https://ntrs.nasa.gov/search.jsp?R=19780011636 2020-03-22T04:18:17+00:00Z

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

E/S No. 1042 NASA CR-156692

(NASA-CR-156692) APPLICATION OF THE ELECTRICALLY SCANNING MICROWAVE RADIOMETER (ESMR) TO CLASSIFICATION OF THE MOISTURE CONDITION OF THE GROUND Final Report, Apr. 1975 - Mar. 1977 (Earth Satellite Corp.) G3/43 07307

N78-19579

HC A03/MF A01

Unclas

APPLICATION OF THE ELECTRICALLY SCANNING MICROWAVE RADIOMETER (ESMR) TO CLASSIFICATION OF THE MOISTURE CONDITION OF THE GROUND

Jack M. Meneely
Earth Satellite Corporation
7222 47th St. (Chevy Chase)
Washington, D. C. 20015

MAR 1978 RECEIVED NASA STI FACILITY STI BRANCH

MARCH 1977

FINAL REPORT FOR PERIOD APRIL 1975 - MARCH 1977

MAR 1978 RECEIVED NASA STI FACILITY

prepared for

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

EARTH SATELLITE CORPORATION ***(EarthSat)***

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Application of the Electrically Scanning Microwave Radiometer (ESMR) to Classification of the Moisture Condition of the Ground	March 1977
	6. Performing Organization Code
7. Author(s) Jack M. Meneely	8. Performing Organization Report No. ES-1042
9. Performing Organization Name and Address Earth Satellite Corporation 7222 47th St. (Chevy Chase) Washington, D. C. 20015	10. Work Unit No.
	11. Contract or Grant No. NAS 5-22328
12. Sponsoring Agency Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771 T. Schmugge, Code 913	13. Type of Report and Period Covered Final Report April 1975-March 1977
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The ability of the Nimbus 5 ESMR to characterize the moisture condition of the uppermost portion of the soil was evaluated. In the absence of snow cover, ESMR-5 brightness temperatures were compared with computed upper soil zone moisture values from a soil moisture budgeting scheme. The study was conducted over the U.S. Great Plains for the late summer and early fall in 1974 and 1975.

Favorable results were limited by the relatively high vegetative cover and infrequent substantial rainfalls at that time of year. Satisfactory characterization of the general moisture condition was deemed feasible in agricultural regions at times of the year when fields were nearly bare.

An additional evaluation demonstrated that ESMR-6 data could delineate the active (southern) boundary of a snow pack.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Soil Moisture Detection Nimbus 5 ESMR	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	39	

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

PREFACE

The objectives of this study were to determine the feasibility of using data from the Electrically Scanning Microwave Radiometer (ESMR) to 1) characterize the moisture condition of the upper soil zone into one of two or three broad classes, and 2) delineate regions of snow cover.

With respect to the first of these, comparisons of ESMR-5 brightness temperatures to soil moisture estimates computed by a daily budgeting scheme were made. These correspond to locations in the U.S. Great Plains in the August-October time period. Despite the drawbacks associated with the time period (relatively high vegetative cover and few substantial rain events), feasibility under a limited set of conditions was demonstrated. The major limitation is the vegetative cover, which must be minimal.

Study of snow pack delineation was limited to a single case, and demonstrated feasibility for ESMR-6.

TABLE OF CONTENTS

ABSTRACT	i
PREFACE	iii
INTRODUCTION	1
BACKGROUND AND APPROACH	3
SOIL MOISTURE BUDGET	5
PROCESSING OF ESMR DATA	9
ANALYSIS OF SOIL MOISTURE	11
SUMMARY OF SOIL MOISTURE ANALYSIS	17
SNOW COVER DELINEATION	19
CONCLUSIONS	21
RECOMMENDATION	23
REFERENCES	39

INTRODUCTION

Recent investigations have demonstrated that data from a satellite-borne radiometer, sensitive to passive radiation at microwave frequencies, can provide information of great potential value to such diverse interests as ship operations, agriculture, and hydrology. In the earlier investigations, the radiometers were flown on aircraft. The first satellite-borne microwave radiometer was the Electrically Scanning Microwave Radiometer (ESMR) carried onboard the Nimbus-5 satellite. ESMR-5 is sensitive to radiation in a narrow band centered at 19.35 GHz (wavelength 1.55 cm). At this frequency, the variations in the observed radiation are strongly influenced by variations in the emissivity of the surface. The major contribution to emissivity is liquid water with its extremely large dielectric constant at microwave frequencies. Many investigations have been concerned with surface phenomena over the ocean. Sea-surface wind speed can be inferred at microwave frequencies through the raising of emitted energy due mainly to wind generated foam. Investigations of this phenomenon have been conducted by Williams (1969), Nordberg et al. (1971), and Sabatini (1975), to name a few. Boundaries of large-scale fields of sea ice can be mapped, even in the presence of clouds, as has been shown by Gloersen et al. (1973) and Sabatini et al. (1975). Sabatini et al. (1975) have also shown that ESMR-5 data is useful in delineating areas of rainfall over the ocean. Detection of rainfall over land is desirable from agricultural and hydrological considerations, but is more difficult due to the highly variable nature of the land background. Wilheit et al. (1975) show that under certain conditions rainfall rate can be roughly estimated over a land surface. Meneely (1975) showed that in relatively level regions of minimal vegetative cover, areas of recent rainfall could be delineated and relative rainfall amounts estimated using ESMR-5 data. Such delineation results from the lowering of the surface emissivity as water permeates the upper portion of the soil. That rainfall study complemented investigations of soil moisture detection with airborne radiometers by Schmugge et al. (1974 and 1976).

A knowledge of the moisture content of the upper soil zone is potentially useful in another context, namely as a key in assessing large-scale moisture flux into the atmosphere, which could serve as an input to a meteorological atmospheric model. It was this potential for determining large-scale moisture flux which provided the motivation for the study reported here.

As specified in the RFP for this study, data from the Nimbus-6 ESMR, due for launch in early 1975, would be used to examine two aspects of ground surface condition. The major emphasis would be on soil moisture, with a brief look at snow cover detection. The test period for the soil moisture study was to be 1 May to 30 June 1975 and for snow cover 15 December 1975 to February 15 1976.

The key element in the study was the calculation of soil moisture values, to be used in a "ground truth" context. In situ measurements of soil moisture are difficult to take and to calibrate. A soil moisture

budgeting scheme previously developed and thoroughly tested by Earth Satellite Corporation was to be used to compute the water content of the upper portion of the soil on a daily basis. The area to be studied was in the Great Plains, extending from southern Canada to northern Mexico.

The Nimbus-6 ESMR differs from ESMR-5 in three important aspects: a) it is sensitive at a shorter wavelength, 0.8 cm; b) it scans along a conical arc so it makes an essentially constant scan angle with the surface; and c) it senses the horizontally and vertically polarized components of the radiation. The actual launch of Nimbus-6 was delayed for several months, precluding the originally planned soil moisture study period. Early problems with availability of properly calibrated ESMR-6 data led to a decision by NASA to use data from ESMR-5. Accordingly, ESMR-5 data for the periods September through October 1974 and August through October 1975 were supplied by NASA for the soil moisture analysis. The resulting analysis demonstrated the limitations imposed by the presence of a crop canopy and lack of many significant rainfalls at this time of year.

BACKGROUND AND APPROACH

The intensity of radiation emitted by a surface is proportional to the product of the emissivity of the surface and its temperature. This product is commonly called brightness temperature (T_B). For satellite-borne radiometers, the received radiation is modified somewhat by attenuation and emission within the atmosphere. For non-precipitating atmospheres, this effect is still quite small and surface emissivity remains the major contribution to variations in the sensed T_B. In the type of application motivating the current study, namely specification of inputs to an atmospheric model, an average value for T_B would be determined for each of a number of large computational cells. As originally conceived for this study, each cell would encompass 2.5° latitude by 2.5° longitude (about 50,000 square kilometers). It would therefore contain some 80 ESMR-5 spots (assuming the sub-satellite spot size of 25 x 25 km). Fifty-six of these computational cells covered the area of interest for this study.

The daily soil moisture was to be calculated based on a scheme originally developed by Baier and Robertson (1966) in which the soil profile is divided into several zones. Moisture is added to or subtracted from each zone based on precipitation, atmospheric demand, soil characteristics, estimated crop root development, and the amount of water already in the zone. For the study reported here, it is the uppermost zone that is of fundamental interest. The scheme is discussed more fully beginning on page 5. One of the basic inputs for this computation is the daily atmospheric demand, or potential evapotranspiration (ETP). Effective definition of this parameter requires meteorological data at six-hour intervals or less. The density of stations reporting data in the required format was such that most of the computational cells would have had only one or two stations within them. It was beyond the scope of this study to perform the operations necessary to interpolate the data to the fine grid mesh needed to accurately characterize each cell. This is particularly true with respect to rainfall which is highly spatially variable. Simple sampling theory such as Tchebycheff's inequality readily shows that such a cell cannot be accurately characterized using only one or two points. The following numerical example illustrating this fact was taken from some calculations performed for the northern Great Plains during 1975. In these calculations, the weather parameters had been determined for grid points with spacing of 12.5 miles of which there are about 110 to 120 in a 2.5° by 2.5° cell. Data for nine such 2.5° cells in the region were examined for the period August 24-30. For the 63 cases (nine cells, seven days), the average moisture content of the uppermost 5 percent of the soil profile varied from as low as 0.6mm to as high as 8.2mm, or nearly equal to the assumed saturation value of 8.75mm. The standard deviation within the cells ranged from 0.6 to 3.1mm. Application of Tchebycheff's inequality showed that specification of the mean cell top zone moisture to within 1.0mm will be achieved at least 90 percent of the time with a sample of that many (110-120) points. For a standard deviation of 2.0, accuracy to within 1.0mm 50 percent of the time still requires eight points within the cell.

In addition to these spatial variations due to rainfall patterns, there are the effects of soil characteristics, type of terrain, land use, and amount of vegetative cover. All these factors interact to produce great variations in the T_B-moisture relationship, making it clearly inappropriate to conduct this soil moisture investigation based on the 2.5° cells. The moisture budget calculations were therefore performed for points corresponding to the actual locations of all weather stations reporting the required meteorological data. The resulting moisture values were compared to spatially averaged T_B values from ESMR-5 in the immediate vicinity of the station. (At least four values surrounding each station location were used to minimize the effect of instrument noise.) As reported by Schmugge et al. (1976), research has shown that microwave detection of soil moisture at shorter wavelengths is strongly affected by the presence of a vegetative cover. This was clearly indicated in the detection of rainfall over land areas by ESMR-5 as reported by Meneely (1975). That study examined two heavy rain events which occurred in the most intensively agricultural portions of Illinois and Indiana in June and July of 1973. Detailed soil moisture calculations using the Baier and Robertson model (see pages 5-7) were performed at six locations. Data from nine ESMR-5 passes over the area were used. A growth model for corn was used in the analysis to estimate the vegetative cover. A summary of the results appears in Figure 1 and shows the observed brightness temperatures plotted against the fractional saturation of the uppermost soil zone. The open symbols correspond to the early June event, for which there was little vegetative cover (a fact confirmed by LANDSAT-I imagery). A strong T_B decrease with increasing moisture was noted, averaging about 40 K from dry to saturated (field capacity). The filled symbols represent the July case, for which the vegetative cover was near 100 percent. Here the T_B decrease was only about 17 K.

It was decided for the study reported here that imagery from LANDSAT-I and II would be used where readily available to define vegetative cover within 25 km of each station. Figure 2 is a map showing the location of the 52 stations for which soil moisture calculations were made. The 42 stations for which LANDSAT images were examined are indicated by circles. Figure 3 presents the estimated percent of vegetative cover at each of these stations. In the southern portions of the study region, imagery for the desired August to October time period was not so readily available, so late springtime imagery was substituted. These values are enclosed in parentheses. The analysis on Figure 3 shows a general geographic consistency and an expected east to west decrease in the cover.

