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Development of Prediction Relationships for Water Requirements with Irrigation Cooling

Digital Object Identifier: https://doi.org/10.13023/kwrri.rr.70

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Research Report No. 70

DEVELOPMENT OF PREDICTION RELATIONSHIPS FOR WATER REQUIREMENTS WITH IRRIGATION COOLING

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Project Number A-028-KY (Completion Report)
Agreement Number 14-31-0001-3217 (FY 1971)
14-31-0001-3517 (FY 1972)
Period of Project - July, 1970 - June, 1972

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Lexington, Kentucky

The work on which this report is based was supported in part by funds provided by the Office of Water resources Research, United States Department of the Interior, as authorized under the Water Resources Research Act of 1964.

February, 1974

ABSTRACT

A model for predicting leaf temperatures during an off-on mist cycle is presented. The model uses a combination of energy budget and aerodynamic techniques. The model was tested for dry leaf temperature and evapotranspiration predictions using average hourly data from Arizona. The accuracy was good. It was also tested for dry leaf temperature predictions using two to three minute data with a widely varying net radiation. When reasonable values of stomatal resistance were used, the agreement was again good.

The model was tested for prediction of wet leaf temperature prediction with a ten minute on, fifty minute off mist irrigation cycle. The agreement was fair when using reasonable input parameters. The poorest predictions were during the mist on cycle.

Descriptors: Irrigation, plant temperatures, energy balance, evapotranspiration.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Dennis Egli for his assistance in growing the sudex used in the experiment, and to the U. S. Water Conservation Laboratory at Phoenix, Arizona for supplying data for testing some of the equations on dry leaves.

Appreciation is also expressed to the University of Kentucky Water Resources Institute and its former director Dr. Robert A. Lauderdale for supporting the project.

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INTRODUCTION

In recent years, control of plant environment by mist irrigation has resulted in significant improvements in quality and yield of certain crops. [Howell, et al., (1971), Robinson et al., (1973)]. Irreversible damage due to high temperatures and solar radiation has also been prevented [Carolus (1964, 1965), Bible (1968), Chesness (1969)]. Mist application of water performs two primary functions; increases the atmospheric humidity, thereby reducing the evapotranspiration potential, and it decreases the atmospheric and plant surface temperature. Evaporative cooling has long been used in temperature control of buildings, but its usefulness in microclimate modification has only recently been realized.

The influence of temperature and humidity upon plant growth has been studied by many investigators, and the optimum temperature for many economic crops has been defined. Less information is available on the effect of humidity. However, it has been shown by Went (1957) and others that many plants grow taller in environments with higher relative humidities. Dale and Shaw (1965) noted that corn yields were correlated to the number of days plant turgor was maintained at high levels. Additional studies in this area are further defining the optimum environmental range.

The success of the initial ventures using mist irrigation to improve plant environment and the need to optimize as much as possible the production of food will lead to an increased use of this form of irrigation for controlling environment. According to Chesness (1969) no attempt has been made to predict the mist application rate for optimum cooling under varying environmental conditions. Hence, irrigation for cooling is currently a highly subjective process with inherent wastage of water.

In addition to the lack of information on the optimum water requirement under varying environments, there is currently no method for relating the change in the microclimate to the irrigation rate. A knowledge of the water requirements for irrigation cooling is of particular importance for water resource planning purposes. Several methods are available for computing water requirements for normal irrigation (Blaney-Criddle Method, Jensen-Haise Method) but these methods are not directly applicable to irrigation for cooling.

In an effort to supply basic information for planning and for optimizing water use for irrigation cooling, the objectives of the proposed research were:

a. Test the validity of the energy budget method for predicting the effect of water application rate upon the microclimate under varying environments and

b. Use the knowledge from objective (a) to predict water requirements for irrigation cooling and to define the design parameters for irrigation cooling systems.

CHAPTER II
THEORETICAL DEVELOPMENT

The approach to attaining objective (a) was through simulation models based on energy budget and aerodynamic analyses. The analyses are similar to the combination equation of Penman (1948) and Van Bavel (1968) with extra terms added for the effects of irrigation water on the energy budget.

The Basic Energy Budget

The energy budget for a plant canopy can be written as (see Figure 1):

$$\begin{bmatrix}\text{Rate of Change}\\ \text{in Storage}\end{bmatrix} = \begin{bmatrix}\text{Net radiation}\\ \text{Flux}\end{bmatrix} = \begin{bmatrix}\text{Sensible Heat}\\ \text{Flux}\end{bmatrix} - \begin{bmatrix}\text{Latent}\\ \text{Heat}\\ \text{Flux}\end{bmatrix} + \begin{bmatrix}\text{Energy Flux}\\ \text{in Water Hit-}\\ \text{ting the Plant}\end{bmatrix} - \begin{bmatrix}\text{Energy Flux in}\\ \text{Water Running}\\ \text{off Plant}\end{bmatrix} \qquad (1)$$

Symbolically this can be written as

$$\frac{ds}{dt} = R_n - H_s - H_L + Q_{on} - Q_{off} \qquad (2)$$

Energy Associated with Irrigation Water

In order to analyze the energy fluxes associated with the irrigation water the following assumptions were made:

a. Irrigation water strikes the leaves at the wet bulb temperature [verified by Pair et al., (1969)].

b. Water runs off the leaves at the leaf temperature [assumption that needs to be justified].

c. Change in energy storage is due to buildup of water ponded on the leaf [true under steady state condition].

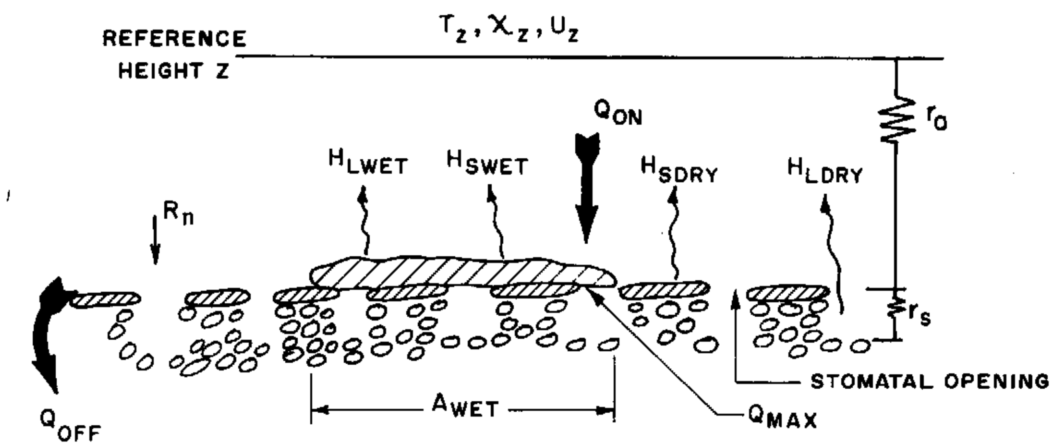

Figure 1. Energy Budget of a Partially Wet Leaf.

Under assumption (a),

$$Q_{on} = \rho_w C_w T_{wb} Q_{w,on} \tag{3}$$

where ρ_w = density of liquid water, C_w is the specific heat of liquid water, T_{wb} is wet bulb temperature of the air and $Q_{w,on}$ is the volume rate of water hitting the leaf. Under assumption (b),

$$Q_{off} = \rho_w C_w T_L \, Q_{w,off} \tag{4}$$

where T_L is leaf temperature and $Q_{w,off}$ is the volume rate of water flowing off the leaf. Under assumption (c),

$$\frac{ds}{dt} = \rho_w C_w T_L (Q_{w,on} - Q_{w,off}) \tag{5}$$

using (3), (4), and (5) in (2), we obtain

$$R_n = H_s + H_L - \rho_w C_w Q_{w,on}(T_{wb} - T_L) \tag{6}$$

Sensible and latent heat fluxes come from both wet and dry areas. Hence, if we denote A_w as the fraction of leaf area wet and A_D as the fraction of leaf area dry, equation (6) becomes

$$R_n = (H_{s,D}+H_{L,D})\, A_D + (H_{s,w}+H_{L,w})\, A_w - \rho_w C_w Q_{w,on}(T_{wb}-T_L) \tag{7}$$

where the second subscript refers to either a wet or dry area.

Sensible and Latent Heat Fluxes

The flux equations can be written in simple notation if one uses the concept of air and stomatal resistance, similar to that of Montieth (1965). Using these concepts, the flux equation becomes

$$H_{s,w} = \frac{\rho C_p (T_{L,w} - T_a)}{r_a} \quad (8a) \qquad H_{L,w} = \frac{\lambda \rho (\chi_{L,w} - \chi_a)}{r_a} \quad (8b)$$

$$H_{s,D} = \frac{\rho C_p(T_{L,D}-T_a)}{r_a} \quad (8c) \qquad H_{L,D} = \frac{\lambda\rho(\chi_{L,D}-\chi_a)}{r_a+r_s} \quad (8d)$$

where ρ is air density, C_p is specific heat of the air; $T_{L,w}$, $T_{L,D}$, and T_a are temperatures of the wet leaf area, dry leaf area, and air respectively; $\chi_{L,w}$, $\chi_{L,D}$ and χ_a are humidity ratios of the wet leaf surface, substomatal cavity, and air respectively, λ is latent heat of vaporization and r_a and r_s are air and stomatal resistance.

The Final Equations

Using equations (8) in (7), we obtain

$$R_n = \left[\frac{\rho C_p(T_{L,D}-T_a)}{r_a} + \frac{\lambda\rho(\chi_{L,D}-\chi_a)}{r_a}\right] A_D + \left[\frac{\rho C_p(T_{L,w}-T_a)}{r_a} + \frac{\lambda\rho(\chi_{L,w}-\chi_a)}{r_a+r_s}\right] \cdot A_w - \rho_w C_w Q_{w,on}(T_{wB}-T_L) \quad (8)$$

Since $\chi_{L,D}$ and $\chi_{L,w}$ are saturation humidity ratio's at the temperature of $T_{L,D}$ and $T_{L,w}$, they are unique functions of $T_{L,D}$ and $T_{L,w}$. Hence equation (8) contains two unknown leaf temperatures as a function of environmental parameters.

