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ENERGY BALANCE MEASUREMENTS FOR CROP WATER STATUS

by

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SUMMARY: Surface energy balance measurements were evaluated for determining soybean evapotranspiration and water status under conditions common to the southeastern USA. These include generally high atmospheric humidity, variable irradiance, and possible limited water supply in sandy soils. A system is described that provides data of sufficient temporal resolution to assess the effects of varying irradiance. Energy balance results and system performance are discussed.

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INTRODUCTION

The southeastern USA has an apparently abundant supply of rain for agriculture. However, because of poor distribution of rainfall, both year-to-year and within growing seasons, short droughts occur frequently. For example, Sheridan et al (1979) reported a 50% probability of a 22-day drought from March to May, and also for an 18-day drought during June-August in Southern Georgia. Such short droughts can reduce yields because of low water holding capacity in shallow, sandy soils. To protect against losses due to drought, irrigation is used to supplement rainfall. Balancing irrigation needs against the probability of rainfall requires a fine control over when to irrigate and how much water to apply. As an example, if 30 mm of water storage capacity exists between the upper and lower limits for crop production, and one should irrigate at 50% depletion of available water, then only 15 mm storage exists for supplemental water. Leaving some storage capacity for potential rainfall further reduces the amount of irrigation water that can be applied. For protection against both drought and aeration stress, the irrigation amount may be limited to the daily crop use.

High-frequency, low-volume irrigation has been proposed and tested for use in humid areas (Phene and Beale, 1976; Phene et al., 1979). Trickle irrigation techniques appear suitable for such applications, but acceptance by growers appears to depend upon the solution of problems observed to occur under condtions common to the SE. Specifically, there appears to be an effect of drought even under irrigated conditions. This applies as well to high-volume irrigation methods, but may be more severe if irrigation capacity is limited, even in a well-designed system. Secondly, if irrigation management allows the crop to deplete the soil water below the desired range, it may be difficult to restore the soil to well-watered status. This has occurred in some research plots (C. R. Camp, 1986, personal communication), and has caused at least one major orchard owner to use higher-volume emmittors rather than trickle techniques (V. Caggiano, panel discussion at SC Land Resources Commission Symposium on Low-volume Irrigation, Dec 11, 1986).

Irrigation management, whether by soil-water balance or by measurement of crop or soil, has been studied extensively in the West. Many guidelines published for the SE have relied on data resulting from these studies, although climate, soil, and crop differences exist. Research in the Southeast has included studies of reliability of equations for estimating potential evapotranspiration (listed in Sadler and Camp, 1986), has raised questions about reliability of infrared thermometry under conditions of varying radiation (Sojka et al., 1984), and has reported inability of standard crop measurements to discriminate between the water status of irrigated and rain-fed crops (Reicosky and Deaton, 1979; Sojka et al., 1984). Several theories have been proposed to explain these phenomena, but basic information of plant-soil-atmosphere interactions is needed under southeastern conditions to arrive at a satisfactory resolution. One major characteristic of the summer climate in the Southeast is the highly variable irradiance caused by scattered clouds. The effect of variable irradiance was studied by Sojka et al. (1984), who documented crop responses to shading within 1 minute. It can be argued that 30-min or hourly averages of climatic variables and crop responses may not be sufficiently resolved to describe physical relationships because of the nonlinearity of many of the basic functions involved.

Concurrent measurements of the surface energy balance and the soil moisture content provide information to investigate such questions. Energy balance measurements provide essentially instantaneous values of latent heat flux, which is directly convertible to units of evapotranspiration ($kg/(m^2hr)$ or mm/hr). Measurements required for the energy balance procedure have been described in detail in several well-known texts (e.g., Rosenberg, et al., 1983), and will be given only briefly here. The energy balance equation is given below.

$$Rnet = H + LE + G \qquad [W/m^2] \tag{1}$$

The net radiation (Rnet) and soil heat flux (G) components are measured directly, and the sensible (H) and latent (LE) components are calculated from literature relationships using differences in temperature and humidity, respectively, between the surface and air. The resistance to sensible and latent heat transfer through the air is calculated from the logarithmic profile theory (Businger, 1956; Van Bavel, 1966). Recent work by Hatfield (1985) used these techniques to obtain the canopy resistance to vapor and heat flow and showed how the resistance depended inversely upon solar irradiance.

The current experiment was established to evaluate the surface energy balance for researching the questions posed above under conditions common to the Southeast. A compact, reliable data collection system was needed to obtain data in an extended field experiment. An adjustable-height, single mast configuration was developed for field data collection. Specific problems in power supply, temporal resolution required, and resolution of information obtained were studied.

MATERIALS AND METHODS

The surface energy balance measurement equipment was placed in a 2.75-ha soybean field on 6 August 1986. Prevailing wind (S-SW) fetch was >100 m. The soybeans had been planted as part of another study on 31 May 1986, in 0.61-m rows oriented SW-NE. The soil around the measurements was a Norfolk loamy fine sand (fine-loamy, siliceous, thermic Typic Paleudult). Data was collected on 48 days between 6 August and 3 October, the latter of which corresponded to start of senescense. Canopy at the start of the measurements was nearing closure, and was about 0.9 m tall.

The measurements made and instruments used are listed in Table 1. The net radiometer, two infrared thermometers (IRTs), the anemometer, and the psychrometer were mounted on a mast of 3-cm diameter aluminum tubing placed inside a stainless steel sleeve driven into the ground. The mast was adjustable in 0.2-m increments to keep the instruments 1±.1 m above the canopy. The net radiometer was placed on a 1.3-m boom and oriented south at 1 m above the canopy, directly over a row. The anemometer was placed 120° around the mast, on an 0.8-m boom, at the same height. The psychrometer was placed at the same height, was oriented 120° from both booms, and was placed nearer the mast because of its greater weight. The two IRT's, one east-facing, the other west-facing, were mounted near the mast on the clamps for the other instruments and aimed about 45° down at a soybean row (see Figure 1).

