Comparison of Scaled Canopy Temperatures with Measured Results under Center Pivot Irrigation

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Abstract

The remote sensing of crop canopy temperatures using infrared thermometers is being used in conjunction with several new developments in the area of irrigation scheduling and control. These include the time-temperature-threshold (TTT) method of irrigation scheduling, the crop water stress index (CWSI) and the creation of field level canopy temperature maps using infrared temperature sensors mounted on self-propelled irrigation systems. A method of estimating the canopy temperature dynamics throughout the day using only a one time-of-day canopy temperature measurement is useful in the application of many of these technologies to self-propelled irrigation systems such as center pivots or linear moves. Two different algorithms developed by Peters and Evett (2004) for doing this were tested using data collected under center pivot irrigation. These algorithms use the canopy temperature dynamics captured at a stationary location to create a reference curve. Sixteen different infrared thermometers were positioned in stationary locations throughout a field with four different irrigation level treatments; 100%, 66%, and 33% of the irrigation requirements, and a dryland, or a non-irrigated treatment. One time-of-day canopy temperatures measurements were taken from these at various times of day and were scaled using the reference curve to estimate diurnal canopy temperature curves. These curves were then compared with the actual measurements and the errors were analyzed. Errors using measurements early in the day (before 0800 h) and late in the evening (after 2200 h) were unacceptably high. However, the absolute mean errors using measurements taken during the middle of the day were approximately 1° C with a standard deviation of about 1° C. The effects of using a reference curve from plants with different water stress levels were also compared and it was found that the stress level of the reference curve crop did not make a significant difference in the absolute mean errors.

Introduction

The ability to estimate diurnal canopy temperature dynamics from a one time-of-day canopy temperature measurement is useful for many reasons. The crop water stress index (CWSI; Jackson, 1982) requires canopy temperature measurements to be taken close to solar noon on clear cloudless days (U.S. Water Conservation Laboratory, 2004). These measurements could be made more convenient if the solar noon canopy temperature could be approximated using a measurement taken at another time of day. Canopy temperature maps of a field are useful feedback mechanisms to precision irrigation control algorithms for showing water, nutrient, or pest damage stresses in various areas of a field. Creating a canopy temperature map using infrared canopy temperature sensors mounted on self-propelled irrigation systems such as center pivots or linear moves requires a method for correcting for temperature changes due to changing climate conditions over the time it takes the self propelled irrigation system to travel across the field (Sadler et al., 2002). The time temperature threshold (TTT) method of irrigation scheduling requires a diurnal canopy temperature curve to determine if the amount of time that the canopy temperature was above the temperature threshold exceeded the time threshold (Wanjura et al., 1992, 1995; Upchurch et al. 1996). However, sensors mounted on a self-propelled irrigation system only provide a one-time-of-day temperature measurement for each spot in the field as they move over the field. All three of these new developments in irrigation scheduling and control could benefit from a method of estimating the diurnal canopy temperature dynamics using only a one-time-of-day temperature measurement.

Peters and Evett (2004) proposed two different methods for estimating the diurnal canopy temperature curve from a one-time-of-day measurement that using the canopy temperature dynamics as measured in a different part of the field as a reference curve. The objective of this study is to further test these methods using canopy temperature data collected from a center pivot automation study done at Bushland, Texas. In particular it is of interest whether the water stress of reference curve has any effect on the accuracy of the diurnal canopy temperature predictions.

Diurnal Canopy Temperature Determination

Extrapolating a diurnal canopy temperature curve from a one-time-of-day measurement requires an estimation of the canopy temperature dynamics due to changing environmental conditions. Several different models exist that can predict the dynamics of the crop canopy temperature as part of a soil-plant-atmosphere energy balance (e.g. Evett and Lascano, 1993). However, these models require as input detailed weather data as well as knowledge of soil-and plant-specific parameters that are neither readily available nor easy to measure. The most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. Peters and Evett (2004) showed that diurnal canopy temperatures in other parts of a field, which may be under different stresses, could be modeled relative to this reference using only a one-time-of-day temperature measurement. Two different methods were proposed; the scaled method and the Gaussian difference method.

