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An integral model to calculate the growing degree-days and heat units, a spreadsheet application

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ABSTRACT

The concept of heat units is used in several phenological studies like the prediction of sowing and harvesting dates, crop yield, length of plant stages, and maturity state. However, calculation of heat units as growing degree-days requires a summation process that is not easily performed like direct-substitution equations. The aim of this work was to develop a simple integral model to calculate the heat units as growing degree-days. The development involved two steps; the first step was applying a non-iterative sinusoidal fit to the discrete temperature data to get a fitting equation of each station in the two datasets, CLIMWAT 2 and FAOCLIM 2. The second step was to integrate each temperature equation to calculate the heat units, either by the average temperature or by both the minimum and maximum temperatures. The results showed that the sinusoidal model properly fits the temperature profiles in most of the studied stations (Most of the stations got the fit with $R^2 > 95\%$ and 98.4% of the stations had <2 °C root mean squared error). Additionally, the results showed no significant differences (in accuracy) between the developed integral model and the conventional summation methods of calculating the heat units, while the new model is faster and easier in application. Finally, it is recommended to use the new integral model with the fitted average temperature due to its accuracy and simplicity.

1. Introduction

Temperature has a significant effect on the plant's life cycle from sowing to harvest. The thermal time or heat units concept (HU) is widely used to determine the growing season's length of vegetables and field crops (McMaster and Wilhelm, 1997; Akinci and Abak, 1999; Russelle et al., 1984; Elnesr et al., 2013). The HU concept is also used to predict grain moisture, crop yield, length of plant stages, maturity, harvesting date, and other phenological properties (Russelle et al., 1984; Griffin and Honeycutt, 2000; Miller et al., 2001; Nielsen and Hinkle, 1996; Swan et al., 1987; Gilmore and Rogers, 1958; Villordon et al., 2009). The heat units value is calculated in terms of the growing degree-days (GDD) (McMaster and Wilhelm, 1997; Akinci and Abak, 1999) as follows:

$$\mathrm{HU} = \sum_{i=1}^{n} \mathrm{GDD}_i \tag{1}$$

$$\mathrm{GDD} = \mathrm{MAX}\{0, (0.5(T_x + T_n) - T_b)\} \tag{2}$$

where T_x and T_n are the maximum and minimum daily temperatures respectively; T_b: is the crop's base temperature; i: an index for each growing day in the crop growing duration (season's length) n [Days]. The GDD value should always be positive, if the calculations lead to negative value it should be recorded as zero. In case of the existence of the average temperature T_a instead of T_x and T_n, some investigators (McMaster and Wilhelm, 1997) simplified Eq. (2) to the form:

$$\mathrm{GDD} = \mathrm{MAX}\{0, (T_a - T_b)\} \tag{3}$$

A study by the University of Dayton, 2003) on over 53,000 records of the Global Summary of the Day dataset (GSOD) found that the absolute value of the deviation between the mean temperature T_a computed from 24 hourly temperature readings and the $0.5(T_x + T_n)$ of the same records were 0.82 °C, which is not statistically significant.

However, the formula of the HU is a summation formula; for each day of the n days of the growing season, it requires one evaluation of Eq. (2). On the method of determining the most suitable sowing date (Elnesr et al., 2013), the method involves computing HU for each day of the year, then to compare it to the acceptable range of HU values, and hence specifying the suitable sowing dates.

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This requires $365 \times n$ evaluations of Eq. (2) that requires long calculation times, in addition to the need of accessing the climate database to find T_x and T_n of each day of the year or storing a massive amount of data in the computer's memory.

Several attempts were made to improve the accuracy of the GDD methods (Higley et al., 1986; Allen, 1976; Cesaraccio et al., 2001), or to compare several methods to find the optimum one (Roltsch et al., 1999). However, all the cited methods depend on summation, which requires hundreds of calculation steps. Accordingly, the target of this work was to find simpler equation that evaluates HU with fewer calculations, and without significant loss in precision, thus we thought about converting the HU summation formula to integral form, which is faster in calculation, and almost as precise as the summation form. The main difference between the summation and the integral forms is the continuity of the data; while the summation involves the discrete values with the upper and lower bounds, whereas the integration involves continuous values. The daily temperature data is discrete, so it should be manipulated by the summation formulas unless we found a method to convert it to continuous values. Several investigators showed that the dry air temperature data can be well fitted using sinusoidal functions in either sine or cosine forms (Mazarron and Canas, 2008; Schawe, 1995; Parton and Logan, 1981; Fabrick, 2015). Converting the discrete data into a continuous sinusoidal fit requires non-linear curve fitting algorithm (trial and error), however, Jacquelin (Jacquelin, 2009) developed a direct-substitution method to fit such data easily and precisely. Our objectives were (1) to verify the goodness of the sinusoidal fit of temperature. (2) To develop the integral formula of the heat units' calculation. (3) To compare the developed formulas to the original method using data from different climate stations worldwide.

