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T. Schmugge, B. Blanchard, A. Anderson, J. Wang[1]

ABSTRACT

Aircraft observations of the surface temperature were made by measurements of the thermal emission in the 8-14 μm band over agricultural fields around Phoenix, Arizona. The diurnal range of these surface temperature measurements were well correlated with the ground measurement of soil moisture in the 0-2 cm layer. The surface temperature observations for vegetated fields were found to be within 1 or 2°C of the ambient air temperature indicating no moisture stress. These results indicate that for clear atmospheric conditions remotely sensed surface temperatures can be a reliable indicator of soil moisture conditions and crop status.

(KEY TERMS: remote sensing, soil moisture, crop status, thermal inertia.)

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SOIL MOISTURE SENSING WITH AIRCRAFT OBSERVATIONS OF THE DIURNAL RANGE OF SURFACE TEMPERATURE

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In a recent paper Reginato et al. (1976) discussed the possibility of using remotely sensed surface temperature data for estimating soil moisture. Their observations were for their laboratory field at the Water Conservation Laboratory in Phoenix. In this paper we will present data acquired by aircraft radiometers operating in the 8-14 μm band for agricultural fields around Phoenix which support their conclusions and extend them to a wider range of conditions.

Temperature observations for fields with a vegetative canopy are also presented. These temperatures were generally within 1 or 2 K of the air temperatures reported for the area which is to be expected for non moisture stressed plants (Idso and Ehrler, 1976).

BACKGROUND

The amplitude of the diurnal range of surface temperature for the soil is a function of both internal and external factors. The internal factors are thermal conductivity (K), density (ρ) and heat capacity (C), the combination $P = (K\rho C)^{1/2}$ defines what is known as "thermal inertia." The external factors are primarily meteorological; solar radiation, air temperature, relative humidity, cloudiness, wind, etc. The combined effect of these external factors is that of the driving function for the diurnal variation of surface temperature. Thermal inertia then is an indication of the soil's resistance to this driving force. Since both the heat capacity and thermal conductivity of a soil increase with an increase of soil moisture, the resulting diurnal range of surface temperature will decrease. Typical values of P in units of cal/cm^2 sec$^{1/2}$°C will range from 0.02 for dry soils to about 0.1 for wet soils.

The basic phenomena are illustrated in figure 1, which presents surface temperatures as measured with a thermocouple for a field versus time, before and after irrigation. These data were obtained by Dr. Ray Jackson and his colleagues at the U.S. Water Conservation Laboratory in Phoenix and have recently been published (Idso et al., 1975).

The solid line in figure 1 is the plot of surface temperature before irrigation, and the solid circles reflect the data on the day following irrigation. There is a dramatic difference in the maximum temperature achieved on these two days. On succeeding days the maximum temperature increases as the field dries out.

The summary of results from many such experiments is shown in figure 2 where the amplitude of the diurnal range is plotted as a function of the soil moisture as measured at the surface and in 0- to 1-cm, 0- to 2-cm, and 0- to 4-cm layers. A good correlation was observed with the soil moisture in the 0- to 2-cm and 0- to 4-cm layers of the soil, and this response is related to the thermal inertia of the soil. Initially, when the surface is moist, the temperatures are more or less controlled by evaporation. Once the surface layer dries below a certain level, the temperature will be determined by the thermal inertia of the soil. These results indicate that for this particular soil, the diurnal range of surface temperature (ΔT) is a good measure of its moisture content.

When these measurements are repeated for different soils ranging in texture from sandy loam to clay there are differences which depend on the soil type, as shown in figure 3. However, when Idso et al. (1975) compared ΔT with the soil water pressure potential (figure 4) the results were largely independent of soil type. This indicates that it may be possible to remotely sense the state of the water independent of soil type.

In two recent papers (Idso and Ehrler, 1976, and Jackson et al., 1977) it was reported that observations of the canopy temperature of a crop were indicative of the moisture status of the crop. Idso and Ehrler found that a positive value for $T_C - T_A$, where T_C is the canopy temperature and T_A is the air temperature, is an indicator of moisture stress in the plant. In the second paper (Jackson, et al., 1977) this concept was extended to the estimation of water use by wheat. They found that the summation of $T_C - T_A$ over time yielded a factor termed the stress degree day which was well correlated with measured water use in six experimental plots.

EXPERIMENTAL DETAILS

The aircraft measurements were made by a Barnes PRT-5 radiometer installed on the NASA P-3A aircraft. The flights were in April, 1974 and March, 1975. The radiometer operating in 8–14 μm band had a 2° field of view and a precision of 1°C. The surface measurements of the soil moisture were made at four points in a 400 x 400 m (40 acre) field. At each point soil samples were taken for the following depths: 0-1, 1-2, 2-5, 5-9 and 9-15 cm. For furrowed fields the five samples were taken from both the top and bottom of furrows. The values of soil moisture presented here are the averages of the four points. The details of the surface measurements are described elsewhere (Blanchard, 1975). To correlate the surface measurements with the aircraft observations air photos were used to locate the aircraft as a function of time.