Scaled Method

If pre-dawn canopy temperatures throughout the whole field (T_e; *e* for early) are assumed to be the same then:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \qquad (1)$$

as in Figure 1 where:

T_{rmt} = calculated canopy temperature at the remote location (°C)

T_{ref} = canopy temperature from the reference location at the same time interval as T_{rmt} (°C)

$T_{rmt,t}$ = one-time-of-day canopy temperature measurement at the remote location at any daylight time *t* (°C)

$T_{ref,t}$ = measured reference temperature from the time that the remote temperature measurement was taken (*t*).

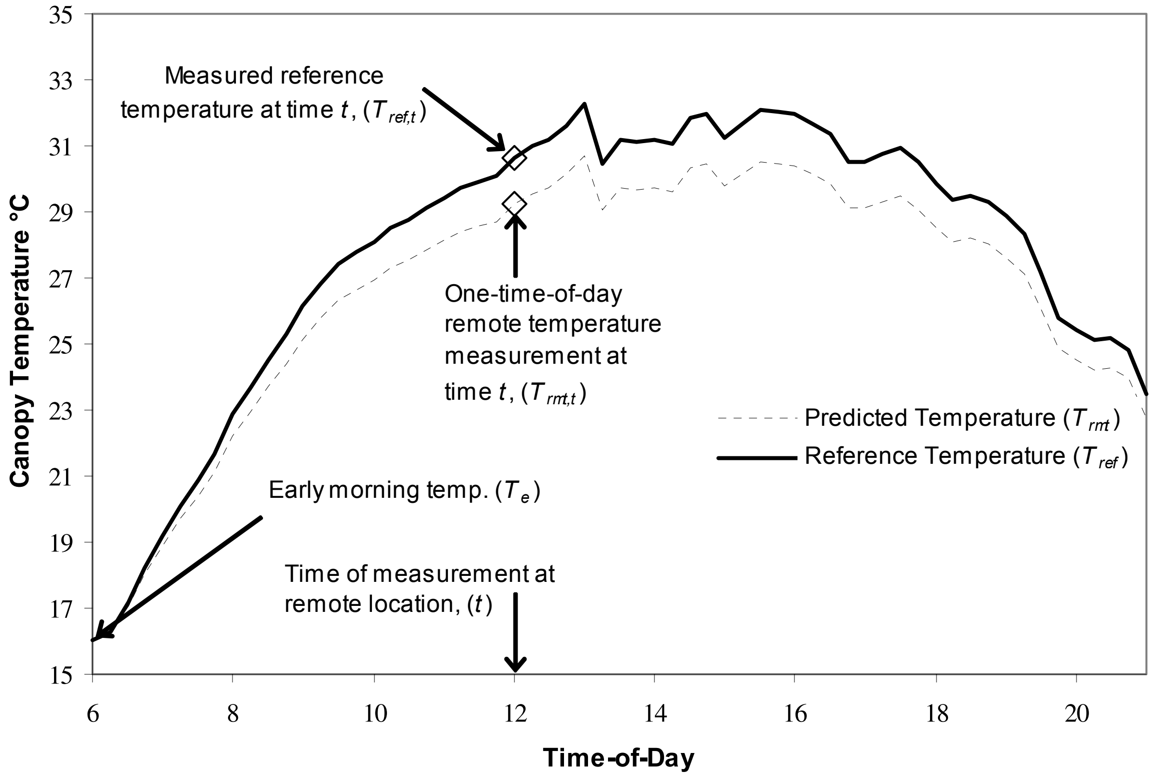

Figure 1. Diagram of the terms used in the scaled method (Eq. 1). Time *t* might be any daylight time at which a canopy temperature ($T_{rmt,t}$) was measured at a remote location in the field. A contemporaneous temperature ($T_{ref,t}$) from the reference temperature data is then used in equation 1 along with the common pre-dawn minimum temperature (T_e) and each value in the reference temperature data (T_{ref}) to predict corresponding temperatures at the remote location throughout the daylight hours (T_{rmt}).