SOIL MOISTURE BUDGET

The scheme used to calculate the daily soil moisture profile was developed by Baier and Robertson (1966) and designated "Versatile Budget" (VB) by them. This scheme divided the total moisture holding capacity of the soil into several zones relating to a wheat plant root structure. Water was subtracted from different depths each day through coefficients which related plant rooting characteristics and soil water evaporation to the daily atmospheric demand. It was the top-most zone that was of interest to this study. This zone was assumed to contain five percent of the total water holding capacity (wilt point to field capacity) of the soil profile. For a typical wheat growing soil of one meter depth, this represented a physical zone depth of about five centimeters.

The VB model for calculating the actual daily moisture extraction from a given soil zone was given by

$$ET_i = K \cdot \left(\frac{S_{i-1}}{C}\right) \cdot Z \cdot ETP_i$$

where

- ET_i = Actual evapotranspiration for the layer on day i ending at sunrise on day i + 1.
- K = Crop/soil coefficient.
- S_i-1 = Available soil moisture in the zone at the beginning of day i-1.
- C = Capacity for plant-available water in the zone.
- Z = Adjustment factor for soil drying characteristics.
- ETP_i = Evapotranspiration potential (atmospheric demand) for day i.

The net soil moisture in a zone at the end of day i was given by

$$S_i = S_{i-1} - ET_i + I$$

where

- I = The infiltration of rainfall into the zone. If the total rainfall for the day was less than 25.4mm, then the total was assumed to be available for infiltration. Otherwise, the amount available for infiltration was given by

$$I_A = 23.31 + 46.0 \cdot \log\left(\frac{R_i}{25.4}\right) - 24.64 \cdot \log\left(\frac{R_i}{25.4}\right) \cdot \left(\frac{S'_{i-1}}{S'}\right)$$

where

R_i = Rainfall in mm for 24 hours ending the morning of day i + 1.

$\frac{S'_{i-1}}{S'}$ = Fraction of soil moisture capacity available in top zone at end of day i-1.

I_A was used to bring the top zone up to capacity. If any excess remained, it was used to fill the lower zones in turn. Any remaining amount was added to run-off.

The crop/soil coefficient (K) was taken to be 0.40 for the top zone. This was representative of most crops in the late growing season or of bare ground, and implied that 40 percent of the atmospheric demand (ETP) would act on the top zone. K represents the <u>average</u> coefficient for the zone. At the top surface K is nearly 1.0, but decreases rapidly with depth. The soil crop-available moisture capacity (C) was a function of the soil type and referred to the amount of moisture in the range from field capacity (-1/3 bar) to permanent wilting (-15 bar). Two general types of soils were considered for this study. One was a clay loam or silt loam with a top zone capacity of 8.75mm. The other was a sandy soil with a top zone capacity of 5.75mm. The adjustment factor for soil drying characteristics (Z), commonly called the "dry-down curve" described the ability of the soil to give up its plant-available water. There are numerous viewpoints on how Z varies with the amount of plant-available water. The relationship used must generally be based on past experience. The following relationships were used in this study. In sandy soils, all the water was assumed to be freely accessible to meet the atmospheric demand. For clay or silt loams, three dry-down curves were defined and computations made for each. Curve "G" assumed that the fraction of the water content available to meet the atmospheric demand decreased linearly from 1.0 when the zone was saturated to zero when the zone was totally dry. Curve "E" assumed that all water was available until 35 percent of zone capacity remained. Then the availability ratio decreased sharply and logarithmically to zero at zero content. Curve "E-normal" was similar to "E" except the transition ratio was 25 percent instead of 35 percent.

The evapotranspiration potential (ETP) was calculated using the method of Penman (1948)

$$ETP = \frac{(\Delta/h_v) \cdot R_{net} + \delta \cdot f_w}{\Delta + \delta}$$

where

Δ = Slope of the saturation vapor pressure curve (mb/°K).
h_v = Heat of vaporization of water.
R_{net} = Net radiation for the day (cal/cm^2).
δ = Psychrometric constant.
f_w = Wind effect on evaporation.

In order to more accurately assess the effects of temporal variations in meteorological parameters, the day was divided into four periods of six hours, each centered about a meteorological observation. The parameters used were air temperature, dew point temperature, wind speed, and cloud types and amounts.

The net radiation consisted of two components: net incoming solar and net outgoing longwave. The solar component was determined by integrating using half-hour time steps to account for the earth's rotation. Attenuation and scattering by dust, water vapor, and clouds, and reflection from the surface were included. The longwave component was subtractive and was a function of the surface temperature (assumed to equal the air temperature) and the water vapor content of the air. Reflection by clouds was also included. The wind effect was a function of the wind speed and the difference between the actual and saturation vapor pressures.

The meteorological data used in these calculations were obtained on magnetic tape from the National Climatic Center in Asheville, North Carolina.

PRECEDING PAGE BLANK NOT FILMED

PROCESSING OF ESMR DATA

Uncertainties in satellite attitude make wholly automated georeferencing of T_B spot values unacceptable. A technique has evolved in which this is done manually using gridded overlays developed from the orbital geometry. The ESMR calibrated brightness temperature tapes are read and the T_B spot values are printed in a format which produces a proportionally correct relationship between the spacing of the spots within a scan line and the spacing of the scan lines themselves. Depending on the sensor (ESMR-5 or 6), the hemisphere (northern or southern), and the direction of satellite travel (northbound or southbound), the proper overlay is selected and initially positioned using the printed ephemeris data for each scan. Water bodies and coastlines, which are readily visible in the T_B field, are outlined and the overlay is shifted as needed to place these at the proper coordinates. The latitude-longitude grid is then transcribed onto the T_B map with an error generally much less than the spot spacing.

Each ESMR-5 scan line consists of 78 individual spots. The quality of the data is seriously degraded at the ends of the scan due to increased atmospheric contribution and poorer resolution. For this reason, only spots which were more than ten positions from either end of the scan were used. The available ESMR-5 orbits were screened and those which included at least a part of the study area within the acceptable region were selected for further analysis. A total of 21 daytime and 11 nighttime passes was selected.

PRECEDING PAGE BLANK NOT FILMED

ANALYSIS OF SOIL MOISTURE

The analysis of daytime and nighttime data could not be combined because of the large differences in surface temperature and the difficulty in unambiguously removing their effects. Only the analysis of daytime data is reported here; the nighttime data set was too small to permit significant conclusions. The soil moisture budget calculations at each station were started a number of days prior to the first ESMR-5 pass (19 days prior in 1974, 25 days in 1975). This allowed the effect of uncertainties in the initial estimates of soil moisture to diminish. Determination of the proper soil type and dry-down curve for each station is a difficult task at best. For this reason, all four combinations of soil type and dry-down curve were used at each station. It was hoped that the resulting comparisons would indicate which soil description was most appropriate at each station. It was found, however, that the results were relatively insensitive to the soil parameters except on the one or two days following rainfall. There were too few instances of significant rainfall with ESMR-5 data available on immediately following days to permit this assessment. Table 1 is an example of the output of the computation for Williston, North Dakota. The soil moisture in the top zone was expressed as a fraction of the capacity. To compress the output to one page, only those days on which or near which a usable ESMR-5 pass occurred were printed. The hand-tabulated brightness temperature values represented the average of the four spot values surrounding each station. Orbits not tabulated indicate that the station was not within an acceptable portion of the scan. The only available daily rainfall totals were for the 24-hour period ending at midnight. Since the daytime ESMR-5 passes occurred near noon, it was not appropriate to use data from a day on which rain fell between midnight and noon. Station reports of rainfall during those hours were indicated by x's. Data from those days were not used (i.e., October 5, 1974 at Williston).

For each station and for each soil/dry-down combination, simple plots of T_B versus fractional saturation in the top zone (f_s) were generated and correlation coefficients were calculated. Figures 4 through 8 present examples for five of the stations. The vertical axes are T_B and the horizontal are the ratio between the actual moisture content of the top soil zone and its field capacity. The number printed at each plotted location is the number of data points occurring at that location. It was felt that much of the scatter appearing in the data was attributable to day-by-day changes in the soil temperature. No soil temperature data were available; however, an attempt was made to compensate for its effects by assuming that the mid-day soil surface temperature could be approximated by the daily maximum air temperature. These results are presented in the lower tier of plots for each station. While this did reduce the scatter for some stations, it increased it for others, and the net result for all stations aggregated was to decrease the magnitude of the correlation coefficient somewhat. A more promising approach might estimate soil temperature based on calculations of the solar energy reaching the soil up to the time of satellite passage. Kansas City, Missouri (Figure 4) had the highest correlation of all the stations, particularly when the temperature adjustment was included. The highest correlation was obtained for dry-down curve G, the lowest for sandy soil. Correlation coefficients were also produced by ex-

TABLE 1: SOIL MOISTURE OUTPUT AND TB TABULATIONS FOR WILLISTON, NORTH DAKOTA.
PERIODS OF MORE THAN FIVE DAYS BETWEEN ESMR-5 DATA ARE NOT PRINTED.

YR	MO	DAY	TEMP MAX	TEMP MIN	PRECIP ENDING * 0000	PRECIP OCCURRING AT 00	03	06	09	12	ZONE 1: FRACTION SATURATION SOIL TYPE: 1 DRY DOWN: G	1 F	1 F*	3 FREE	BRIGHTNESS TEMPERATURE NIGHTTIME PASS	DAYTIME PASS	MO	DAY
74	9	20	289	277	0.0	.	.	.	.	.	0.15	0.21	0.15	0.0		270	9	20
74	9	21	288	271	0.0	.	.	.	.	.	0.13	0.19	0.13	0.0			9	21
74	9	22	296	280	0.0	.	.	.	.	.	0.11	0.18	0.12	0.0		266	9	22
74	9	23	300	276	0.0	.	.	.	.	.	0.09	0.17	0.11	0.0			9	23
74	9	24	297	281	0.0	.	.	.	.	.	0.05	0.16	0.11	0.0			9	24
74	9	25	301	279	0.0	.	.	.	.	.	0.02	0.15	0.10	0.0		269	9	25
74	9	26	299	279	0.0	.	.	.	.	.	0.0	0.15	0.10	0.0			9	26
74	9	27	285	274	0.0	.	.	.	.	.	0.0	0.14	0.10	0.0		265	9	27
74	9	28	291	274	0.0	.	X	.	.	.	0.0	0.14	0.10	0.0	—		9	28
74	9	29	284	266	0.3	.	.	.	.	.	0.03	0.17	0.13	0.05		257	9	29
74	9	30	286	265	0.0	.	.	.	.	.	0.02	0.17	0.12	0.0			9	30
74	10	1	281	267	0.0	.	.	.	.	.	0.01	0.16	0.12	0.0		258	10	1
74	10	2	299	276	0.0	.	.	.	.	.	0.0	0.16	0.11	0.0		268	10	2
74	10	3	294	280	0.0	.	.	.	.	.	0.0	0.15	0.11	0.0			10	3
74	10	4	284	279	0.0	.	.	.	.	.	0.0	0.15	0.10	0.0		264	10	4
74	10	5	280	271	0.3	X	X	.	.	.	0.03	0.18	0.13	0.05	—	263	10	5
75	8	26	296	277	3.8	.	.	.	.	.	1.00	1.00	1.00	1.00		253	8	26
75	8	27	302	285	0.0	.	.	.	.	.	0.79	0.76	0.76	0.73			8	27
75	8	28	303	290	0.0	.	.	.	.	.	0.58	0.45	0.45	0.16		270	8	28
75	8	29	298	283	0.0	.	.	.	.	.	0.42	0.23	0.17	0.0			8	29
75	8	30	301	281	0.0	.	.	.	.	.	0.31	0.19	0.13	0.0	—	265	8	30
75	9	15	301	277	0.0	.	.	.	.	.	0.05	0.14	0.10	0.0		—	9	15
75	9	16	304	284	0.0	.	.	.	.	.	0.01	0.14	0.09	0.0			9	16
75	9	17	291	282	0.0	.	.	.	.	X	0.0	0.13	0.09	0.0	256		9	17
75	9	18	282	278	9.1	.	X	.	X	X	1.00	1.00	1.00	1.00			9	18
75	9	19	281	277	10.7	X	X	.	.	.	1.00	1.00	1.00	1.00	241		9	19
75	9	29	289	281	0.0	.	.	.	.	.	0.52	0.33	0.27	0.22		—	9	29
75	9	30	285	274	0.0	.	.	.	.	.	0.41	0.22	0.15	0.0			9	30
75	10	1	296	276	0.0	.	.	.	.	.	0.37	0.21	0.14	0.0	248	260	10	1
75	10	2	300	275	0.0	.	.	.	.	.	0.30	0.19	0.13	0.0			10	2
75	10	3	300	276	0.0	.	.	.	.	.	0.23	0.17	0.12	0.0		266	10	3
75	10	4	293	282	0.0	.	.	.	.	.	0.19	0.17	0.11	0.0			10	4
75	10	5	292	279	2.0	.	.	.	.	.	0.40	0.39	0.34	0.35	242	252	10	5
75	10	6	302	279	0.0	.	.	.	.	.	0.34	0.25	0.18	0.04			10	6
75	10	7	291	280	0.0	.	.	.	.	.	0.24	0.19	0.13	0.0			10	7
75	10	8	280	274	0.0	.	.	.	.	X	0.19	0.18	0.12	0.0			10	8
75	10	9	279	273	0.0	X	.	.	.	.	0.19	0.18	0.12	0.0			10	9
75	10	10	280	273	0.0	.	.	.	.	.	0.18	0.17	0.12	0.0			10	10
75	10	11	283	274	0.0	.	.	.	.	.	0.17	0.17	0.12	0.0	—		10	11
75	10	12	282	277	0.0	.	X	X	.	.	0.17	0.17	0.11	0.0			10	12
75	10	13	280	273	0.0	.	X	.	.	.	0.16	0.17	0.11	0.0	254		10	13
75	10	14	276	272	17.3	X	X	X	X	.	1.00	1.00	1.00	1.00			10	14
75	10	15	284	270	11.2	.	.	.	.	.	1.00	1.00	1.00	1.00		240	10	15
75	10	16	281	275	0.5	.	.	.	.	.	1.00	0.99	0.99	0.99		239	10	16
75	10	17	292	273	0.0	.	.	.	.	.	0.97	0.96	0.96	0.94	240		10	17
75	10	18	296	276	0.0	.	.	.	.	.	0.85	0.83	0.83	0.74			10	18
75	10	19	291	274	0.0	.	.	.	.	.	0.78	0.74	0.74	0.60		242	10	19
75	10	20	289	277	0.0	.	.	.	.	.	0.68	0.59	0.59	0.38			10	20
75	10	21	284	275	0.0	.	.	.	.	.	0.56	0.41	0.41	0.10		243	10	21
75	10	22	280	271	0.0	.	.	.	.	.	0.51	0.32	0.31	0.0			10	22
75	10	23	281	268	0.0	.	.	.	.	.	0.48	0.27	0.25	0.0			10	23
75	10	24	282	268	0.0	.	.	.	.	.	0.45	0.24	0.20	0.0			10	24
75	10	25	282	270	0.0	.	.	.	.	.	0.40	0.22	0.16	0.0			10	25
75	10	26	287	274	0.0	.	.	.	.	.	0.36	0.20	0.14	0.0			10	26
75	10	27	276	270	0.0	.	.	.	.	.	0.32	0.19	0.13	0.0	23		10	27

