CIVE 519 - Irrigation Water Management

FALL 2024

Lecture 18

Crop Water Stress Index (CWSI) Approach:
Determining crop stress and water use

Infra-red Thermometer (IRT) calibration

José L. Chávez, Ph.D., Associate Professor

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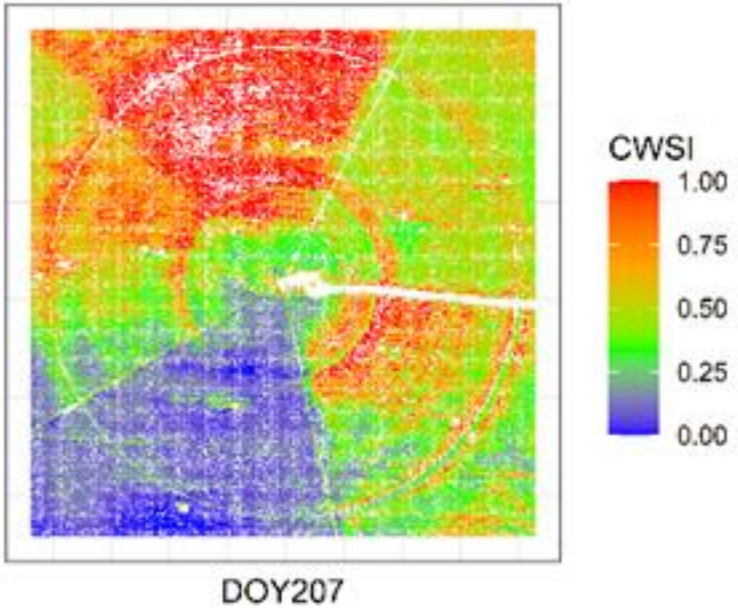
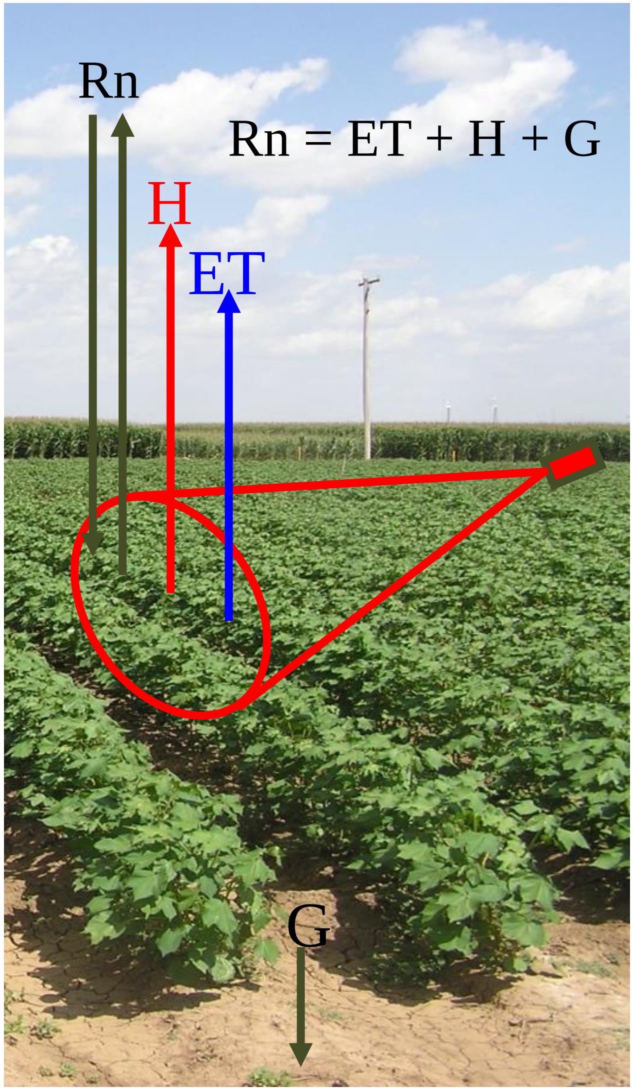
Colorado State University
Department of Civil & Environmental Engineering

Learning Objectives

- To learn how to detect crop water stress based on canopy temperature
- To calculate the level of crop stress and water use - ETa (and reduction) on crops based on canopy temperature
- To calibrate an infra-red thermometer



Why is plant canopy temperature useful?



Colaizzi et al.

- Related to water status of plant and soil
  - The ET process cools the plant
  - If ET is inhibited the plant heats up
- Can be measured by non-contact infrared thermometers (IRTs)

Why is plant canopy temperature useful?

- Non-contact (proximal remote sensing) measurement
  - Integrates larger area compared with sensors that make physical contact with plant or soil
  - Can be mobile or stationary
  - Center pivot can be used as a mobile platform

- Can automate irrigation systems (drip and CP)
- Can prioritize irrigation schedules
- Can alert manager to unusual field conditions
  - Equipment malfunction
  - Biotic stress
- Can reduce management time required

Crop Water Stress

- "Stress," in the context of plants, is a broad term used to describe some type of adversity that, if prolonged, can result in economic yield loss (Jackson, 1982).
- "Water stress" then describes a condition where the supply of water in plant leaves is insufficient to carry out photosynthesis and respiration using all available energy.
- The shortage of water could be caused by abiotic stresses (i.e., resulting from soil water depletion) or biotic stresses (i.e., from pests or disease).
- Under water stress conditions, a greater amount of available energy must be converted to sensible heat compared with what would have occurred for non-water-stressed conditions. The result is that the temperature of the plant canopy (i.e., the ensemble of plant leaves) increases over the temperature that would have resulted for no shortages in water.

CWSI

- The Crop Water Stress Index (CWSI; Jackson et al., 1981; Idso et al., 1981) has received the most attention of any water stress index.

- It is derived from the energy balance where, for a given set of meteorological conditions, a range of “canopy - air temperature” differences exist that are bound by a lower limit (no water stress) and an upper limit (complete water stress where no ET is occurring).