Gaussian Difference Method

An alternative method was developed and tested that uses the one time-of-day measurement to approximate the diurnal differences between the reference temperature curve and the predicted curve. The diurnal differences were approximated using a three-parameter Gaussian equation:

$$T_d = Ae^{\left[-0.5\left(\frac{t-t_p}{w}\right)^2\right]} \qquad [2]$$

where T_d is the predicted temperature difference ($T_{rmt,t} - T_{ref,t}$) from the reference (°C) at time of day t (h), A is the amplitude of the peak difference (°C), t_p is the hour of day (h) of the peak, and w is a factor that predicts the width of the peak (h).

Peters and Evett (2004) gave constant values for t_p = 14 h and of w = 2.63 h in Eq. [2]. They also stated that the value for t_p will be dependent upon the site longitude in reference to time zone demarcation lines (i.e. solar noon occurs at slightly different times). To use Eq. [2] to predict canopy temperature at a remote location, the measured time (t) and the canopy temperature difference (T_d) are used in Eq. [2] to solve for A. Once A is known, the remainder of the points in the diurnal canopy temperature curve are calculated by computing the temperature difference at each point using Eq. [2] and adding that difference to the reference temperature value.

Materials and Methods

Data from an experiment in center pivot automation based on the time-temperature-threshold (TTT) method of irrigation scheduling were used. The experiment site was a three-tower, 127 m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (Figure 2). Only half of the field was used. Soybeans were planted in concentric circles out from the center point. Agronomic practices common in the region for high yields were applied. Four different water level treatments were applied radially out from the center point (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no irrigation treatment). Each drop was pressure regulated to 6 psi. The irrigation level was controlled by nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The furrows were dammed/diked to limit water movement in the furrows. Two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving as the block separation line. There were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied in alternate wedge shapes to block for differing soil types underneath the pivot. Two additional rows of soybeans are planted around the outside and inside edges of the pivot to help minimize border effects.

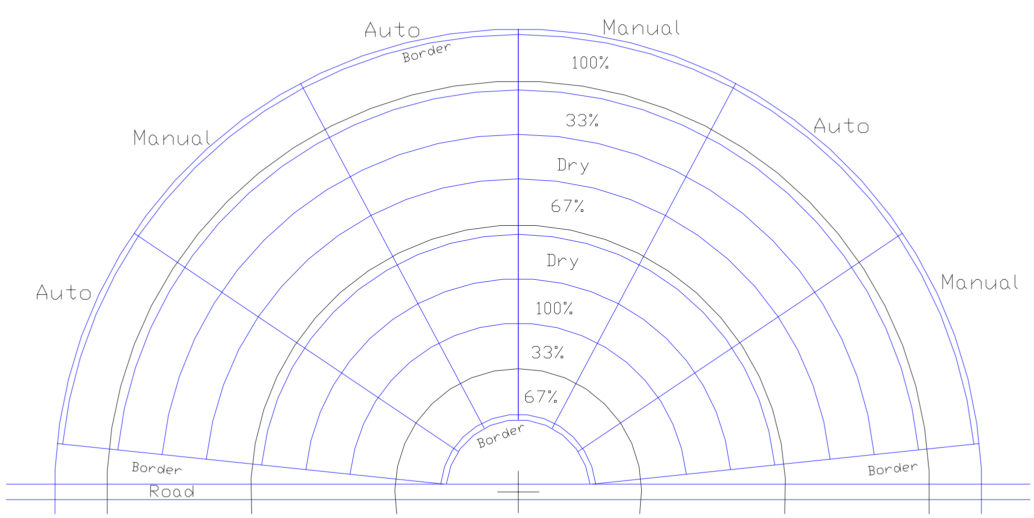

Figure 2. Center pivot automation plot plan.