BEST AVAILABLE COPY
ORIGINAL PAGE IS POOR

cluding the driest data points. This was done because at some localities there seemed to be too many points grouped at this end of the curve to allow a meaningful result. In most cases, however, the correlation did not change much and the reduced sample contained too few data points to be meaningful. Des Moines, Iowa (Figure 5) is another station which displayed a relatively high correlation coefficient, but in this case the lowest correlation was for dry-down curve G. While these two stations had fairly high correlation coefficients, the sensitivity of T_B to moisture content was not great - about 15 K from dry to saturated. This is likely due to the relatively high vegetative cover (estimated at 50 percent and 65 percent, respectively). Figure 6 presents another station with a high correlation coefficient - Williston, North Dakota. In this case, there is a much greater sensitivity to moisture content - about 30 K from dry to saturated. This is consistent with the estimated vegetative cover of about 25 percent. Two other stations, only about 100 miles apart, are shown to demonstrate the gross differences in response which they display. One of the stations is Oklahoma City, Oklahoma, which displays a high correlation coefficient and a dry to wet range of about 25 K; the other is Tulsa, Oklahoma, which displays no correlation at all. The fraction of vegetative cover is similar at these two locations, but the discrepancy probably arises from the fact that the Tulsa area is highly forested, while the Oklahoma City area is mostly range and cropland.

Figure 9 is a map of the test region on which the correlation coefficients have been plotted and analyzed. Several stations across the center of the region had very little rainfall during the test period. In these cases, insufficient data was available at higher moisture levels to allow meaningful results. These stations are indicated by asterisks. There seems to be a tendency for the regions where grain crops are predominant to be the most highly correlated. This includes the spring wheat belt from north central and eastern Montana across North Dakota to western Minnesota, the western portions of the corn belt, and the winter wheat belt through southern Kansas, western Oklahoma, and the Texas panhandle. In the time period being considered, the spring wheat will have been mostly harvested and the winter wheat will be in an early stage of growth, implying a fair percentage of bare soil. In the corn belt, harvesting will be at an early stage; however, in the western portions there may well be a great enough mix of crops to assure some bare soil.

Figure 10 presents a plot of all the T_B versus fractional saturation data points for the 52 stations. There is a great amount of scatter in the data and only a weakly discernible slope. Figures 11 through 13 present similar plots for the three regions of highest correlation coefficients visible in Figure 9. In these cases, the trends in T_B are much more clearly discernible. Many of the outlying points, particularly those with high T_B values at higher moisture levels are not present in Figures 11 through 13. The dashed line on Figure 10 (all points) defines the limit above which no points exist on the three following plots. These outlying points represent, for the most part, locations with heavier natural vegetation lying outside the major agricultural regions. These grasslands or forests mask the return from the wet soil beneath. In the spring wheat and winter wheat regions (Figures 11

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

and 13), the T_B changes from wilt point to field capacity are 24.5 K and 23.3 K, respectively as determined by least-squares regressions. These correspond to average vegetative cover estimates of about 40 percent. In the corn belt region (Figure 12) where the average vegetative cover is estimated at 55 percent, the T_B decreases by only 11.7 K.

In these three figures, the most notable outlying points are those associated with low calculated soil moisture in conjunction with low observed brightness temperature. These are likely manifestations of shortcomings in the soil moisture model. In particular, the eight points lying below the dashed line of Figure 11 were subjected to further scrutiny.

The following is a list of the locations, dates, observed noon-time T_B, and fractional saturation (f_s) estimates for the upper soil zone:

Station	Date (1975)	T_B(K)	f_s
Minot, ND	Oct 1	247	0.22
Williston, ND	Oct 5	252	0.34
Billings, MT	Oct 19	253	0.13
Havre, MT	Oct 19	252	0.17
Glasgow, MT	Oct 21	245	0.19
Havre, MT	Oct 21	251	0.12
Minot, ND	Oct 21	243	0.22
Williston, ND	Oct 21	243	0.41

These observations have two things in common. First, they all occur in October 1975 and, second, all of the stations are located in the northern Great Plains. This proximity in space and time suggests that the anomalies are a result of real physical causes and not merely random deviations from the average.

Addressing the Williston, Oct. 5 observation first, an inspection of the rainfall data indicates that a light rainfall (2mm) occurred on the evening of Oct. 4. The soil moisture model estimated that this rainfall brought the level of saturation to 0.34 in the top zone. The design of the model is such that the moisture is introduced uniformly throughout the (approximately) five centimeter depth of the zone. However, since the rainfall occurred just the evening before the satellite observation, the moisture could reasonably be expected to be concentrated in the top few millimeters of the soil. In such a case, the satellite would detect the wet soil surface and would produce readings of T_B which correspond to greater soil moisture than the model estimates.

The above explanation might be applied to the Minot, Oct 1 observation. A trace of rain was detected at Minot on Sept. 30. This could indicate that the Minot area had a light rain which failed to infiltrate or evaporate significantly by the noon observation on October 1. The morning of that day was mostly cloudy and cool with high relative humidity, further supporting this assumption.

An inspection of the meteorological data for the area for the week prior to Oct 21 indicates a cause different than the one above for the remaining six anomalous observation points. For a six day period, Oct. 11-16, precipitation occurred in North Dakota and Montana. The total amounts for the stations in the list varied from slightly over 12mm at Billings to over 40mm at Minot. Very importantly, a sizeable portion of this precipitation was snowfall. Although warm temperature caused rapid melting and none of the stations reported any snow cover after Oct. 17, the snowfall could cause the observed T_B to be lower than otherwise expected in two ways. First, patches of snow might still exist at observation time in the areas near the stations. The patches of snow would contaminate the T_B observation because of the cold temperature and different emissivity of the snow surface. Second, and more importantly, the snow cover acts as a source of moisture until it is melted. The soil moisture model makes no allowance for this effect of snow cover and begins depletion immediately after the last precipitation, using the energy which melts the snow to evaporate the water instead. This premature depletion of soil moisture by the model when precipitation falls as snow will cause under-estimation of the amount of soil moisture for several days after the last precipitation and can result in such anomalous points as were observed on Oct. 19 and Oct. 21.

PRECEDING PAGE BLANK NOT FILMED

SUMMARY OF SOIL MOISTURE ANALYSIS

At short wavelengths, such as the 1.55 cm value for ESMR-5, the absence of a vegetation canopy is critical to its ability to detect soil moisture variations. This is clearly illustrated by Schmugge et al. (1976) in comparing ESMR-5 T_B values with those for two radiometers carried on Skylab. The Skylab radiometers had wavelengths of 2.2 cm and 21.0 cm. The data were for a 300 km swath across north-central Texas on June 5, 1973. The soil moisture in the top 2.5 cm varied from 15 percent to 70 percent of field capacity. The 21 cm radiometer displayed a T_B range of 45 K, while the range at 2.2 cm was 15 K. The ESMR-5 range was no more than 5 K.

The cases presented here showed that only in the presence of minimal vegetative cover could ESMR-5 meet the basic objective motivating this study. That was the ability to specify whether the soil moisture was at or below the wilt point ($f_s \leq 0$), saturated ($f_s \geq 1$) or between these extremes. If the slope of the T_B variation is small with respect to the scatter in the data, then little confidence will exist in the assignment of a moisture class based on an observed T_B. Even in those cases of lesser vegetative cover (Figures 1-open symbols, 11 and 13) there still exists a great deal of scatter. There are a great many possible sources for this scatter, including:

a) variations in ground temperature among the data points;

b) variations in the water content of the atmosphere;

c) uncertainties associated with the soil moisture model, in particular, the large thickness (up to 5 cm) of the uppermost zone in comparison to the wavelength of ESMR-5 (1.55 cm) and the characterization of the atmospheric demand response of the entire zone by a single coefficient;

d) local topographical effects (as they influence water retention and runoff).

SNOW COVER DELINEATION

Because the microwave emissivity of a snow cover can differ markedly under many conditions from nearby bare ground, a microwave radiometer provides the opportunity to map the extent of a snow pack, even in the presence of clouds. A brief analysis of some ESMR-6 data was conducted to verify that useful information can indeed be obtained. The orbit selected was a daytime pass over the central U.S. on December 9, 1975. Figure 14 is a portion of the analyzed map of the horizontally-polarized T_B (T_{HOR}) centered over east-central Minnesota. The outline of a portion of Lake Superior was indicated by the 200 K isotherm. Circled numbers represent snow depths in centimeters as reported at cooperative observing stations in the NOAA publication Climatological Data. This snow pack was several days old and some prior melting had occurred, although air temperatures were well below freezing on the day of this image. A sharp change in T_{HOR} was noted at the southern boundary of the snow field, with snow-covered areas being 15 K to 30 K lower. The 230 K isotherm (shaded) appears to be a good delineater of this boundary, where the snow water equivalent is highest and where the greatest melting has occurred. The 230 K line to the north does not indicate a boundary, but merely reflects a northward increase in the pack emissivity as its surface characteristics change.

Analysis of the vertically polarized component showed similar trends but the range of magnitudes was less. Analysis of the difference of the two T_B components demonstrated little relationship to the snow field.

