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Abstract

The concept of thermal time, measured in degree-days, is widely used among the agricultural community in Nebraska to make decisions in corn (*Zea Mays* L.) production. Instead of the real-time temperatures that are experienced by corn plants, most of the widely available temperature data are limited to daily timescale observations from standard meteorological stations. And a variety of equations are used by different agricultural groups (e.g., researchers, advisors, farmers, and seed companies) to estimate thermal time for corn. Two problems could arise: a) the estimation method is lacking in accuracy; and b) different estimation methods are used for the same purpose by different groups. Consequently, citing these inaccurate and maybe inherently different thermal time results could lead to biased decisions in corn production. The goal of this study is to evaluate six commonly used estimation methods by comparing the estimated thermal time with the hourly-temperature approximated thermal time. We analyzed the root mean square error and mean absolute error for six metrics of total growing season (from May through September) degree-days based on the temperature data from a total of 14 long-term observing locations in Nebraska. In particular, we selected four location-extreme year cases to demonstrate the six methods' estimation performance on a daily timescale. We found that the most commonly used adjusted T_{max} and T_{min} rectangle method provided poor estimation in the study area. Instead, single-sine, double-sine, or T_{avg}-based method was more superior depending on the metric of degree-days.

1. Introduction

The concept of thermal time (or heat units), measured in degree-days, is widely used in crop research and field management to track crop phenological development (Cross and Zuber, 1972; Gilmore and Rogers, 1958; Russelle et al., 1984). Thermal time is the cumulative measure for temperature-based crop development, and ideally would be measured with temperatures that are actually experienced by the plants. However, most of the widely available temperature data are restricted to observations from meteorological stations that are in the vicinity of crop fields, usually including daily maximum and minimum temperatures. Thermal time is commonly estimated based on these two daily temperatures, with three types of methods as follows: (1) averaging (or so called rectangle) methods, such as T_{avg}-based method (T_{avg} is the arithmetic mean of daily maximum and minimum temperatures) and adjusted T_{max} and T_{min} method (Arnold, 1960; McMaster and Wilhelm, 1997); (2) sine-wave methods, such as single-sine method (Baskerville and Emin, 1969), and double-sine method (Allen, 1976); and (3) triangulation methods, such as single-triangulation method (Lindsey and Newman, 1956; Neild, 1967), and double-triangulation method (Sevacherian et al., 1977). Averaging methods are relatively simple to use, especially the T_{avg}-based method, however, using such methods raises a concern that the arithmetic mean of daily maximum and minimum temperatures may not accurately represent the true daily average temperature, as illustrated by Bigelow (1909). The principal assumption of sine-wave and triangulation methods is that the diurnal temperature curve is similar to the trigonometric sine curve or triangulation curve. Double-sine and double-triangulation methods account for the fact that minimum temperature at the beginning and the end of a specific 24-hour period may not necessarily be the same; hence, they use the next day's minimum temperature. Specifically, double-sine and double-triangulation methods divide each day into two 12-hour periods and then represent the first 12-hour period by daily minimum and maximum temperatures of that day while representing the second 12-hour period by daily maximum temperature of that day and daily minimum temperature of the following day (Allen, 1976; Sevacherian, et al., 1977).

According to Kumudini et al. (2014), the above-mentioned estimation methods for thermal time are all categorized as empirical linear, based on their temperature response and derivation. Two temperature thresholds are usually involved in an empirical linear estimation method, including a lower threshold below which crop development ceases and an upper threshold above which crop development rate will not further increase. Upper-threshold cut-off techniques include horizontal, vertical, and intermediate (Roltsch et al., 1999). When daily average temperature, the arithmetic mean of daily maximum and minimum temperatures, is used to estimate thermal time, there are three possible situations that need to be considered: (1) daily average temperature is at or above the upper threshold; (2) daily average temperature is at or above the lower threshold but remains below the upper threshold; and (3) daily average temperature is below the lower threshold. When daily maximum and minimum temperatures are directly used to estimate thermal time, there are six possible situations that need to be considered: (1) daily minimum temperature is below the lower threshold, and daily maximum temperature is either: (a) below the lower threshold, (b) at or above the lower threshold but below the upper threshold, or (c) at or above the upper threshold; (2) daily minimum temperature is at or above the lower threshold but below the upper threshold, and daily maximum temperature is either: (a) at or above the lower threshold but below the upper threshold, (b) at or above the upper threshold; or (c) both daily minimum temperature and daily maximum temperature are at or above the upper threshold.

When observed hourly temperature data are available, there would be no need to depict the diurnal temperature curve with daily maximum and minimum temperatures. Instead, thermal time could be more realistically approximated as the number of degree days that hourly temperatures fall between the lower and upper thresholds (Zalom et al., 1983). Zalom et al. (1983) used a 14-day-period dataset to compare thermal time (with a lower threshold of 12.8°C and an upper threshold of 32.2°C) derived from five different estimation methods with that based on hourly temperature. McMaster and Wilhelm (1997) compared thermal time for corn estimated with the two types of averaging methods, with a lower threshold of 10°C and an upper threshold of 30°C. Roltsch et al. (1999) evaluated seven different estimation methods for thermal time at nine locations in California during a two-year study period.

In Nebraska, agricultural community for corn widely uses degree-days to choose corn variety, predict corn phenology, and so on. However, different groups (e.g., researchers, agricultural advisors, farmers, seed companies, etc.) have used divergent methods or thresholds to estimate thermal time for corn. In particular, researchers use T_{avg}-based averaging method with a lower threshold of 10°C and an upper threshold of 30°C (Feng and Hu, 2004); agricultural advisors use adjusted T_{max} and T_{min} method with a lower threshold of 10°C and an upper threshold of 30°C (https://drinet.hubzero.org/groups/u2u/tools/gdd); seed company Monsanto uses T_{avg}-based averaging method with a lower threshold of 10°C but no upper threshold, although this is not well documented; crop simulation model CERES-Maize (Jones and Kiniry, 1986) uses a combination of averaging method and 3-hour correction method with a lower threshold of 8°C and an upper threshold of 34°C, while Hybrid-Maize model (Yang et al., 2004) uses single-sine wave method with the same lower and upper thresholds.

Without knowing the error of estimated thermal time, directly citing each other's results could lead to biased decisions. The goal of this study is to analyze estimation error of thermal time derived from those six commonly used empirical linear methods based on daily temperatures. Unlike other similar studies, this analysis is based on a long-term dataset and focuses on the active corn growing season in Nebraska. We made two assumptions for this study, first, thermal time approximated with hourly temperatures is superior to that estimated with empirical linear methods based on daily temperature; second, these estimation errors are significant enough to be considered when being applied in corn production, such as predicting corn phenology, though observed corn phenology data would be needed in order to test this (Kumudini et al., 2014).

2. Methodology

The study area was the state of Nebraska, which is one of the main corn production states in the United States (USDA NASS, 2014; USDA NASS, 2015). Hourly averaged air temperature data were obtained from the High Plains Regional Climate Center's Automated Weather Data Network (AWDN) through the online Climate Data Services (http://www.hprcc.unl.edu/services, accessed 10 December 2015). These data were quality controlled by the HPRCC staff with a spatial regression test; the advantages of this test were stated by Hubbard and You (2005), Hubbard et al. (2007), and You et al. (2008). A combination standard of data completeness and corn production representativeness was used to choose the study locations. From the beginning year of record to year 2015, the maximum acceptable amount of missing data for each station for this study was set at 5%. Missing data were replaced by reliable estimates, estimates based on weighted linear regression from surrounding stations, or unreliable estimates (HPRCC, 2015). Only two of the stations had no unreliable estimates of hourly temperature data, but that would be too few to represent the entire state's climate. Therefore, stations with up to 0.03% unreliable estimates were included in this study; these unreliable estimates were manually checked to ensure that they are climatologically reasonable. By consulting with local agronomists, a total of 14 observing stations (40.08°–42.47°N and 96.48°–101.72°W, Fig. 1) that are located in active corn production areas were chosen for the analysis. Depending on the station, the beginning year of study spans from 1982 to 1991. The elevation of the stations ranges from 347 to 1029 m. In this study, active corn growing season was defined as from May 1 to September 30 based on the USDA reports (USDA NASS Agricultural Statistics Board, 1997; USDA NASS, 2010). The obtained hourly temperature data were used to compute daily temperatures, including maximum, minimum, and average temperatures. During a 24-hour period (i.e., from 0:00 to 23:59), the highest hourly temperature was considered as daily maximum temperature; the lowest hourly temperature was considered as daily minimum temperature; and the arithmetic mean of hourly temperature was considered as daily average temperature. This daily average temperature often differs from that derived from daily maximum and minimum temperatures alone.

