Calibration of Low cost infrared thermometer to measure Crop Water Stress index

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Abstract.
The advent of low-cost handheld infrared (IR) thermometers has led to a proliferation of non-contact surface temperature measurements that can be used in many applications from food processing to measuring the water stress of plants. In order to use the IR thermometers in crop water stress measurements (CWSI), the instruments must be calibrated in the plant surface temperature range of use. The low–cost infrared thermometers measure the infrared temperature by using uncooled thermopile detectors that adsorb radiation in the 8 um to 14 um spectral range. These detectors are uncooled; therefore radiation emitted by the detector itself must be considered in the calibration process. When measuring the non water stressed CWSI using the IR thermometers, correction for reflected radiation from the sky is not necessary because the CWSI calculation is the relative difference between the canopy and surrounding air temperature. However, if the CWSI measurements are to be used to calculate the actual transpiration rate of the crop, then the IR thermometer reading must be corrected for the reflected sky radiation and change in emissivity.

Keywords. *Crop Water Stress index, canopy resistance, aerodynamic resistance, evapotranspiration*

1. Introduction

The advent of low-cost handheld infrared (IR) thermometers ($25-$50 U.S.) has led to a proliferation of non-contact surface temperature measurements that can be used in many applications from food processing to measuring the water stress of plants in the field. Plant leaf temperature increases with plant water stress (Howell 1996) and this temperature measurenment can be used to calculate the Crop Water Stress Index (CWSI).

We use the CWSI as a water management tool to maintain optimal water stess levels throughout the growing season; because seasonal maintainence of some water stress, depending on the plant, can increase water use efficiency while not affecting yield. (Chai, et al., 2016). Irrigation amounts restricted to maintain the desired water stress for a paticular crop (Moller, et al., 2007) should be monitored for impacts on the plant water stress level.

To use the IR thermometers to measure plant water stress level, the instruments must be calibrated in the temperature range of use. Low cost infrared thermometers measure the infrared temperature by using thermopile detectors that detect radiation in the 8 um to 14 um spectral range. Radiation emitted by the detector itself must be considered in the calibration process, because these detectors are uncooled. The emissivity setting on the thermometer can either be adjustable as a setting on the IR thermometer or a fixed value of 0.95. The thermometers that have a fixed emissivity value are lower in cost.

1.1 CWSI

An index of crop water stress (CWSI) is defined for sunlit canopy surface temperatures, collected by a hand held infrared thermometer as:

$$CWSI = 1 - ET_a/ET_{ns} \quad (1)$$

where The ratio ET_a/ET_{ns} is the relative ET. ET_a is the actual ET and -ET_{ns} is the non-stressed ET of the plants.

The CWSI can be calculated from canopy temperature (T_c), air temperature (T_a), and vapor pressure deficit (VPD) (from air temperature and relative humidity), and from a knowledge of the upper and lower surface temperatures at the possible extremes of ET, represented graphically by upper and lower base lines in Figure 1.

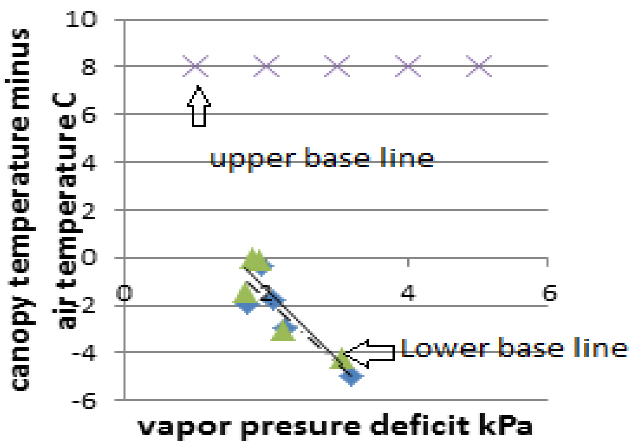

Figure 1. Upper and lower base lines for the CWSI for grapes in Napa California measured with a low cost infrared thermometer.