Sixteen IRTs (model IRt/c.2-T-80, Exergen Corp.)[1] were mounted in stationary locations. One IRT was mounted in each irrigation level of both the automatic and manual treatments in the East end of the field. Each IRT was mounted in the nadir position over the crop row close enough to the canopy so that soil was not included in the field-of-view. These IRTs were adjusted up throughout the season with the changing height of the canopy. They were all connected through a multiplexer (AM25T, Campbell Scientific) and to a datalogger (CR21X, Campbell Scientific). The datalogger logged the five minute averages of each of the IRT readings collected on 10 second intervals. Each IRT was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRT was individually corrected after the season was over.

A reference curve was created from the average of the two 100%, manual irrigation treatments. A one-time-of-day temperature measurement from a particular IRT in the field was then used to estimate a diurnal canopy temperature curve using both the scaled (Eq. [1]) and the difference (Eq. [2]) methods and the absolute mean error and the standard deviation of the errors was recorded. This was done for each time of day on five minute intervals from 530 h to 2215 h, for every day of year (DOY) from DOY 99 to DOY 239, and for each of the 16 IRTs individually. This whole process was repeated using a reference curve created from the average of the two 66%, 33%, and dryland manual irrigation treatments to determine if the conditions of the reference curve had a significant effect. Daylight savings time was not applied so that solar noon was near 1300 h during the growing season.

Results and Discussion

The average of the absolute mean errors for every day and across each of 16 different IRTs for both methods (Eq, [1] and [2]) were compared (Figure 3.) The absolute mean error for both methods was close to 1° C during the middle of the day. Temperatures predicted from one-time-of-day measurements taken early in the day (before approximately 0800 h) or late in the evening (after approximately 2200 h) resulted in unacceptably high errors. The Gaussian difference method was slightly more accurate with one-time-of-day measurements taken during the middle of the day (between about 1200 h to 1600 h) than the scaled method. However the scaled showed better accuracy early in the day (between 0800 h and 1000 h) and later in the day (between 1800h and 2000 h). The probability that the differences between these two methods were due to variability is shown in Figure 4. Where the two lines crossed there was no significant difference of course, but significant differences were found during the middle of the day (from about 1300 h to 1400 h) and early (about 0800 h to 1000 h) and late (about 1900 h to 2000 h) in the day. The standard deviations of the absolute mean errors of both methods behaved very similar to the means (Figure 5) with the average being close to 1° C during the middle of the day.

The Gaussian difference method shows quite a bit more stability in predicting accurate diurnal canopy temperature curves than the scaled method (Figure 3). Upon further investigation, the instability in the scaled method was caused by a few points during cool days when the afternoon temperatures were very near the early morning temperatures. This caused the denominator