The aspirated psychrometer is diagrammed in Figure 2. An enclosure for a 0.12x0.12x0.03-m fan was constructed of 6-mm plexiglas. A 0.2-m length outer shield was made of 76-mm diameter PVC pipe, and an inner shield, of 51-mm diameter PVC pipe. A divider of 6-mm plexiglas provided support for the shields as well as the thermocouples, wick, and water delivery tubing. The dry bulb thermocouple was made of 0.51 mm diameter (24-ga) type T thermocouple wire. The wet bulb was made of a 0.3 m length of 0.13 mm diameter (36-ga) type T wire with the larger gauge wire used to extend to the data collector. The wick extended approximately 30 mm from the end of the water supply tube, and the thermocouple was inserted completely to the leading end of the wick. An adjustable Marriotte bottle provided a zero-head water supply through flexible tubing.

Soil heat flux and soil temperature were measured for both in-row and mid-row locations beneath the net radiometer (see Figure 1). Soil heat flow disks were placed at 0.05-m depth, and the soil temperature was measured at 0.025-m depth. The pyranometer was placed on a separate platform approximately 5 m north of the main mast.

The data collector used was a Campbell Scientific, Inc. (CSI, Logan, Utah) CR21XL[1] with a CSI 32-channel multiplexor. These were mounted on a second, lower mast 2 m north of the main mast. The net radiometer, pyranometer, anemometer, and soil heat flow disks were read directly. Thermocouples were read using the built-in type T compensation. The IRT's required a single regulated DC power supply in the 4.5-8 V range, and were driven at 5.0 V. They provided two DC outputs: one a detector temperature, and the other a temperature difference between the detector and target. The former was a non-linear function of signal, and was reduced using the polynomial computation program in the data collector. The 5th-order polynomial equation was fitted to data in the IRT manual. The detector-target difference was a linear function of the second signal, and was computed using appropriate programs within the data collector. Coefficients and program steps for this reduction can be obtained from the authors if a reader has use for this information.

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[1] Mention of manufacturers is for information only, and does not imply endorsement over other manufacturers of similar equipment.

Two means of supplying power to drive the aspiration fan and IRT's were used. In the first, a portable generator was the primary source. A small DC power supply was used for continuous IRT excitation, and an AC fan was used in the psychrometer. During interruptions, a DC-AC invertor was used with a 12V battery. Later, a DC fan was installed in the psychrometer and driven from the 12VDC common to the battery and the data collector. The IRT's were driven from the internal power supply of the data collector. A switching relay was constructed to allow the data collector to switch off the fan at night, when no data was collected. During recharging, the portable generator provided power through the recharging transformer for the data collector. Other experiments have recently been reported with similar DC-based power sources plus a solar panel to extend the battery life. We will evaluate the performance of such a system with the additional load of the fan in later experiments.

All instruments were interrogated at 15-second intervals, and averages stored each minute. Internal data storage was sufficient for 24000 data values. Data was written to audio tape using the CSI SC92 interface and a small cassette recorder. Cassettes were read daily so that raw data could be plotted to show possible sensor malfunctions. Cassettes were read in the laboratory using a CSI C20 cassette reader connected via RS-232 to a DEC VAX 11-750 minicomputer (Digital Equipment Corp., Maynard, Mass.). Data was entered into a SAS (SAS Institute, Inc, Cary, NC) format data set in compact form. Raw and reduced data plots were generated and statistical analyses were made using the SAS software system and a DEC LN01S laser page printer in graphics emulation mode. The plotting speed of this system enabled many detailed plots to be generated in a short time relative to a standard pen plotter, thus facilitating quality assurance of the data.

Equations used to compute the energy balance components are given below. In brief, the sensible heat flux was computed from the crop-air temperature difference, then added to the soil heat flux and net radiation. Latent heat of vaporization was found through the balance equation as the residual. The equation relating latent heat flow to humidity gradient was then solved for the canopy resistance.

Sensible heat flow is given by equation 2.

$$S = \rho Cp * \frac{Tc-Ta}{ra} \tag{2}$$

Where ρ is density (kg/m^3), Cp is heat capacity (J/kg/^{o}C), Tc and Ta are crop and air temperature (^{o}C), and ra is the aerodynamic resistance of the air above the crop (s/m).

$$ra = \left[\ln\left(\frac{z-d}{zo}\right)\right]^2 / \left(k^2 * U\right) \tag{3}$$

where z is the height (m) of measurement of Ta, Tdew, and wind speed, d is the displacement height (m), zo is the roughness height (m), k is von

Karman's constant (0.40), and U is the windspeed (m/s). Stability corrections were made as follow.

$$rac = ra * \left[1 - \frac{5g(z-d)(Tc-Ta)}{Tav*U*U}\right] \tag{4}$$

where g is acceleration due to gravity (9.81 m/s^2), and Tav is average temperature of the surface and the air (^{o}K).

Soil heat flux, measured at 0.05-m depth, was adjusted for heat storage above the sensor using the temperature of the soil measured at 0.025 m. Resolution of the temperature measurement was 0.01^{o}C, which corresponded to ~15 W/m^2 over the 1-min measurement interval. The last-digit noise imposed major effects on the soil heat flux result, so 10-minute, weighted running averages were computed for the soil temperature. These were then used to calculate the surface heat flow.

$$G_0 = G_{.05} + \int_{.05}^{0} C_s \frac{dT}{dt} dz \tag{5}$$

where G_0 is G at the surface and $G_{.05}$ is G measured at 0.05-m depth. C_s is soil heat capacity (J/m^3/^{o}C), as estimated for bulk density of 1.4 Mg/m^3 and water content of 0.1 m^3/m^3 (Hanks and Ashcroft, 1980). These values are typical for the soil measured and were used because soil conditions were not measured, but they must be measured for rigorous application of the thermal storage correction. Finally, t is time (s), and z is depth (m).

The diffusion equation for LE was solved for rc as follows.

$$rc = \frac{\lambda \rho Cp}{\gamma} * \frac{es - ea}{LE} - ra \tag{6}$$

where λ is the latent heat of vaporization (J/m^3), γ is the psychrometric constant (kPa/^{o}C), es is the saturation vapor pressure at the crop temperature (kPa), ea is the vapor pressure of the air (kPa), rc is the canopy resistance (s/m), and the other factors are as before.

