Growing degree-days: one equation, two interpretations

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Abstract

Heat units, expressed in growing degree-days (GDD), are frequently used to describe the timing of biological processes. The basic equation used is GDD = $[(T_{MAX} + T_{MIN})/2] - T_{BASE}$, where T_{MAX} and T_{MIN} are daily maximum and minimum air temperature, respectively, and T_{BASE} is the base temperature. Two methods of interpreting this equation for calculating GDD are: (1) if the daily mean temperature is less than the base, it is set equal to the base temperature, or (2) if T_{MAX} or $T_{MIN} < T_{BASE}$ they are reset equal to T_{BASE}. The objective of this paper is to show the differences which can result from using these two methods to estimate GDD, and make researchers and practitioners aware of the need to report clearly which method was used in the calculations. Although percent difference between methods of calculation are dependent on T_{MAX} and T_{MIN} data used to compute GDD, our comparisons have produced differences up to 83% when using a 0°C base for wheat (*Triticum aestivum* L.). Greater differences were found for corn (*Zea mays* L.) when using a base temperature of 10°C. Differences between the methods occur if only T_{MIN} is less than T_{BASE}, and then Method 1 accumulates fewer GDD than Method 2. When incorporating an upper threshold, as commonly done with corn, there was a greater difference between the two methods. Not recognizing the discrepancy between methods can result in confusion and add error in quantifying relationships between heat unit accumulation and timing of events in crop development and growth, particularly in crop simulation models. This paper demonstrates the need for authors to clearly communicate the method of calculating GDD so others can correctly interpret and apply reported results. © 1997 Published by Elsevier Science B.V.

1. Introduction

Since 1730 when Reaumur introduced the concept of heat units, or thermal time, many methods of calculating heat units have been used successfully in the agricultural sciences. Particularly in the areas of crop phenology and development, the concept of heat units, measured in growing degree-days (GDD, °C-day), has vastly improved description and predic-

tion of phenological events compared to other approaches such as time of year or number of days (e.g., Cross and Zuber, 1972; Gilmore and Rogers, 1958; Klepper et al., 1984; McMaster, 1993; McMaster and Smika, 1988; Russelle et al., 1984).

The canonical form for calculating GDD is:

$$GDD = \left[\frac{(T_{MAX} + T_{MIN})}{2} \right] - T_{BASE} \qquad (1)$$

where T_{MAX} is the daily maximum air temperature, T_{MIN} is the daily minimum air temperature, and

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T_{BASE} is the temperature below which the process of interest does not progress. T_{BASE} varies among species and possibly cultivars, and likely varies with growth stage or process being considered (Wang, 1960). To simplify Eq. (1), the quantity $[(T_{MAX} + T_{MIN})/2]$ is sometimes set equal to T_{AVG}. The intent of Eq. (1) is to describe the heat energy received by the crop over a given time period (i.e., integrate the area under the diurnal temperature curve, sum the daily heat energy over an interval of time, and then relate the accumulation of heat energy to progress in development or growth processes).

Many modifications to enhance the biological meaning of Eq. (1) have been suggested such as (1) incorporating an upper temperature threshold (Gilmore and Rogers, 1958; McMaster and Smika, 1988; Wang, 1960), (2) converting to photothermal units by adding a photoperiod variable (Masle et al., 1989; Nuttonson, 1948), (3) using only the maximum or minimum temperature or portion of the day (Cross and Zuber, 1972; Masle et al., 1989), and (4) incorporating functions for other environmental factors that affect phenology or the process being considered (e.g., water, nutrients, light quality or quantity, CO_2; McMaster et al., 1992b; Wilhelm and McMaster, 1995). Also, much effort has been directed toward improving the way Eq. (1) represents the integral of the diurnal temperature curve such as (1) calculating T_{AVG} using hourly temperatures (Cross and Zuber, 1972) or as a modified sine wave or other diurnal temperature patterns (Allen, 1976; Pruess, 1983; Zalom et al., 1983) and (2) correcting for variable observation times of T_{MAX} and T_{MIN} (DeGaetano and Knapp, 1993). While these efforts often improve the accuracy of predictions, many anomalies continue to exist that violate underlying assumptions. Obvious examples include weather fronts occuring during a day shifting maximum and minimum temperatures from typical times and changing the diurnal pattern significantly from the assumed pattern. For detailed review of the concept of GDD, see Arnold (1960), Pruess (1983), Wang (1960), and Zalom et al. (1983).