A simplification of equation (8) can be made by assuming that heat conduction from the wet to dry area (or vice versa) is negligible compared to other modes of heat transfer. This allows one to write two energy balance equations, vis.

$$R_n = \frac{\rho C_p(T_{L,D}-T_a)}{r_a} + \frac{\lambda\rho(\chi_{L,D}-\chi_a)}{r_s+r_a} - \rho_w C_w Q_{w,on}(T_{wB}-T_{L,D}) \quad (9a)$$

and

$$R_n = \frac{\rho C_p(T_{L,w}-T_a)}{r_a} + \frac{\lambda\rho(\chi_{L,w}-\chi_a)}{r_a} - \rho_w C_w Q_{w,on}(T_{wB}-T_{L,w}) \quad (9b)$$

Given the atmospheric and plant parameters of net radiation, air temperature and relative humidity, the rate of water application, and the stomatal and air resistance, one can predict the wet and dry leaf temperature. These parameters are normally available or can be estimated. The average leaf temperature can then be computed from the relationship

$$T_{L,AVG} = T_{L,W} A_W + T_{L,D} A_D \tag{10}$$

Air resistance can be computed from several relationships. In this research effort the KEYPS wind profile relationship was used (See Appendix I-A for the derivation). It can be expressed as

$$r_a = [\ln \frac{Z-d}{Zo} - \psi(Ri)]^2/C_1 k^2 u\alpha \tag{11}$$

where u is the windspeed at a reference height Z, Zo and d are the roughness height and zero displacement height respectively, α is the ratio of eddy diffusivity of heat and mass to that of momentum in free air (See Appendix I-C), Ψ(Ri) is adiabatic wind profile correction factor (See Appendix I-B), k is (vonkarmon's) constant, and C is an empirical constant which accounts for the fact that the sink for momentum in a plant canopy can differ significantly from that for heat and mass. Ri is Richardson's Number given in this case by

$$Ri = \frac{2g}{(T_{L,AVG}+T_a)} \frac{(T_{L,AVG}-T_a)}{u^2} (Z-d) \tag{12}$$

Equations (9a) and (9b) along with the air resistance term given by equation (11) comprise the basic model used in evaluating the effects of mist irrigation on leaf temperatures. In order to make the predictions, one must know air temperature and relative humidity during misting. A model for evaluating the effects of irrigation on air temperature and relative humidity is currently under development using concepts proposed by Seginer (1970). This model will be reported in a subsequent publication.

Correcting Net Radiation for the Effects of Mist

The net radiation term given in the basic model is that at the leaf surface. All available observations are for radiation over a crop surface without a mist. A radiation correction equation is needed of the form

$$R_N = R_{N,\ ABOVE} + \delta R_N \tag{13}$$

where $R_{N,\ ABOVE}$ is the radiation above the canopy. In order to calculate δR_N, the assumption was made that the mist is transparent to solar radiation and opaque to long wave radiation. Under this assumption, the correction term, δR_N becomes

$$\delta R_N = \sigma T_a^4 \left(1 - \varepsilon_p \frac{T_p^4}{T_a^4}\right) \tag{14}$$

where ε_p is emissivity of the sky above the mist, T_a air temperature within the mist and T_p is the normal free air temperature under the same conditions without the mist. The rationale behind equations (13) and (14) as well as the method for evaluation of ε_p is given in Appendix II.

CHAPTER III
EXPERIMENTAL ANALYSIS

Evaluation of the Model on Dry Leaves

An initial evaluation was made of the model under non-misted conditions to see if temperatures and energy fluxes were being adequately predicted since energy fluxes under a mist irrigation system would be very difficult to measure accurately. For dry leaf conditions, $Q_{w,on}$ becomes zero and equation (9a) reduces to

$$R_n = \frac{\rho C_p (T_{L,AVG} - T_a)}{r_a} + \frac{\rho \lambda (\chi_{L,AVG} - \chi_a)}{r_a + r_s} \quad (15)$$

From input meteorological and plant morphology data, the plant temperature $T_{L,D}$ can be solved from equation (15) and the evaporative flux solved for from equation (8d).

Prediction of Hourly Temperatures and Evaporative Fluxes

A detailed set of data collected at the U.S. Water Conservation Laboratory in Phoenix, Arizona on grain sorghum (sorghum vulgara) were made available for testing the dry leaf model. The measurements are described in detail in Ehrler and Van Bavel (1966) and Van Bavel and Ehrler (1967). Measurements were taken on one day, July 13, 1965, with stomates fully open and one day, July 20, 1965, with stomates partially closed. Input data are shown in Figures 2 and 3. These data represent hourly averages.

Leaf temperatures were predicted using equation (15). These are presented in Figure 4 along with the measured leaf temperature. The average error was 2.8°C. Using the calculated temperature, the evaporative flux was predicted using equation (8d). These results are presented in Figure 6 along with the measured evapotranspiration. The agreement between predicted and observed values was considered to be quite good.

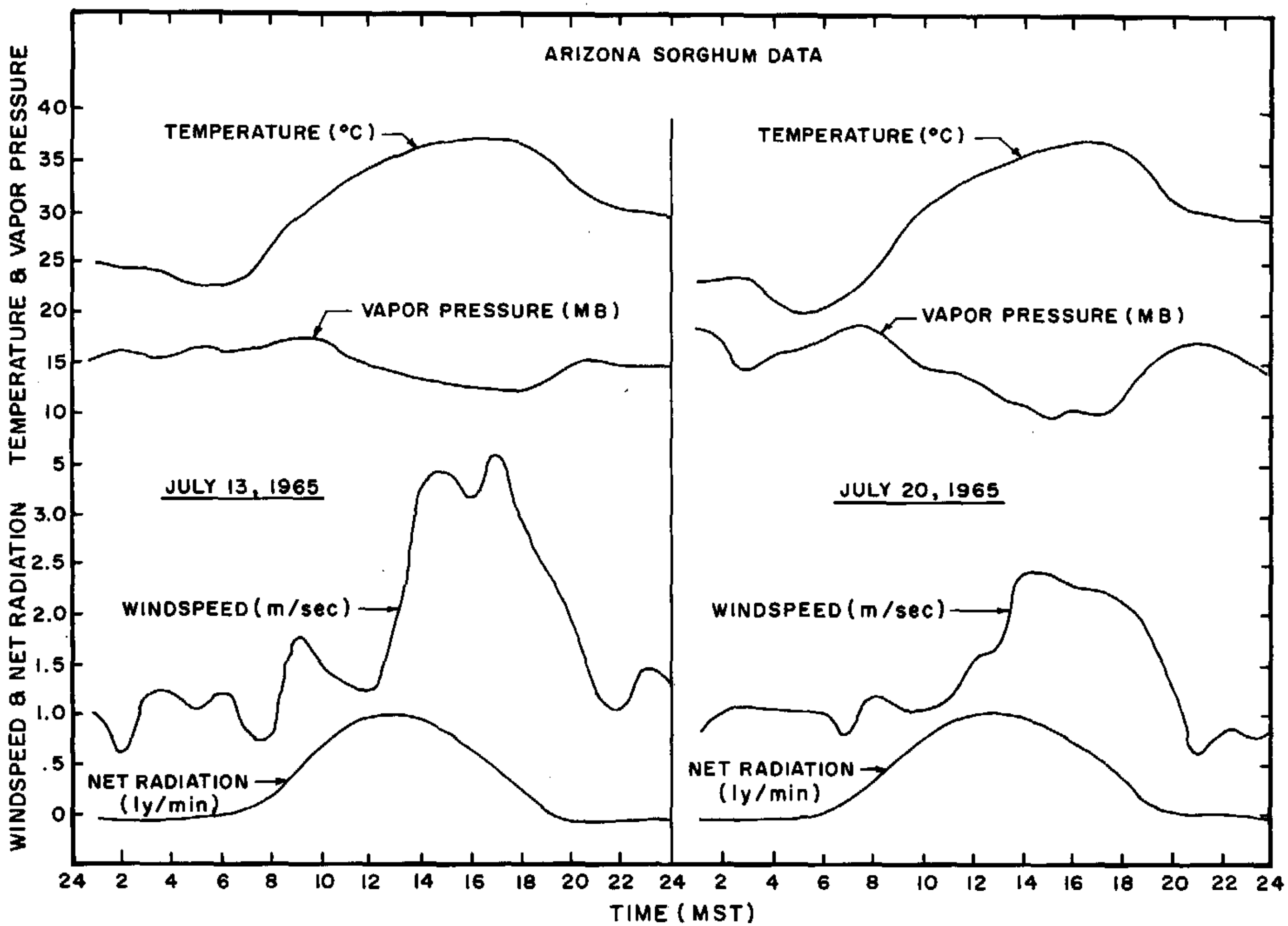

Figure 2. Input Meteorological Data for Sorghum Grown in Arizona.

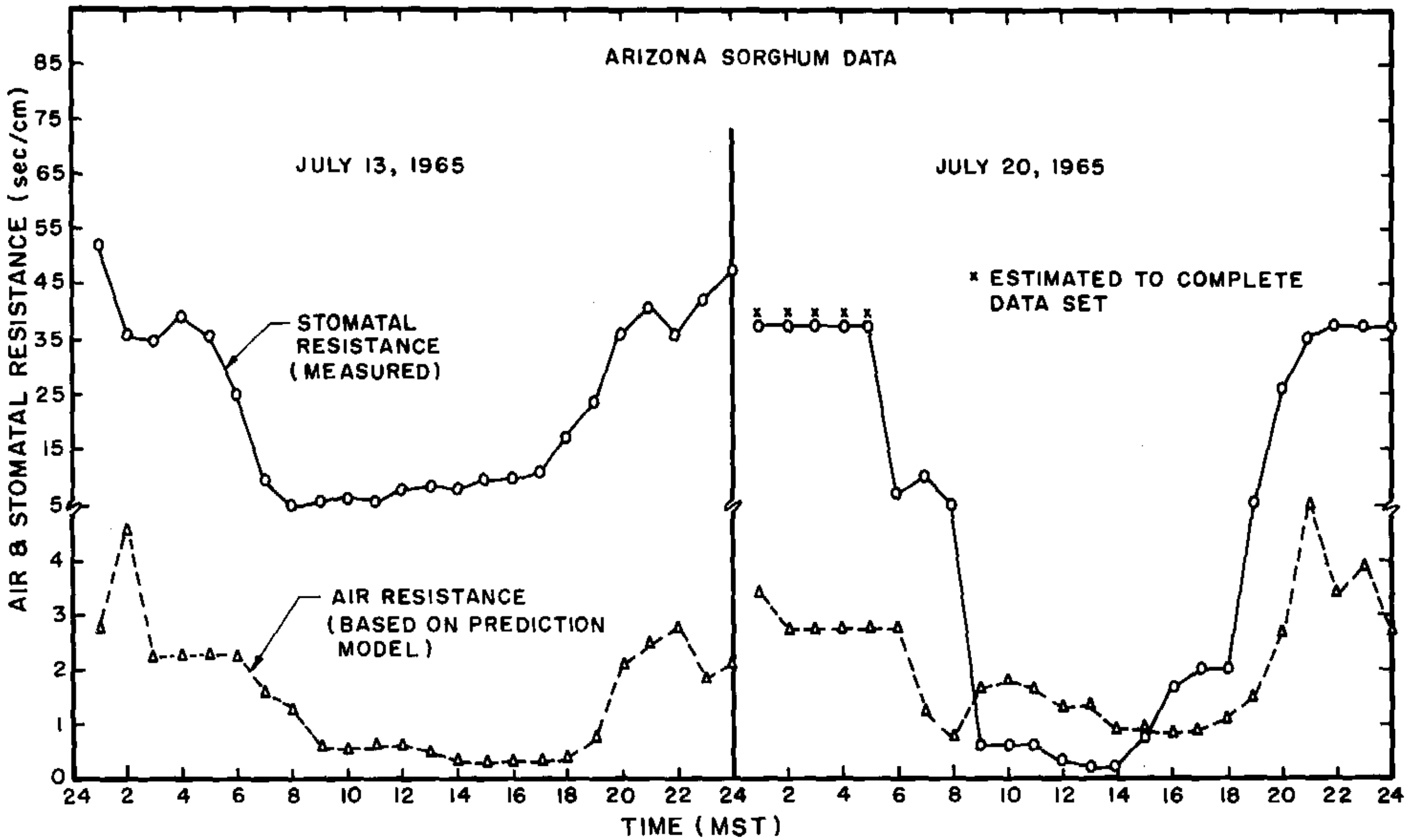

Figure 3. Measured Stomatal Resistance and Calculated Air Resistance for Arizona Sorghum Data.

