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SATELLITE MICROWAVE OBSERVATIONS OF SOIL MOISTURE VARIATIONS

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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November 1975

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ABSTRACT: The Electrically Scanning Microwave Radiometer (ESMR) on the Nimbus 5 satellite was used to observe microwave emissions from vegetated and soil surfaces over an Illinois-Indiana study area, the Mississippi Valley, and the Great Salt Lake Desert in Utah. Analysis of microwave brightness temperatures (T_B) and antecedent rainfall over these areas provided a way to monitor variations of near-surface soil moisture. Because vegetation absorbs microwave emission from the soil at the 1.55 cm wavelength of ESMR, relative soil moisture measurements can only be obtained over bare or sparsely vegetated soil. In general T_B increases during rainfree periods as evaporation of water and drying of the surface soil occurs, and drops in T_B are experienced after significant rainfall events wet the soil. Microwave observations from space are limited to coarse resolutions (10-25 km), but it may be possible in regions with sparse vegetation cover to estimate soil moisture conditions on a watershed or agricultural district basis, particularly since daily observations can be obtained. Further applications to agriculture and water resources need to be explored.

(KEY TERMS: soil moisture; microwave emission; satellites; agriculture; water resources.)

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T. J. Schmugge, A. Rango and R. Neff[1]

INTRODUCTION

The Nimbus-5 satellite launched on 12 December 1972 carried a new sensor capable of receiving thermal radiation from the earth's surface in the microwave portion of the spectrum. This instrument called the Electrically Scanning Microwave Radiometer (ESMR) receives the thermal radiation at a wavelength of 1.55 cm. The radiometer scans ±50° about the nadir with a spatial resolution of 25 km at the nadir and is therefore capable of mapping the radiation from a 2500 km swath. The satellite is in a sun synchronous orbit at a nominal altitude of 1100 km. The equator crossings are local noon and midnight. In this paper we will describe some of the observations made with this instrument that indicate the potential for using microwaves for water resources monitoring. The microwave region of the spectrum is well suited for water resources applications because of the large contrast between the dielectric properties of water and solid materials. This contrast is apparent when the emissivities for these materials are examined. Table 1 is a listing of emissivities at the 1.55 cm wavelength for several materials, calculated using Fresnel equations for the reflectivity of an electromagnetic wave at a smooth dielectric boundary.

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Because of surface roughness effects, the emissivity of naturally occurring soil surfaces will be somewhat higher than in Table 1. This variation of emissivity has been observed by a radiometer operating at the 1.55 cm wavelength from an aircraft platform (Schmugge, unpublished data, 1975). Figure 1 is a plot of aircraft observed brightness temperature (T_B), i.e., the product of emissivity and surface temperature, versus soil moisture. These data were obtained over bare agricultural fields near Phoenix, Arizona and in the Imperial Valley of Southern California. The soil moisture values are expressed as the percent of field capacity in an attempt to normalize the effect of different soils. There is a 50-60 K variation of T_B between dry and saturated soils. These aircraft observations indicate the sensitivity of the radiometer to soil moisture variations.

Similar direct comparisons of T_B with ground measurements of soil moisture would be very difficult with the Nimbus-5 satellite due to the fact that soil moisture measurements would be needed over large areas. Because these data are not commonly available, we have compared the satellite values of T_B to the antecedent rainfall of a particular area. It is reasoned that recent rainfall totals are indicative of moisture variations in the near-surface soil which is the layer for which the Nimbus-5 radiometer data are most pertinent. Monitoring of antecedent rainfall and T_B variations was conducted for three separate cases and areas; a series of heavy rainfall events over central Illinois and Indiana during June 1973, the heavy rain in the Mississippi Valley in the winter of 1973, and a continuing series of observations of the effect of rain on T_B over the Salt Desert in Utah. The last case has been described elsewhere (Ulaby et al., 1975) and will only be briefly discussed here.

CENTRAL ILLINOIS — INDIANA CASE

During scanning of the Nimbus-5 ESMR data, a low T_B feature was observed during the daylight pass (approximately 12:00 noon) over central Illinois and Indiana on 6 June 1973. Figure 2a is a T_B contour map for the area; the lowest temperatures (<220 K) were about 50-60 K less than the temperatures observed at the same time further to the west over Iowa. This range of T_B values is consistent with the aircraft results presented in Figure 1. A comparison with the total rainfall received in the study area during six days preceding the Nimbus-5 pass (Fig. 2b) indicated that the region with lower brightness temperatures had received greater than 7.5 cm of rain during this period. Upon further examination it was observed that there were other sections of the bi-state area that had received equally heavy rains but whose T_B values were about 20 K higher or about 240 K.

The reason for this difference was clarified after Landsat-1 imagery for the area was studied. The Landsat-1 data were obtained from adjacent passes over Indiana and Illinois on 9 and 10 June 1973. False color infrared images were interpreted with respect to the relative amount of vegetation cover and the results are presented in Figure 2c. The comparison of the three maps indicates that the area with the lowest values of T_B was nearly free of vegetation (due to an extremely late planting of crops) whereas the areas in the southern part of the state which had also received heavy rain possessed a dense vegetation cover. Thus it appears that vegetative cover over wet soil can significantly modify the microwave emission so as to raise a normally low T_B. In this same study area there was another period of heavy rain during 15-20 June. Figure 3 presents the contour maps of T_B on 20 June, the antecedent rainfall for the 15-20 June period, and the Landsat land-cover analysis. Again the correlation of low T_B, heavy rain, and nearly bare ground is consistent with the earlier pass.

In order to examine a rain-free period, the contours of T_B for the daytime pass on 10 June are presented in Figure 4. The weather during the period 6-10 June was clear and dry and would most likely result in significant evaporation of water from the nearly bare soil, thus drying out the near-surface layer. This is reflected in the higher T_B (>280 K) observed over the nearly bare soil areas which previously had received heavy rain during the first week of June (areas getting more than 7.5 cm of rain during this period are shaded in Figure 4). This increase of T_B when the surface layer of the soil dries has been observed for irrigated fields in the aircraft experiment previously discussed. The magnitude of the increase (about 60 K) is also in good agreement with the results from that same aircraft experiment. Another interesting feature is that the lowest T_B is now observed over the densely vegetated area in the southern part of the bi-state area. The T_B in this southern area only increased 10-20 K from 6 to 10 June.

Although the suppression of a large increase in T_B in this southern area may be due in part to the retention of more moisture, it appears more likely that a dense vegetation cover is an effective screen that produces a reduced microwave sensitivity to soil moisture during both wet and dry periods, at least at the 1.55 cm wavelength.

Examination of synoptic weather conditions from 1 to 20 June 1973 indicates that on the dates of microwave analysis (6, 10, and 20 June) no precipitation and little, if any, possible cloud contamination of T_B patterns could have occurred. On 10 June conditions were clear over the entire Illinois-Indiana area. On 6 and 20 June similar cold fronts had passed through the area and were located on the Indiana-Ohio border. No rain and generally clear sky conditions existed over the entire study area at the time of satellite overpass (about 12:00 noon).