PRECEDING PAGE BLANK NOT FILMED

CONCLUSIONS

8.1 Soil Moisture

The most important conclusion resulting from this study is:

A microwave radiometer of short wavelength (less than 2.0 cm), such as ESMR-5, appears to be able to provide useful information on the moisture condition of the upper soil zone provided that all of the following conditions are met:

1. Little or no vegetative cover (less than 40 percent) must exist over a wide region.

   This implies that the areas must be either arid or heavily agricultural with either cropland or mixed crop and range land, and confined to the time of year when fields are bare or nearly bare.

2. Soil surface temperature must be estimated within the region.

   Since the soil moisture directly affects the emissivity, those influences on T_B which are not manifested in emissivity must be accounted for. Soil temperature is a major item in this category.

3. A regional T_B/moisture relationship calibration must be made.

   This will allow for some of the effects of differing soil characteristics, drainage efficiency, and land use mix to be factored out.

Much more successful large-area soil moisture determinations over a greater part of the year would be possible with a radiometer sensitive at a considerably greater wavelength.

Determination of the feasibility of extrapolation into the winter season or into arid regions with wide mixes of terrain type requires further study.

8.2 Snow Mapping

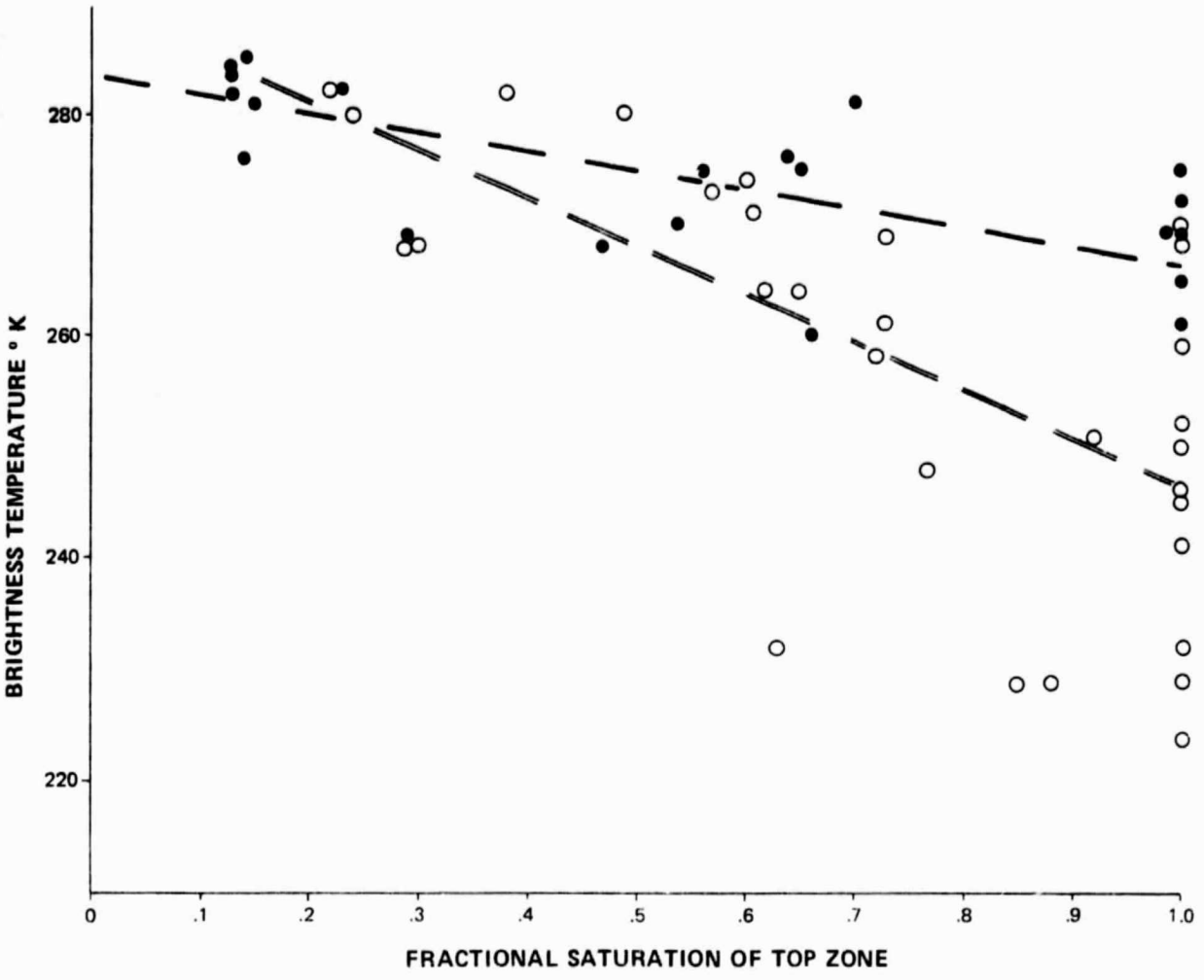
Mapping the active (southern) margin of a snow pack using microwave radiometers is feasible. A horizontally-polarized T_B component of 230 K seems to be a reasonable delimiter.

PRECEDING PAGE BLANK NOT FILMED

RECOMMENDATION

The overriding recommendation resulting from this study is for a more detailed evaluation based on data for the months March through June in the northern Great Plains and the Midwest. In such a study, morning solar radiation calculations would allow reasonable estimates of soil surface temperature to be made. Three or four regions would be defined and the data aggregated to that level to permit assessment of regional differences.

PRECEDING PAGE BLANK NOT FILMED



PRECEDING PAGE BLANK NOT FILMED

FIGURE 1: Brightness temperature versus fractional saturation of top zone for six locations in Illinois and Indiana, June - July 1973. Open symbols indicate less than 20% crop canopy. Filled symbols indicate more than 70% crop canopy.

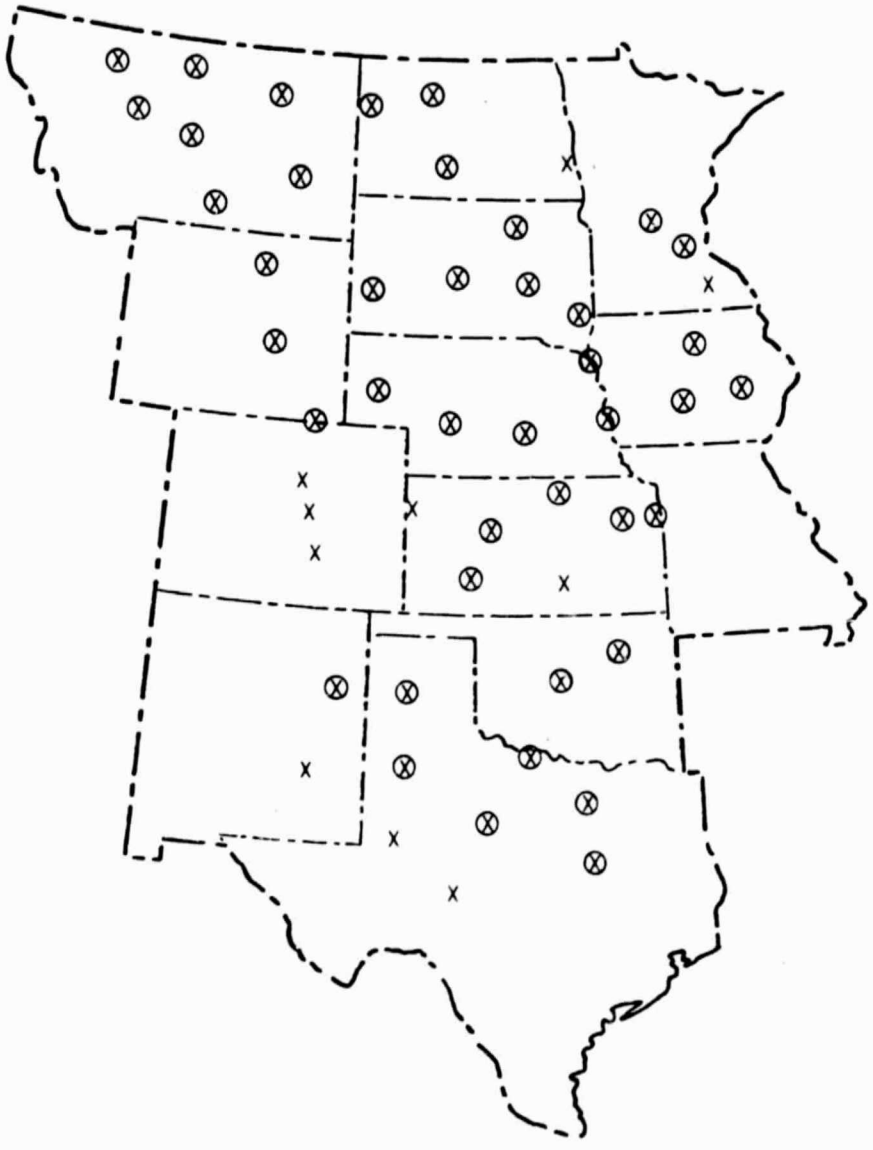


FIGURE 2: Locations of the 52 stations for which soil moisture calculations were made are indicated by X. The 42 stations for which LANDSAT imagery was obtained are circled.