Surface temperature observations were made during pre-dawn and early afternoon flights on March 18 and 22, 1975. The area was cloudy for the afternoon flight on March 22, thus rendering the surface temperature measurements on this day unusable for remote sensing purposes. The observations on March 18 agree with those reported in Idso et al. (1975) for both the diurnal range of soil temperature and the soil-air temperature difference.

The 1974 flights were on the afternoon of April 5 and the early morning of April 6. A complete set of soil moisture measurements were made for afternoon flight only. For this flight the range of the PRT-5 was set for a maximum temperature 40°C, surface temperatures above this value were extrapolated using the gray levels of an imager (Texas Instrument RS-14). The details of this process are given in the report of that mission (Schmugge et al., 1976).

As noted in figure 3 ΔT for given soil moisture depends on soil type, but that ΔT is related to soil moisture expressed in terms of pressure potential independent of soil type. Since we do not have data on the moisture characteristics of the soils studied we have chosen to relate the measured soil moisture to field capacity for the soil estimated from soil texture information for each field. This was done using regression relationships developed from data of over 100 soils for which the moisture characteristics and texture information were available (Schmugge, et al., 1976). The expression used for estimating the field capacity (FC) was:

$$FC = 25.1 - 0.21 \times \text{sand} + 0.22 \times \text{clay}$$

where sand and clay are their respective fraction expressed in percent.

RESULTS

There were three passes flown over each line for both the morning and afternoon flights on 3/18/75. In the morning the flights were from 6:00 to 7:31 MST, sunrise being at 6:08. The minimum temperatures were observed during the second pass between 6:26 and 6:52, i.e., before solar heating had an effect on the surface. The afternoon flights were between 12:10 and 1:20 MST with the maximum temperatures observed during the third pass 1:00 and 1:20. It is possible that higher surface temperatures may have been attained later in the afternoon (i.e., around 2:00) but it is expected that the difference would be approximately 1 or 2°C.

The data for the difference between the third pass in afternoon and the second pass in the morning are presented in figures 5a and b. The soil moisture values used here are the averages of the data taken during the predawn and afternoon flights. Jackson et al. (1976) have shown that the 24 hour average soil moisture is well represented by the averages of measurements made at 0500 and 1400 hours. These were approximately the times of the 1975 measurements, and thus our moisture values should accurately reflect the average moisture content for the day. On the basis of detailed sampling done for one field the uncertainty of the 0-2 cm moisture sample using only four points per field is estimated to be 15% (Schmugge et al., 1976). The estimates of field capacity from soil texture also introduces uncertainty at about the same level resulting in total uncertainty of about 25%.

In figure 5a the ΔT values are plotted versus the raw soil moisture, the correlation coefficient (r) is 0.82. The value of r increased to 0.89 when soil moisture is expressed as a percent of field capacity, in spite of the increased uncertainty introduced by our estimate of field capacity.

The April 1974 data are presented in figure 6. The correlation for these data alone is 0.70, when the 1975 data are added the correlation is improved to 0.78. The soil moisture measurements were only for the afternoon, and would be expected to be drier than the 24 hour average. Scatter in the data for low soil moistures is due partially to 1 to 2°C uncertainty of the measurements above 40°C, and also the uncertainty of the soil moisture estimates. The range of ΔT's observed in both of these data sets agree with those of Reginato (et al., 1976) i.e., about 40°C for dry fields and 20°C for the wet fields.

When our 1975 aircraft results are compared with the total measurement set of Reginato et al. (1976) the agreement is very good. In figure 7 we have plotted our data on figure 2a of their paper. To compare the soil moisture values between the two experiments a value of 0.176 was taken as field capacity of the Avondale loam soil (Jackson, private communication). Our data from figure 5 are plotted on their graph using the value 0.176 as 100% of field capacity. It is evident that the values of ΔT measured from aircraft data have the same variation with soil moisture as their combined data set acquired by several different means.

The aircraft observations of canopy temperature for several vegetated fields are presented in Table I. The 2 PM temperature at the Phoenix airport was 21.7°C. The airport is located approximately 20 km east of the southern end of the flight line. The canopy temperatures were approximately within a degree or so of air temperature. This would appear to indicate a slight amount of moisture stress, which probably isn't the case since the 0-15 cm average soil moisture is above 50% of field capacity in each case. However, the two wheat fields with the highest temperature had the shortest plants, implying that some of the bare ground may be contributing to the observed emission.

DISCUSSION

These results have demonstrated the feasibility of using aircraft observations of the diurnal range of surface temperature for soil moisture sensing over a wider range of field conditions than those presented in the paper of Reginato et al. (1976). The comparison of remotely sensed canopy temperature with air temperatures as reported by the local weather station is a means of qualitatively assessing the state of moisture stress in the plant. This approach may be applied to determine the status of pasture grasses. Thus the condition of rangeland, which is distributed throughout the agricultural areas of the world, may be used as an index of the local soil moisture conditions. Indices of this nature would enhance opportunities for estimating crop yields and for improving current flood prediction technology.

