FINAL REPORT
on the
MEMORANDUM OF UNDERSTANDING

between the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER

and the

U. S. WATER CONSERVATION LABORATORY
WESTERN REGION, AGRICULTURAL RESEARCH SERVICE
U. S. DEPARTMENT OF AGRICULTURE
4331 E. Broadway
Phoenix, Arizona 85040

RFP5-39531-255
Contract S-53769A
Agreement No. 12-14-5001-6047
WRU No. 508-5510-12262

Three specific tasks were outlined in Article I - STATEMENT OF WORK - of the subject agreement. Of the three, two were accomplished. The third was partially accomplished, and will be completed when data from a U-2 flight becomes available. The three tasks will be discussed in the following paragraphs.

1.1 A procedure was developed for calculating 24-hour totals of evaporation from wet and drying soils that utilizes surface temperature data that can be obtained remotely. Its application requires a knowledge of the daily solar radiation and the maximum and minimum air temperatures (standard Weather Service measurements), moist surface albedo, and maximum and minimum surface temperatures (obtainable from surface or airborne sensors). Details of this procedure are given in the appended reprint from SCIENCE 189:991-992, 1975, entitled "Estimating evaporation: A technique adaptable to remote sensing," by S. B. Idso, R. D. Jackson, and R. J. Reginato.

1.2 The thermal inertia method of remotely sensing soil moisture was further developed by an experiment in which the surface temperatures were obtained from thermocouples, hand-held radiation thermometers, and the thermal IR band of a multispectral scanner mounted in a NASA aircraft. Data were obtained for both rough and smooth soil surfaces, and from soils that were considerably wetter than in previous experiments. Results confirm and extend the earlier work on relations between thermal inertia and remote sensing, and show that airborne sensors are an excellent means of obtaining surface temperatures. Details of this experiment are given in the appended manuscript "Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements," by R. J. Reginato (USWCL), S. B. Idso (USWCL), J. F. Vedder (NASA/AMES), R. D. Jackson (USWCL), M. B. Blanchard (NASA/AMES), and R. Goettelman (LFE Corp), which has been accepted for publication in the JOURNAL OF GEOPHYSICAL RESEARCH. A second manuscript concerning the relationships between reflected solar radiation and soil water content is in the rough draft stage.

A problem that is bothersome to the thermal inertia technique for estimating soil moisture is environmental variability. For example, a change in the content of water vapor in the atmosphere changes the rate of surface cooling at night and this changes the surface temperature. A procedure was developed that utilizes Weather Service air temperature data to normalize the measured surface temperatures to largely account for environmental variability. This procedure is discussed in the appended manuscript entitled "Normalization of surface temperature data to compensate for environmental variability in the thermal inertia approach to remote sensing of soil moisture," by S. B. Idso, R. D. Jackson, and R. J. Reginato. The manuscript has been submitted to the JOURNAL OF APPLIED METEOROLOGY.

1.3 A NASA U-2 aircraft carrying the HCMR simulator was flown over Phoenix on 3 September 1975 at 1400 hours. Concurrently, surface temperatures were obtained, using a PRT-5 infrared radiation thermometer, on 20 ten-acre fields at the Cotton Research Center farm. Bare soil temperatures ranged from 59 to 64 C. Alfalfa temperatures were 33 to 34 C, and cotton plots ranged in temperature from 33 to 37 C. Some cotton plots were being irrigated at flight time. This was a calibration flight for the HCMR simulator. Processed data from the U-2 are not yet available to compare with the ground-based data.

Ray D. Jackson

Ray D. Jackson
Principal Investigator

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14 January 1976

Dr. T. J. Schmugge
Hydrology & Oceanography Branch
NASA Goddard Space Flight Center, Code 913
Greenbelt aryland 20771

Dear Dr. Schmugge:

I am enclosing 15 copies of our final report to complete the Memorandum of Understanding S-53769A. The distribution of the report is as per the Memorandum.

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Would you please see that proper distribution is made.

Sincerely,

Ray D. Jackson
Ray D. Jackson
Research Physicist

15 Encl.

Estimating Evaporation: A Technique Adaptable to Remote Sensing

Abstract. *A procedure is presented for calculating 24-hour totals of evaporation from wet and drying soils. Its application requires a knowledge of the daily solar radiation and the maximum and minimum air temperatures (standard Weather Service measurements), moist surface albedo (readily estimated or obtainable from a one-time measurement), and maximum and minimum surface temperatures (obtainable from surface or airborne sensors). Tests of the technique on a bare field of Avondale loam at Phoenix, Arizona, have shown it to be independent of season.*

Evaporation of water from soils and crops is an important factor in managing both irrigated and dryland farming operations. It influences the time of seeding, the scheduling of irrigations, and various tillage practices (*1*). Evaporation is also important in determining the water balance of watersheds, which allows prediction and estimation of runoff and groundwater recharge. Thus, several techniques have been developed over the years to estimate evaporation rates (*2*). Most of these techniques, however, have been of rather limited usefulness in two respects. First, they have depended on many environmental parameters and surface characteristics that are generally difficult to measure over extended areas, that is, vapor pressure, air temperature, wind speed gradients, soil water content, and surface roughness length. Second, many have been applicable only to potential evaporation—the rate that prevails over a surface of any configuration under a given set of meteorological conditions if there is no saturation deficit at the surface, that is, a condition of nonlimiting water supply (*3*).

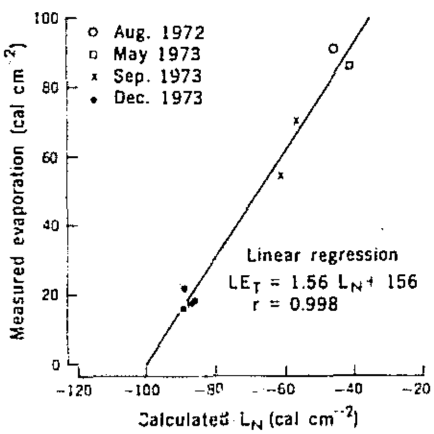

Fig. 1. Total evaporation induced by thermal radiation (LE_T) from a smooth bare field of Avondale loam at Phoenix, Arizona, as a function of the total net thermal radiation (L_N) calculated as ($R_A - R_S$) from average values of T_A and T_S, as determined from nighttime data; r = correlation coefficient.

In light of the seriousness of the current and projected world food shortage, we must overcome these limitations and develop a method of evaporation estimation readily adaptable to rapid application over large areas that handles both the potential rate phase of evaporation and the post-potential (falling rate or soil-limiting) phase of evaporation, where the surface water supply is limiting and acts to decrease evaporation rates below the potential rate that would occur if water were nonlimiting. In this report we describe the first step in the development of such an evaporation estimation technique and its initial tests on a field of bare soil. In addition to standard Weather Service measurements of daily solar radiation and maximum and minimum air temperatures, it requires only a one-time measurement or estimate of moist surface albedo and daily measurements of maximum and minimum surface temperatures.

We note first that the evaporation energy equivalent (LE) is largely proportional to net radiation (R_N) in the potential rate phase, and that net radiation can be readily subdivided into its two component parts: net solar radiation (S_N) and net thermal radiation (L_N). Since S_N is an external forcing function thermally independent of evaporation whereas L_N is in part determined by the evaporation process by virtue of its effects on surface temperature, we assume that the total 24-hour evaporation is directly equal to the daily S_N plus some function of the 24-hour summation of L_N; that is, we assume

$$LE = LE_S + LE_T = S_N + f(L_N) \quad (1)$$

where LE_S and LE_T are, respectively, the components of the total evaporation induced by solar and thermal radiation.

To explicitly derive the relation $LE_T = f(L_N)$, we utilized nighttime data, when no solar radiation was present. On several clear nights we measured evaporation from a smooth bare surface of Avondale loam with two weighing lysimeters. We plotted these measurements against nighttime totals of L_N, obtained from calculations of ($R_A - R_S$) where R_A is the incoming atmospheric thermal radiation and R_S is the outgoing surface thermal radiation. The quantity R_A was obtained from the Idso-Jackson formula (*4*) as

$$R_A = \sigma T_A^4 (1 - 0.261 \exp[-7.77 \times 10^{-4} (273 - T_A)^2]) \quad (2)$$

where σ is the Stefan-Boltzmann constant and T_A is the air temperature measured at 1 m above the surface. The quantity R_S was obtained from the Stefan-Boltzmann equation for blackbody radiation as

$$R_S = \sigma T_S^4 \quad (3)$$

where T_S is the surface temperature. Values of both T_A and T_S were obtained from fine-wire, copper-constantan thermocouples at 20- or 30-minute intervals through the night. The results (Fig. 1) indicated that, when the soil surface is moist and evaporation is in the potential rate phase,

$$LE_T = 1.56 L_N + 156 \quad (4)$$

In testing our basic hypothesis, we next computed 24-hour representative values of T_A and T_S as averages of their maximum and minimum values and used these average values to compute 24-hour totals of L_N (which were all negative). These values were then used as the independent variable in the linear regression equation (Eq. 4) to determine the negative evaporation component to be algebraically added to the daily S_N. We compared

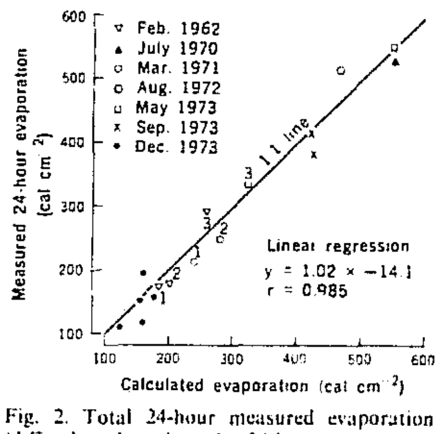

Fig. 2. Total 24-hour measured evaporation (LE) plotted against the 24-hour evaporation calculated as $LE = S_N + 1.56 L_N + 156$, with L_N in this instance calculated from the averages of the maximum and minimum values of T_A and T_S for the 24-hour period.