RESULTS AND DISCUSSION

Two types of results are presented: first, the performance of the system, and second, samples of the data obtained. System performance was evaluated with respect to power supply, instrument performance, and utility of the equations and assumptions under southeastern conditions.

All instruments and the data collection system worked satisfactorily during the test period, with two minor exceptions. Moisture accumulated in the connectors supplied with the IRT's, causing loss of data when the contacts corroded, but this was solved by enclosing the connectors in plastic. During generator use, induction from the power supply to the IRT leads was occasionally observed to impress noise on the signal. This was corrected by grounding and separation, then eliminated entirely after switching to a completely DC system.

Several problems were observed related to the use of the inexpensive, portable generator. These included mechanical failure of the generator caused by vibration and prolonged use, occasional interruptions assumed to be caused by impeded fuel flow, ozone damage to plants in the immediate vicinity of the generator, and labor requirements for starting and maintenance. Interrupted power caused loss of IRT and psychrometer data. These problems were eliminated after switching to the DC-based system. Labor requirements in this latter system were reduced by using the data collector to control data collection, aspiration fan power, and IRT excitation. Labor requirements were then limited to cassette changes and data operations (performed daily), refilling the Marriotte bottle (weekly), and checking battery charge (daily).

The 12V battery was recharged daily to avoid possible loss of data, even though a full charge could have lasted 2-3 days. The steady-state DC fan load was about 300 ma, although startup current was much greater. The data collector load was negligible between sensor interrogations and about 125 ma for 2 seconds during readings. To avoid deep discharge of the data collector batteries, the voltage level was monitored and if it fell below 12 volts the aspiration fan was shut off.

The aspirated psychrometer constructed for this test was evaluated for wick wetting, air flow, and agreement to a standard. The wick was fully wetted at all observations in the field, and at no time was there evidence of water dripping from the wick, indicating that water flow was adequate and not excessive. Air flow in the inner tube measured with a Kurz model 490 hot wire anemometer (Kurz Instruments, Inc., Carmel Valley, California) was ~4 m/s with the original AC fan, and ~6 m/s with the DC fan installed later, both of which meet the guidelines for psychrometer aspiration (Fritschen and Gay, 1979). The psychrometer was tested several times against a standard Assmann psychrometer, both in the laboratory and the field. There was no discernable difference detected between the two in any test.

Since the calculation of sensible heat depends upon a temperature difference, and that of latent heat upon the wet-bulb depression, a laboratory comparison of all temperature sensors was made to determine systematic differences. The IRT's, the soil thermocouples, and the psychrometer (dry wick) were set up in an insulated box and monitored using the data collector as programmed for the field. The means for 136 1-minute observations (each a mean of 4 points) showed small, significant differences between the temperature sensors, with the total range of $0.335^{o}C$. The IRT's were on average $0.23^{o}C$ higher than the air temperature sensor. The thermocouple-based measurements agreed to within $0.06^{o}C$. Since the transfer equations are quite sensitive to even small errors in the canopy-air temperature difference, these offsets were corrected in the reduction of data.

Performance of the data reduction procedure showed several conditions for which the system did not provide suitable accuracy. The first was during rainfall, which violates the assumptions inherent in the energy balance equations above; there is heat flow associated with the mass flow of liquid water. Rain is relatively infrequent, and loss of data during rain poses little problem. Of more importance was the inability of the system to provide adequate information for times with low wind speed. Data for rc and LE diverged if indicated wind speed fell below about 0.7 m/s. It is difficult to determine whether this arose from the failure of the equation for ra at low wind speeds, or whether anemometer threshold or possible nonlinearity caused erroneous wind speeds in the low range, thus propagating an error through the equations. The values for ra at low wind speeds appear high, and since the rc term is found by the residual, any error accumulates in rc.

Lastly, there existed significant periods during which dew was deposited on or evaporated from a wet surface. This posed no problem for the energy balance, which accounts only for the exchange of heat. For the calculation of canopy resistance, however, one must account for the assumptions implicit in the formulation. If the surface is wet, there is no appreciable stomatal resistance. Small errors in ra calculations or in any measurement cause rc magnitudes greater than the assumed small value. The definition of rc includes resistances of the leaf surface and diffusion resistance to the top of the canopy, but the residual values obtained do not appear to be attributable to transfer through the canopy. Because of the frequent coincidence of low wind speeds and dew, it may be that the two problems are related. We avoided both problems by screening out data with wind speeds below 0.7 m/s or with crop temperatures less than 0.3^{o}C above the wet bulb temperature. It is more difficult to screen out data for which the surface of the canopy is heterogenous with respect to presence of dew. This occurs frequently, and results in values of rc rising from zero to the expected value. The phenomena can also be detected from the standard plot of canopy-air temperature difference versus vapor pressure deficit.

Once the aforementioned drawbacks are accounted for, the resulting data provide some interesting comparisons to classical energy balances and other data of western origin. First is the expected effect of higher humidity in maintaining a crop temperature higher than observed in western conditions: often, near or above the air temperature. For many of the days, there was no gain of sensible heat by the crop until late in the afternoon, when radiative cooling caused the crop temperature to drop below the air temperature. An example daily pattern is shown in figure 3.

Secondly, the diurnal trace of the Tc-Ta (ΔT) variable against vapor pressure deficit (Δe) suggests answers to some questions raised by others working in the Southeast. Sojka and Parsons (1983) observed positive slopes for these curves in both morning and afternoon for well-watered crops. Midday values for well-watered crops were scattered, with a weak negative correlation. These data were derived from thermistor leaf temperatures and 30-min averages of air temperature and humidity at a weather station 100 m from the soybean field. The temporal resolution and siting of the current system confirms that the daily trace does follow this pattern. When the ΔT vs Δe plots were developed to normalize climatic demand and crop response, only clear-sky, midday values were used. Sojka and Parsons (1983) took data during cloud-free periods, but included non-midday values in the plots. Implicit in the interpretation of the ΔT vs Δe plots for crop water stress is the assumption that only water stress is active in reducing stomatal aperture. For morning and late afternoon periods, there appears to be light-dependent stomatal closure as well. For Sojka's well-watered soybeans, this explains only the positive slopes for the morning and afternoon values, and not the non-existence of the expected well-watered baseline during midday. Sojka postulated that the well-watered baseline was dependent upon humidity, similar to hypotheses made by Geiser et al (1982) on data from Minnesota. Since soil moisture measurements were not made during this evaluation of the energy balance measurements, resolution of this question is left for later experiments.