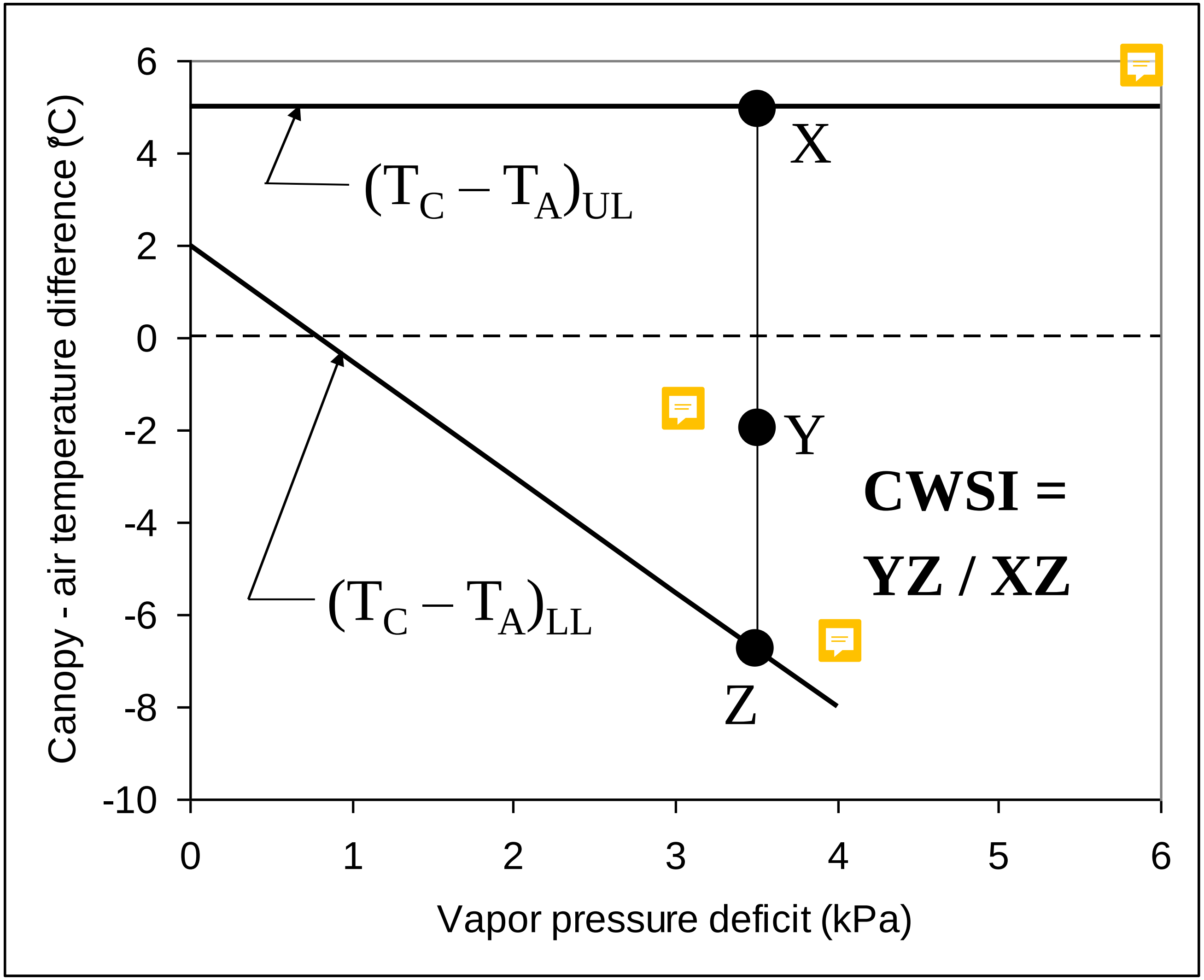
- The measured “canopy - air temperature” difference should fall within these lower and upper limits, and is normalized as an index where zero indicates no water stress and one indicates complete water stress.

Irrigation Scheduling with Infrared Thermometry (Crop Water Stress Index Method, CWSI)

- Use infrared sensor to monitor crop canopy temperature (Tc),
- Simultaneously measure air temperature (Ta) and vapor pressure deficit (VPD = $e_s - e_a$), with thermometer and humidity sensor,
- When 'Tc – Ta" deviates from a "baseline" of 'Tc – Ta" vs. VPD the crop is stressed and it is time to irrigate,
- Tc increases due to stress, and 'Tc – Ta" becomes more positive and the point rises above the baseline,
- This method requires one to be able to order water and irrigate either immediately or within one day, because by the time the 'Tc-Ta" value deviates from the baseline, the crop is already stressed and needs water,
- This method should always be used between local 12:00 noon and 2:00 pm (standard time), and on sunny days, for consistency in measurements.

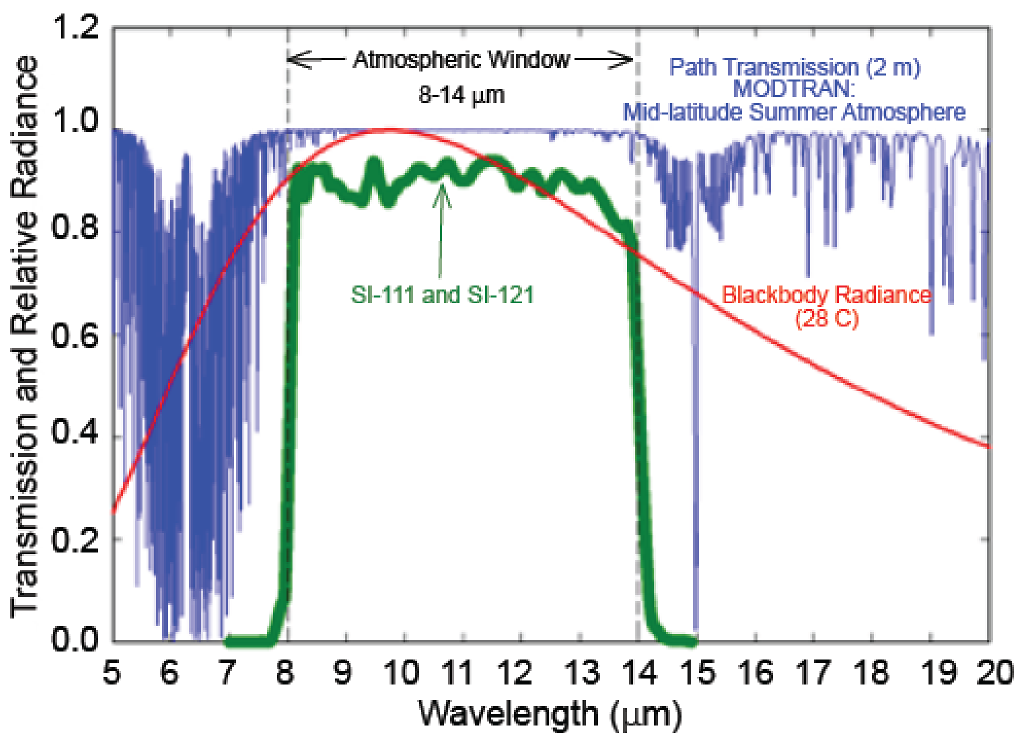
Crop Water Stress Index (CWSI = YZ / XZ)