A number of scientists have tested the accuracy of various forms of the basic GDD equation (Eq. (1)) in predicting various growth and development processes in several species. For example, Perry et al. (1986) noted 14 variations of calculating GDD for

cucumber (*Cucumis sativus* L.), Cross and Zuber (1972) discuss 22 methods, and Gilmore and Rogers (1958) examined 15 different methods of calculating GDD for corn.

Among all the methods of calculating GDD and its modifications, it was not until very recently that important differences in implementing Eq. (1) became apparent to us. Depending on the method of implementation, which as a general rule seems to vary depending on the crop, different values of GDD are calculated. In examining the literature and discussing this among scientists using GDD calculations on a regular basis, we realized that Eq. (1) is being implemented differently and users are unaware of this difference in implementation. This can be important in simulation models where values of GDD for duration of a process are estimated. If the method of calculating GDD is not the same in both the model and values used to parameterize the model, error is introduced. The same problem would apply to practitioners using GDD estimates calculated differently from how they calculate GDD.

The objectives of this paper are to describe the two implementations of calculating GDD from Eq. (1), what this means, and to stress the importance of clearly noting which method is being used when reporting GDD. Differences in implementation of Eq. (1) can also be a problem in many of the variations of the canonical equation defined by Perry et al. (1986), Cross and Zuber (1972), and others.

2. Calculations

Two interpretations of Eq. (1) are reported in the literature which differ in how the base temperature is incorporated into the equation.

2.1. Method 1

$$GDD = \left[\frac{(T_{MAX} + T_{MIN})}{2} \right] - T_{BASE}$$

where if $[(T_{MAX} + T_{MIN})/2] < T_{BASE}$, then $[(T_{MAX} + T_{MIN})/2] = T_{BASE}$. This method seems to be the most widespread method used for calculating GDD, particularly in simulation models (e.g., Davidson and

Campbell, 1983; Gallagher, 1979; Goyne et al., 1977; Jefferies and Mackerron, 1987; Kirby, 1995; Mathan, 1989; Masle et al., 1989; McMaster and Smika, 1988; Narwal et al., 1986; Nield and Seeley, 1977). This method predominates among researchers and practitioners involved with small grain cereals such as wheat and barley (*Hordeum vulgare* L.).

2.2. Method 2

$$GDD = \left[\frac{(T_{MAX} + T_{MIN})}{2} \right] - T_{BASE}$$

where if $T_{MAX} < T_{BASE}$, then $T_{MAX} = T_{BASE}$, and if $T_{MIN} < T_{BASE}$, then $T_{MIN} = T_{BASE}$. Sometimes a variation is comparing only T_{MIN} to T_{BASE}. This is the most commonly used method in calculating GDD for corn, but is used for other crops as well (e.g., Baker et al., 1986; Bauer et al., 1988; Cutforth and Shaykewich, 1989; Edwardson and Watt, 1987; Ketring and Wheless, 1989; Masoni et al., 1990; Russelle et al., 1984; Swanson and Wilhelm, 1996; Tollenaar et al., 1979; Wilhelm et al., 1987, 1989). Occasionally, a combination of the two methods is used (e.g., Baker et al., 1986).

The important distinction between the two methods is when temperatures are compared to the base temperature. In Method 1, the comparison to T_{BASE} occurs after calculating T_{AVG}, whereas in Method 2 the comparison to T_{BASE} is made before calculating $\frac{(T_{MAX} + T_{MIN})}{2}$ by comparing T_{MAX} and T_{MIN} to T_{BASE} individually.