The upper base line represents complete stress where ET is zero. The lower base line represents the no water stress condition. Measurement of leaf – canopy temperature difference and VPD determines the relative distance between these two extremes and the relative ET in equation 1. The lower base line must be measured when there is no moisture, fertilizer or insect stress. Nitrogen stress along with water stress can cause stomatal closure with a resulting increase in T_c-T_a. (Rudnick, and Irmak , 2014)

The graphical solution of the CWSI was developed by Tanner (1963), Jackson et al. (1981), and Idso (1982). CWSI base lines have been developed for soybeans (Candogan et al, 2013), grapes (Bellvert et al. (2013), corn (Payero and Irmak, 2006), Broccoli (Gültaş 2010) and potatoes (Erdem et al., 2005) and many other crops including ornamentals (Sammis and Jerrigan, 1992).

2.0 Theory of IR thermometers measurements.

All objects emit radiation in the form of electromagnetic waves distributed across the electromagnetic spectrum. The distribution and intensity of the radiation emitted is determined by the surface temperature of the object according to Planck's law (Fowler, 1998). Leaf surfaces near air temperature emit radiation contained within the infrared part of the electromagnetic spectrum, at wavelengths ranging from 8–14 μm. The IR thermometer detector adsorbs the radiation received over this wavelength range, which increases its temperature, and in turn, it provides a voltage, or current, in proportion to intensity of the radiation load it receives. The signal strength (S) is a nonlinear function of the canopy temperature and is described by the Sakuma–Hattori interpolation equation [Sakuma and Kobayashi 1997],

$$S(T)= C/ [\exp (C_2/ (AT+ B))-1] \quad (2)$$

Where: A, B, and C are calibration constants related to the properties of the IR thermometer.
C_2 is the second Planck function constant equal to 14,388 um K
T is the surface temperature in degree K

The microprocessor contained in the infrared thermometer solves equation 2 for T and displays as degree C or degree F on the IR thermometer output screen. The constant C is set to one in equation 2 and A and B are calculated as a function of the central wavelength of the sensor (λ_o) in microns and width of the wave length range ($\Delta \lambda$) expressed by Eq. 3 and Eq. 4.

$$A= \lambda_o [1- (\Delta \lambda^2/2 \lambda_o^2)] \quad (3)$$

$$B= C_2 \Delta \lambda^2/ 24 \lambda_o^2 \quad (4)$$

The sources of radiation received by the IR sensor are IR emitted by the canopy and reflected sky radiation. These depend on the temperatures of the canopy, its emissivity (ε_s), and the air temperature. Meanwhile, the sensor emits IR as a function of the sensor temperature.

A black body has an emissivity of one and the canopy of a crop has an emissivity of ~0.98 (Chen, 2015). Consequently if the low cost IR thermometer has an emissivity set internally to 0.95 then the calibrated temperature must be corrected to an emissivity of 0.98 if the absolute temperature is required. The infrared thermometers are factory calibrated in a constant controlled temperature indoor environment. Therefore the infrared thermometer temperature must also be corrected for the radiation (Q) the infrared thermometer receives from the sky when using the thermometer outdoors to measure CWSI.

Q(received) =0.98*Q(crop) + 0.02*Q(sky) or (5)

Q(crop)=[Q(received)-0.02*Q(sky)]/0.98

Where the emissivity of the crop is 0.98

A more detailed description of the measurement errors associated with using low cost, low temperature IR thermometers is given by Saunder (2009).

2.1 *Field of View*

Target size and distance are critical to the accuracy for most IR thermometers. Every IR instrument has a field of view (FOV), that is, a family of angles of vision over which it averages the radiation received. IR thermometers have fixed focus optics, the minimum measurement spot occurs at the specified focal distance that can range for general purpose IR Thermometers from 50 to 150 cm. The FOV can range from 12:1 to 10:1 or 8:1 . When using the infrared thermometer to measure CWSI, it is important to be close enough to measure canopy temperature and not include the temperature of the soil, or the stakes supporting the canopy in the case of grape vines.

2.2 *Calibrating the infrared thermometer to measure CWSI*

The manufactures assume that the temperature of the surrounding and the detector along with the emissivity of the instrument and the emissivity of the canopy are the same, so the only error would be the reflected sky radiation. The IR thermometer factory calibration needs to be improved over the desired temperature range of crops by using a black body calibration source with an emissivity of one discussed in the methods section. The factory calibration is over a wide range of temperature (20 degree C to 520 degree C) and consequently, its resolution is too low in the canopy range of temperature of 20 degree C to 40 degree C.