In order to test the sensitivity of estimation methods to different temperature thresholds, three sets of lower and upper thresholds that are commonly used for corn were included in the analysis. They are: 8° and 29°C (Butler and Huybers, 2012), 10°C (predominantly used by seed companies) and 30°C (McMaster and Wilhelm, 1997), as well as 8° (used in crop models such as CERES-Maize and Hybrid-Maize) and 34°C (Kropff and van Laar, 1993). In addition to degree-days that are between lower and upper thresholds (i.e., $DD_{8, 29}$, $DD_{10, 30}$, $DD_{8, 34}$), the performance of different estimation methods on degree-days that are above upper thresholds (i.e., DD_{29+}, DD_{30+}, DD_{34+}) were also analyzed in this study. Accumulated above-upper-threshold temperatures have often been used to measure heat stress (Butler and Huybers, 2012; Lobell et al., 2011).

First, total growing season degree-days were calculated based on the observed hourly temperature data for each metric of thermal time at the study locations using Eqs. (2.1), (2.2), and (2.3), as described in Lobell et al. (2011):

$$DD_{lower,upper} = \sum_{d=1}^{N} DD_d \quad (2.1)$$

$$DD_d = \sum_{h=1}^{24} DD_h \quad (2.2)$$

$$DD_h = \begin{cases} 0 & if\ T_{\mathrm{h}} < T_{\mathrm{lower}} \\ (T_{\mathrm{h}} - T_{\mathrm{lower}})/24 & if\ T_{\mathrm{lower}} \le T_{\mathrm{h}} < T_{\mathrm{upper}} \\ (T_{\mathrm{upper}} - T_{\mathrm{lower}})/24 & if\ T_{\mathrm{h}} \ge T_{\mathrm{upper}} \end{cases} \quad (2.3)$$

Where N is the number of days (153) for crop development over the growing season spanning from May 1 to September 30, unitless; DD_d is the daily degree-day, °Čžday; DD_h is the hourly degree-day, °Čžday; T_h is the hourly temperature, °C; T_{lower} is the lower threshold, °C; and T_{upper} is the upper threshold, °C.

Second, daily degree-days were estimated based on the calculated daily temperature data for each metric of thermal time at the study locations. A total of six estimation methods are evaluated in this study: T_{avg}-based rectangle method, adjusted T_{min} and T_{max} rectangle method, single-sine and double-sine methods with horizontal cut-off technique, and single triangulation and double triangulation methods with horizontal cut-off technique. For the two rectangle methods, Eqs. (2.4) and (2.5) were used to estimate daily degree-days, respectively. The detailed formulas to estimate daily degree-days for single-sine, double-sine, single-triangulation, and double-triangulation methods with horizontal cut-off technique are found at the UC IPM (2005). Eq. (2.1) was used to calculate total growing season degree-days for the six estimation methods.

$$DD_{\mathrm{lower,upper}} = T_{\mathrm{avg\_adj}} - T_{\mathrm{lower}} \quad (2.4)$$

$$DD_{\mathrm{lower,upper}} = \frac{(T_{\mathrm{max\_adj}} + T_{\mathrm{min\_adj}})}{2} - T_{\mathrm{lower}} \quad (2.5)$$

Where T_{avg_adj} is the adjusted daily average temperature, °C; T_{max_adj} is the adjusted daily maximum temperature, °C; and T_{min_adj} is the adjusted daily minimum temperature, °C. They are adjusted to lower threshold if they are below the lower threshold, and to upper threshold if they are above the upper threshold.

For the six metrics of thermal time analyzed in this study, degree-days approximated with hourly temperature was taken as true. The differences between degree-days estimated with daily temperature and degree-days approximated with hourly temperature were considered as errors. According to the recommendations from Chai and Draxler (2014), a combination of statistical metrics of root mean square error (RMSE) and mean absolute error (MAE) was used to assess the performance of different estimation methods. At every study location, Eqs. (2.6) and (2.7) were used to calculate RMSE and MAE for each metric of thermal time during the study period, respectively.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \quad (2.6)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |e_i| \quad (2.7)$$

In these equations, n is the number of total study years at the study location, unitless; e_i is the error of total growing season degree-days, °Cžday.

3. Results

The analysis results are focused on three perspectives: first, the estimation errors of the six methods; second, comparison of estimated degree-days with true degree-days; and third, daily performance of the six estimation methods in extreme cool and warm years at the selected locations.

3.1. Estimation errors of the six methods

During the study period, the composite RMSE of total growing season degree-days for the six estimation methods at the 14 study locations ranged from 12.2 to 40.8°Cžday for the three metrics of thermal time that were defined as between lower and upper thresholds, and from 0.6 to 60.2°Cžday for the three metrics of thermal time that were defined as above upper thresholds. Meanwhile, the composite MAE ranged from 10.5 to 34.7°Cžday for the three metrics of $DD_{8, 29}$, $DD_{10, 30}$, and $DD_{8, 34}$; and from 0.4 to 56.5°Cžday for the three metrics of DD_{29+}, DD_{30+}, and DD_{34+}. For all six metrics of thermal time, the adjusted T_{min} and T_{max} rectangle method uniformly showed the greatest composite RMSE and MAE. By contrast, the single-sine method showed the smallest composite RMSE and MAE for $DD_{8, 29}$ and $DD_{10, 30}$; the T_{avg}-based rectangle method showed the smallest composite RMSE and MAE for $DD_{8, 34}$; and the double-sine method showed the smallest composite RMSE for DD_{29+} and DD_{30+}. Both single-sine and double-sine methods showed the smallest composite RMSE and MAE for DD_{34+}.

At the majority of the study locations, the single-sine method showed the smallest estimation error for $DD_{8, 29}$ and $DD_{10, 30}$. The T_{avg}-based method showed the smallest RMSE (MAE) for $DD_{8, 34}$ at a total of 13 (12) out of the 14 study locations (Table 2). In other words, the single-sine method was sensitive to the lower and upper thresholds; it performed the best when the upper threshold was relatively low (e.g., 29 and 30°C). When the upper threshold was relatively high (e.g., 34°C), the T_{avg}-based method outperformed the single-sine method. For the three metrics of thermal time that were defined as above upper thresholds, the double-sine method uniformly showed the smallest estimation error at the majority of the study locations. For the adjusted T_{min} and T_{max} rectangle method, the smallest RMSE and MAE of total growing season degree-days for corn only occurred in two situations: $DD_{8, 29}$ at Elgin and $DD_{10, 30}$ at Holdrege.

Table 1
Composite RMSEs and MAEs (in parentheses) of total growing season degree-days for corn for the six estimation methods during the study period at the 14 study locations in Nebraska (unit: °Cžday).

Method	**$DD_{8, 29}$**	**$DD_{10, 30}$**	**$DD_{8, 34}$**	**DD_{29+}**	**DD_{30+}**	**DD_{34+}**
T_{avg}-based	40.4 (34.1)	24.5 (19.7)	12.2 (10.5)	51.6 (46.4)	38.9 (33.9)	8.2 (6.0)
Adjusted T_{max} and T_{min}	40.8 (34.7)	28.1 (22.7)	23.6 (20.7)	60.2 (56.5)	48.2 (44.2)	14.1 (11.1)
Single-sine	17.2 (14.3)	17.7 (14.9)	18.5 (15.6)	3.9 (3.3)	2.9 (2.4)	0.6 (0.4)
Double-sine	17.5 (14.6)	18.0 (15.1)	18.9 (15.9)	3.8 (3.2)	2.8 (2.3)	0.6 (0.4)
Single-triangulation	23.3 (20.2)	21.0 (17.7)	18.8 (15.4)	15.5 (14.2)	12.6 (11.1)	3.7 (2.7)
Double-triangulation	23.9 (20.9)	21.5 (18.1)	19.2 (15.7)	15.7 (14.3)	12.7 (11.3)	3.7 (2.7)

Table 2
Numbers of study locations that show the smallest RMSE and MAE (in parentheses) of total growing season degree-days for corn for the six estimation methods during the study period in Nebraska.