MISSISSIPPI VALLEY CASE

On 22 January 1973 a region of low T_B was also observed over the Mississippi Valley with Nimbus-5 ESMR. The contours of T_B are schematically presented in Figure 5. This region of low T_B (shaded area) approximately corresponds to an outwash aquifer, where unconsolidated sand and gravel deposits are capable of storing large amounts of ground-water. The upland areas surrounding the aquifer are predominantly hardwood forests while the aquifer area is primarily agricultural land which would generally have minimal amounts of vegetation in the January time frame. Similar to the Illinois-Indiana case, it was hypothesized that lowered T_B values observed in the valley resulted from saturated soil conditions in response to recent rains. To study this further the average value of T_B and the daily average rainfall for the area were examined. The area of interest is shown in Figure 6 which is a map showing the principal rivers and the boundaries (shaded areas) between the uplands and the aquifer area. The study area was divided into two parts: (1) a northern region from the confluence of the Ohio and Mississippi Rivers down to Memphis, Tennessee and extending from the Mississippi River to the western upland boundary, and (2) a southern region along the Mississippi River from Memphis to Vicksburg, Mississippi stretching from the river to the eastern upland boundary. The average values of T_B for the two regions were calculated about every other day when the satellite track was approximately centered over the area so that only data within ±30° of nadir were used. The results for the northern region are shown in Figure 7 and compared with the average daily rainfall. The average rainfall over the northern region was determined by averaging 0800 data from 28 stations. In general low values of T_B were observed for the period immediately after a heavy rainfall, e.g. the sharp drop in T_B observed around 20 January. This was generally followed by a gradual warming trend as the area dried out. The anomalous values (e.g. the value on 7 January) were days on which precipitation was occurring during the satellite overpass. The effect of rain over oceans has been to raise observed T_B above the low value observed for water ($T_B \sim 130\,K$). For example a T_B as high as 250 K over the Gulf of Mexico was observed for rainfall rates on the order 10 mm/hr (Wilheit, et al., 1975). There would also be a rise in

T_B over land when the T_B of the ground is less than the temperature of the rain cloud such as would be the case for wet ground. Estimates of rainfall from ESMR are not easy to obtain over land because the variable and unknown T_B of the ground makes it difficult to determine the emission from the rain. Thus for our purposes the rain obscures the surface and causes several of the anomalous values observed in Figures 7 and 8 (southern region).

Conversely, the effects of non-raining clouds are much less severe because of the smaller size of the liquid water droplets (less than 50μm radius) in these situations. Table 2 is a listing of the effects for three cloud cases calculated using a model developed by Wilheit (unpublished data, 1975). T_B at the satellite was determined assuming a surface temperature of 270 K and surface emissivities of 0.7 and 0.9, wet and dry soil conditions, for the mid-latitude winter standard atmosphere (Valley, 1965). The effect of clouds is seen to be primarily dependent on the amount of liquid water present in the cloud and it is only for the drizzle situation that cloud effects become serious enough to significantly decrease the contrast between warm and cold targets. Therefore, we would expect that during rainfree periods the T_B measured by the satellite radiometer is within about 10 K of that at the surface. The effects calculated for the same situations using the summer atmosphere were qualitatively similar but of a somewhat greater magnitude due to the larger amount of water vapor in the atmosphere.

The results for the southern region using 20 rainfall stations are presented in Figure 8. Again there is the sharp drop in T_B observed after the heavy rains of 22 January 1973. This is followed by a gradual rise until 15 February during which there were several additional rains. For the last half of February, which was dry, there is a sharp rise in T_B, presumably due to the drying out of the surface layer of the soil. Although possibly due to some climatic and/or vegetation factors unique to the southern region, the lack of a decrease of T_B in response to the rains of 5-9 January is not presently understood. Aside from this instance, the results indicate that ESMR responds to large soil moisture changes when they occur in this region over a sufficiently wide area.

GREAT SALT LAKE DESERT CASE

The hydrology of the desert area west and south-west of the Great Salt Lake is distinctly different from the previous two situations. The desert is an intermountain basin which generally drains into the Great Salt Lake by means of sub-surface water movement. The water table is located less than one meter beneath the surface near the center of the desert and between 2 and 3 meters deep at the margins (Nolan, 1928). The values of T_B observed over the desert in June 1973 were significantly lower than the surrounding area. This result was observed with both ESMR and the 2.2 cm and 21 cm radiometers on board Skylab. A complete discussion of microwave observations is documented by Ulaby, et al. (1975) and only the ESMR observations pertinent to the previously described studies in the Illinois-Indiana and Mississippi Valley areas are presented here.

The contours of T_B from the daytime pass on 5 June 1973 for the Great Salt Lake Desert are presented in Figure 9. The minimum T_B over the desert was less than 220 K or about 60 K cooler than the surrounding areas. For the following night pass the minimum over the Salt Desert remained about the same but the T_B of the surrounding desert decreased by about 20 K, to less than 260 K. The minimum values of T_B for the Salt Desert from the daytime passes for an 18-month period from June 1973 to December 1974 were subsequently studied. These data were compared with the value of T_B for a spot 60 km west of the desert which indicated the seasonal variations to be expected for the terrain surrounding the desert area (Fig. 10). In general, T_B for this reference location varies rather smoothly from a maximum of 280 K in July and August down to a minimum of 240 K for January and February and appears to repeat from one year to the next. The minimum T_B over the Great Salt Lake Desert followed a similar sort of seasonal variation with its maximum occurring in July and August. However, the minima were in November in response to the Autumn rains during both years. There is a significant difference in the level of T_B for the summers of 1973 and 1974. The minimum temperatures observed over the Great Salt Lake Desert in the Summer of 1974 were 20-30 K higher than those observed during the Summer of 1973. The rainfall during the Summer of 1974 was only 50 percent of normal while in 1973 it was slightly above normal. The average monthly rainfall for eight stations surrounding the basin is shown on the bottom of Figure 10 and clearly indicates this difference in rainfall for the two Summers. The response to the heavier Autumn rains of November, 1973 and October, 1974 is indicated, and, in particular, the lowest T_B was observed on 18 November 1973 when an average of more than 1 cm of rain was recorded at the eight stations. In this case, it appears that the radiometer may be responding to a combination of surface water resulting from the rain and a connected rise in the level of the water table.

DISCUSSION AND CONCLUSIONS

It has been shown in the Illinois-Indiana case that satellite microwave observations can be used to monitor the relative amount of moisture in the soil, with some qualifications. First, because any significant amount of vegetation absorbs the microwave emission from the soil at the 1.55 cm wavelength, the target area must be bare soil or covered with only low density vegetation for meaningful measurements to result. Second, only moisture in the near surface layer (0-2 cm approximately) of the soil can be monitored at 1.55 cm. Longer wavelengths should provide the capability for observing moisture variations at greater depth. The monitoring of rainfall and microwave brightness temperature (T_B) over nearly bare agricultural land in the Mississippi Valley for two months in 1973 showed that T_B increases were experienced during relatively dry periods and drops in T_B occurred soon after rainfall events. In a somewhat different situation, T_B and rainfall over the Great Salt Lake Desert were monitored for two years. Fluctuations in T_B were related to rainfall events, but the radiometer appeared to be responding to a probable rise in the shallow groundwater table beneath the desert surface. In general the satellite T_B observations provide a means for detecting changes in moisture levels at and beneath the soil surface depending on wavelength. This capability provides a new dimension to the monitoring of water resources with remote sensing.