An example of a daily pattern of ΔT vs Δe is plotted in figure 4. The day starts with Tc below Ta, near the dew point depression, during the time of dew deposition (Points noted 'A' and 'B' on figure 4). When the deposition ends and evaporation is from the fully-wetted surface, Tc is still below Ta, but now near the wet bulb depression ('B'). As part of the canopy dries and part is still wetted, the trace departs from the vertical axis and trends upward at about a 45^{o} angle ('C' and 'D'). The slope change to the horizontal is apparently the point at which the canopy surfaces are fully dried. This corresponds to a similar slope change in the rc vs Rs curve. From that time until higher irradiance conditions, the trace is nearly horizontal, and the ΔT value is positive ('D' to 'F'). During midday, the values for both ΔT and Δe vary, apparently in response to varying irradiance, such that trends are not always clear ('G' to 'L'). As the irradiance declines in the afternoon, the trend re-establishes as vapor pressure deficit declines ('M'). The slope change back toward the origin apparently corresponds to ΔT matching the dew point depression again ('N'). From this point, the trend toward the origin appears to correspond to dewfall as Δe declines. Screening all values corresponding to either wetted surfaces ($Tc-Tw < 0.3^{o}C$) or low irradiance conditions ($Rs < 300 W/m^{2}$) results in values for this day as shown in figure 5. The entire data set, screened similarly, is shown in figure 6.

An example plot of rc versus Rs is given for 2 days in figure 7. On the wetter day, August 15th (+ in figure 7), values of rc are nearly independent of solar irradiance over the range 200-1100 W/m^{2}. Hatfield's (1985) curves for well-watered wheat show similar independence over this range. He also showed dependence of midday rc values on available soil water that indicate that as the soil dries, the rc curve as shown here would be elevated over that for a well-watered crop. The rc data for the drier day, October 1st, agrees with this prediction. The morning rc values (diamonds) start in the area of 50 s/m and 500 W/m^{2}. As the irradiance increases, rc increases to 100-150 s/m. In the afternoon, as irradiance declines, the values for rc (stars) do not decline, but remain nearly constant in the 150-200 s/m range. This suggests that the crop water status differs for equal irradiance in the morning and afternoon, which could mean that soil water has been depleted, that the crop water content has decreased, or that the crop water status is flux-dependent. These questions bear directly on the application of traditional water status indicators in a variable environment, but resist explanation until concurrent soil measurements can be made.

SUMMARY AND CONCLUSIONS

The system of measurements performed well for the test period chosen and looks promising for planned future experiments. The system was simple, compact, and easily maintained, which is important when used in a season-long experiment. The system was able to resolve data under highly variable irradiance conditions. The maintenance requirements were within practical limits for the 12 VDC power system. Battery life was limiting, but should be extended to reasonable duration with solar panels that will be evaluated in future experiments. Data quality was greatly enhanced because sensor malfunctions were observable on plots within a day after occurring. This was enabled by the speed and ease of data transfer, reduction, and plotting.

Most of the equations and functions worked as expected, which is satisfying because most work with these systems has been in areas outside of the Southeast. Some refinement of these relationships are now under study, particularly, the aerodynamic resistance for wind speeds below 1 m/s. Increased resolution of low wind speeds and evaluation of data during periods of dew should aid in the refinement of this equation.

Although the purpose of this study was to evaluate the suitability of the measurement technique and sensors for the conditions of the humid Southeast, the data obtained bear further discussion. Previous crop-air temperature versus vapor pressure deficit data from the area, somewhat controversial when published, was partially verified. Additionally, the results indicate that single-time-of-day measurements may not be practical for evaluating crop water stress under the variable irradiance. Hysteresis in crop water status indicators suggest that crop water status is particularly sensitive to the evapotranspiration rate under conditions of moderate to severe water stress. Additional study of soil water content and hydraulic conductivity is needed in conjunction with these type data to evaluate the cause for the diurnal variation observed in water status.

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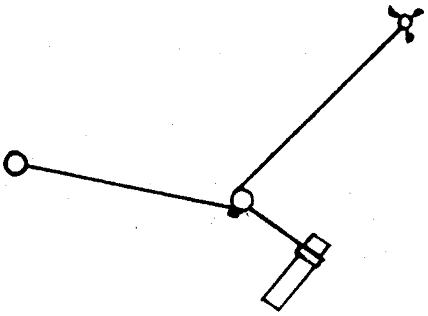
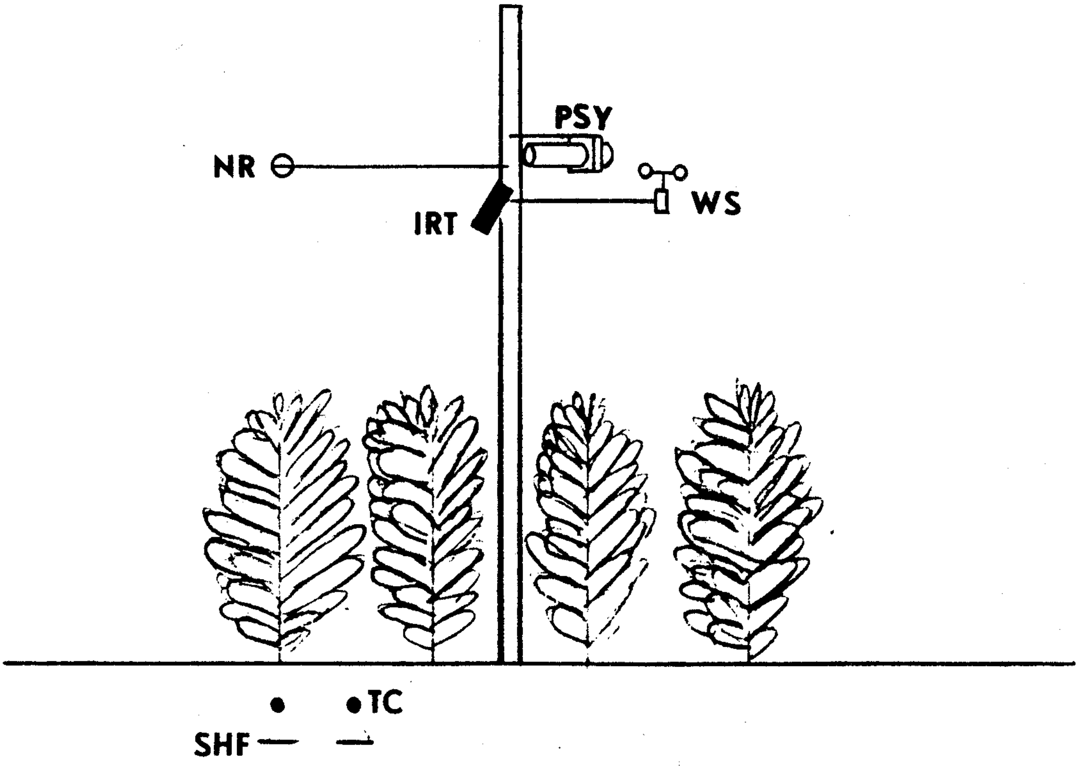
Table 1. Instruments used in surface energy balance measurements.

