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THE CORRELATION OF SKYLAB L-BAND BRIGHTNESS TEMPERATURES WITH ANTECEDENT PRECIPITATION

by

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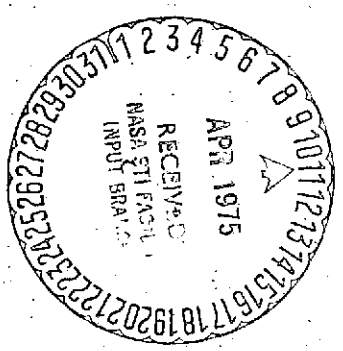

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ABSTRACT

The S194 L-band radiometer flown on the Skylab mission measured terrestrial radiation at the microwave wavelength of 21.4 cm. The terrain emissivity at this wavelength is strongly dependent on the soil moisture content, which can be inferred from antecedent precipitation. For the Skylab data acquisition pass from the Oklahoma panhandle to southeastern Texas on 11 June 1973, the S194 brightness temperatures are highly correlated with antecedent precipitation from the preceding eleven day period, but very little correlation was apparent for the preceding five day period. The correlation coefficient between the averaged antecedent precipitation index values and the corresponding S194 brightness temperatures between 230 K and 270 K, the region of apparent response to soil moisture in the data, was -0.97. The equation of the linear least squares line fitted to the data was: API (cm) = 31.99 - 0.114 T_B (K), where API is the antecedent precipitation index and T_B is the S194 brightness temperature.

THE CORRELATION OF SKYLAB L-BAND BRIGHTNESS TEMPERATURES WITH ANTECEDENT PRECIPITATION

Introduction

The accurate determination of the temporal and spatial distribution of soil moisture is of importance in several disciplines. The meteorologist is interested in the moisture content of the upper several centimeters of the soil due to the governing effects of soil moisture on the soil thermal properties, the evapotranspiration rates, and the resulting influence on the heat and moisture transport at the atmosphere-earth boundary. As an example, studies of the severe thunderstorm indicate that the inflow air source region is from the near surface layer of the atmosphere (Marwitz, 1972; Davies-Jones, 1974; and Sasaki, 1973). The addition of either heat or moisture to the inflow air adds energy to the storm. Beebe (1974) found that the tornado frequency maxima in the Texas panhandle was centered in the region of intense irrigation and attributed the maxima to the increased water vapor content of the lower atmosphere as a result of evapotranspiration from the irrigated fields. The hydrologist is interested in the soil moisture content because the soil moisture in the upper several centimeters largely determines the amount of precipitation which appears as surface runoff, the component responsible for flooding. The productivity of agricultural areas and rangeland is a function

of the soil moisture available for plant growth. If the moisture content could be monitored, better usage of rangeland and improved crop yield estimates are possible.

Before the advent of remote sensing technology, accurate soil measurements were possible through such direct methods as neutron scattering probes, tensiometers, and oven drying and weighing. These methods all share common problems; they are time-consuming and representative of only very small areas. Measurements of soil moisture distribution over large areas, especially those with differing vegetative cover and soil type and those not readily accessible, are not possible by direct methods. Because of a pronounced need for soil moisture information, those hydrologists responsible for river stage forecasting and flood warnings have developed various parameters derived from precipitation measurements to quantify the soil moisture over the fairly large areas encompassed by river watersheds.

Based on the obvious but complex relationships between precipitation, evapotranspiration, surface and subsurface runoff, and soil moisture, the precipitation history over an area is commonly used to infer the soil moisture. From this, the amount of precipitation required to produce flooding given the inferred soil moisture content can be empirically determined. Many models for characterizing the precipitation history have been devised; one of the simplest in concept and computation is (Linsley, Kohler, and Paulhus, 1958):

$$API = \sum_{i=1}^{n} K^{i} P_{i}$$

where API = antecedent precipitation index, and P_i = daily precipitation for each day from n days previous to the current day. The parameter K which is less than unity characterizes the loss of moisture from the soil due to evapotranspiration and subsurface runoff. The values normally are empirically assigned in the range 0.85 to 0.95 as a function of soil type, slope, season, and vegetative cover. The value may either be constant or may vary as a function of time.