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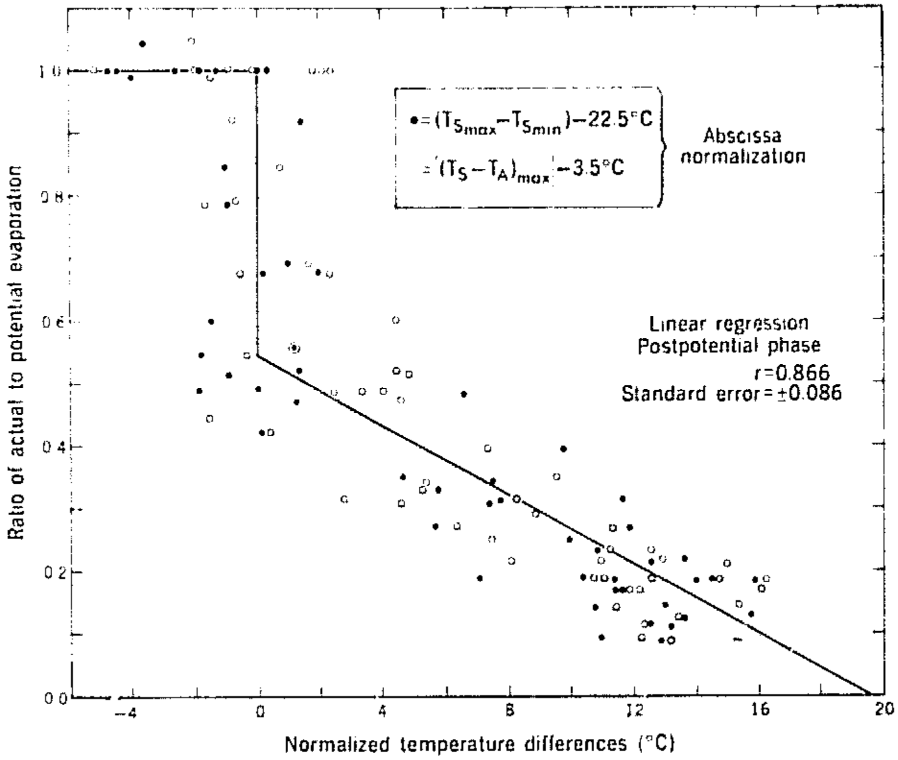

Fig. 3. Ratio of total 24-hour actual-to-potential evaporation as a function of the two thermal parameters defined at the top center of the graph, as determined for a field of Avondale loam at Phoenix, Arizona.

the results of this procedure with measurements of potential evaporation (Fig. 2), which showed that our basic hypothesis produced acceptable results.

Equations developed to calculated evaporation will often give good results in one season or climate but not in another (*2*); that is, in a windy, dry situation they may do well, but in a calm, humid situation they may perform poorly, or vice versa. We consider our approach potentially adaptable to various situations, for it incorporates T_S, which is directly and strongly linked to the evaporation rate. For example, between day 1 and day 3 after heavy irrigations of our field (72 by 90 m) in February 1962 and again in March 1971, the average daily wind speed more than doubled, greatly increasing the evaporation rates; yet our calculation procedure, which does not explicitly account for wind speed, gave equally good results under both sets of conditions. Why? Because the increased evaporation rates on the windy days lowered the T_S of the soil relative to T_A, which resulted in a less negative L_N flux for the day and a less negative value of LE_T to be algebraically added to the LE_S component of the total evaporation. There is a similar automatic adjustment for humidity variations. Over the range of conditions depicted in Fig. 2, vapor pressure, another component not explicitly accounted for in our procedure, varied by a factor of 5; yet our evaporation calculations were equally good over the entire range. In addition, no specification of surface type was made in developing our technique. Thus, we believe that relations similar to the one derived for bare soil in Fig. 1 could be developed for other surface types such as crops.

For bare soils, we next confront the problem of postpotential (falling rate or soil-limiting) phase evaporation, where the surface becomes dry and evaporation rates drop significantly. For this problem we again utilized T_S and T_A. Idso *et al.* (*5*) have shown that for several soils, ranging from sandy loams to clays, both the maximum value minus the minimum value of the daily surface soil temperature wave ($T_{S,max} - T_{S,min}$) and the maximum value of the surface soil temperature minus the air temperature [$(T_S - T_A)_{max}$] are good predictors of soil water pressure potential (the work required to move a unit mass of water against a force field from zero potential to the point in question), independent of the soil type. Thus, since evaporation is probably related to water pressure potential of the surface soil in the drying stages, we felt it would also be related to these thermal parameters.

To test this idea, we plotted ratios of 24-hour actual-to-potential evaporation against the thermal parameters [$(T_{S,max} - T_{S,min}) - 22.5°C$] and [$(T_S - T_A)_{max} - 3.5°C$)] for several periods after approximate 10-cm irrigations of our field (Fig. 3). The potential evaporation for all days was taken to be equal to the measured potential evaporation at the start of each time series before the surface soil dried, that is, day 1 immediately after irrigation. (Weather conditions for all days of each drying run were very similar.) On the normalized basis depicted in Fig. 3, one line adequately describes the relation between relative evaporation and both of the thermal parameters. Combined with our procedure for obtaining actual potential evaporation totals for the initial days of such drying periods, these results allow estimates of actual evaporation totals to be made throughout both the potential and postpotential stages of soil drying, although there still remains some uncertainty at the transition point between these two regimes.

The prime significance of these results lies in the fact that they indicate that actual evaporation rates throughout all stages of soil drying may be obtained from remotely acquired surface temperatures and routine weather network data. Measurements of maximum and minimum air temperatures are the most basic measurements made at all weather stations; solar radiation is rapidly becoming a standard measurement also. Moist surface albedo can be obtained from information in the literature (*6*) or from a one-time measurement. Thus, maximum and minimum surface temperatures are the only additional data needed for successfully estimating evaporation, and these measurements can be made over large areas by radiometric means. Such temperature measurements may thus be capable of specifying actual soil evaporation rates wherever air temperature and solar radiation data are available.

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References and Notes

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5. S. B. Idso, T. J. Schmugge, R. D. Jackson, R. J. Reginato, *J. Geophys. Res.* 80, 3044 (1975).
6. S. B. Idso and R. J. Reginato, *Hydrol. Water Res. Ariz. Southwest* 4, 41 (1974).
7. Contribution from the Agricultural Research Service, U.S. Department of Agriculture.

14 April 1975, revised 27 May 1975

SOIL WATER CONTENT AND EVAPORATION DETERMINED BY THERMAL PARAMETERS OBTAINED FROM GROUND-BASED AND REMOTE MEASUREMENTS[1/]

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1/ Contribution from the Agricultural Research Service, U.S. Department of Agriculture; and the National Aeronautics and Space Administration. This investigation was partially supported by funds provided by NASA, memorandum of understanding S-53769A.

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Abstract

Soil water contents from bot[illegible]th and rough bare soil were estimated from remotely sensed surfa[illegible]oil and air temperatures. We found an inverse relationship between two thermal parameters and gravimetric soil water content for Avondale loam when its water content was between air-dry and field capacity. These parameters, daily maximum minus minimum surface soil temperature and daily maximum soil minus air temperature, appear to describe the relationship reasonably well. These two parameters also describe relative soil water evaporation (actual/potential). Surface soil temperatures showed good agreement between three measurement techniques: *in situ* thermocouples, ground-based infrared radiation thermometer, and the thermal infrared band of an airborne multispectral scanner.

Periodic assessment of soil water content and evaporation rates can greatly benefit agriculture, hydrology, and civil works [Idso et al., 1975a]. Recent research has shown that daily maximum minus minimum surface soil temperature and daily maximum surface soil minus air temperature (this latter value measured at the time soil maximum occurs) can be used to estimate soil-water content and bare soil evaporation rates [Idso et al., 1975c,d]. These results were obtained using temperatures derived from thermocouples. To extend these techniques to large land areas requires remote radiometric assessment of soil temperature, whether from just above ground, from aircraft, or from satellites. The objective of this paper is to compare measured soil water contents and bare soil evaporation with estimates derived from thermal parameters measured by (1) *in situ* thermocouples, (2) a portable infrared radiation thermometer just above the ground, and (3) an aircraft-mounted multispectral scanner.

SOIL WATER CONTENT AND EVAPORATION MEASUREMENTS

Three soil moisture conditions were established in a 72 x 90 m field of bare Avondale loam (fine-loamy, mixed (calcareous), hyperthermic Anthropic Torrifluvent) at Phoenix, Arizona. The conditions were: a continually wet section (#3), a continually dry section (#1), and an initially wet section (#2) that was allowed to dry during the week of the experiment. During the evening of 17 March 1975, two sections (#2 and #3) were flood-irrigated with about 5 cm of water. A similar amount of water was also applied to the surface of a weighing lysimeter in section #2. Thereafter, section #3 was replenished with water on the evenings of 18, 20, and 22 March; section #2 received no additional water. Section #1 and its associated weighing lysimeter were not irrigated at any time during the experiment.

Each section had two surface soil conditions -- smooth and rough. The smooth soil was flat and level and had not been cultivated for the past 5 years. The lysimeters located within the smooth part of the section also had smooth surfaces. In contrast, the rough areas were chiseled and disked to give an uneven surface with roughness elements of 0 to 10 cm. The rough areas were located on the southern portions of all three sections.

Gravimetric soil moisture samples were taken from all three moisture treatments on both the smooth and rough plots in identical fashion to that described previously [Idso et al., 1975d], except sampling was not continuous but restricted to two 2-hour periods daily: 0430 to 0630 and 1300 to 1500 mountain standard time. Five sets of samples were taken during these time periods (at half-hour intervals) in each of the three sections in both the smooth and rough parts. Depth intervals sampled were 0 to 0.2, 0 to 0.5, 0 to 1, 1 to 2, 2 to 4, 4 to 6, 6 to 8, and 8 to 10 cm. The five samples were averaged to give one value per time period for each depth interval for both the smooth and rough parts of the three sections.