There are many limitations on the applicability of this technique, e.g. clouds, atmospheric water vapor, and variations in surface slope, but there is the potential that frequent high resolution coverage would yield much useful data. This potential will be studied from spacecraft altitudes when NASA launches the Heat Capacity Mapping Mission satellite in the spring of 1978. The purpose of the mission is to measure the diurnal range of surface temperatures over large areas with an infrared radiometer operating in the 10-12 μm band and having a spatial resolution of 500 meters. These diurnal measurements will be repeated every eight days for most areas, daytime only coverage will be repeated every three days. Thus this sensor should acquire sufficient data to adequately test the applicability of this technique over wide areas.

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Table I

Surface Temperature for Cropped Fields

Field No.	Temp. °C	Crop Cover Type and Height	0-15 cm Soil Moisture	% of FC
97	23.1	alfalfa, 50 cm	22.0	70.5
106	24.1	wheat, 20 to 30 cm	29.0	94.5
111	21.3	wheat, 60 to 70 cm	27.3	87.5
112	22.7	wheat, 20 to 30 cm	28.8	96.0
113	21.5	wheat, 30 to 40 cm	27.5	85.0
114	22.6	wheat, 30 to 40 cm	22.6	69.5
115	24.1	wheat, 15 to 25 cm	24.8	89.0