[1] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture

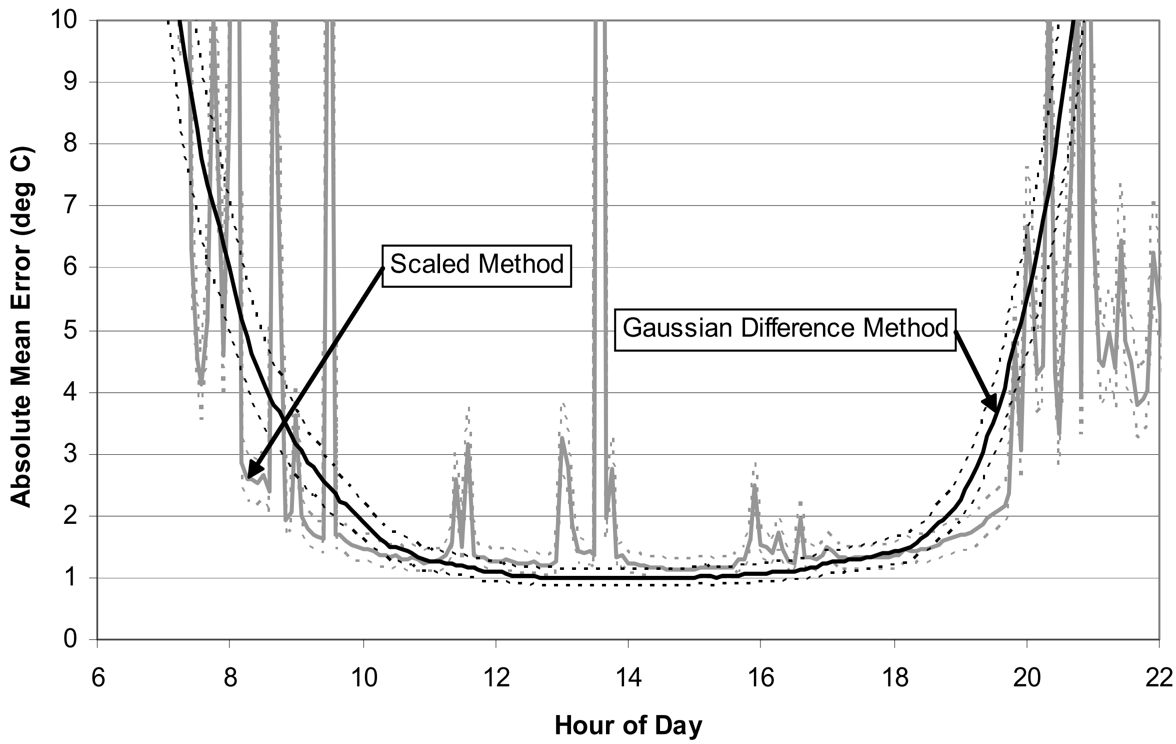

Figure 3. Comparison of the absolute mean error between the scaled and difference methods of determining a diurnal canopy temperature curve using a one time of day measurements from various times (hours) of the day. The 95% confidence interval on each of the means is also shown. The average of the 100%, manual irrigation plots was used as a reference curve.

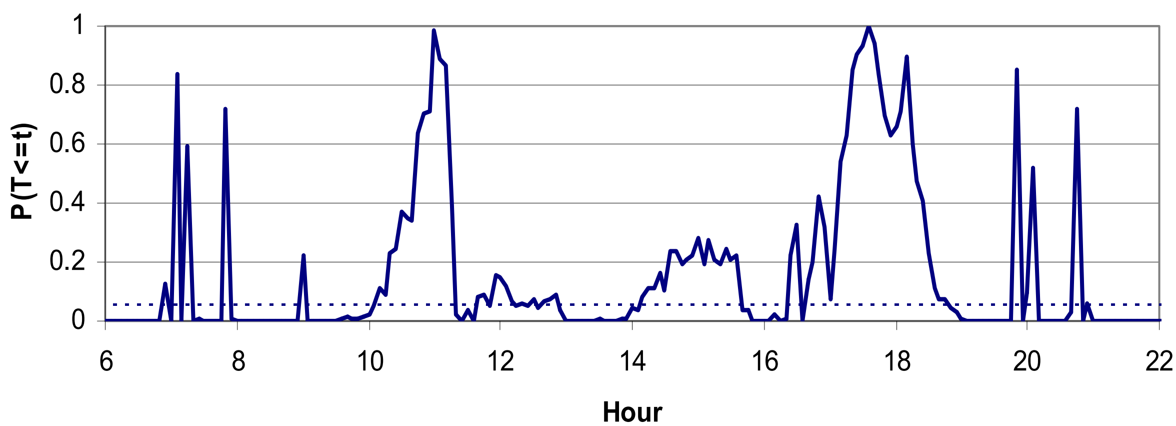

Figure 4. Shows the probability that the measured T statistic is less than the critical t statistic (P(T<=t) for the means (Figure 3 above) at all times of day. This is the probability that the differences between the means is due to variability.