When examining the literature, it is often difficult to ascertain which method was used. Based on our experience, and then discussing this with others, it appears that researchers assume incorrectly that all others apply Eq. (1) as they do. For example, in McMaster and Smika (1988) and Wilhelm et al. (1987, 1989), we calculated GDD as we thought correct (McMaster, Method 1; Wilhelm, Method 2), but did not clearly present the method used in the papers. When collaborating (McMaster and Wilhelm, 1997) we discovered this difference in implementing Eq. (1).

Once aware of the discrepancy in calculating GDD, we asked other scientists how they calculated GDD to determine if one of us was in error, and

soon realized that there was no commonly agreed upon method. Examination of the literature (see examples cited above), confirmed this realization, yet we did not know if the discrepancy was important.

3. Methods

We used both methods to compute GDD for several sets of temperature data and compared the results. The first data set was hypothetical to ensure that various combinations of maximum, minimum, and base temperatures were tested. These temperatures were within commonly expected temperatures for winter wheat and corn in the central Great Plains. The second data set was collected at the Colorado State University Horticulture Farm in 1987 using a standard Class A weather station (McMaster et al., 1994). Daily maximum and minimum air temperatures were recorded at 2 m above the soil surface. Growing degree-days were calculated for the winter wheat growing season (September through July) and corn (April through October). The base temperature used for winter wheat was 0°C (McMaster and Smika, 1988) and for corn was 10°C (Cross and Zuber, 1972).

Because GDD for corn normally are calculated using an upper temperature threshold (T_{UT}), we modified both methods to also incorporate T_{UT} to better assess differences between the two methods. We set T_{UT} equal to 30°C for corn (Cross and Zuber, 1972) and 25°C for wheat (McMaster and Smika, 1988). Upper threshold temperatures are incorporated into the GDD calculations using the following temperature adjustments before evaluating Eq. (1). Method 1: before entering temperature data into Eq. (1), the average temperature $\left[\frac{(T_{MAX} + T_{MIN})}{2} \right]$ is set equal to T_{BASE} if less than T_{BASE} and is set equal to T_{UT} when greater than T_{UT}. Method 2: before entering temperature data into Eq. (1), T_{MAX} and T_{MIN} are set equal to T_{BASE} if less than T_{BASE} and are set equal to T_{UT} when greater than T_{UT}.

4. Results and discussion

A hypothetical 10-day temperature data set illustrates how the methods differ in calculating GDD. A

Table 1
Example of calculating growing degree-days using two different methods for wheat. The data are hypothetical and used to illustrate various temperature combinations. The base temperature used is 0°C

Day	T_{MAX} (°C)	T_{MIN} (°C)	T_{AVG} (°C)	Method 1[a]			Method 2[b]			
				Adjusted T_{AVG} (°C)	GDD (°C-day)	Sum (°C)	Adjusted T_{MAX} (°C)	Adjusted T_{MIN} (°C)	GDD (°C-day)	SUM (°C-day)
1	20	10	15.0	15.0	15.0	15.0	20	10	15.0	15.0
2	10	1	5.5	5.5	5.5	20.5	10	1	5.5	20.5
3	8	−2	3.0	3.0	3.0	23.5	8	**0**	4.0	24.5
4	6	0	3.0	3.0	3.0	26.5	6	0	3.0	27.5
5	10	5	7.5	7.5	7.5	34.0	10	5	7.5	35.0
6	5	−5	0.0	**0.0**[c]	0.0	34.0	5	**0**	2.5	37.5
7	−2	−7	−4.5	**0.0**	0.0	34.0	**0**	**0**	0.0	37.5
8	−5	−10	−7.5	**0.0**	0.0	34.0	**0**	**0**	0.0	37.5
9	10	−2	4.0	4.0	4.0	38.0	10	**0**	5.0	42.5
10	15	2	8.5	8.5	8.5	46.5	15	2	8.5	51.0

[a] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$.

[b] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$.