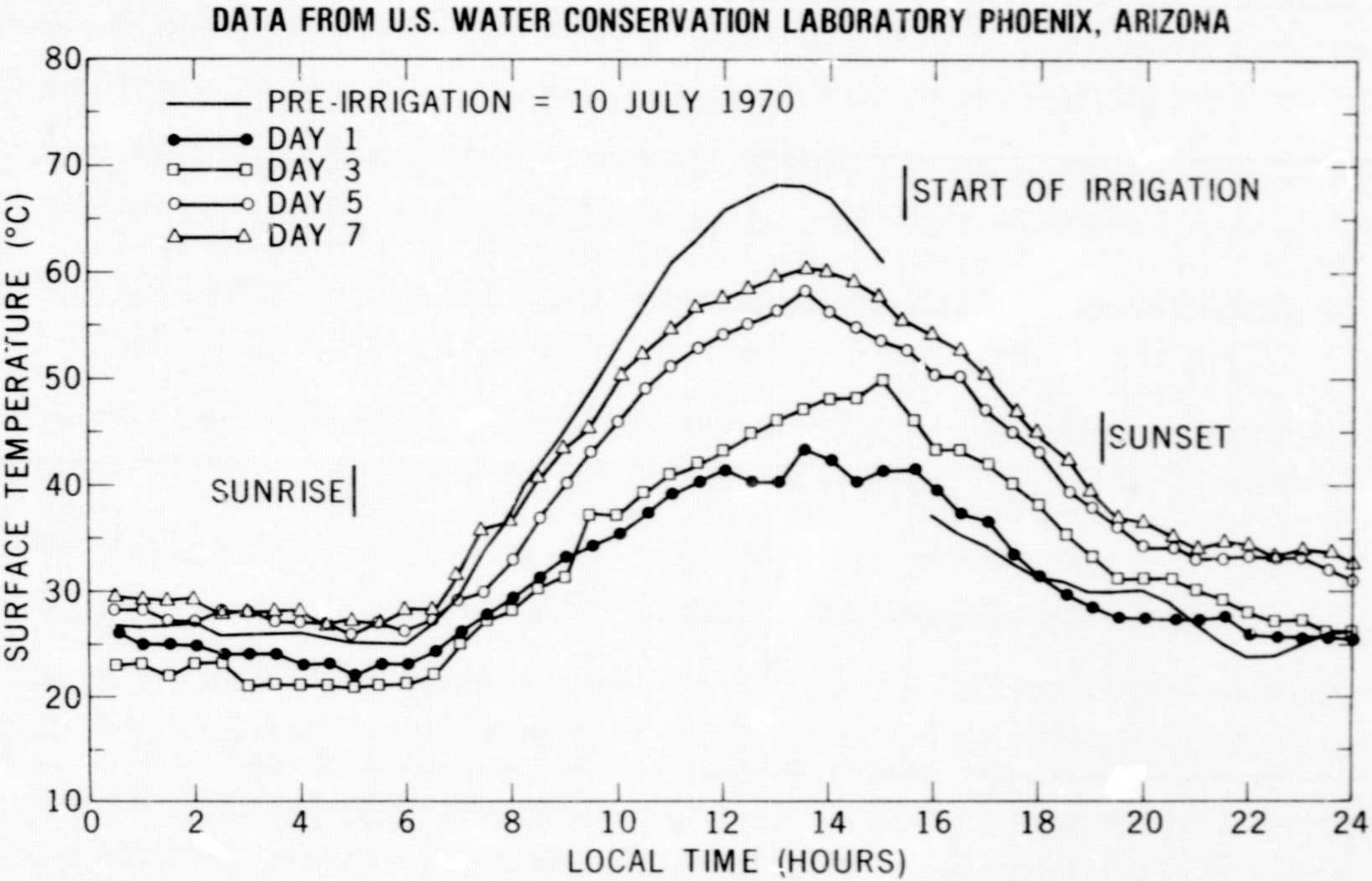

Figure 1. Diurnal surface temperature variation as measured by a thermocouple. Data from U.S. Water Conservation Laboratory in Phoenix, Arizona.

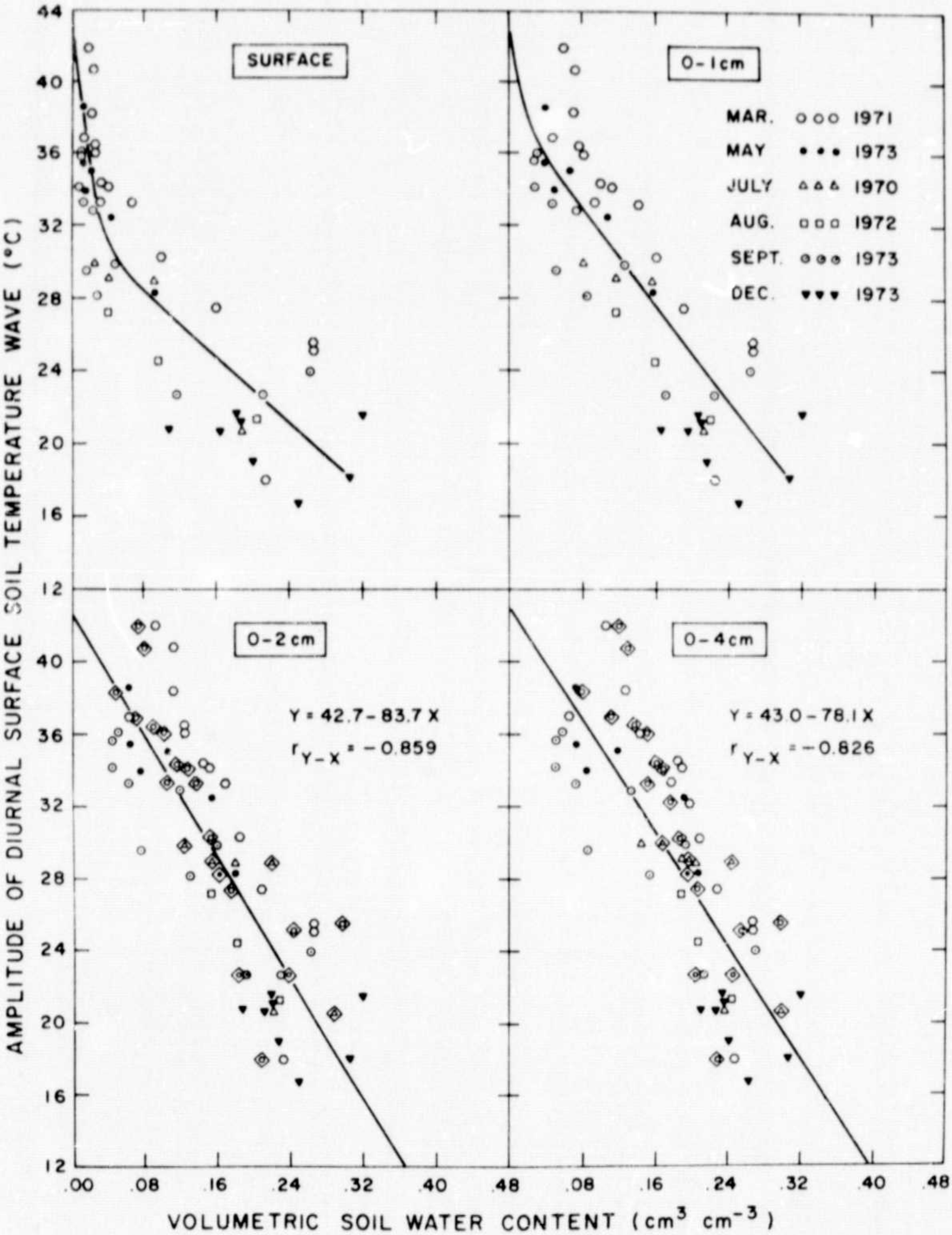

Figure 2. Summary of results for the diurnal temperature variation versus soil moisture. From Idso et al., 1975.