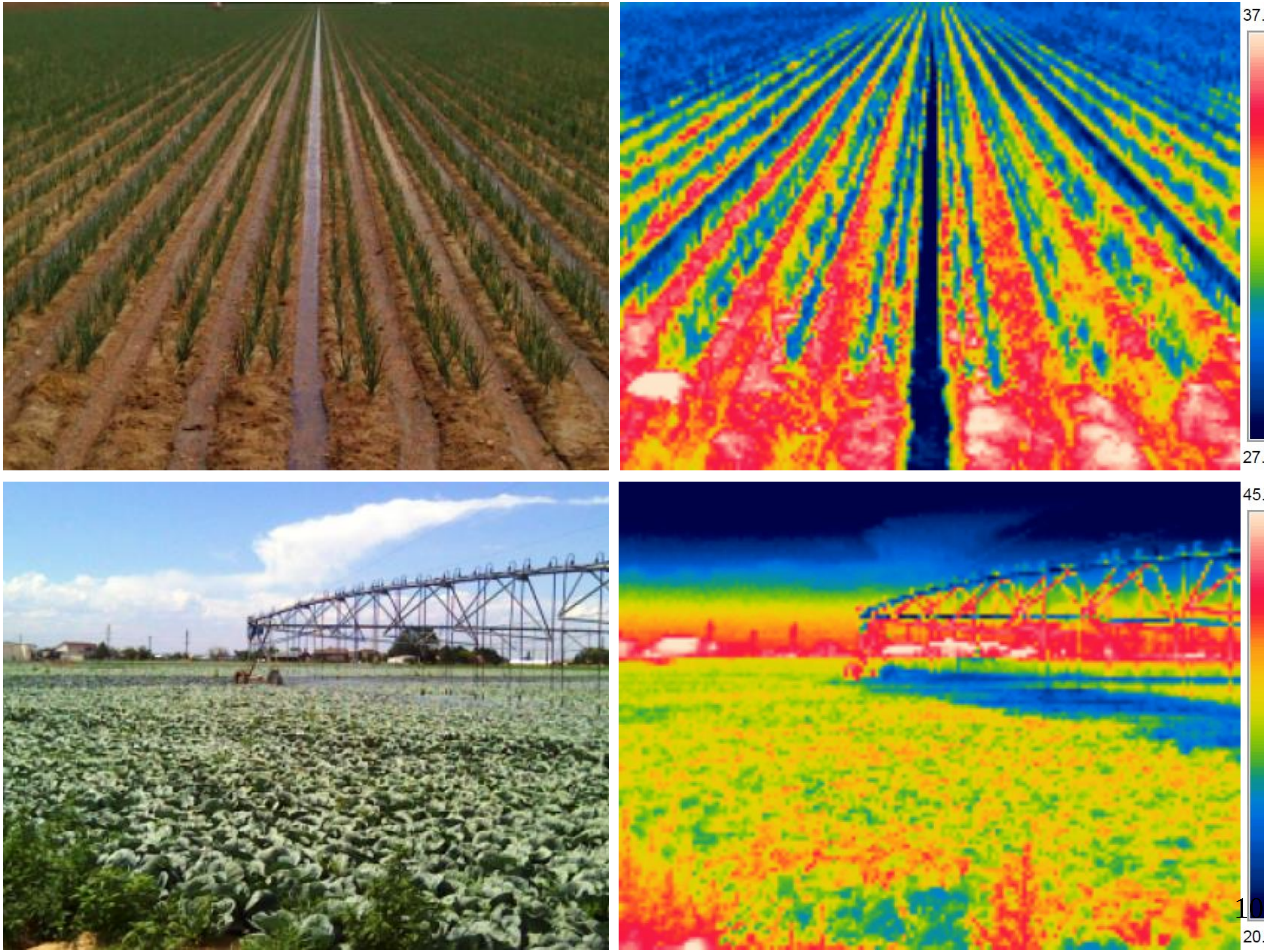
$$CWSI = \frac{(T_C - T_A)_M - (T_C - T_A)_{LL}}{(T_C - T_A)_{UL} - (T_C - T_A)_{LL}} = \frac{YZ}{XZ}$$

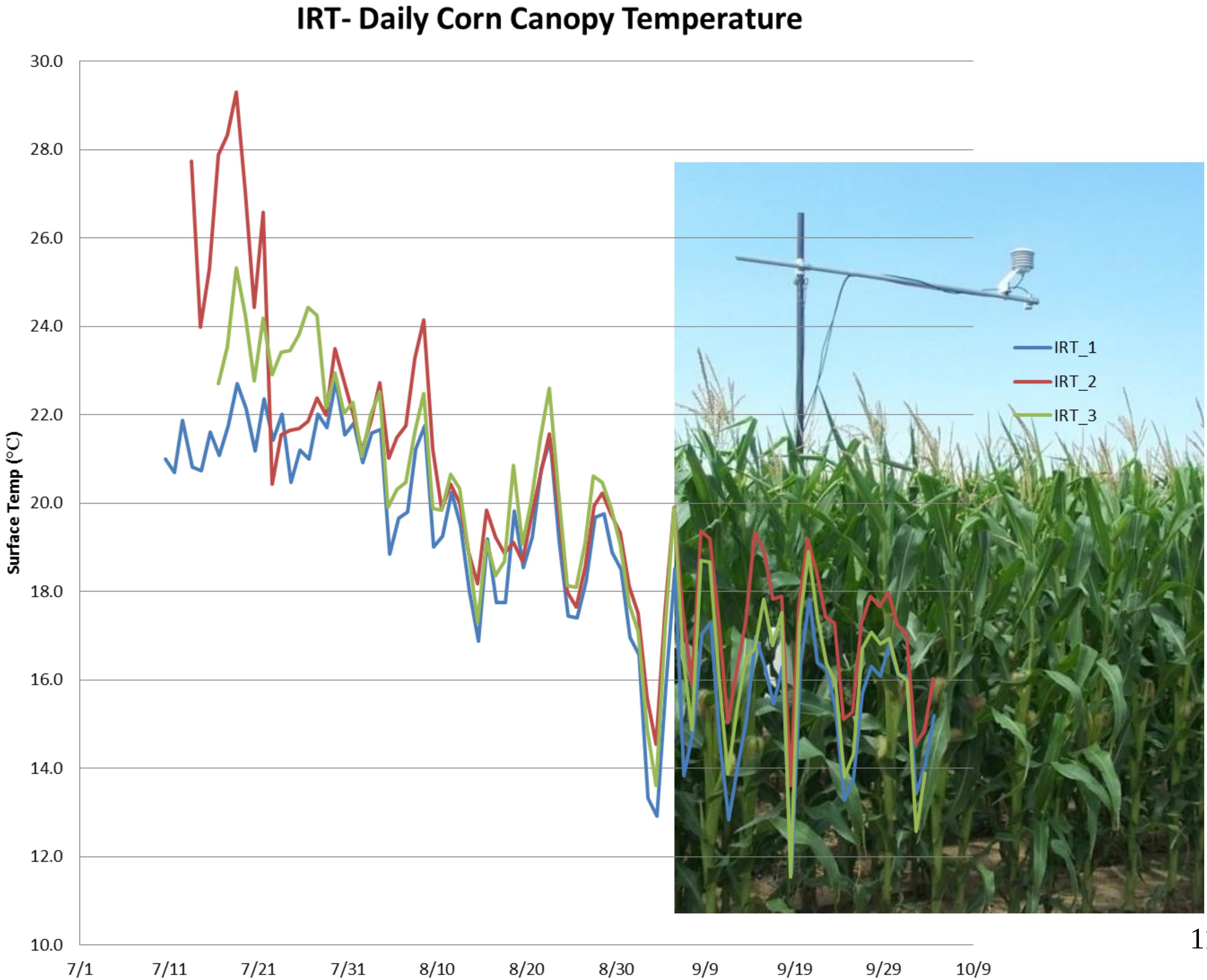


Infra-red thermometer (IRT) Apogee model SI-111

Response time: < 1 sec,
Accuracy: +/- 0.2 ºC
Temperature range: -10 to 65 ºC
Wavelength: 8-14 micro meters (um)
Mass: 190 g
Optics: Germanium lens
22º FOV half angle




37.0
27.0
45.0
20.0


IRT- Daily Corn Canopy Temperature
Surface Temp (°C)
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
7/1
7/11
7/21
7/31
8/10
8/20
8/30
9/9
9/19
9/29
10/9
IRT_1
IRT_2
IRT_3

Obtaining ETa from CWSI

$$CWSI = \frac{dT - dT_{mn}}{dT_{mx} - dT_{mn}}$$

$$CWSI = 1 - \frac{ET_a}{ET_c}$$

CWSI range: 0-1,

where:

dT = $T_c - T_a$

dT_{mn} : f (VPD) = a (VPD) + b

dT_{mx} : f (VPG) = a (VPG) + b

$$ET_a = (1 - CWSI)ET_c$$

$$ET_c = K_c \times ET_{ref}$$

Definition of the upper and lower dT

- dT_{min} or dT_{LL} is the temperature difference between canopy and air when there is no crop water stress,
- dT_{max} or dT_{UL} is the temperature difference between canopy and air when there is maximum crop water stress,
- Linear relationship between dT_{LL} and vapor pressure deficit (VPD)
- Linear relationship between dT_{UL} and 'vapor pressure gradient' (VPG). Where VPG is the difference between saturated vapor pressure at air temperature and at a higher temperature equal to air temperature plus the coefficient "b" of the dT_{LL} fitted linear regression line.