Method	$DD_{8,29}$	$DD_{10,30}$	$DD_{8,34}$	DD_{29+}	DD_{30+}	DD_{34+}
T_{avg}-based	0 (0)	3 (3)	13 (12)	0 (0)	0 (0)	0 (0)
Adjusted T_{max} and T_{min}	1 (1)	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)
Single-sine	8 (9)	5 (6)	0 (0)	4 (4)	4 (4)	4 (5)
Double-sine	2 (0)	4 (3)	1 (2)	10 (10)	10 (10)	10 (9)
Single-triangulation	2 (3)	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)
Double-triangulation	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

3.2. Comparison of estimated degree-days with true degree-days

During the study period, estimated total growing season degree-days with the adjusted T_{max} and T_{min} rectangle method uniformly showed the largest deviation from that approximated with the observed hourly temperature data for the three metrics of thermal time that were defined as between lower and upper thresholds. In particular, this method performed the worst for total growing season $DD_{8,29}$ (Fig. 2(a)), and the deviation was caused by overestimation of the relatively small values and underestimation of the relatively large values. Meanwhile, estimated total growing season degree-days with the single-sine method showed the smallest deviation from that approximated with the observed hourly temperature data for both $DD_{8,29}$ and $DD_{10,30}$. Especially, the single-sine method performed the best for total growing season $DD_{8,29}$ (Fig. 2(b)). Meanwhile, the T_{avg}-based rectangle method showed the smallest deviation for total growing season $DD_{8,34}$ (Fig. 3(b)). As compared with degree-days approximated with the observed hourly temperature data, the six estimation methods showed a similar performance pattern for the three metrics of thermal time that were defined as above upper thresholds: the T_{avg}-based rectangle method drastically underestimated, the adjusted T_{max} and T_{min} rectangle method largely overestimated, the single-sine and double-sine methods provided the best estimation, and the single-triangulation and double-triangulation methods tended to underestimate (Fig. 4). Moreover, during relatively warm growing seasons, the adjusted T_{max} and T_{min} rectangle method overestimated the three metrics of DD_{29+}, DD_{30+}, and DD_{34+} to a greater extent (Fig. 4(b)); the single- and double-triangulation methods underestimated the three metrics of DD_{29+}, DD_{30+}, and DD_{34+} to a greater extent (Fig. 4(e), (f)).

3.3. Selected cases in the extreme cool and warm years

Based on the mean growing season average temperature during the study period, we identified the extreme cool and warm years at the 14 study locations in Nebraska (Table 3). During these extreme cool and warm years, the six estimation methods showed an inverse pattern in total growing season degree-days for corn that were defined as between lower and upper thresholds (Figs. 5 and 6). At the majority of the study locations, the T_{avg}-based method underestimated the three metrics of $DD_{8, 29}$, $DD_{10, 30}$, and $DD_{8, 34}$ in extreme cool years but overestimated them in extreme warm years. The opposite held true for the adjusted T_{max} and T_{min} rectangle method, single-sine and double-sine methods, which overestimated the three metrics of $DD_{8, 29}$, $DD_{10, 30}$, and $DD_{8, 34}$ in extreme cool years and underestimated them in extreme warm years. For single- and double-triangulation methods, this inverse pattern between extreme cool and warm years was relatively weak due to the internal inconsistency in estimation performance. In extreme cool years, the single- and double-triangulation methods underestimated $DD_{8, 29}$ at half of the study locations, and underestimated $DD_{10, 30}$ and $DD_{8, 34}$ at 57% of the study locations. In extreme warm years, the single- and double-triangulation methods overestimated $DD_{8, 29}$ and $DD_{10, 30}$ but underestimated $DD_{8, 34}$ at the majority of the study locations.

Table 3

Years and mean growing season average temperatures (in parentheses, unit: °C) for the extreme cool and warm years during the study period at the 14 study locations in Nebraska.

Location	Extreme cool year	Extreme warm year
Beatrice	1992 (19.7)	2012 (22.6)
Champion	1993 (17.9)	2012 (21.3)
Concord	1985 (17.7)	1988 (21.2)
Curtis	1992 (18.5)	2012 (22.2)
Dickens	1993 (17.5)	2012 (21.4)
Elgin	1992 (17.9)	2012 (21.0)
Havelock	1992 (19.4)	2012 (23.5)
Holdrege	1992 (18.7)	2012 (21.6)
McCook	1992 (18.8)	2012 (22.4)
Mead	1992 (19.2)	1988 (22.4)
North Platte	1992 (17.8)	2012 (21.7)
O’Neill	1992 (17.4)	2012 (21.5)
Ord	1992 (18.3)	1988 (21.8)
Red Cloud	1992 (19.4)	2000 (24.0)

In extreme cool years, the T_{avg}-based rectangle method showed the smallest composite MAE for $DD_{8, 29}$ and $DD_{8, 34}$, and the single-sine method showed the smallest composite MAE for $DD_{10, 30}$. In extreme warm years, the single-sine method showed the smallest composite MAE for $DD_{8, 29}$ and $DD_{10, 30}$, and the T_{avg}-based rectangle method showed the smallest composite MAE for $DD_{8, 34}$. By contrast, the adjusted T_{max} and T_{min} rectangle method showed the greatest composite MAE for the three metrics of $DD_{8, 29}$, $DD_{10, 30}$, and $DD_{8, 34}$ in both extreme cool and warm years, with the exception of $DD_{8, 29}$ in extreme cool years. In extreme cool years, the double-triangulation method showed the greatest composite MAE for $DD_{8, 29}$. Among all the estimations for the three metrics of $DD_{8, 29}$, $DD_{10, 30}$, and $DD_{8, 34}$ in extreme years, the adjusted T_{max} and T_{min} rectangle method was the worst to estimate $DD_{8, 29}$ in extreme warm years, with an underestimation error ranging from 36.3 to 118.0°Cžday (Fig. 6(a)).

In extreme cool and warm years, the six methods showed similar predominant patterns in estimation performance for the three metrics of thermal time that were defined as above upper thresholds in Nebraska. At the majority of the study locations, the T_{avg}-based rectangle method underestimated the three metrics of DD_{29+}, DD_{30+}, and DD_{34+} in both extreme cool and warm years; the adjusted T_{max} and T_{min} rectangle method overestimated them in both extreme cool and warm years; the single- and double-sine methods overestimated them in both extreme cool and warm years; and the single- and double-triangulation methods underestimated them in both extreme cool and warm years (Figs. 7 and 8). Among the six methods, the double-sine method showed the smallest composite MAE for the three metrics of DD_{29+}, DD_{30+}, and DD_{34+} in extreme years; and the adjusted T_{max} and T_{min} rectangle method showed the greatest composite MAE for the three metrics of DD_{29+}, DD_{30+}, and DD_{34+} in extreme years. In extreme cool years, all six methods estimated DD_{34+} as zero at the three locations of Havelock, Elgin, and Red Cloud, which matched the results that were approximated from the observed hourly temperature data (Fig. 7(c)).

In addition, four cases were selected to present how the six methods performed on a daily timescale during the growing season in extreme years. For the three metrics of thermal time that were defined as between lower and upper thresholds, the two cases that had the greatest total absolute errors were: $DD_{8, 34}$ at Concord in 1985 (extreme cool year) and $DD_{8, 29}$ at Red Cloud in 2000 (extreme warm year). During the extreme cool year at Concord, all six methods underestimated total growing season $DD_{8, 34}$; among them, the T_{avg}-based rectangle method showed the smallest estimation error and the estimation error remained steady throughout the growing season, while the double-triangulation method showed the greatest estimation error and the estimation error increased with time during the growing season (Fig. 9(a)). During the extreme warm year at Red Cloud, the T_{avg}-based rectangle method showed the greatest overestimation error and the overestimation error increased with time during the growing season; the adjusted T_{max} and T_{min} rectangle method showed the greatest underestimation error and the underestimation error increased with time during the growing season (Fig. 9(b)). For the three metrics of thermal time that were defined as above upper thresholds, the two cases that had the greatest total absolute errors were DD_{29+} at McCook in 1992 (extreme cool year) and DD_{29+} at Champion in 2012 (extreme warm year). During the extreme years at McCook and Champion, the six methods showed similar performance: the T_{avg}-based rectangle method and both the single- and double-triangulation methods underestimated, while the adjusted T_{max} and T_{min} rectangle method and both the single- and double-sine methods overestimated. Among which the T_{avg}-based method showed the greatest underestimation error as would be expected, in particular, the T_{avg}-based method estimated daily DD_{29+} as zero throughout the growing season at McCook in the extreme cool year. Meanwhile, the adjusted T_{max} and T_{min} rectangle method showed the greatest overestimation error, and this overestimation error increased over time during the growing season. Both of the single- and double-sine methods performed well in the early growing season, but started to overestimate in the middle-to-late growing season. Both of the single- and double-triangulation methods underestimated and the error increased with time, especially in the second half of the growing season (Fig. 10).