Three readings from each of the two lysimeters were obtained every 20 minutes, allowing smooth traces of the diurnal soil water evaporation trends to be obtained. For comparison with the remote sensing techniques, these diurnal trends were integrated to yield 24-hour totals of bare soil evaporation. Also, daily totals of free water evaporation were recorded from buried insulated tanks [Cooley, 1970]. To obtain potential soil water evaporation rates for the week's experiment (since there was no lysimeter in section 3), the ratio of the daily evaporation from the lysimeters during the first 2 days when the soil was wet to the daily evaporation from the tanks was computed. This ratio (1.04) was then used with tank evaporation data to estimate potential soil water evaporation for days when evaporation from the soil was below potential.

TEMPERATURE MEASUREMENTS

<u>Thermocouples</u>. Copper-constantan thermocouples were used to obtain air temperature (125 cm above each section) and surface soil temperature (about 1 mm below the soil surface) at two locations in the smooth-surface parts of the three sections and in the two lysimeters. Temperatures were recorded every 20 minutes for the week's experiment. Previous research had demonstrated that the minimum surface soil temperature occurred just before sunrise, while the maximum occurred about one and one-half hours after solar noon. To standardize the measurement times, temperatures recorded at 0540 and 0600 hours were averaged for the minimum, and readings at 1340 and 1400 hours were averaged for the maximum temperature.

<u>Ground-based radiation thermometer</u>. A portable, precision, infrared radiometer (Barnes Engineering[5/] PRT-5) was used to measure surface soil temperatures at 30-minute intervals during each of the two 2-hour sampling periods, from 0430 to 0630 and from 1300 to 1500, for the week's experiment. This instrument yields equivalent blackbody temperature with a resolution of $\pm$ 0.5°C within the 8 to 14 μm band. Measured temperatures were corrected for emittance using a value of 0.96 for Avondale loam [<u>Idso and Jackson</u>, 1969]. Temperature measurements were taken both in the smooth and rough plots of the three sections and in the two weighing lysimeters. The PRT-5, with a 20° field of

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<u>5/</u> Trade and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture or NASA.

view, was hand-held at a 1-m height and aimed at a point about 4 m distant into the plots, and about 0.4 m high directly over the lysimeters.

Airborne scanner. Temperatures were obtained using data from the thermal channel (8 to 14 μm wavelength range) of a multispectral scanner (Bendix M^2S[5/]) mounted in the NASA NP-3A aircraft. Radiance data in the visible region, 0.4 to 1.1 μm, were obtained from the M^2S. At approximately 0540 and 1350 hours each day of the experiment, the aircraft passed over the experimental site at about 300 m. The equivalent blackbody temperatures were corrected for emittance in the same manner as was the PRT-5 data. The effective spatial resolution of the scanner for this experiment was about 0.8 x 0.8 m, with a temperature resolution of approximately ± 0.5°C. Complete data sets were obtained for 4 of the 6 days: 18, 19, 20, and 23 March 1975. Instrument malfunction caused some data loss on the afternoon of 21 March and the morning of 22 March.

RESULTS AND DISCUSSION

Previous work [Idso et al., 1975b] demonstrated that volumetric water content in the upper 2 cm of Avondale loam could be obtained from albedo measurements. These measurements appear to be sensitive only to the very surface of the soil, whereas surface soil temperatures seem to be influenced by soil conditions somewhat deeper. This statement is illustrated in Figure 1 which shows a computer-enhanced picture from the airborne scanner data of the experimental field on the last day of our study. The three sections are as follows: #1 on the left was the continually dry plot; #2 in the center was wet initially and allowed to dry; and #3 on the right was continually wet. Note that sections 1 and 2 both appear light in the visible region, while section 3 is dark. However, in the infrared region there is a definite difference between all three sections: #1 being the lightest, #2 intermediate, and #3 the darkest. Thus, the thermal infrared region of the spectrum seems to hold more promise than does the visible region for the remote assessment of soil moisture with depth.

Soil water content. The relationships between the two thermal parameters, daily maximum minus minimum surface soil temperature and daily maximum surface soil minus air temperature differential, and gravimetric soil water content are shown in Figure 2 for the 0- to 2-cm soil depth for both the smooth and rough surface conditions. Earlier results had shown a good correlation between the thermal parameters and the soil water content in the 0- to 2-cm layer. Data from these previous experiments (1970 to 1973) for the 0- to 2-cm depth on smooth

Avondale loam for several seasons of the year are shown as solid dots in parts A and C. The lines describing the relationships for water contents less than 0.19 were derived from the 1970 to 1973 data using linear regression analysis. Also plotted are data obtained in March 1975 from (1) the in situ surface thermocouples (□), (2) the ground-based infrared thermometer (○), and (3) the airborne multispectral scanner (Δ).

In Figure 2A, the recent data for gravimetric water contents less than 0.19 are fairly well described by the line derived from the 1970 to 1973 data. However, at water contents greater than 0.19 the inverse relationship does not appear to hold. This is probably explainable as follows: for Avondale loam, the soil surface (0- to 2-cm layer) remains wet within the water content range from saturation to about 0.19. When the surface is wet, the evaporation rate, which greatly influences soil temperature, is controlled by meteorological conditions. With uniform day-to-day weather, a relatively constant maximum minus minimum soil temperature could be expected. For variable meteorological conditions, however, this would not hold true. Thus, the data scatter in Figure 2 for water contents greater than 0.19 is, at least in part, due to variations in meteorological conditions. For water contents below 0.19, the rate of movement of water towards the surface limits evaporation and, indirectly, soil temperatures, thereby making evaporation and soil temperature less responsive to meteorological conditions. Thus, for Avondale loam, less scatter exists below a water content of 0.19, which corresponds roughly to the so-called "field capacity," a term used to describe the amount of water remaining in the soil 2 to 3 days after irrigation.

Since no previous data were available for a rough soil surface, the relationship from the smooth soil was used in Figure 2B. Although the data points from the rough surface do not fall directly on the line, they are within the limits of scatter (Figure 2A). There appears to be little, if any, difference between smooth and rough surfaces in terms of the thermal parameter-water content relationship described in Figure 2A and B.

The second thermal parameter, daily maximum surface soil minus air temperature differential, is shown as a function of water content for both a smooth (Figure 2C) and a rough (Figure 2D) surface. The same inverse linear relationships for gravimetric soil water contents less than 0.19 appear to hold for this second thermal parameter as they did for the first. The slopes of these lines are nearly identical. For water contents greater than 0.19 this thermal parameter appears also to be dependent on meteorological conditions.

Based on the information derived during 1970 to 1973 relative to the two thermal parameters and water content or relative evaporation, the standard errors of estimate from the March 1975 data are shown in the four panels of Figure 2 as $S_{y.x}$. The differences between the four values are minimal, indicating that regardless of which thermal parameter is used or the condition of the soil surface, estimates of soil-water content are quite comparable. A similar analysis of the data was made for the 0- to 4-cm depth with identical results.

Agreement is good between the three techniques for measuring surface soil temperature: *in situ* thermocouples, ground-based infrared radiometer, and airborne multispectral scanner. These results are similar to those obtained by Marlatt [1966]. If water content *per se* were of interest, each soil type or possibly some broader soil classification unit would be calibrated from rather simple ground-based measurements. Subsequent routine thermal measurements from aircraft or satellites could be used to characterize the soil moisture status over large land areas.

Soil water evaporation. The ratio of actual to potential daily soil water evaporation as a function of the two previously described thermal parameters is shown in Figure 3A and B. Standard error of estimate values were derived in a similar manner as previously described for Figure 2, and are shown in Figure 3 as $S_{y.x}$. The break between the potential and the falling rate stage is at 22°C for the daily maximum-minimum surface soil temperature parameter, and at 3.5°C for the daily maximum soil minus air temperature parameter. These are the same values noted in Figure 2 for water content determinations. Intuitively, one would expect this similarity. When the soil water content is high, the hydraulic conducting property of the soil is relatively high, thereby allowing enough water to flow to the soil surface to meet the meteorological evaporative demand of the potential rate. However, as soil water becomes limiting the potential evaporation rate cannot be met, and the relative evaporation rate declines with decreasing water content. The applicability of these relations to other soils in other areas must be examined to determine the usefulness of the technique over large areas.

CONCLUDING REMARKS

Our data showed that remotely sensed surface soil temperature can be used to estimate soil water content and evaporation from bare soil. For water content estimations, both smooth and rough soil surfaces gave similar results.

From an air-dry soil water content to a water content corresponding to field capacity for Avondale loam, there is an inverse relationship between the two thermal parameters and gravimetric soil water content. Both parameters, daily maximum minus minimum surface soil temperature and daily maximum soil minus air temperature, appear equally good for describing the relationship. Relative soil water evaporation (actual/potential) is also described by these two parameters equally well.

Surface soil temperatures showed good agreement between the three measurement techniques: <u>in situ</u> thermocouples, ground-based infrared radiation thermometer, and the thermal infrared band of an airborne multispectral scanner.

To determine the extent of applicability of the above evaluations, measurements must be made at locations with different soils and under different climates.