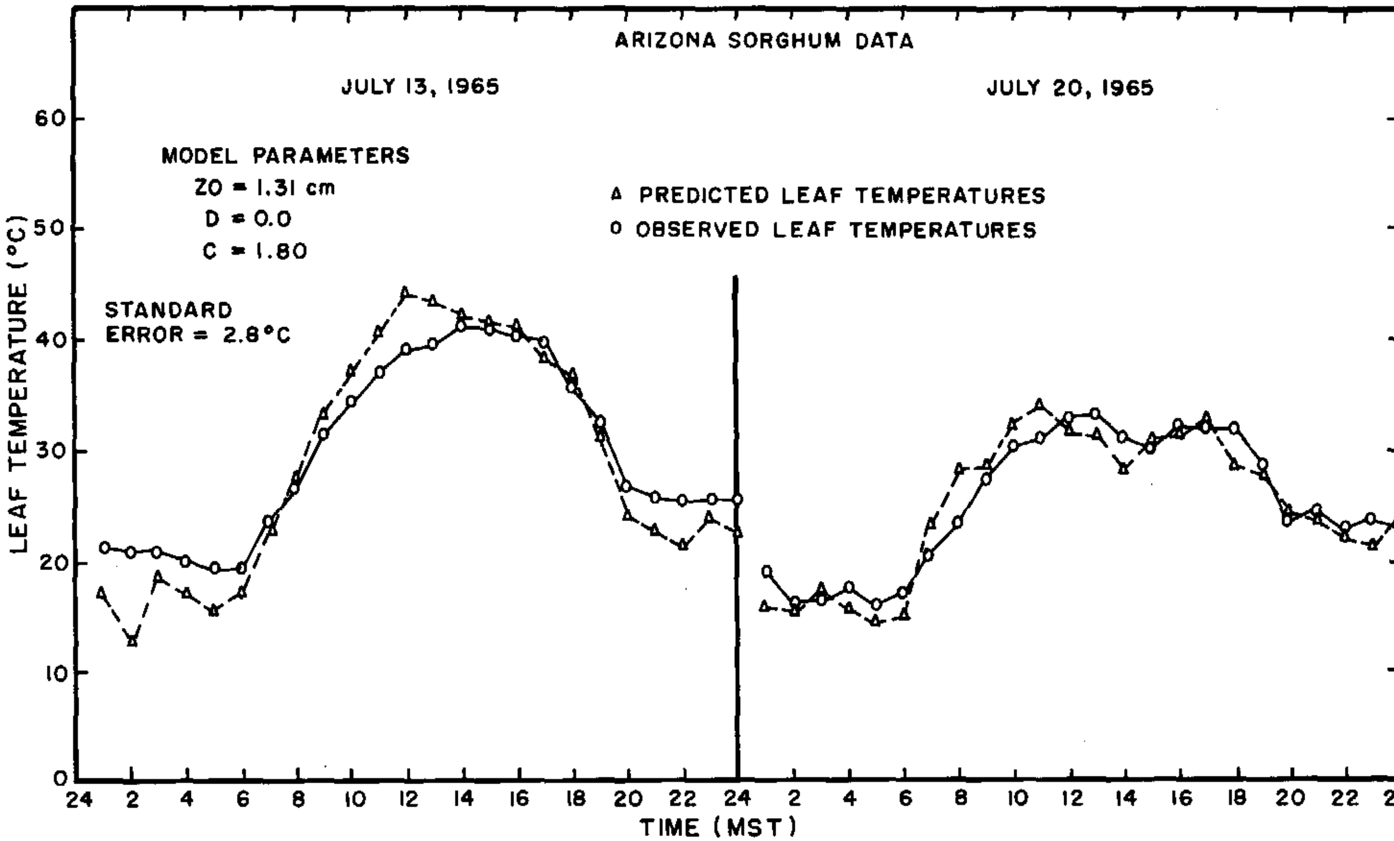

Figure 4. Measured and Predicted Leaf Temperatures for Arizona Sorghum Data.

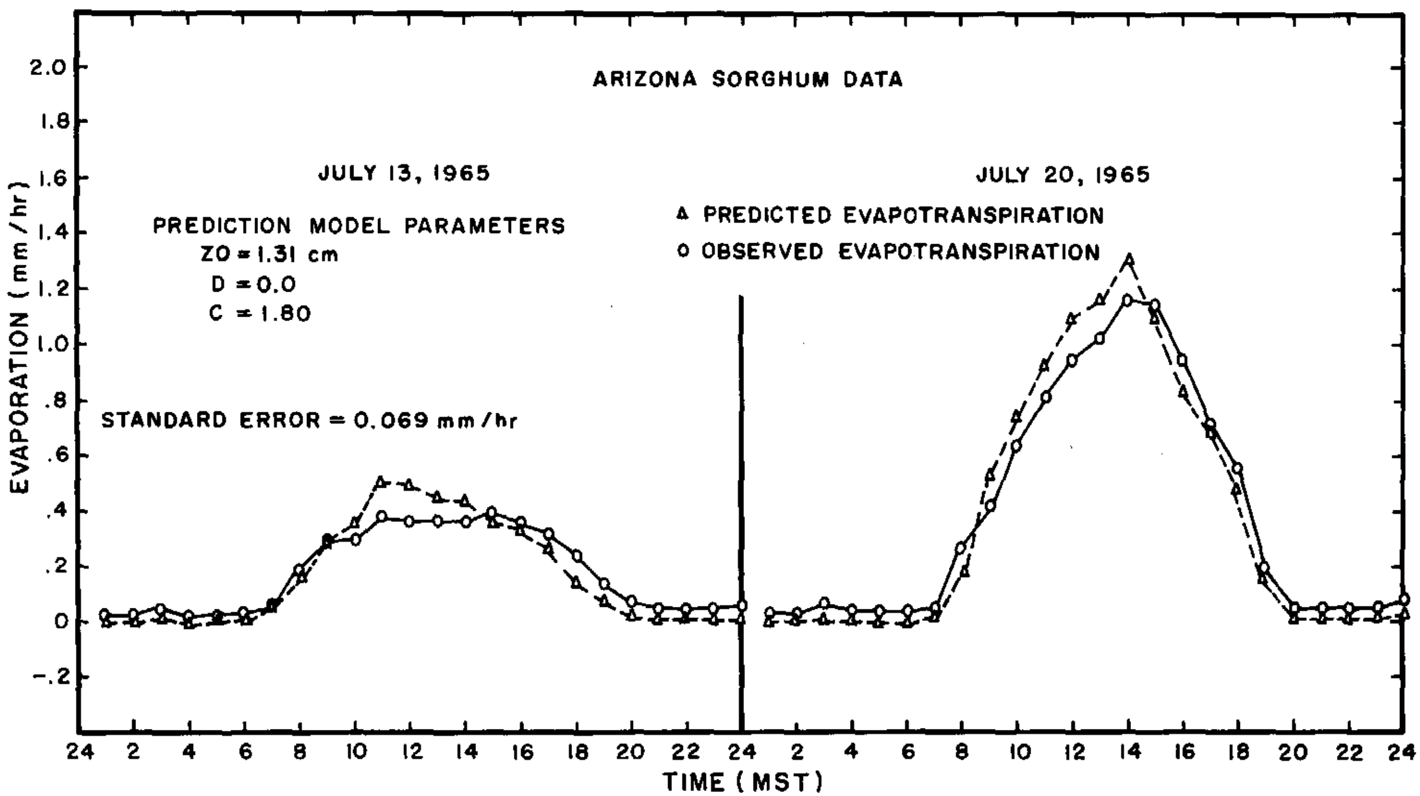

Figure 5. Measured and Calculated Evapotranspiration for Arizona Sorghum Data.

Prediction of Dry Leaf Temperatures Over Short Time Periods. The concepts presented in Chapter II are based primarily on semi-imperical transport equations developed from hourly average meteorological data. Mist irrigation systems, however, normally operate on an off-on cycle of 10 to 15 minutes. In order to simulate plant temperatures during these wetting and drying periods, it is necessary to simulate average temperatures for conditions varying over time periods of less than five minutes.

The validity of equation (12) for predicting temperatures over short time periods needed to be evaluated. To accomplish this, data wasttaken at two to three minute intervals over a three hour time period at Lexington, Kentukcy for Sudex. Input environmental and plant data are shown in Figures 6 and 7. The anemometer available only yielded hourly average windspeed. Equipment used for each measurement is listed in Table I. A layout of the experimental site is shown in Figure 8.