Remote Sensing of Soil Moisture

The remote sensing of soil moisture is possible through several physical properties of water and the water-soil mixtures. Water has a greater specific heat than soil, so for a given input of heat energy, the temperature of moist soil will be lower than that of dry soil. Similarly, after radiational cooling, the moist soil will have a higher temperature due to its thermal inertia. Thus remote sensing in the thermal infrared at two or more times during the day can be used to indirectly determine the amount of water present in the surface layer of soil (Blanchard, Greely, and Goettelman, 1974).

Another remote sensing technique is based on the darkening (decreased reflectance) of soil as it is progressively moistened, apparently as a result of the optical effects of surrounding the soil particles with free water. Within a narrow range of soil types and for bare earth, remote sensing in the optical to near infrared can be used to determine the soil moisture areal distribution.

Both of these techniques, although successful under con-

trolled conditions, most notably bare ground, are completely overshadowed in scope and importance by remote sensing in the microwave portion of the spectrum. Water has the highest dielectric constant of naturally occurring abundant materials; soils have very low dielectric constants at microwave frequencies. When varying amounts of water are added to the soil, the resulting mixture will have a dielectric constant proportional to the relative amounts of water, soil, and air present (Poe, Edgerton, and Stogryn, 1971). However, if small amounts of water are added to completely dry soil, the water is tightly bound to the soil particles (with a structure resembling that of ice which has a low dielectric constant), and the dielectric constant of the mixture does not appreciably change (Schmugge, Gloerson, and Wilheit, 1972 and Schmugge, et.al., 1974). This low water content probably corresponds to hygroscopic water so is not available for evapotranspiration and plant growth. With a greater water content, the water appears as free water in the soil pore spaces and produces the dielectric constant changes predicted and observed in the soil-water-air mixture as the moisture content ranges from the wilting point to field capacity.

Since the emissivity in the microwave wavelengths of radiation is strongly influenced by the dielectric constant, remote sensing in the microwave frequencies has a significant potential in the determination of soil moisture.

Microwave Remote Sensing of Soil Moisture

Although soil moisture has a pronounced influence on the

microwave emission, the factors of soil type, surface roughness, and vegetative cover also affect the emissivity. The soil type and soil moisture determine the soil emissivity; the surface roughness and vegetative cover modify the emission from the underlying soil by scattering and surface emission (Newton, Lee, Rouse, and Paris, 1974). The effects of surface roughness and vegetative cover are wavelength dependent. The effect of small scale variations of soil type and soil moisture is minimized in remote sensing from aircraft or earth satellite altitudes since the antenna receives radiation that is effectively integrated over a fairly large ground area, thus providing soil moisture information representative of large areas (Eagleman and Ulaby, 1974).

At longer wavelengths, the skin depth (the depth of the surface layer contributing to the total emitted microwave radiation) increases. Although some investigators have reported skin depths in excess of the free space wavelength at L-band wavelengths (Poe and Edgerton, 1972), a general consensus of the skin depth is of the order of several centimeters under varying field conditions. The major significance is that remote sensing in L-band microwave can provide measurements of the sub-surface soil moisture content under varying conditions of soil type, surface roughness, and vegetative cover.

A further advantage of the longer wavelength is that atmosphere and weather phenomena including clouds and precipitation are essentially transparent to the emitted microwave radiation due to the small particle size in relation to the wavelength. At L-band

wavelengths, remote sensing operation is not restricted by adverse weather conditions. At shorter microwave wavelengths, such as the one to ten centimeter range commonly used for weather radar, however, the larger cloud particles and precipitation particles are effective scatterers and absorbers of emitted microwave radiation.

For L-band wavelengths, the terrain apparent radiometric temperature (the brightness temperature) received at the antenna can be expressed as the product of the emissivity and the actual or thermometric temperature of the radiating terrain skin depth. The atmospheric emission and the surface reflection of sky radiation components of the brightness temperature are both very small (Allison, et.al., 1974 and Blanchard, 1974). Since the emissivities are less than one and absolute surface temperatures range from 270 K to 310 K, the brightness temperature is more sensitive to changes in emissivity than to normal changes in surface temperature. Again, the averaging effect of the large footprint is advantageous.