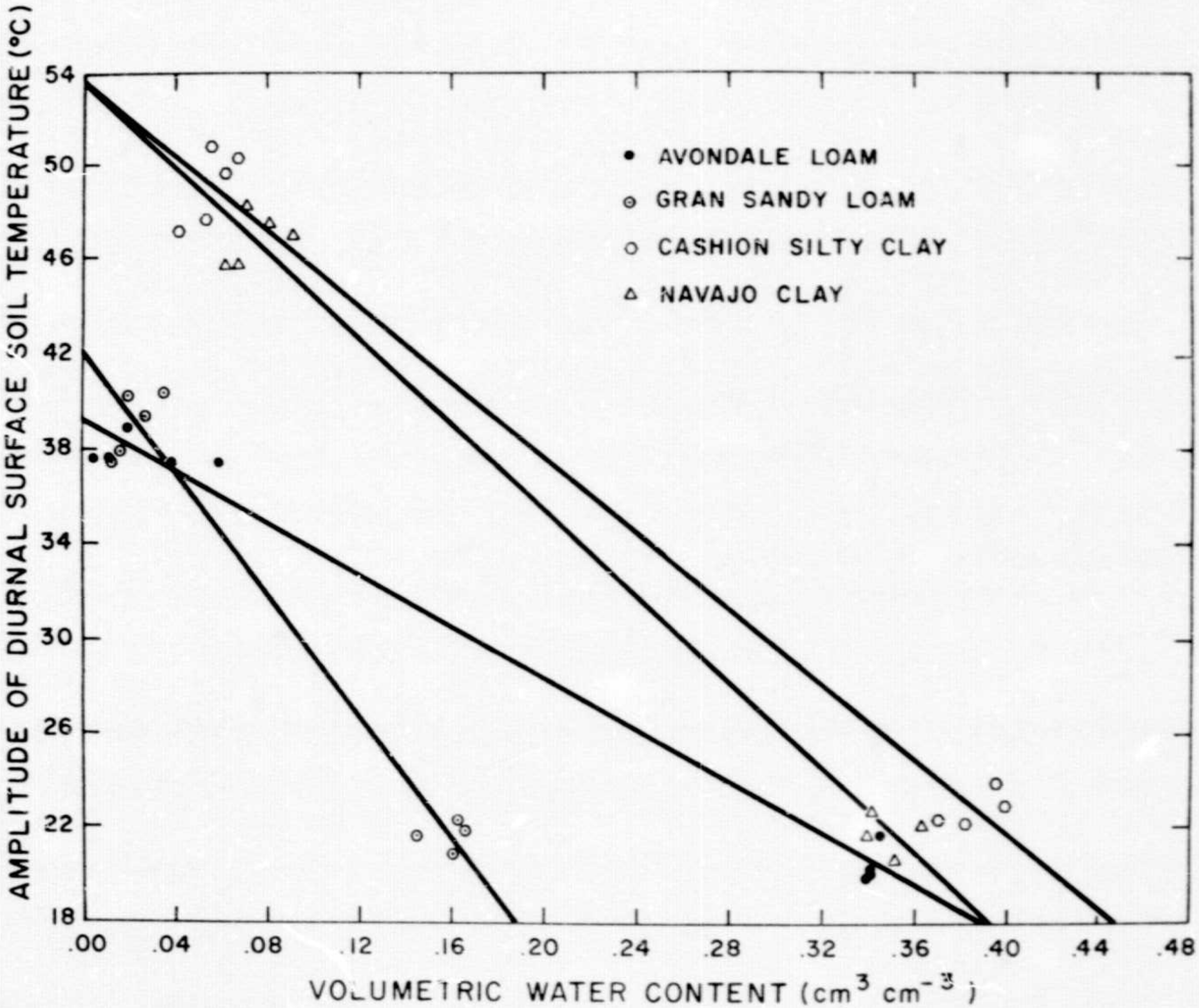

Figure 3. The amplitude of the diurnal surface soil temperature difference versus the mean daylight volumetric soil water content of the 0-2 cm depth increment for four different soils (Idso, et al., 1975).