Example of lower limit dT functions

For Corn:

$dT_{min} = (Tc - Ta)_{min} = b + a\ VPD$

(Idso, 1982)

$dT_{min} = 3.11 - 1.97\ VPD$,

(Nielsen &Garden (1987)

$dT_{min} = 2.67 - 2.06\ VPD$,

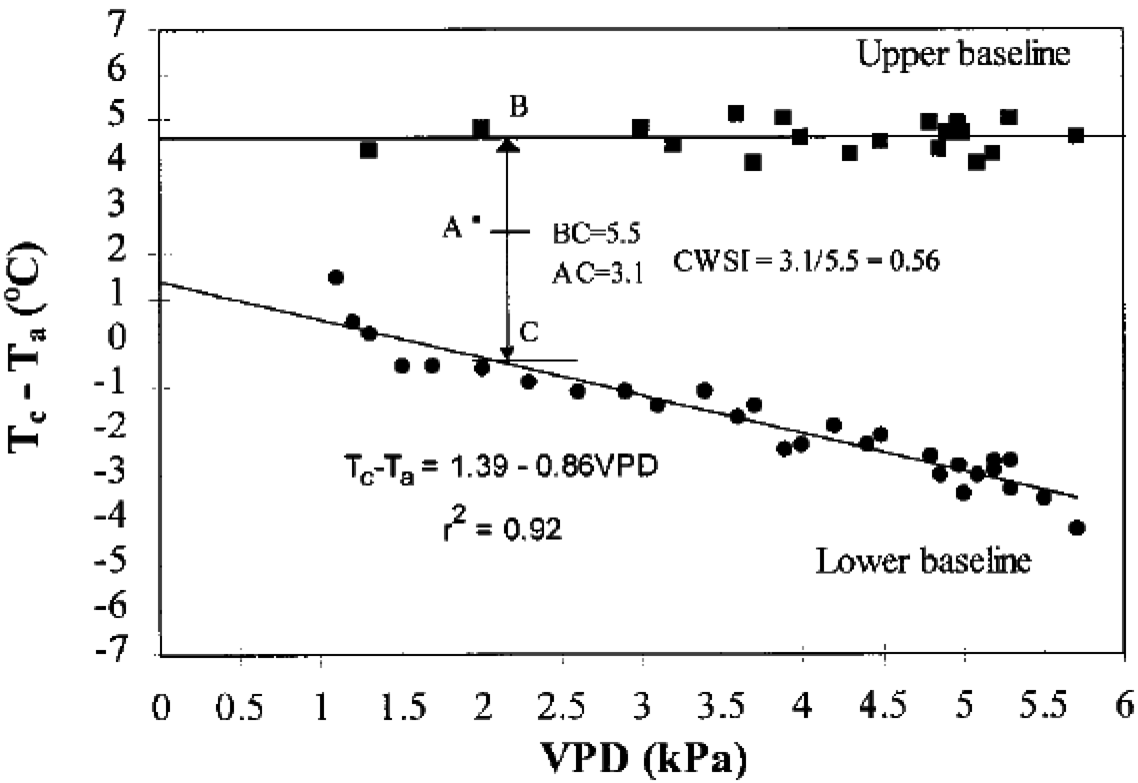


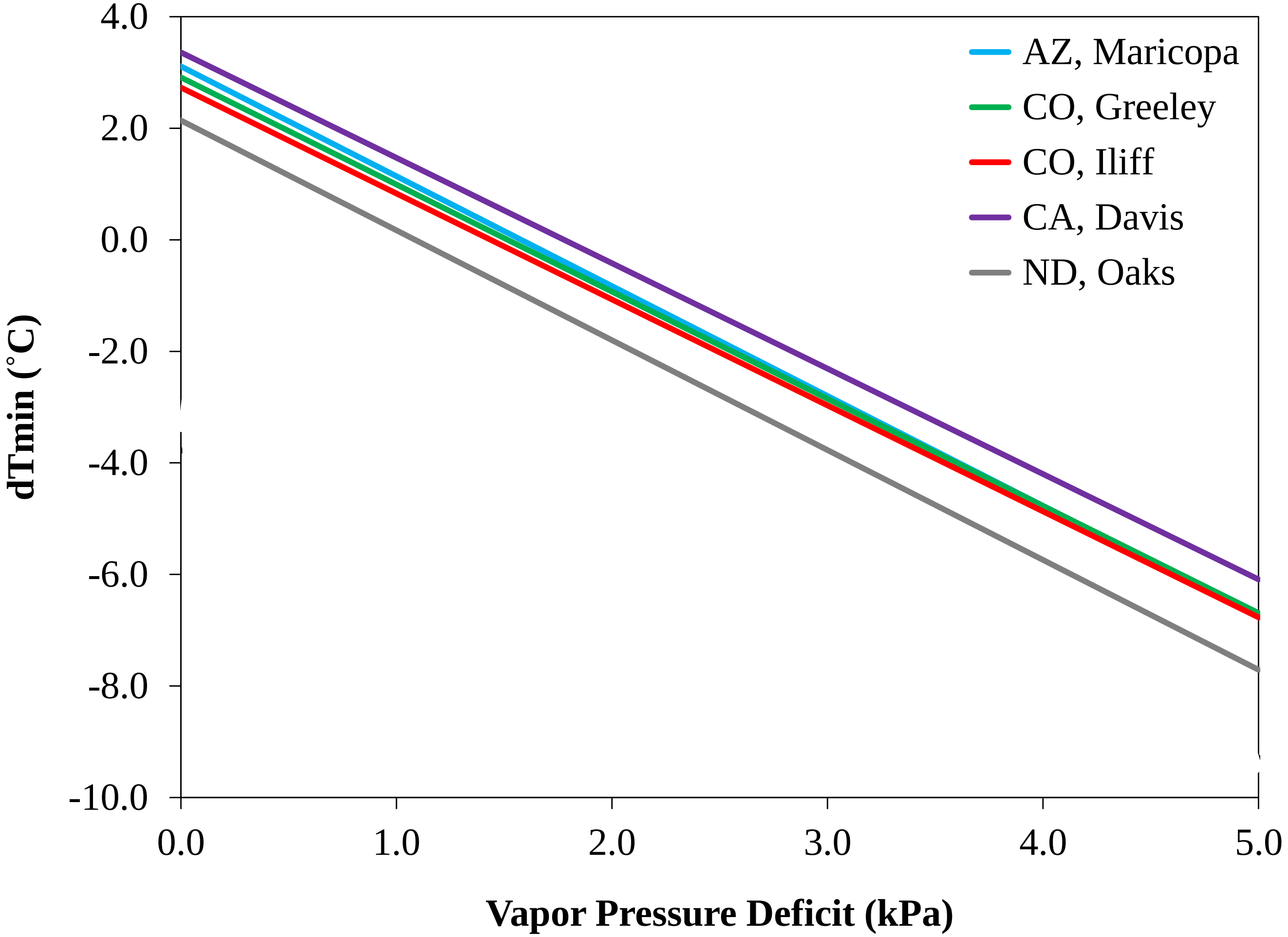
Fig. 1. Relationships between canopy temperature minus air temperature ($T_c - T_a$) and vapor pressure deficit (VPD) of summer-grown corn at Atalya, Turkey. A is the point which was used as an example of how CWSI value is calculated. B and C represent the upper and lower limits for point A, respectively. BC is the vertical distance between upper and lower baselines, AC is the vertical distance between point A and lower baseline, and the CWSI is the crop water stress index.