The Skylab soil moisture experiment conducted by Dr. J. R. Eagleman of the University of Kansas has produced excellent results in the correlation of S194 brightness temperature and soil moisture (Eagleman, 1974; Eagleman and Ulaby, 1974; and Eagleman, et.al., 1974). For five data sets of tracks of 100 to 300 km length in Kansas and Texas, soil moisture measurements at six depths for six km intervals along the ground track centerline were correlated with the S194 brightness temperatures. The correlation coefficients of brightness temperature to soil moisture (percent water by weight)

ranged from -0.808 to -0.984 for the uppermost 2.5 cm layer and -0.765 to -0.979 for the uppermost 7.5 cm layer for the five data sets (Eagleman, 1974).

Since the half power footprint has a diameter in excess of 100 km, the 100 km to 300 km track lengths represent few independent measurements. Another greater problem lies in the representativeness of center-line soil moisture measurements at selected sites to the actual soil moisture within the footprint area, especially if the footprint area is not suited for conventional soil moisture sampling, or if evapotranspiration or precipitation occurs between the time-consuming sampling and the sensor pass time. However, in view of the good agreement between the data sets, these high correlations are indicative of the response of the S194 L-band radiometer to soil moisture.

Skylab S194 L-band Radiometer and Data Acquisition

The S194 L-band radiometer was one of six sensors known collectively as the Earth Resources Experiment Package (EREP) flown on the NASA Manned SKYLAB missions from May 1973 to February 1974. The L-band radiometer measured terrestrial surface brightness temperatures along the satellite ground track in the microwave radiation band centered at 21.4 cm wavelength (1.41 GHz). The footprint, or sensor instantaneous ground viewing area, at the half power point (-3dB) is a circular area with a 115 km diameter area for the 15 degree viewing angle. A footprint size of approximately 280 km diameter accounted for 90 percent of the total energy received at the antenna. The spacecraft altitude was 439.24 km (237 nmi) with

an altitude velocity of 7.65 km/sec. The S194 data acquisition rate was approximately three data points per second (one data point per 2.48 surface kiometers). In this study, every third data point, termed a measurement point, was used in the correlations. For the halfpower footprint of 115 km diameter, the footprint overlap from one measurement point to the next was near 87 percent. The footprint overlap for each data point was near 95 percent. For the 930 km length of the ground track used in this study (Figure 1) there were eight independent sensor footprint areas at the halfpower footprint size.

For a more detailed description of the S194 Radiometer and descriptions of the other EREP sensors, see the "Skylab EREP Investigator's Data Book" (NASA, 1972a) and the "Summary of Flight Performance of the Skylab Earth Resources Experiment Package (EREP)", (NASA, 1974). The S194 data used in the study was gathered in support of the severe storm environments (EPN-582) task of atmospheric investigations (NASA, 1972b).

The S194 brightness temperatures over the study area ranged from 229.8 K to 275.2 K. These values for an assumed emitting skin depth temperature of 298 K, the approximate air temperature along the ground track at the time of the data pass, would produce an emissivity range from .77 for very moist terrain and .92 for very dry terrain; both vegetated. Beyond the study area, the brightness temperatures decreased to 95 K over the Gulf of Mexico for an emissivity of .31 (water temperature assumed to be near 300 K from airborne PRT-5 thermal infrared readings).

The study area includes the loose sandy soils and sparse

vegetative cover of the high plains of the Texas and Oklahoma panhandles to the tight clay soils and heavily vegetated terrain of eastern Texas. The weather conditions at the time of the pass at 1518 to 1520 GMT (1018 to 1020 CDT) varied from thin broken cirrus (not visible in the S190A color photography) over the Texas and Oklahoma panhandles to multi-layered overcast conditions from just south of the Red River to the Louisiana border. Precipitating moderate thunderstorms with an areal coverage of 30 percent were occurring from the Fort Worth area to near 100 miles southeast along the ground track. Their rainfall amounts were generally light since the cells, as determined from GSW weather radar film, were three to five miles in diameter and were moving toward the north at 20 knots. The air temperatures along the track ranged from 294 K to 299 K.