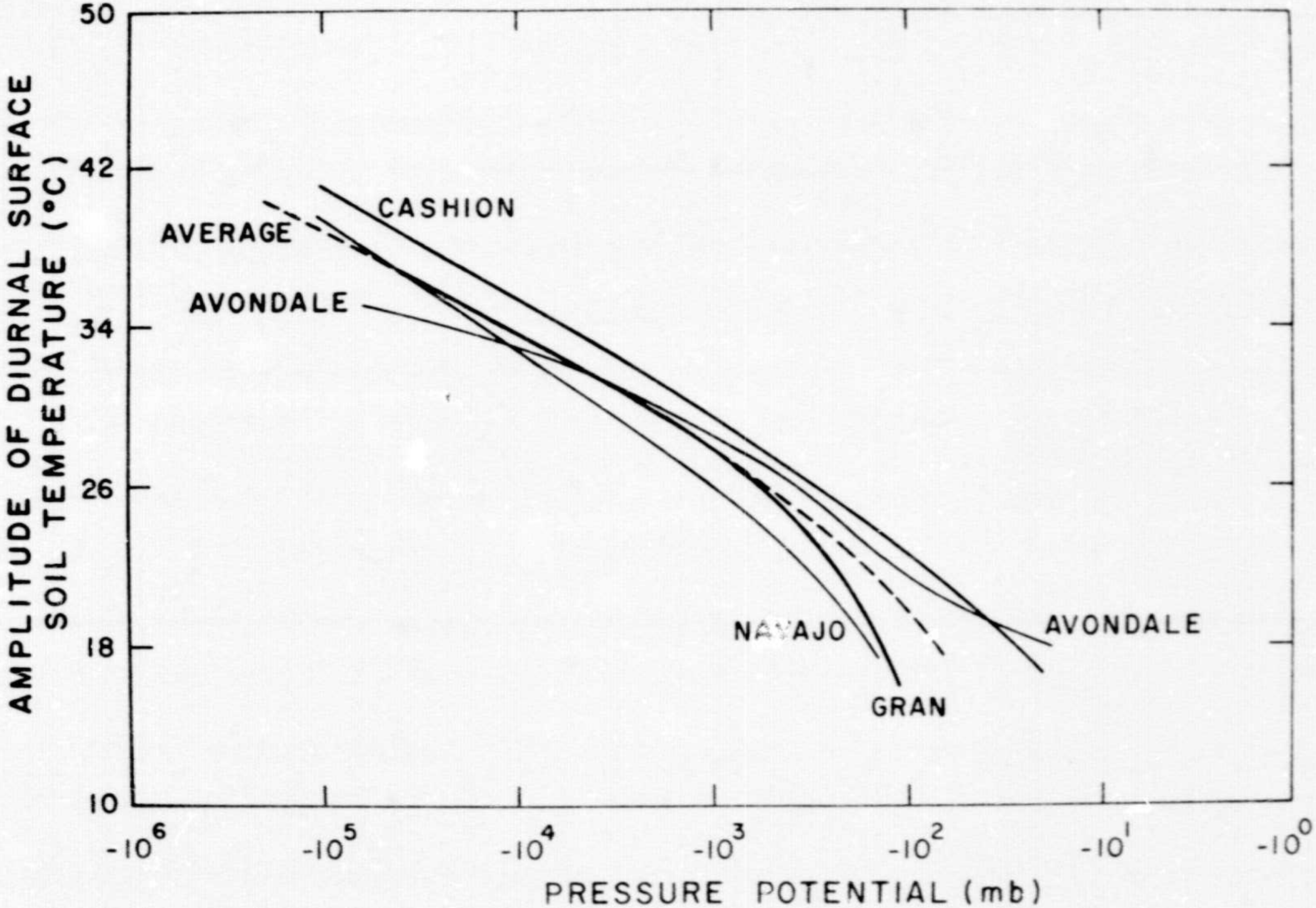

Figure 4. The amplitude of the diurnal surface soil temperature difference versus the mean daylight soil water pressure potential of the 0-2 cm depth increment for four different soils (Idso, et al., 1975).