[c] Numbers in boldface were adjusted.

difference of 4.5 GDD, or about 10%, occurred between the two methods when using $T_{\text{BASE}} = 0°C$ for wheat (Table 1). Graphical illustration of different estimates for the two methods is shown in Fig. 1. In situations where T_{MAX} and T_{MIN} exceed T_{BASE} (Fig. 1A) or T_{MAX} and T_{MIN} are less than T_{BASE} (Fig. 1C), both methods result in the same estimate of T_{AVG}, and therefore estimate the same GDD (in the latter case). When $T_{\text{MIN}} < T_{\text{BASE}} < T_{\text{MAX}}$, Method 2 estimates more GDD than Method 1 because the adjusted T_{AVG} is greater due to resetting T_{MIN} to T_{BASE} (Fig. 1B).

With field data, much greater differences between the methods are observed. For wheat, the greatest difference occurred during February, with Method 2 having 83% (45 GDD) more thermal units than Method 1 (Table 2). Even greater differences between the methods were obtained for corn ($T_{\text{BASE}} = 10°C$), with the month of October having the greatest difference of 376% (94 GDD) between the methods (Table 3). When GDD were summed over the growing season, the two methods differed by 9 and 28% (254 and 326 GDD) for wheat and corn, respec-

tively. Differences of this magnitude can be quite important.

Using wheat to illustrate the impact of the differences noted in the two interpretations of Eq. (1) and assuming that T_{AVG} is 18°C in June, then a cumulative difference of 254 GDD between the methods is equivalent to approximately 14 calendar days. Estimating maturity will therefore be in error by at least 14 days just due to the different methods of calculating GDD. Actually the error will probably be greater because most of the differences in the calculations occurred during months with much lower T_{AVG}, and therefore even more calendar days are equivalent to 254 GDD. This suggests that predicting growth stages such as jointing will have greater error than for growth stages such as maturity.

Another way of assessing the importance of the difference defined in the previous paragraph between the methods is to realize that most of the difference resulted during the vegetative stage of development for winter wheat. If we assume a phyllochron, or rate of leaf appearance, of 105 GDD leaf^{-1} (McMaster and Wilhelm, 1995; McMaster et al., 1992a), then a
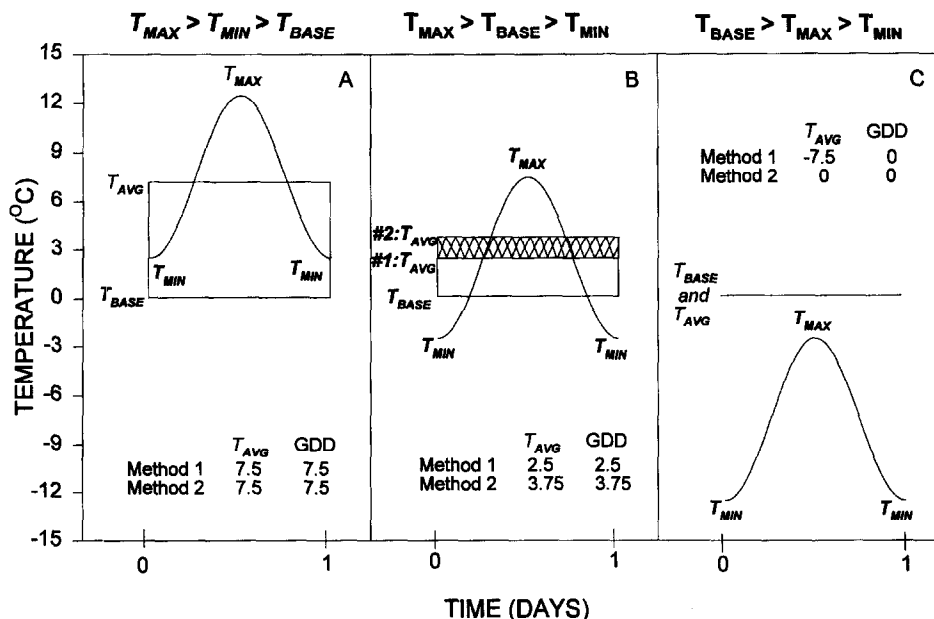

Fig. 1. Visual representation of the different integration areas by the two methods of calculating GDD for different conditions. For illustrative purposes, the diurnal temperature curve is represented as a sine curve. In these examples, (A) represents situations where $T_{\text{MAX}} > T_{\text{MIN}} > T_{\text{BASE}}$, (B) represents conditions where $T_{\text{MAX}} > T_{\text{BASE}} > T_{\text{MIN}}$, and (C) $T_{\text{BASE}} > T_{\text{MAX}} > T_{\text{MIN}}$. The base temperature is 0°C. The cross-hatched area in (B) denotes the difference estimated by the two methods. In (A) and (C) both methods estimate the same GDD.