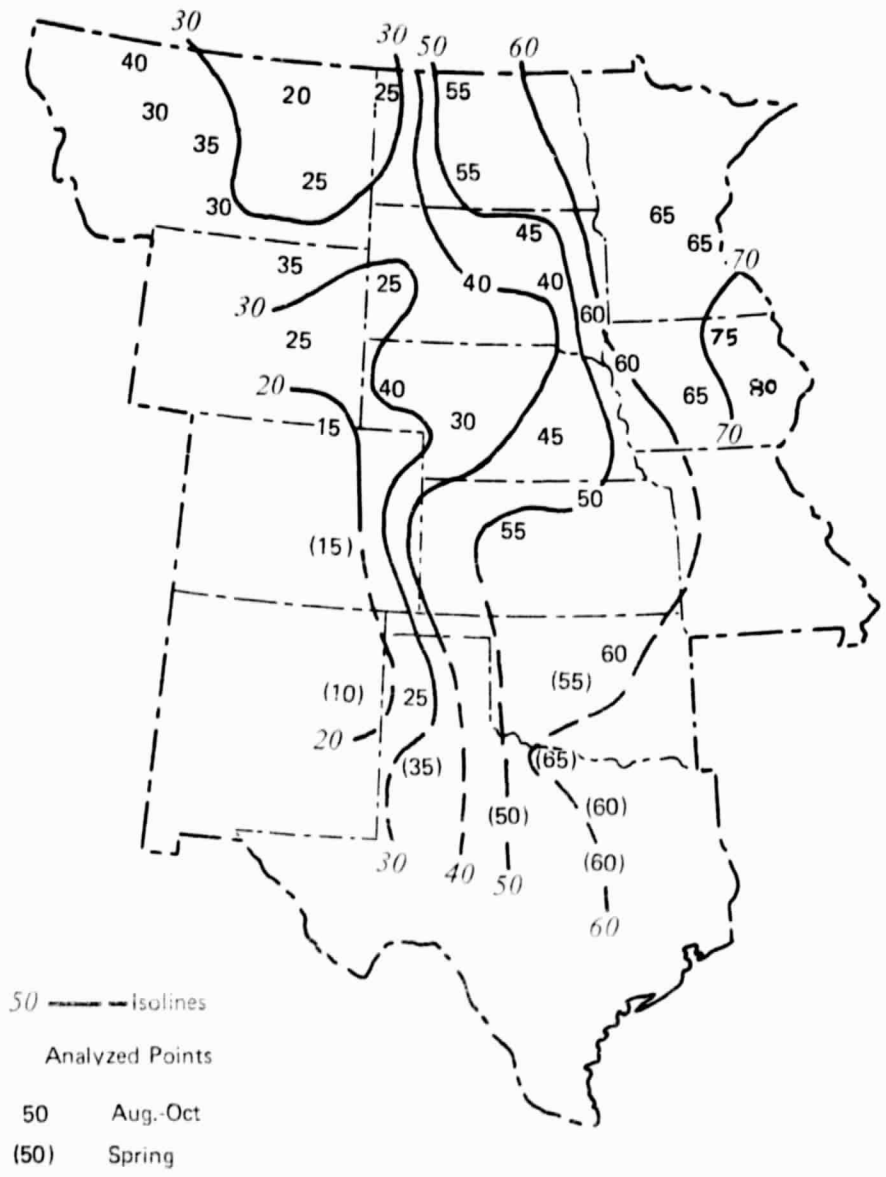
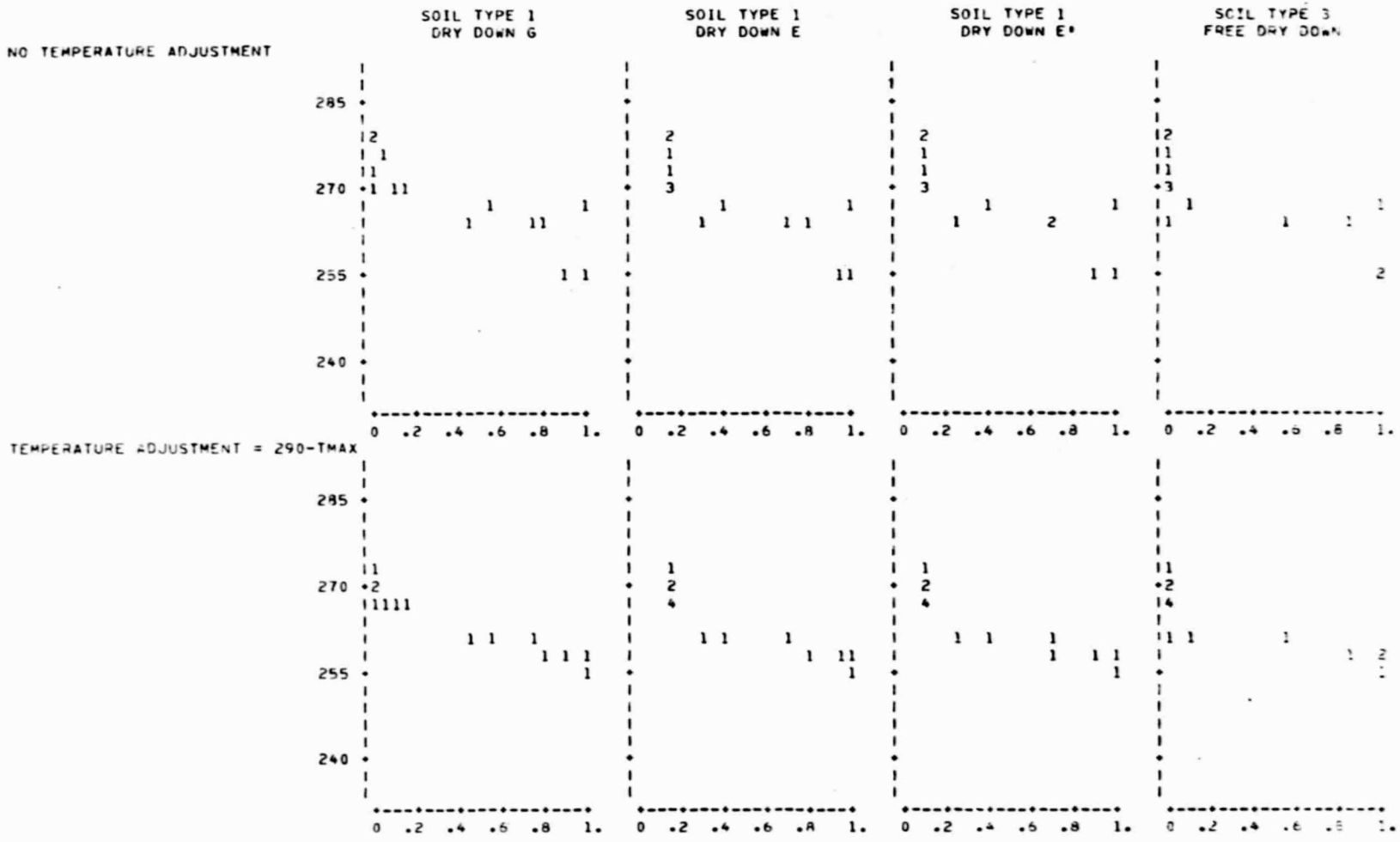


FIGURE 3: Estimated percentage of vegetative cover based on LANDSAT imagery.



CORRELATION COEFFICIENTS (NO. OF PTS.)

	SOIL TYPE 1 DRY DOWN G	SOIL TYPE 1 DRY DOWN E	SOIL TYPE 1 DRY DOWN E'	SOIL TYPE 3 FREE DRY DOWN
NO TEMP. ADJUSTMENT				
ALL DATA POINTS	-0.842 (14)	-0.809 (14)	-0.802 (14)	-0.764 (14)
FRAC. SAT. > 0	-0.808 (10)	-0.809 (14)	-0.802 (14)	-0.565 (7)
FRAC. SAT. > 0.1	-0.726 (9)	-0.809 (14)	-0.727 (9)	-0.609 (6)
WITH TEMP. ADJUSTMENT				
ALL DATA POINTS	-0.960 (14)	-0.904 (14)	-0.904 (14)	-0.820 (14)
FRAC. SAT. > 0	-0.972 (10)	-0.904 (14)	-0.904 (14)	-0.834 (7)
FRAC. SAT. > 0.1	-0.962 (9)	-0.904 (14)	-0.900 (9)	-0.750 (6)

FIGURE 4: Daytime brightness temperature (T_B, ° K) vs. fractional saturation in top soil zone for Kansas City, Missouri. Estimated vegetative cover is 50%.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

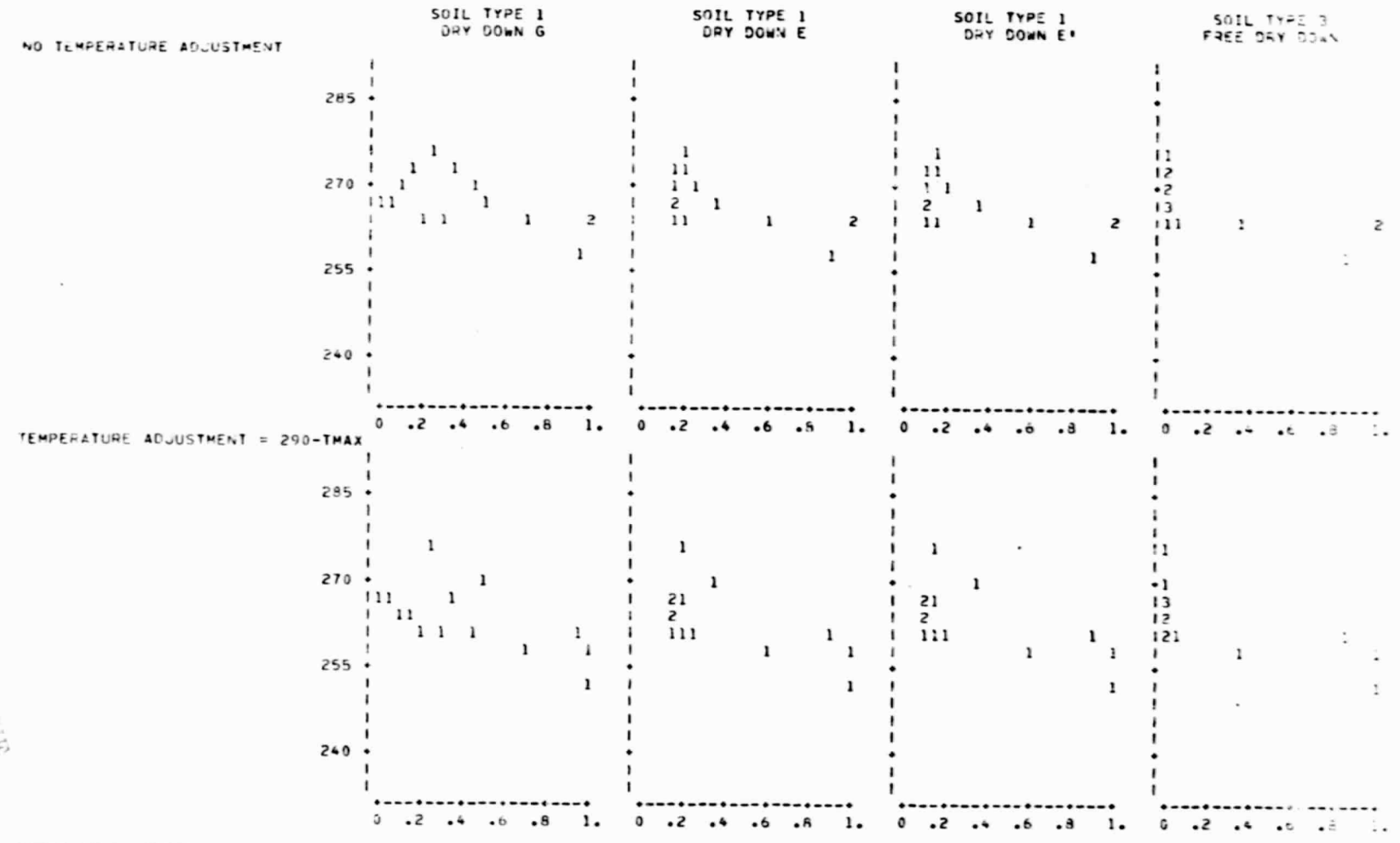
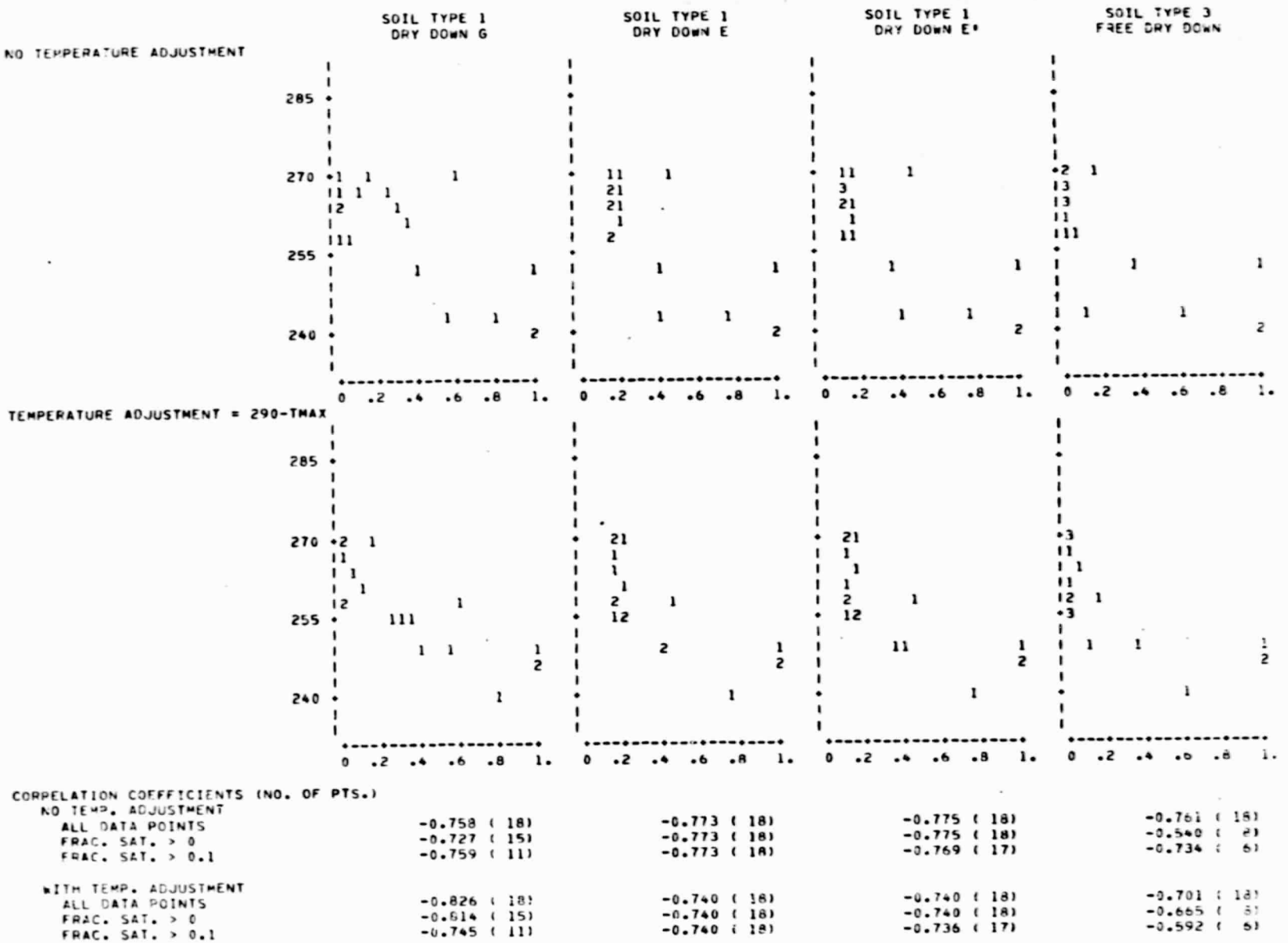


FIGURE 5: Daytime brightness temperature (T_B, ° K) vs. fractional saturation in top soil zone for Des Moines, Iowa. Estimated vegetative cover is 65%.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR



CORRELATION COEFFICIENTS (NO. OF PTS.)