Correlation of S194 Brightness Temperatures and API

Since soil moisture measurements were not available along the ground track, the soil moisture was parameterized by the antecedent precipitation index. The antecedent precipitation index (API) was calculated for each of the 180 precipitation reporting stations of the NOAA Climatological network along the ground track (NOAA, 1973a and 1973b). The ground track, the sensor viewing area (115 km diameter), and the location of the precipitation reporting stations are shown in Figure 2. Two sets of API were calculated for each station. One API set was calculated for the preceding eleven days (1-11 June) precipitation data and the other

API set was calculated for the preceding five days. The set for eleven days was then plotted and contoured to investigate the continuity of the API values and possible influence of events not represented from centerline values. This pattern is shown in Figure 3.

The precipitation totals for the first eleven days of June 1973 ranged from zero in the Texas and Oklahoma panhandles to near 25 cm (10 inches) in the Dallas area. To eliminate the influence of very high daily point values of precipitation in the calculation of the API, the maximum daily rainfall for the API calculation was arbitrarily set at 5.08 cm (2.0 inches). The physical rationale for the assumption is that amounts in excess of 5.08 cm contribute to immediate runoff but probably do not contribute to increased soil moisture.

The arithmetic average of the API for the 115 km diameter footprint coincident with the position of the spacecraft for every third data point was then calculated for correlation with the S194 brightness temperatures. The value of the parameter K was set at 0.9 after trails within the range 0.85 to 0.95 showed the best correlation of API to S194 brightness temperatures at that value, although the correlations were good for all values in the range. The S194 brightness temperature at every third data point (one measurement point) and the footprint API are displayed in Figures 4a, 4b, and 5. Several features are noteworthy:

1) There is a pronounced correlation between the S194 brightness temperature and the eleven-day API averaged over the footprint.

2) There is very little correlation between the S194 brightness temperature and the five-day API. As evident in Figure 4b, there had been no precipitation over much of the ground track within the previous five days. If the S194 is used as the "ground truth" for the API accuracy as a soil moisture indicator, then the API must include precipitation data for a longer period than five days, the number of days used in the antecedent moisture conditions (AMC) in the Soil Conservation Service Handbook of Hydrology (1972).

3) The correlation is best for values of the API above 1.75, which is consistent with theory for low moisture values. This relationship is especially evident from Figure 5.

4) The influence of surface water of precipitation and lakes is not readily apparent, possibly due to the small areal extent in comparison with the sensor footprint. The surface water of precipitation may contribute to the lowest S194 values, but this cannot be confirmed.

Conclusions

In at least one data set of API and S194 brightness temperatures, several significant points emerged. In addition to the known capability of L-band remote sensors to accurately detect soil moisture for small bare-ground areas, the L-band appears well-suited as a sensor for the spatial mapping of soil moisture over large inhomogeneous areas with respect to soil type, vegetative cover, terrain, and weather. Also the API even in a very simple form appears to be an accurate index of soil moisture but only

when a precipitation history in excess of five days is included; the optimal precipitation history period may be as long as one month. As these study results are confirmed by independent data sets, the API may be refined as an accurate soil moisture indicator for meteorological and agricultural applications and L-band microwave radiometry may be used to develop and refine models of evapotranspiration and runoff.