Parameter	Description	Manufacturer
Net radiation	Fritschen type	Micromet Instruments, Bothell, WA
Solar irradiance	Eppley Precision #8-48 radiometer	Eppley Laboratories, Stamford, CT
Crop temperature	Infrared thermometer Everest #4000	Everest Interscience, Tustin, CA
Wind speed	Analog cup anemometer RM Young # 12001	RM Young and Associates, Traverse City, MI
Soil heat flow	Heat flow disk # 610	CW Thornthwaite and Associates, Princeton, NJ
Air temp & humidity	Wet/dry bulb aspirated psychrometer	Made on-site
Soil temperature	Thermocouple	Made on-site



Top View



Side View

Figure 1. Diagram of the field installation for measuring components of the surface energy balance.

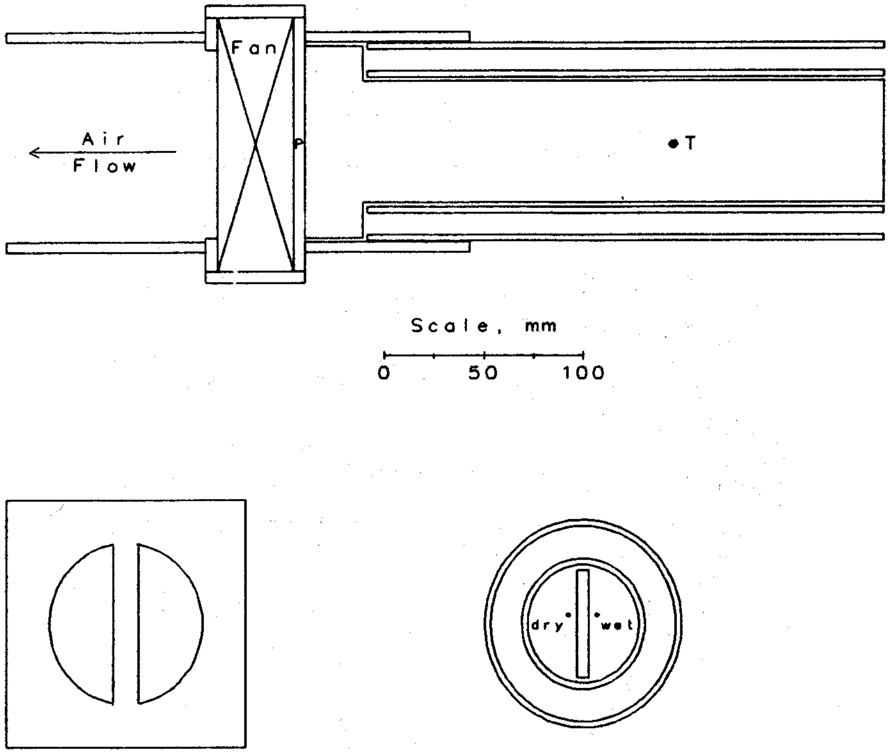


Plate P, front view

Section at T

Figure 2. Diagram of the aspirated psychrometer.