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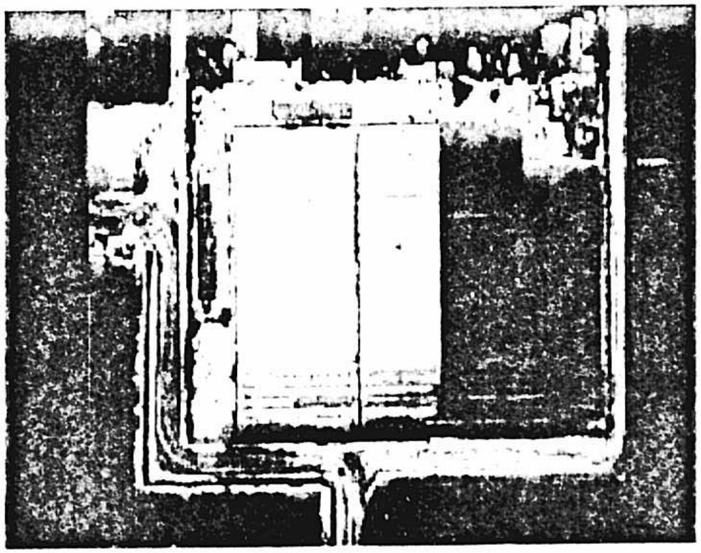
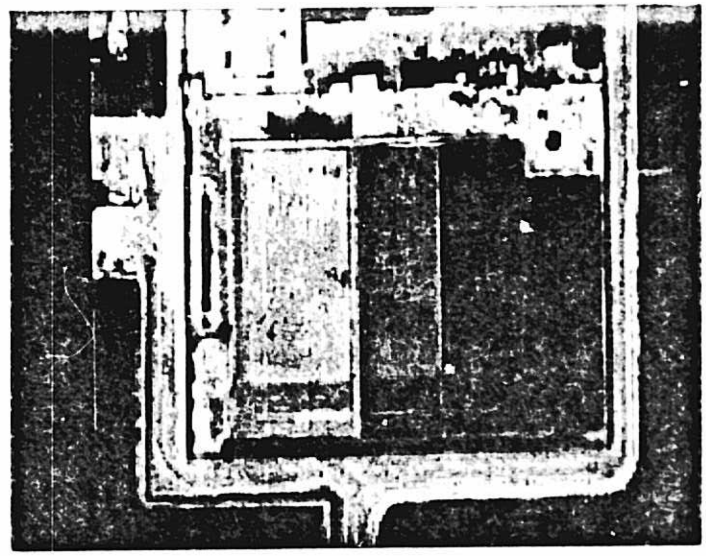
List of Figures

VISIBLE AND INFRARED IMAGERY OF THREE FIELDS IN DIFFERENT STAGES OF DRYING



VISIBLE (.65 -.69 micrometers)



IR (8 - 14 micrometers)

Fig. 1.

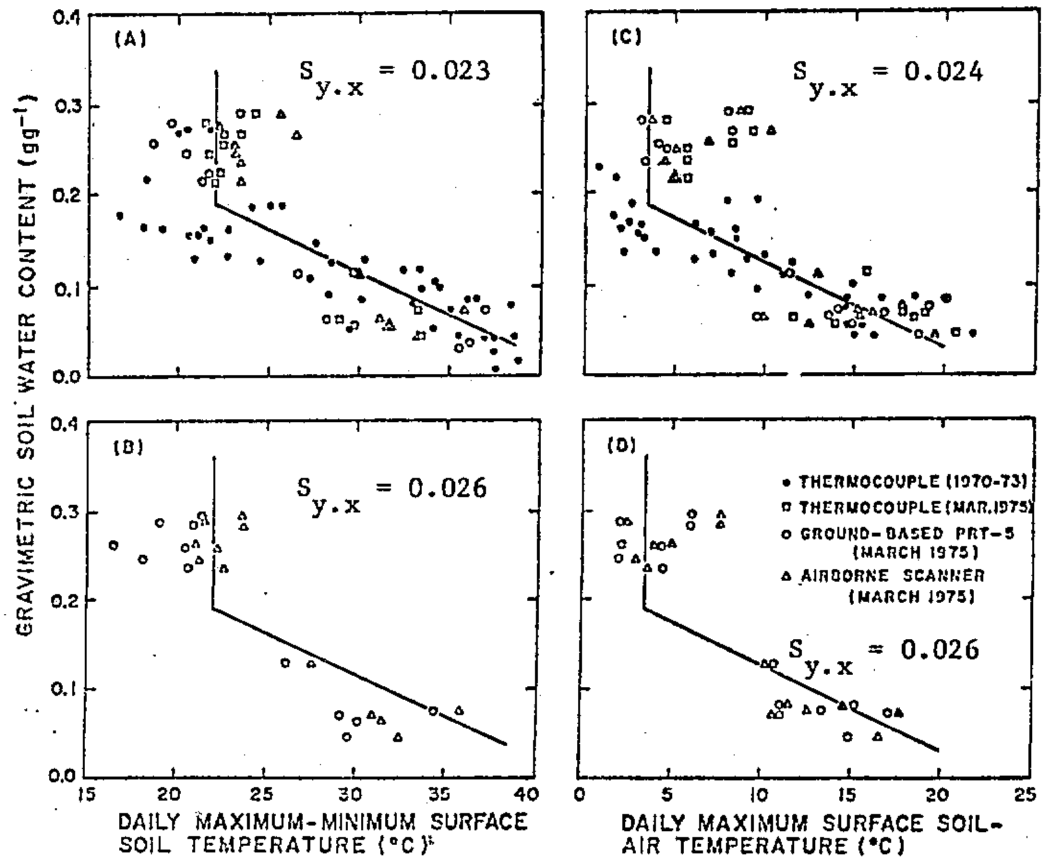


Fig. 2. Daily average gravimetric soil water content in the surface 0- to 2-cm layer of bare Avondale loam vs daily maximum minus minimum surface soil temperature for (A) smooth soil and (B) rough soil; and vs daily maximum soil minus air temperature for (C) smooth soil and (D) rough soil.

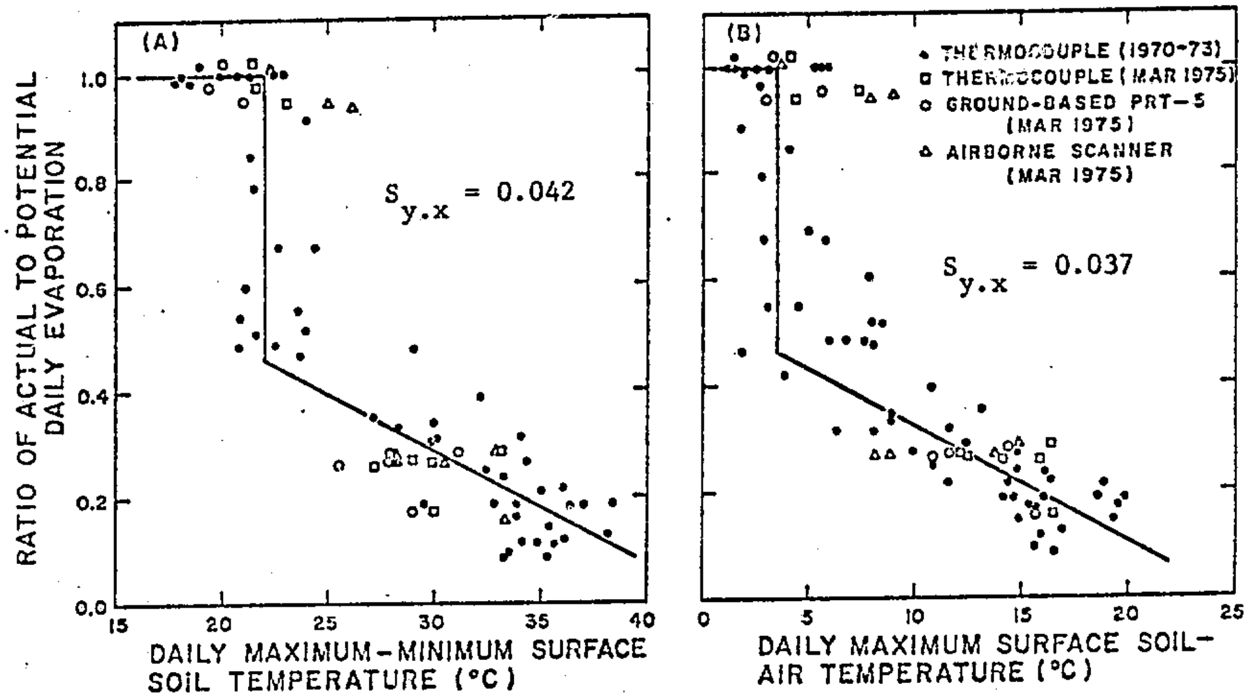


Fig. 3. Ratio of actual to potential daily soil water evaporation from a smooth bare field of Avondale loam vs (A) the daily maximum minus minimum surface soil temperature and (B) the daily maximum surface soil minus air temperature.

NORMALIZATION OF SURFACE TEMPERATURE DATA TO COMPENSATE FOR ENVIRONMENTAL VARIABILITY IN THE THERMAL INERTIA APPROACH TO REMOTE SENSING OF SOIL MOISTURE[1/]

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ABSTRACT

A procedure is developed for normalizing surface temperature data that are used in the thermal inertia approach to remote sensing of soil moisture. The procedure removes data scatter due to environmental variability in time and space. Tests of its basic premise on a bare soil and a cropped field indicate it to be conceptually sound. It is possible the technique could also be useful in other thermal inertia applications, such as lithographic mapping.

INTRODUCTION

A major goal of several scientific groups in the United States is to develop a practical procedure for estimating water contents near the surfaces of bare soils and throughout the root zones of crops from data that can be gathered remotely. Such a feat, if accomplished, would open the door to a host of economically important activities, such as predicting world harvests, crop pest outbreaks, plant disease epidemics, fertilizer requirements, irrigation needs, etc. (Idso, et al., 1975a). Two basic approaches to achieving this goal that have shown substantial indications of success are to relate soil water contents to (1) the magnitudes of the differences between daily maximum and minimum soil or crop canopy temperatures, and (2) the differences between maximum soil or crop canopy temperature and concurrent air temperature (Idso, et al., 1975b; Idso and Ehrler, 1976).

The first of these procedures is what has been known historically as the "thermal inertia" approach. It has previously been used in determining the nature of lunar surface materials prior to spacecraft landings (Wesselink, 1948; Jaeger, 1953; Sinton, 1962) and in the lithographic mapping of portions of the earth's surface (Watson, 1973, 1975; Watson, et al., 1971; Pohn, et al., 1974; Kahle, et al., 1975), based on the fact that the thermal inertia of a given substrate is inversely proportional to the amplitude of its diurnal surface temperature oscillation. A problem equally bothersome to both of these applications is environmental variability - the non-uniformity from day-to-day or from season-to-season or from place-to-place of the external forcing functions of the daily surface temperature wave. In this paper we present a solution to this problem that may considerably expand the potentials for both remote sensing of soil moisture and lithographic mapping.