4. Conclusions

At the 14 study locations in Nebraska, the single- and double-sine methods were generally the best to estimate thermal time for corn during the growing season, with an exception of $DD_{8, 34}$ that was best estimated by the T_{avg}-based rectangle method. This implies that the single- and double-sine methods were sensitive to the lower and upper thresholds. Though being the most widely used method in corn production in the study area, the adjusted T_{max} and T_{min} rectangle method showed the greatest composite RMSE and MAE for all six metrics of thermal time. We conclude that the adjusted T_{max} and T_{min} rectangle method was not ideal for estimating growing season thermal time for corn in Nebraska. When citing the growing season degree-days for corn that was computed with the T_{min} and T_{max} rectangle method, it is crucial to check the accuracy.

At the majority of the study locations, the adjusted T_{max} and T_{min} rectangle method overestimated the three metrics of $DD_{8, 29}$, $DD_{10, 30}$ and $DD_{8, 34}$ in extreme cool years but underestimated them in extreme warm years; the single- and double-sine methods tended to overestimate the three metrics of $DD_{8, 29}$, $DD_{10, 30}$ and $DD_{8, 34}$ in extreme cool years but underestimate them in extreme warm years. In both extreme cool and warm years, the adjusted T_{max} and T_{min} rectangle method showed the greatest composite MAE. In particular, the six studied estimation methods performed the worst for $DD_{8, 34}$ at Concord in extreme cool year and $DD_{8, 29}$ at Red Cloud in extreme warm year. At Concord, all six methods uniformly underestimated total growing season $DD_{8, 34}$ in the extreme cool year of the study period. In the extreme warm year of the study period at Red Cloud, the T_{avg}-based rectangle method showed the greatest overestimation error for total growing season $DD_{8, 29}$; the adjusted T_{max} and T_{min} rectangle method showed the greatest underestimation error for total growing season $DD_{8, 29}$; and these two daily overestimation and underestimation errors increased with time within the growing season.

For the three metrics of thermal time that were defined as above upper thresholds, the six methods performed similar dominant patterns in extreme cool and warm years. At the majority of the study locations, the T_{avg}-based rectangle method and single- and double-triangulation methods tended to underestimate the three metrics of DD_{29+}, DD_{30+}, DD_{34+}; while the adjusted T_{max} and T_{min} rectangle method and single- and double-sine methods tended to overestimate. In both extreme cool and warm years, the double-sine method showed the smallest MAE for the three metrics of DD_{29+}, DD_{30+}, DD_{34+}, while the adjusted T_{max} and T_{min} rectangle method showed the greatest MAE. The six studied methods performed the worst for DD_{29+} at McCook in extreme cool years and DD_{29+} at Champion in extreme warm years. In particular, the adjusted T_{max} and T_{min} rectangle method overestimated in both of the two cases, and this overestimation error became worse over time within the growing season for corn.

For the three metrics of thermal time that were defined as between lower and upper thresholds, the recommended methods could be used by corn producers to choose the varieties to replant to compensate for the loss of the emerged corn plants in early growing season when destroying weather events occur and replanting is still an option. For the three metrics of thermal time that were defined as above upper threshold, the recommended methods could provide high-accuracy degree-days to quantify the potential heat stress for corn plants. The adjusted T_{max} and T_{min} rectangle method, though being used the most in the study area, is not recommended to estimate total growing season degree-days for corn with daily temperature data. In particular, the adjusted T_{max} and T_{min} rectangle method overestimated the three metrics of $DD_{8,29}$, $DD_{10,30}$ and $DD_{8,34}$ in extreme cool years but underestimated them in extreme warm years at the study locations. The adjusted T_{max} and T_{min} rectangle method was found to overestimate the three metrics of DD_{29+}, DD_{30+}, DD_{34+} in both extreme cool and warm years at the study locations; furthermore, this overestimation tended to worsen with time within the growing season. However, the 14 study locations may not fully cover the climate regime in the entire corn-growing area in Nebraska. Therefore, additional verifications would be necessary before applying these recommendations to other corn-belt states.

Declarations

Conflict of Interest:

We declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Author’s Contribution:

Shuwei Dai conceived of the presented idea and performed the computations. Martha D. Shulski contributed to data analyses and the results interpretation. Haishun Yang contributed to the analytical methods verification and provided critical feedback. Roger W. Elmore contributed to the location selection and helped shape the analysis. Shuwei Dai wrote the manuscript in consultation with Martha D. Shulski, Haishun Yang, and Roger W. Elmore. All authors discussed the results and contributed to the final manuscript.

Availability of data and material:

The data and material will be available to the readers upon request only.

Code availability:

The custom code is not available to the readers.

Ethics approval:

Not applicable.

Consent to participate:

Not applicable.

Consent for publication:

Not applicable.

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Figures

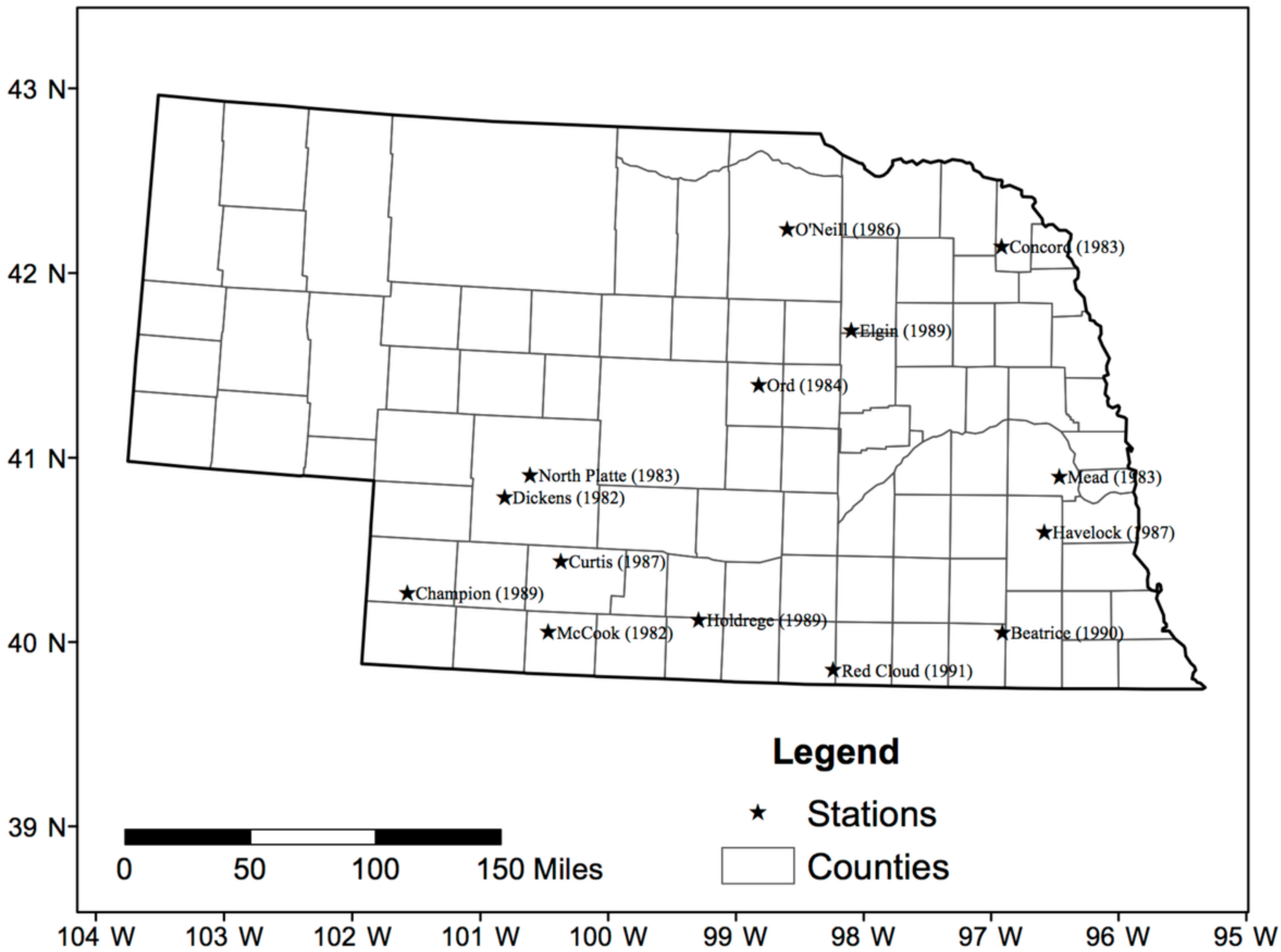

Figure 1

Locations of the 14 meteorological stations in Nebraska, U.S.. The beginning year of study for each location is included in parentheses after the name of the station.