Irmak et al. (2000)

Lower limit or boundary of dT (for corn)

$dT = T_c - T_a$

dT_{min} : 2.73 × (VPD) – 1.90; Developed w/ data from Iliff, CO



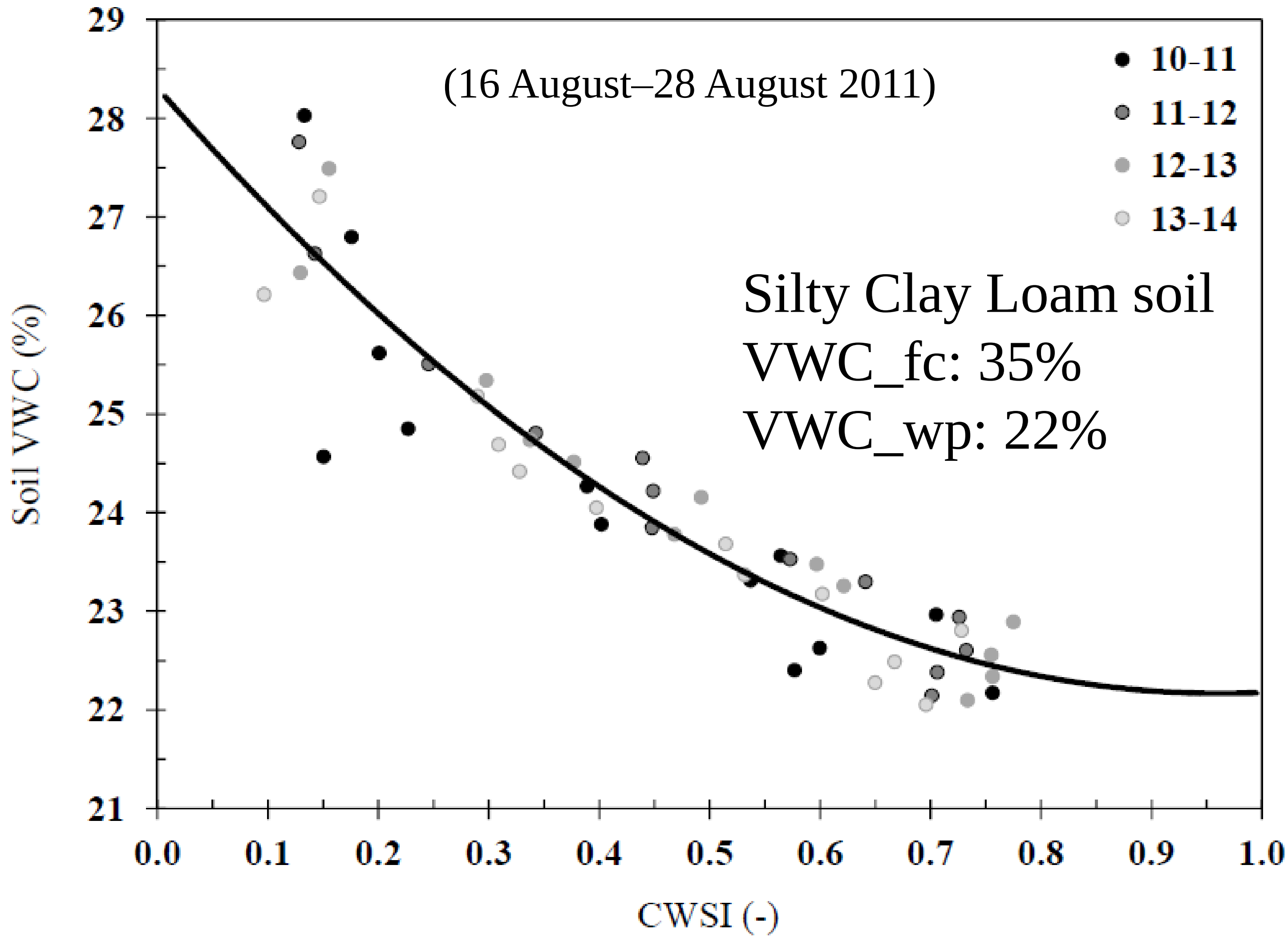
CWSI:

a) RH

b) T_{air}

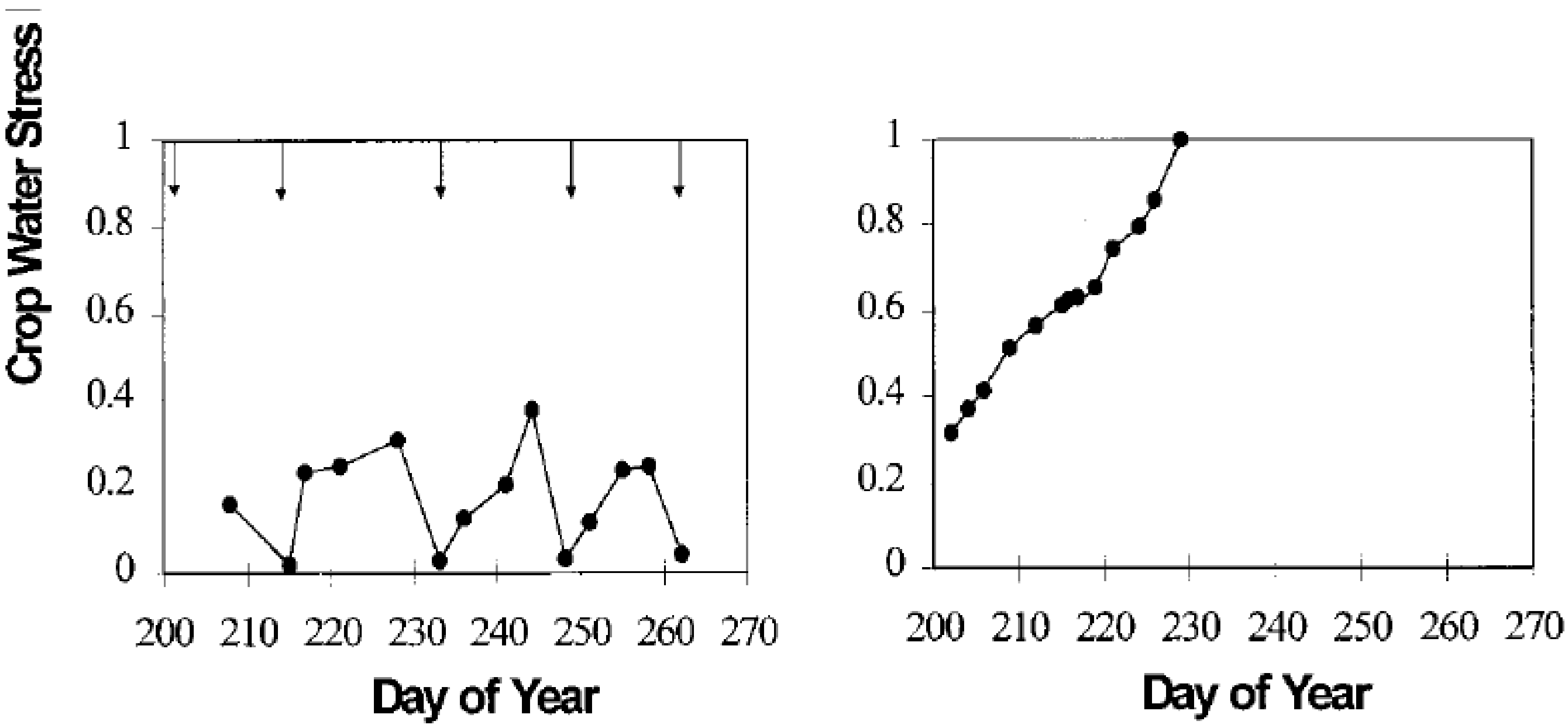
c) T_{canopy}

CWSI *vs.* volumetric water content (VWC)



