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AN EVALUATION OF THE SPATIAL RESOLUTION OF SOIL MOISTURE INFORMATION

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ABSTRACT

The objective of this study is to evaluate and quantify the relative merits of soil moisture observations at a 1-km resolution rather than at a 10-km resolution. Soil moisture information is of value for improved runoff prediction and crop yield forecasting, and if soil moisture is to be determined using microwave radiometers from satellites, the resolution requirements have considerable impact on the specification of the satellite systems. The evaluation of the resolution of soil moisture information is divided into three major areas; these are an assessment of the rainfall-amount patterns in the central regions of the U.S., an investigation of the spatial scales of surface features and their corresponding microwave responses in the mid western U.S., and an evaluation of the usefulness for U.S. government agencies of soil moisture information at scales of 10 km and 1 km.

From an investigation of 494 storms, it was found that the rainfall amount resulting from the passage of most types of storms produces patterns which can be resolved on a 10-km scale. The land features causing the greatest problem in the sensing of soil moisture over large agricultural areas with a radiometer are bodies of water. Over the mid-western portions of the U.S., water occupies less than 2% of the total area, and consequently, the water bodies will not have a significant impact on the mapping of soil moisture. Over most of the areas, measurements at a 10-km resolution would adequately define the distribution of soil moisture. The spatial variation and the microwave response of other surface features, for example, urban and forest areas, are also discussed. With respect to the value of soil moisture information, crop yield models and hydrological models would give improved results if soil moisture information at scales of 10 km was available.

TABLE OF CONTENTS

1. INTRODUCTION

The objective of the study is to evaluate the improved usefulness of soil moisture observations from space with microwave radiometers having resolutions of 10 km and 1 km. The evaluation of the resolution of soil moisture information is divided into three major areas; these are: (1) an assessment of the rainfall patterns in the central regions of the U.S., (2) an investigation of the spatial scales of surface features of the mid-western U.S., and (3) an evaluation of the usefulness of soil moisture information at scales of 10 km and 1 km for U.S. government agencies.

Since the major input for producing soil moisture variability is rain, it is essential to determine the fine-scale structure of rainfall amounts. Eagleson (1978), Brady (1975), Eddy (1976), Huff (1971, 1979), and Huff and Shipp (1969) have investigated and described techniques for the determination of patterns of rainfall amount. In some cases (Eddy, 1976), the primary effort was directed toward the rain gage network density and procedures which would be required to estimate the rainfall over a given area within a given accuracy. In other cases (Huff, 1971; and Eagleson, 1978), the main attempt was to describe the average structure of rain or the structure of various types of storms on a monthly or seasonal basis. Generally, spatial correlations between the rainfall amounts at each of the gages were obtained. The results of the correlation analysis showed differences between each of the major types of storms. The study described herein uses rainfall amount information from 494 storms to determine some of the characteristics of rainfall amount patterns which in turn contribute in a major way to soil moisture variability. The analysis consisted of (1) contouring the rainfall amounts for each storm, (2) measuring the rainfall amount at various locations from the storm center, (3) assigning a synoptic type for each storm day, and (4) deriving statistics of the storm patterns for each synoptic type. With the exception that the peak rainfall amount will usually be underestimated, it was found that the rainfall amount patterns will be well represented by systems having a resolution of 10 km.

The second major area of investigation is an evaluation of the surface features and land use patterns in the central region of the U.S. The evaluation is aimed at a determination of the spatial scales of surface features that could affect the microwave response. Although there is a wide variety of scales of surface features within the regions chosen for study, water bodies were found to occupy less than 2% of the total area. Also, the features usually had characteristic scales of more than 50 km. Thus, for the monitoring of large regions, a sensor having a resolution of 10 km would be adequate over the central U.S. However, for the monitoring of either small areas of less than a few tens of kilometers in size or those areas with a preponderance of small scale features, a sensor with a 10-km resolution would often lead to erroneous estimates of soil moisture.

The third area of this study is to define sources of spatial resolution constraints for soil moisture information as currently used for crop yield conditions (forecasting) and streamflow forecasting. Having defined the spatial resolutions and their constraint sources, the research evaluation task is to evaluate qualitatively the improvement in soil moisture information that would result by changing from a 10-km to a 1-km resolution.

2. RAINFALL PATTERN ANALYSIS

2.1 Previous Studies on Rainfall Patterns

Rainfall is a prime contributor to the pattern of soil moisture. At a particular instant in time, it is known that intense rainfall cells having diameters of about 2.5 km can occur (Crane, 1979). The cell diameter, as defined by Crane (1979), was the distance across the cell as detected by radar where the radar reflectivity fell to one-half of the maximum. The one-minute rainfall rate maps presented by Changnon and Huff (1980, p.121) show cell diameters, again using the one-half the maximum rate as the definition, of between 2.7 and 4.1 km. However, these near instantaneous rainfall rate patterns and the radar patterns are not representative of the total rainfall-amount patterns produced during the course of an entire storm event. Crane and Hardy (1981) have demonstrated that storms characterized by rainfall rates of more than about 12 mm hr^{-1} are usually made up of several storm elements with each element containing several clusters, and in turn the clusters may be made up of from one to about six individual cells. Similarly, Changnon and Huff (1980, p.25) present hourly maps of rainfall amount over a 10-hour period for a storm on 21 August 1953, and these maps clearly demonstrate the passage of three distinct rainfall events being advected over the same region of the network. This feature of distinct cells passing over the same area was also demonstrated in storm data presented by Eddy (1978).

It is the summation or integration of the rainfall over the entire storm period over a day which is of concern for this particular study. These patterns have much larger scales than exhibited by the individual cells within a storm. For example, Huff and Shipp (1969) present correlation patterns of total rainfall amounts about the central rain gage for summer storms in central Illinois. Over a distance of 5 km from the central gage, the correlation is very high and ranges from a low of .9 for air mass storms to about .97 for storms associated with low centers or for steady rain. Consequently, it is evident that the rainfall amount patterns produced by an entire storm have larger scales than the scales seen instantaneously by a weather radar or the scales represented by one-minute rainfall rate maps.

One of the major concerns for this study is how representative is the rainfall pattern as determined from given raingage networks. With an average spacing of 4.8 km as occurs in the Chickasha, Oklahoma rain gage network, Mignogno et al. (1980), report that the correlation of precipitation amount between neighboring gages averages 0.9 for all precipitation types combined. This correlation is consistent with the values given by Huff (1979) for different types of storms in central Illinois. On the other hand, Fogel and Duckstein (1969) report much larger variability in Arizona storms in which the duration was less than two hours; these authors analyzed storm data for a 50 km^2 network with an average gage spacing of 1.6 km. It was found that the rain amounts at adjacent gages were better correlated as the amount at the center of the storm increased. For example, if the storm center rainfall was 25 mm, the amount at 5 km is, on the average, only .4 mm or about 1.5% of the maximum; if the storm center rainfall was 100 mm, then at 5 km the rainfall amount is about 57% of the maximum. Eddy and Hembree (1978) also demonstrate this feature by the consideration of both a small storm with maximum rain amount of less than 2.5 mm in a total area of about 62 km^2 and a large storm in which the average rainfall amount over an area of about 1700 km^2 was more than 5 mm. Eddy and Hembree (1978) used data from the Montana HIPLEX rain gage network which had an average separation distance of about 3.5 km. From an analysis of both radar and rain gage data for the small storm, Eddy and Hembree (1978) state "(the storm) wormed its way rather nicely between the gages".

It is evident that the spacing of the rain gages in a network is an important factor for the accurate depiction of rainfall patterns. Moreover, a network designed for giving the distribution of annual rainfall will probably be inadequate for depicting the patterns of individual storms. In this regard, the results of past studies as summarized above point to the inference that networks having gage spacings of about 5 km will be adequate for describing the patterns of entire storms or of daily rainfall amounts. In addition, for a given network, the patterns of rainfall amounts will be more representative of the true patterns as the total rain amount over the network increases.

The primary objective of the rainfall pattern analysis in this study is to determine the spatial characteristics of rainfall amount for entire storm periods. These characteristics are considered to be adequate to provide the information needed as a first step in describing soil moisture patterns. The variability of the rainfall amounts between different storm types is also presented.

2.2 The Sources of Rain Gage Data

The rain gage data used in this study were obtained from two sources; these are from (1) Project HIPLEX (High Plains Cooperative Program) of the Water and Power Resources Service (formerly the Bureau of Reclamation) and (2) the U.S. Department of Agriculture's Washita River Watershed observation network centered near Chickasha, Oklahoma.

The HIPLEX rain-gage networks at Goodland, Kansas and Big Spring, Texas provided data for the summer periods of May-August 1977 and 1978; data for a few storms which occurred in April, September or October were also included. The Goodland site contained 38 gages with a network density of 1 gage per 16.8 km^2 (spacing of about 4.5 km). The Big Spring network contained 68 gages with an average density of 1 gage per 104 km^2 (spacing was variable from 4 to 12 km). Figures 2-1 and 2-2 show the rain gage placements for the Goodland, Kansas and Big Spring, Texas networks. The rain gage information for both sites was stored in 15-minute intervals.

For the purposes of this study, a storm in the HIPLEX networks was defined by a minimum precipitation duration of 30 minutes, and a particular gage must have reported a minimum precipitation amount of 0.01 inches before it was counted as contributing to the storm pattern. Separate storms were identified when they were separated by a period of three hours or more in which no rain was observed in the network; usually the storms had durations of less than 12 hours, but on a few occasions storms in the HIPLEX networks had durations exceeding 48 hours. The cases were selected for plotting when a minimum of 90% of the network gages reported precipitation. Consequently, some small weak convective storms, which only covered a fraction of the network, were eliminated; this limitation was imposed in order to exclude storms which would have a minimal effect on soil moisture.

The rain-gage network at Chickasha, Oklahoma furnished information for the non-summer periods of September-May 1976 and 1977. The network

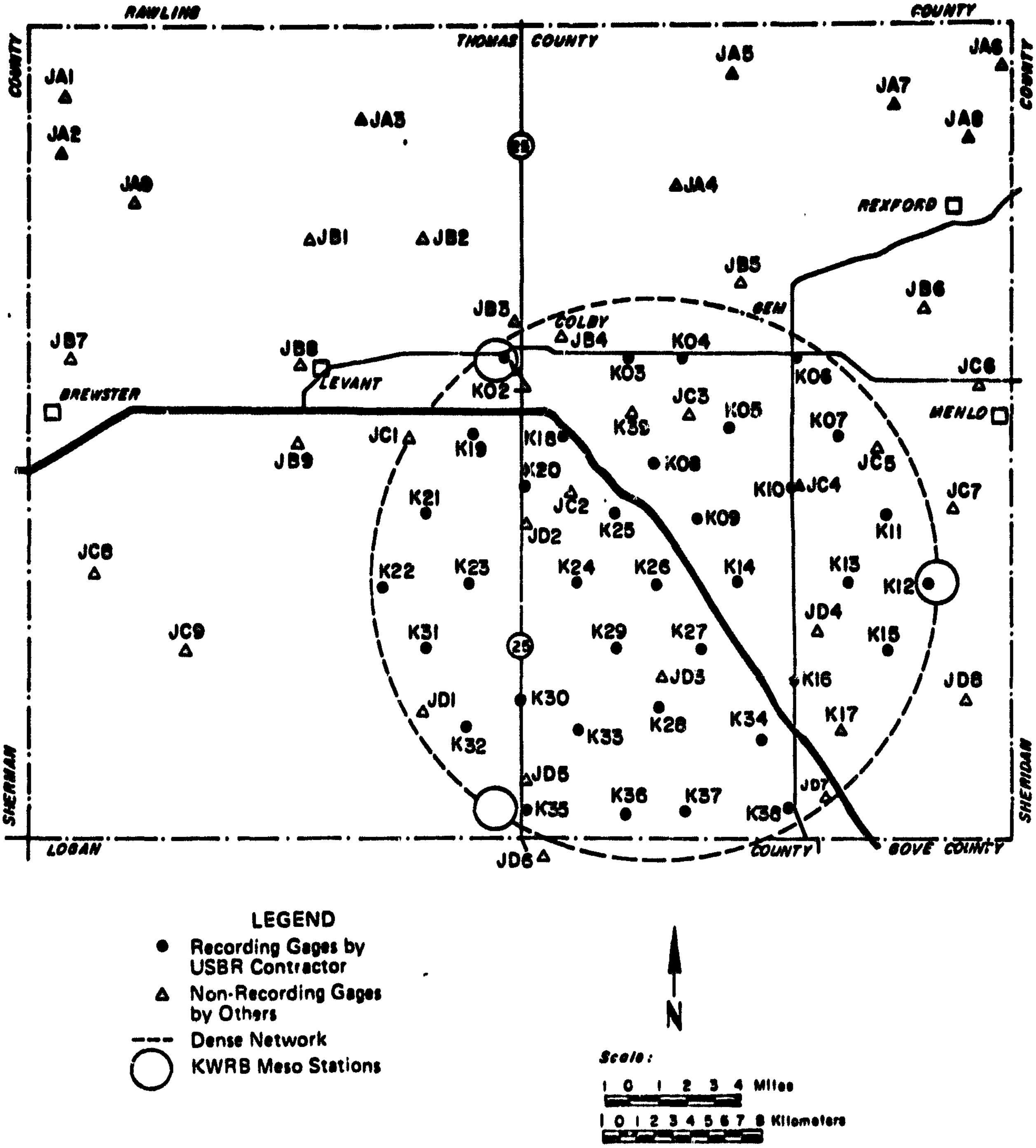


Figure 2-1 Location of the HIPLEX rain-gage network in the Goodland-Colby, Kansas area

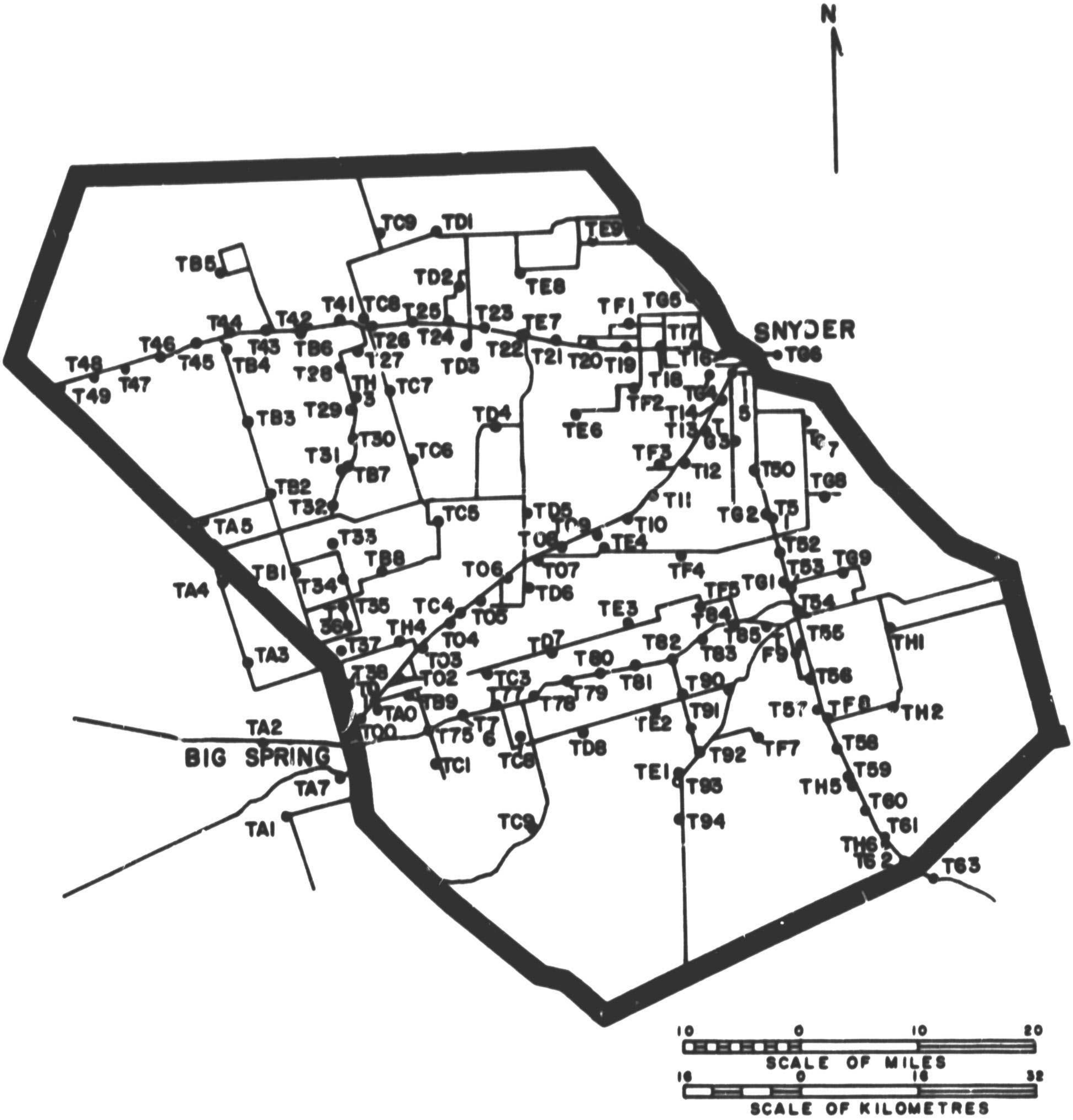


Figure 2-2 Location of the HIPLEX rain-gage network in the Big Spring, Texas area

contained 168 gages with a spacing between gages of about 4.8 km (Mignogno et al., 1980). Figure 2-3 shows the placement of rain gages for the Oklahoma network. The precipitation amounts were for 24-hour intervals. Therefore, the storm duration as defined for the Oklahoma data was for a fixed period of 24 hours.