Table 2

Comparison of methods for winter wheat using 1987 weather data from Fort Collins, CO. Months are ordered from September, when winter wheat is normally planted, through July, when typically harvested

Month	Base only[a]						Base and upper threshold[b]					
	Interval			From 1 September			Interval			From 1 September		
	Method 1[c]	Method 2[d]	Diff.	Method 1	Method 2	Diff.	Method 1[e]	Method 2[f]	Diff.	Method 1	Method 2	Diff.
	GDD	GDD	%	GDD	GDD	%	GDD	GDD	%	GDD	GDD	%
Sep	424	424	0	424	424	0	424	412	−3	424	412	−3
Oct	240	279	16	664	703	6	240	278	16	664	690	4
Nov	103	144	40	767	847	10	103	144	40	767	834	9
Dec	0	3	–	767	850	11	0	3	–	767	837	9
Jan	64	109	70	831	959	15	64	109	70	831	946	14
Feb	54	99	83	885	1058	20	54	99	84	885	1045	18
Mar	100	151	51	985	1209	23	100	151	51	985	1196	21
Apr	276	306	11	1261	1515	20	276	301	9	1261	1497	19
May	415	415	0	1676	1930	15	415	411	−1	1676	1908	14
June	553	553	0	2229	2483	11	553	511	−8	2229	2419	9
July	631	631	0	2860	3114	9	631	557	−12	2860	2976	4

[a] Using T_{BASE} only (0°C).

[b] Using T_{BASE} (0°C) and an upper threshold (25°C).

[c] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$.

[d] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$.

[e] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$; if $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] > T_{UT}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{UT}$.

[f] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$; if $T_{MAX} > T_{UT}$, $T_{MAX} = T_{UT}$; if $T_{MIN} > T_{UT}$, $T_{MIN} = T_{UT}$.

Table 3

Comparison of methods for corn using 1987 weather data from Fort Collins, CO. Months are ordered from April, when corn is normally planted, through October, when typically harvested

Month	Base only[a]						Base and upper threshold[b]					
	Interval			From 1 April			Interval			From 1 April		
	Method 1[c]	Method 2[d]	Diff.	Method 1	Method 2	Diff.	Method 1[e]	Method 2[f]	Diff.	Method 1	Method 2	Diff.
	GDD	GDD	%	GDD	GDD	%	GDD	GDD	%	GDD	GDD	%
Apr	58	138	138	58	138	138	54	133	146	54	133	146
May	111	165	49	169	303	79	107	160	50	161	293	82
June	253	264	4	422	567	34	211	221	5	372	514	38
July	321	328	2	743	895	20	247	254	3	619	768	24
Aug	257	268	4	1000	1163	16	222	233	5	841	1001	19
Sep	129	198	53	1129	1361	21	117	186	59	958	1187	24
Oct	25	119	376	1154	1480	28	24	117	388	982	1304	33

[a] Using T_{BASE} only (10°C).

[b] Using T_{BASE} (10°C) and an upper threshold (30°C).

[c] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$.

[d] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$.

[e] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$; if $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] > T_{UT}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{UT}$.

[f] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$; if $T_{MAX} > T_{UT}$, $T_{MAX} = T_{UT}$; if $T_{MIN} > T_{UT}$, $T_{MIN} = T_{UT}$.