NO TEMP. ADJUSTMENT				
ALL DATA POINTS	-0.758 (18)	-0.773 (18)	-0.775 (18)	-0.761 (18)
FRAC. SAT. > 0	-0.727 (15)	-0.773 (18)	-0.775 (18)	-0.540 (8)
FRAC. SAT. > 0.1	-0.759 (11)	-0.773 (18)	-0.769 (17)	-0.734 (6)
WITH TEMP. ADJUSTMENT				
ALL DATA POINTS	-0.826 (18)	-0.740 (18)	-0.740 (18)	-0.701 (18)
FRAC. SAT. > 0	-0.814 (15)	-0.740 (18)	-0.740 (18)	-0.665 (8)
FRAC. SAT. > 0.1	-0.745 (11)	-0.740 (18)	-0.736 (17)	-0.592 (6)

FIGURE 6: Daytime brightness temperature (T_B, ° K) vs. fractional saturation in top soil zone for Williston, N. Dakota. Estimated vegetative cover is 25%.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

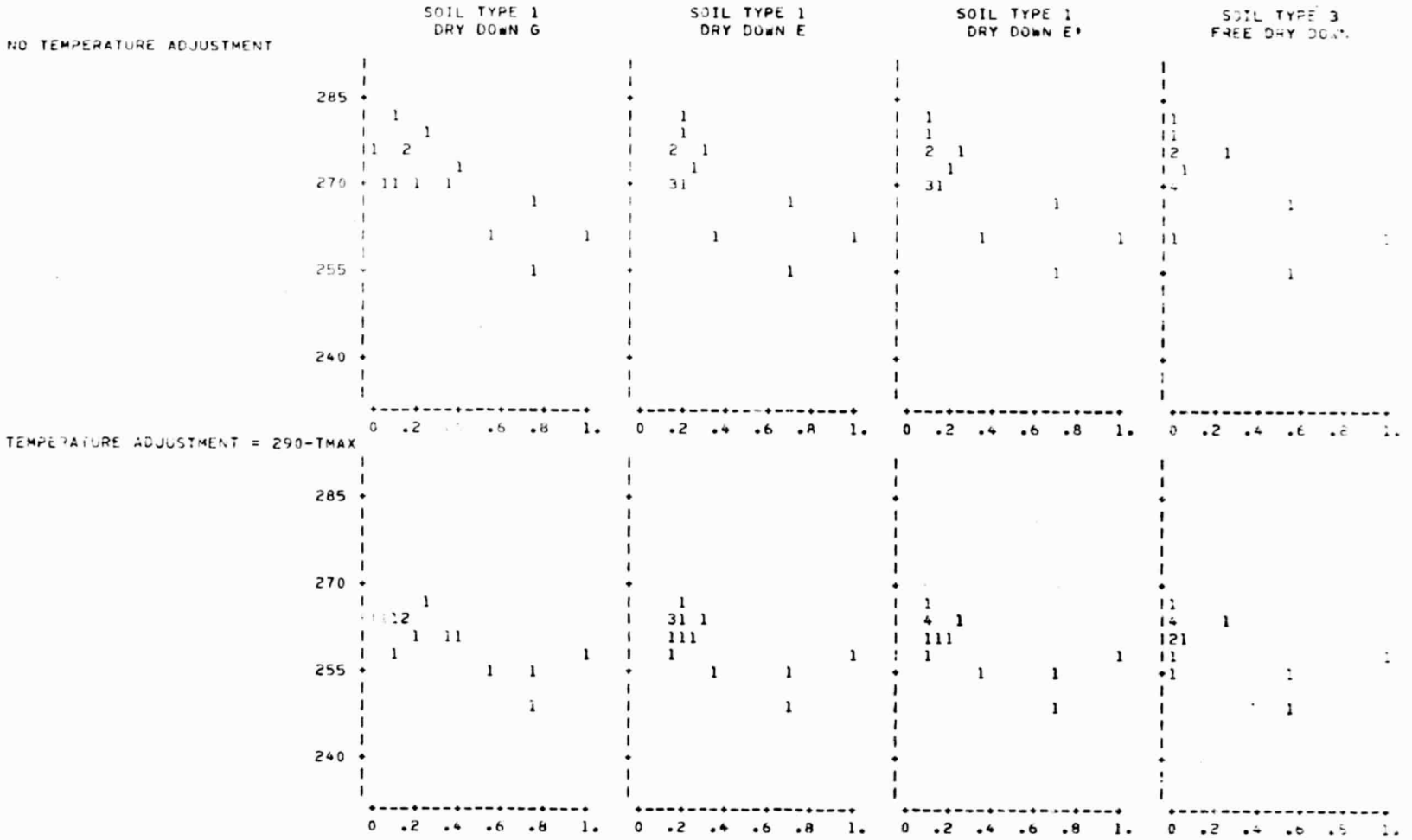
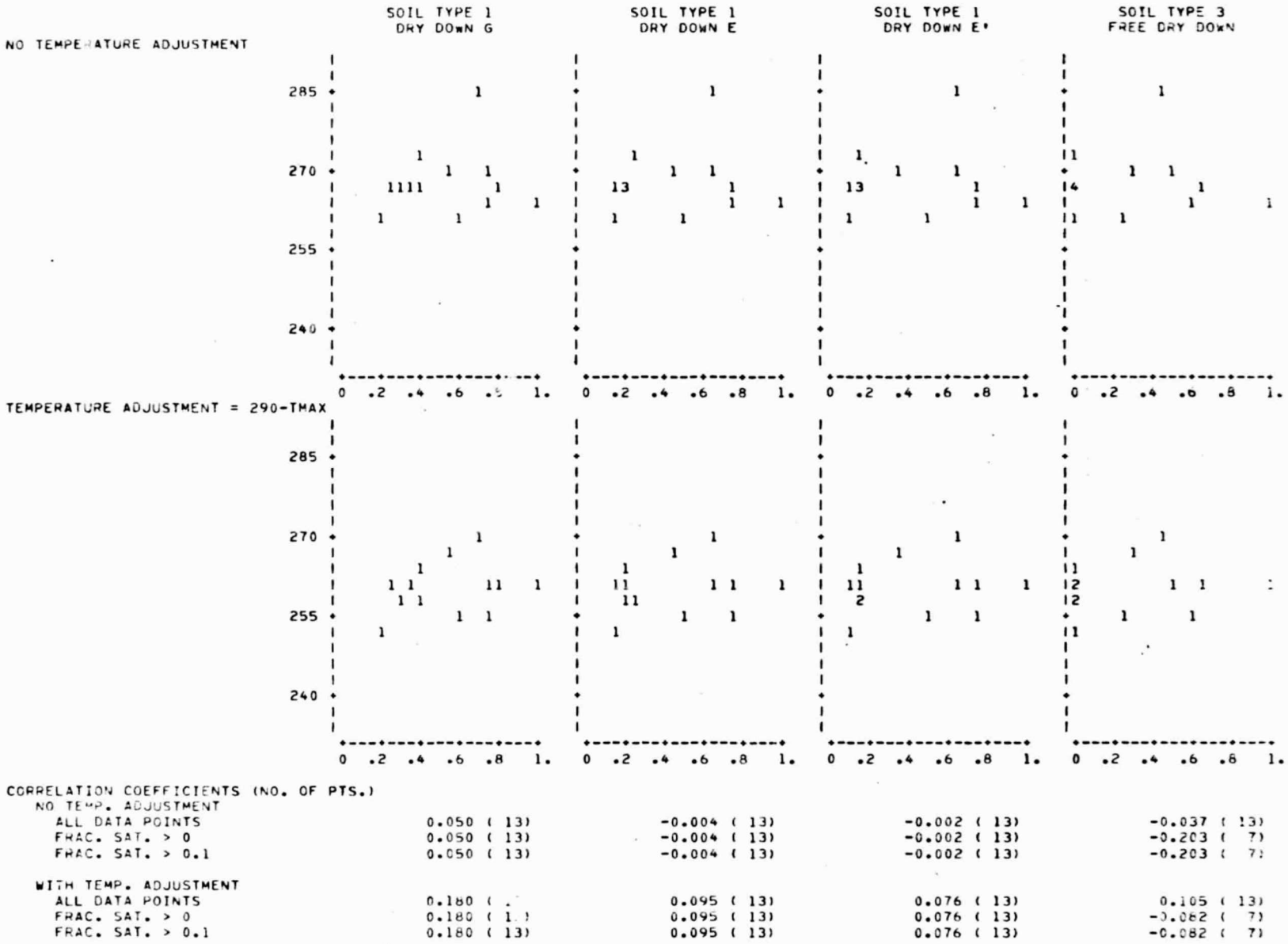


FIGURE 7: Daytime brightness temperature (T_B, ° K) vs. fractional saturation in top soil zone for Oklahoma City, Oklahoma. Estimated vegetative cover is 55%.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



CORRELATION COEFFICIENTS (NO. OF PTS.)

NO TEMP. ADJUSTMENT				
ALL DATA POINTS	0.050 (13)	-0.004 (13)	-0.002 (13)	-0.037 (13)
FRAC. SAT. > 0	0.050 (13)	-0.004 (13)	-0.002 (13)	-0.203 (7)
FRAC. SAT. > 0.1	0.050 (13)	-0.004 (13)	-0.002 (13)	-0.203 (7)
WITH TEMP. ADJUSTMENT				
ALL DATA POINTS	0.180 (13)	0.095 (13)	0.076 (13)	0.105 (13)
FRAC. SAT. > 0	0.180 (13)	0.095 (13)	0.076 (13)	-0.082 (7)
FRAC. SAT. > 0.1	0.180 (13)	0.095 (13)	0.076 (13)	-0.082 (7)

FIGURE 8: Daytime brightness temperature (T_B, ° K) vs. fractional saturation in top soil zone for Tulsa, Oklahoma. Estimated vegetative cover is 60%.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