The intent of this study is to obtain patterns of rainfall for all seasons. Only summer storms were observed during the HIPLEX programs. Therefore, data for non-summer storms were obtained from the Oklahoma network. Figure 2-4 shows the monthly distribution of the number of storm days used for this study. There were 20 days of storm data from Texas, 24 days from Kansas, and 129 days from Oklahoma. The number of storm days analyzed totaled 173.

2.3 The Analysis of the Data

The HIPLEX data from the Kansas and Texas networks were analyzed by means of a contour plotting routine (Water and Power Resources Service, a) which provided isohyets of the storms. The output was obtained from an interactive computer display and an example is illustrated in Figure 2-5. The Oklahoma data were not available on computer tape or cards and consequently it was most efficient to hand plot the data and carry out a manual analysis of the isohyets. The contour intervals for the HIPLEX data were between 0.1 and 0.2 inches whereas the intervals for the Oklahoma data were between 0.01 and 0.2 inches; the larger intervals were used when the maximum rainfall amount was large.

Once the contours of rainfall amount were obtained, the problem remained of how the patterns were to be catalogued. Since the primary objective was to determine the spatial features of individual storms, a spatial correlation analysis about the central gage of the network, as was carried out by Huff and Shipp (1969), was not considered to be an optimum technique. That is, an objective correlation analysis taken without regard to the position of the storm centers would not provide the required statistical information about the structure of the storms. A correlation analysis centered around a storm maxima was a possibility, but this was thought to be an unnecessarily detailed approach considering

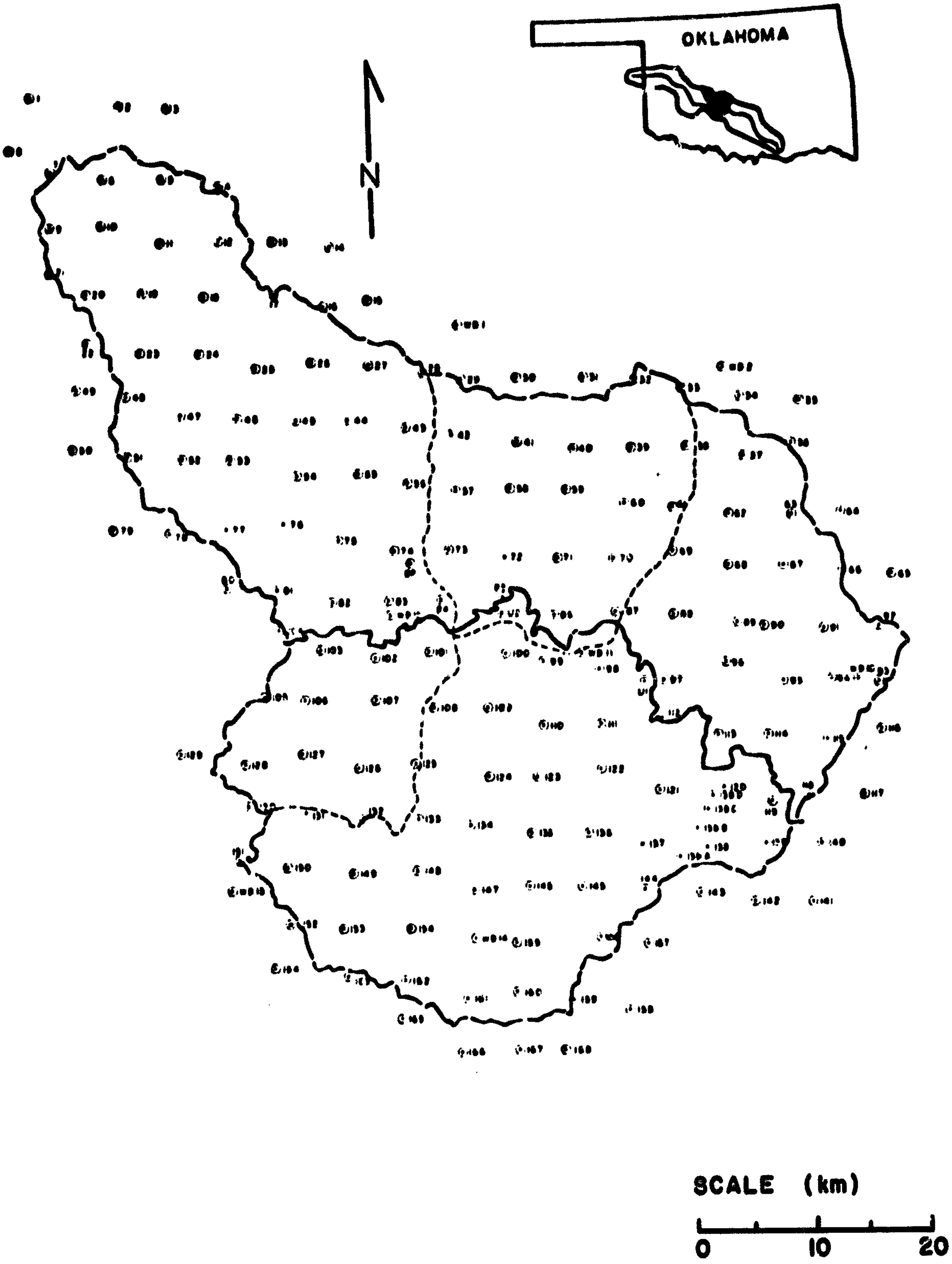


Figure 2-3 Location of the HIPLEX rain-gage network in the Washita River Watershed area

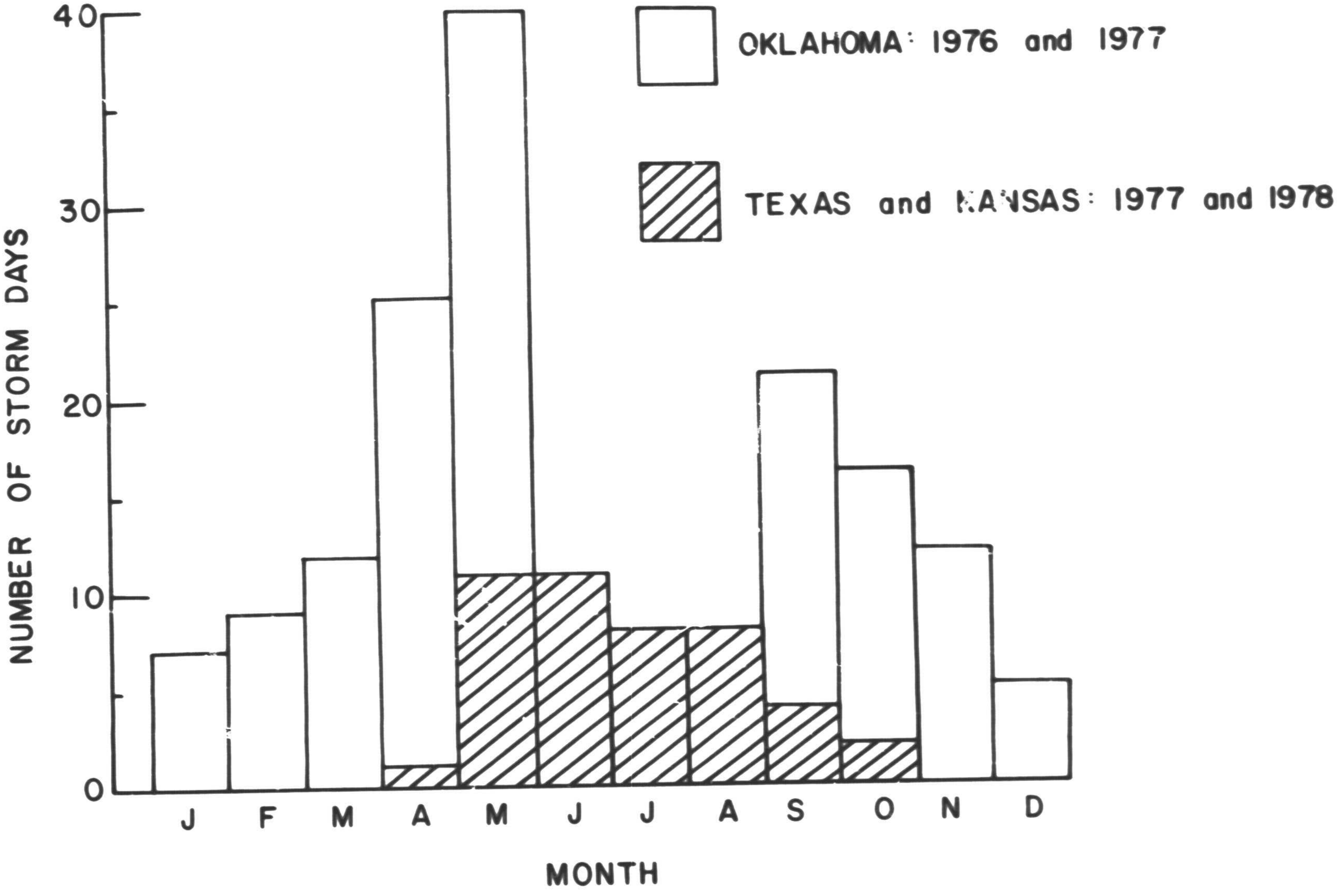


Figure 2-4 Monthly distribution of storm days for Oklahoma and for Texas and Kansas combined

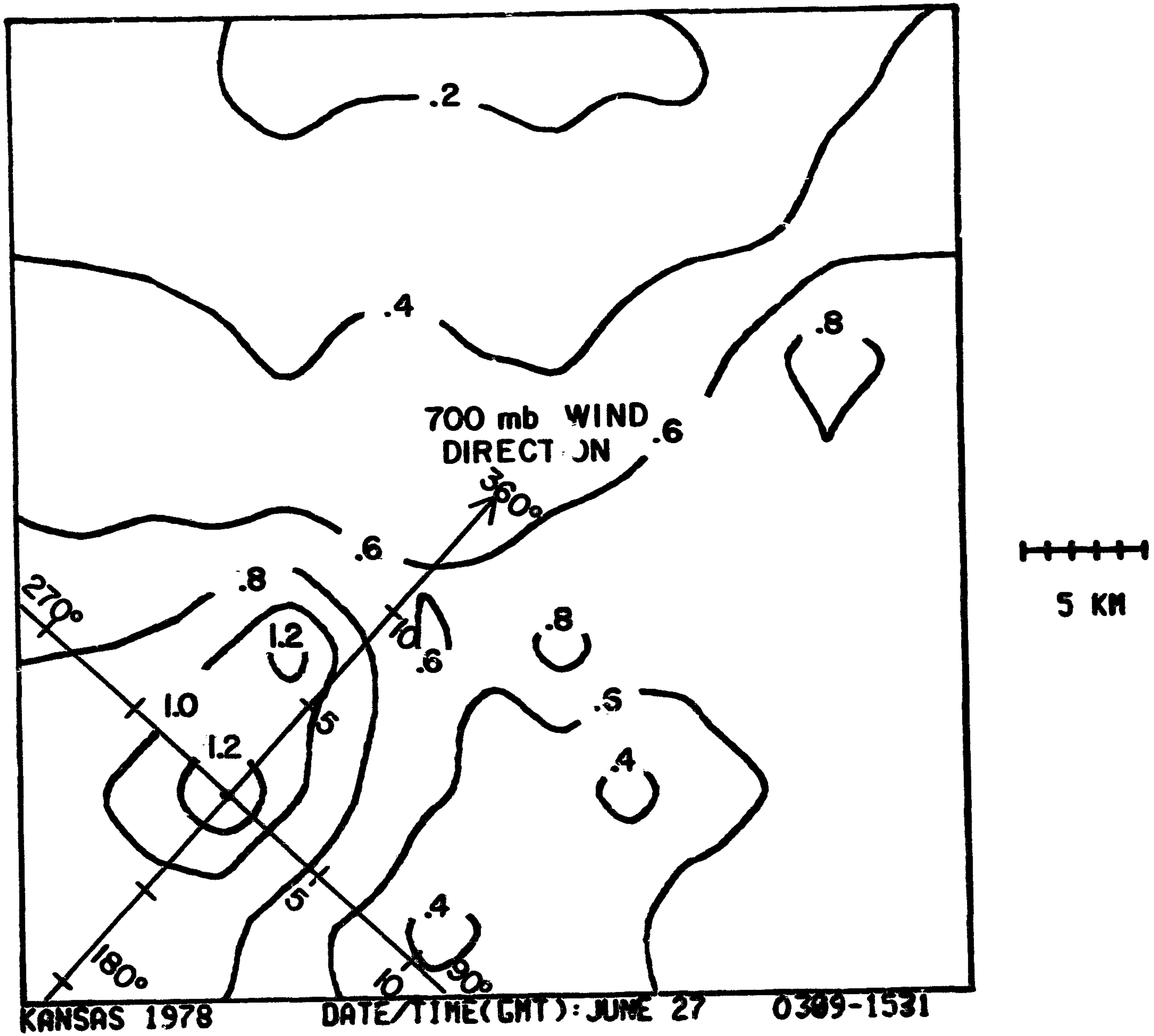


Figure 2-5 An example of the contours of rainfall amount which were obtained from the computer plotting routine. The data are from the Kansas HIPLEX program on 27 June 1978 when a maximum of 1.41 inches of rain was recorded at one of the gages.

that the data were obtained from gages spaced at intervals of about 5 km. The technique selected was rather straightforward and was designed to obtain the desired feature of the storms in a quantitative manner. This technique involved determining the probable direction of the storm motion by using the direction at the 700 mb level. The direction was obtained from radiosonde data which were considered to be representative for conditions over the network at the time of the storm. A grid in this direction and perpendicular to the direction was then centered over the maximum rainfall amount for the storms in the network. By making measurements parallel and perpendicular to the general direction of storm movement, information on the storm shape will be obtained. The correlation patterns presented by Huff (1979) for Illinois show an orientation effect for both individual storm rainfall and annual rainfall; the orientation is generally southwest to northeast which is the most frequent direction of travel for storms moving across Illinois. Often, there would be more than one maximum within the analyzed field and in these cases each maximum was considered as a separate storm. Thus, although 173 storm days were considered, a total of 494 individual storm maxima were identified and measurements from all of these were obtained. Once the rainfall maximum had been identified and the grid aligned along the 700 mb direction, the precipitation amount at a distance of 5 km (and sometimes 10 km) from the storm maximum was determined in the four directions of the grid. An example of the grid as it would apply to the storm of 27 June 1978 is given in Figure 2-5. A direction of 360°, as used in this analysis, is the direction of the 700 mb wind which was applicable for each of the storms. These basic measurements provided an estimate of how rapidly the rainfall amount diminished from the storm maximum. A rapid drop would indicate a small storm cell, whereas a slow decrease in the amount would indicate a generally larger storm. The format for the information extracted for each storm cell and the listing of the data for the 494 storms are given in Appendix A.