Table 4
Example of calculating growing degree-days using two different methods for corn when adding an upper threshold. The data are hypothetical and used to illustrate various temperature combinations. The base temperature used is 10°C; the upper threshold is 30°C

Day	T_{MAX} (°C)	T_{MIN} (°C)	T_{AVG} (°C)	Method 1[a]			Method 2[b]			
				Adjusted T_{AVG} (°C)	GDD (°C-day)	Sum (°C-day)	Adjusted T_{MAX} (°C)	Adjusted T_{MIN} (°C)	GDD (°C-day)	Sum (°C-day)
1	30	15	22.5	22.5	12.5	12.5	30	15	12.5	12.5
2	35	20	27.5	27.5	17.5	30.0	35	20	17.5	30.0
3	37	27	32.0	**30.0**[c]	20.0	50.0	37	27	22.0	52.0
4	40	32	36.0	**30.0**	20.0	70.0	40	32	26.0	78.0
5	31	20	25.5	25.5	15.5	85.5	31	20	15.5	93.5
6	27	15	21.0	21.0	11.0	96.5	27	15	11.0	104.5
7	20	8	14.0	14.0	4.0	100.5	20	**10**	5.0	109.5
8	17	5	11.0	11.0	1.0	101.5	17	**10**	3.5	113.0
9	9	3	6.0	**10.0**	0.0	101.5	**10**	**10**	0.0	113.0
10	15	12	13.5	13.5	0.0	101.5	15	12	3.5	116.5

[a] If $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$; if $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] > T_{UT}$, then $\left[\dfrac{(T_{MAX} + T_{MIN})}{2}\right] = T_{UT}$.

[b] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$; if $T_{MAX} > T_{UT}$, $T_{MAX} = T_{UT}$; if $T_{MIN} > T_{UT}$, $T_{MIN} = T_{UT}$.

[c] Numbers in boldface were adjusted.

Table 4 **CORRECTED**

Example of calculating growing degree-days using two different methods for corn when adding an upper threshold. The data are hypothetical and used to illustrate various temperature combinations.
The base temperature used is 10°C; the upper threshold is 30°C

Day	T_{MAX} (°C)	T_{MIN} (°C)	T_{AVG} (°C)	Method 1[a]			Method 2[b]			
				Adjusted T_{AVG} (°C)	GDD (°C-day)	Sum (°C-day)	Adjusted T_{MAX} (°C)	Adjusted T_{MIN} (°C)	GDD (°C-day)	Sum (°C-day)
1	30	15	22.5	22.5	12.5	12.5	30	15	12.5	12.5
2	35	20	27.5	27.5	17.5	30.0	**30**	20	15.0	27.5
3	37	27	32.0	**30.0**[c]	20.0	50.0	**30**	27	18.5	46.0
4	40	32	36.0	**30.0**	20.0	70.0	**30**	**30**	20.0	66.0
5	31	20	25.5	25.5	15.5	85.5	**30**	20	15.0	81.0
6	27	15	21.0	21.0	11.0	96.5	27	15	11.0	92.0
7	20	8	14.0	14.0	4.0	100.5	20	**10**	5.0	97.0
8	17	5	11.0	11.0	1.0	101.5	17	**10**	3.5	100.5
9	9	3	6.0	**10.0**	0.0	101.5	**10**	**10**	0.0	100.5
10	15	12	13.5	13.5	3.5	105.0	15	12	3.5	104.0

[a] $[(T_{MAX} + T_{MIN})/2] < T_{BASE}$, then $[(T_{MAX} + T_{MIN})/2] = T_{BASE}$; if $[(T_{MAX} + T_{MIN})/2] > T_{UT}$, then $[(T_{MAX} + T_{MIN})/2] = T_{UT}$.
[b] If $T_{MAX} < T_{BASE}$, $T_{MAX} = T_{BASE}$; if $T_{MIN} < T_{BASE}$, $T_{MIN} = T_{BASE}$. $T_{MAX} > T_{UT}$, $T_{MAX} = T_{UT}$; $T_{MIN} > T_{UT}$, $T_{MIN} = T_{UT}$.
[c] Numbers in boldface were adjusted.

difference of about 2.4 leaves would be predicted based on the difference between methods. In simulation models such as MODWht (Rickman et al., 1995) and SHOOTGRO (McMaster et al., 1992a; Wilhelm et al., 1993), or conceptual models of development (e.g., Klepper et al., 1984), where phenological development is closely integrated using the phyllochron, errors of 2.4 leaves are significant in predicting the timing of events, canopy development, and other processes.