THEORY

The amplitude of the diurnal surface temperature wave of any substrate material, be it soil, rock, or plant canopy, is a function of both internal and external factors. The internal factors are thermal conductivity (λ), density (ρ), and specific heat (C), where

$$P = (\lambda \rho C)^{1/2} \tag{1}$$

defines what is known as "thermal inertia." The external factors include such items as solar radiation, air temperature, atmospheric precipitable water content, cloudiness, wind, aerosol concentration, etc. These factors generally are not treated individually in the mathematical formalism of thermal inertia analyses, however; but their myriad combinations are instead expressed in the single resultant forcing function G, the surface heat flux.

As environmental conditions vary over the earth and in time, G may vary considerably, which in turn causes the amplitude of the surface temperature wave (0.5 ΔT_s) to vary. This variation is not due to variations in P and therefore creates problems for both lithographic mapping (based on P discrimination from ΔT_s measurements) and soil water content, Θ_v, estimation (based on Θ_v vs. ΔT_s relations as surrogate Θ_v vs. P relations).

As a first step in compensating for environmental variability, we normalize ΔT_s measurements to what they would have been for some arbitrary standard value of surface heat flux (G_{std}). That is, we transform actual ΔT_s data into normalized ΔT_s data ($\Delta T_{s,Nor}$) via the relationship

$$\frac{\Delta T_s}{T_{s,Nor.}} = \frac{G}{G_{std.}} \tag{2}$$

Thus, in any situation where ΔT_s is measured and G is known, we can transform ΔT_s into $\Delta T_{s,Nor.}$, allowing us to make use of a standard $\Delta T_{s,Nor.}$ vs. P relation that is reasonably independent of environmental conditions.

A problem with this approach is that G is usually not known. Thus, a surrogate for it must also be found. Air temperature (T_A) would appear to be the ideal candidate for two reasons. First, it is probably the most commonly measured meteorological parameter on earth. Second, air temperature responds in very similar fashion to the effects of environmental factors that affect surface temperature. Indeed, it does so because its diurnal variation is driven by convective coupling with the surface. Thus, we postulate that

$$\frac{\Delta T_s}{\Delta T_{s,Nor}} = \frac{G}{G_{std}} = \frac{\Delta T_A}{\Delta T_{A,std}} \tag{3}$$

and propose that all ΔT_s data be normalized with respect to an arbitrary standard diurnal air temperature variation.

TEST OF THE HEAT FLUX-AIR TEMPERATURE RELATIONSHIP

During three of our extensive experiments on Θ_v vs. ΔT_s relationships in a smooth bare field of Avondale loam (Idso, et al., 1975b), we also obtained measurements of soil heat flux at a depth of 1 cm. These measurements were made with National Instruments Laboratory[2/] Model HF-1 heat flow discs calibrated by the procedure of Idso (1972). Since our analysis of the T_s data indicated that the variations in ΔT_s as Θ_v changed were due primarily to changes in $T_{s,Max}$, and since G_{Min} also appeared to be quite invariant, we plotted daily G_{Max} vs. ΔT_A as shown in Fig. 1, where the T_A data were obtained from the nearby National Weather Service Station. The results clearly indicate that there is indeed a linear relation between G_{Max} and ΔT_A of such a nature as to justify equation (3).

TEST OF THE NORMALIZATION PROCEDURE APPLIED TO BARE SOIL

Figure 2 contains the original ΔT_s vs. Θ_v data of Idso, et al. (1975b), plus some more recent data obtained by Reginato, et al. (1976) on the same Avondale loam soil at Phoenix. For each of the days represented by data points in Fig. 2, we obtained the maximum and minimum air temperatures recorded by the National Weather Service

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2/ Trade names or company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

and utilized equation (3) to transform the ΔT_s values into $\Delta T_{s,Nor}$ values by arbitrarily assigning $\Delta T_{A,std}$ a value of 18 ^{o}C. With this operation the data of Fig. 2 were transformed into the data of Fig. 3, where the scatter among the data points is seen to be somewhat reduced.

The choice of 18 ^{o}C for $\Delta T_{A,std}$ is completely arbitrary. Any number could have been chosen. However, to make data from different locations and seasons compatible, once a number has been chosen, it must be used exclusively.

TEST OF THE NORMALIZATION PROCEDURE APPLIED TO A CROP

Four separately irrigated 1-hectare plots of Avondale loam planted to alfalfa at Phoenix, Arizona, were studied from 16 June to 23 July 1975. Every Monday, Wednesday, and Friday, canopy surface temperatures were measured just before sunrise and about an hour and a half past solar noon. On Tuesdays and Thursdays, only the afternoon measurements were made. The canopy temperatures were measured with a 20-degree field-of-view Barnes PRT-5 infrared thermometer[2/], hand-held at about a 45-degree angle with the ground approximately 1 meter above the crop surface. Preliminary tests using a utility platform that could be raised 9 meters high indicated that once the alfalfa was 30 cm high, canopy temperatures did not vary when they were obtained at viewing angles ranging from 0 to 50 degrees from perpendicular over the height range 1 to 9 meters.

At the same times that canopy temperatures were measured, air temperatures were measured one meter above the crop canopy by means of an aspirated psychrometer. Every Monday, Wednesday, and Friday, we also sampled gravimetric soil water content in each of the four fields at 30-cm increments to about 2 meter's depth.

The first analyses we made with these data were to test the two basic procedures for estimating root-zone soil water contents. Thus, in Fig. 4 and 5 we plotted the 1400-hour canopy-air temperature differential vs. the volumetric water content of the 0 to 2-meter root zone, and the 1400-0500-hour canopy temperature differential vs. the same parameter. Volumetric water contents were obtained by multiplying the measured gravimetric values by the soil's mean bulk density.

The lines drawn on Fig. 4 depict the relation developed by Idso and Ehrler (1976) for cotton and sorghum grown on the same soil type. Our results for alfalfa show essentially the same pattern, where data for non-water-stressed plants essentially fill up the "bathtub" part of the graph. The plants we studied were always irrigated at the proper intervals, however, so that they were never really stressed.

With this thought in mind, let us consider the data of Fig. 5. At first glance they appear to be devoid of much meaning. However, it is noticed that they fall into two major groups: "pre-monsoon" and "during monsoon." Since our data were all gathered at one location and we could not traverse great latitude changes to experience different air temperature regimes due to solar altitude variations, we conducted our experiment over the period of abrupt climatic change that occurs with the arrival of Arizona's summer monsoon. During

June, Arizona normally experiences very dry weather. However, in early July it becomes immersed in moist air from both the Gulf of Mexico, at high levels, and the Gulf of California, at low levels. The low-level source has recently been documented to be the primary source (Hales, 1974), which causes the atmospheric precipitable water content to about triple in very abrupt fashion. The effect of this change in atmospheric humidity is to greatly reduce the amplitude of the diurnal air temperature wave, as shown in Fig. 6. Thus, data obtained before and after the monsoon's arrival present an ideal opportunity for testing our normalization procedure.

Operating upon the data of Fig. 5, then, in analogous fashion to our normalization of the bare soil data that transformed Fig. 2 into Fig. 3, we now find Fig. 5 transformed into Fig. 7. The reduction of data scatter in this instance is even more than for the bare soil case. Indeed, the scatter is cut to only about a third of what it was prior to normalization.

The maximum surface-air temperature differential approach cannot claim this same advantage, however, since correct <u>absolute</u> values are required for both the surface and air temperatures in order to get a valid differential value. To illustrate, if National Weather Service air temperatures are used instead of air temperatures measured just above the crop, the plot of Fig. 4 transforms into that of Fig. 8. Considerably more scatter is inherent in the data of Fig. 8; and the pre-determined soil water content relationship is significantly violated.

CONCLUDING REMARKS

In normalizing both the bare soil surface temperature data and the alfalfa canopy temperature data, we utilized maximum and minimum air temperatures measured at the Phoenix National Weather Service Station. Although one cannot expect absolute magnitudes of maximum and minimum air temperatures to be the same over a transpiring crop or moist soil surface and an asphalt-surrounded airport site several kilometers away, the maximum-minimum air temperature differentials apparently may be quite similar. This fact greatly increases the potential for using the standard thermal inertia approach in remote sensing of soil moisture, since no *in situ* measurements need to be made. It is also possible the technique may be of some usefulness in certain lithographic mapping applications, in areas where the required air temperatures are available.

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LIST OF FIGURES

Fig. 8. Same as Fig. 4, except that the air temperature data used were obtained from the National Weather Service Station, rather than 1 meter above the crop canopy as in Fig. 4.