In addition to the precipitation data, descriptive parameters for synoptic classification were also collected. Initially, each case was assigned a type code for both the 500 mb and the surface synoptic patterns. Although 10 types or patterns were originally assigned, it was found that only four types occurred with significant frequencies.

These were identified by the surface weather map and are as follows:

- cold front,
- stationary front,
- surface high, and
- surface low.

The surface high cases were those in which a high pressure dominated the regions east of the networks resulting in a generally easterly flow or upslope flow over the network under consideration. The surface high classification is the one that is used to indicate the situation often catalogued or identified as air-mass showers. The surface low cases were characterized by a low pressure to the west of the networks and generally southwest to northwest flow over the network. The frontal cases were chosen by the proximity to the network of the frontal type.

The classification of the storm days by synoptic scale features proved to be difficult because two or more choices for a given situation were sometimes possible. Figures 2-6 and 2-7 illustrate the difficulty. A day classified as a surface low is shown in Figure 2-6; a weak low is centered near the southwest corner of Kansas with a stationary front running from southwest to northeast across the state. The flow at the surface over the HIPLEX rain gage network in Kansas is easterly and the rainfall pattern shows an increase from east to west. A day classified as a surface high is shown in Figure 2-7; a high is to the north of Kansas, but there is a front in a similar position as for the case in Figure 2-6 and the flow over the network is also easterly. The rainfall pattern is more showery in nature than for the case shown in Figure 2-6.

Both of the cases in Figure 2-6 and 2-7 might have been classified as stationary front cases; it is also evident that the basic flow pattern differs only slightly for the cases chosen to illustrate a surface low and a surface high classification. With these types of difficulties in using a synoptic classification scheme, there is bound to be some overlap in the attempts to isolate the rainfall patterns associated with large scale weather patterns.

There is, however, a more basic problem with using synoptic-scale features to classify precipitation which generally occurs at much smaller

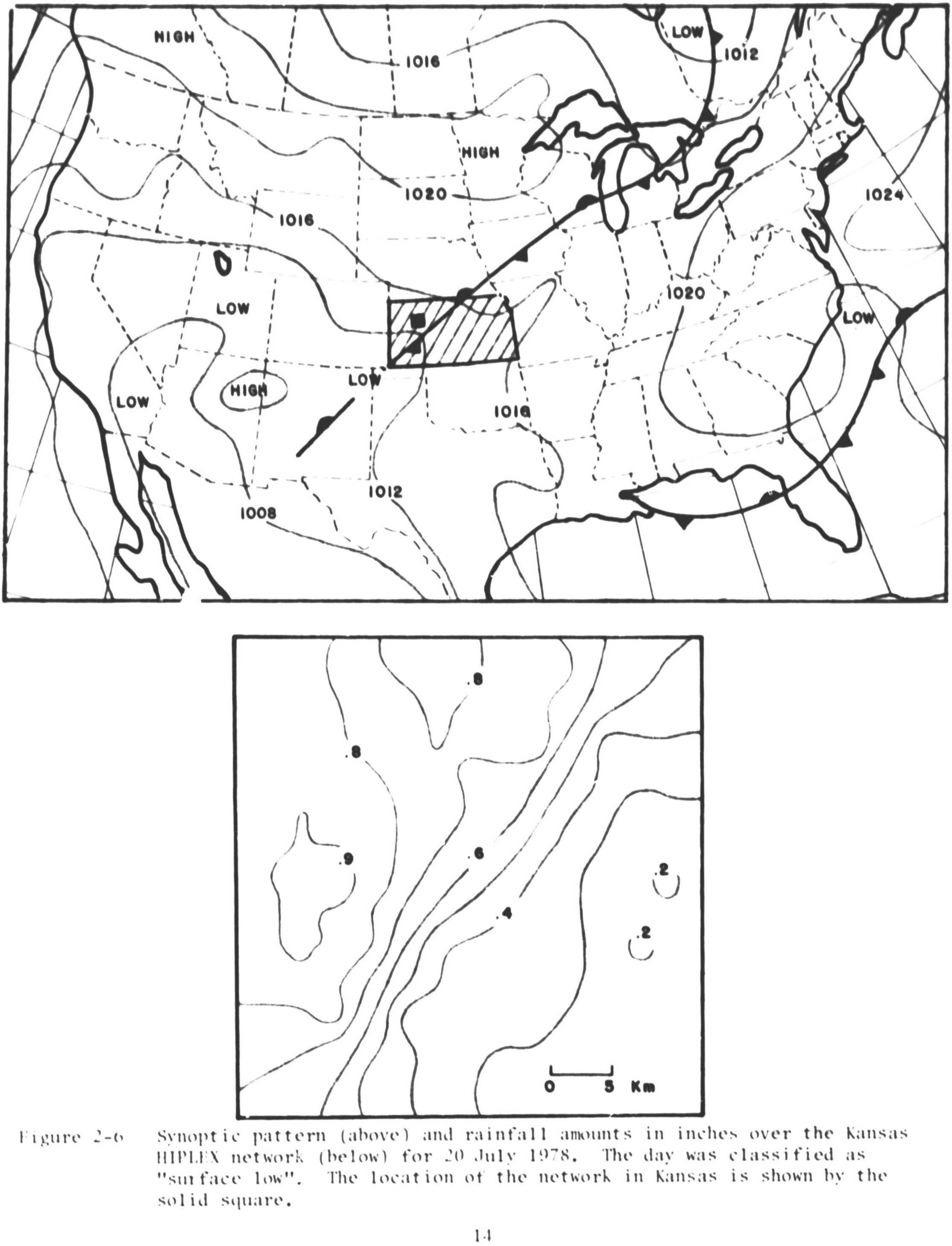


Figure 2-6 Synoptic pattern (above) and rainfall amounts in inches over the Kansas HIPLEX network (below) for 20 July 1978. The day was classified as "surface low". The location of the network in Kansas is shown by the solid square.

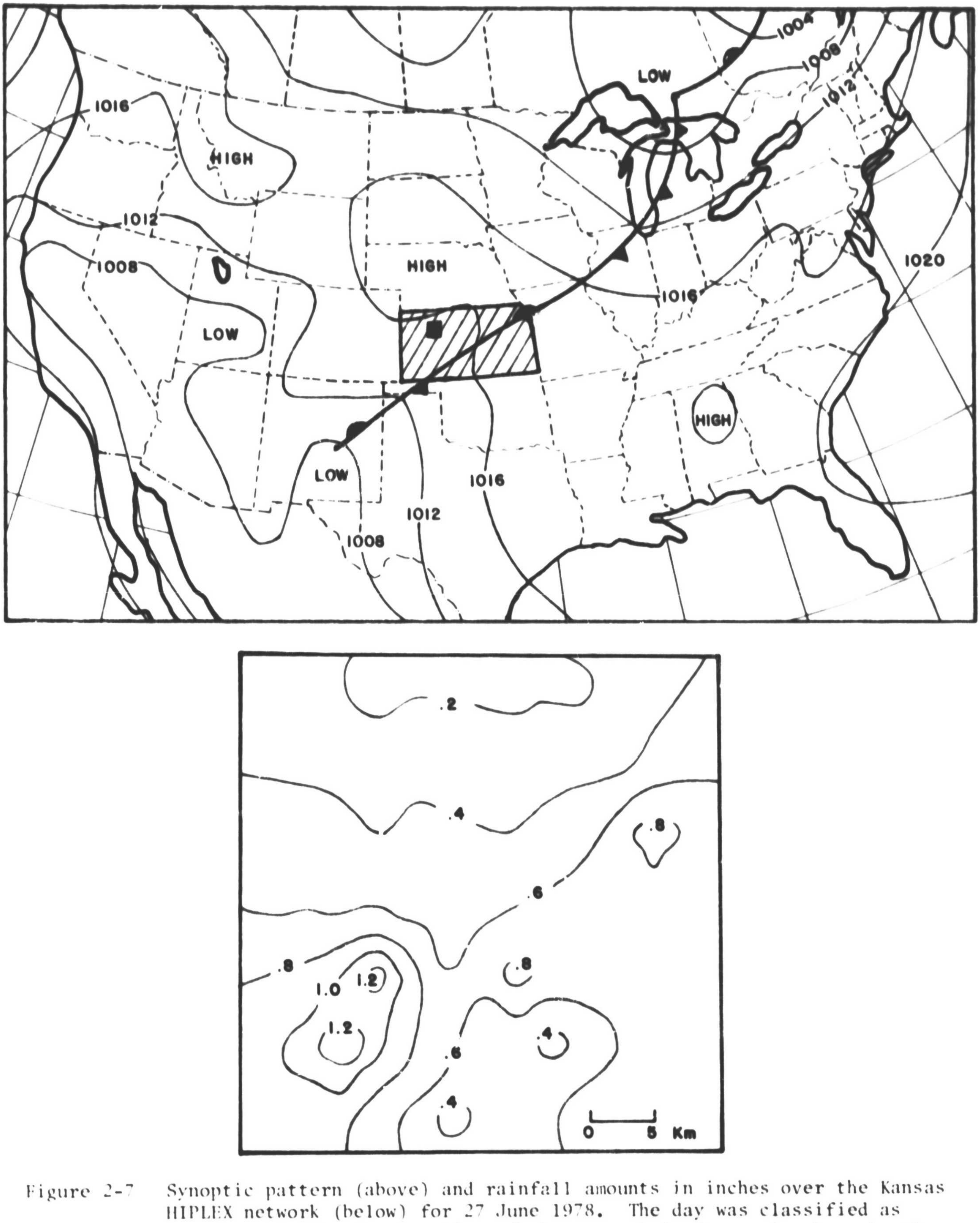


Figure 2-7 Synoptic pattern (above) and rainfall amounts in inches over the Kansas HIPLEX network (below) for 27 June 1978. The day was classified as "surface high". The location of the network in Kansas is shown by the solid square.

scales. The problem as quoted from Lilly (1975) is "that the actual development of convective cloud arrays occurs on a considerably smaller scale (than the synoptic scale) and often with a degree of organization which is clearly nonrandom but also largely unresolvable from conventionable data processed in conventional operational ways". Ludlam (1976) also describes sub-synoptic scale features which may control the precise location of convective activity, although he emphasizes that favorable large scale flows must be present before any important convection is initiated. These interactions between synoptic-scale and smaller scales cannot be sorted out in the present study in which the days were classified only through synoptic-scale features.

Data from the four points of the grid at a 5 km (and sometimes also at a 10 km) distance from the storm center were extracted for all storm cells. The total of the maximum rainfalls for the 355 Oklahoma storms was about 210 inches, and for the 139 storms in the Kansas and Texas networks it was about 190 inches. The breakdown of the number of storms having a maximum rainfall within three categories for both the HIPLEX and the Oklahoma storms is presented in Table 2-1. For the purposes of statistical analysis, the rainfall amount patterns were normalized to the maximum precipitation for the storm.

TABLE 2-1

CATEGORIES OF RAINFALL AMOUNT USED IN THE ANALYSIS

Rainfall Amount	Code		Number of Storms	Percentage Occurrence
HIPLEX				
less than 1.0 inch	1		44	31.7%
1.0 to 1.75 inch	2		48	34.5%
greater than 1.75 inch	3		47	33.8%
		Total	139	
OKLAHOMA				
less than 0.25 inch	1		110	31.0%
0.25 to 0.75 inch	2		115	32.4%
greater than 0.75 inch	3		130	36.6%
		Total	355	

The rainfall amount categories in Table 2-1 refer to the maximum amount recorded at a gage for a particular storm. The amounts are separated into three categories of about equal frequency although the HIPLEX rainfall categories are considerably larger than those for Oklahoma.

Each of the rainfall amount categories shown in Table 2-1 were subdivided into the four weather types (cold front, stationary front, surface high, or surface low). Then, for each storm, the value of the rainfall amount, expressed as a ratio to that of the maximum for the storm, was obtained at distances of 5 km and often also at 10 km in each of the four directions of the grid as illustrated in Figure 2-5. For each weather type and for each of the rainfall amount categories of Table 2-1, the normalized value at each grid point was tabulated and average and standard deviation values were calculated. This led to a total of 22 normalized patterns of storm types. The maximum number of categories would be 24 because there were four weather types for three rainfall categories for both the HIPLEX and the Oklahoma networks. However, there were insufficient cases to warrant the computation of average and standard deviation values for the stationary front with rainfall less than .25 inches in Oklahoma and for a surface low with rainfall greater than 1.75 inches in the HIPLEX networks.

2.4 The Results of the Statistical Analysis

An example of one of the patterns of rainfall amount is shown in Figure 2-8. The pattern is for storms classified as occurring with a stationary front when the maximum rainfall amount of the storms fell between 1.0 and 1.75 inches in the Texas and Kansas HIPLEX networks. The upward direction of the figure is in the direction of the wind at 700 mb. The values along the axes are the mean values of the normalized rainfall amount at 5 and 10 km from the storm center. The numbers in brackets are the standard deviations computed for the approximately 17 cases which were used to determine the pattern. For each point in the grid the number of available cases usually varied because locations at 5 or 10 km from the storm center would sometimes fall outside the rain gage network.