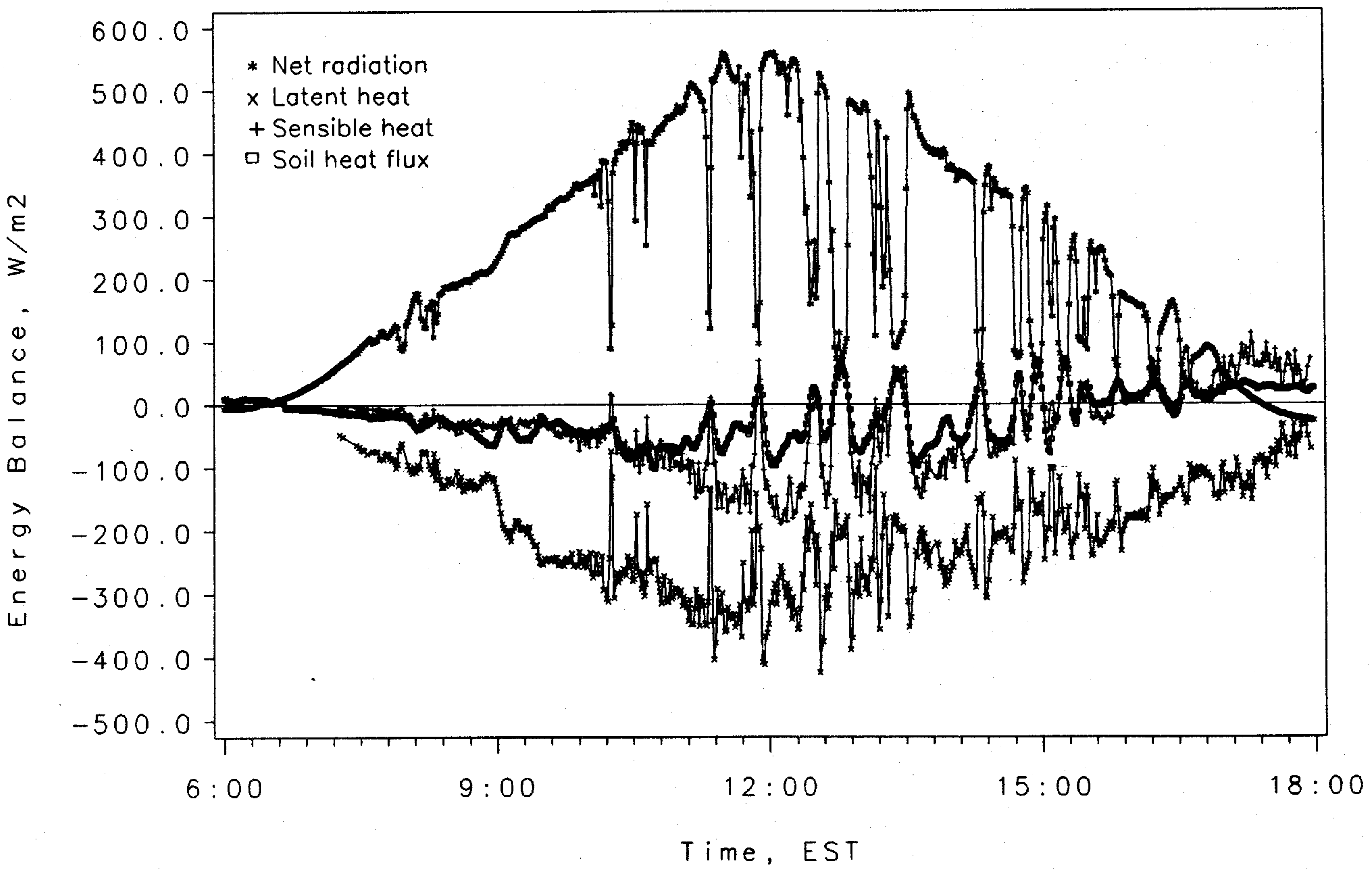


Figure 3. Example daily pattern of the energy balance components.

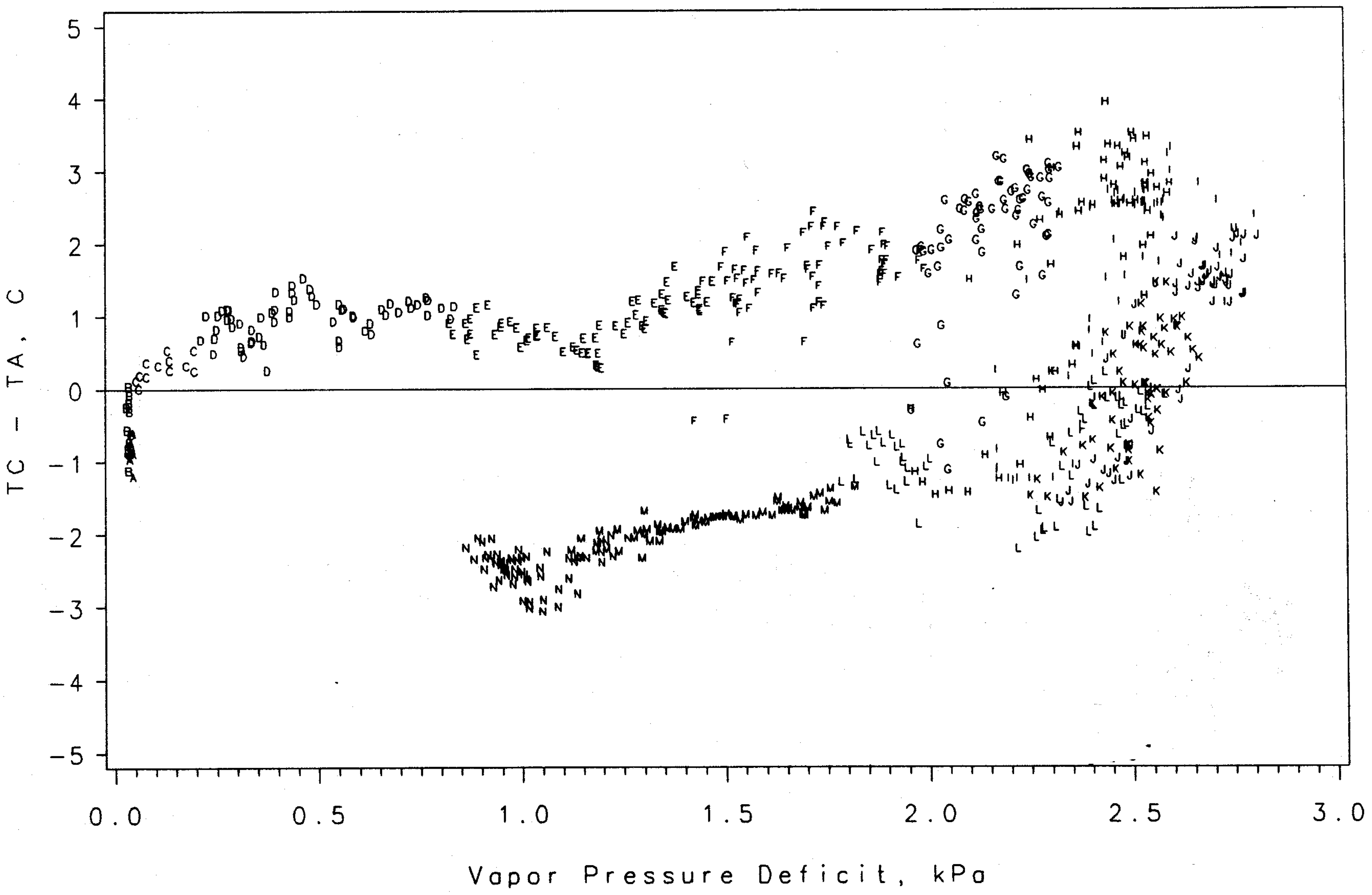


Figure 4. Plot of canopy-air temperature difference for 1 Oct 1986. Data points are coded according to time of day: A is 5:00-6:00, B is 6:00-7:00,...N is 18:00-19:00.