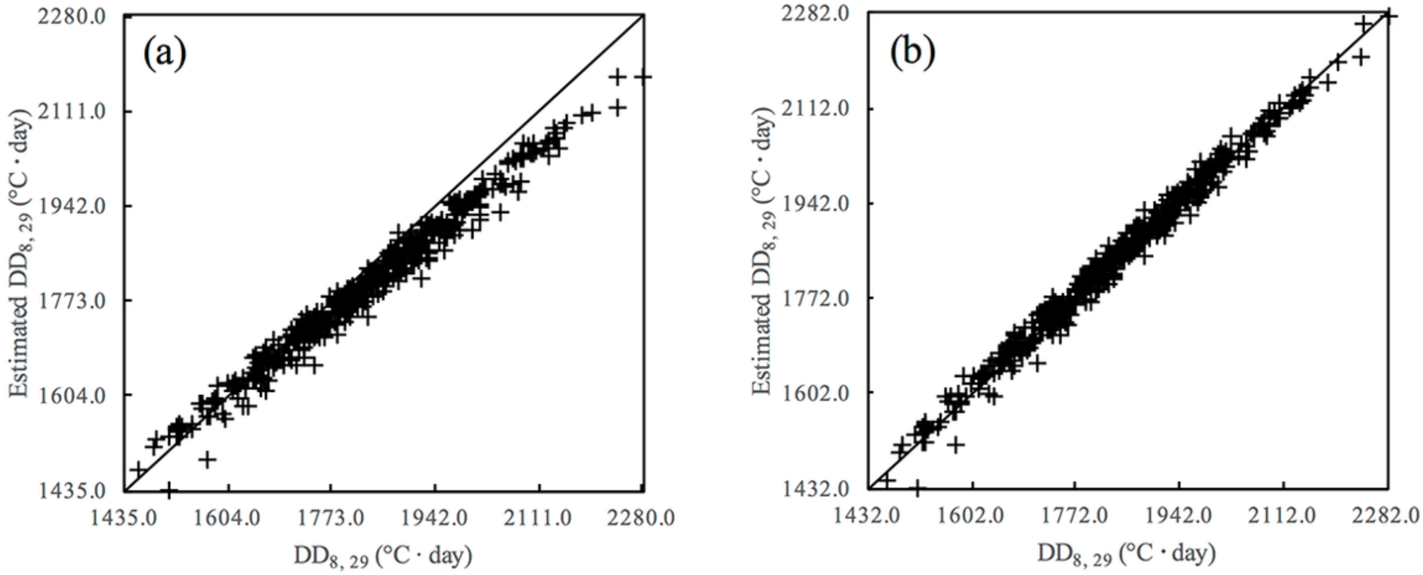

Figure 2

Comparison of estimated total growing season DD8, 29 with (a) the adjusted Tmax and Tmin rectangle method and (b) the single-sine method with approximated total growing season DD8, 29 based on the observed hourly temperature data during the study period at the 14 study locations in Nebraska.

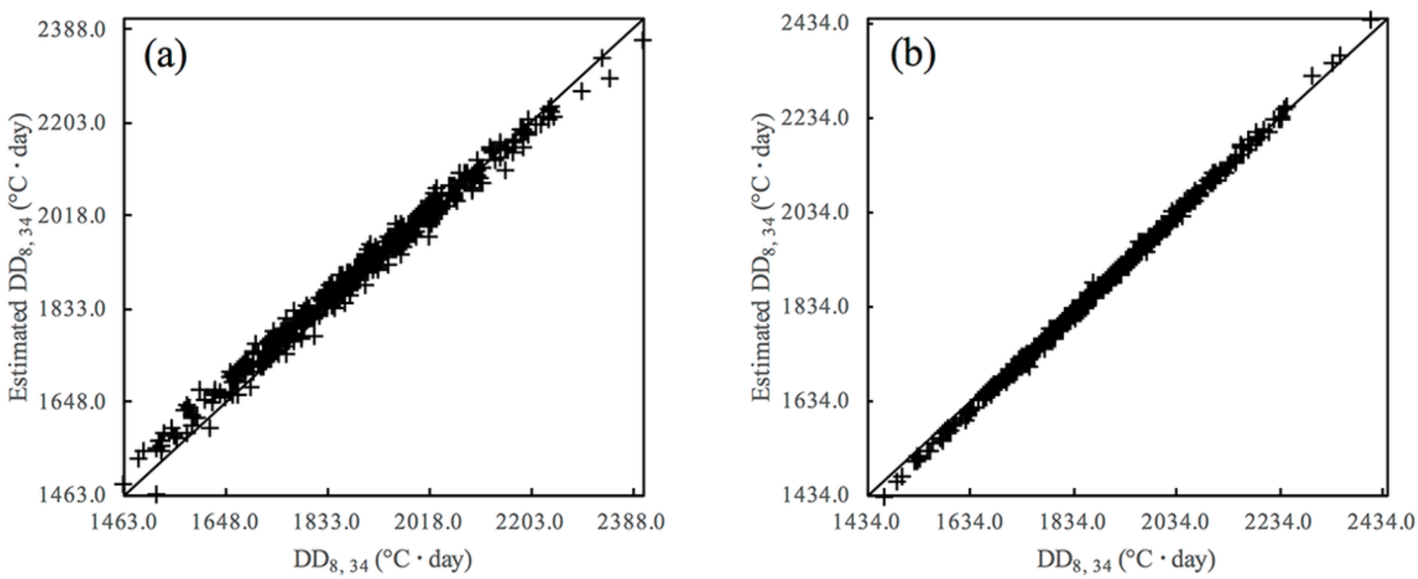

Figure 3

Comparison of estimated total growing season DD8, 34 with (a) the adjusted Tmax and Tmin rectangle method and (b) the Tavg-based rectangle method with approximated total growing season DD8, 34 based on the observed hourly temperature data during the study period at the 14 study locations in Nebraska.