Taghvaeian, S., J.L. Chávez, and N.C. Hansen. (2012). Infrared Thermometry to Estimate Crop Water Use and Stress Index of Irrigated Maize in Northeastern Colorado. Special issue: Advances in Remote Sensing of Crop Water Use Estimation. Remote Sens. 2012, 4(11), 3619-3637

CWSI and levels of irrigation



Some limitations of the CWSI

- The accuracy of the CWSI can be limited when VPD is low. As VPD decreases, the range of temperature limits becomes smaller, and the distances between points X, Y, and Z in graph decrease. The result is that small errors in $(T_C - T_A)_M$, $(T_C - T_A)_{LL}$, and $(T_C - T_A)_{UL}$ will lead to increasingly larger errors in CWSI, increasing the probability of out-of-bounds CWSI values; i.e., less than zero and greater than one (Jones, 2004).

- Somewhat related is the influence of incoming solar irradiance, where overcast skies also reduce the range of temperature limits. Both conditions are more prevalent in humid climates, but in arid and semiarid climates, low VPD is common in the morning (especially over irrigated fields) and greater cloud cover occurs frequently in the afternoon during summer months. Consequently, the CWSI is less responsive to plant and soil water conditions in humid locations, and has been found to be most responsive during clear skies and within a few hours of solar noon.

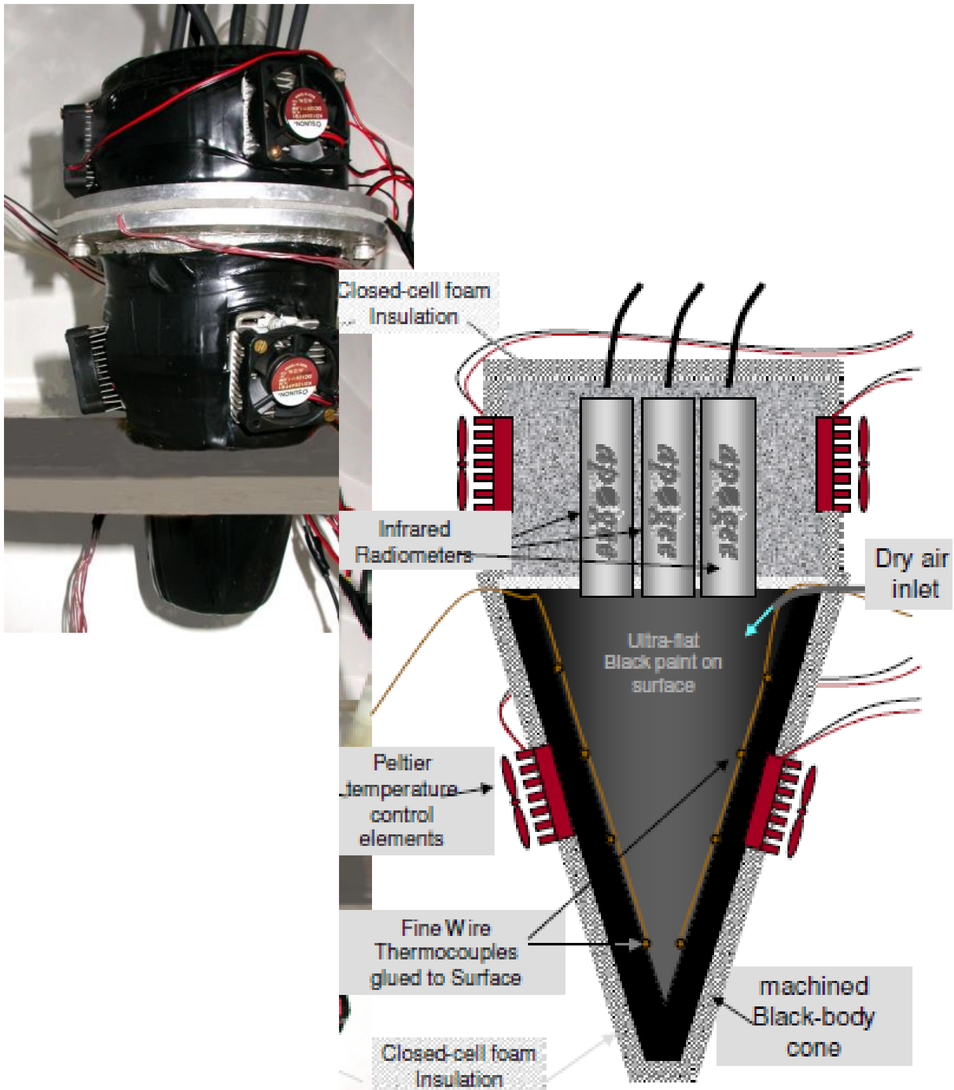
(Colaizzi et al., 2012)

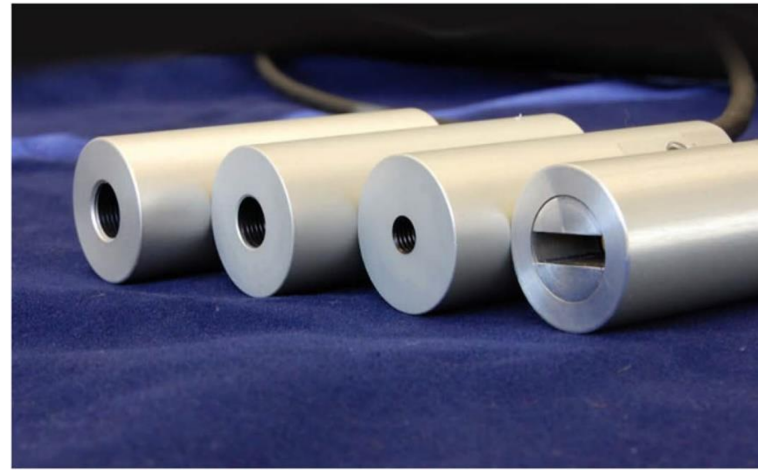
Some limitations of the CWSI cont'd

- Incomplete canopy cover is also a serious limitation of the CWSI, which exists during some (and perhaps all) of the irrigation season. The temperature of dry, sunlit soil is typically 30° C greater than green, transpiring vegetation.
- Therefore, T_C measurements can be greatly overestimated, resulting in overestimates of CWSI if soil appears in the radiometer field of view. The temperature of shaded soil is also usually different from vegetation, which may also introduce errors in CWSI calculations.
- The view of vegetation can be maximized and soil minimized by pointing a radiometer at an angle and perpendicular to crop rows, and the radiometer can be designed to have a smaller field of view. However, the radiometer view still may not be completely free of soil, especially early in the season.

