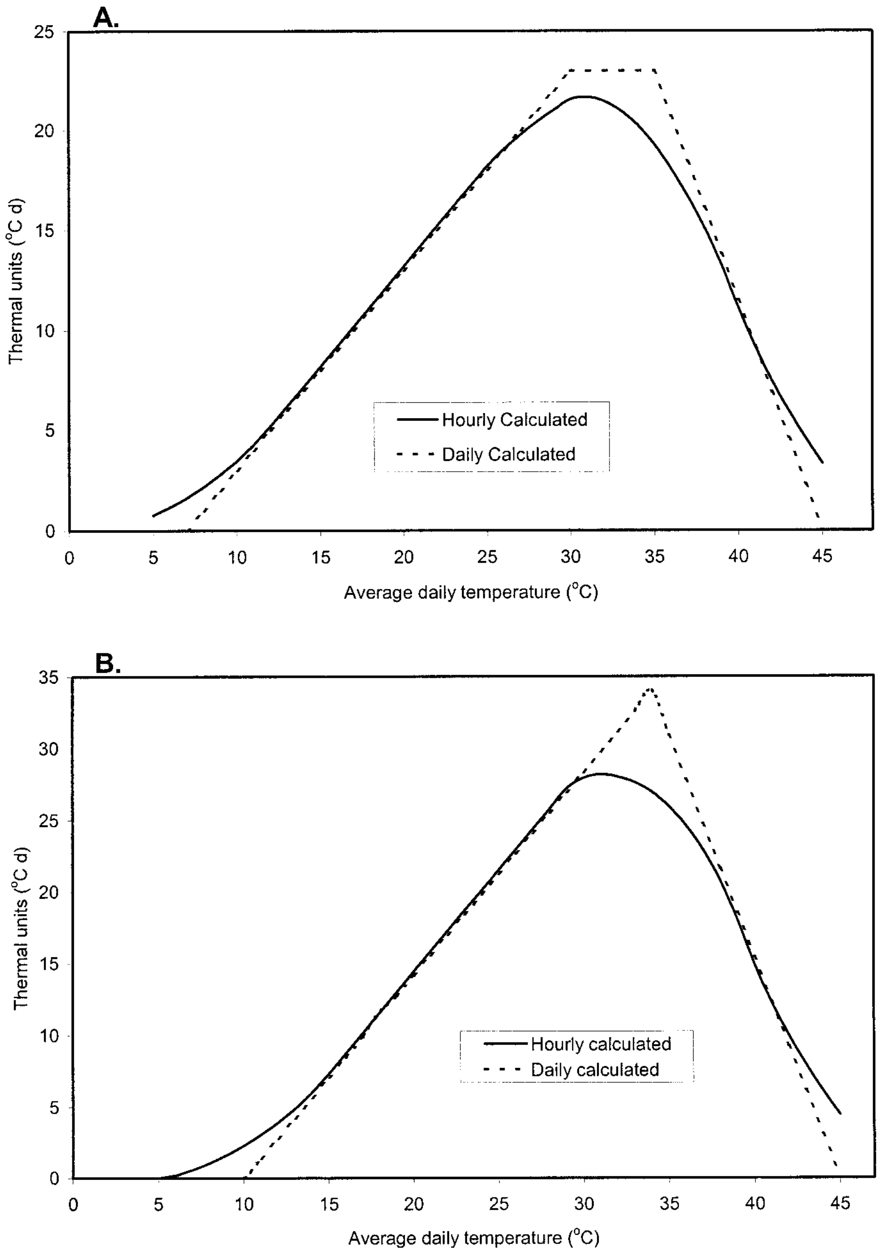

Fig. 3. Simulated thermal unit accumulation for one day calculated on a daily thermal-unit basis or an hourly thermal-unit basis as a function of the average daily temperature. For all calculations, minimum temperature was assumed to be 10°C less than maximum temperature and daylength was 14 h. Thermal units were calculated using the cardinal temperatures of (A) Boote et al. (1998) or of (B) Baker and Reddy (2001).

for sequential days differed greatly. These results are similar to those found by Cesaraccio et al. (2001) who found for several sites in California that hourly temperature predictions using the Parton and Logan (1981) model agreed best with observed values in summer months ($r^2 = 0.89$), but predictive ability decreased slightly in spring ($r^2 = 0.87$) and fall ($r^2 = 0.87$) and were lowest in winter ($r^2 = 0.83$).

For both sets of cardinal temperatures illustrated in Fig. 1, DTU and HTU were virtually identical across the range of ADT values from 15 to 34°C. When ADT <10°C (Fig. 3A) or <12°C (Fig. 3B), DTU was up to 1.6°C d less than HTU. When ADT was >42°C, DTU was also from 0.5 to 4.5°C less than HTU. For the cardinal temperatures presented by Boote et al. (1998, Fig. 1), the largest discrepancy between DTU and HTU occurred when ADT = 35°C with a difference of 3.7°C d (Fig. 3A). A 3.7°C d difference in thermal unit calculation would affect a prediction of phenological development by 0.15 d (i.e., 3.7°C d out of a maximum of 24°C d). For the cardinal temperatures presented by Baker and Reddy (2001, Fig. 1), the maximum discrepancy between DTU and HTU occurred when ADT = 34°C with a difference of 7.0°C d (Fig. 3B). A 7.0°C d difference in thermal unit calculation would affect a prediction of phenological development by 0.21 d (i.e., 7.0°C d out of a maximum of 34°C d). Therefore, several errors of this magnitude or greater would be required to change the prediction of a phenological event by 1 d. The importance of a difference of this magnitude would depend on the quantity of thermal units associated with development, the accuracy expected from the prediction, and

Table 1. Descriptive statistics of the number of days simulated to cumulate 200°C d beginning on three different days of the year (DOY) from 43 yr of weather data at Fayetteville, AR. Thermal units were calculated on either an hourly (HTU) or daily (DTU) basis using cardinal temperatures described by Boote et al. (1998) and Baker and Reddy (2001).