Because the angular resolution of the passive microwave instruments is determined by the physical size of the receiving antennas, the optimum attainable spatial resolution in the near future will be on the order of 1-10 km, depending on wavelength. This resolution limitation of course restricts the applicability of this technique to observation of large area events such as those described in this paper. Although this coarse resolution will prevent the acquisition of soil moisture conditions for individual fields, it may be possible to estimate soil moisture levels on a watershed or agricultural district basis, particularly if daily observations are employed. These observations will only be possible before the planting of crops and during the early growing season when vegetation cover is sparse. If longer microwave wavelengths ($\geqslant$10 cm) are used, it is speculated that increased transmission through the vegetation canopy will occur. These early season observations should be of great value in deciding on the time and type of crop planting and for general early season irrigation scheduling when the root zone is still in close proximity to the surface. Additionally, these kinds of data have the potential for predicting the location of pest outbreaks (Idso, et al., 1975) because of the sensitivity of pest development to relative soil moisture levels.

The potential value of the microwave observations for soil moisture accounting applications and promising initial results merit further investigations into the effects of vegetation on microwave emission and the microwave sensitivity to soil moisture at longer wavelengths. It is possible that by combining various levels of aircraft and satellite platforms and both passive and active microwave instruments, a truly effective system for the detailed monitoring of soil moisture will be feasible in the future.

ACKNOWLEDGMENTS

The authors would like to thank Mr. L. Allison for his initial efforts in the acquiring of ground data. ESMR principal investigator T. Wilheit also made the ESMR data readily available for this study and was frequently consulted during interpretation of the microwave data.

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Wilheit, T., M. S. V. Rao, T. C. Chang, E. B. Rodgers and J. S. Theon, 1975. A Satellite Technique for Quantitatively Mapping Rainfall Rates Over the Ocean. NASA/Goddard Space Flight Center, Document X-911-75-72, 28 pp.

Table 1

Emissivities of Several Selected Natural Materials (1.55 cm)

Material	Emissivity
Water at 20°C	0.40
Dry Soil	0.94
Wet Soil (above field capacity)	0.60
Pure Ice	0.92

Table 2

Calculated brightness temperature, T_B, for several weather conditions. The density of liquid water (ρ) for 1 km thick stratus clouds is given for reference.

Condition	Transmissivity	Satellite T_B in Kelvins		cm of Liquid Water in Column
		e = 0.7	e = 0.9	
T_B at Surface		189	243	
Clear	0.97	193	244	0
Stratus (ρ = 0.1 g/m)	0.96	194	245	0.01
Dense Stratus (ρ = 0.25 g/m)	0.95	196	245	0.025
Drizzle (0.2 mm/hr)	0.82	211	250	0.18

FIGURE CAPTIONS

Figure 1. The Relationship Between Aircraft (600 m Altitude) Observed Values of Microwave Brightness Temperatures and Soil Moisture for Bare Agricultural Fields Near Phoenix, Arizona in Early March 1972

Figure 2. Comparison of Nimbus 5 ESMR Microwave Brightness Temperatures, Antecedent Rainfall, and Cover Type Over the Illinois-Indiana Area in Early June

Figure 3. Comparison of Nimbus 5 ESMR Microwave Brightness Temperatures, Antecedent Rainfall, and Cover Type Over the Illinois-Indiana Area in Late June

Figure 4. Comparison of Nimbus 5 ESMR Microwave Brightness Temperatures and Cover Type Over the Illinois-Indiana Area in Mid-June.

Figure 5. A Microwave Brightness Temperature Contour Map of the Lower Mississippi Valley on 22 January 1973 (Contour Interval is 10 K).

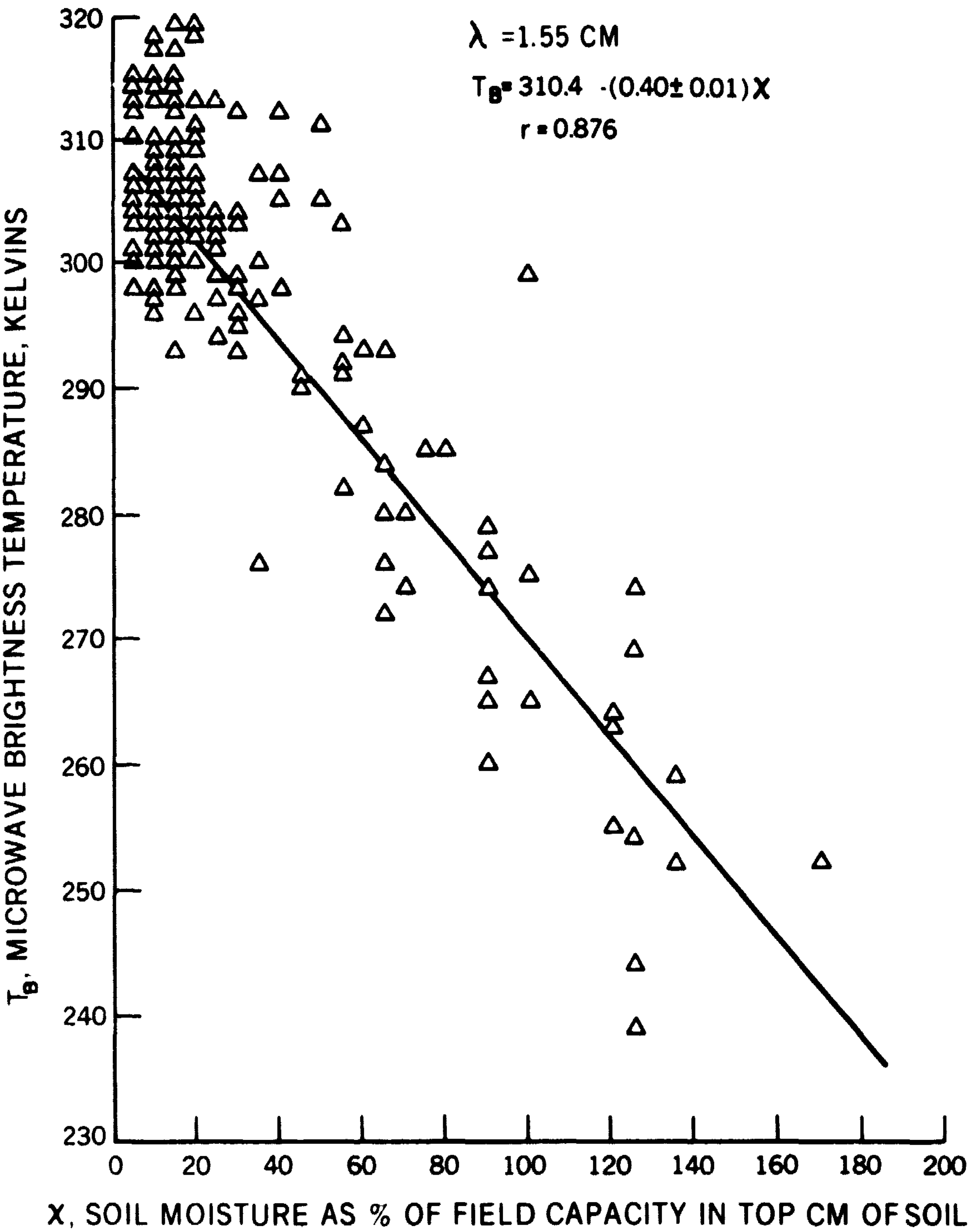
Figure 6. A Map of the Mississippi Valley Study Area Showing the Boundaries Between the Alluvial Aquifer and the Surrounding Uplands as Shaded Areas