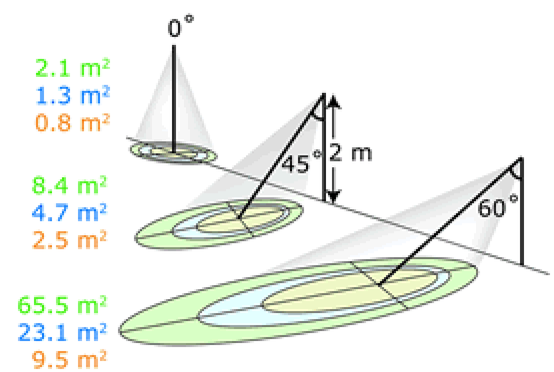
(Colaizzi et al., 2012)

Infra-red Thermometers (IRTs)





Type	Model	Half Angle
Standard	SI-111	22°
Narrow	SI-121	18°
Ultra-Narrow	SI-131	14°



Sensor calibration sheet provided by the manufacturer

Certificate of Calibration

APOGEE INSTRUMENTS INFRARED RADIOMETER
SI SERIES

Calibration Overview

Model/Serial Number	:	**SI-111_EXAMPLE**
Calibration Date	:	8-Jul-2013
Recommended Recalibration Date	:	8-Jul-2015
Mean of Differences from Target	:	0.001 °C
Target Temperature Uncertainty (95% confidence) from -30 to 65 °C	:	**0.133 °C**
Maximum Difference from Target	:	0.148 °C
Minimum Difference from Target	:	-0.119 °C
Maximum Detector Response	:	1.379 mV
Minimum Detector Response	:	-0.804 mV
Average Output Sensitivity	:	66.794 μV / °C

Custom Calibration Coefficients

CRBasic

	C2	C1	C0
m	81170.5	7187980	1334780000
b	2295.07	245405	-6557540

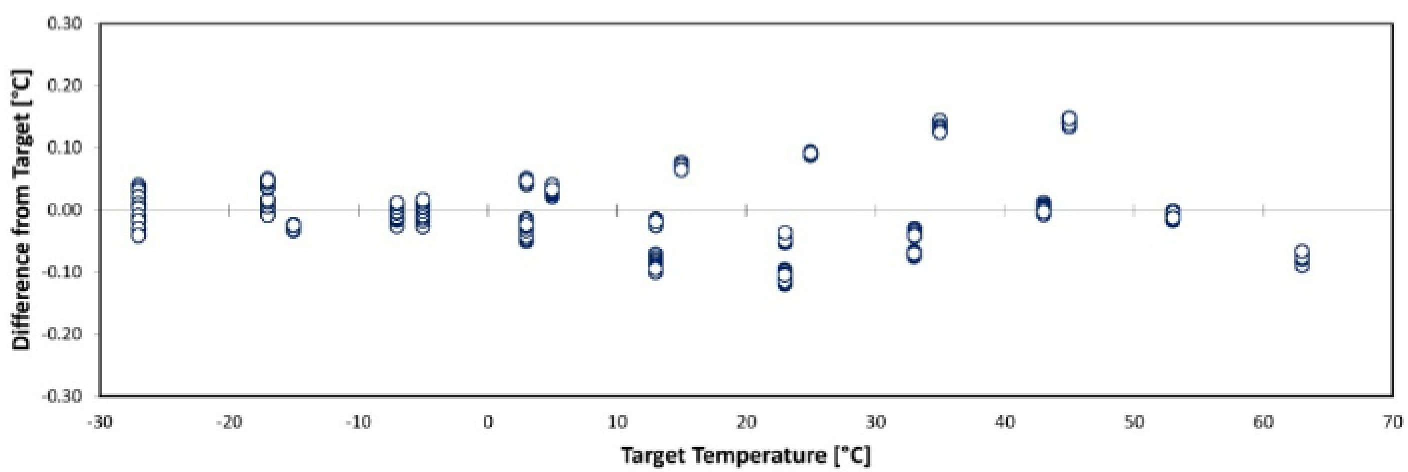
See the SI-100 series manual for how to apply these coefficients in determining target temperatures.

Edlog

	C2	C1	C0
m(SB)	0.81171	71.88052	13347.93348
b(SB)	0.02295	2.45407	-65.57606

Use these coefficients in Edlog programs for older Campbell Scientific dataloggers.

Coefficient Correction Errors



Calibration of an Apogee IRT sensor

Target Temperature Measurement:

The detector output from SI-100 series radiometers follows the fundamental physics of the Stefan-Boltzmann Law, where radiation transfer is proportional to the fourth power of absolute temperature. A modified form of the Stefan-Boltzmann equation is used to calibrate sensors, and subsequently, calculate target temperature:

$$T_T^{\ 4} - T_D^{\ 4} = m \cdot S_D + b \qquad (1)$$

where T_T is target temperature [K], T_D is detector temperature [K], S_D is the millivolt signal from the detector, m is slope, and b is intercept. The mV signal from the detector is linearly proportional to the energy balance between the target and detector, analogous to energy emission being linearly proportional to the fourth power of temperature in the Stefan-Boltzmann Law.

Calibration of an Apogee IRT sensor cont'd

During the calibration process, m and b are determined at each detector temperature set point (10 C increments across a -15 C to 45 C range) by plotting measurements of $T_T^4 - T_D^4$ versus mV. The derived m and b coefficients are then plotted as function of T_D and second order polynomials are fitted to the results to produce equations that determine m and b at any T_D:

$$m = C2 \cdot T_D^{\;2} + C1 \cdot T_D + C0 \qquad (2)$$

$$b = C2 \cdot T_D^{\;2} + C1 \cdot T_D + C0 \qquad (3)$$

Where C2, C1, and C0 are the custom calibration coefficients listed on the calibration certificate (shown above) that comes with each SI-100 series radiometer (there are two sets of polynomial coefficients, one set for m and one set for b). Note that T_D is converted from Kelvin to Celsius (temperature in C equals temperature in K minus 273.15) before m and b are plotted versus T_D.

To make measurements of target temperatures, Eq. (1) is rearranged to solve for T_T [C], measured values of S_D and T_D are input, and predicted values of m and b are input:

$$T_T = \left(T_D^{\;4} + m \cdot S_D + b\right)^{\frac{1}{4}} - 273.15 \qquad (4)$$

Calibration of an Apogee IRT sensor: Example

- Calibration coefficients for a SI-111 IRT:

	C2	C1	C0
m =	6.6104E+04	8.1115E+06	1.3876E+09
b =	2.3018E+04	-4.8556E+05	9.4958E+05

- Calibrate the IRT readings (mV) to obtain target temperatures (T_{target} °C)

Signal (mV)	R_T (Ω)	SBTempC (°C)
-0.5	10880	23.1
0	12500	20.0
1.5	14000	17.5

- Where **SBTempC is sensor body temperature or detector temperature** (T_D) and Signal is the millivolt signal from the detector (S_D), from the reading of the target surface.

Calibration of an Apogee IRT: Example cont'd

$$m = C2 \cdot T_D^{\,2} + C1 \cdot T_D + C0 \qquad (2)$$

$$b = C2 \cdot T_D^{\,2} + C1 \cdot T_D + C0 \qquad (3)$$

- For first data point: S_D = -0.5 mV, and SBTempC = T_D = 23.1 °C.
- m = 6.6104E+04 x $(23.1)^2$ + 8.1115E+06 x 23.1 + 1.3876E+09 = 1.61E+09
- b = 2.3018E+04 x $(23.1)^2$ + -4.8556E+05 x 23.1 + 9.4958E+05 = 2.01E+06

$$T_T = \left(T_D^{\,4} + m \cdot S_D + b\right)^{\frac{1}{4}} - 273.15 \qquad (4)$$

- T_{target} (°C) = $((23.1+273.15)^4$ + 1.61E+09 x (-0.5) + 2.01E+06$)^{0.25}$ – 273.15

- T_{target} = 15.0 °C.