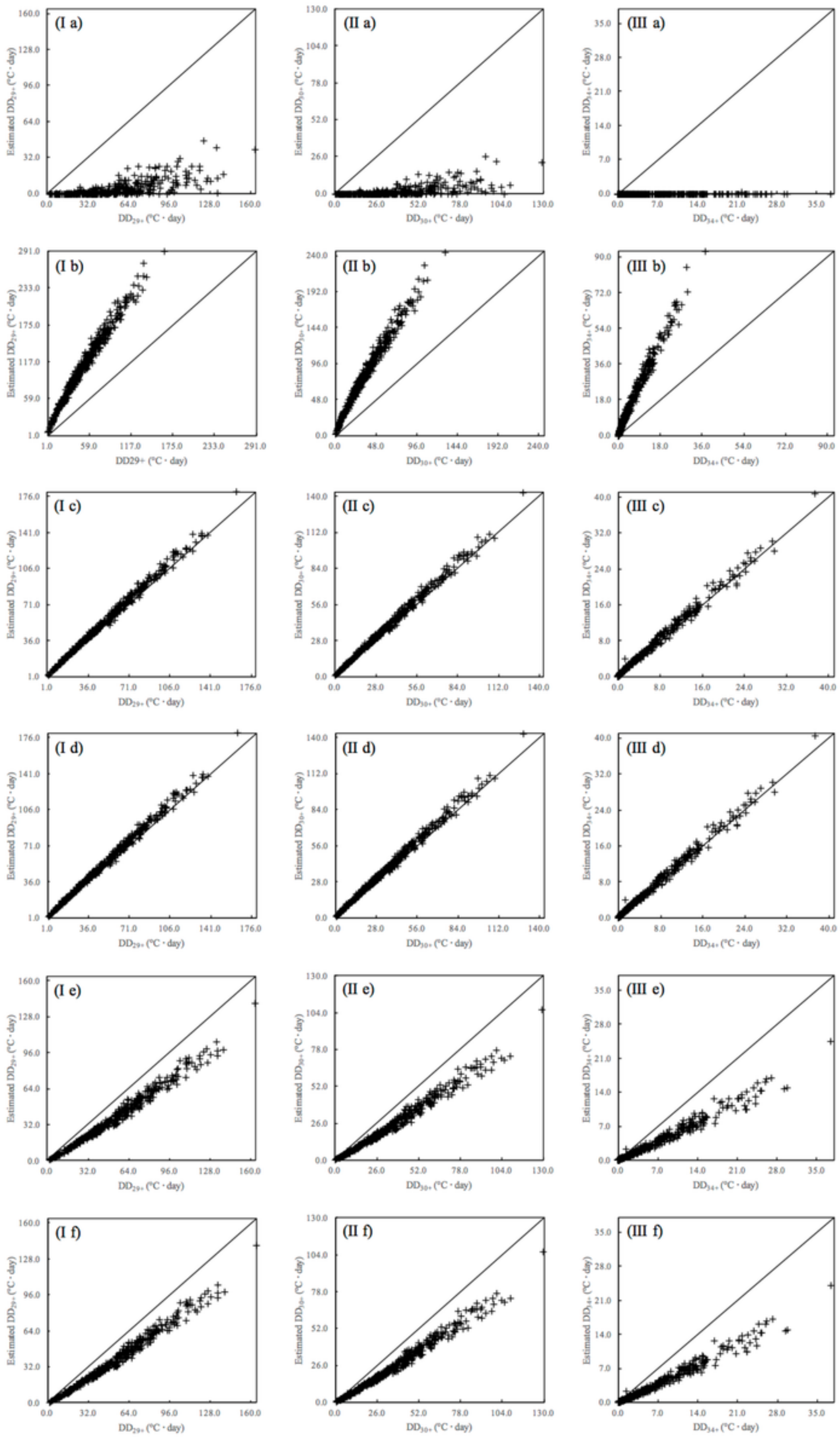

Figure 4

Comparison of estimated total growing season degree-days with the six methods with approximated total growing season degree-days based on the observed hourly temperature data during the study period at the 14 study locations in Nebraska. (I) DD29+. (II) DD30+. (III) DD34+. (a) The Tavg-based rectangle method. (b) The adjusted Tmax and Tmin rectangle method. (c) The single-sine method. (d) The double-sine method. (e) The single-triangulation method. (f) The double-triangulation method.

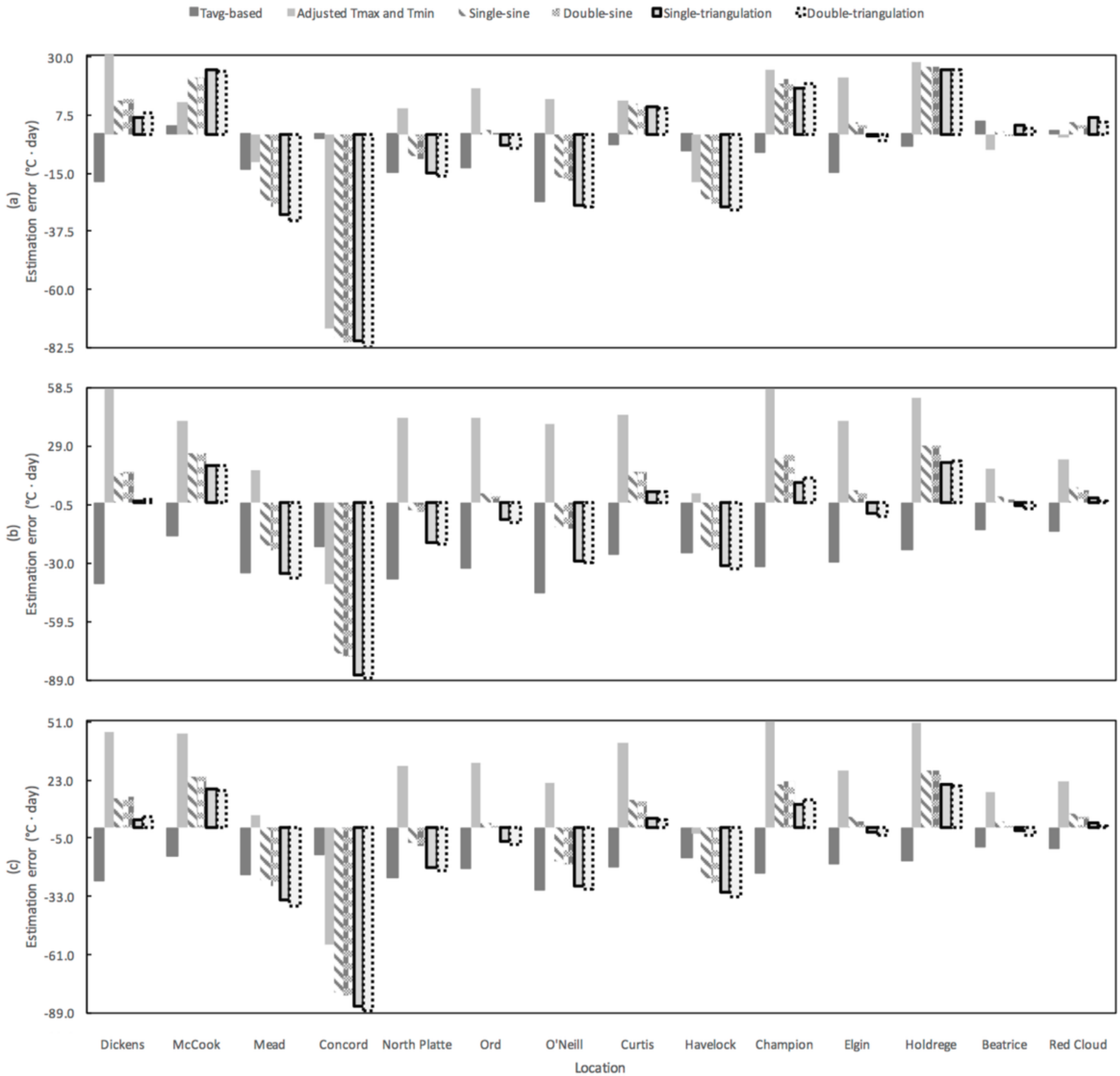

Figure 5

Estimation errors of the six methods in total growing season degree-days in extreme cool years for the 14 study locations in Nebraska. (a) DD8, 29. (b) DD10, 30. (c) DD8, 34.