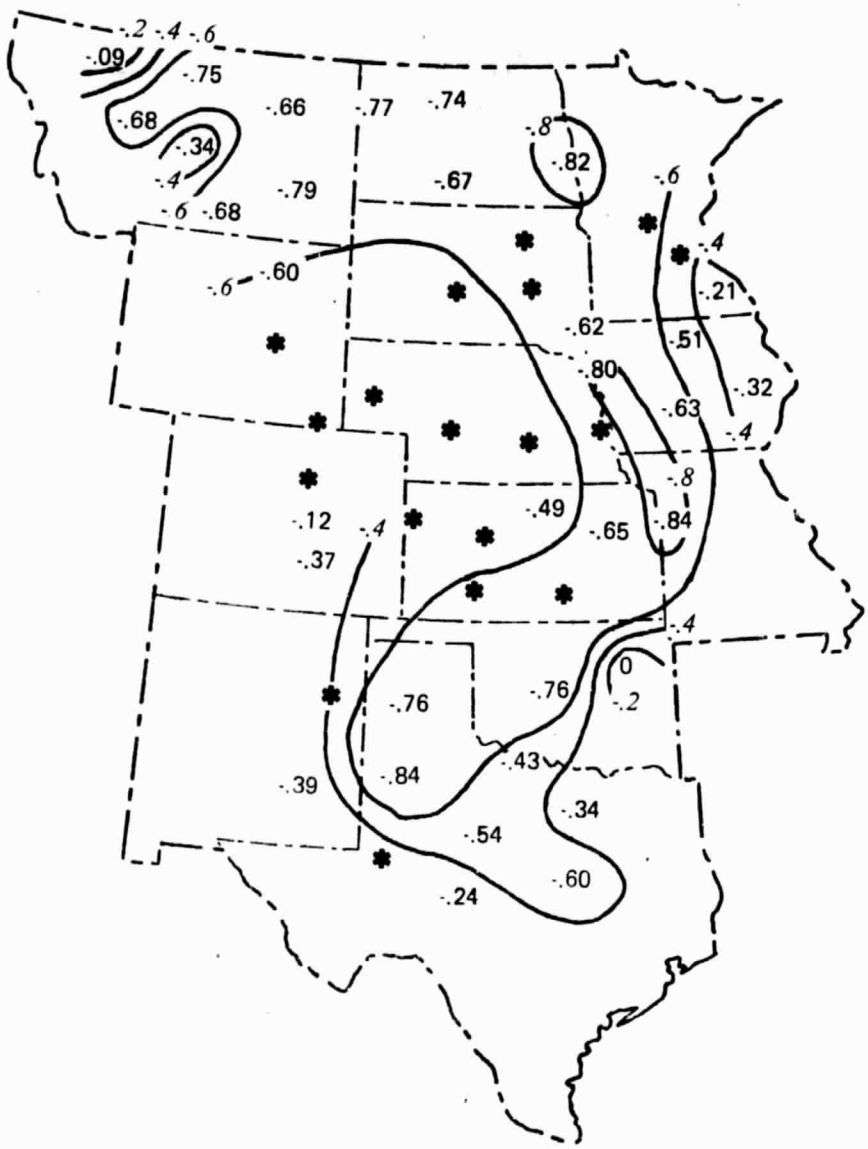


FIGURE 9: Map of correlation coefficients of brightness temperature vs. fractional saturation of soil top zone. Asterisks (*) indicate those stations with too little rainfall to permit computation.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

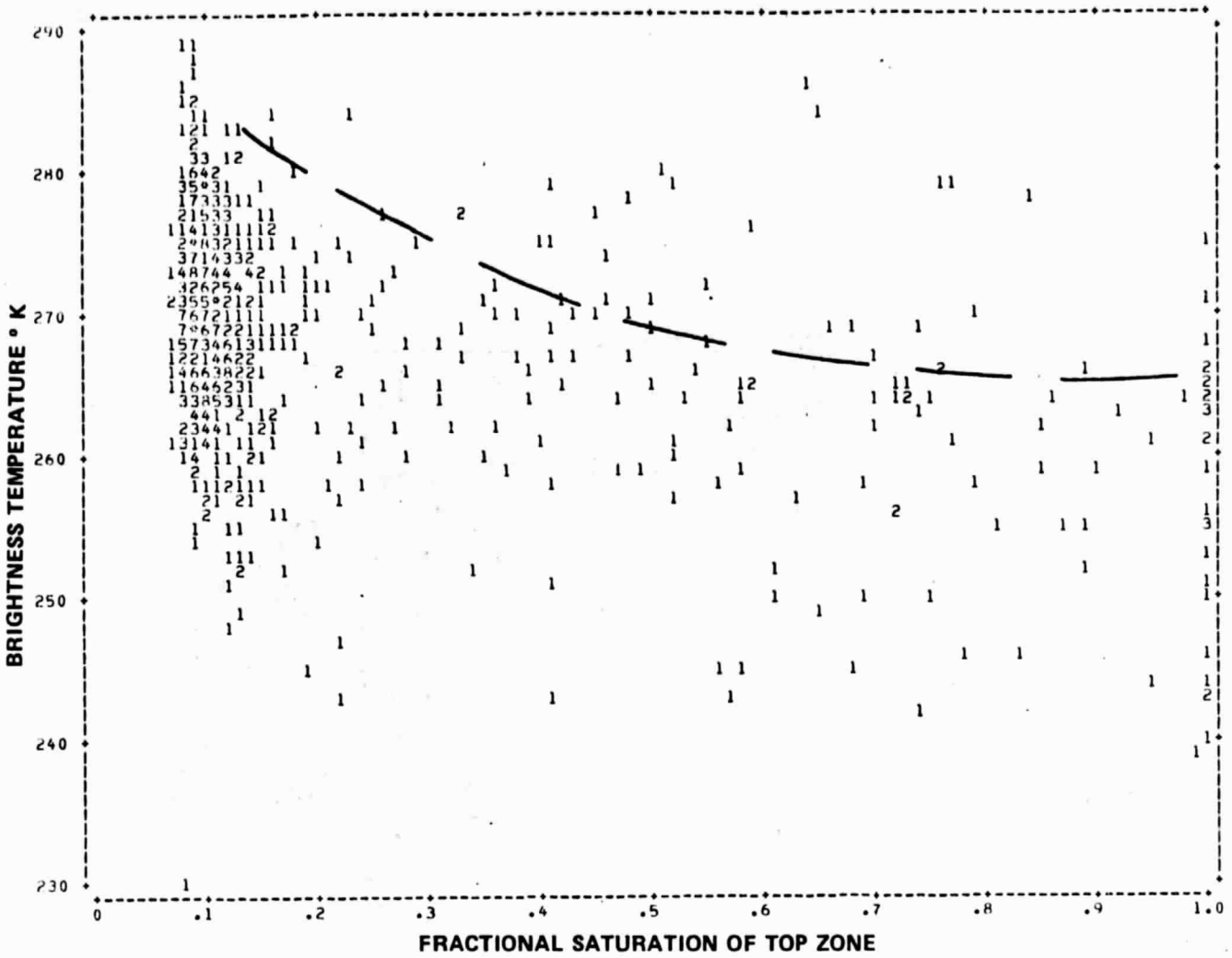


FIGURE 10. Daytime brightness temperature versus fractional saturation of top zone for 52 stations in the United States Great Plains for September - October 1974 and August - October 1975. Numerals give number of data points at each position. Asterisk (*) indicates ten or more. Dashed line defines upper limit of data in Figures 11 through 13.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

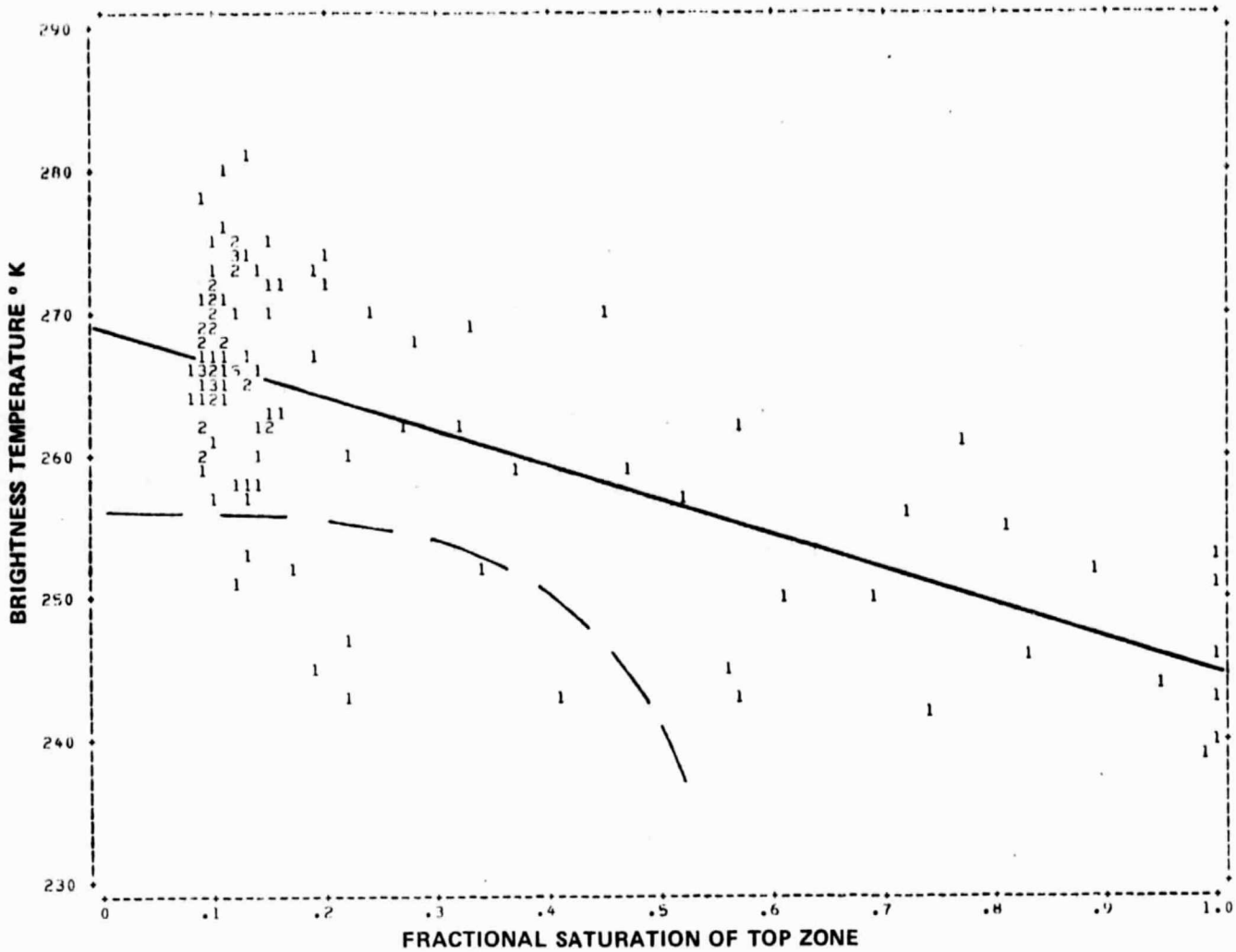


FIGURE 11. Daytime brightness temperature versus fractional saturation of top zone for eight stations in the United States spring wheat belt for September - October 1974 and August - October 1975. Numerals give number of data points at each position. Best-fit linear regression line is shown. Vegetative cover was estimated at 40 % . Dashed line encloses anomalous data points which were investigated more fully.