Figure 7. Comparison of ESMR Microwave Brightness Temperatures with Average Daily Rainfall for the Northern Mississippi Valley Test Area

Figure 8. Comparison of ESMR Microwave Brightness Temperatures with Average Daily Rainfall for the Southern Mississippi Valley Test Area

Figure 9. ESMR Microwave Brightness Temperature Contours Over the Great Salt Lake Desert Test Site on 5 June 1973 (Ulaby, et al., 1975).

Figure 10. Temporal Variations of the Minimum Recorded ESMR Brightness Temperature Over the Great Salt Lake Desert (X) Compared with the ESMR Brightness Temperature of the Reference Point Outside the Desert (O) Indicated in Figure 9 (Ulaby, et al., 1975)



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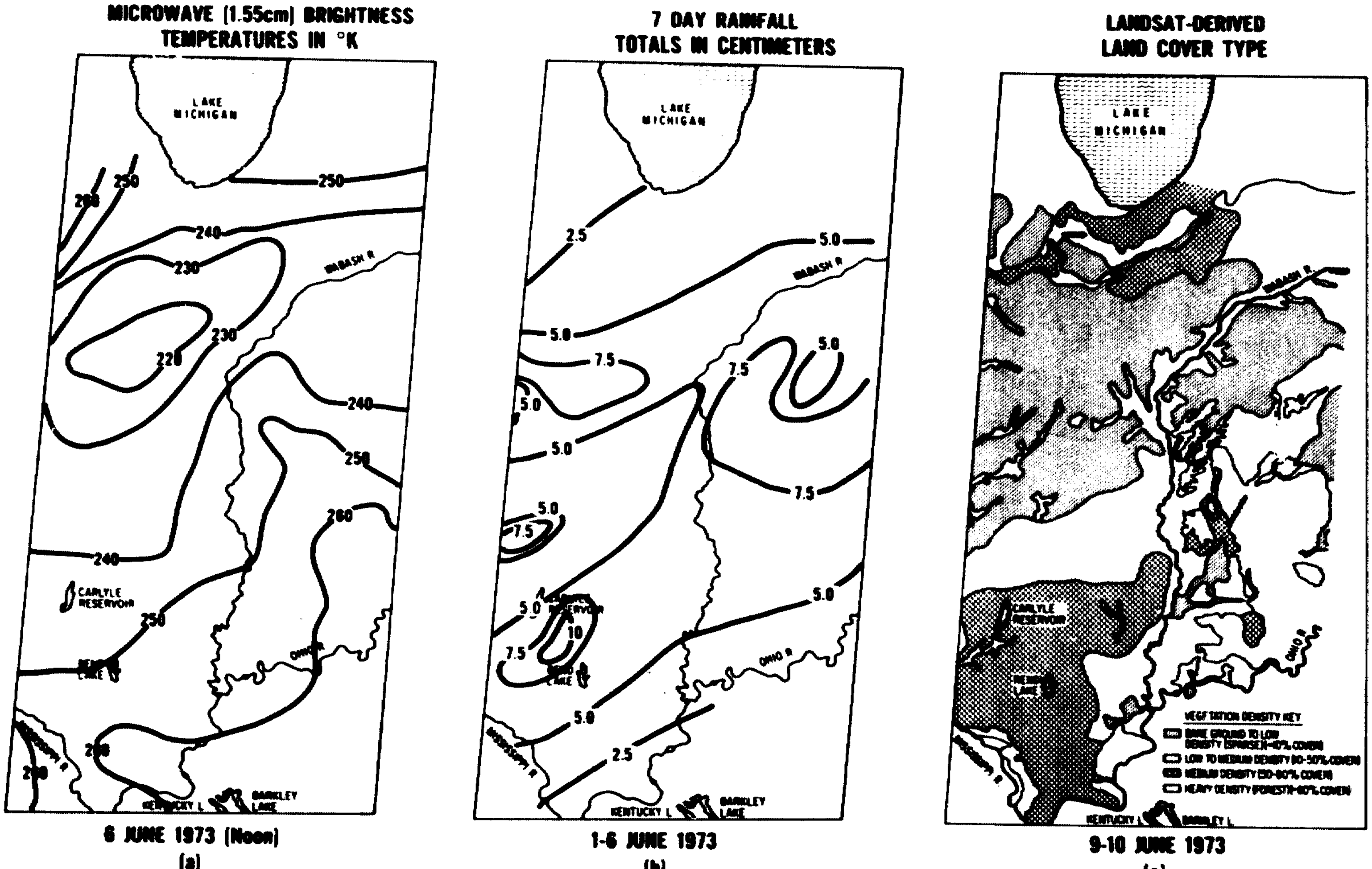