2. Material and methods (model development)

2.1. Data sources and datasets description

In this research, we used resources from four datasets, three for climatic information, and the fourth for crop information. The first is the CLIMWAT 2.0 dataset, which offers observed agroclimatic monthly data of over 5000 stations worldwide (Muñoz and Grieser, 2006; FAO, 2006). This dataset provides long-term monthly mean values of seven climatic parameters: maximum and minimum temperature, relative humidity, wind speed, sunshine hours, solar radiation, total and effective rainfall, and the Penman–Monteith reference evapotranspiration. In this paper, we used only the maximum and minimum temperature values. This dataset was used for calculating the fitting equations for each climatic station in the development and validation stage.

For verification, we used another dataset that provides daily observations, that is the 'Weather Underground' dataset, which provides historic daily observations and forecasts for more than 169,000 weather stations worldwide (140,000 stations in North America, and 29,000 stations worldwide) (Masters, 2015). The dataset provides more than 20 meteorological factors, but we only used the maximum, average, and minimum temperature daily observations. We selected 15 stations representing all continents and meteorological conditions, the selected stations' information are shown in Table 1.

Finally, we used the FAOCLIM-2 database, which covers monthly data for 28,100 stations, for up to 14 observed and computed agroclimatic parameters (FAO, 2001). This dataset were used to apply the model on it after verification.

Regarding the crop information, the crop thermal data were obtained from several publications (Elnesr et al., 2013; Splittstoesser, 1990; Alsadon, 2002; Clarke et al., 2001; Maynard and Hochmuth, 2006). The obtained data includes the crop's maximum, minimum, optimum, and base temperatures, along with the prevailing season's length, and the percent heat tolerance above the optimal heat units.

2.2. The non-iterative sinusoidal fitting model

The simple form of the sinusoidal equation representing relationship between the temperature (T) and the Julian day number (j) is as follows:

$$T(j) = a + \rho \sin(\omega j + \varphi) \tag{4}$$

where a: the mean temperature on the curve, °C; ρ: the amplitude of the sine wave (half the peak-to-peak distance of the curve), °C; ω is the frequency (number of occurrences of the curve per year, usually $\approx \pi/180$), radians; and φ: the phase (the fraction of the wave cycle that has elapsed relative to the origin), radians (Ballou, 2005).

The sinusoidal model is nonlinear that is normally solved by successive iterations, which is a lengthy operation that require special software or code to perform. Jacquelin (2009) introduced a straight-forward algorithm that requires no iteration to obtain the fitting parameters of the sinusoidal curve, this algorithm is easier, faster, and more precise than any other iterative algorithm. The algorithm can be summarized in the following:

- Given the dataset pairs the Julian day j and its corresponding temperature $T(j)$, sorted ascending on j.
- For each i in the n members of the dataset (if we are fitting the monthly data, $n = 12$; when fitting daily data, $n = 365$; etc.), calculate the two supporting variables S_i and G_i (where $S_1 = 0$ and $G_1 = 0$):

$$S_i = S_{i-1} + 0.5(T_i + T_{i-1})(j_i - j_{i-1}) \tag{5}$$
$$G_i = G_{i-1} + 0.5(S_i + S_{i-1})(j_i - j_{i-1}) \tag{6}$$

- Solve the matrix system for the temporary variables A_1, B_1, C_1, and D_1:

$$\begin{pmatrix} A_1 \\ B_1 \\ C_1 \\ D_1 \end{pmatrix} = \begin{pmatrix} \Sigma G_i^2 & \Sigma G_i j^2 & \Sigma G_i j & \Sigma G_i \\ \Sigma G_i j_i^2 & \Sigma j_i^4 & \Sigma j_i^3 & \Sigma j_i^2 \\ \Sigma G_i j_i & \Sigma j_i^3 & \Sigma j_i^2 & \Sigma j_i \\ \Sigma G_i & \Sigma j_i^2 & \Sigma j_i & n \end{pmatrix}^{-1} \begin{pmatrix} \Sigma T_i G_i \\ \Sigma T_i j_i^2 \\ \Sigma T_i j_i \\ \Sigma T_i \end{pmatrix} \tag{7}$$

- Calculate the first estimate of the variables ω, a, b, and c, where b and c are step parameters to calculate ρ and φ:

$$\omega_1 = \sqrt{A_1} \tag{8}$$
$$a_1 = 2B_1/\omega_1^2 \tag{9}$$

Notice that the subscript 1 refers to the first estimate in all the variables except for j where it reflects the value of the first item in the dataset

$$\begin{matrix} b_1 \\ c_1 \end{matrix} = (B_1 J_1^2 + C_1 J_1 + D_1 - a_1) \begin{matrix} \times \sin \\ \times \cos \end{matrix} (\omega_1 J_1) + (C_1 + 2B_1 J_1) \begin{matrix} \times \cos \\ \times \sin \end{matrix} (\omega_1 J_1) \tag{10}$$

For b_1, take the upper-row functions (sin and cos), while for c_1 take the lower row functions (cos and sin).

$$\rho_1 = \sqrt{b_1^2 + c_1^2} \tag{11}$$

$$\varphi_1 = \begin{cases} \tan^{-1}(c_1/b_1) & b_1 > 0 \\ \pi + \tan^{-1}(c_1/b_1) & b_1 < 0 \\ \pi/2 & b_1 = 0, c_1 > 0 \\ -\pi/2 & b_1 = 0, c_1 < 0 \end{cases} \tag{12}$$