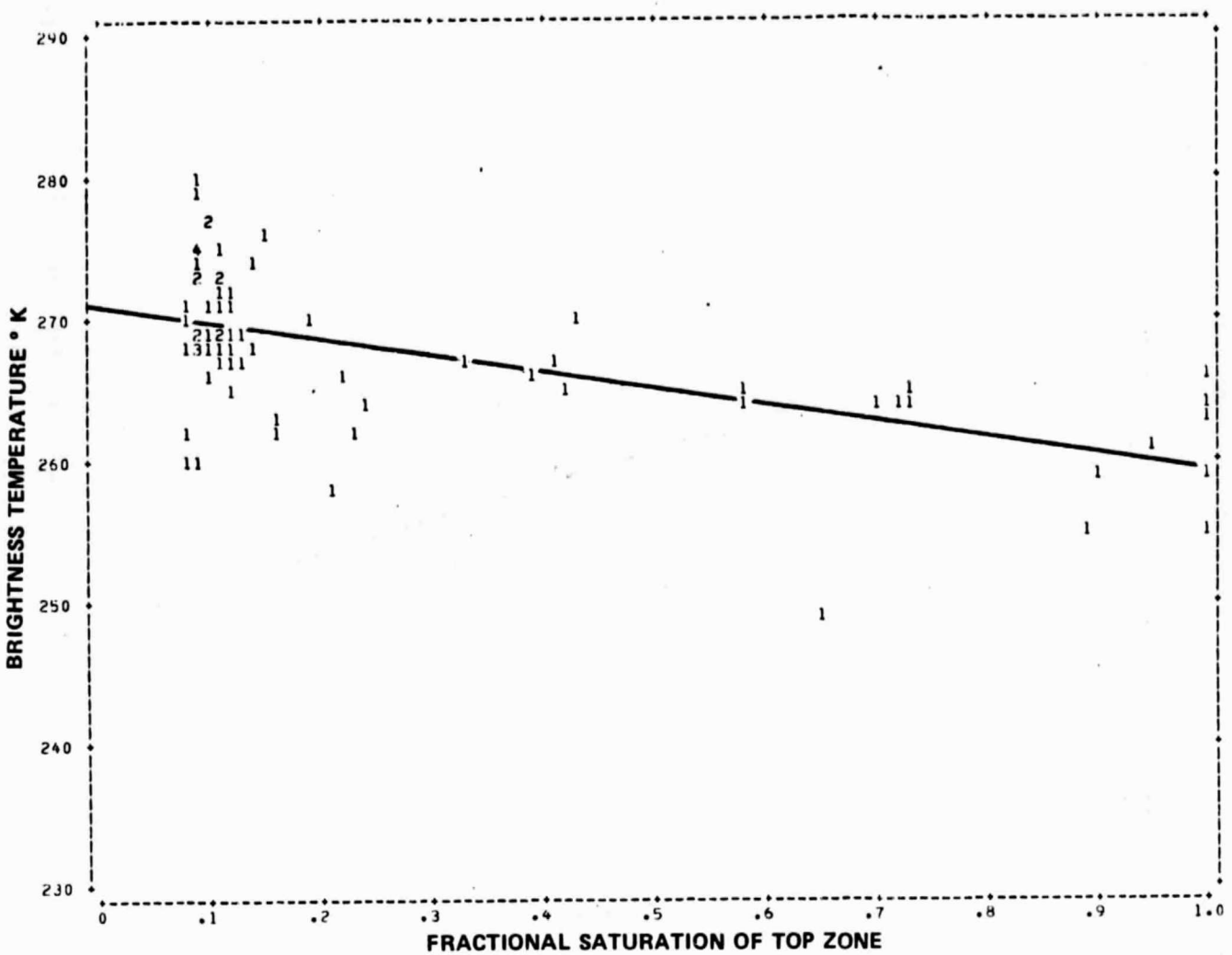


FIGURE 12. Daytime brightness temperature versus fractional saturation of top zone for five stations in the western part of the United States corn belt for September - October 1974 and August - October 1975. Numerals give number of data points at each position. Best-fit linear regression line is shown. Vegetative cover was estimated at about 55 % .

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

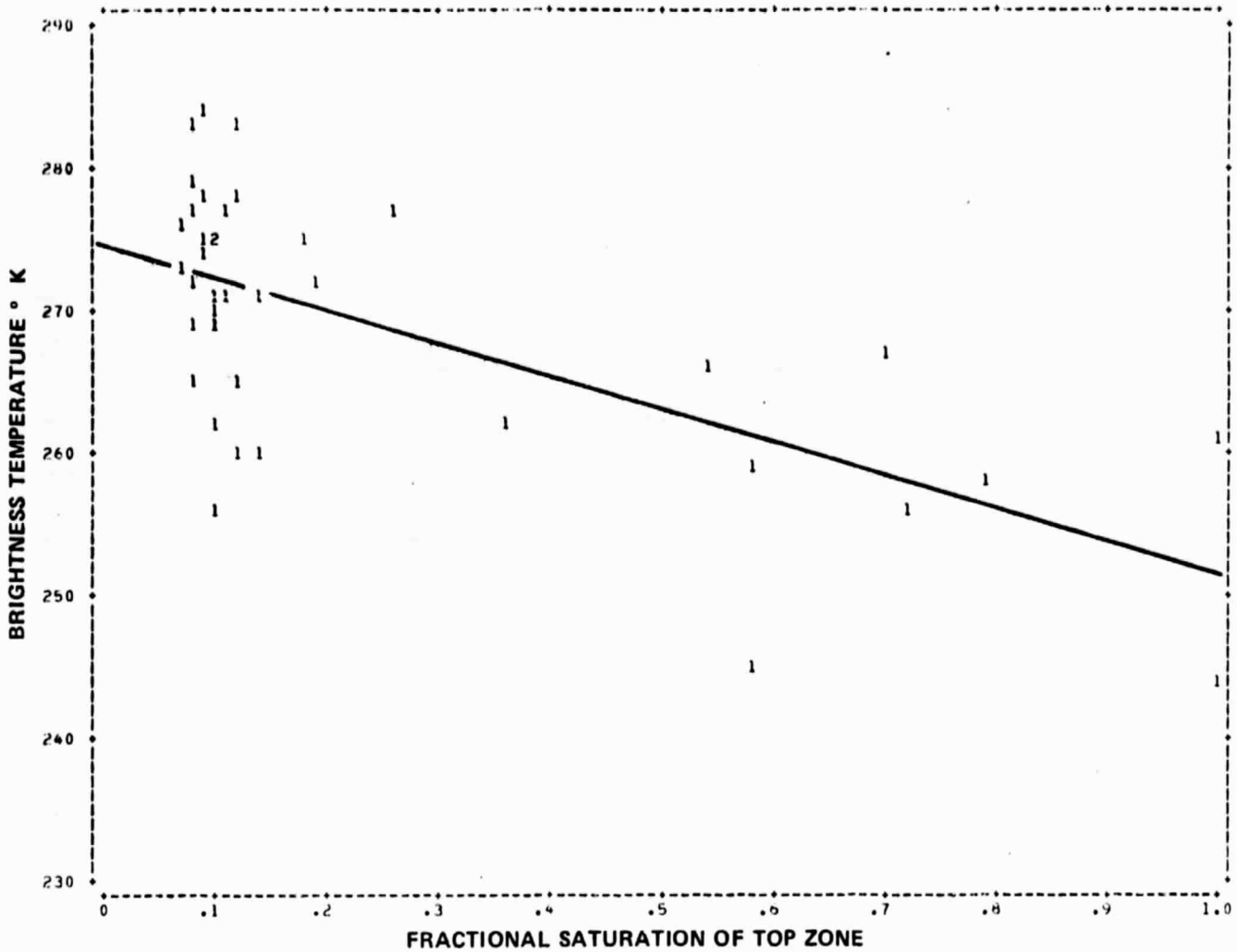


FIGURE 13. Daytime brightness temperature versus fractional saturation of top zone for three stations in the southern part of the United States winter wheat belt for September - October 1974 and August - October 1975. Numerals give number of data points at each position. Best-fit linear regression line is shown. Vegetative cover was estimated at about 40% .

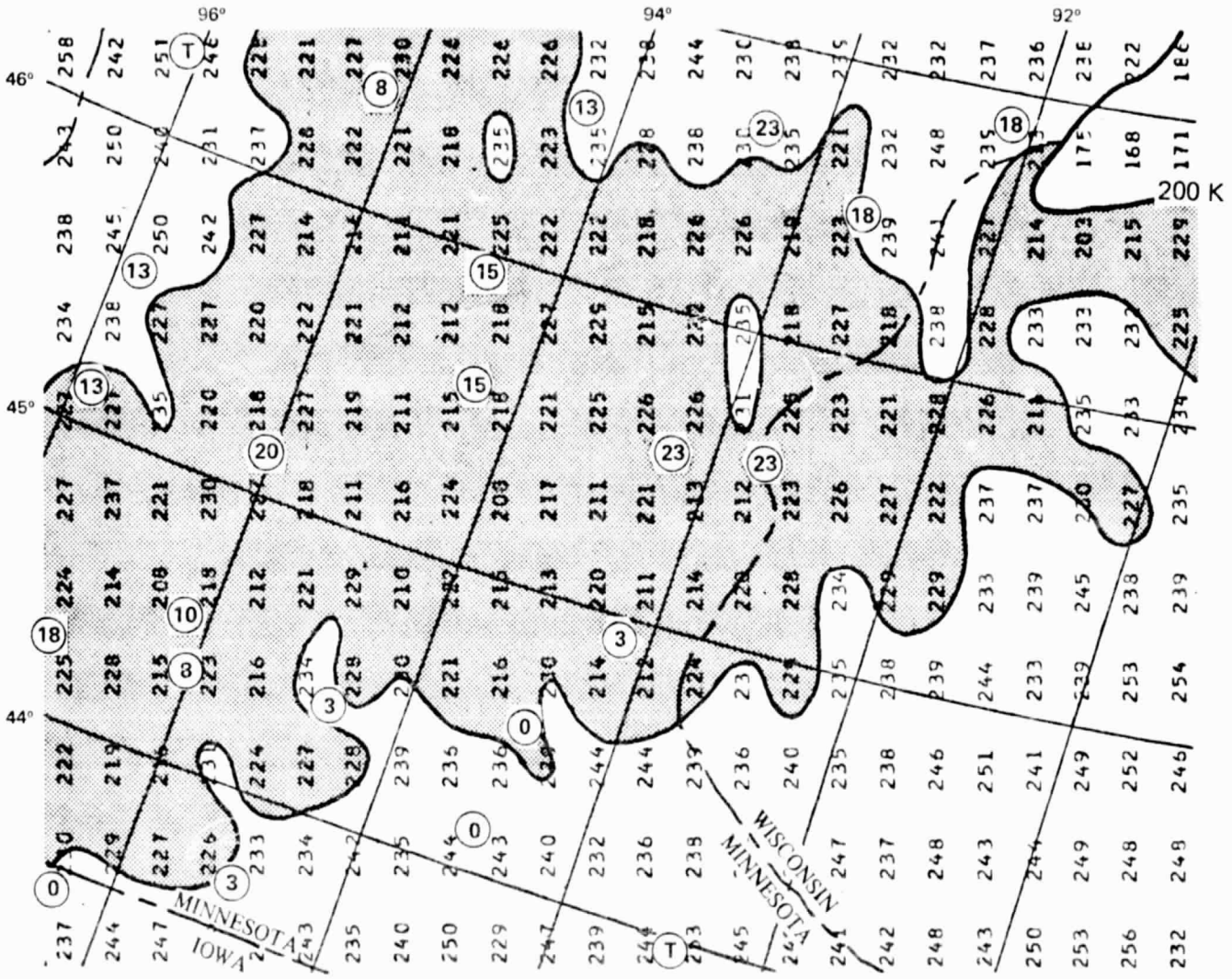


FIGURE 14: Analyzed ESMR-6 map of T_{HOR} over Minnesota, 9 Dec 1975, 1718 GMT. Numbers in circles are snow depth reports in centimeters.

REFERENCES

Baier, W. and Robertson, G.W., A new versatile soil moisture budget. Can. J. Plant Sci., 46, p. 299-315, 1966.

Gloersen, P., Chang, T.C., Wilheit, T.T., and Campbell, W.J., Polar sea ice observations by means of microwave radiometry. NASA-X-652-73-341, 1973.

Meneely, J.M., Application of the Nimbus 5 ESMR to rainfall detection over land surfaces, Final Report, contract NAS5-20878, Earth Satellite Corporation, November 1975.

Nordberg, W., Conaway, J., Ross, D.B., and Wilheit T., Measurements of microwave emission from a foam-covered, wind-driven sea. J. Atmos. Sci., 28, p. 429-435, 1971.

Penman, H.I., Natural evaporation from open water, bare soil, and grass. Proceedings of the Royal Society of London, 193:120-145, 1948.

Sabatini, R.R., Sea-surface wind speed estimates from the Nimbus 5 ESMR, Final Report, contract N66856-4120-5501, Earth Satellite Corporation, February 1975.

Sabatini, R.R., Hlavka, D.L., and Arcese, R., Applications of the Nimbus 5 ESMR to rainfall detection over the oceans and to sea ice detection, Final Report, contract N66314-73-C-1572, Earth Satellite Corporation, April 1975.

Schmugge, T., Gloersen, P., Wilheit, T., and Geiger, F., Remote sensing of soil moisture with microwave radiometers. J. Geophys. Res., 79, p. 317-322, 1974.

Schmugge, T., Wilheit, T., Webster W., Jr., and Gloersen, P., Remote sensing of soil moisture with microwave radiometers - II, NASA TN D-8321, September 1976.

Wilheit, T.T., Rao, N.S.V., Chang, T.C., Rodgers, E.B., and Theon J.S., A satellite technique for quantitatively mapping rainfall rates over the oceans, NASA-X-911-75-72, March 1975.

Williams, G.F., Jr., Microwave radiometry of the ocean and the possibility of marine wind velocity determination from satellite observations. J. Geophys. Res., 74, p. 4591-4594, 1969.