The pattern in Figure 2-8 is almost symmetrical although it is somewhat elongated in the direction of storm motion. The storms which

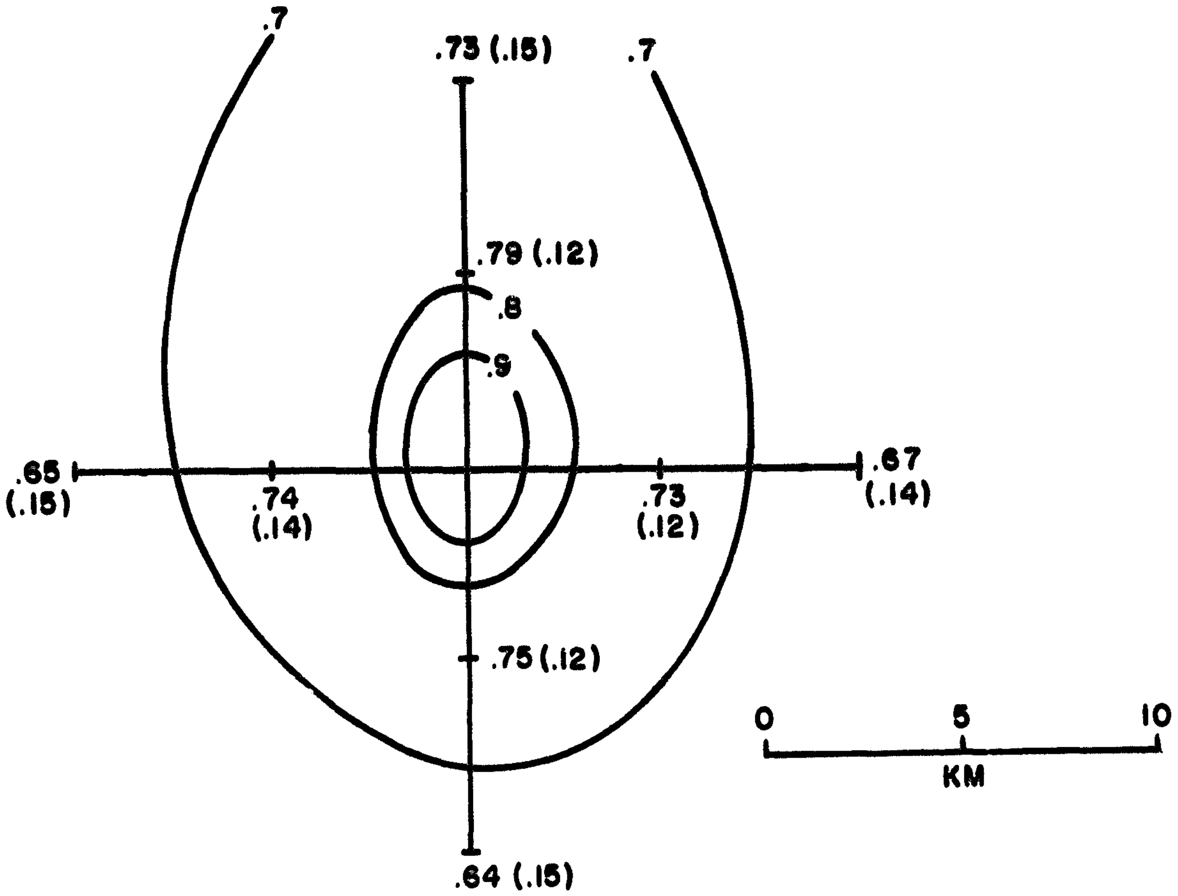


Figure 2-8 The average pattern of rainfall amount, normalized to the amount at the storm center, for summer storms in the Texas and Kansas HIPLEX rain gage networks. The pattern is for the 17 stationary front cases when the maximum rainfall of the storms observed in the network ranged from 1.0 to 1.75 inches. The number in brackets is the standard deviation for the rainfall amount at the point indicated.

make-up the pattern are relatively large since rainfall amounts at 10 km are still about two-thirds of the value at the storm center. The pattern shown in Figure 2-8 is fairly typical of those found for the other 21 categories; all 22 patterns are included in Appendix B.

One of the more variable patterns is shown in Figure 2-9. It is for non-summer storms occurring over the Oklahoma rain gage network and classified as being associated with a stationary front. The maximum rainfall amount of each storm ranged from 0.25 to 0.75 inches and approximately 7 cases were included. In contrast to the almost symmetrical pattern of Figure 2-8, the Oklahoma storms of Figure 2-9 exhibit considerable differences between the along-track and the cross-track values fall to 0.17 or lower, whereas the 10 km along-track values are 0.53 and 0.60. Thus, the storms are definitely elongated in the direction of the storm motion and the gradient in the cross-track direction is much larger than that for the data on the HIPLEX storms represented in Figure 2-8. The standard deviations of the values of Figure 2-9 are somewhat larger than these for most of the patterns. Generally, the standard deviations are about 15% of the mean value at the 5-km locations and about 25% of the mean value at the 10-km locations.

The mean values of the normalized rainfall amounts at 5 km, and also at 10 km when these were obtained, are shown in Table 2-2 for the HIPLEX storms and in Table 2-3 for the Oklahoma storms. The values are also plotted and the patterns drawn for all the 22 cases. Although there is considerable variability of the values between the categories given in Tables 2-2 and 2-3, generally the rainfall amounts along the axis of storm motion were about 10% higher than at the same distances perpendicular to the storm axis for the Oklahoma storms; the along-axis values were only 5% higher than the cross axis values for the HIPLEX storms. This difference between the HIPLEX and Oklahoma storms may be caused by the different temporal resolution of the data sources (Section 2.2). In this regard, the 24-hour data for Oklahoma during the winter generally show smaller storms than those depicted by the finer temporal data for the HIPLEX sites; that is, the rainfall amounts for the Oklahoma storms fall-off more rapidly from the storm center than for the HIPLEX storms.

There is no consistent trend of the normalized rainfall amount values

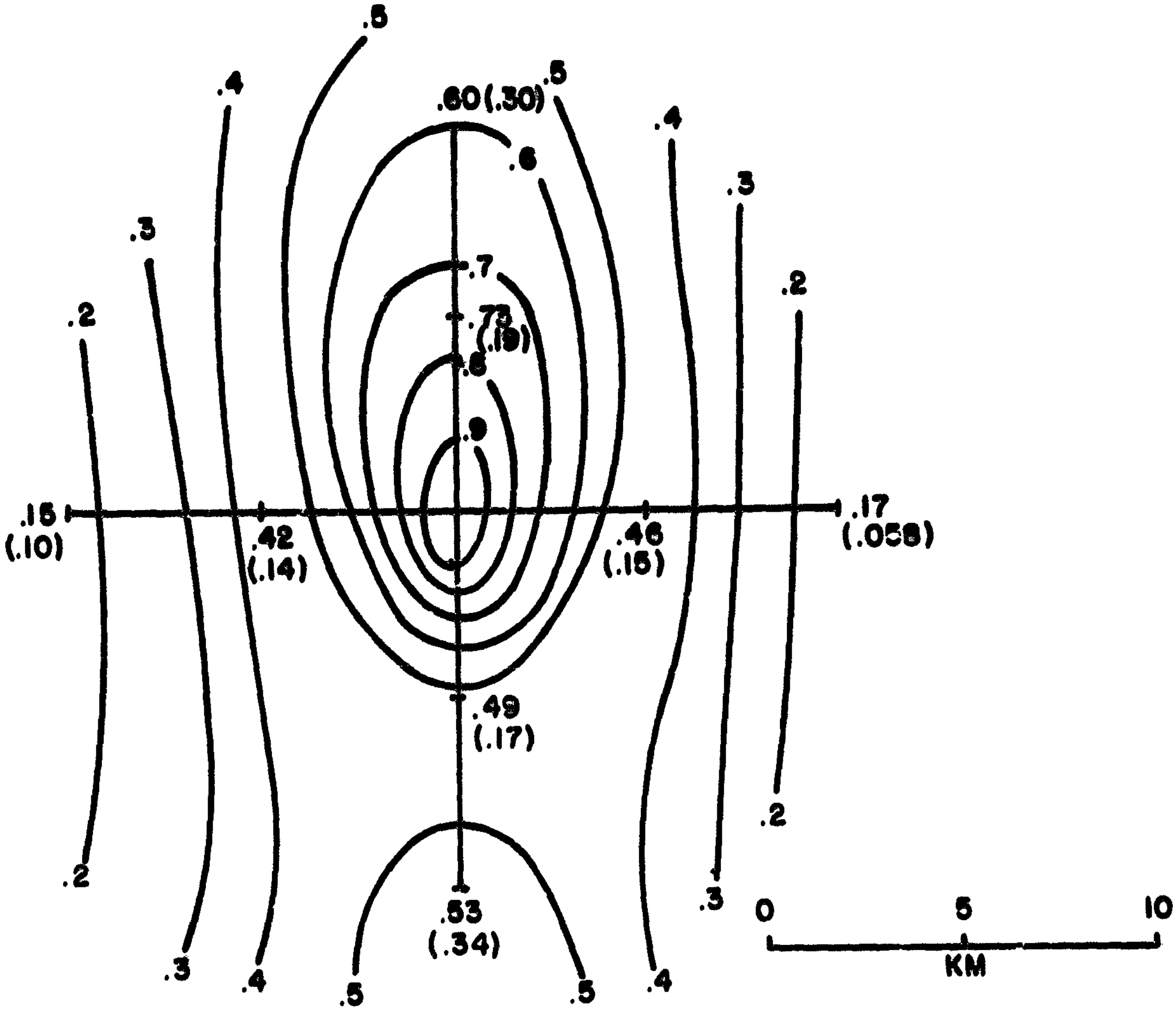


Figure 2-9 The average pattern of rainfall amount, normalized to the amount at the storm center, for non-summer storms in the Oklahoma rain gage network. The pattern is for the 7 stationary front cases when the maximum rainfall of the storms observed in the network ranged from 0.25 to 0.75 inches. The number in brackets is the standard deviation for the rainfall amount at the point indicated.

TABLE 2-2

THE VALUE OF THE RAINFALL AMOUNTS, EXPRESSED AS
A RATIO OF THE STORM MAXIMUM,
AT THE LOCATIONS INDICATED FOR THE HIPLEX DATA

Type of Pattern	Maximum Rainfall Amount (inches)	REDUCTION IN RAINFALL AMOUNT Direction from Storm Motion (deg)/Distance (km)							
		360/5	360/10	90/5	90/10	180/5	180/10	270/5	270/10
Cold Front	<1.0	.76		.77		.69		.73	
	1 - 1.75	.77	.64	.73	.61	.77	.68	.75	.60
	>1.75	.77	.49	.73	.53	.79	.59	.70	.38
Stationary Front	<1.0	.80	.77	.74	.70	.77	.62	.75	.63
	1 - 1.75	.79	.73	.73	.67	.75	.64	.74	.65
	>1.75	.72		.64		.66		.62	
Surface Low	<1.0	.80	.76	.78	.70	.78	.60	.78	.72
	1 - 1.75	.80		.75		.85		.75	
Surface High	<1.0	.66		.68		.72		.64	
	1 - 1.75	.78		.65		.72		.73	
	>1.75	.82	.74	.79	.72	.81	.69	.77	.68

TABLE 2-3

THE VALUE OF THE RAINFALL AMOUNTS, EXPRESSED AS A RATIO OF THE STORM MAXIMUM, AT THE LOCATIONS INDICATED FOR THE OKLAHOMA DATA

Type of Pattern	Maximum Rainfall Amount (inches)	REDUCTION IN RAINFALL AMOUNT Direction from Storm Motion (deg)/Distance (km)							
		360/5	360/10	90/5	90/10	180/5	180/10	270/5	270/10
Cold Front	<.25	.82	.55	.65	-	.76	.75	.66	.75
	.25 - .75	.80	.72	.62	.53	.72	.62	.63	.55
	>.75	.69	.54	.56	.44	.70	.52	.62	.53
Stationary Front	.25 - .75	.73	.60	.46	.17	.49	.53	.42	.15
	>.75	.83		.68		.83		.76	
Surface Low	<.25	.65		.59		.60		.55	
	.25 - .75	.74		.67		.68		.52	
	>.75	.76		.62		.75		.55	
Surface High	<.25	.65	.57	.66	.48	.63	.69	.60	.53
	.25 - .75	.77		.70		.74		.68	
	>.75	.76		.70		.73		.66	

at 5 km as a function of the maximum amount for the storm (see Tables 2-2 and 2-3 and Appendix B). At a distance of 5 km from the storm maximum for the HIPLEX data, the normalized rainfall amounts for the cold front and surface-low situations are about the same regardless of the maximum rainfall amount. For the stationary front patterns, the storms are smaller, in a normalized sense, for higher rainfall amounts, but the reverse is the case for the storms associated with the surface high patterns. For the Oklahoma data (Table 2-3), the cold front storms have smaller normalized values at 5 km when the precipitation amount exceeds .75 inches, but the reverse is the case for all other storm types.

In general, for the HIPLEX storms, the rainfall amount at 5 km from the storm center is about 75% of the storm maximum; at 10 km from the storm center, the rainfall amount is about 65% of the maximum. For the Oklahoma storms which occurred in the September to May period, the rainfall amount at 5 km is about 65% of the maximum and at 10 km it is about 50% of the maximum.

2.5 Implications of the Rainfall Patterns for Soil Moisture Retrieval

Figures 2-8 and 2-9 illustrate the variation of the rainfall patterns derived from an analysis of 494 individual storms which were separated into various categories of synoptic type and of the maximum rainfall amount at the storm center. The storm centers were chosen to be at locations within the network where the rain gages reported a peak in the rainfall amount. With a spacing of about 5 km between gages, it is probable that the actual peak of the storm would fall in-between the gages and thus, the maximum values used in this study would be underestimated. Nevertheless, for the storm total rainfall amounts or the daily amounts used in this study, the patterns obtained from the networks are considered to be representative of the actual patterns.

As shown for the patterns of rainfall amount in Figures 2-8 and 2-9 and for most of the patterns in Appendix B, the largest gradients in the rainfall amount occur within the first 5 km from the storm center. Viewing the rainfall patterns obtained in this study with a remote sensor having a dimension of about 10 would usually result in an underestimate of the peak rainfall amounts. Beyond 5 km from the storm center, the gradients are considerably reduced and the patterns would be reasonably well represented by a system which had a 10-km resolution. The worst case or the pattern having the largest gradients is shown in Figure 2-9. Near the storm center, a sensor with a 10-km resolution may underestimate the true value by about 20%. But beyond 5 km from the center, a 10-km resolution would lead to a good representation of the patterns for all the categories of storms.

The general conclusion is that over about 75% of the storm area, a 10-km sensor will adequately represent the patterns of rainfall amounts for individual storms or daily values. Because the gradients are large near the center of the storms, the peak radius of rainfall amount will nearly always be underestimated when viewed with a 10-km system unless some correction factor is applied to the observed data.

3. MICROWAVE RESPONSE TO LAND FEATURES

3.1 General Factors Affecting the Microwave Brightness Temperature

Thermal microwave radiation from soil depends on the dielectric coefficient and the physical temperature of the soil. Moisture produces a marked increase in both real and imaginary parts of the dielectric coefficient of soil, leading to a decrease in the soil's emissivity. Since emissivity decreases with increasing dielectric constant, the brightness temperature of soils at microwave frequencies decreases with increasing moisture content. Experimental observations and theoretical calculations indicate that the emissivity of soils at microwave frequencies, defined as the ratio of the microwave brightness temperature to the physical temperature, can range from >0.95 for dry soils to <0.6 for very moist soils.

It should be noted that radiometers at shorter wavelengths (1-4 cm) are only sensitive to the surface moisture content. At longer wavelengths (5-25 cm), radiation from deeper in the soil can be obtained due to the longer skin depths for the longer wavelengths. For a fixed antenna diameter, the spatial resolution for space borne radiometers is nearly proportional to the wavelength (longer wavelength, coarser resolution). Atmospheric effects, on the other hand, decrease for longer wavelength. The atmosphere is essentially transparent above 5 cm.

The effect of the soil type on the dielectric coefficient is coupled to soil moisture, and consequently the soil type influences the microwave brightness temperature. The coupling results because of the different strengths by which water molecules adhere to the soil particles. In order to compensate for the differences in different types of soils, the brightness temperature data can be plotted as a function of the percentage of field capacity which becomes essentially independent of the soil type (Schmugge, 1977). Thus, the percentage field capacity provides a better description of the water availability to plants and the degree of soil saturation.

The surface roughness is yet another factor that affects the microwave brightness temperatures. It increases surface emissivity due to scattering and therefore, the brightness temperature of rough surface is also expected to be higher. This results in the observational fact that emissivities are never lower than 0.6 for real soil surfaces. Choudhury et al. (1979) developed a single modification parameter to characterize roughness effect. The results indicate that roughness effects are large for wet soils where the difference between smooth and rough surfaces can be as great at 50°K. Since a comprehensive model to treat all scales of surface roughness at various wavelengths is not developed, the simple type of modification parameter proposed by Choudhury et al. (1979) can be introduced, and it can be treated as an additional noise contribution to the observed brightness temperatures.

Surface slope affects the observed brightness temperature due to the relative change in the look angle from the antenna to the surface. Emissivity of the vertical polarization component increases from nadir to larger look angles until the Brewster angle (>60°) and then decreases with angle; emissivity of the horizontal polarization component varies in the opposite manner. For satellite sensors the look angle is usually between 45° and 55°. In this range a change of slope of 10° can affect the brightness temperature by 10° to 20°K.