Dry leaf temperatures predicted from equation (12) are shown in Figure 9. The value of the factor C used was 1.8 as determined from the Arizona Data since grain sorghum and sudex are similar plants. The average stomatal resistance was measured with a diffusive resistance meter during the tests. The average value obtained was 5.35 sec./cm. The average error between predicted and measured leaf temperatures using measured stomatal resistance was less than 2°C. Although this is a reasonable accuracy, a stomatal resistance of 5.35 sec./cm is high for well watered sorghum. Van Bavel and Ehrler (1968) reported values closer to 1.0 sec./cm. By varying stomatal resistance in the model, the optimum prediction was made with a value for the stomatal resistance of 1.35 sec./cm. This stomatal resistance is consistent with other observations. It was discovered during the field data collection that the humidity element in the stomatal resistance meter inadvertantly got wet. This caused a shift in the calibration curve and probable errors in the measurements. For these reasons, it was assumed that

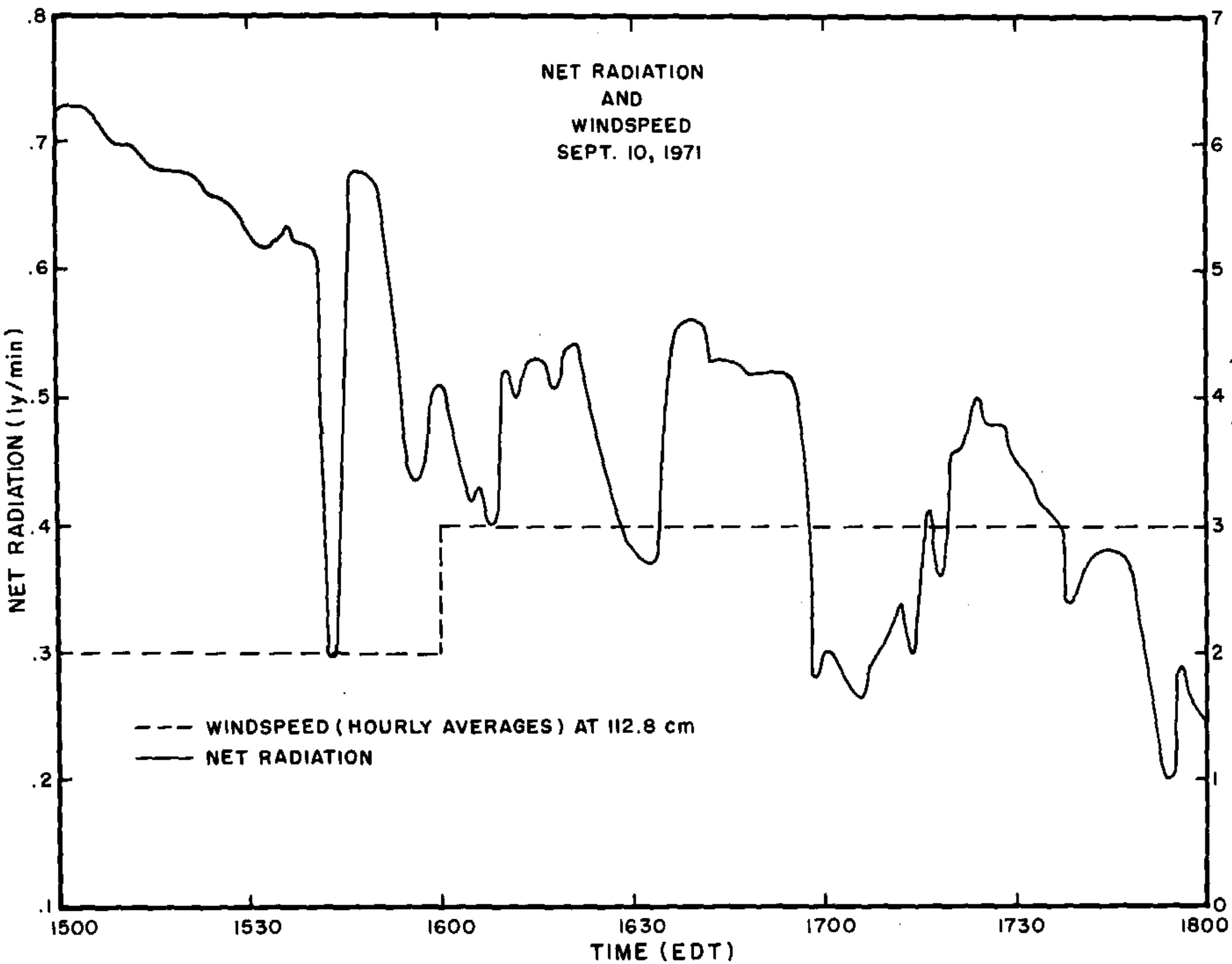

Figure 6. Net Radiation and Windspeed Measured Over Sudex at Lexington, Kentucky, September 10, 1971.

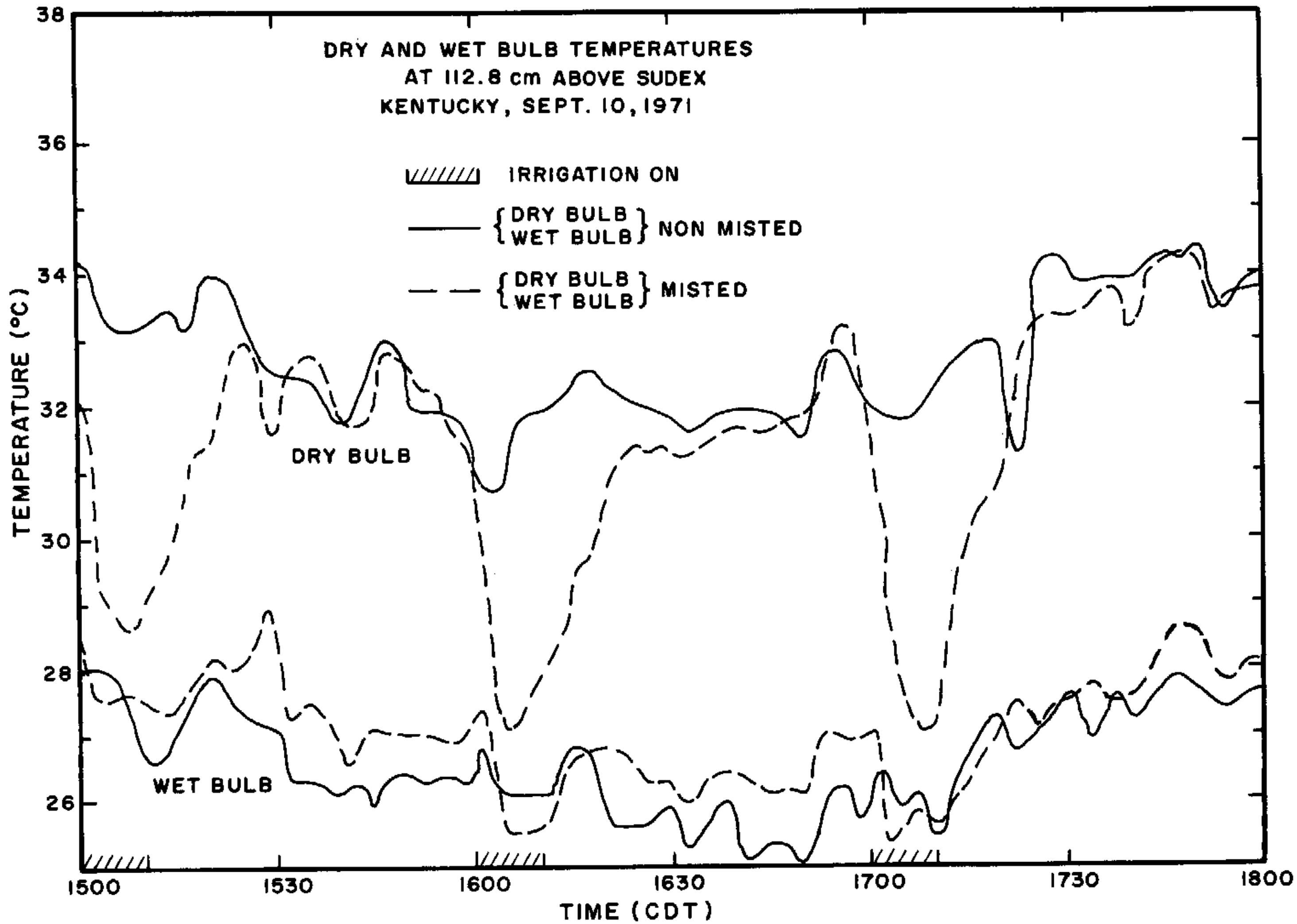

Figure 7. Dry and Wet Bulb Temperatures at 112.8 cm Above Sudex at Lexington, Kentucky.

TABLE I

LIST OF EQUIPMENT FOR FIELD MEASUREMENTS

Parameter	Equipment
Leaf Temperature	40 gauge Cu-Co Thermocouple*
Dry Bulb Temperature	12 gauge Cu-Co Thermocuople*
Wet Bulb Temperature	12 gauge Cu-Co Thermocouple inserted in a shielded aspirated wick.*
Net Radiation	Thornthwaite Net Radiometer.
Wind Speed	Stewart Totalizing Anemometer set to pulse at 0.5 miles.
Stomatal Resistance	Lambda Instruments Diffusive Meter Model L150.

*MV output of Thermocouples recorded on a Datex 100 point data logger.

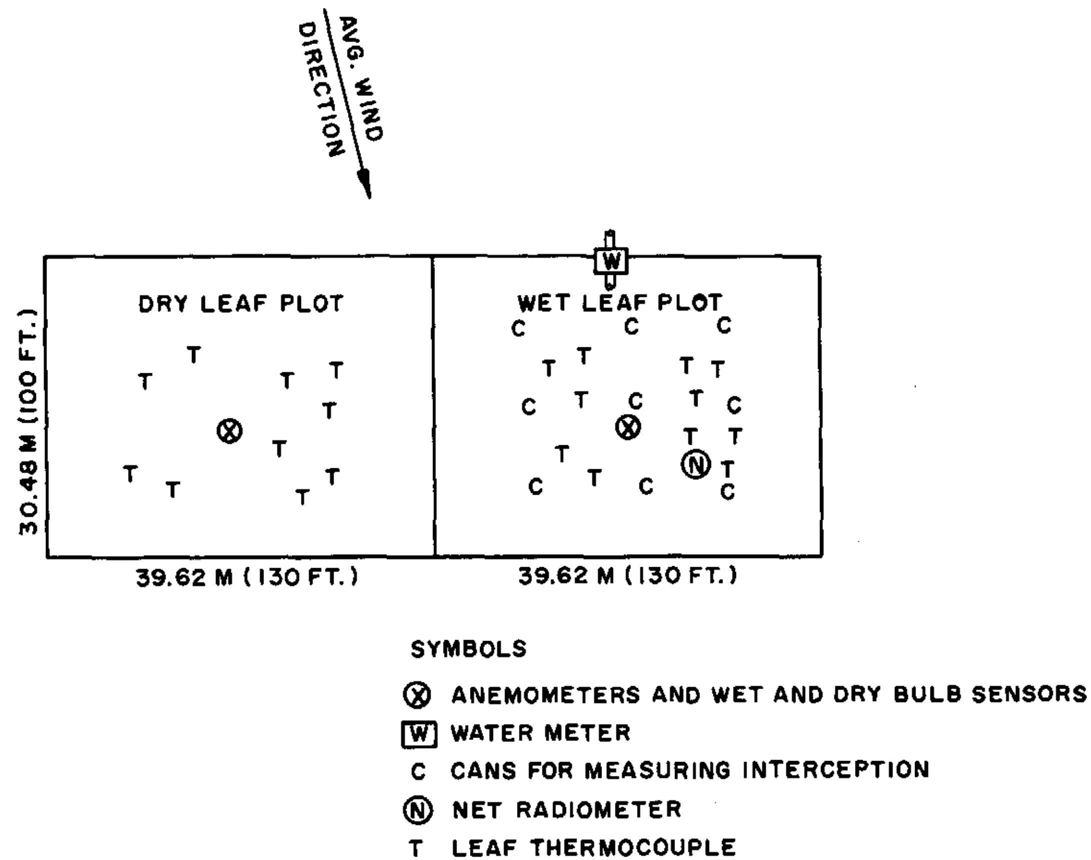

Figure 8. Layout of Experimental Site.