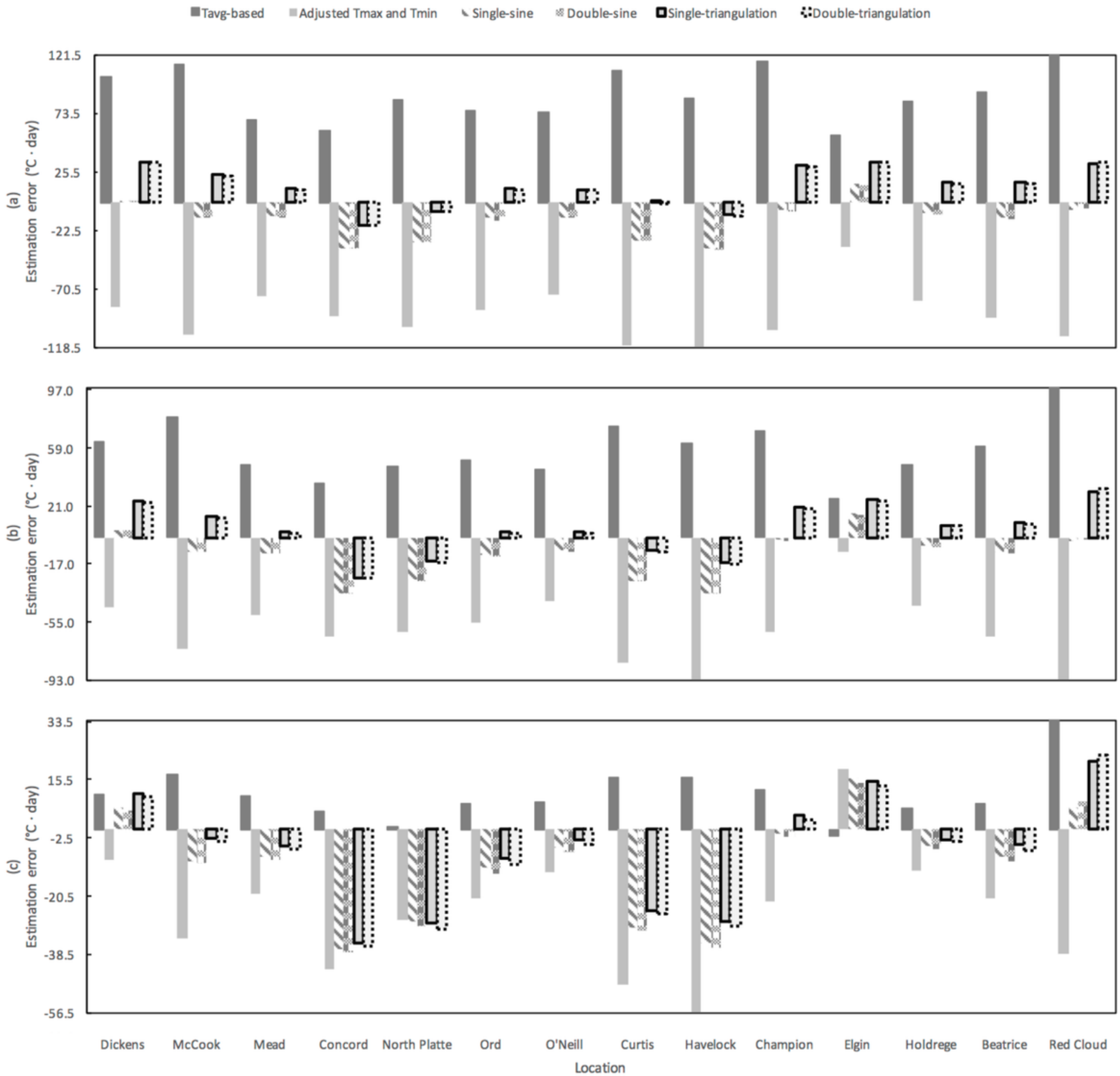

Figure 6

Estimation errors of the six methods in total growing season degree-days in extreme warm years for the 14 study locations in Nebraska. (a) DD8, 29. (b) DD10, 30. (c) DD8, 34.

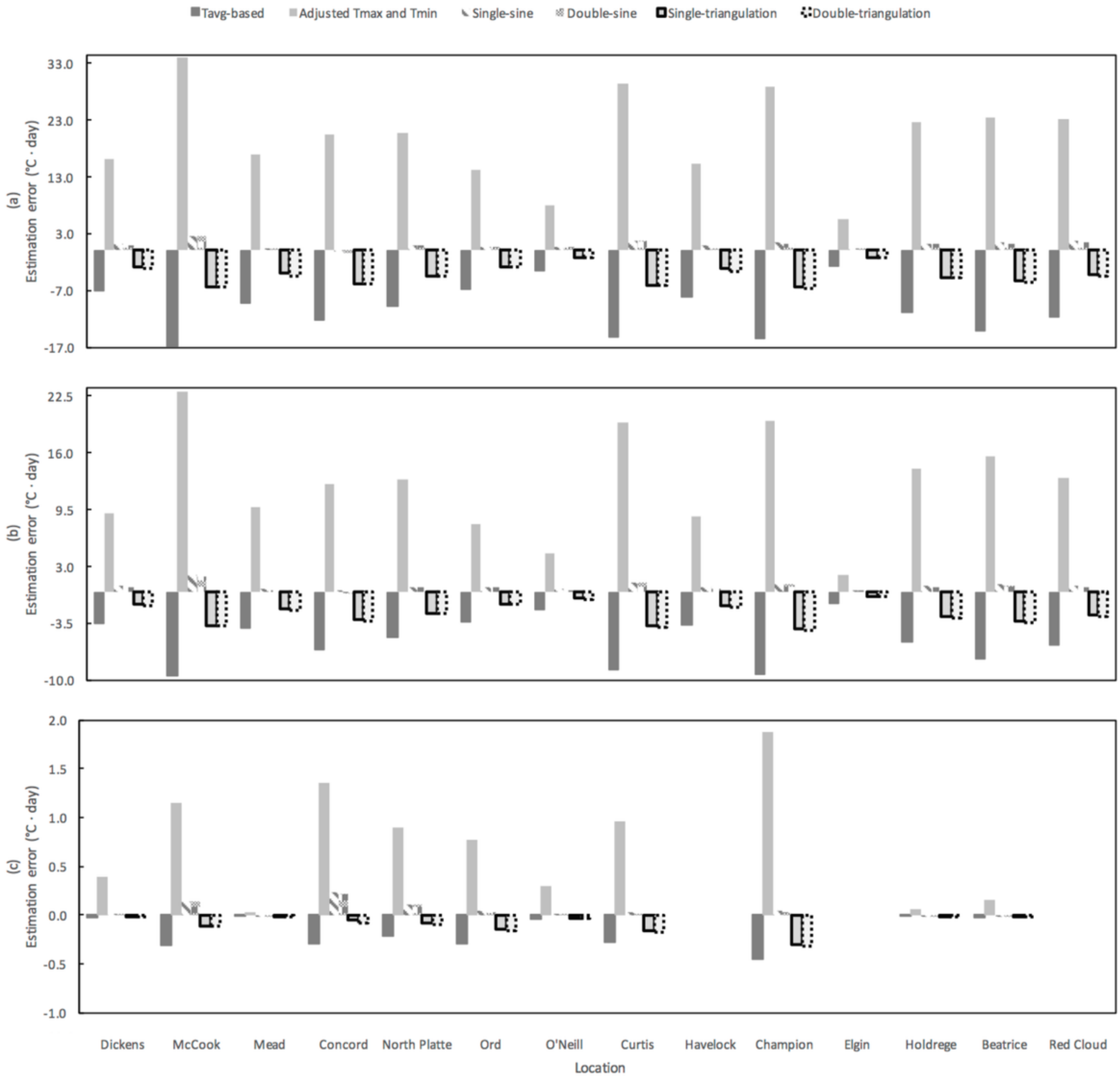

Figure 7

Estimation errors of the six methods in total growing season degree-days in extreme cool years for the 14 study locations in Nebraska. (a) DD29+. (b) DD30+. (c) DD34+.

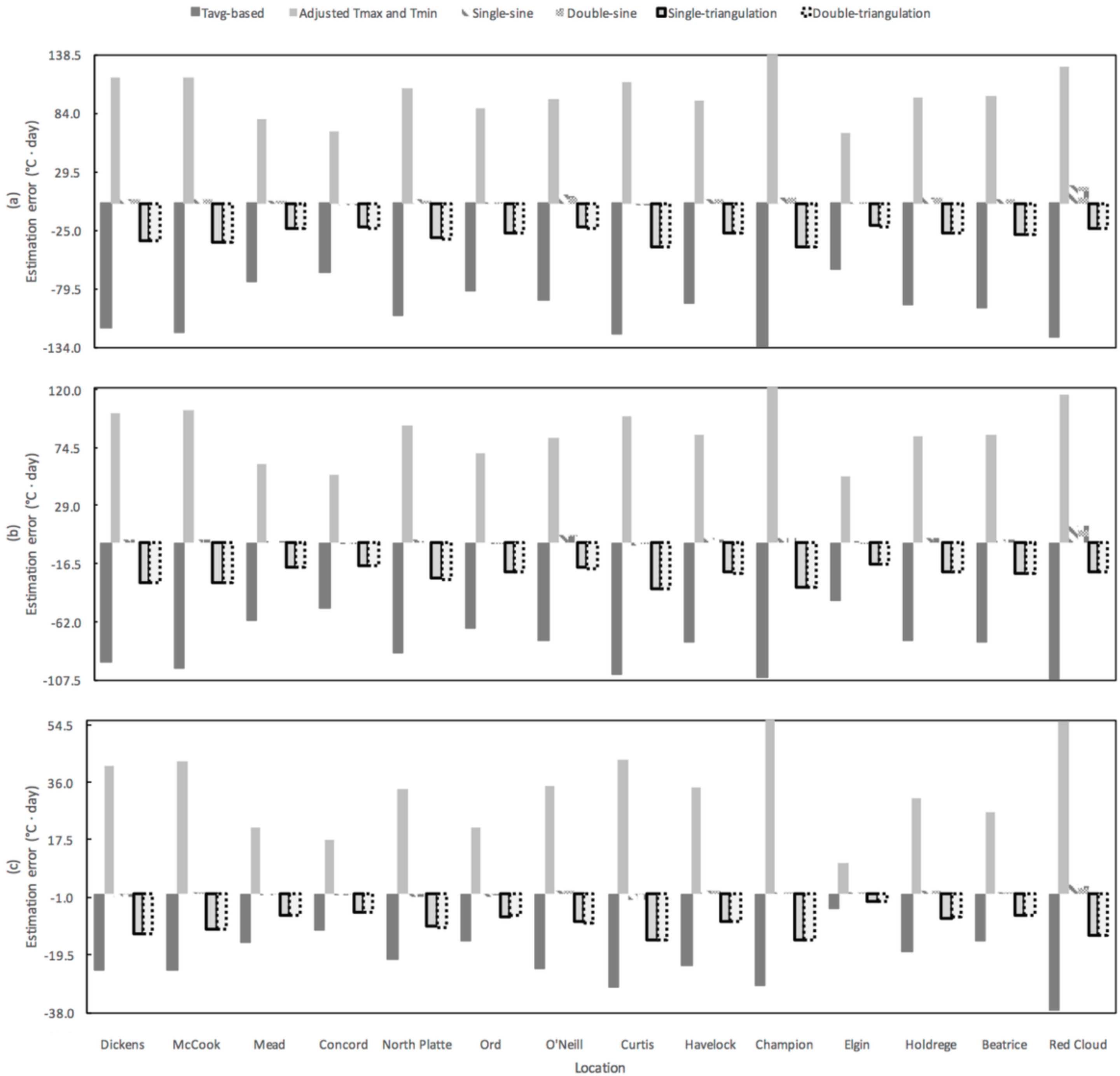

Figure 8

Estimation errors of the six methods in total growing season degree-days in extreme warm years for the 14 study locations in Nebraska. (a) DD29+. (b) DD30+. (c) DD34+.