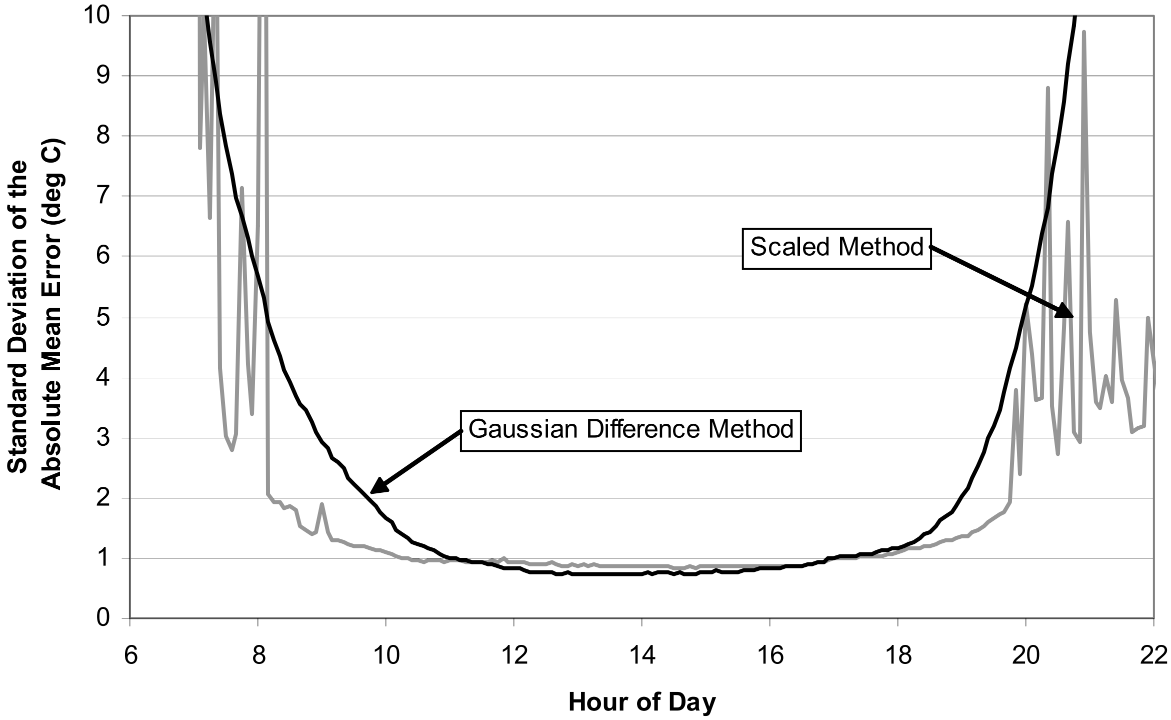

Figure 5. The standard deviation of the absolute mean error between the scaled and difference methods for determining a diurnal canopy temperature curve from a one time-of-day measurement.

($T_{ref,t} - T_e$; the difference between the early morning temperature and the reference temperature at the one-time-of-day measurement) in Eq. [1] to be very small at certain times of day. When this happened the scaled term exploded causing absolute mean error numbers to be many significant digits higher than what was typical. This resulted in error spikes in the curve. These large errors occur only in rare instances when the afternoon temperatures were very near the early morning temperatures and only at those times of day. However the errors using the scaled equation during these instances were very large. This problem may be mitigated programmatically by doing some checking of the method against the Gaussian difference method, or by disallowing the denominator in Eq. [1] to be less than a specified limit, or less than zero. When the few cool days of year with afternoon temperatures near the early morning temperatures were removed these spikes all but disappeared (Figure 6). Many spikes can still be seen during the morning and evening hours when the temperature difference from the early morning temperatures was not very large.

It would be ideal if a reference curve could be measured at any point in the field without having to worry about if water, pest or disease stress of the reference canopy has any negative effects on the accuracy of the diurnal canopy temperature predictions. In order to test this, the same analysis as shown in Figures 3 and 4 was run using reference curves created from the average of the 66%, the 33% and the dryland manual irrigation treatments. Figure 7 shows that the water stress (and therefore the temperature) of the plants chosen for the reference curve had very little effect on the accuracy of the scaled method. Figure 8 shows the same conclusion for the difference method.