A vegetation canopy essentially obscures the soil surface such that the sensitivity of soil moisture content to the brightness temperature is greatly reduced. Over forest areas, the soil moisture information is lost at all microwave wavelengths. For agriculture fields, the moisture information is essentially lost at shorter wavelengths (1-4 cm) but it can be retrieved at longer wavelengths (5-25 cm), although with less sensitivity than if the ground were bare. Complete modeling of the vegetation effect in the microwave region is not available, but its general tendency (increasing the observed brightness temperature with increasing vegetation) is well understood and can be applied.

The above summarizes the overall microwave response to various features of land surfaces. It has been demonstrated that microwave remote sensing is a useful means of soil moisture monitoring from space. There are limitations; for example, surface roughness and a vegetation canopy degrade the sensitivity to a certain extent. Various soil types and surface slope can add more uncertainty to moisture retrieval. However, over extended farming areas, these factors are usually at a spatial scale of more than 10 km. Therefore, sensors with a spatial resolution of 10 km or less will be relatively unaffected by the scale of the variability in soil type and surface slope.

On the other hand, the microwave signature can be greatly affected if there are small water bodies within the field of view. Emissivity of water ($\sim$.3) is substantially lower than land surfaces in the microwave range. A mixture of dry soil and water bodies in the same field of view can easily be interpreted as wet soil. Figure 3-1 demonstrates the effect of brightness temperature of dry land with various percentages of water body (or bodies) within one field of view (solid line). The dashed horizontal lines are the corresponding brightness temperatures with soil backgrounds of various moisture content but without any water body. It is obvious that finer spatial resolutions can greatly reduce the ambiguities which result from the presence of small water bodies. This topic will be treated in more detail in the next section.

3.2 Spatial Scales of Surface Features of the Study Region

3.2.1 General Features of the Study Region

In addition to soil moisture content, there are other factors of natural terrain which directly affect the microwave response of land backgrounds. Using microwave measurements, large areas having specific characteristics can be delineated, for example, large water bodies, urban areas, and forest. All these features have distinct signatures in the microwave spectral region. Over water bodies the brightness temperatures are low and exhibit substantial polarization differences. The brightness temperatures over urban areas are also low but with little polarization difference. Over forest and dense vegetated areas, the brightness temperatures are approximately the same as bare lands but with less polarization difference. These can be distinguished from dual polarized microwave measurements or simply from existing geological information.

The defined region for this study is shown in Figure 3-2. Major urban areas within the study region (between 32°N and 42°N, 104°W and 90°W) include Dallas/Fort Worth and Lubbock in Texas, Oklahoma City and Tulsa in Oklahoma, Wichita in Kansas, St. Louis and Kansas City in Missouri, Des Moines in Iowa and Omaha in Nebraska. These densely popu-

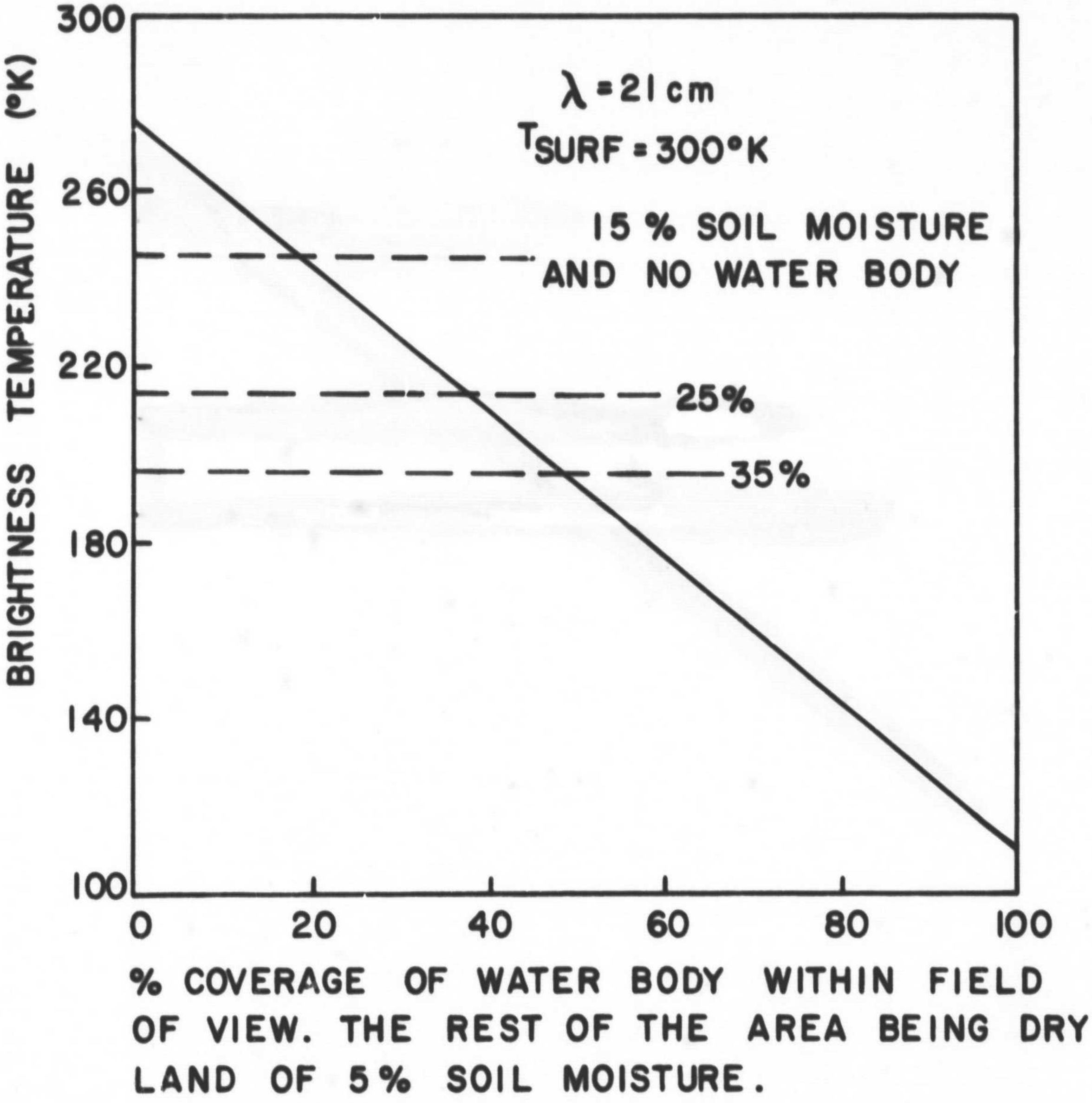


Figure 3-1 The response of microwave brightness temperature at 21 cm for backgrounds mixed with dry soil (5% soil moisture content) and various amounts of water bodies. The dashed horizontal lines are brightness temperatures with land background of various moisture content but no water body.

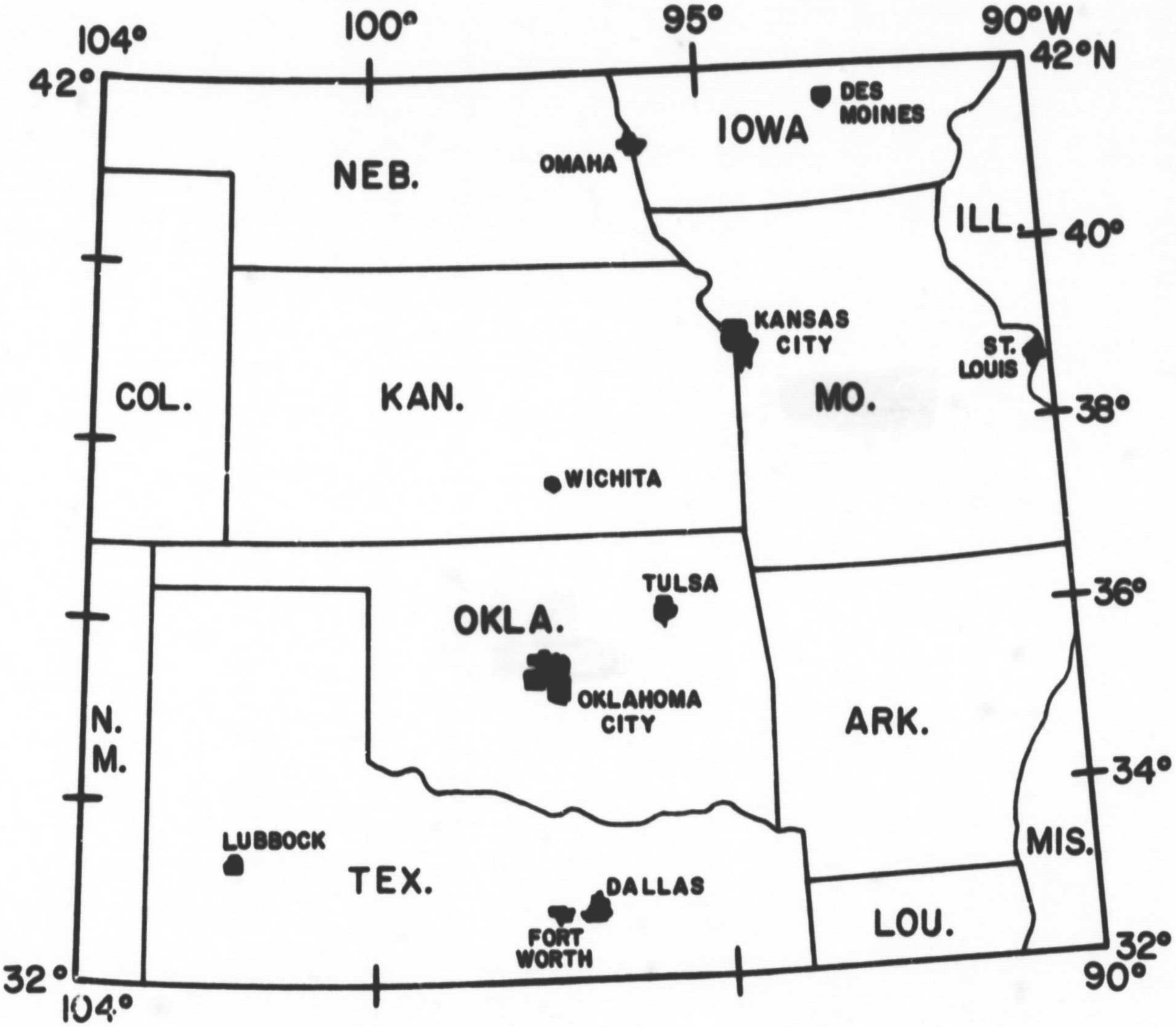


Figure 3-2 Densely populated areas within the study region. Each area has population over 200,000.

lated and developed areas have dimensions which are usually of the order of 20-60 km, and they should be easily distinguishable in the microwave region.

The general features of the defined region for this study are carried out using information contained in the National Atlas of the U.S.A. (1970) and also from Landsat and other satellite imagery. In the National Atlas of the U.S.A., the potential natural vegetation of the U.S. is divided into 106 categories with spatial resolution of the order of 20-50 km. Analysis for the study region utilizing these categories are carried out and recombined into three general categories; grasslands in the western part, forests in the eastern part and mixed grasslands/forests in between the two parts; the distribution of these categories is shown in Figure 3-3a. The characteristic dimensions of the vegetation types shown in Figure 3-3a were determined along latitude (east-west) and longitude (north-south) lines at 1° intervals. The dimension of a specific vegetation type along a line was taken; when the vegetation type along the line changed, then another dimension appropriate for the new vegetation type would be obtained. A histogram of the dimensions for the vegetation map of Figure 3-3a is shown in Figure 3-3b. The grasslands have a fairly uniform distribution of sizes, but the other two vegetation types have a predominate dimension of less than 50 km. This general feature can be seen qualitatively in Figure 3-3a.

The features are also spot-checked with Landsat and other satellite imagery. In summary, this region includes pasture and forest land of the inland south, extensive cropland of the Great Plains, and irrigated cotton lands of the Texas High Plains. Much of the western portion of the study area is dominated by smooth plains, prairie grasses, and large areas of dry land wheat. An extensive area of irrigated cropland can be found in the Lubbock, Texas and other areas. The eastern portion of the study area is highly diversified in both land surface form and land use. The northeastern section consists of open hills, tablelands, high hills and low mountains; land use includes cropland, forest and woodland, and cropland with pasture. The southeastern section is largely smooth plains, irregular plains, plains with hills, and tablelands; predominant land use in this section could be described as woodland and forest interspersed with cropland and pasture.

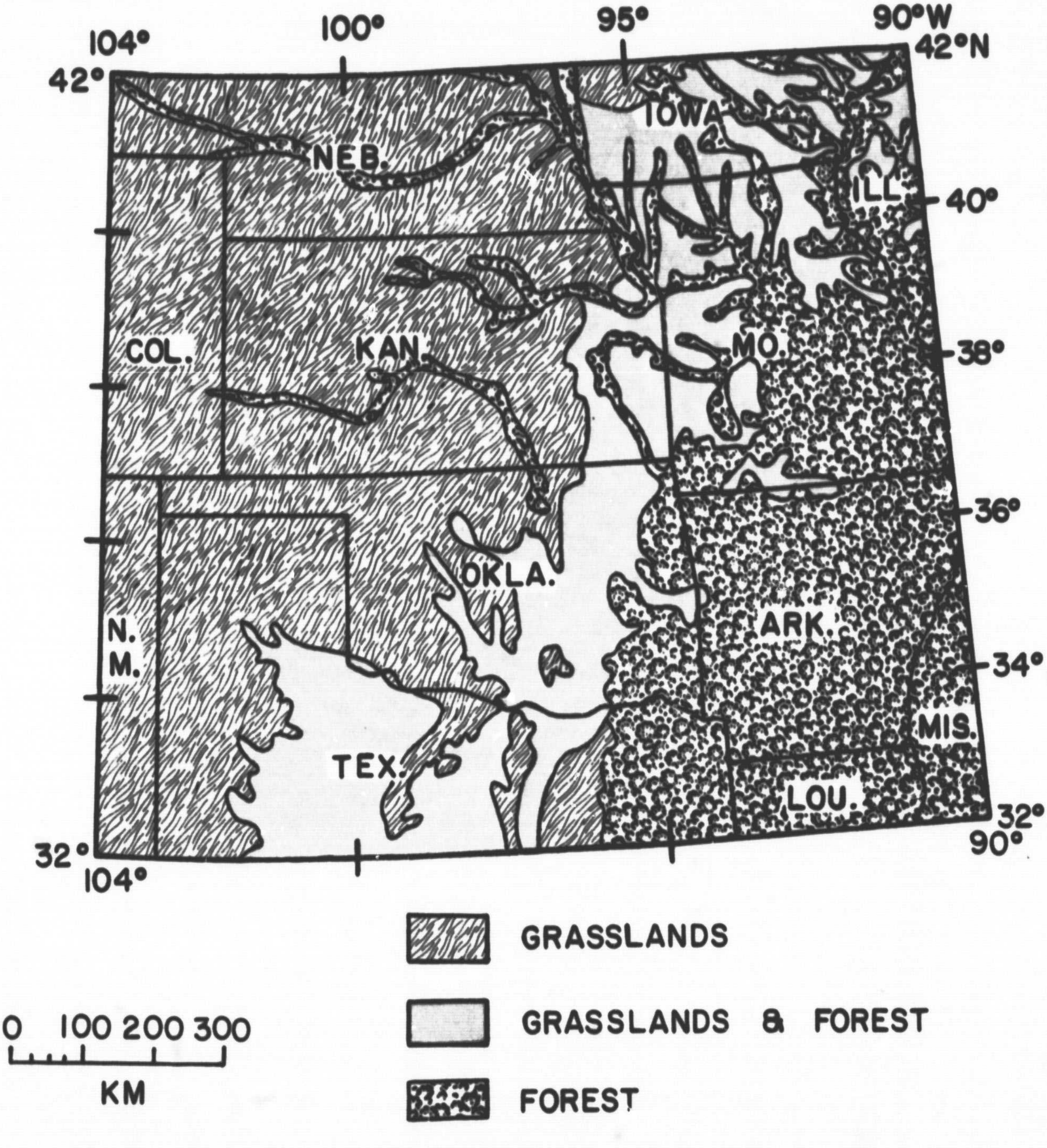


Figure 3-3a The study region categorized according to grasslands, forest and mixture of grasslands and forest.