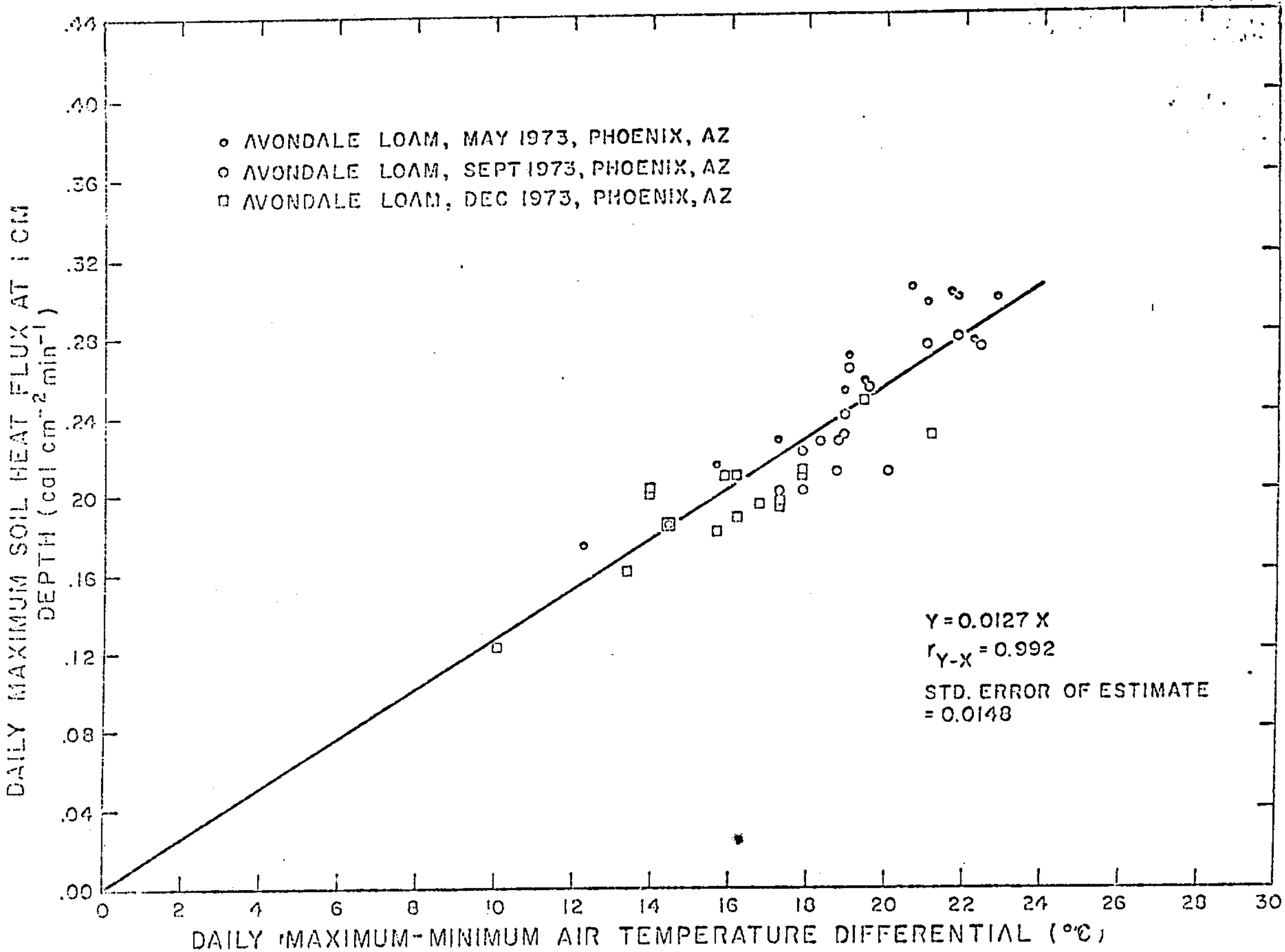

Fig. 1. The daily maximum soil heat flux at 1 cm depth in a smooth bare field of Avondale loam at Phoenix, Arizona, vs. the daily maximum-minimum air temperature differential measured at the Phoenix National Weather Service Station.

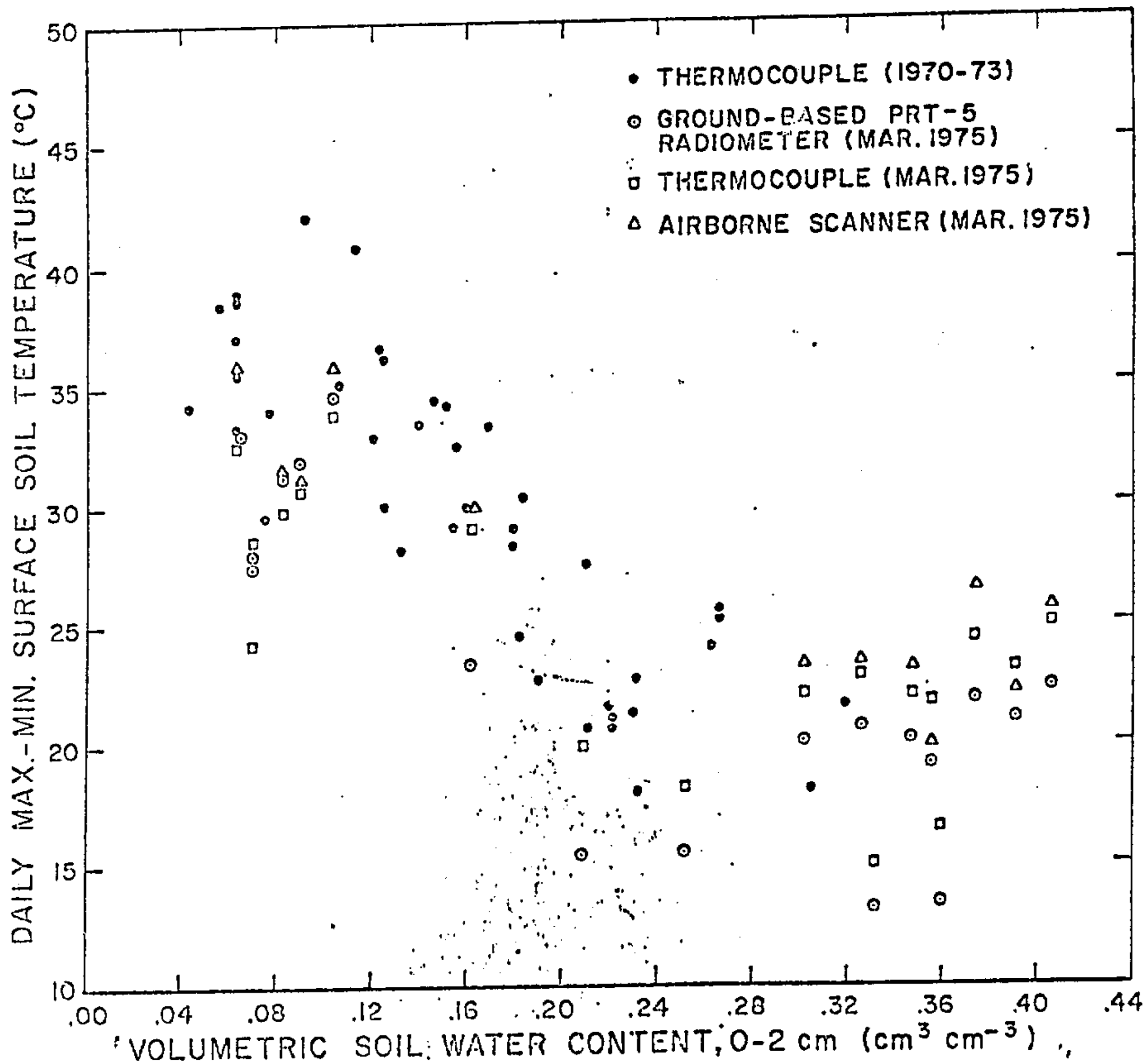

Fig. 2. The maximum-minimum surface temperature differential of a smooth bare field of Avondale loam vs. the average daily volumetric soil water content of the uppermost 2 cm.

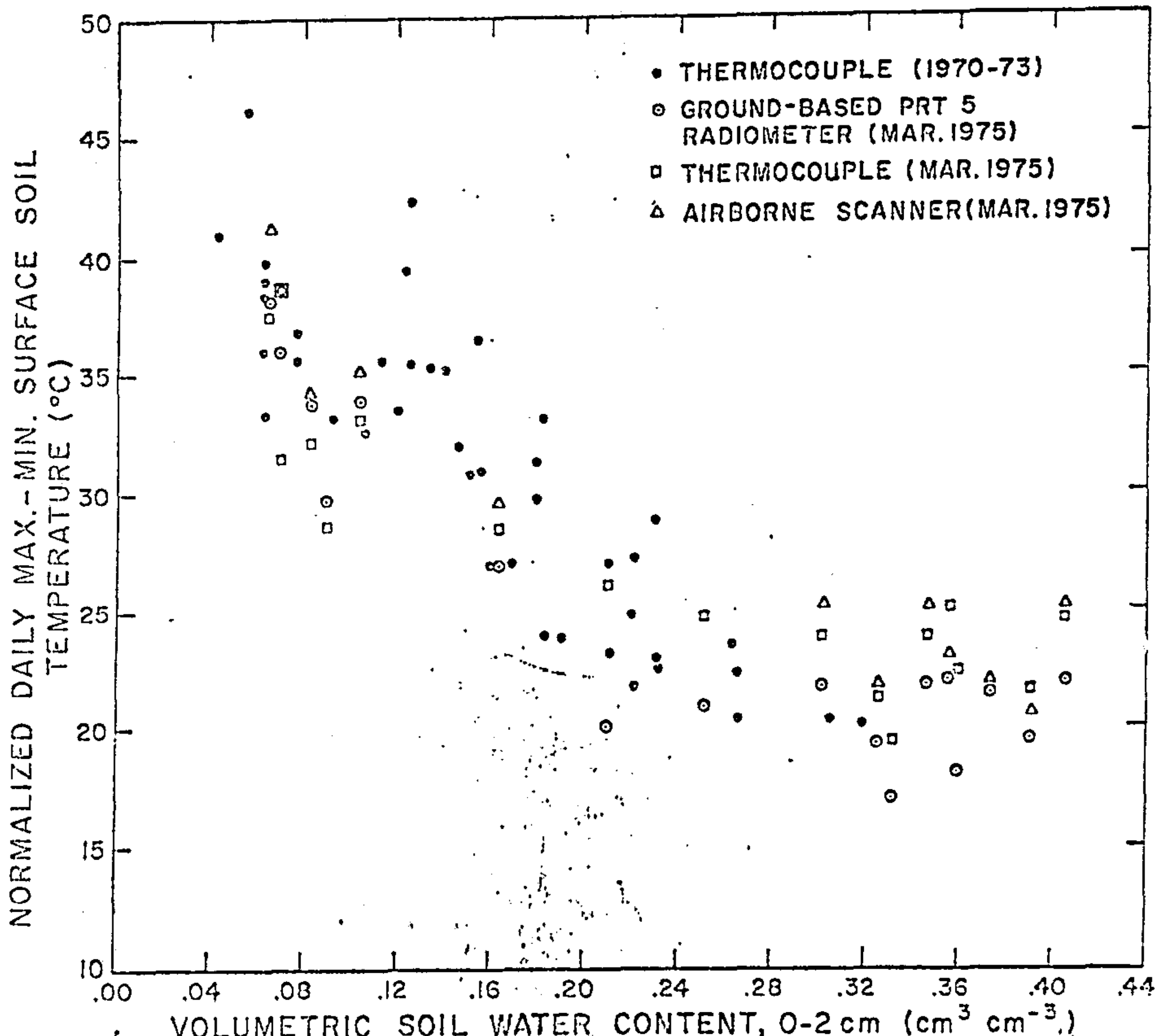

Fig. 3. Same as Fig. 2, except that the ordinate values of the data points have been normalized according to the procedure described in the text.