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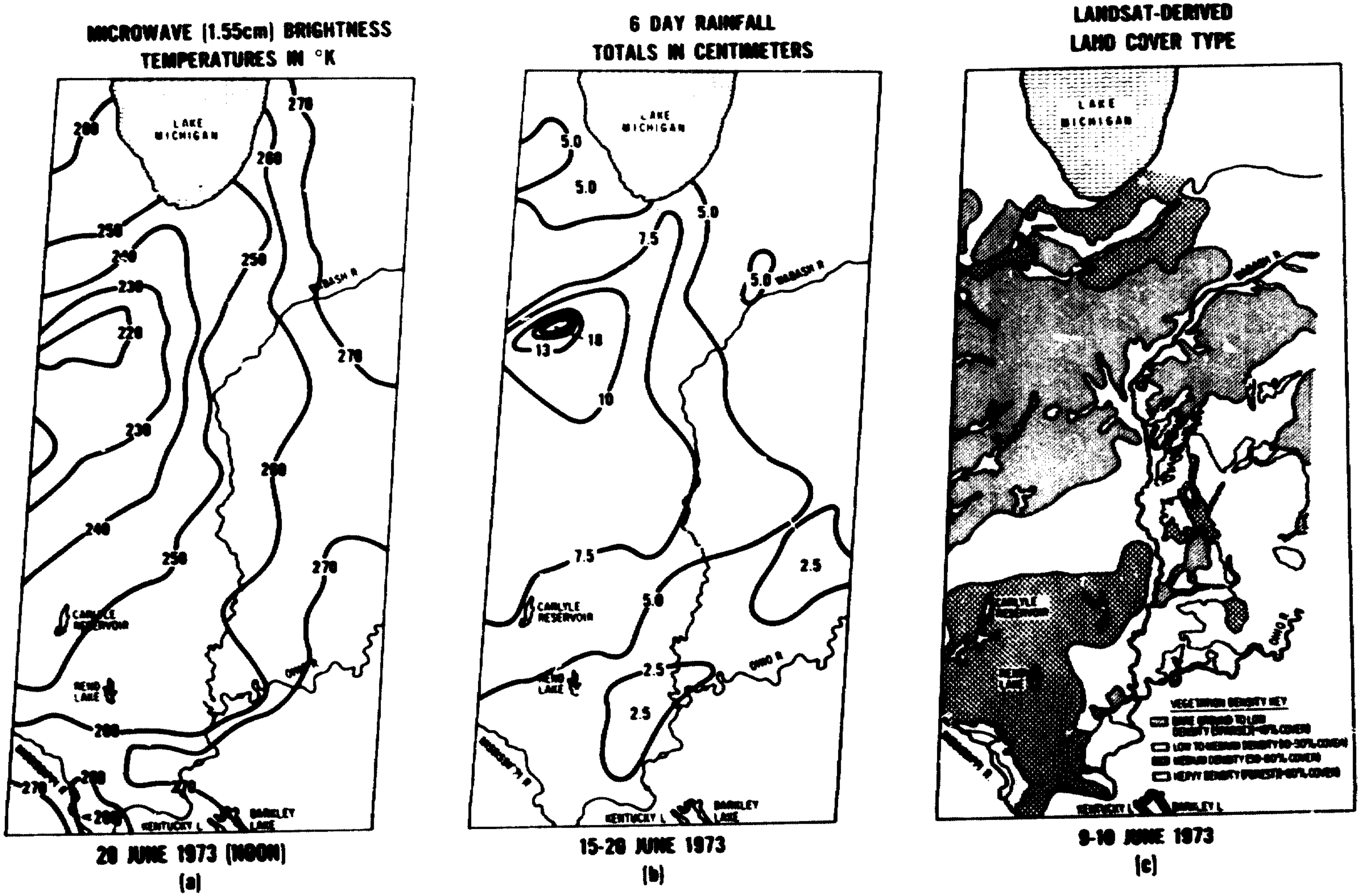
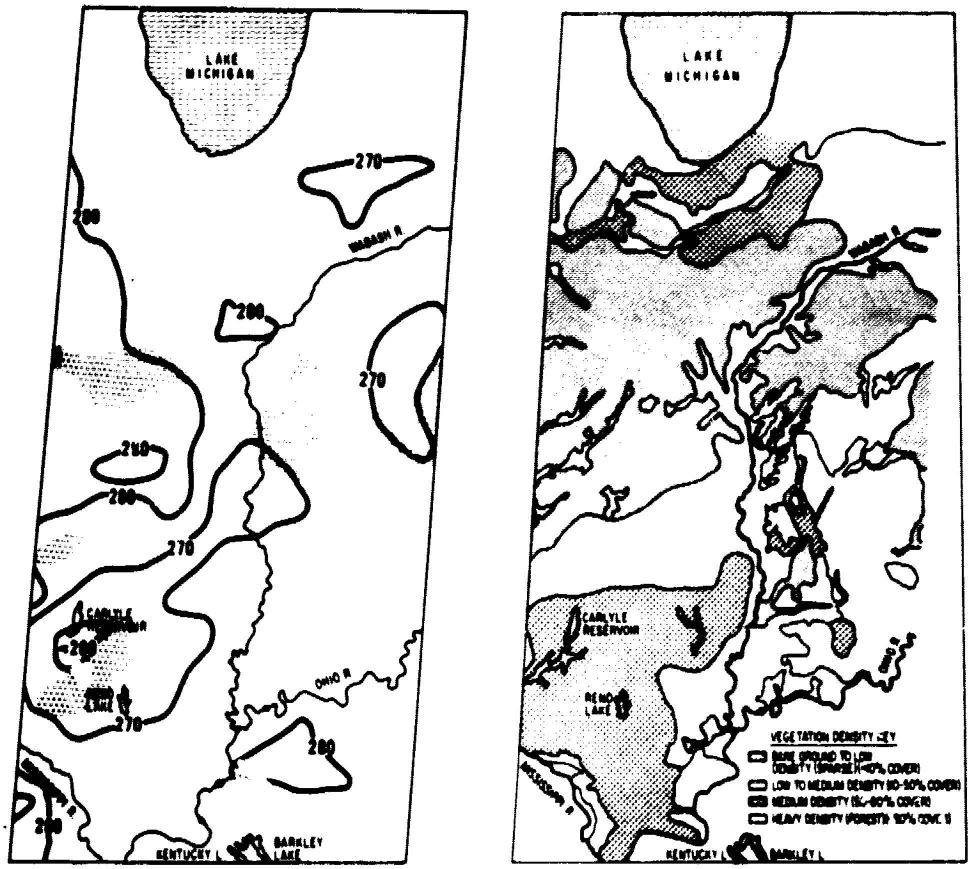


Figure 3. Comparison of Nimbus 5 ESMR Microwave Brightness Temperatures, Antecedent Rainfall, and Cover Type Over the Illinois-Indiana Area in Late June