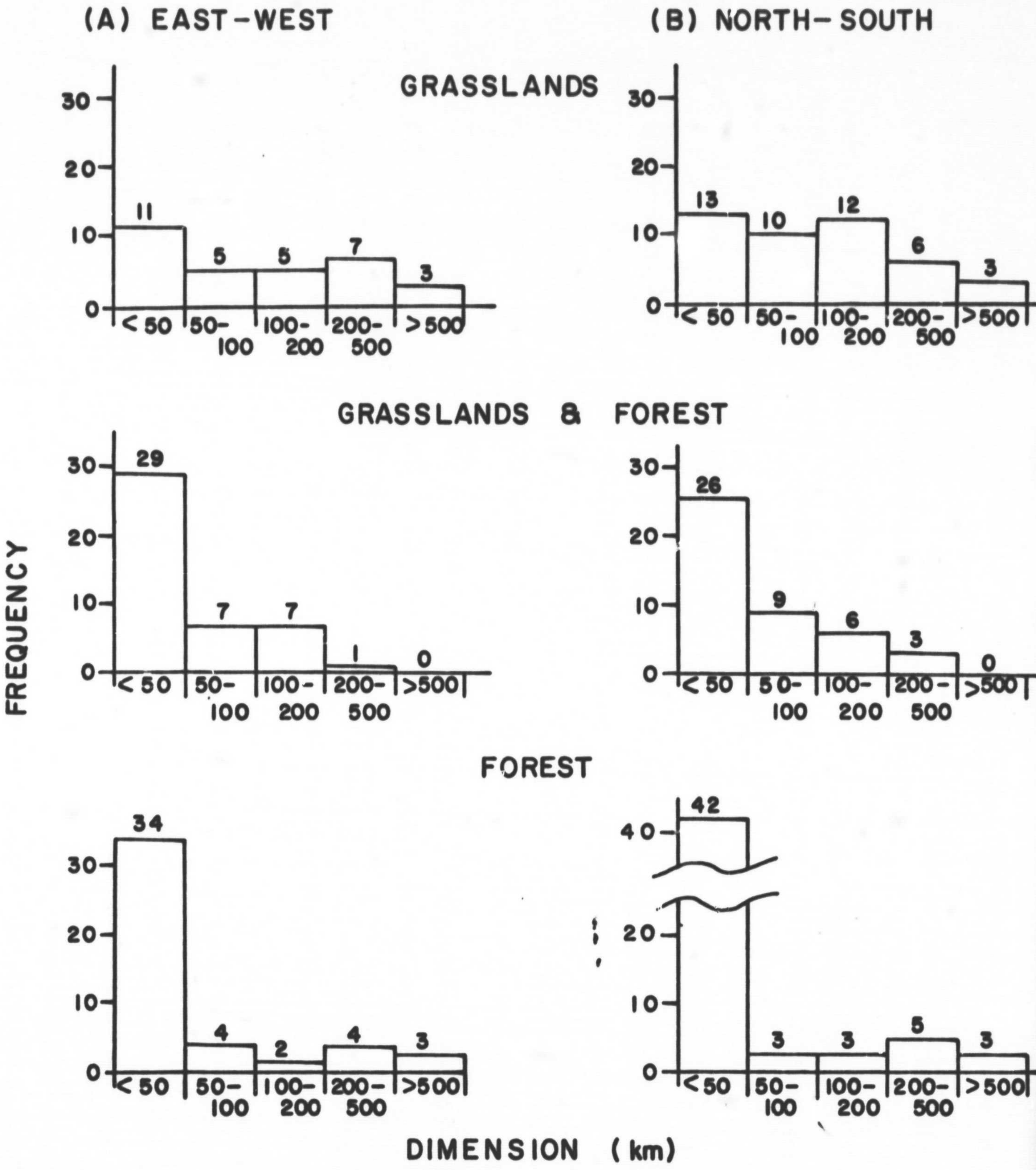


Figure 3-3b Histograms of the dimensions of grasslands, forest and mixture of grasslands and forest. They are obtained from Figure 3-3a along latitude (east-west) and longitude (north-south) lines at 1° intervals.

3.2.2 Detailed Features of Selected Sites

This section includes a description of the water bodies within the study region, and the details of land use for three test sites are mapped. The water areas are investigated in more detail due to the fact that they produce very different microwave signatures than land. For a mixed background of water bodies and dry land, the microwave signature resembles that of wet land. Therefore, if small water areas exist within agriculture land, they could cause ambiguities in the interpretation of microwave measurements. The three test sites are representative of the "scenes" expected over the whole study region. Each is a circular area of 50 km in diameter such that variations of 10-km and 1-km scales can be demonstrated.

Water Areas Within Mid-Western USA

Information of total water and residual water areas was obtained from an analysis of ERTS-1 data (Serebreny et al., 1975). By definition, residual water area is the difference between the total water area and the water area of those lakes equal to or greater than 10 km^2; it may include both rivers and small lakes. Some of the areas analyzed by Serebreny et al. (1975) are contained in the study region of this project and are indicated in Figure 3-4. The common regions include:

1) eastern Colorado, southwestern Nebraska and northwestern Kansas;
2) southeastern Nebraska and north-northeastern Kansas; and
3) the panhandle of Texas, northeastern New Mexico, southeastern and southwestern corners of Kansas and Colorado respectively.

Each of the three regions of Figure 3-4 has an area of 195,200 km^2 (440 km to a side). Among the three regions shown in Figure 3-4, the total water areas are all less than 2% of the total area. Furthermore, of this 2% of water area, 70% or more of it is composed of smaller lakes and streams which make up the residual water area. These aspects were

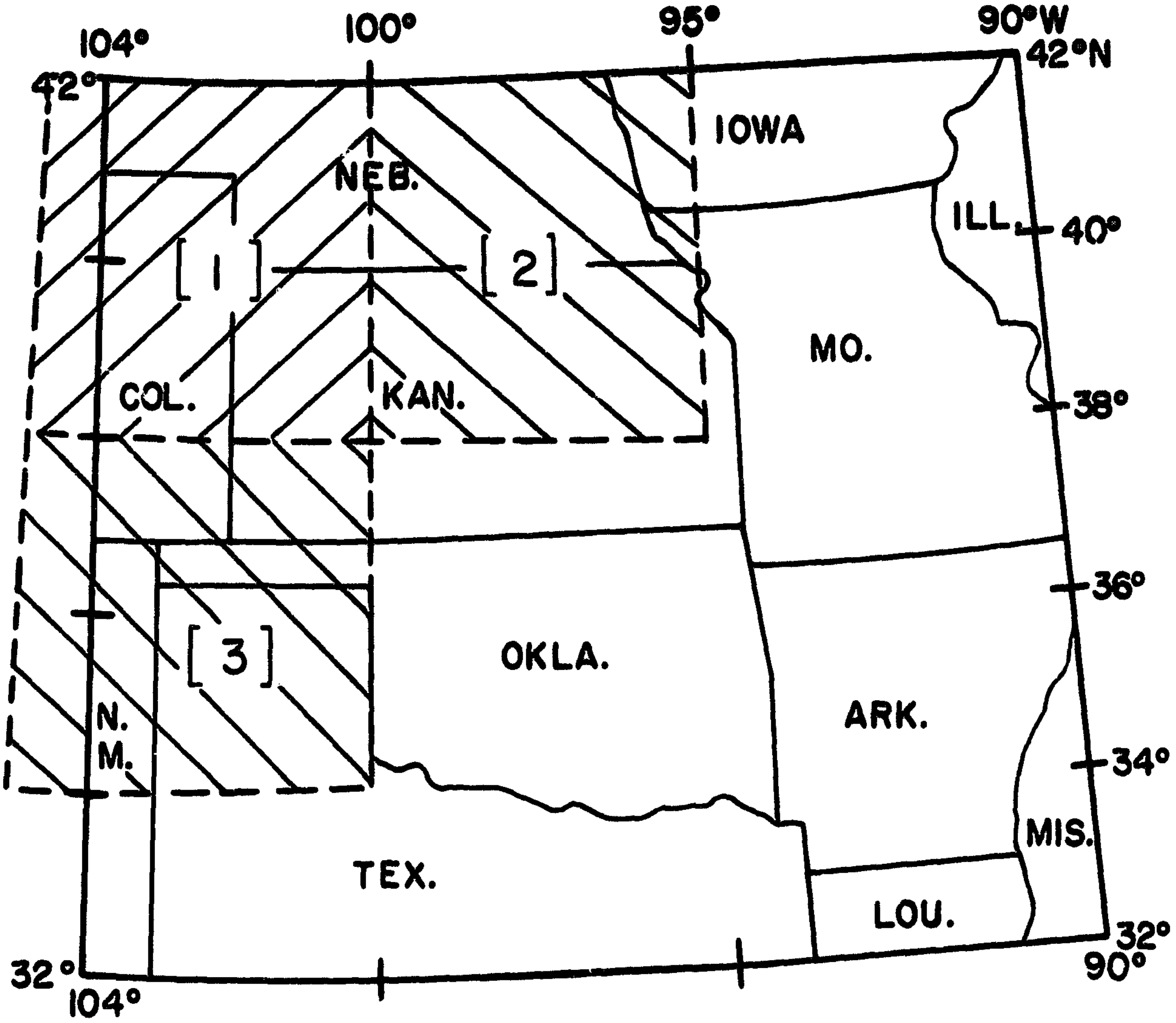


Figure 3-4 Areas with known total and residual water information from ERTS-1 data within the study region.

derived from data given by Serebreny et al. (1975) and shown in Table 3-1 which lists the size, total water area, total lake area and residual water are of each of the regions.

Based on the information of water area for the regions in Figure 3-4, the following conclusions can be summarzed:

1) for large area monitoring of more than a few hundred kilometers in size in regions such as the mid-west region of the U.S. studied here, spatial resolution in the order of 10 km for the microwave radiometer would not seriously jeopardize accurate and efficient soil moisture monitoring due to the presence of water bodies. This conclusion is reached from the fact that water bodies occupy less than 2% of the total area of interest. A simple way to retrieve soil moisture information would be to first discard any extremely low brightness temperatures which could be due to the presence of water bodies. Then after averaging a number of pixels of data, the areal soil moisture content should be representative; and

2) for small area monitoring (less than a few tens of kilmeters in size), water bodies can pose a problem since over 70% of all the water bodies are less than 10 km^2 in size. Any water body within the area can produce erroneous information of soil moisture. However, for the monitoring of specific small areas, regions with substantial water bodies should be known beforehand and these can therefore be treated separately by using the existing geological information.

In summary, soil moisture measurements using a microwave radiometer system with a spatial resolution of 10 km will be relatively unaffected by the presence of the water bodies which occur in the mid-western U.S. The use of a system with a 1-km spatial resolution would generally not provide significantly improved soil moisture information. Further details on the basis for this conclusion are provided through the analysis of the land use maps described in the next section.

TABLE 3-1

WATER AREA MEASUREMENTS

Region	Area (km^2)	Total Water Area and % of Total Area	Total Lake (>10 km^2) Area and % of Total Water Area	Residual Water Area and % of Total Water Area
1	195200 (440 x 440)	3598 km^2 1.84%	438 km^2 12.2%	3160 km^2 87.8%
2	195200	3135 km^2 1.61%	957 km^2 31.5%	2178 km^2 69.5%
3	195200	1336 km^2 0.68%	192 km^2 14.4%	1145 km^2 85.6%

Representative Sites for Demonstration

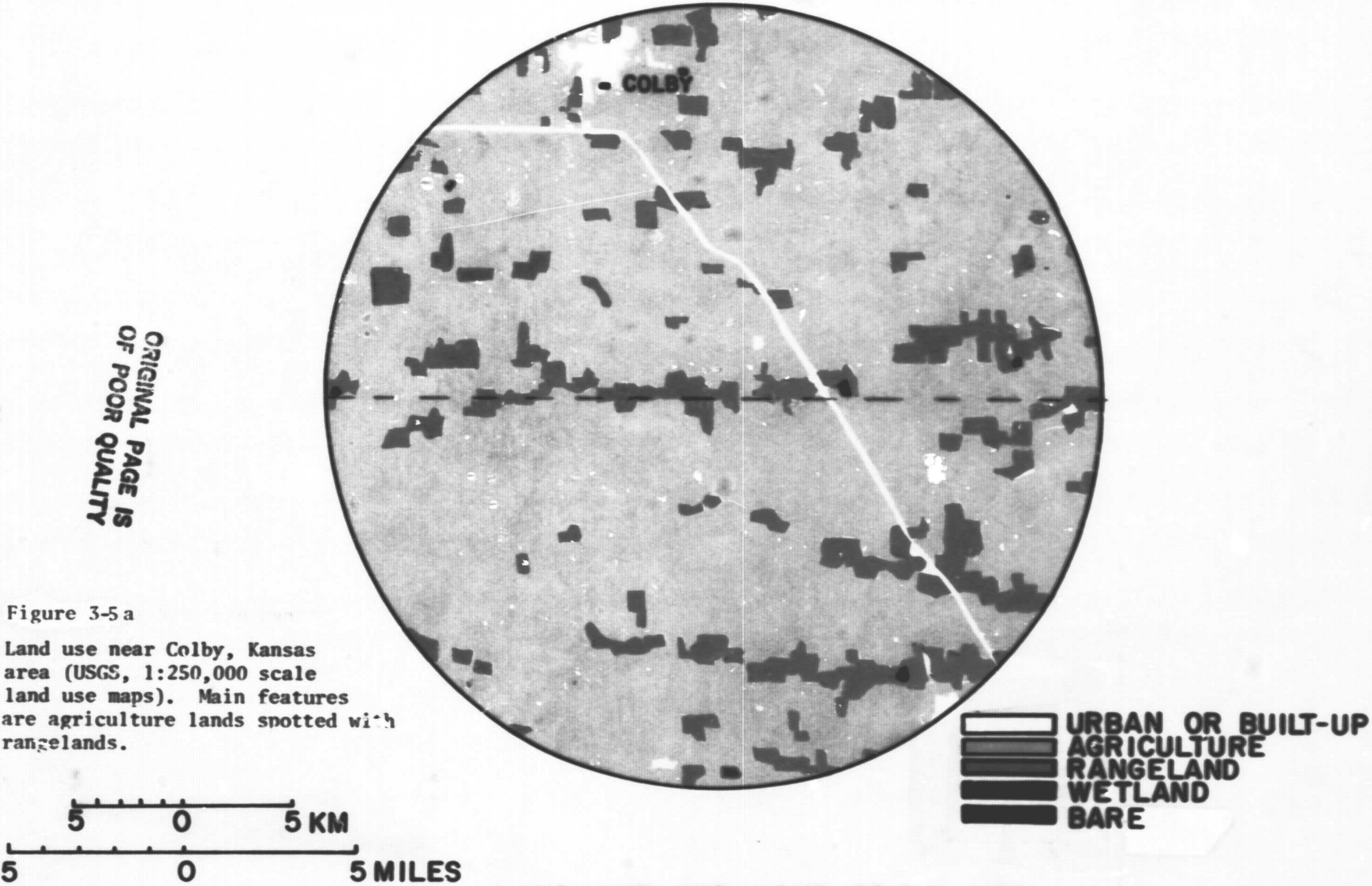
The three selected study areas are (1) Colby, Kansas, a typical mixed agriculture/grassland area; (2) St. Louis, Missouri, with mixed urban/agriculture background; and (3) Fort Smith, bordering Oklahoma and Arkansas, a typical watershed area surrounded by forests. The area maps used for these study sites were obtained from the USGS 1:250,000 scale land use maps.