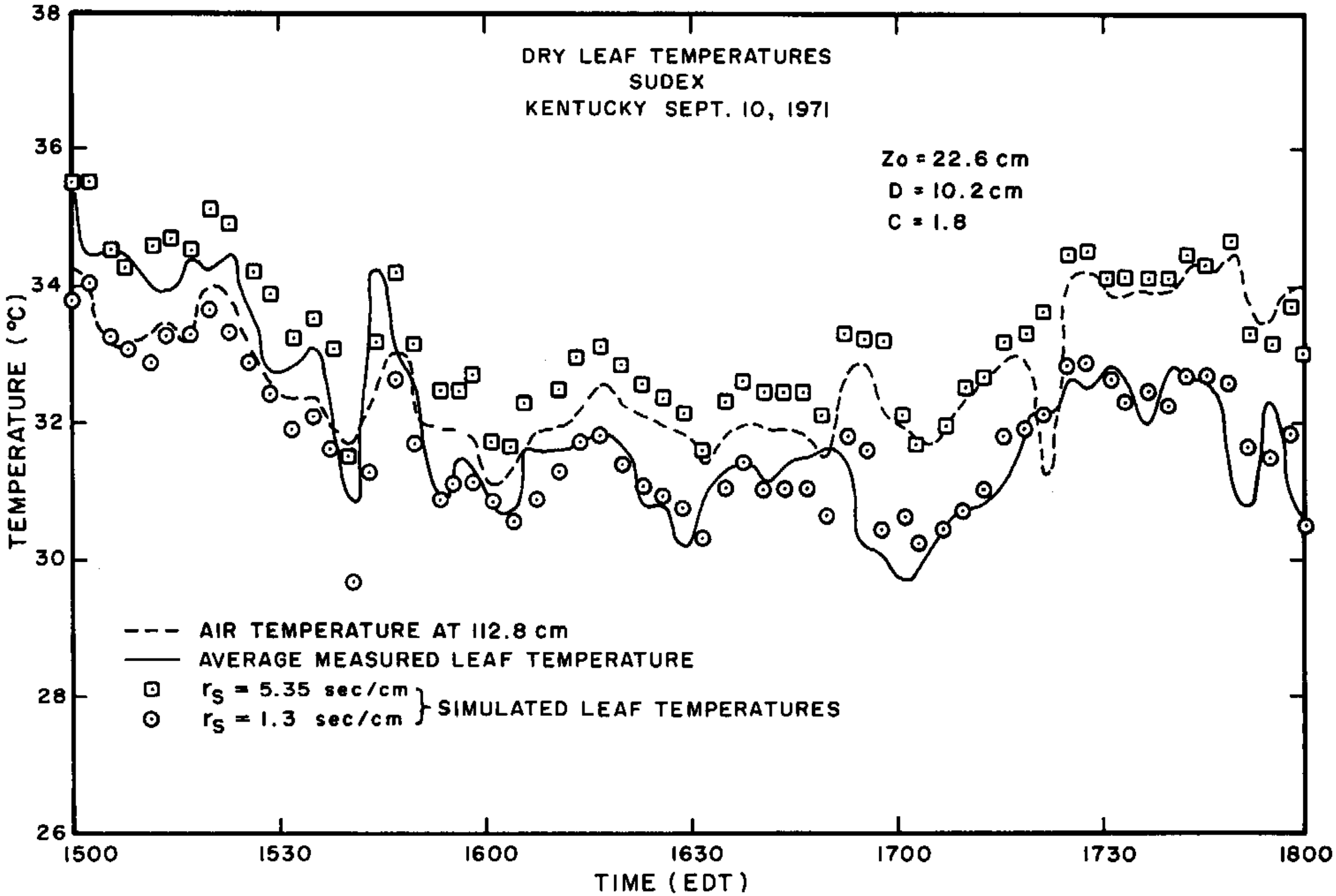

Figure 9. Measured and Predicted Dry Leaf Temperatures for Sudex at Lexington, Kentucky, September 10, 1971.

1.35 sec./cm was more indicative of the stomatal resistance than the measured value.

Evaluation of the Model on Wet Leaves

Irrigation System. The wet leaf plot was irrigated with Rainbird Model MP10 Nozzles on a diamond spacing of 4.6 meters (14 feet) operated at a pressure of 80 psi. The nozzles were mounted on 1 meter (3.08 ft.) risers. No data were taken on the drop size distribution.

Calculation of Water Held on Leaves and the Fraction of Leaf Surface Wet. In order to caluclate leaf temperatures during the drying cycle, it is necessary to know the fraction of the leaves covered with water at any time after the onset of drying. One approach to the problem would be to assume that the fraction of leaf wet remains constant and that evaporation merely decreases film thickness. This would be applicable for leaves wet with droplets, but appears to have little validity for film wetting. Another more plausible assumption is that the film remains approximately constant in thickness and that evaporation decreases the area wet. Visual observations of leaves drying in the laboratory appeared to more closely follow this latter assumption. Under this assumption,

$$A_W = A_{W,I} \left(1-\frac{Q_{TOT}}{Q_{MAX}}\right) \qquad (16)$$

where $A_{W,I}$ is the fraction of the leaf initially wet, Q_{TOT} is the total amount of water evaporated after the water is turned off, and Q_{MAX} is the amount of water held on the leaf at the end of the mist cycle. A thorough experimental analysis of the manner in which leaves dry needs to be made before a final model is accepted.

Field evaluations were made during the experiment of water applied and intercepted. Nine cans were placed above and below the sudex canopy to make the measurements. The results are shown in Table II. The amount of water applied was also measured with standard water meters whose accuracy

TABLE II

AVERAGE IRRIGATION INTERCEPTION AND APPLICATION RATES

Irrigation Period (EDT)	Amount Intercepted in.	mm	Application Rate in./hr.	mm/sec.
1500-1510	.054	1.3716	1.08	7.62×10^{-3}
1600-1610	.068	1.7374	1.05	7.41×10^{-3}
1700-1710	.078	1.9812	1.04	7.31×10^{-3}

was checked to be better than one percent. The can measurements and water meter measurements of water applied agreed within ten percent.

Measurements of intercepted water using cans above and below a canopy are useful in a water balance for a watershed, but do not provide the information needed for an energy budget model such as that proposed in this study. In order to do an energy budget analysis as proposed, a measurement is needed of the amount of water held on the sunlit leaves at the end of mistings. Interception as measured by cans gives water held on sunlit and shaded leaves as well as stemflow and storage on plant modes. Studies by Barfield, et al., (1973) showed that leaf storage of individual natural leaves ranged up to .19 mm whereas the intercepted water in this study was approximately 10 times that amount.

Predicting Wet Leaf Temperatures. The wet leaf temperature model consists of using equation (8) and (9) for the energy budget, equations (13) and (14) to correct net radiation, and equation (16) to calculate the fraction of leaf wet at any time. Initial calculations were made of leaf temperatures using the measured stomatal resistance of 5.35sec./cm and the intercepted water of .2 mm as Q_{MAX} and assuming that the entire leaf surface was wet at the end of the mist. The results are shown in Figure 10 along with measured air temperature at 3.7 ft. and measured average leaf temperatures. The predicted and observed leaf temperatures curves do not agree too well. The predicted fraction of leaf area wet versus time is shown in Figure 11. The predictions based on measured conditions indicate that the leaves would not be dry by the end of each cycle. This contradicted visual observation which indicated that the leaves were dry.

Possible explanations for the discrepencies include:

1. The total leaf area was not wet at the end of each ten minute misting period. (Unreported laboratory studies at the University of Kentucky indicate that this is probably true.)