		Boote et al. (1998)			Baker and Reddy (2001)		
Begin simulation	Statistic	HTU	DTU	Diff.†	HTU	DTU	Diff.
DOY		Days					
100	Mean	22.1	23.1	−0.9	22.0	24.1	−2.1
	Standard error	0.5	0.6	0.1	0.6	0.8	0.2
	Minimum	16.0	17.0	−3.0	15.0	16.0	−5.0
	Maximum	30.0	32.0	0.0	32.0	36.0	0.0
150	Mean	12.9	13.2	−0.3	11.4	11.8	−0.3
	Standard error	0.2	0.2	0.1	0.2	0.2	0.1
	Minimum	11.0	11.0	−1.0	9.0	9.0	−1.0
	Maximum	16.0	16.0	0.0	15.0	15.0	0.0
200	Mean	10.2	9.9	0.3	8.2	8.2	0.1
	Standard error	0.1	0.1	0.1	0.1	0.2	0.1
	Minimum	9.0	8.0	−1.0	7.0	7.0	−1.0
	Maximum	12.0	12.0	2.0	10.0	10.0	1.0

† Differences in days between HTU and DTU were evaluated as a separate variable in a manner analogous to HTU and DTU.

the frequency with which these relatively rare temperature extremes occur.

The largest differences between DTU and HTU occurred under extreme conditions not found frequently for many cropping situations, such as ADT >34°C (Fig. 3A, 3B). Weather data for 43 yr at Fayetteville, AR, were used to determine if the frequency of these extreme conditions resulted in DTU or HTU calculations giving different results in the prediction of when accumulation of 200°C d occurred. Using the cardinal temperatures of Boote et al. (1998), the number of days required to cumulate 200°C d, beginning on DOY 100, 150, or 200, did not differ significantly whether calculated using DTU or HTU (Table 1). As the starting date for thermal unit accumulation increased from DOY 100 to 200, the time required to accumulate 200°C d progressively decreased from 22 to 10 d, which reflects the increasing temperatures for the later starting dates.

Using the cardinal temperature values of Baker and Reddy (2001), the number of days required to cumulate 200°C d beginning on DOY 100 was 22 d using HTU and 24 d using DTU, which differed significantly during the 43 yr period (Table 1). As the starting date for thermal unit accumulation increased to DOY 150 and 200, the number of days required to cumulate 200°C d decreased to 11 and 10 d, respectively, and there was no significant difference between the calculation methods.

The maximum discrepancy between the DTU and HTU calculation methods for both sets of cardinal values occurred when thermal unit accumulation began on DOY 100. For the cardinal values presented by Boote et al. (1998), in one year, to cumulate 200°C d was predicted to require 24 d using DTU calculations and 21 d using HTU. For the cardinal temperatures presented by Baker and Reddy (2001), there were several years in which the number of days predicted to cumulate 200°C d differed by 5 d between DTU and HTU methods. These represented the maximum discrepancies between DTU and HTU for the 43-yr simulations, and these occurred in early spring when there were several days when ADT was within 2°C of T_b. Fig. 3A and 3B show that as ADT approaches T_b, HTU is greater than DTU, resulting in a shorter period to cumulate 200°C d for HTU.

The extreme conditions resulting in the discrepancies between DTU and HTU shown in Table 1 would not likely occur for a warm-season cropping situation in that the first frost-free-day of spring in Fayetteville (P = 0.05) is DOY 112 (L.C. Purcell, T.R. Sinclair, and R.W. McNew, 2003, unpublished data), and a warm-season crop would not likely be sown before this date. Nevertheless, the mean difference in the number of days to cumulate 200°C d, as calculated by DTU and HTU for these simulations with a starting date on DOY 100, was <1 d using the Boote et al. (1998) coefficients and ≈2 d using the Baker and Reddy (2001) coefficients (Table 1). When the starting date for thermal unit cumulation was on DOY 150 and 200, differences between DTU and HTU for either set of cardinal temperatures averaged <1 d. Roltsch et al. (1999) and Cesaraccio et al. (2001) found that during summer months in California, several different methods of estimating DTU agreed well with estimates based on HTU.

The analyses presented in this paper indicate that there is little difference between thermal unit accumulation calculated on a daily basis or an hourly basis for representative warm-season crops. Conditions where there is some discrepancy between methods occurred at extreme temperatures to which a warm-season crop would be infrequently exposed. It is concluded that for warm-season annual crops with cardinal temperature values similar to those evaluated in this report, there is no benefit in calculating thermal unit accumulation on an hourly basis relative to calculations on a daily basis.

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