The Colby, Kansas study site is largely an area of smooth to irregular plains underlaid by Upper Tertiary sedimentary rocks with 50 to 100% of the area gently sloping; 50 to 75% of this gentle slope is in the uplands. Local relief is 100 to 300 feet, and the region has a mean annual precipitation of 16 inches. Annual surface runoff is less than 0.5 inches with usable reservoir capacities generally exceeding average annual inflow. This is an area of mostly cropland (wheat and small grains) with grazing land.

Figure 3-5a demonstrates the general land use and background for the Colby area. The area was selected as it is representative of the major areas of agriculture and rangeland throughout the mid-western U.S. In this test area, populated and built-up areas are relatively sparse with the test area relatively smooth and uniform throughout the whole region. Regional soil moisture is of major concern for crop yield. For this type of area a spatial resolution of 10 km should be sufficient due to its uniformity. Figure 3-5b demonstrates variations of brightness temperatures at 21 cm along a scan line on 1-km and 10-km scales. Two background soil moisture conditions are assumed; dry (5%) and wet (35%). As can be seen, little additional usefulness can be obtained from soil moisture measurements with spatial resolution of the order of 1 km.

Both the St. Louis and the Fort Smith study sites are largely areas of irregular plains, underlaid by Upper Paleozoic sedimentary rocks, with 50 to 80% of the surface gently sloping; 50 to 75% of this gentle slope is in the lowlands. In both sites usable reservoir capacities exceed average annual inflow. Wheat and small grains dominate the cropland theme of the Oklahoma site; with mixed cropland, pasture and forestland occurring in the St. Louis site.

The St. Louis, Missouri area (Figure 3-6a) was also selected due to its uniqueness of mixed background of urban, water, agricultural and



LAND USE AND LAND COVER, 1974
COLBY , KANSAS

Figure 3-5 a

Land use near Colby, Kansas area (USGS, 1:250,000 scale land use maps). Main features are agriculture lands spotted with rangelands.

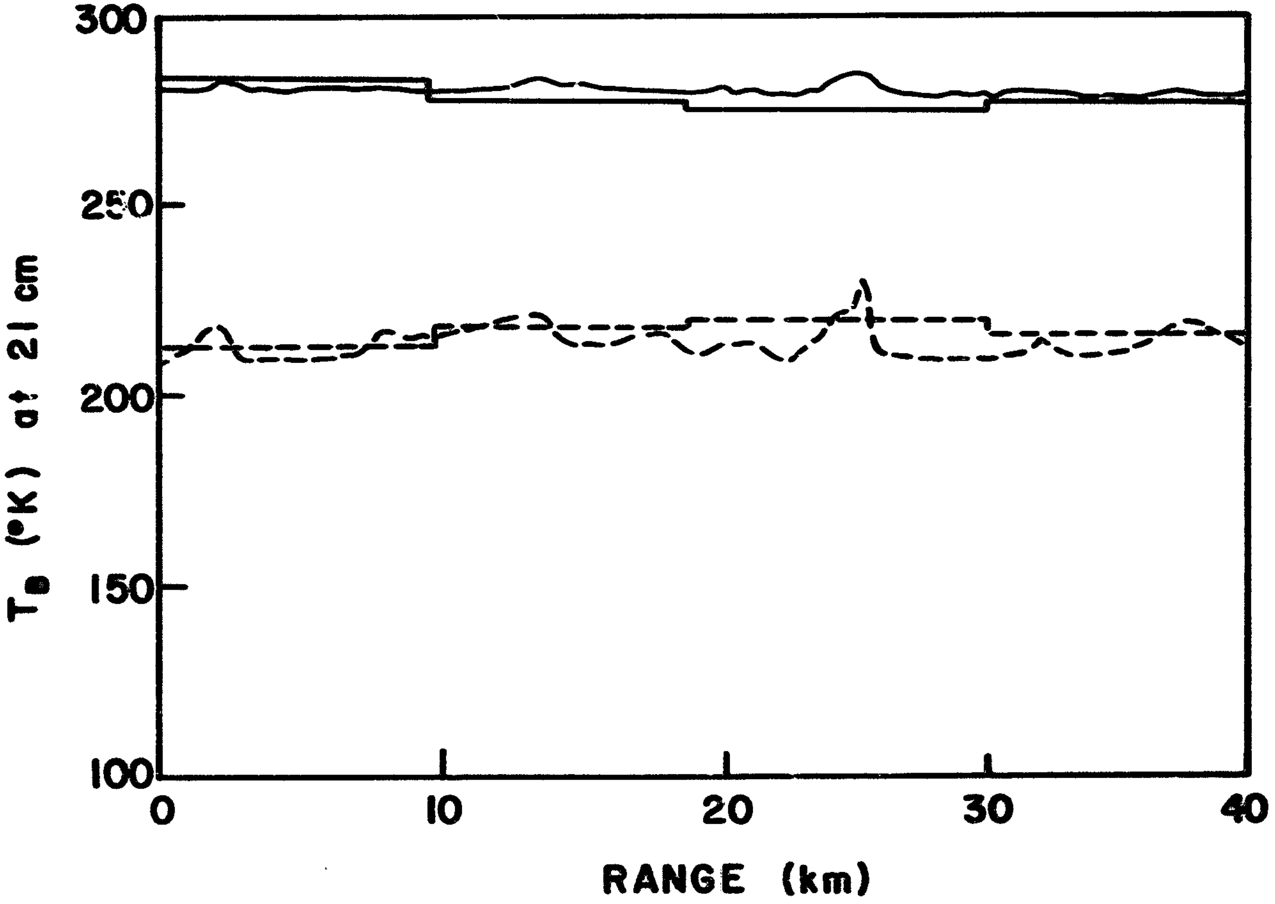


Figure 3-5b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-5a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

forest areas. The area is divided by the Mississippi River into two parts. The region that is west of the river consists of more than 95% urban or built-up areas. East of the river, the region becomes quite mixed; 30% is populated areas with scales of 5-10 km, 40% is agricultural land with scales ranging between 1-10 km, and the rest are spotty water, forest and bare land spread throughout with scales of the order of 1 km for each type. Precise monitoring from satellite should require spatial resolution of 1 km or better due to the variability of the background. However, due to its closeness to the major urban area, there is no large-scale farming business in the area. A sensor with spatial resolution of 10 km would flag most of this area as urban or densely populated and soil moisture information would be unavailable. The loss of information due to the use of a system with a 10-km resolution can be regarded as minimal since outside the urban area there will be large agricultural areas for which soil moisture information could be obtained with acceptable accuracy. The soil moisture information obtained from adjacent areas can then be applied to the areas of mixed background. Information obtained this way should be at least as good as direct measurement over the area with a 1-km resolution since the background would often be variable even with a 1-km "cell" resolution; thus the 1-km data would lead to difficulties in interpretation. The brightness temperature responses at 21 cm over 1-km and 10-km scales are also demonstrated in Figure 3-6b.

Figure 3-7a demonstrates the land use and background of the Fort Smith area. This area was chosen as a typical watershed area. The land use is predominantly agriculture. There is a large water body created by a dam, and the water covers a significant fraction of the western half of the area. Spotty wetlands and forest regions also occur throughout the entire region. Soil moisture information is obtainable with a microwave system over agriculture and bare areas which account for more than 50% of the total reference area. From Figure 3-7a, it is seen that the scales are in the order of 5-10 km for water bodies, 1-5 km for forest areas and 1 km for urban lands. Figure 3-7b demonstrates the brightness temperatures at 1 km and 10 km resolutions as carried out for the other two sites. Satellite monitoring of the soil moisture information for an area of this type would again require spatial resolution in the order of

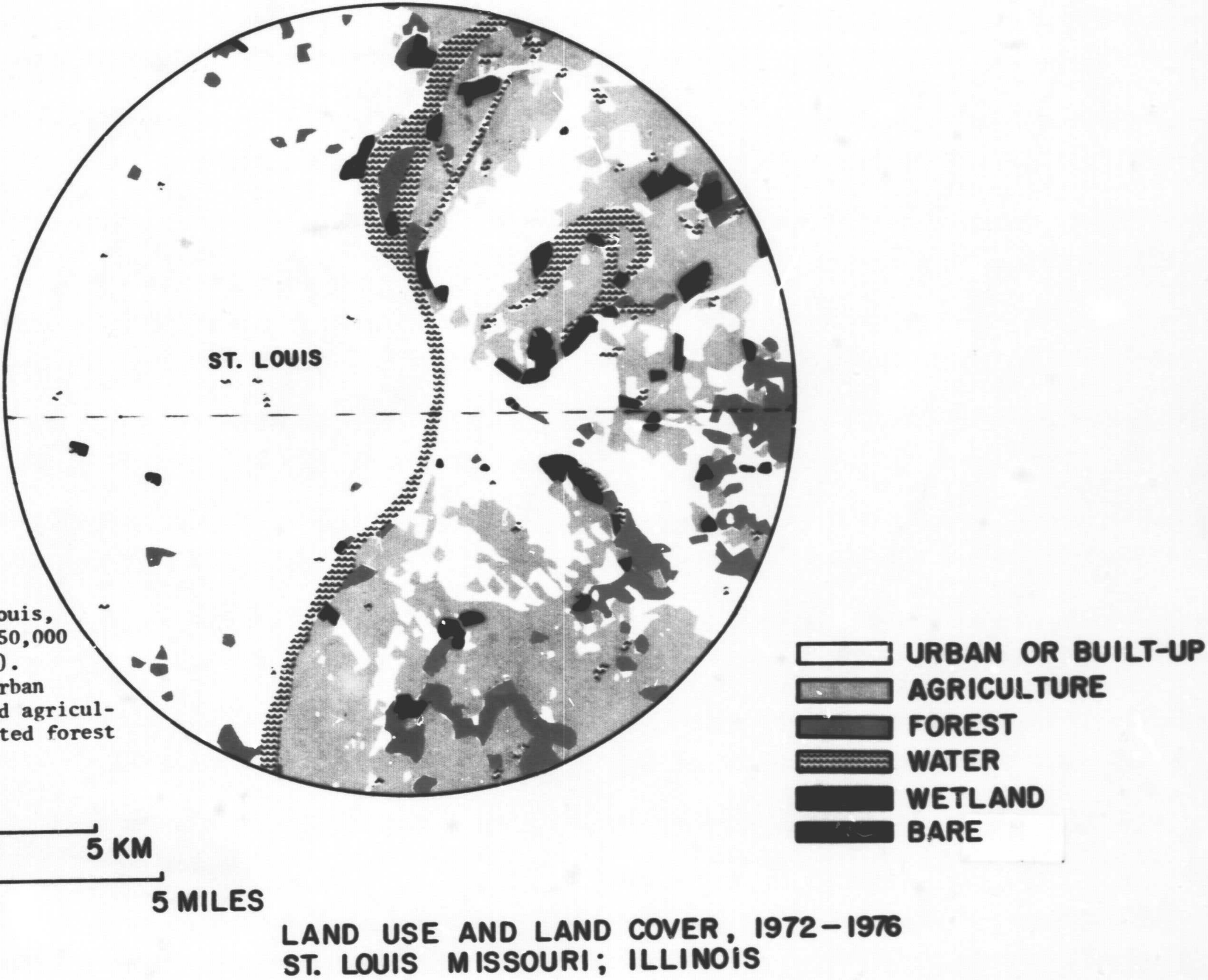


Figure 3-6a

Land use near St. Louis, Missouri (USGS, 1:250,000 scale land use maps). Main features are urban areas with scattered agriculture lands and spotted forest and water areas.

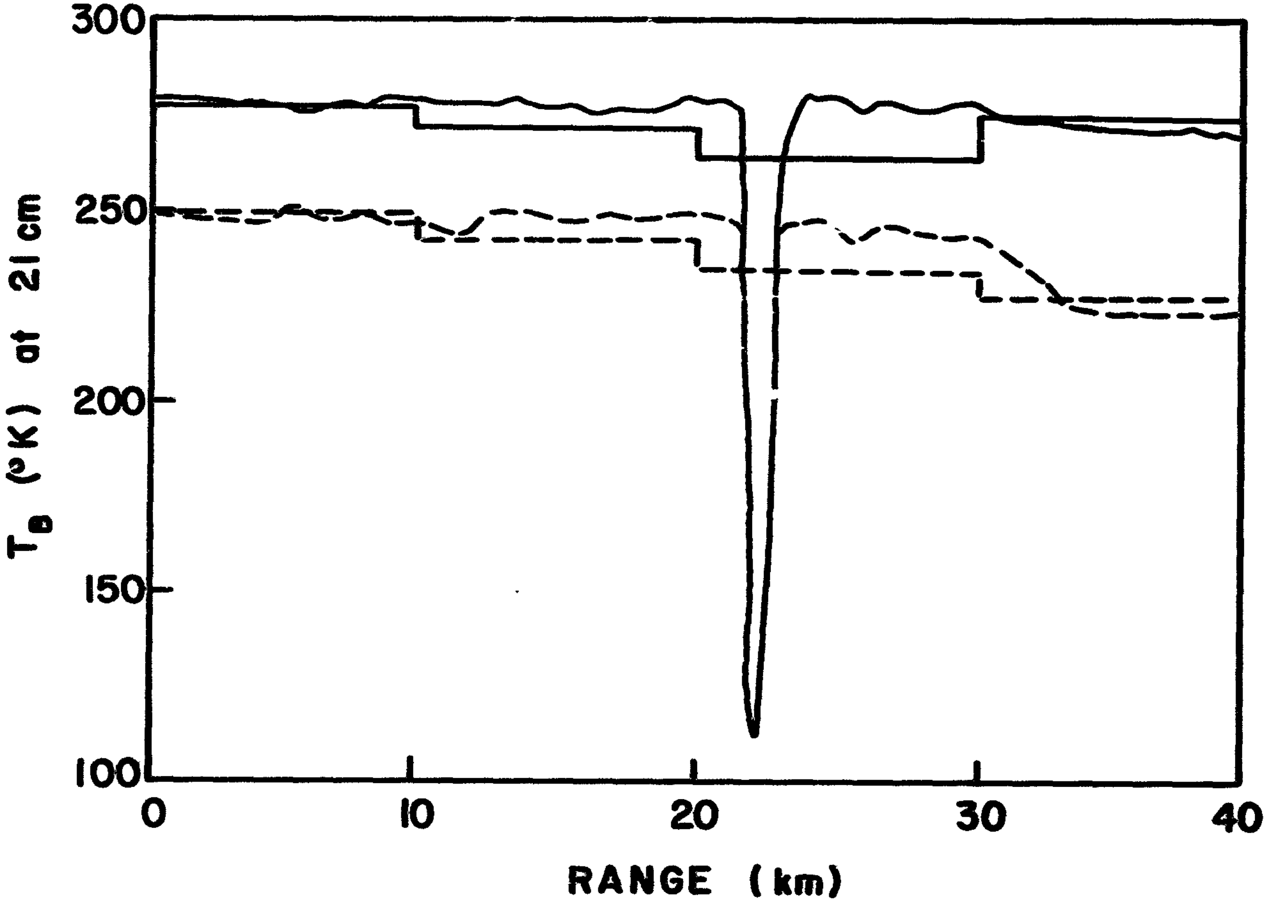


Figure 3-6b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-6a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