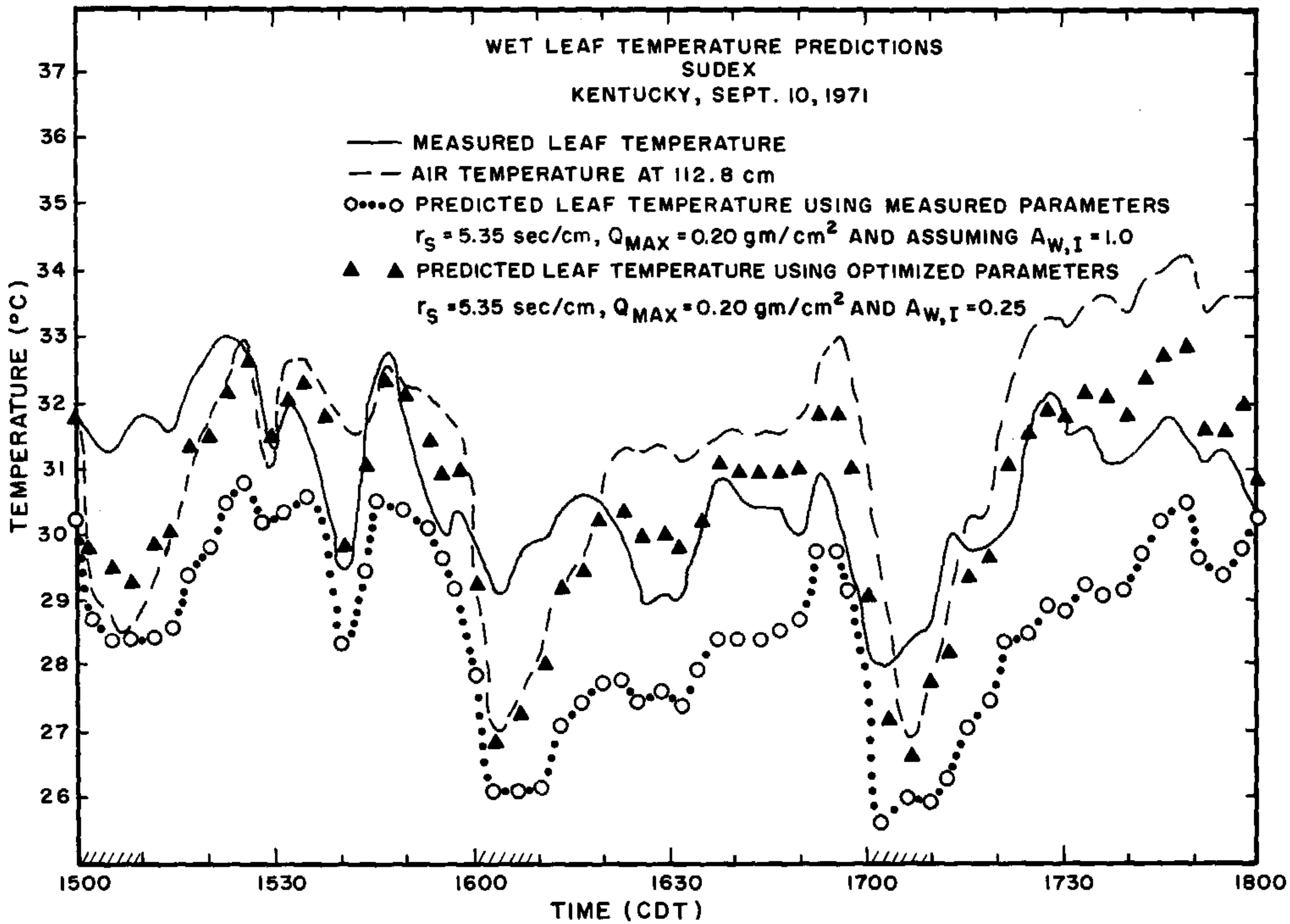

Figure 10. Predicted Leaf Temperatures for Measured and Optimized Input Parameters. Hatched area indicates when irrigation is on.

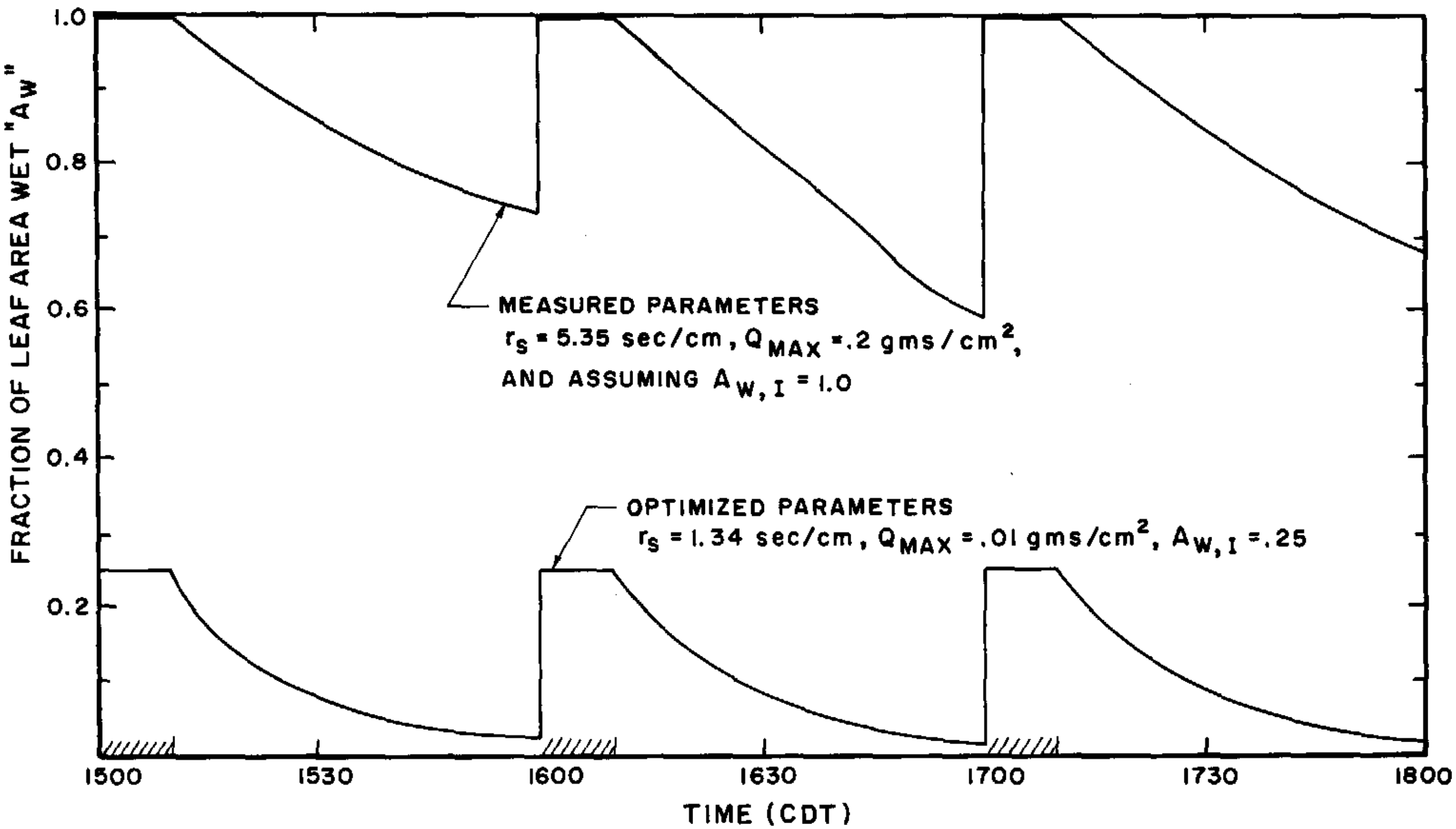

Figure 11. Predicted Fraction of Leaf Area Wet for Measured and Optimized Input Parameters. Hatched area indicates when irrigation is on.

2. The amount of water to be evaporated from the sunlit leaves, Q_{MAX}, was much less than that assumed.
3. The measured stomatal resistance, r_s, of 5.35 sec./cm is in error. Leaf temperature predictions for dry leaves indicate that a value of 1.35 sec./cm is more reasonable.

Since these three stated assumptions seemed reasonable, the values of stomatal resistance (r_s), initial fraction of leaf wet (A_W,I) and water to be evaporated (Q_{MAX}) were varied to determine if an improved prediction accuracy could be obtained. The objective was not to determine optimized values for the above parameters, but to see if improved predictions could be obtained using values which were believed to be reasonable. The criteria used were:

A. The predicted final leaf area wet (A_W,F) had to be less than .01 at the end of each drying cycle.
B. Values of Q_{MAX} should agree with those measured by Barfield, et al., (1973). ($.052 > Q_{MAX} > .007$ Grams/cm^2).
C. The stomatal resistance should be close to 1.35 sec./cm as determined for optimum dry leaf predictions.

The standard deviation of the difference between predicted and observed temperatures (σ) as well as leaf area wet at the end of the drying cycle (A_W,F) was evaluated for each set of parameters used. The results are presented in Figures 12 and 13. By using the first criteria, the value of Q_{MAX} could be selected for each initial area wet (A_W,I) which gave the minimum standard deviation. These values are shown in Figures 12 and 13.

The minimum standard deviation satisfying constraint A and B corresponded to a stomatal resistance of 1.35 sec./cm, an A_W,I of 0.25, and a Q_{MAX} of 0.01 grams/cm^2. The "optimum"

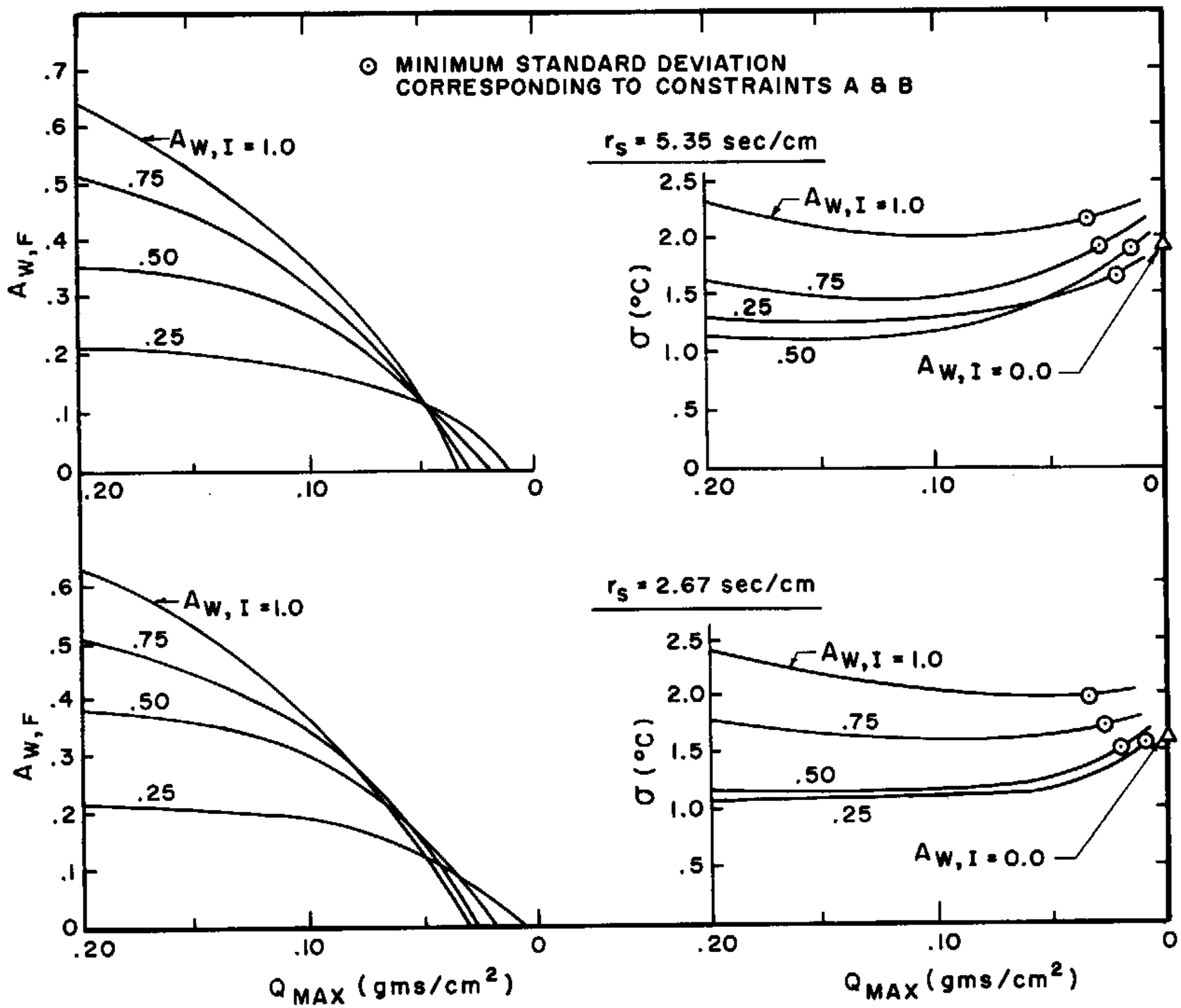

Figure 12. Predicted Fractional Leaf Area Wet at End of Drying Cycle ($A_{W,I}$) and Standard Deviation of Predicted Minus Observed Temperature (σ) for Stomatal Resistances of 5.35 and 2.67 sec/cm.