These results suggest that differences of well over 50% can occur between the two methods of calculating GDD. As a result, estimating GDD by one method and applying the estimate to an algorithm parameterized by the other method results in unnecessary errors. The magnitude of the error is entirely dependent on the temperature data used to calculate GDD. If T_{MIN} is never less than T_{BASE}, the methods produce identical results (Fig. 1A; Table 1, days 1, 2, 5, and 10). However, this is rarely, if ever, encountered in field situations. When only T_{MIN} is less than T_{BASE}, Method 1 will calculate fewer GDD than Method 2 (Fig. 1B; Table 1, days 3, 6, and 9). This situation occurs when temperatures are normally near T_{BASE}. For winter wheat in Colorado, this is late fall and winter and early spring (Table 2). For corn, this is spring and late fall (Table 3). When both T_{MAX} and T_{MIN} are less than T_{BASE}, again both methods will calculate the same GDD (Fig. 1C; Table 1, days 7 and 8). For winter wheat, this occurs during winter; for corn it occasionally occurs in late spring and early fall. Changing the base temperature does not resolve the problem, it only changes the timing of the difference between methods.

When an upper threshold is incorporated into the GDD calculations, as is normally done for crops such as corn (e.g., Cross and Zuber, 1972; Gilmore and Rogers, 1958; Russelle et al., 1984), significant differences continue to result between the two methods. An upper threshold is incorporated into the calculation the same way as the base temperature, except that either T_{AVG}, T_{MAX}, or T_{MIN} are reset to T_{UT} whenever they exceed T_{UT} (Table 4). For corn, the upper threshold is typically set to 30°C (Cross and Zuber, 1972; Russelle et al., 1984). With the incorporation of an upper threshold, the differences in GDD calculated between the two methods is slightly greater than when using only a base tempera-

ture for corn (Table 3) and slightly less for wheat when using a 25°C upper threshold (Table 2). Even when differences between methods were decreased when adding an upper threshold, the differences remained large. In the situation where $T_{MAX} > T_{UT} > T_{MIN}$, Method 1 estimates more GDD than Method 2, the opposite of when $T_{MIN} < T_{BASE} < T_{MAX}$ (Fig. 1B) where Method 1 estimates fewer GDD than Method 2. Therefore, when summing GDD over a growing season, differences in methods may negate each other. However, daily estimate differences will still exist.

The GDD approach is often used in crop models (e.g., Baker and Landivar, 1991; Kiniry and Bonhomme, 1991; Rickman et al., 1995; Weir et al., 1984; Wilhelm et al., 1993; Williams et al., 1989). Both methods of calculating GDD are used in crop models, and to be certain of the method used, one must examine the code because documentation is usually not clear. To avoid unnecessary error, the methods used in calculating GDD in the model must agree with the values used to parameterize the model. Because models are usually parameterized from literature data and the literature usually does not specify which method was used to calculate GDD, it is likely that the problem we identified is common in models.

Given there are two interpretations for calculating GDD, it is tempting to suggest a standard. We have several problems with doing this. First, we do not feel either method is more correct. In fact, both methods ere only approximations for the true GDD (Arnold, 1960). Second, both methods are, and have been, widely used. In essentially all cases, it is not possible to recalculate the GDD because it is either not known which method was used, or the data are not available, or both. Third, the decision to create a standard would best be made by a group composed of individuals with diverse experiences in crop research and management and the standard may need to better approximate the true GDD value (Pruess, 1983; Zalom et al., 1983).

5. Conclusion

There are two implementations of the basic GDD equation:

$$\text{GDD} = \left[\frac{(T_{MAX} + T_{MIN})}{2} \right] - T_{BASE} \quad \text{in}$$

wide-spread use today. These implementations result in different GDD estimates. Therefore, we strongly urge authors to precisely describe the method of calculating GDD in their papers. By clearly defining the method used to compute GDD, research results can be interpreted and applied correctly by others.

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