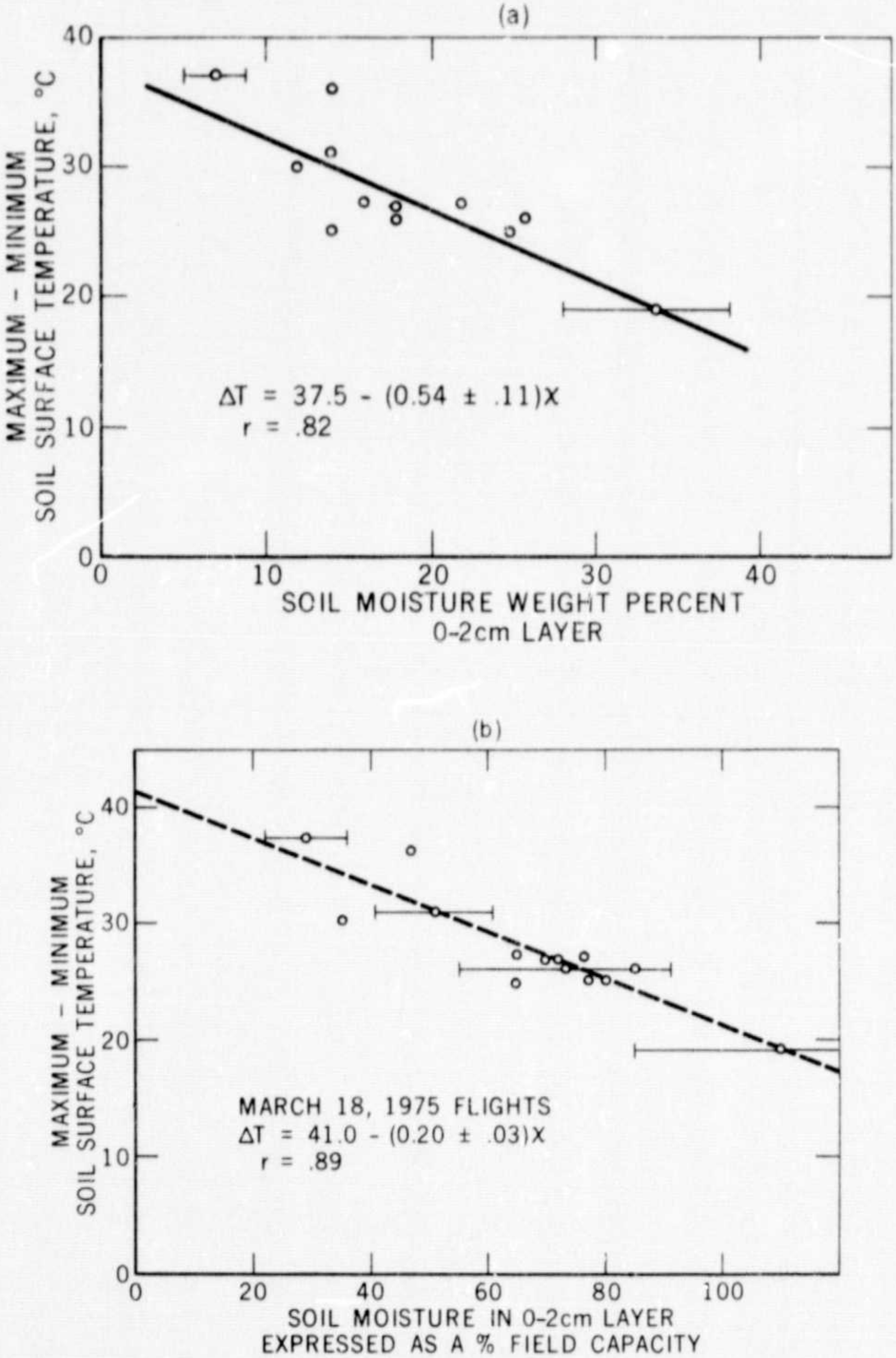

Figure 5. Aircraft observations of ΔT from the March 18, 1975 flight plotted versus: (a) soil moisture in the 0-2 cm layer expressed in weight percent and (b) soil moisture in the 0-2 cm layer expressed as a percent of field capacity.