ACKNOWLEDGMENTS

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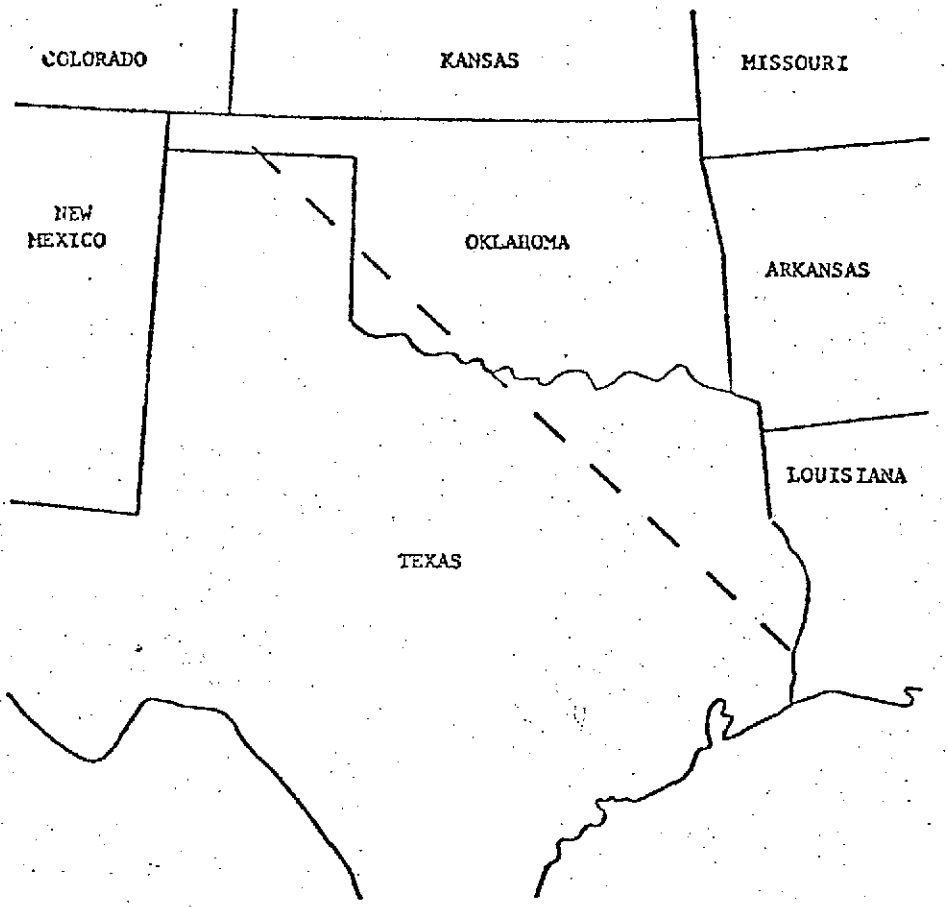

Figure 1. Skylab ground track, 1518 - 1520 GMT, 11 June 1973.

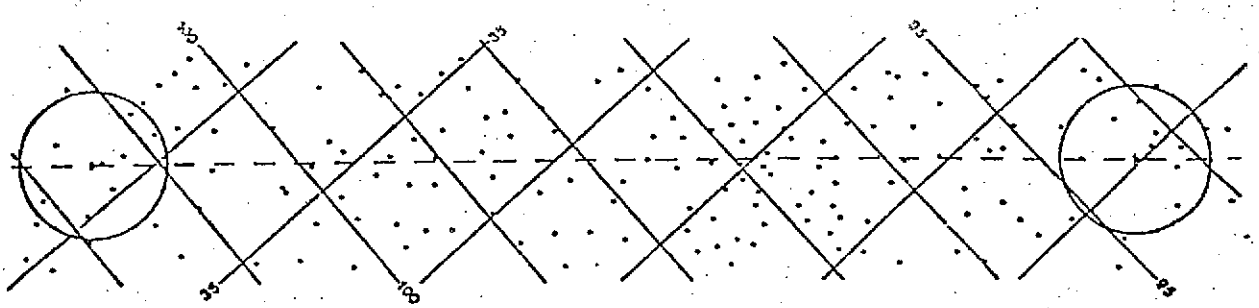

Figure 2. Location of the precipitation reporting stations used in the computation of antecedent precipitation. The approximate (due to map projection) sensor footprint area is shown as the circular areas at each end of the study area.