Solution: T_{target}

Signal (mV)	R_T (Ω)	SBTempC (°C)	m	b	T_{Target} (°C)
-0.5	10880	23.1	1.61E+09	2.01E+06	15.0
0	12500	20.0	1.58E+09	4.41E+05	20.0
1.5	14000	17.5	1.55E+09	-4.99E+05	38.7

Emissivity correction

Appropriate correction for surface emissivity is required for accurate surface temperature measurements. The simple (and commonly made) emissivity correction, dividing measured temperature by surface emissivity, is incorrect because it does not account for reflected infrared radiation.

The radiation detected by an infrared radiometer includes two components: 1. radiation directly emitted by the target surface, and 2. reflected radiation from the background. The second component is often neglected. The magnitude of the two components in the total radiation detected by the radiometer is estimated using the emissivity (ε) and reflectivity (1 - ε) of the target surface:

$$E_{Sensor} = \varepsilon \cdot E_{Target} + (1 - \varepsilon) \cdot E_{Background} \quad (1)$$

Emissivity correction cont'd

where E_{Sensor} is radiance [W m^{-2} sr^{-1}] detected by the radiometer, E_{Target} is radiance [W m^{-2} sr^{-1}] emitted by the target surface, $E_{Background}$ is radiance [W m^{-2} sr^{-1}] emitted by the background (when the target surface is outdoors the background is generally the sky), and ε is the ratio of non-blackbody radiation emission (actual radiation emission) to blackbody radiation emission at the same temperature (theoretical maximum for radiation emission). Unless the target surface is a blackbody (ε = 1; emits and absorbs the theoretical maximum amount of energy based on temperature), E_{sensor} will include a fraction (1 – ε) of reflected radiation from the background.

Since temperature, rather than energy, is the desired quantity, Eq. (1) can be written in terms of temperature using the Stefan-Boltzmann Law, $E = \sigma T^4$ (relates energy being emitted by an object to the fourth power of its absolute temperature):

$$\sigma \cdot T_{Sensor}{}^4 = \varepsilon \cdot \sigma \cdot T_{Target}{}^4 + (1 - \varepsilon) \cdot \sigma \cdot T_{Background}{}^4 \qquad (2)$$

T_{target} = true target temperature,
T_{sensor} = target temperature uncorrected for surface emissivity & background effects

where T_{Sensor} [K] is temperature measured by the infrared radiometer (brightness temperature), T_{Target} [K] is actual temperature of the target surface, $T_{Background}$ [K] is brightness temperature of the background (usually the sky), and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}). The power of 4 on the temperatures in Eq. (2) is valid for the entire blackbody spectrum.

Emissivity correction example

- T_{sensor} = **28.2** °C, (equivalent to uncorrected T_{target})
- Target or surface emissivity (ε)= 0.98 (full cover, green, healthy plant, ε_v). For bare soil is 0.93 or ε_s,
- $T_{background}$ = sky temperature = **-15** °C

Rearrangement of Eq. (2) to solve for T_{Target} yields the equation used to calculate the actual target surface temperature (i.e., measured brightness temperature corrected for emissivity effects):

$$T_{Target} = \sqrt[4]{\frac{T_{Sensor}^{4} - (1-\varepsilon)\cdot T_{Background}^{4}}{\varepsilon}} \quad . \qquad (3)$$

- T_{target} = [((**28.2**+273.15)^4 – (1-0.98)x (**-15.0**+273.15)^4)/0.98]$^{0.25}$

- T_{target} = 302.06 K or **28.9** °C, (corrected for emissivity, true temperature)

Surface emissivity calculation

NDVI is the normalized difference vegetation index

NDVI = (R2 – R1) / (R2 + R1)

Where R2 is surface reflectance in the near infra-red band, and R1 is surface reflectance in the red band.

$NDVI_{max}$ ~ 0.90
$NDVI_{min}$ ~ 0.15

N* = scaled NDVI

$$N^* = \frac{\mathrm{NDVI} - \mathrm{NDVI}_0}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_0} \tag{3}$$

where NDVI_0 is the NDVI value corresponding to bare soil, and $\mathrm{NDVI}_{\max}$ is the value corresponding to full vegetation. Gillies *et al.* (1997) presented a relationship relating N^* to fractional vegetation cover ([0,1] dimensionless): i.e.,

$$Fr = N^{*2}. \tag{4}$$

Note that this is a nonlinear function due to the nonlinear relationship between NDVI and LAI (i.e., NDVI values saturate at higher LAI values).

Assuming an image is comprised of a two-component soil and vegetation system, the emitted radiance from the pixel is

$$\varepsilon_i \sigma \overline{T^4} = \varepsilon_v \sigma \overline{T_v^4} + \varepsilon_s \sigma \overline{T_s^4} \tag{5}$$

where ε_v represents the emissivity of the vegetation, ε_s is the emissivity of the soil, and ε_i is the pixel's emissivity. The effective emissivity of the pixel can be written as a function of the fractional vegetation cover as

$$\varepsilon_i = Fr \cdot \varepsilon_v + (1 - Fr) \cdot \varepsilon_s. \tag{6}$$

This is a reasonable extension due to the high emissivity of vegetated surfaces and the relatively lower emissivity of non-vegetated sites.

CWSI and ETa calculations: example

(Idso, 1982)

$dT_{min} = 3.11 – 1.97$ VPD,

- **Input data**:
- Date: August 26th, 2010
- Location: Greeley, CO
- Crop: corn
- Sensor: IRT Apogee SI-111 (oblique), Time of reading: 2 pm,
- Tc = 28.9 °C (target temperature corrected for surface emissivity)
- ***In-situ*** weather data: Ta = 32.0 °C, RH = 25.5%, ETc = 8.2 mm/d
- **Output**:
- Compute the vapor pressure deficit (VPD): VPD = e_s(Ta) – e_a(Td)
- 0.6108*EXP(17.27 x Ta/(Ta+237.3)) - 0.6108 x EXP(17.27 x Ta/(Ta+237.3))x RH /100 = 3.54 kPa
- Compute the vapor pressure gradient (VPG): VPG =e_s(Ta) – e_s(Ta + b)
- 0.6108*EXP(17.27 x Ta/(Ta+237.3)) - 0.6108 x EXP(17.27 x (Ta+3.11)/((Ta+3.11)+237.3)) = -0.9 kPa

CWSI example cont'd

$$CWSI = \frac{dT - dT_{mn}}{dT_{mx} - dT_{mn}}$$

- **<u>Output</u>**:
- Compute the dTmin as: 3.11 - 1.97 x (3.54) = -3.86 °C
- Compute the dTmax as: 3.11 - 1.97 x (-0.9) = 4.89 °C
- Compute actual dT as: 28.9 – 32.0 = -3.1 °C
- Compute the CWSI:

- CWSI = [(-3.1) – (-3.86)] / [(4.89) – (-3.86)] = 0.09

- This result means 9% crop water stress.
- Then, ETa = (1 – 0.09) x ETc = 0.91 x 8.2 = 7.46 mm/d