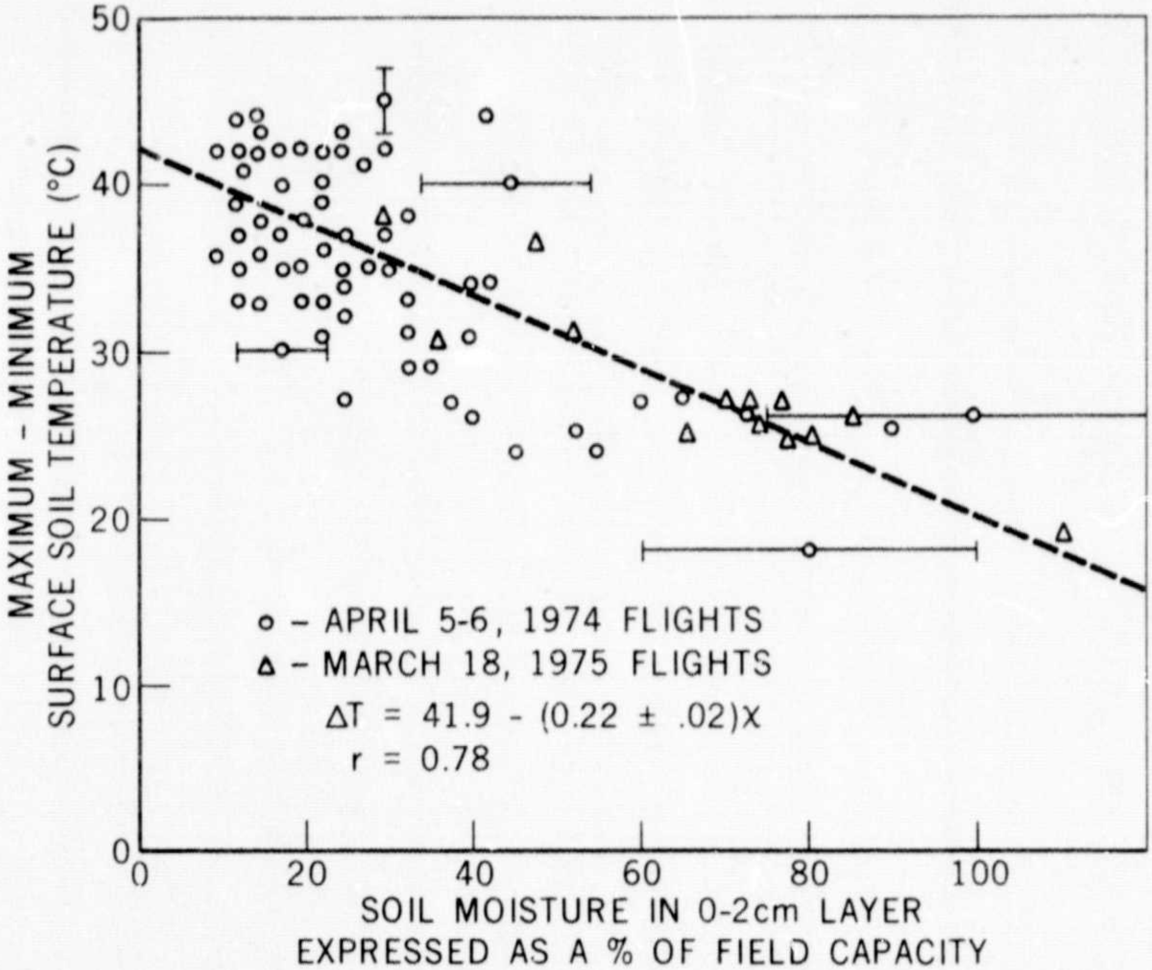

Figure 6. The combined data of the 1974 and 1975 flights over Phoenix.

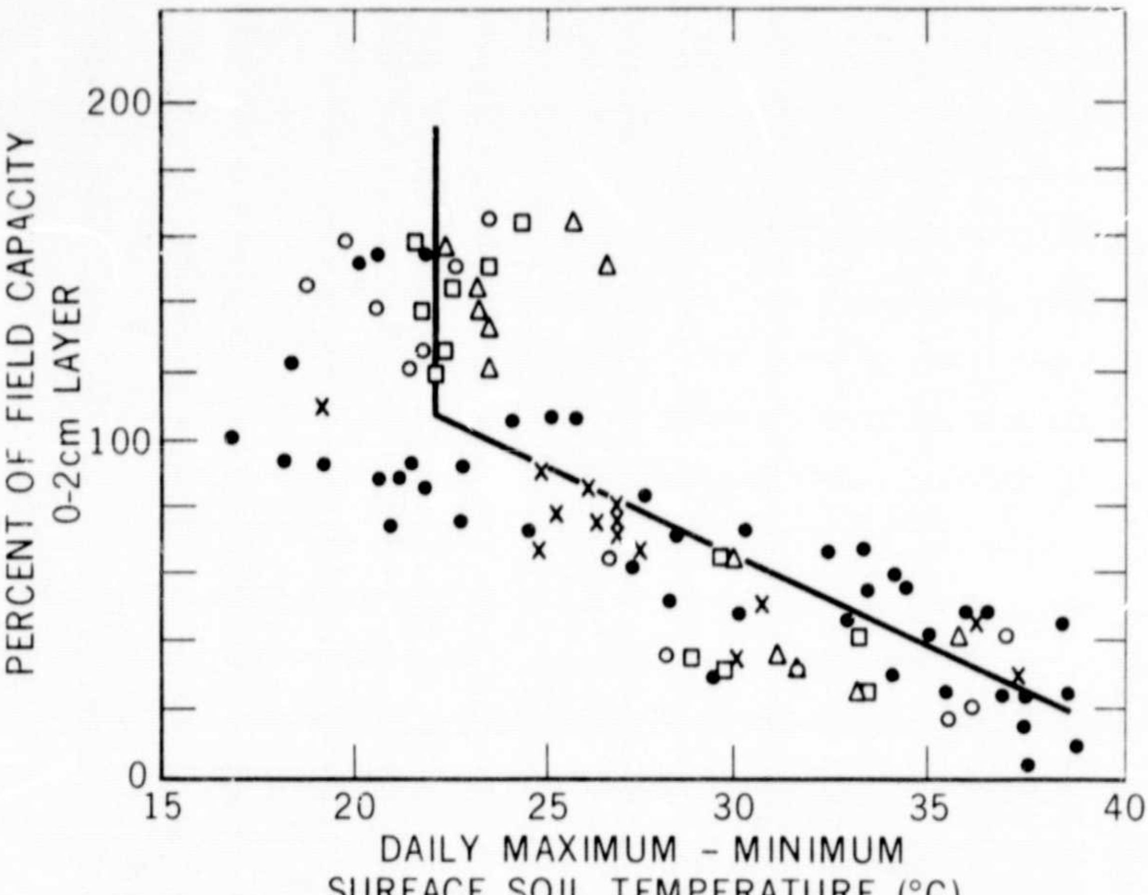

Figure 7. Plot of ΔT data from this paper combined with that from Reginato et al., (1976) versus soil moisture in the 0-2 cm layer. The symbols represent the different types of temperature measurement: •, □ - surface thermocouple, ○ - hand held PRT-5, △ - aircraft data over their test plot, and × data from this paper.