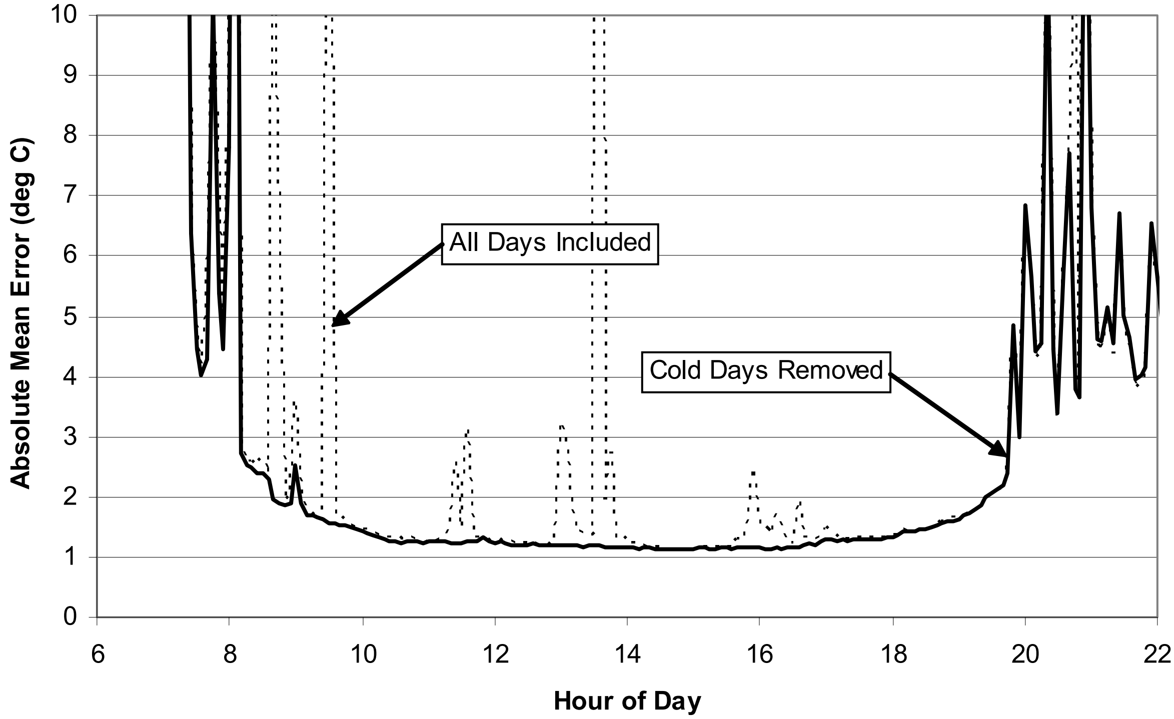

Figure 6. The scaled method with the removal of days when the difference between Tref,t and Te were small (i.e. temperatures near the middle of the day were not significantly warmer than the pre-dawn temperatures.)