3. Methods

Twelve infrared thermometers (Sun model EM520B) with a fixed emissivity of 0.95 and a field of view of 8:1 were purchased and calibrated by putting them in a greenhouse where the temperature ranged from 18 to 39 degree C throughout the day. Specification of the infrared sensor is given in Table 1.

Specifications	**Range**
Temperature Range	-20 C to 520 C
Repeatability	+- 2 C
Response time	500 mSec, to reach 95 % of reading
Spectral Response	7-18 um
Emissivity	0.95
Relative humidity operation range	10-95%Rh
Power	9V
FOV	8:1

Table 1 Specifications of All Sun Model Em520B infrared thermometer (AllSun, 2016)

The thermometers were used to measure the temperature in a compactor cup (ThermoWorks compactor cup, 2016) which consisted of an aluminum cup painted black to establish an emissivity of 1.0. An access hole in the cups top was used for the radiation measurements. A second horizontal hole on the cup bottom side was for the precision placement of a thermocouple (type t) connected to a fluke thermometer (model 52-2) with an accuracy of

-+0.3 C (Fluke 2016). Four infrared thermometer readings of the compact cup temperature were taken. Each reading took 3 -5 seconds. During the infrared temperature measurements the fluke thermometer was read continually to make sure that the compact cup was as a constant temperature and in equilibrium with the surrounding air temperature measured with an additional thermocouple. Both the infrared thermometer and the compactor cup temperatures were recorded by hand and the data plotted in an excel spreadsheet. Care was taken to make sure the compacter cup, infrared thermometer and the air thermocouple were not in direct sunlight and consequently, the infrared thermometer case was at air temperature. Besides using a greenhouse, similar measurements were made in an auto interior on a clear day when the interior of the car heated up due to direct sunlight falling on the car but not the compactor cup and infrared thermometer.

One of the thermometers was placed in direct sunlight for 10 minutes to determine the impact of heating the infrared thermometer above air temperature.

A second brand (Cen-Tech) fixed emissivity infrared thermometer (number 13) was purchased to compare to the 12 All Sun thermometers. An additional infrared thermometer [Thermoworks infrared thermometer (2016) Ir-Gun-S (Number 14)] was purchase. It had a variable setting for emissivity and was set to 1.0, which was the same emissivity as the compactor cup. The identical calibration procedure was conducted with these thermometers.

The factory calibration was used for the RH-temperature sensor model -PYLE PTHM20 when making CWSI measurements of grapes (Pyle 2016) using the low cost infrared thermometer.

3. **Results**

The mean black body temperature minus the infrared temperature of the 12 infrared thermometer instrument measurements plotted against the blackbody temperature showed a linear increase in measurement error with increasing temperature (coefficient of determination 0.95) when averaged over all the sensors (Figure 2). However, the large difference between the average and max and min values shows the need for individual calibration of each infrared thermometer. A single calibration function cannot be used to correct the infrared thermometer to the correct black body temperature. Also the difference between the black body temperature and the infrared temperature can be, on average, as much as 2 degrees C ; it is essential to calibrate the low cost infrared thermometers before using them to measure the CWSI. The difference between canopy minus air temperature in the CWSI measurements usually varies from +2 for small leaves to +8 for large leaves to minus 6 degrees C for both size leaves. An error of 2 degrees in the canopy measurement would result in a 20 percent error in the calculation of the CWSI.