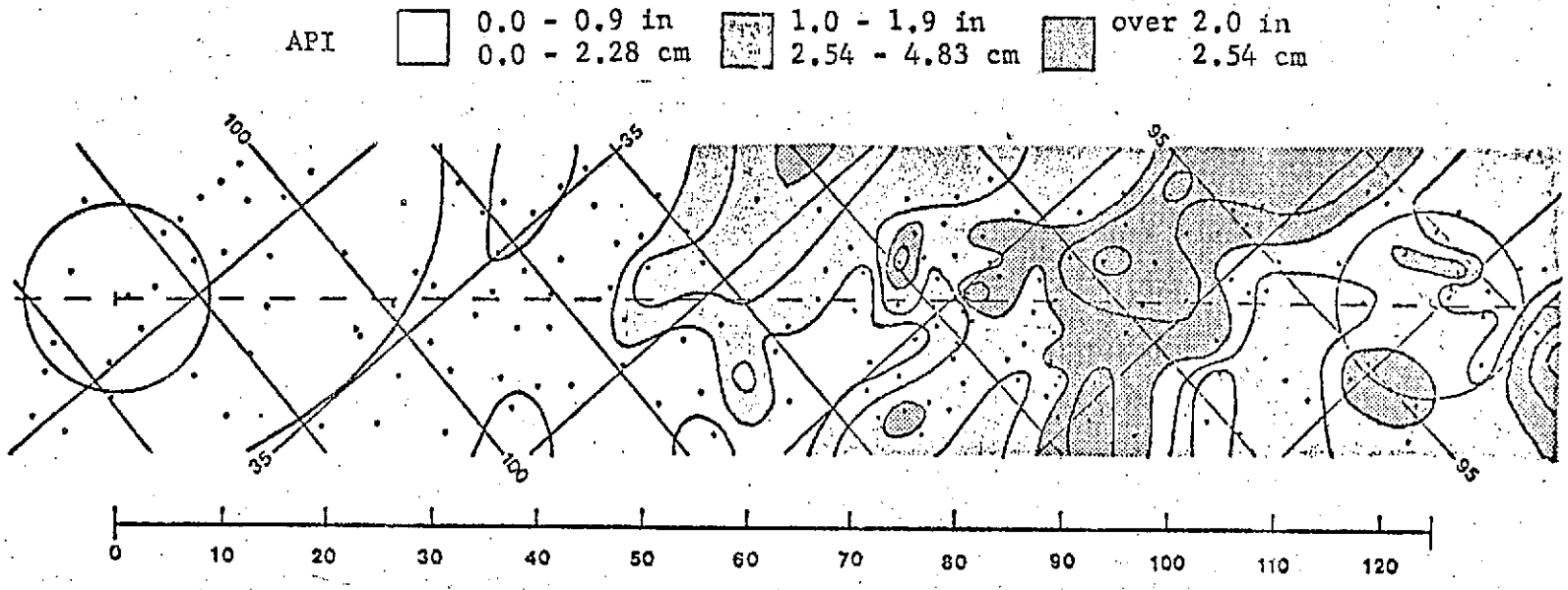

Figure 3. Contoured API values for the eleven day antecedent precipitation, 11 June 1973. The centerline values of API are not always representative of the averaged API within the sensor footprint area.