MICROWAVE (1.55cm) BRIGHTNESS TEMPERATURES IN °K

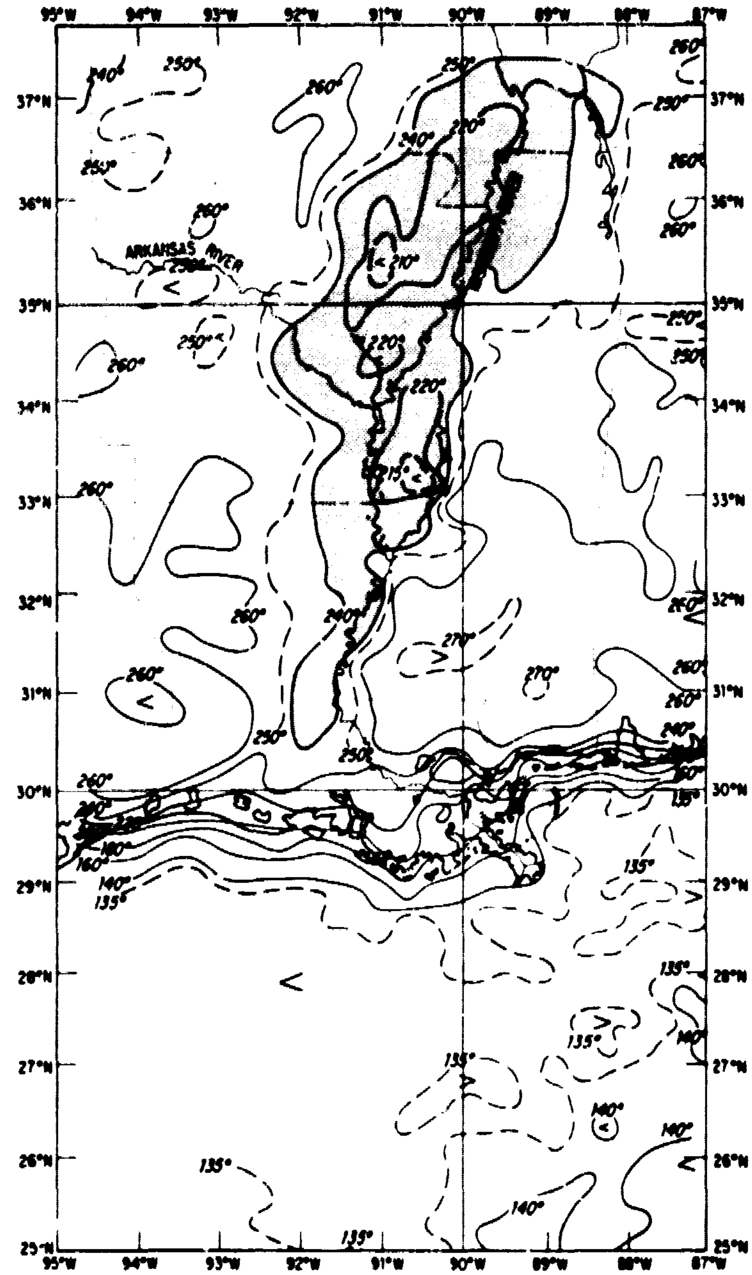
LANDSAT-DERIVED LAND COVER TYPE



10 JUNE 1973
(SHADED AREAS RECEIVED GREATER THAN 7.5 CENTIMETERS OF RAIN 1-6 JUNE 1973)

9-10 JUNE 1973

Figure 4. Comparison of Nimbus 5 ESMR Microwave Brightness Temperatures and Cover Type Over the Illinois-Indiana Area in Mid-June



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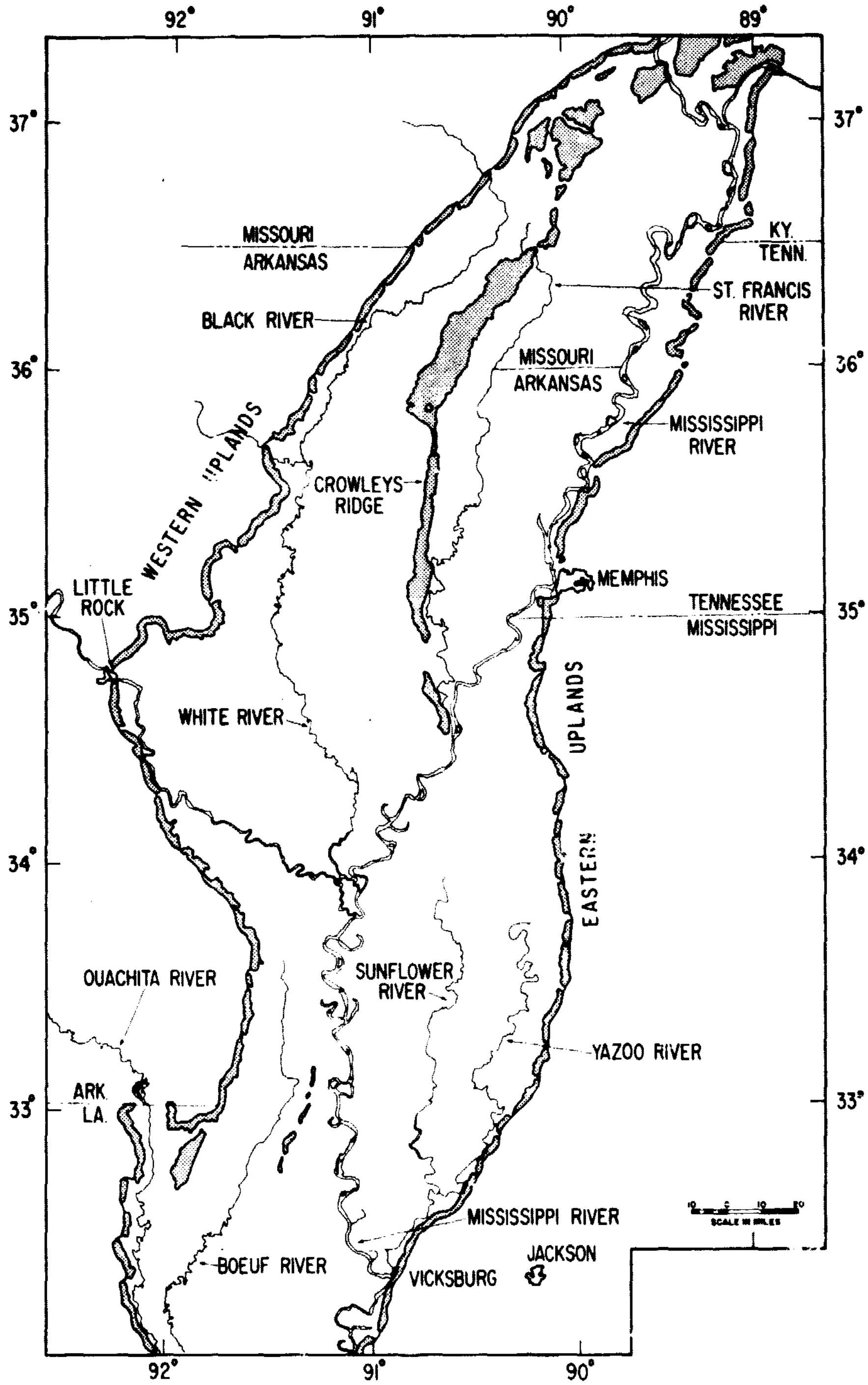