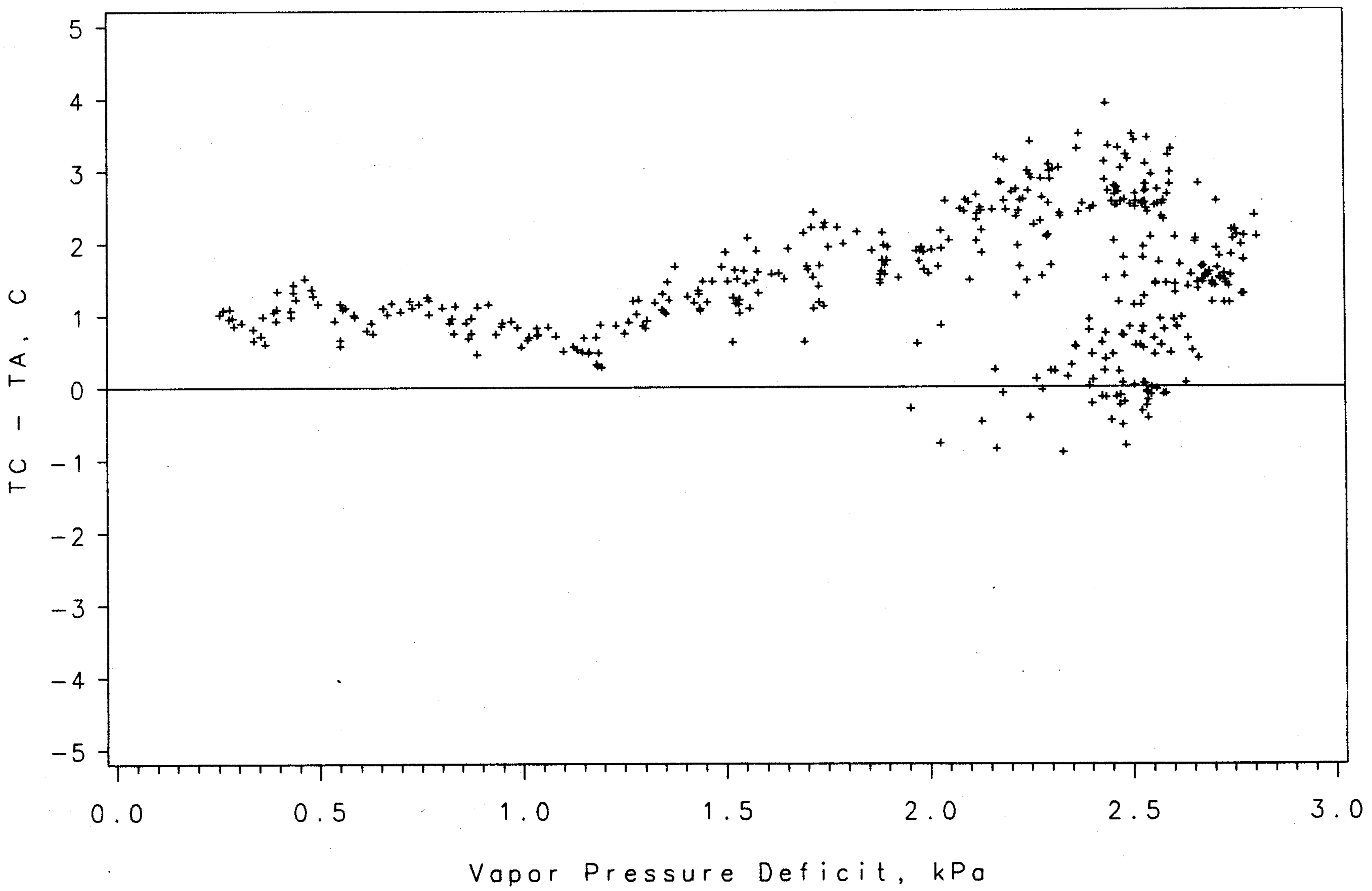


Figure 5. Plot of points in figure 4, but with low irradiance (<300 W/m^2) and wetted surface (T_c-T_w<0.3°C) values removed.