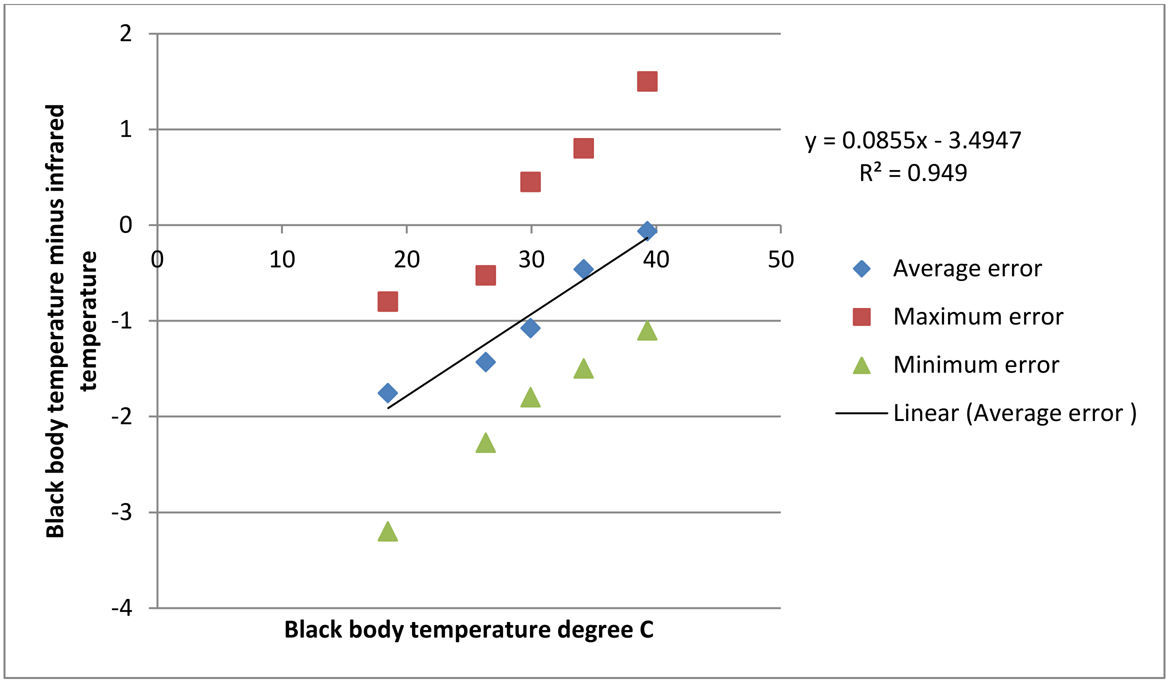

Figure 2. Average and Max and Min difference between the correct surface temperature of a black body and that measured by a low cost infrared thermometer with a fixed emissivity.

The linear calibration of the infrared individual thermometers (back body temperature- infrared thermometer temperature) must be added to the infrared measured temperature as shown for thermometer 3 (Figure 3). The coefficient of determinations of the linear individual infrared thermometers calibration functions ranged from 0.91 to 0.99 for an infrared thermometer with a fixed emissivity of 0.95 (Table 2).

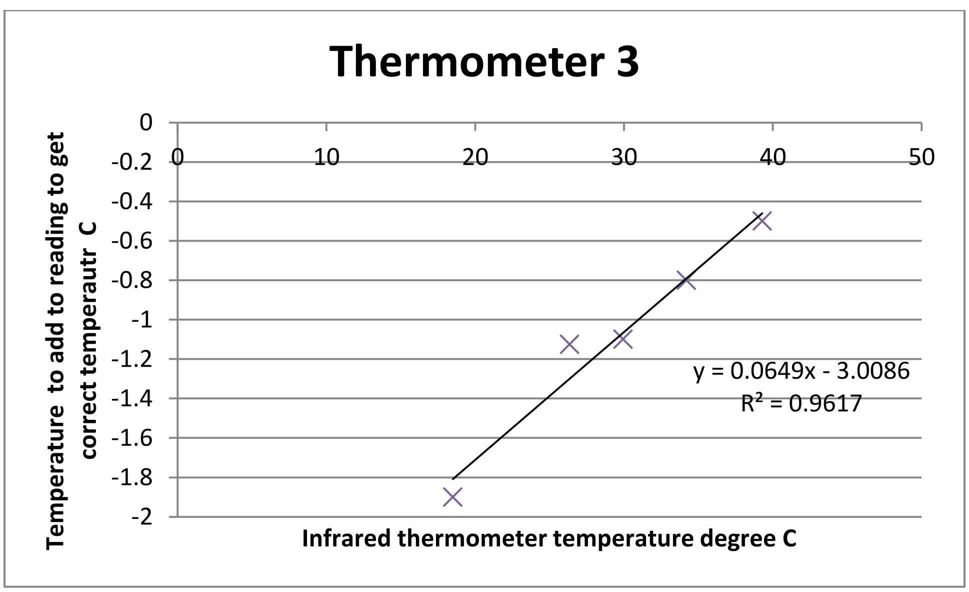

Figure 3. Linear calibration function for infrared thermometer 3.

Table 2 Individual calibration of infrared thermometers with compared to a black body temperature.