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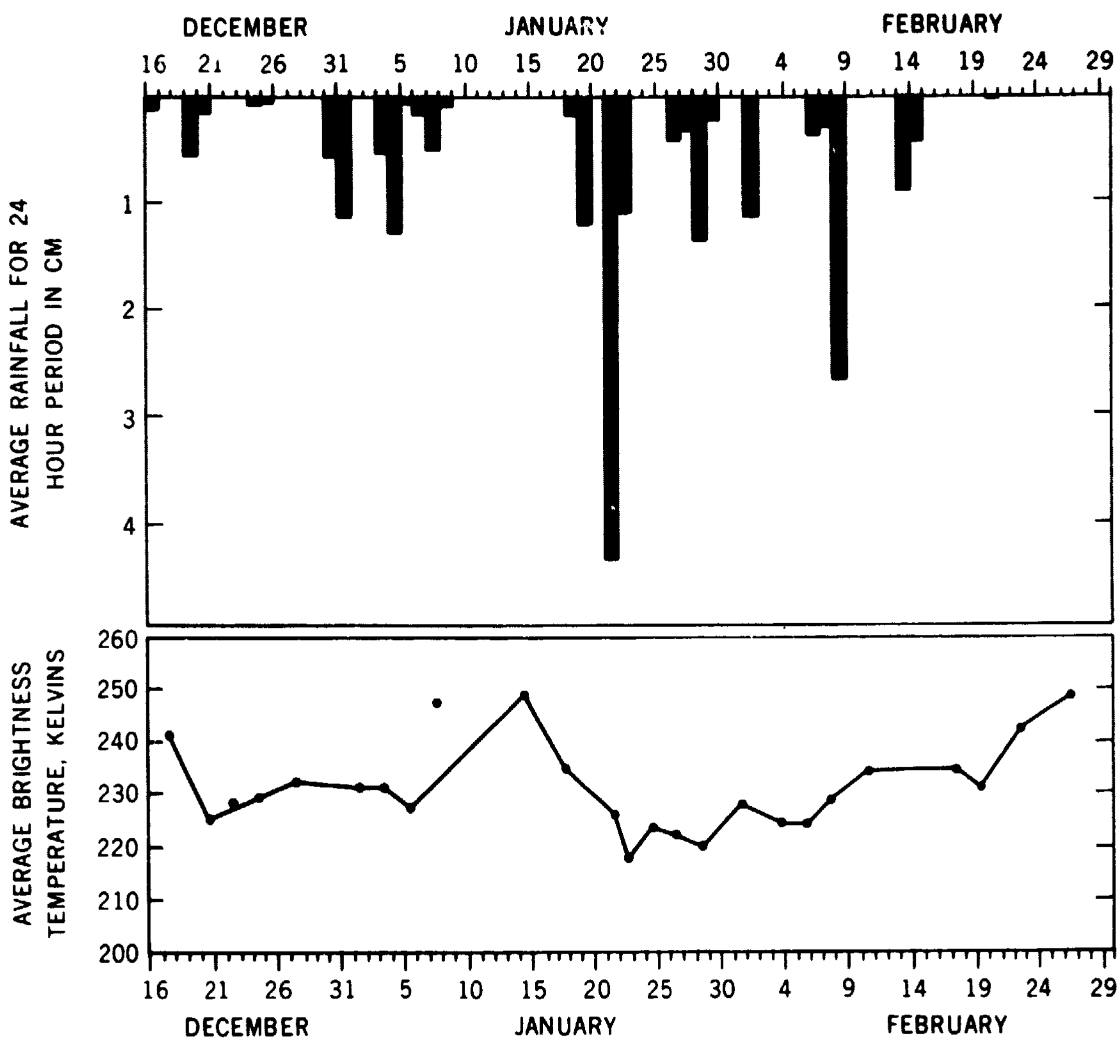

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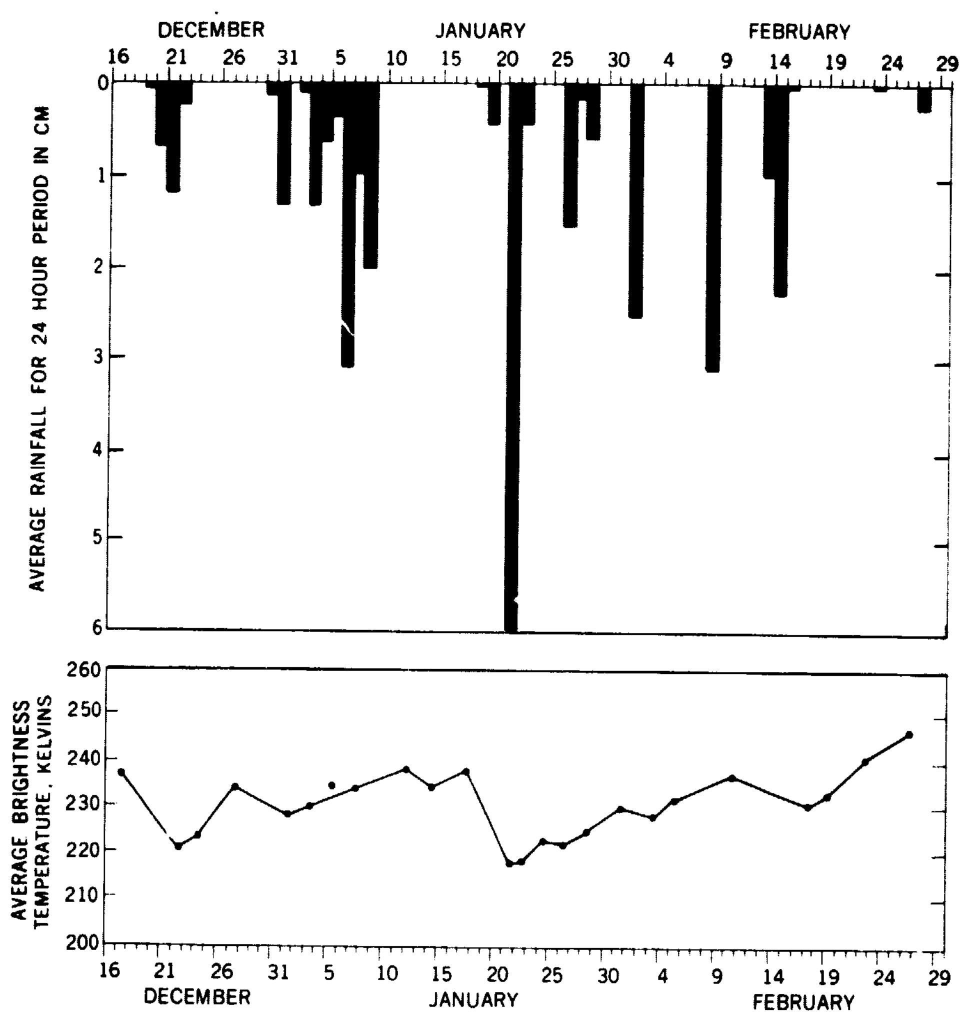

Figure 8. Comparison of ESMR Microwave Brightness Temperatures With Average Daily Rainfall for the Southern Mississippi Valley Test Area