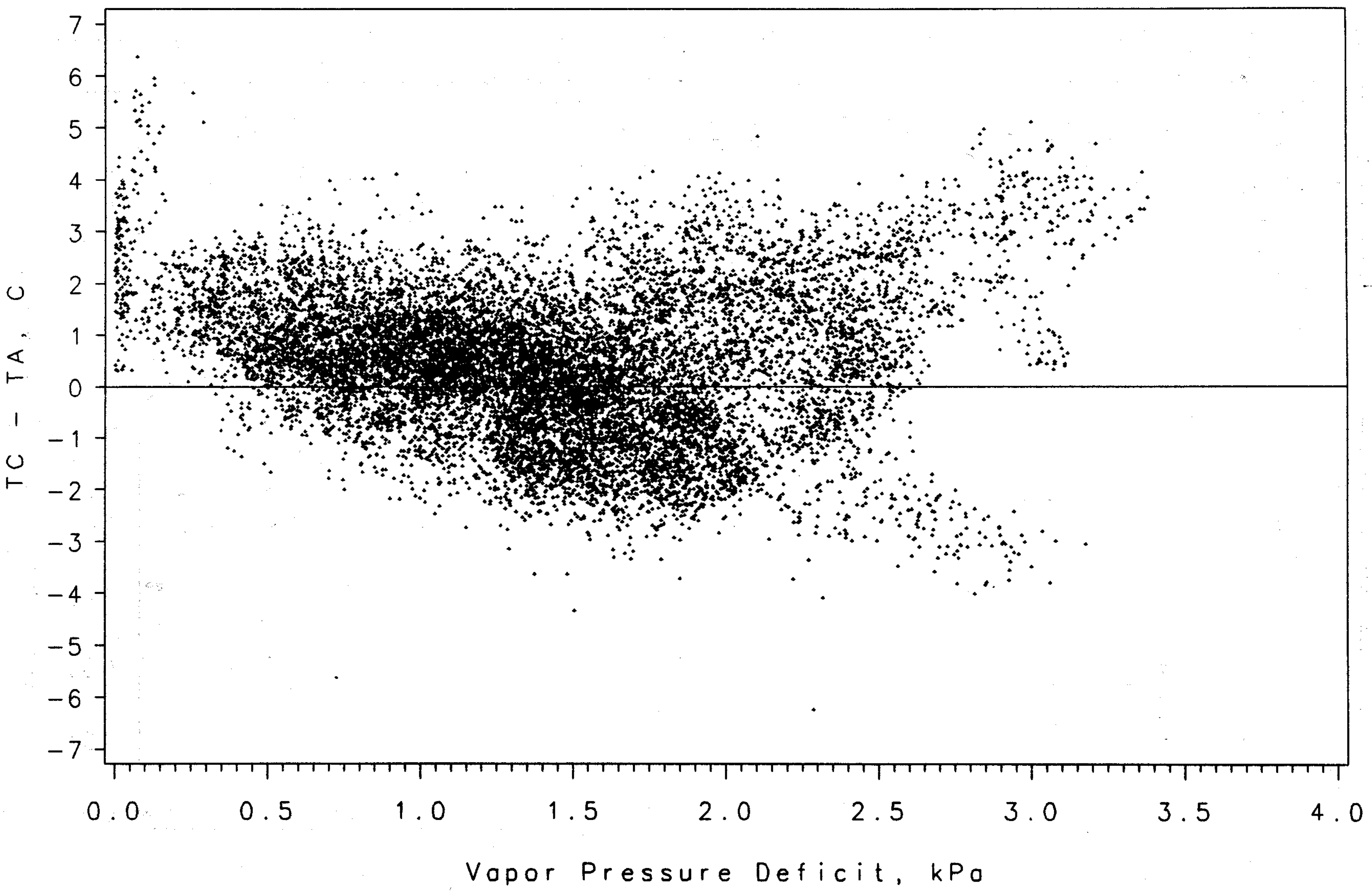


Figure 6. Plot of all points obtained from 6 Aug to 3 Oct with low irradiance and wetted surface values removed.

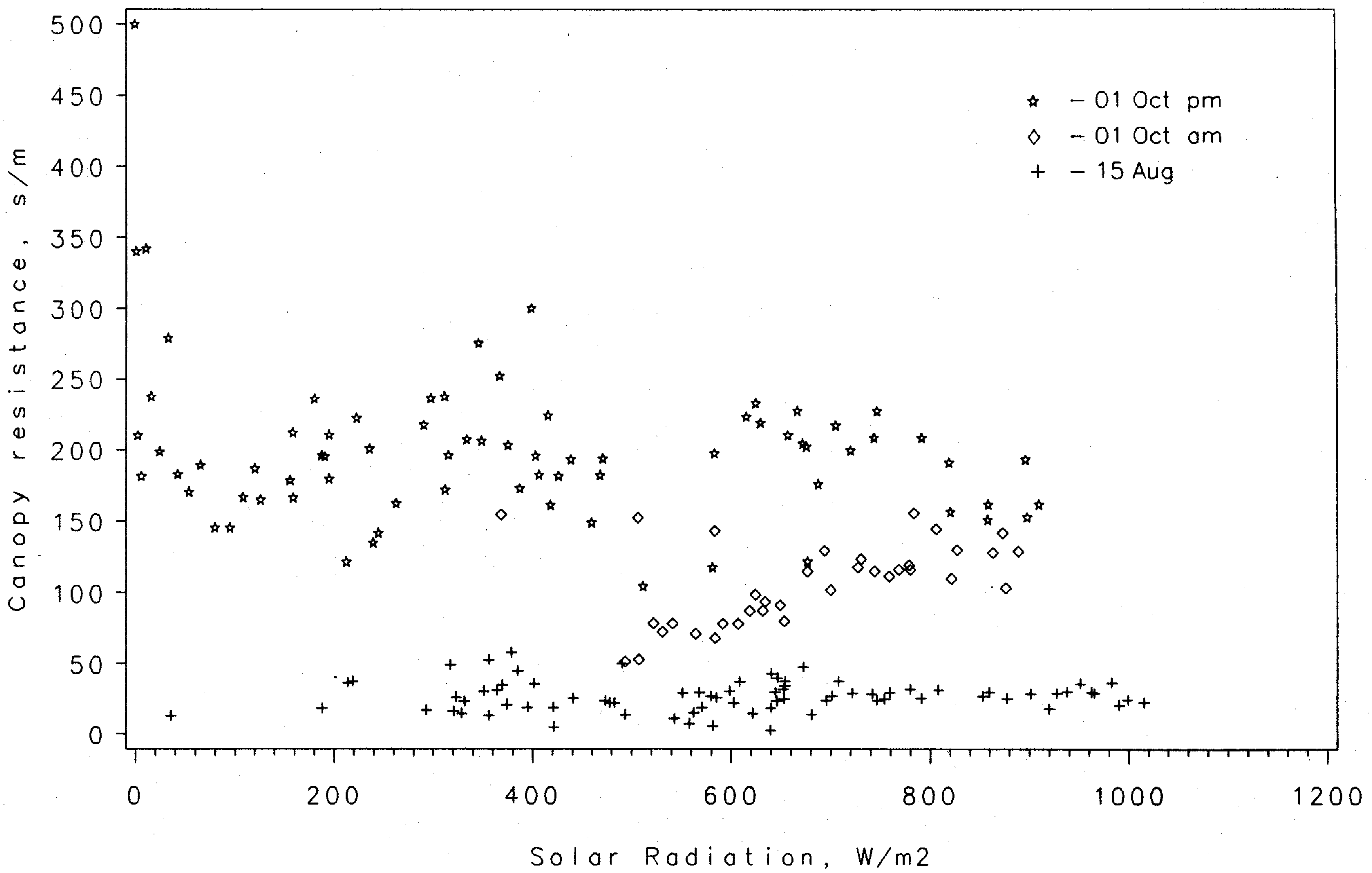


Figure 7. Plot of canopy resistance, rc, versus solar radiation, Rs, for an example of wet soil conditions (15 Aug: plus), and for dry soil conditions (1 Oct). Points for 1 Oct are identified by morning (diamond) and afternoon (star).