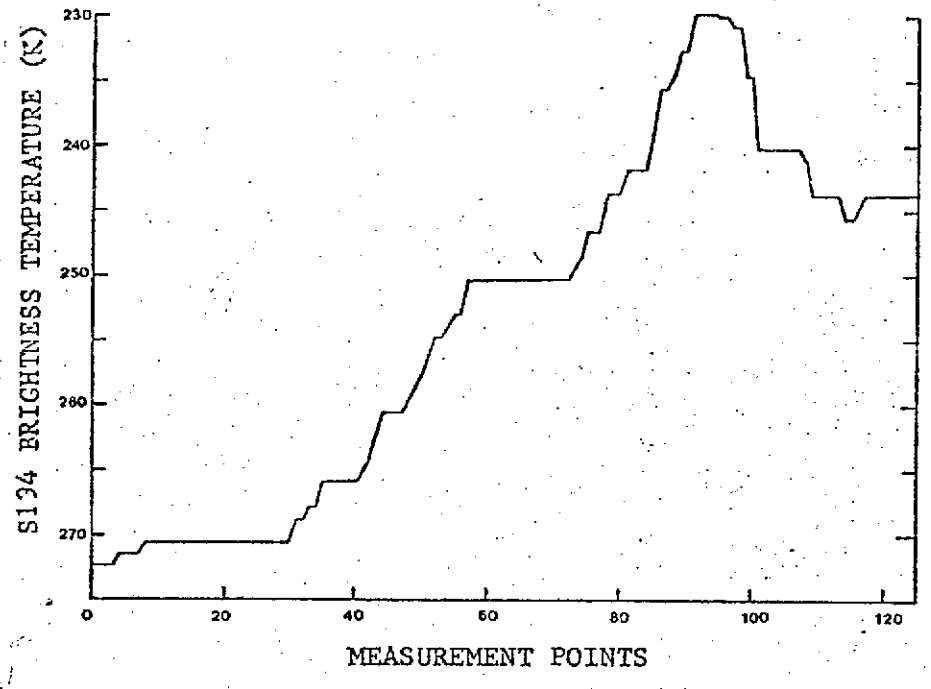

Figure 4a. S194 brightness temperature along the ground track.

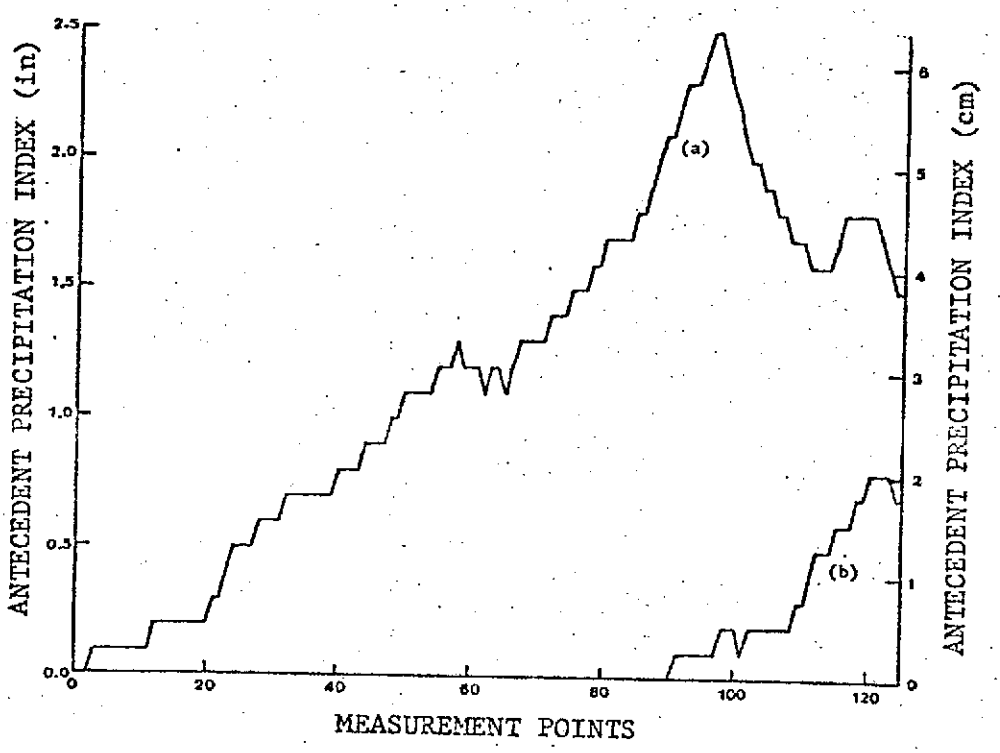

Figure 4b. Antecedent precipitation index (API) along the ground track. The eleven day API is (a); the five day API is (b).