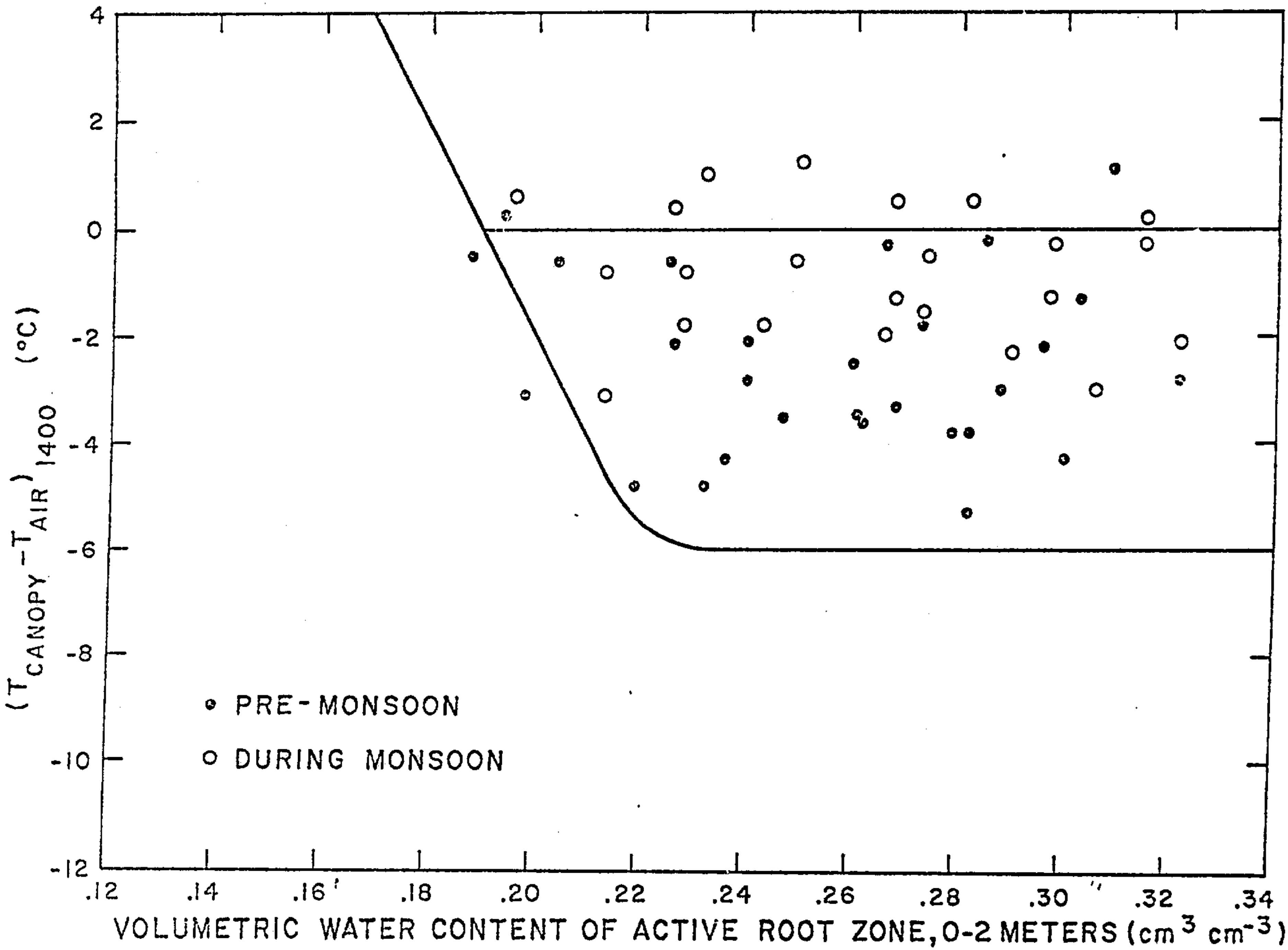

Fig. 4. Maximum canopy-air temperature differential of four different fields of mature alfalfa as obtained from measurements made at 1400 hours local time vs. the volumetric water content of the crops' active root zone.

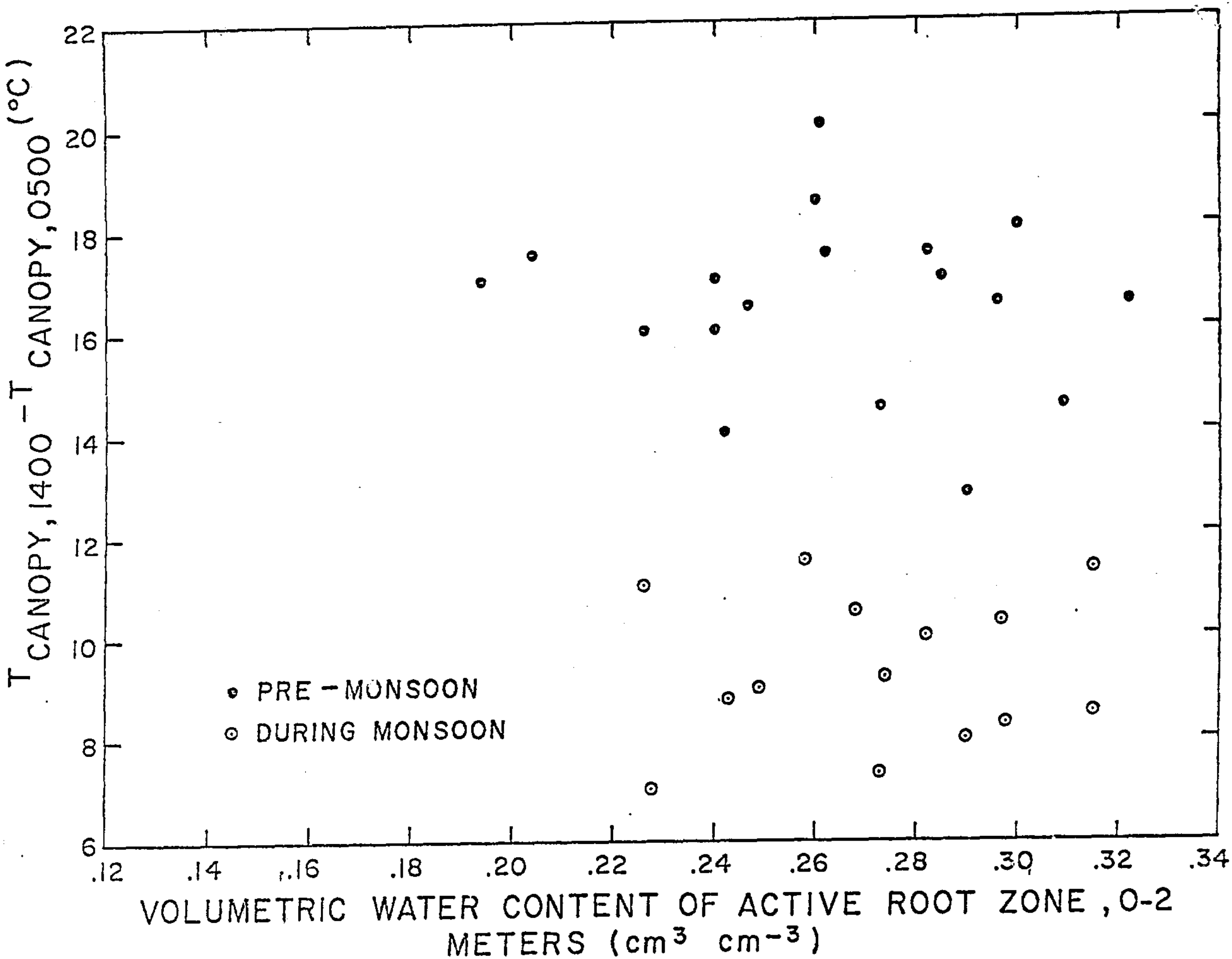

Fig. 5. The maximum-minimum canopy temperature differential of four different fields of mature alfalfa as obtained from measurements made at 1400 and 0500 hours local time vs. the volumetric water content of the crops' active root zone.