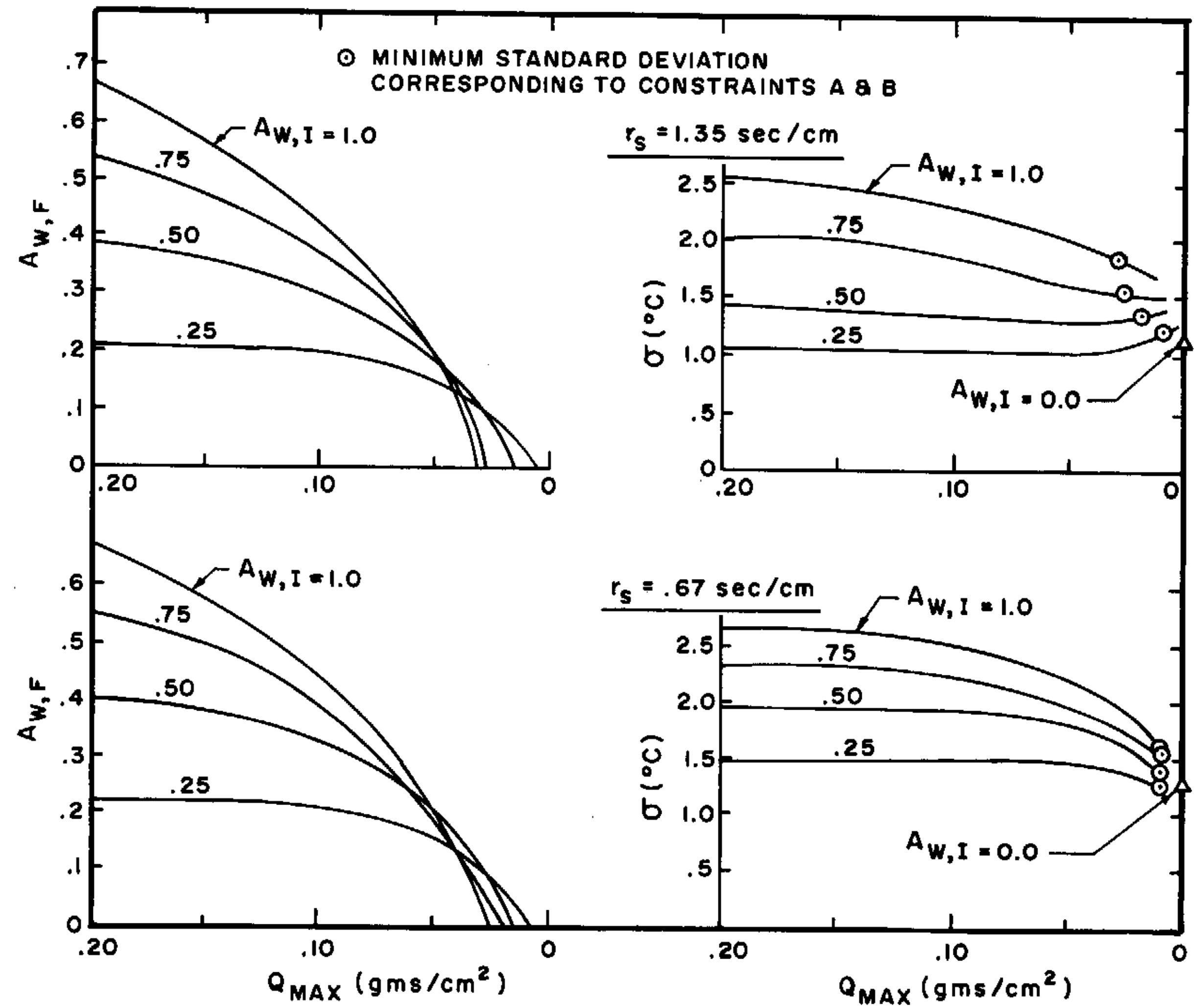

Figure 13. Predicted Fraction of Leaf Area Wet at End of Drying Cycle ($A_{W,F}$) and Standard Deviation of Predicted Minus Observed Temperature, (σ) for Stomatal Resistances of 1.34 and .67 sec/cm.

stomatal resistance corresponds to that which gave the best dry leaf predictions. Although there are no reference conditions with which to compare the "optimum" fraction of leaf wet after misting, A_W,I, a value of 0.25 does appear reasonable. High speed photography taken at the University of Kentucky of leaves subjected to a mist indicate that only a small fraction of the leaf is covered with water when the leaf is at the maximum water holding capacity.

The "optimum" value of Q_{MAX}, which was obtained when constraints A and B were applied was slightly above the minimum limiting value for Q_{MAX}. If the constraints A and B were not applied, the minimum standard deviation was obtained when A_W,I and Q_{MAX} were both equalto zero. These would both be unrealistic values since it would mean that zero leaf area was wet, which is totally inconsistent with experimental evidence. The next value of A_W,I used in the program was 0.25. The value of Q_{MAX} for A_W,I satisfying constraint A also satisfied constraint B and hence was accepted. This problem was not considered to be serious since the difference between the standard deviations was less than 0.1°C.

Predicted leaf temperatures and fraction of wet leaf area were determined using the "optimum" parameters. These values were plotted versus time in Figures 10 and 11. The agreement between predicted and observed temperatures was good during the drying cycles. The maximum deviation was less than 1.1°C. During the mist cycle, theaagreement is not good with all the predictions being low. The maximum difference is still less than 2.5°C.

These results indicate that the model gives reasonable predictions of wet leaf temperatures, especially during the drying cycle. Further theoretical work needs to be conducted on energy fluxes during misting.

The temperature predictions were sensitive to values of Q_{MAX} and A_W,I. At present time, there are no known methods for either predicting or measuring these variables. Research needs to be conducted in this area before a final model can be developed.

SUMMARY AND RECOMMENDATIONS

A model for predicting leaf temperatures during an off-on mist cycle is presented. The model uses a combination of energy budget and aerodynamic techniques. The model was tested for dry leaf temperature and evapotranspiration predictions using average hourly data from Arizona. The accuracy was quite good. It was also tested for dry leaf temperature predictions using two to three minute data with a widely varying net radiation. Again the agreement was good when using reasonable values of stomatal resistance.

The model was tested for prediction of wet leaf temperature prediction with a ten minute on, fifty minute off mist irrigation cycle. The agreement was fair when using reasonable input parameters. The poorest predictions were during the mist on cycle.

Recommended areas for future research include:

1. Prediction of air temperature and relative humidity during misting.
2. Prediction of fraction of leaf wet and water held on a plant at the end of the mist cycle.
3. Theoretical analysis of energy fluxes during misting.
4. Evaluation of net radiation during misting.
5. Theoretical and experimental analysis of the way leaves dry.

APPENDIX I

A. FUNCTIONAL RELATIONSHIP FOR AIR RESISTANCE

The functional relationship given for air resistance in equation (11) is derived in this appendix. The following assumptions are made in the derivation

(a) Shear, mass flux, and sensible heat flux are invariant with height.

(b) The logarithmic profile holds under neutral conditions (conditions such that bouyancy has no effect on mixing).

(c) The effects of stability on the momentum transfer coefficient can be described by a simple functional relationship.

(d) The ratio between the momentum and heat transfer coefficient is invariant with height.

From assumption (a) and (b), we can write for neutral conditions

$$\tau = \tau_o = \rho K_m \frac{du}{dZ} \qquad \text{(I-A-1)}$$

and

$$u = \frac{U_*}{k} \ln\left(\frac{Z-d}{Z_o}\right) \qquad \text{(I-A-2)}$$

where τ is the shear at any height and τ_o is the shear at the surface, K_m is the eddy momentum transfer coefficient and U_* is the shear velocity given by $\sqrt{\tau_o/\rho}$ It should be noted that (I-A-2) only applies to neutral conditions. From (I-A-1) and (I-A-2) we can determine K_m for neutral conditions as

$$K_{m,Neutral} = kU_*(Z-d) \qquad \text{(I-A-2)}$$

Using assumption (c) we can relate K_m at any stability condition to $K_{m,Neutral}$ by

$$K_m = K_{m,Neutral} \quad \phi(Ri) = kU_*(Z-d)\ \phi(Ri) \qquad \text{(I-A-3a)}$$

From (I-A-3a) and (I-A-1) we obtain

$$U_*^2 = kU_*(Z-d)\ \phi(Ri)\ \frac{du}{dZ} \qquad \text{(I-A-3b)}$$

Separating variables and integrating yields

$$u = \frac{U_*}{k}\ \left[\ln \frac{Z-d}{Z_o} - \Psi(Ri)\right] \qquad \text{(I-A-4a)}$$

where

$$\Psi(Ri) = \int_o^{Ri} \frac{1-1/\phi(\varepsilon)}{\varepsilon}\, d\varepsilon \qquad \text{(I-A-4b)}$$

The only restriction on $\phi(Ri)$ is that it be to expandable in a series. Equation (I-A-4) is known as the KEYPS relationship. [See Lumley and Panofsky (1964) p. 111].