Infrared thermometer number	Linear calibration function, temperature added to reading to correct to black body temperature y=ax +b		Coefficient of determination	Emissivity of infrared thermometer
	a	B		
1	0.1018	-2.8219	0.91	0.95
2	0.0747	-3.152	0.96	0.95
3	0.0649	-3.0086	0.96	0.95
4	0.0442	-2.8815	0.91	0.95
5	0.0299	-2.5884	0.96	0.95
6	0.0380	-2.1648	0.92	0.95
7	0.0651	-3.0907	0.91	0.95
8	0.0652	-3.2743	0.94	0.95
9	0.1189	-3.2124	0.99	0.95
10	0.2345	-8.3782	0.95	0.95
11	0.0651	-3.0907	0.91	0.95
12	0.2119	-7.2205	0.91	0.95
13	0.032	-1.879	0.73	0.95
14	No linear calibration function			1.0

When the calibration was conducted on the infrared thermometers that had adjustable emissivity settings, no linear calibration function (Figure 3) could be determined for thermometer 14. A low coefficient of determination (0.73, Table 2) was determined for the other fixed emissivity infrared thermometer (number 13).

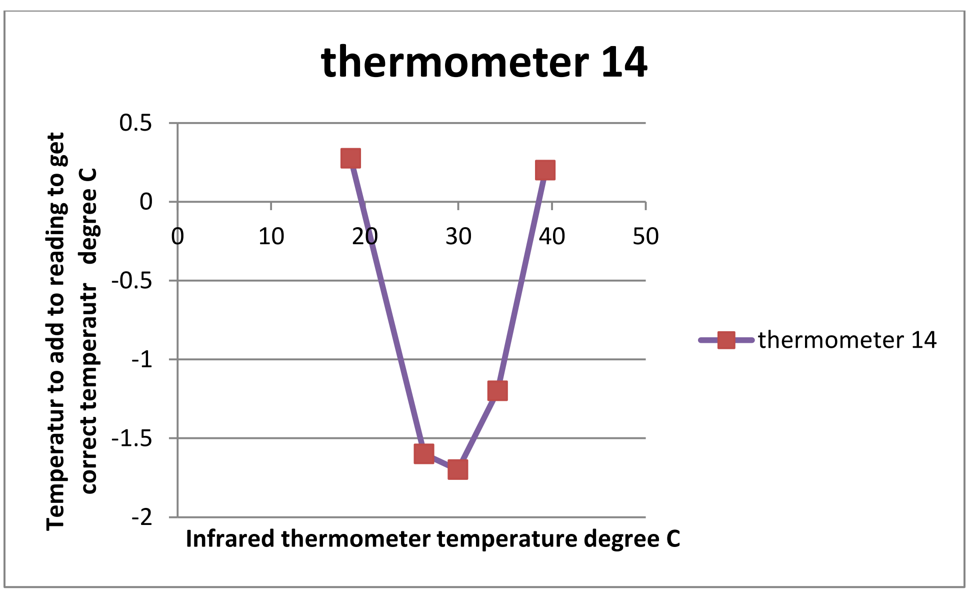

Figure 3. Difference between the correct surface temperature of a black body and that measured by a low cost infrared thermometers with variable emissivity, set to one.

Figure 4 shows that error in canopy temperature measured with a low cost infrared thermometer calibrated for an emissivity of one when not corrected for clear sky radiation and crop canopy emissivity of 0.98.