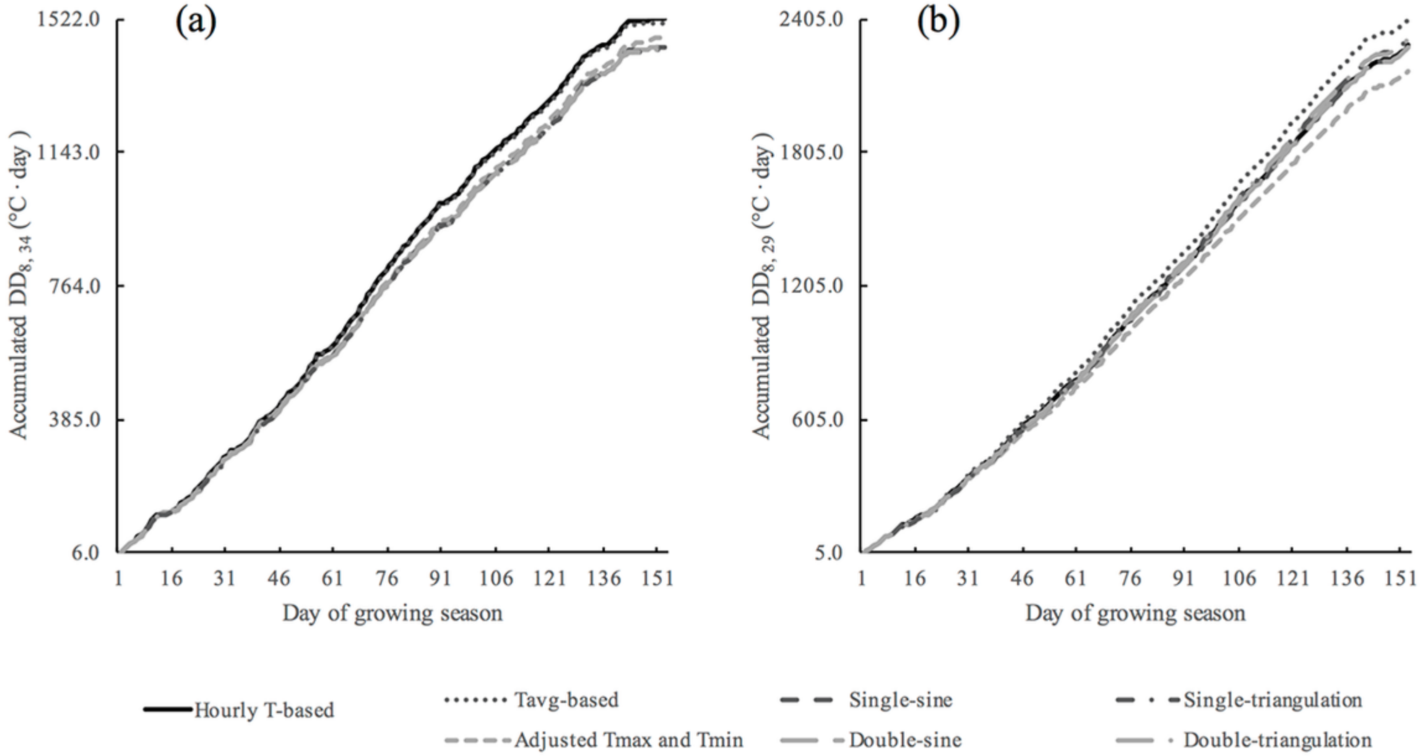

Figure 9

Accumulated degree-days within the growing season of extreme years at particular locations. (a) DD8, 34 at Concord, NE in the extreme cool year of 1985. (b) DD8, 29 at Red Cloud, NE in the extreme warm year of 2000.

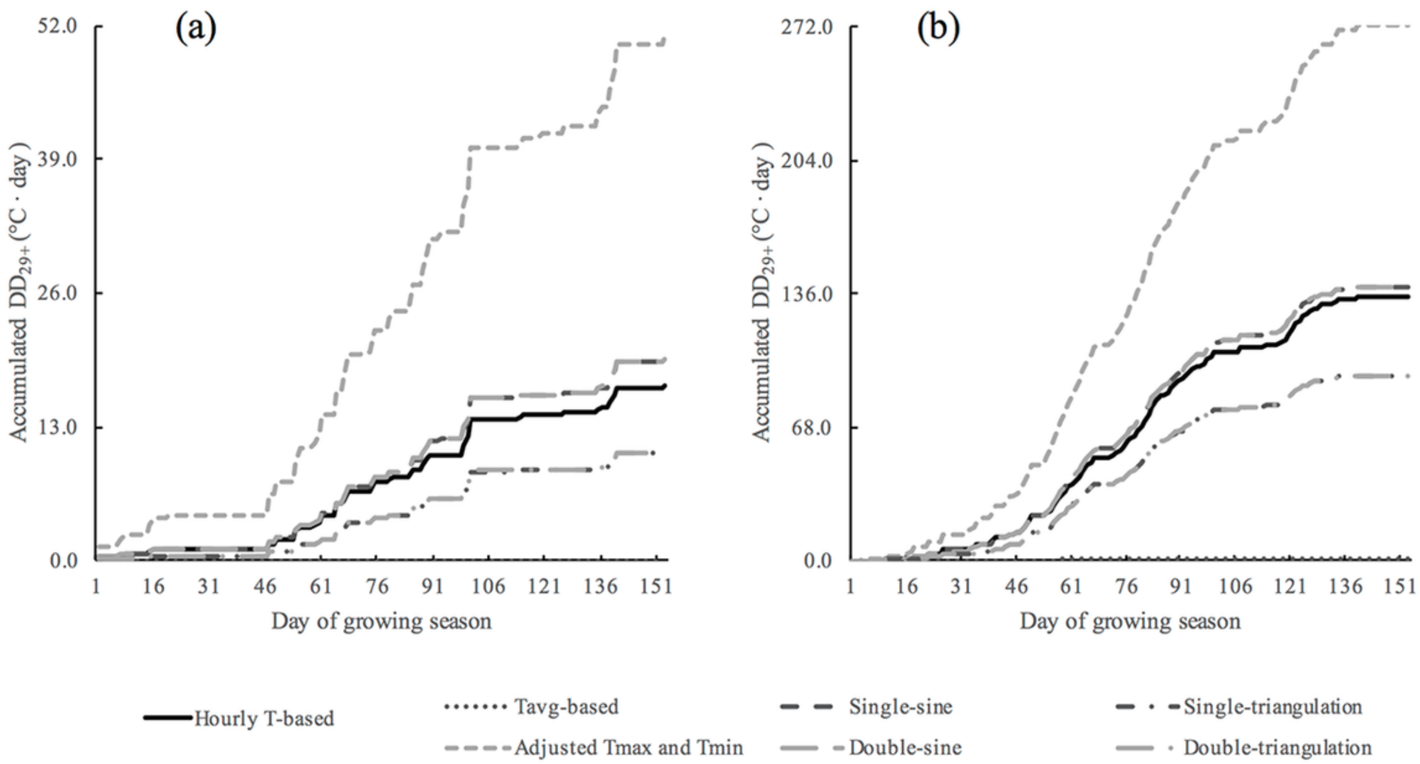

Figure 10

Accumulated degree-days within the growing season of extreme years at particular locations. (a) DD29+ at McCook, NE in the extreme cool year of 1992. (b) DD29+ at Champion, NE in the extreme warm year of 2012.