Using these relationships for the wind profile, one can derive the expression for r_a given by equation (11). Using the turbulent analogy to Fourier's heat flux equation, we write

$$H_s = -\rho\ C_p\ K_H \frac{dT}{dZ} = -\rho\ C_p\ K_m \frac{K_H}{K_m} \frac{dT}{dZ} \qquad \text{(I-A-5)}$$

or

$$H_s = -\rho\ C_p\ kU_*\ (Z-d)\ \phi\ (Ri)\ \frac{K_H}{K_m} \frac{dT}{dZ}$$

where K_H is the eddy diffusivity for sensible heat. Assuming that H_s is invariant with height, and representing $\frac{K_H}{K_m}$ by α and assuming that α is invariant with height, we can write,

$$\frac{H_s}{\rho C_p \alpha k U_*} \int_{Z_o}^{Z} \frac{dZ}{(Z-d)\phi(Ri)} = \int_{T_L}^{T_a} dT \qquad \text{(I-A-6)}$$

or

$$\frac{H_s}{\rho C_p \alpha k U*} \ln\frac{Z-d}{Z_o} - \psi(Ri) = T_L - T_a \qquad \text{(I-A-7)}$$

solving for U* from (I-A-4) and simplifying (I-A-7), we have

$$H_s = \frac{\rho C_p \alpha k^2 u(T_L - T_a)}{[\ln \frac{Z-d}{Z_o} - \psi(Ri)]^2} \qquad \text{(I-A-8)}$$

The assumption is made in this derivation that momentum and heat sinks in the canopy are the same. Actually, they differ, hence an empirical correction coefficient must be used. Using this coefficient, we can write (I-A-8) as

$$H_s = \frac{\rho C_p (T_L - T_A)}{r_a} \qquad \text{(I-A-9)}$$

where

$$r_a = [\ln \frac{Z-d}{Z_o} - \psi(Ri)]^2 / C_1 \alpha k^2 u \qquad \text{(I-A-10)}$$

Equation (I-A-10) is the same as equation (11).

B. ESTABLISHING A FUNCTIONAL RELATIONSHIP FOR $\psi(Ri)$

Data are available from Lettau (1962) and Lumley and Panofsky (1964) for $\psi(Ri)$ in either tabular or graphical form. In order to use the equations in a model, it is desirable to have an explicit equation relating $\psi(Ri)$ to Ri. Linear and non-linear regression was tried using a wide variety of equations to predict $\psi(Ri)$. The only suitable expressions found are somewhat complicated. For positive Richardson's number, the best expression found was

$$\psi_3(Ri) = 3.433 \ln [1-6.510 Ri] - 5.723 [1-\exp(3.504 Ri)] \qquad \text{(I-B-1)}$$

For negative Richardson's numbers, the best expession found was

$$\psi_2(Ri) = .894\ Ri + \frac{2.707\ Ri}{\sqrt{1-18Ri}} - \frac{8.003\ Ri}{(1-18Ri)^{0.4}} - \frac{0.085\ Ri\ |Ri|^{0.4}}{(1-18Ri)} \quad \text{(I-B-2)}$$

A plot of the data from Lettan (1962) and Lumley and Panofsky (1964) along with the functions ψ_2 and ψ_3 is shown in Figure I-B-1.

C. FUNCTIONAL RELATIONSHIPPBETWEEN K_H/K_m AND RICHARDSON NUMBER

Several investigators have looked at the ratio between K_H/K_m (α) and Richardson number. A summary of these relationships is givenbby Morgan, et al., (1971). The relationship used in this work was proposed by Panofsky (1965) and gave the best fit where used with the Arizona data. This relationship is

$$\alpha = 1.0 \quad ; Ri>o$$

$$\alpha = 30 - 1.4 \exp\left[-1.5\left|\frac{Z}{L}\right|\right]; Ri<o \quad \text{(I-C-1)}$$

where L is the familar dimensionless height proposed by Monin. The dimensionless number Z/L has been related to Richardson number [See Lumley and Panofsky (1964, pp. 114] by the relationship.

$$Z/L = \frac{Ri\quad Ri}{(1-18Ri)^{1/4}} \quad \text{(I-C-2)}$$

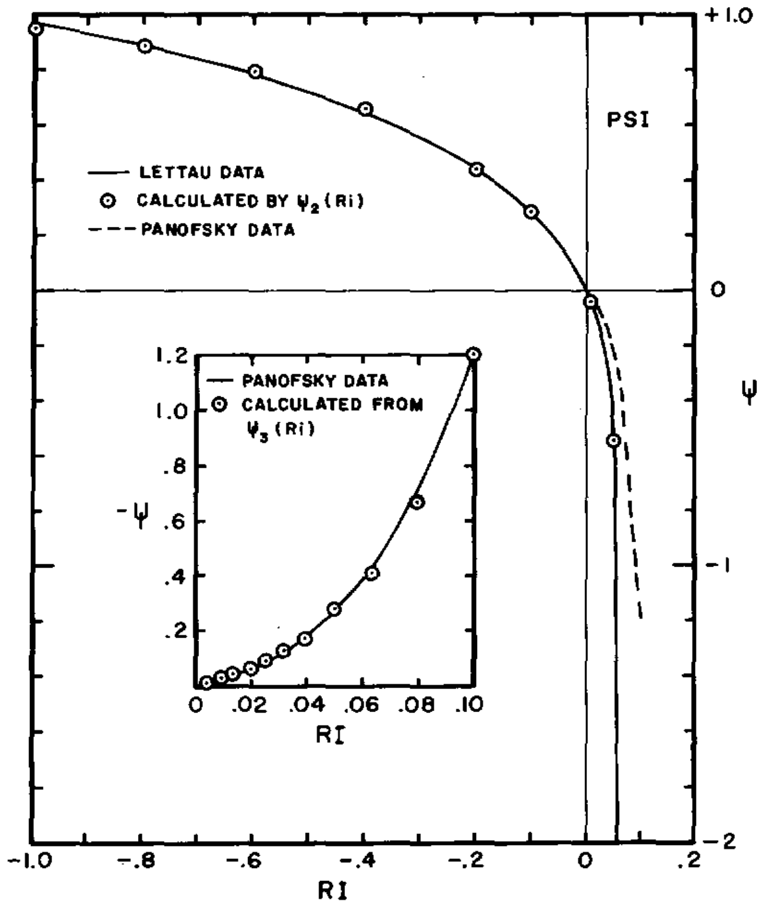

Figure I-B-1. Graph of the Function ψ(Ri) from Lettau (1962) and Lumley and Panofsky (1964) and the Predicted Values from ψ_2(Ri) and ψ_3(Ri).

APPENDIX II

CORRECTING NET RADIATION FOR THE EFFECTS OF MIST

The equation for net radiation is

$$R_N = R_I - r_f R_I + \varepsilon_a \sigma T_a^4 = \varepsilon_s \sigma T_s^4 \qquad \text{(II-1)}$$

where R_N is net radiation, R_I is incoming shortwave radiation, r_f is the reflectivity of the surface for shortwave radiation, ε_a is the emissivity of the sky, σ is the Stephan Boltzman constant, T_a is air temperature, ε_s is the emissivity of the soil, and T_s is the soil temperature. Assuming a change due to increased moisture,

$$\delta R_N = \delta(R_I) + \delta(r_f R_I) + \delta(\varepsilon_a \sigma T_a^4) - \delta(\varepsilon_s \sigma T_s^4) \qquad \text{(II-2)}$$

In the model used in this study, it was assumed that incoming shortwave radiation was unaffected by mist. Also, it was assumed that the emissivity of the surface and the surface temperature were unaffected. Under these assumptions (II-2) becomes

$$\delta R_N = \delta(\varepsilon_a \sigma T_a^4) = \varepsilon_a \sigma T_a^4 - \varepsilon_p \sigma T_p^4 \qquad \text{(II-3)}$$

where ε_p is the emissivity of the sky under the same conditions without mist and T_p is the free air temperature without the mist. During most misting operations, sufficient water is added to the air to make ε_a approach unity. Hence, the change in net radiation becomes

$$\delta R_n = \sigma T_a^4 \left(1 - \varepsilon_p \frac{T_p^4}{T_a^4}\right) \qquad \text{(II-4)}$$

Using data from Bliss (1971), ε_p can be estimated from,

$$\varepsilon_p = .803 + .003233\ T_{dp} \qquad \text{(II-5)}$$

where T_{dp} is the dew point temperature at the air. This relationship was used in the model.

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LIST OF SYMBOLS

1. A_D Fraction of leaf area dry.
2. A_W Fraction of leaf area wet.
3. $A_{W,I}$ Fraction of leaf area wet immediately after misting ends.
4. C_1 Empirical constant accounting for the effect of differential sinks for momentum and heat.
5. C_p Specific heat of dry air.
6. C_W Specific heat of liquid water.
7. H_L, $H_{L,w}$, $H_{,D}$ Latent heat flux (average from wet leaf, from dry leaf).
8. H_s, $H_{s,w}$, $H_{s,D}$ Sensible heat flux (average from wet leaf, from dry leaf).
9. K_H Eddy diffusivity for heat and mass (assumed to be equal).
10. K_m Eddy diffusivity for momentum.
11. $K_{m,Neutral}$ Eddy diffusivity for Ri = 0.
12. L Monin Obukov characteristic length.
13. Q_{MAX} Amount of water held on the leaf after misting ends.
14. Q_{off} Energy flux in water running off plant.
15. Q_{on} Energy flux in water hitting plant.
16. Q_{TOT} Amount of water evaporated at any time after the mist is turned off.
17. $Q_{w,off}$ Volume rate of water running off plant.
18. $Q_{w,on}$ Volume rate of water hitting plant.
19. Ri Richardson Number given by equation 12.
20. R_n Net radiation.
21. $R_{N,ABOVE}$ Net radiation above the mist.
22. T_a Air temperature at height Z above canopy.
23. T_L, $T_{L,w}$, $T_{L,D}$ Leaf temperature (average, wet leaf, dry leaf).
24. $T_{L,AVG}$ Average leaf temperature of wet and dry area weighted for fraction wet and fraction dry.

25. T_p Free air temperature prior to misting.
26. T_{wB} Wet bulb temperature at height Z above canopy.
27. U_* Shear velocity ($\sqrt{\tau_{o/\rho}}$)
28. Z Vertical coordinate.
29. Z_o Roughness height.

Small Letters

1. d displacement height of crop.
2. g acceleration of gravity
3. k VonKarmon's constant ($\cong$ 0.4)
4. r_a air resistance given by equation (11).
5. r_s stomatal resistance.
6. s energy stored in plant.
7. t time.
8. u windspeed at height Z above crop.

Greek Symbols

1. ψ(Ri) Dimensionless function of Richardson Number which corrects air resistance for stability effects.
2. ϕ(Ri) Dimensionless function of Richardson Number.
3. ε_p emissivity of the sky above the mist.
4. λ latent heat of vaporization of water.
5. ρ mass density of dry air.
6. ρ_w mass density of liquid water.
7. σ Stefon-Boltzman constant.
8. $\propto$ Ratio of eddy diffusivity for heat to that for momentum ($\frac{K_H}{K_m}$)
9. $\chi_L, \chi_{L,w}, \chi_{L,D}, \chi_a$ Humidity ratio (saturation at average temperature of leaf, saturation at temperature of wet leaf, saturation at temperature of dry leaf, actual of free air.
10. $\chi_{L,AVG}$ Humidity ratio at the average temperature of the plant ($T_{L,AVG}$).