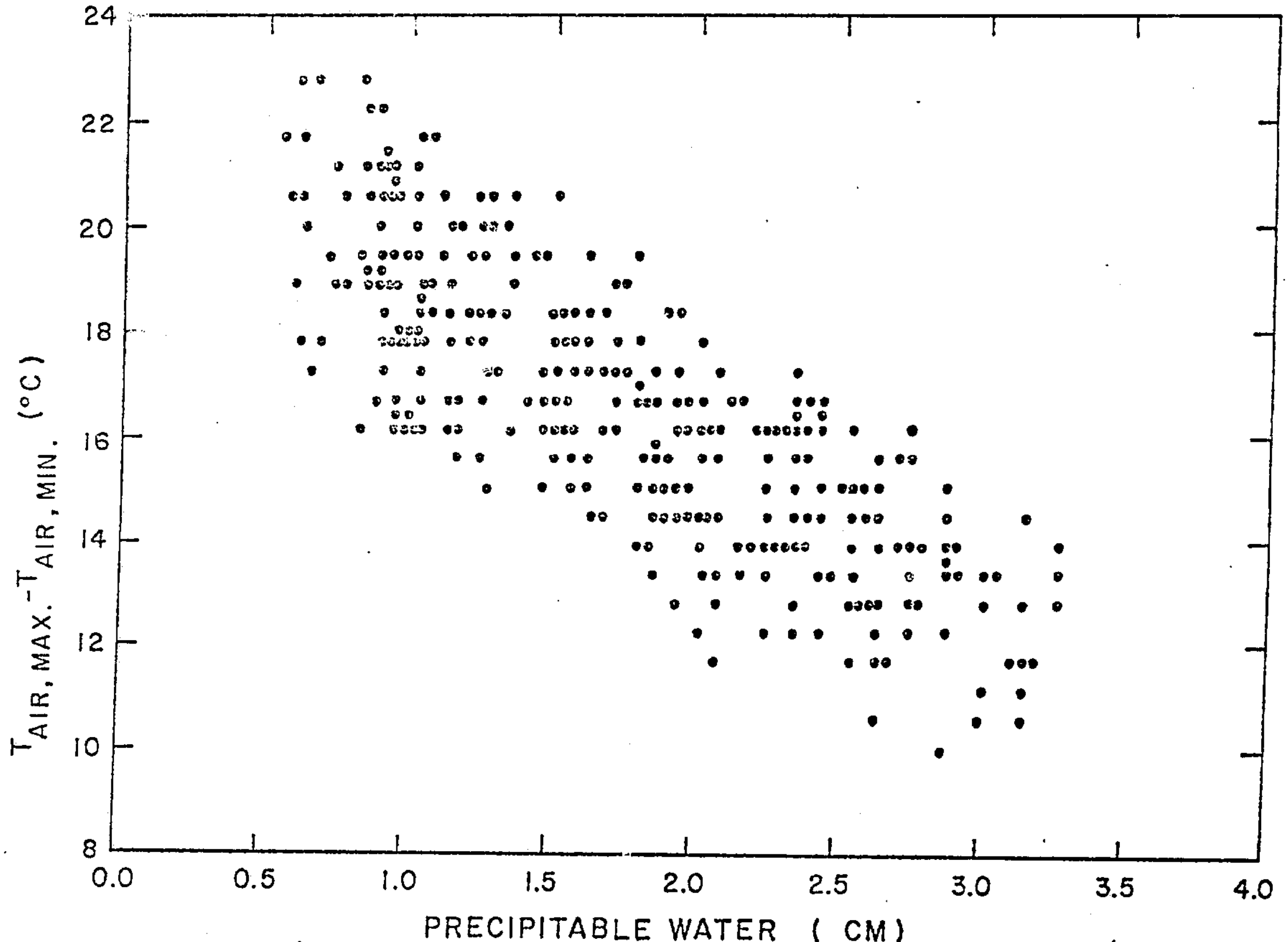

Fig. 6. The maximum-minimum air temperature differential obtained from official National Weather Service records for Phoenix, Arizona, vs. the mean daily atmospheric precipitable water content obtained from National Weather Service dew-point data and a procedure outlined by Idso (1969).

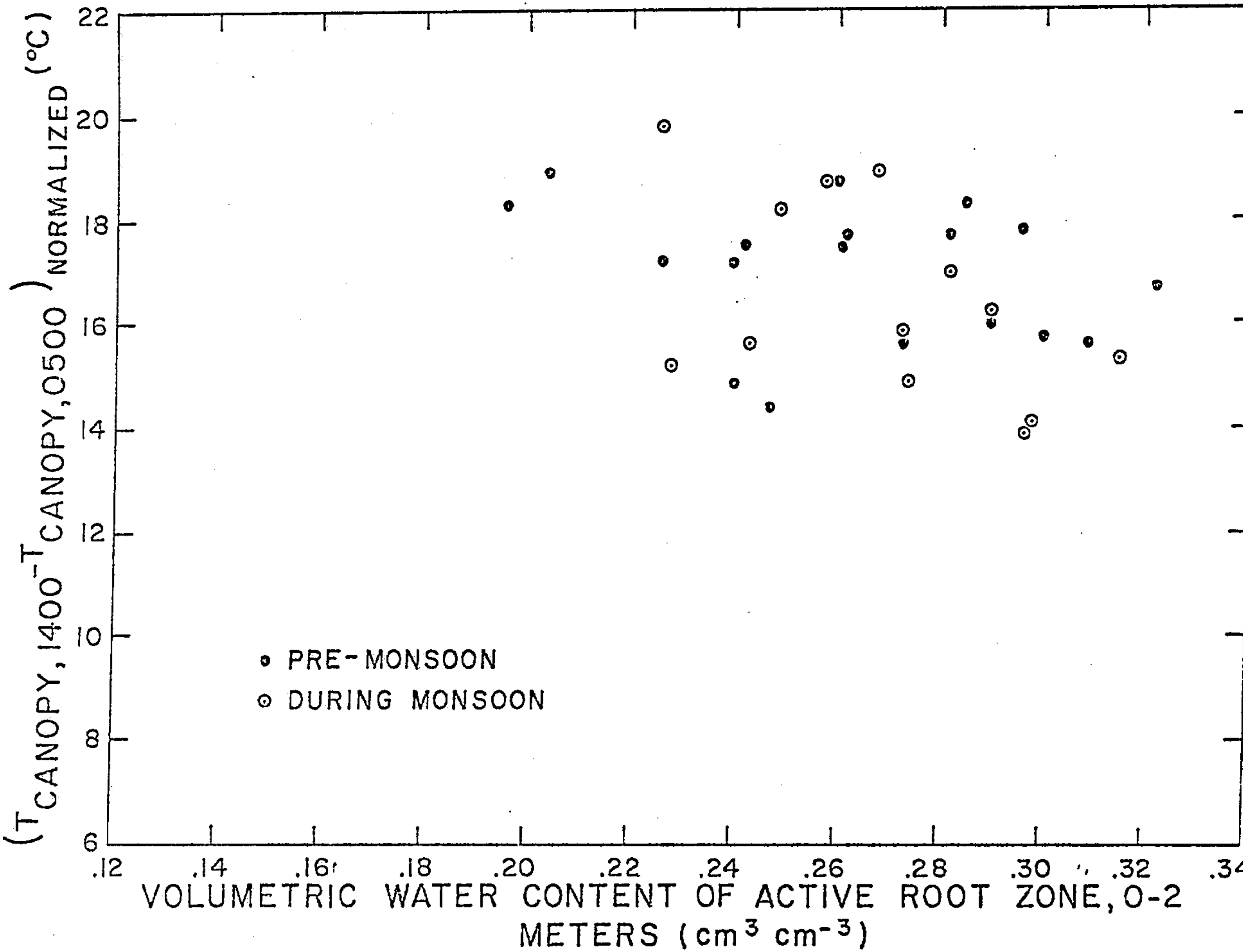

Fig. 7. Same as Fig. 5, except that the ordinate values of the data points have been normalized according to the procedure described in the text.

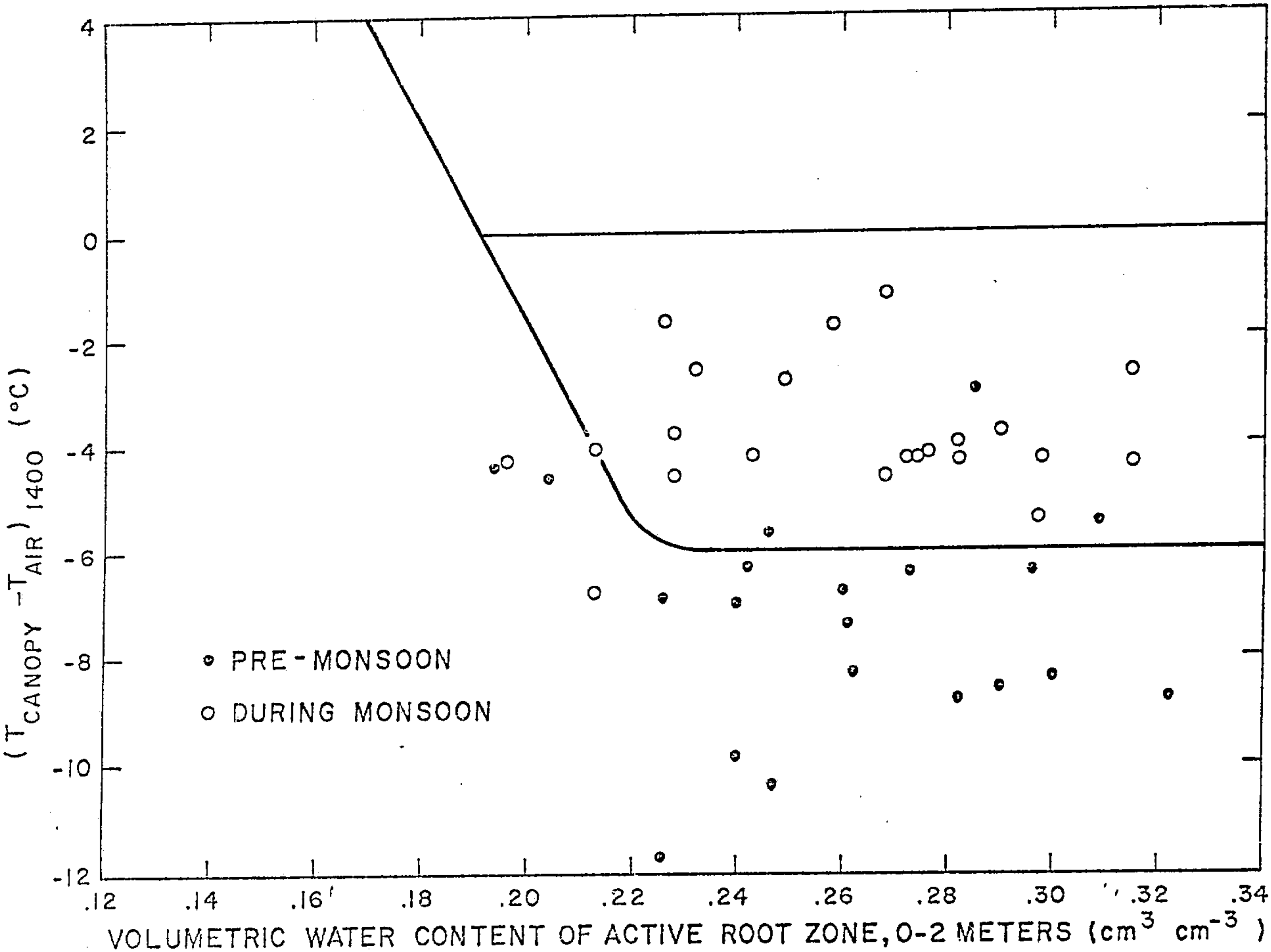

Fig. 8. Same as Fig. 4, except that the air temperature data used were obtained from the National Weather Service Station, rather than 1 meter above the crop canopy as in Fig. 4.