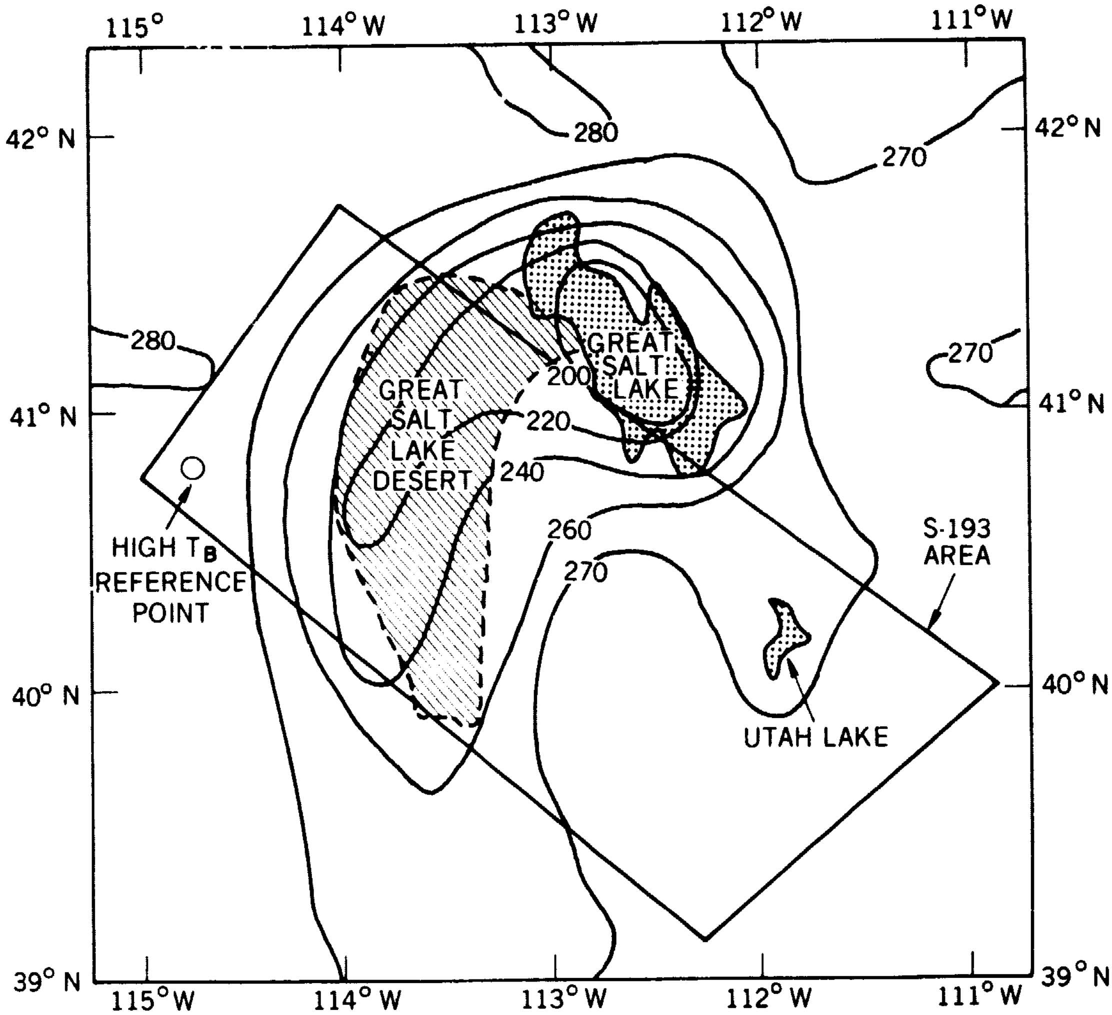

Figure 9. ESMR Microwave Brightness Temperature Contours Over The Great Salt Lake Desert Test Site on 5 June 1973 (Ulaby, et al., 1975)

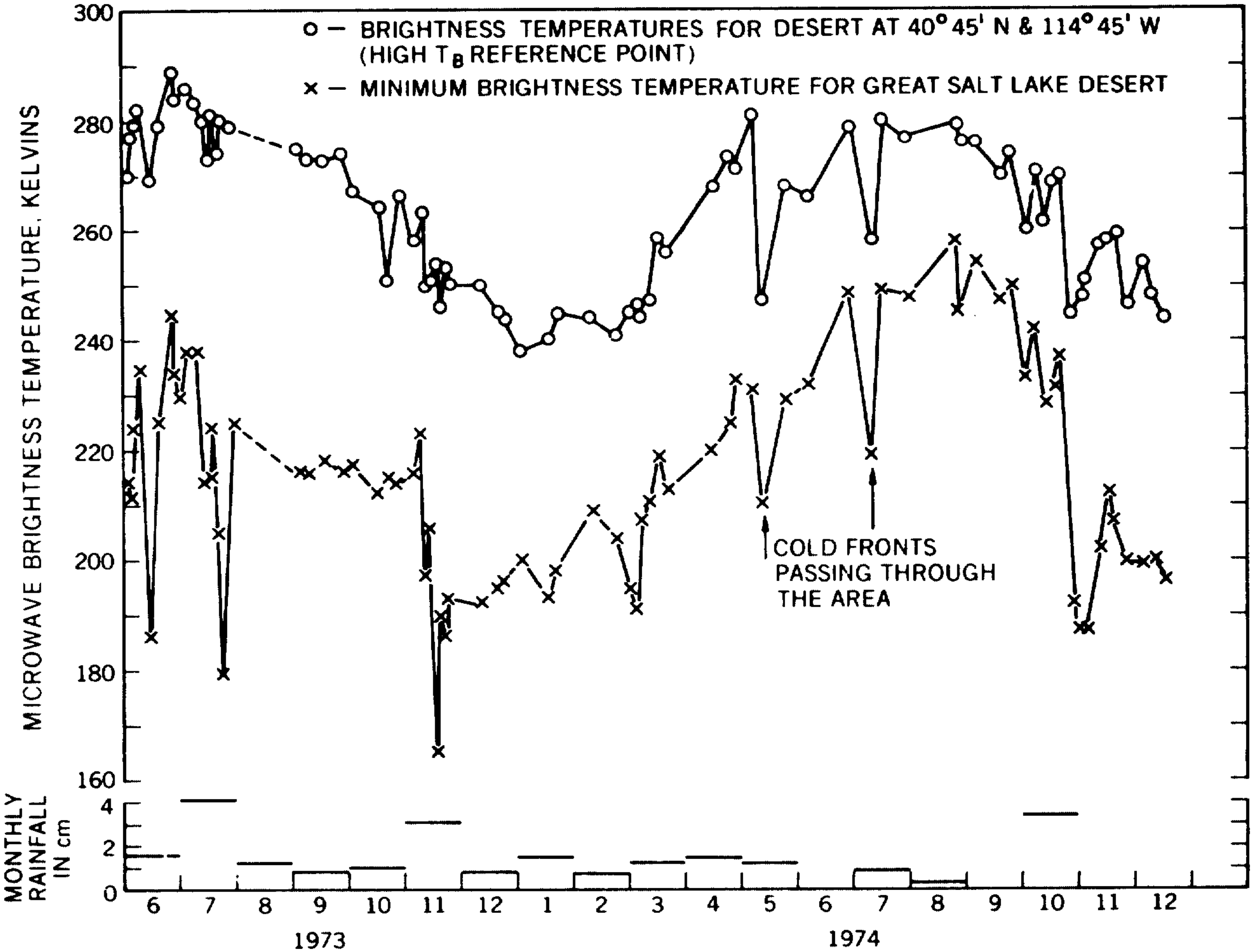

Figure 10. Temporal Variations of the Minimum Recorded ESMR Brightness Temperature Over the Great Salt Lake Desert (X) Compared with the ESMR Brightness Temperature of the Reference Point Outside the Desert (O) Indicated in Figure 9 (Ulaby, et al., 1975)