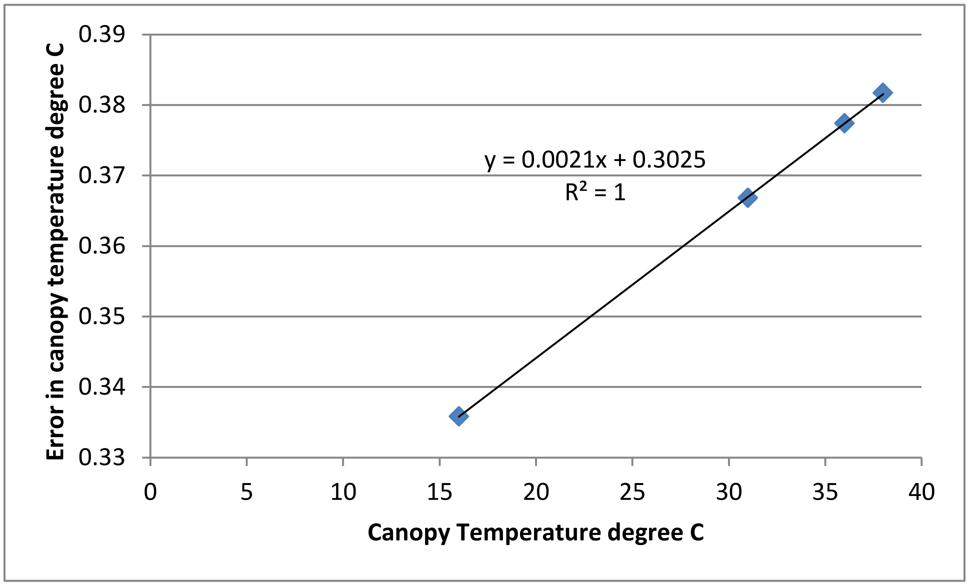

Figure 4. Error in canopy temperature measured with a low cost infrared thermometer calibrated for an emissivity of one when not corrected for clear sky radiation and crop canopy emissivity of 0.98

The infrared thermometer left in the sun for 10 minutes before measurements became sufficiently hot that the temperature display increased 4 to 6 degrees C.

4 Discussion

If the infrared thermometer is not calibrated then an error of up to 20 percent can occur in calculating the CWSI. The canopy and aerodynamic resistance and evapotranspiration rate of the canopy can be calculated using the lower base line slope and intercept of the CWSI and the O'Toole equation (O'Toole and Real 1986) but the error can be significant (10%) if the canopy temperature is not also corrected for emissivity and clear sky in addition to the infrared thermometer calibration. However, the maximum error of not making the emissivity and clear sky correction in the CWSI graphical calculation by Idso and Jackson (1969) is only 2 percent for VPD near zero because the correction has to be applied to both the lower and upper base line temperature measurements. The error decreases below 0.2% as the vapor pressure deficit increases from 0 to 4 MPa at measurement time.

If the infrared thermometer is left in the sun before taking canopy temperature measurements a 35 % error or more can occur in the calculated CWSI. Consequently, it is imperative that the IR thermometer be place in the shade for 15 minutes to equilibrate to air temperature before taking measurements. It is best to shade the instrument from direct sunlight when taking the measurements. In the calibration of the infrared thermometer, the thermometer temperature must also be in equilibrium with the air temperature as must the compactor cup used in the calibration process.

More accurate infrared thermometers that correct for the body temperature of the sensor do not need calibration but the cost is considerable higher (greater than $600) than the low cost infrared thermometers ($25-$50). The more expensive infrared thermometers can be connected to a data logger and the measurements taken automatically from a tractor or all-terrain vehicle as it moves through the field.

However, because of the cost of the of high end infrared thermometers, the calibrated low cost infrared thermometers can be purchased to calculate the CWSI and experience gained by the grower to determine if monitoring of irrigation management by use of the CWSI is desirable before spending the additional money.

5 **Conclusions**

The low cost infrared thermometers measure the infrared temperature by using uncooled thermopile detectors that detect radiation in the 8 um to 14 um spectral range. Because these detectors are uncooled, radiation emitted by the detector itself must be considered in the calibration process.

Linear calibration to correct the infrared thermometer to a black body temperature in the range of 18 to 39 degree C resulted in coefficients of determination for fixed emissivity thermometers ranging from 0.91 to 0.99. The variable emissivity infrared thermometers had no linear calibration function.

Each individual low cost infrared thermometer must be calibrated.

In order to use low cost IR thermometers in crop water stress measurements (CWSI), the instruments must be calibrated in the temperature range of use otherwise the CWSI error can be as high as 20 percent. Shading the thermometer is important in both the calibration and field measurement procedures. If the infrared thermometer is left in the sun before taking canopy temperature measurements a 35 % error or more can occur in the calculated CWSI.

When measuring the CWSI using the IR thermometers, correction for reflected radiation from the sky and emissivity that is not a black body is not necessary when using the CWSI graphical calculation by Idso (1982) because the error is small, less than 2 percent.

However, if the CWSI measurements are used to calculate the canopy and aerodynamic resistance and the transpiration rate of the crop, then the IR thermometer reading after calibration must be corrected for the reflected sky radiation and change in emissivity or the error can be as high as 10% in the canopy and aerodynamic resistance values.

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