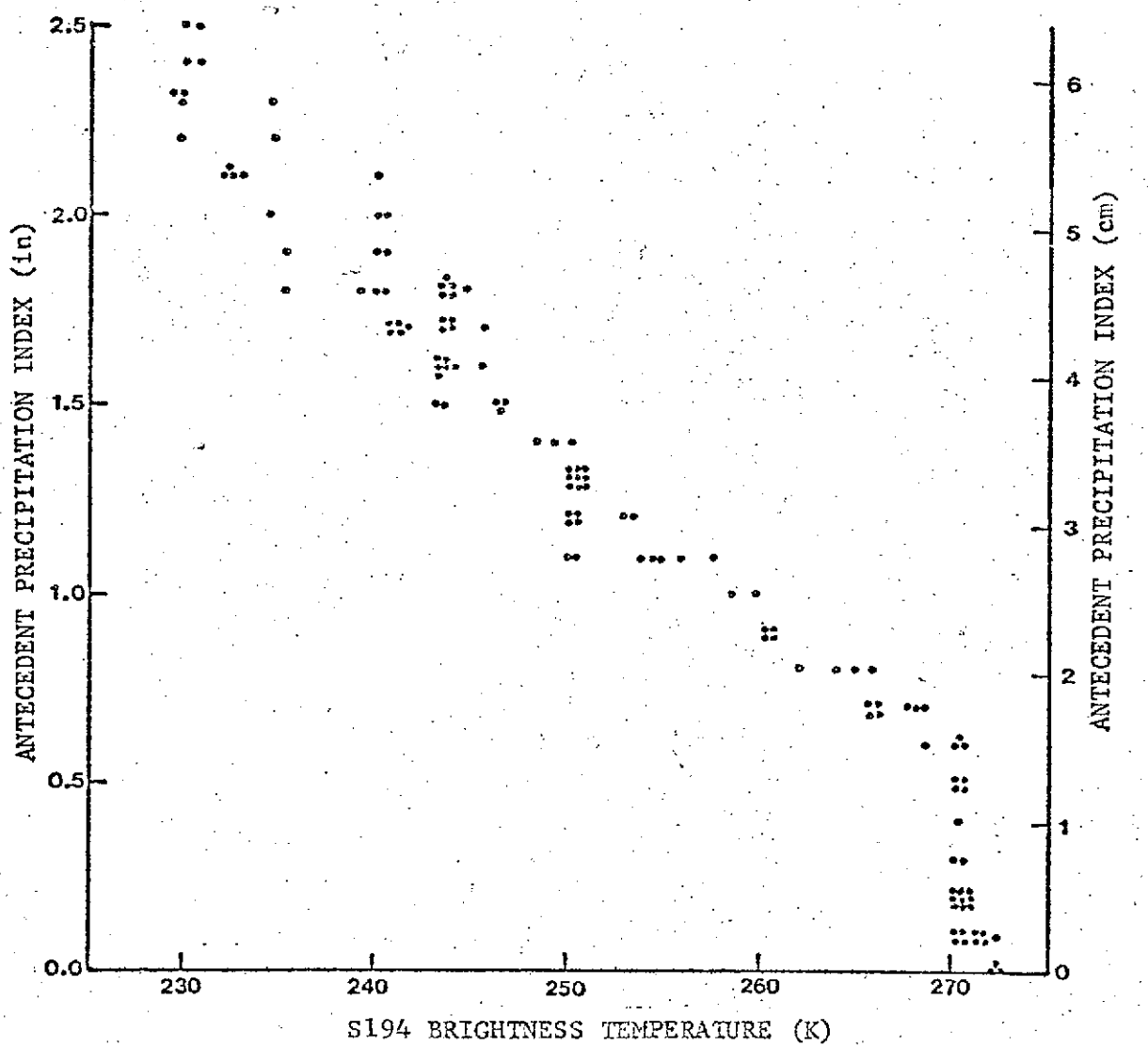

Figure 5. Correlation of S194 brightness temperature to antecedent precipitation index (API). The lack of response of the brightness temperature at low API values, which correspond to low soil moisture, is consistent with theory. For the units in inches the linear least squares line fitted through the data points between 230 K and 270 K is: API = 12.61 - 0.045 T_B. For API in cm, the equation is: API = 31.99 - 0.114 T_B. The correlation coefficient for the brightness temperature range 230 to 270 K was -0.9715.