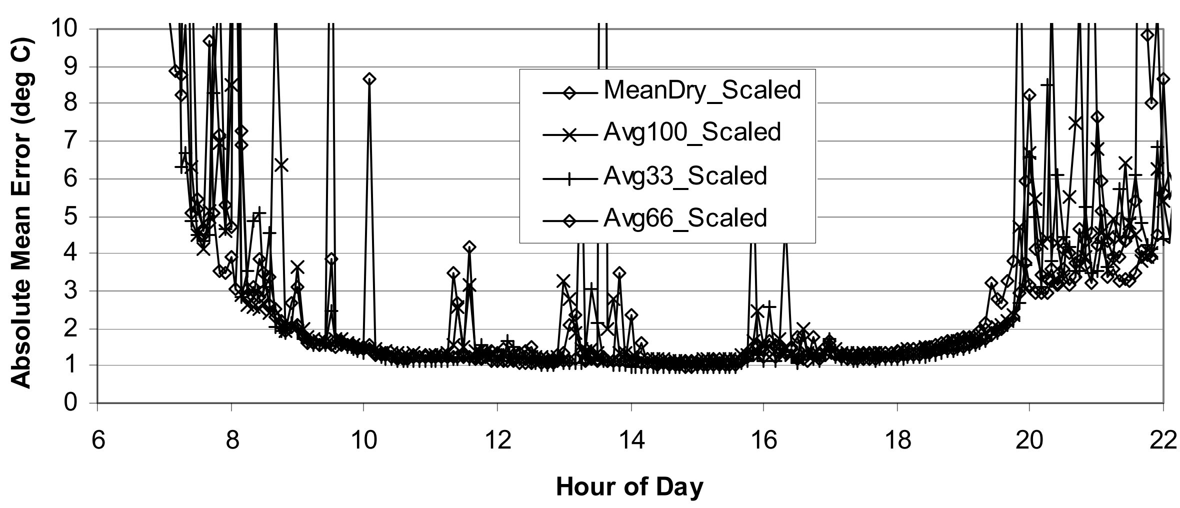

Figure 7. Comparison of the scaled method using each of the four treatments as a reference curve.

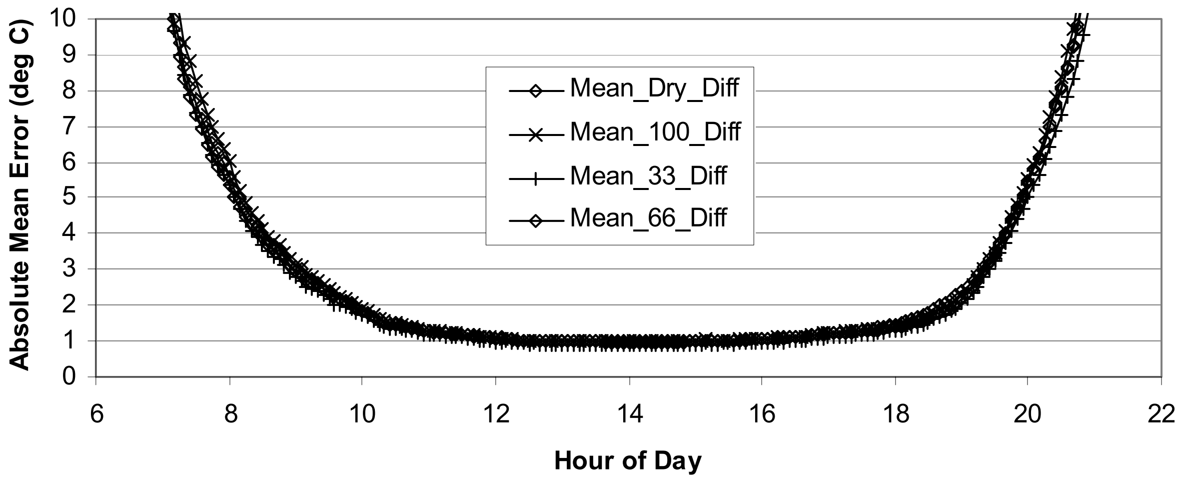

Figure 8. Comparison of the Gaussian “difference” method using each of the four treatments as a reference curve.

Conclusions

These data show that the scaled method (Eq. [1]) and the Gaussian difference method (Eq. [2]) are both viable methods for predicting the diurnal canopy temperature dynamics from a one-time-of-day measurement using a reference temperature during daylight hours. At night, the closest approximation of the canopy temperatures in the remote location is simply the reference temperature. The scaled method is more accurate early in the morning and late at evening while the difference method is more accurate during the middle of the day. Although the difference method is more accurate during the middle of the day, these differences are small and may not be important. The scaled method exhibited instability when the temperature of the reference was near the early morning temperature at the time of the one-time-of-day measurement. The difference method was much more stable. The water stress condition of the reference curve had very little effect on the overall accuracy of the diurnal canopy temperature predictions. When the canopy temperature dynamics are captured at a stationary location to create a reference curve these methods enable the prediction of canopy temperatures at times of day other than when a canopy temperature measurement is taken. These methods simplify the collection of data for the CWSI, enable the creation of canopy temperature maps using infrared thermometers mounted on self-propelled irrigation systems, and also enable the use of the TTT method for irrigation scheduling in fields underneath a self propelled irrigation platform.

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