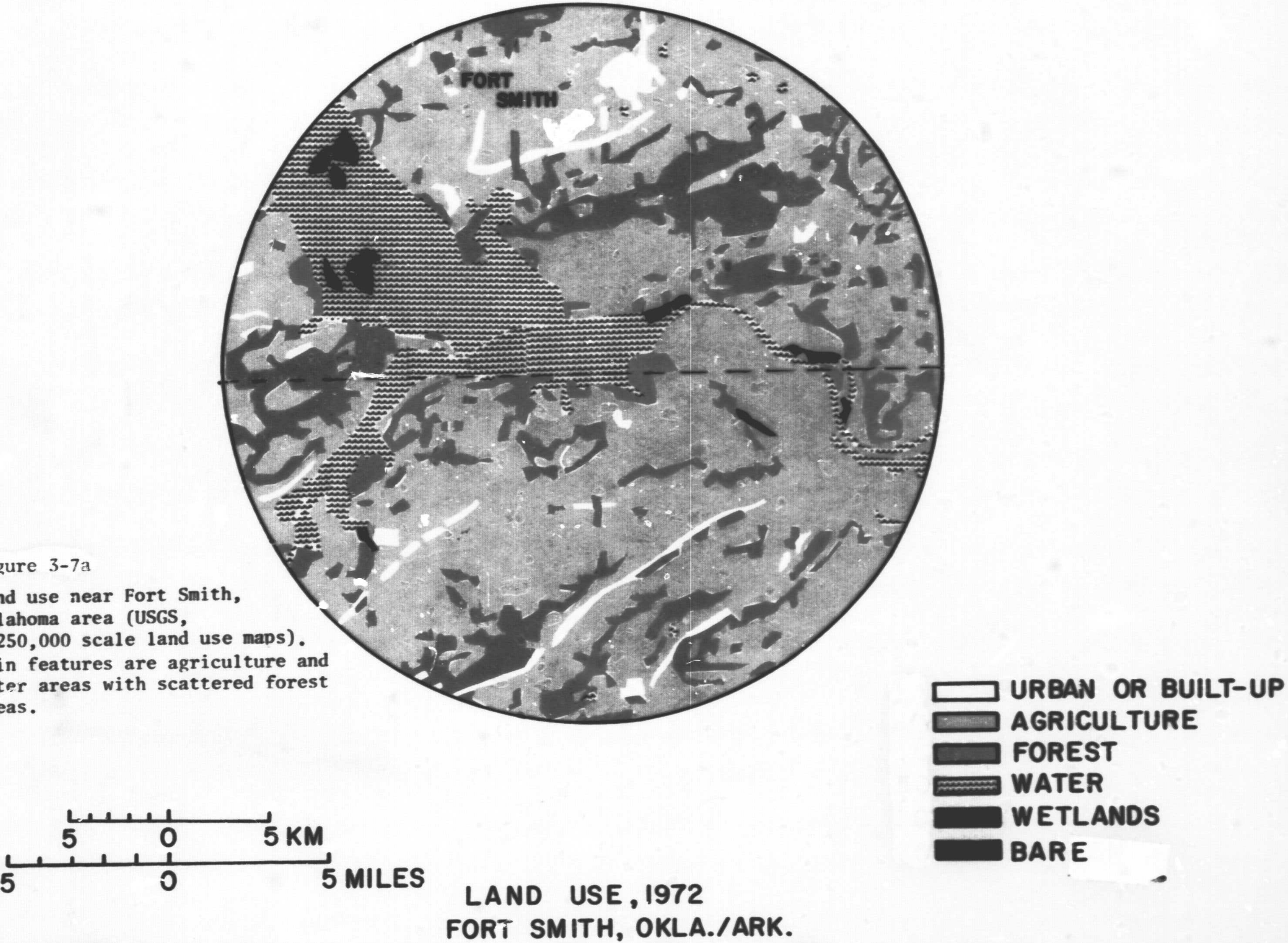


Figure 3-7a

Land use near Fort Smith, Oklahoma area (USGS, 1:250,000 scale land use maps). Main features are agriculture and water areas with scattered forest areas.

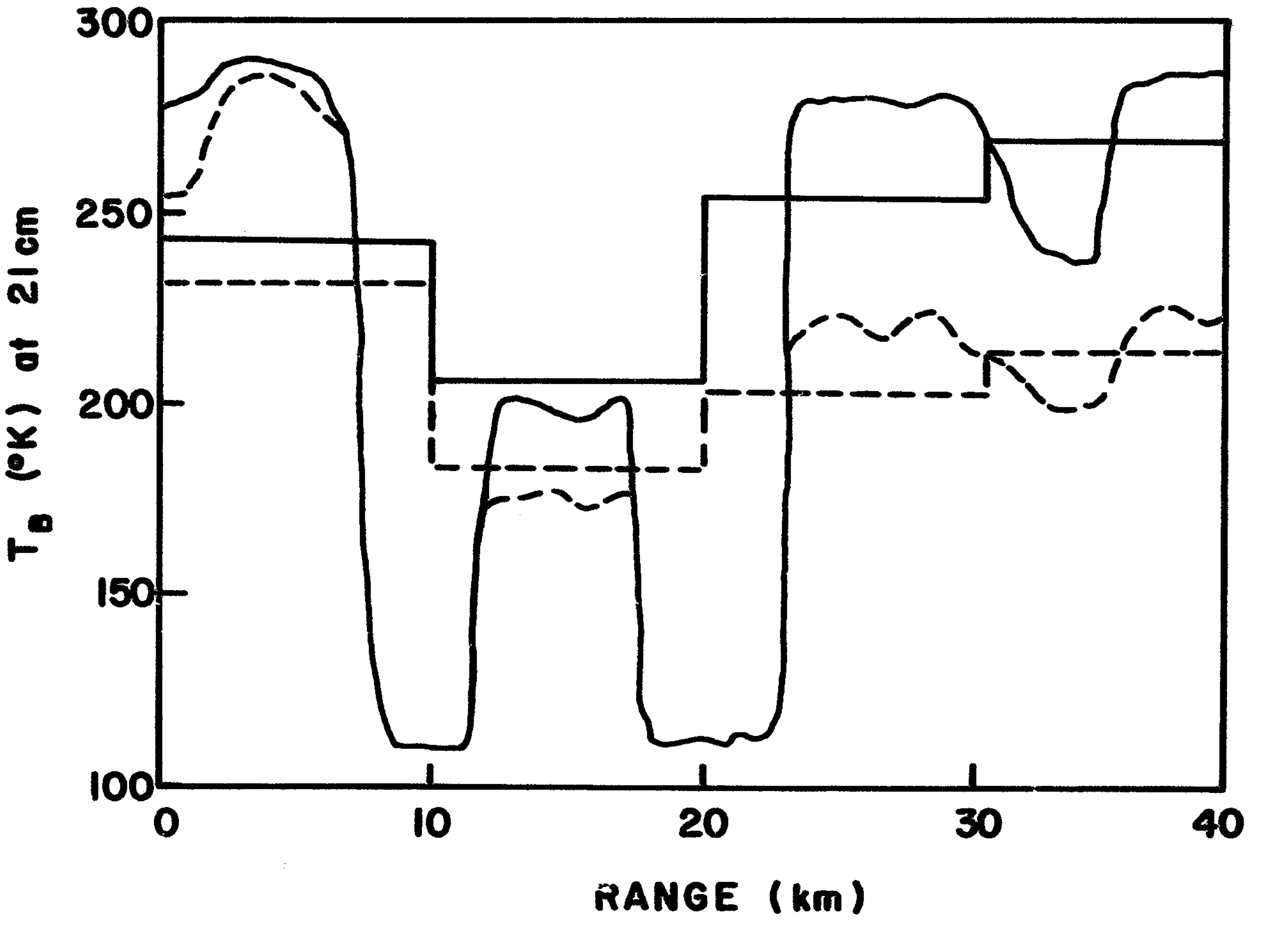


Figure 3-7b Simulated brightness temperatures at 21 cm along a scan line from Figure 3-7a (center, east-west) on 1 km x 1 km and 10 km x 10 km scales. Two background soil moisture conditions are assumed: solid lines for dry (5%) and dashed lines for wet (35%) conditions.

1 km due to the areal variability. However, prediction of watershed runoff, a resource for irrigation and flood control, may be of more interest than soil moisture retrieval for areas of this type. The microwave brightness temperatures are high for low soil moisture content, rough surfaces, sandy soils and dense vegetation. All these conditions tend to reduce watershed runoff (Blanchard, 1974). For a specific drainage area, information on the type and roughness of the soil, the coverage of permanent water, and the regions of forest and dense vegetation can all be used as input to obtain an expected brightness temperatures applicable for the entire watershed drainage area under both saturated and dry conditions. These conditions can then be used as a minimum and maximum reference indicators for the watershed surface storage capacity. In this case, the resolution requirement can be greatly reduced.

The concluding remark for this watershed area, and similar ones, is that direct soil moisture information from satellite measurements should ideally be obtained at a spatial resolution of 1 km or less. Realistically, however, an "index" of the watershed surface storage capacity can be obtained more efficiently with a 10-km resolution provided the general land/water surface features for the season are known.

4. SOIL MOISTURE RESOLUTIONS FOR USE IN CROP YIELD AND HYDROLOGICAL MODELS

4.1 Current Soil Moisture Related Information

Present users of soil moisture information rely on gross estimates covering large geographic areas. The Palmer Index and Crop Moisture Index (CMI) is presented weekly during the growing season by the U.S. Dept. of Agriculture (USDA) and the National Oceanographic and Atmospheric Administration (NOAA). Both indices utilize Palmer's two-layer soil moisture model to evalute the weekly moisture status (Palmer, 1965, 1968). An example of a map of CMI is given in Figure 4-1. The CMI and Palmer Index utilize temperature and precipitation data from approximately nine climatological divisions per state. There are 25-30 stations within each division which provide precipitation reports (Denny, 1979). The average area per station is $(50\ \mathrm{km})^2$ but can be up to $(100\ \mathrm{km})^2$ for station sparse area. A map showing the divisions used for a determination of the soil moisture index is shown in Figure 4-2. The two models are designed to provide indices which are indicative of agricultural drought and crop moisture stress.

Another agricultural drought monitoring program at NOAA is operated by their Environmental Data Service's Center for Climate and Environmental Assessment (CCEA). This Cumulative Precipitation program utilizes both climatological and current values of precipitation amount (Reid, 1977). The world-wide program does not use soil moisture information but it does use soil water-holding capacity data for rainfall stations (Reid, 1979).

Crop estimates, which are based on field reports, are reported by the USDA, Economics Statistical Cooperative Service (ESCS). The ESCS has been evaluating forecasting models to be applied in an operational program (Wilson, 1979). However, soil moisture data have not yet become part of an operational program.

Another major user of the soil moisture information is the Office of Hydrology of NOAA. The River Forecast Service of the office is responsible for river and water supply forecasts. Soil moisture is one parameter that can significantly improve the confident level of mathematical models.

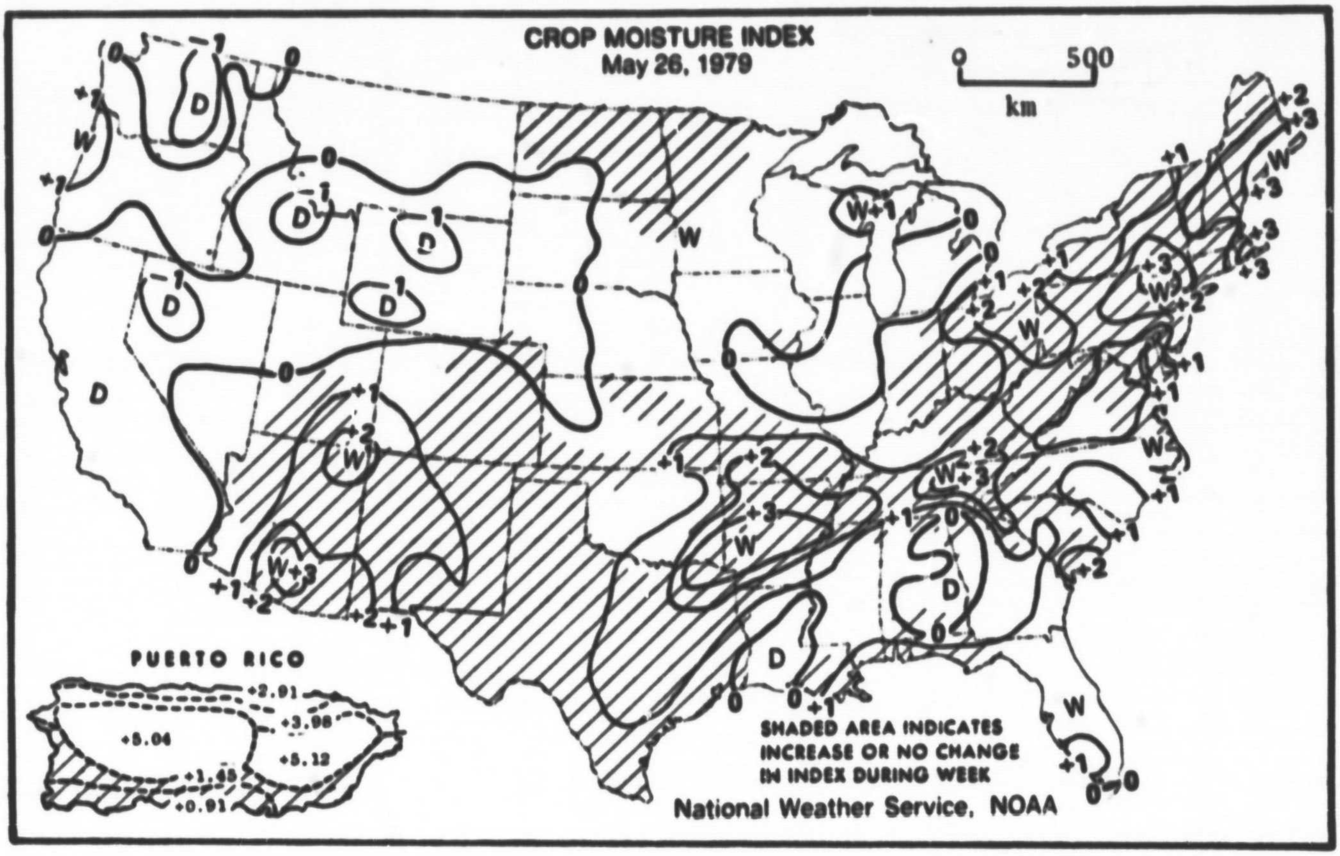


Figure 4-1 A Sample of the Map of Crop Moisture Index (Weekly Weather and Crop Bulletin, NOAA Department of Commerce and Department of Agriculture)

Some general guidelines are as follows:

Unshaded Areas: Index Decreased

Above 3.0	Some drying but still excessively wet
2.0 to 3.0	More dry weather needed, work delayed
1.0 to 2.0	Favorable, except still too wet in spots
0 to 1.0	Favorable for normal growth and fieldwork
0 to -1.0	Topsoil moisture short, germination slow
-1.0 to -2.0	Abnormally dry, prospects deteriorating
-2.0 to -3.0	Too dry, yield prospects reduced
-3.0 to -4.0	Potential yields severely cut by drought
Below -4.0	Extremely dry, most crops ruined

Shaded Area: Index Increased or Did Not Change

Above 3.0	Excessively wet, some fields flooded
2.0 to 3.0	Too wet, some standing water
1.0 to 2.0	Prospects above normal, some fields too wet
0 to 1.0	Moisture adequate for present needs
0 to -1.0	Prospects improved but rain still needed
-1.0 to -2.0	Some improvement but still too dry
-2.0 to -3.0	Drought eased but still serious
-3.0 to -4.0	Drought continued, rain urgently needed
Below -4.0	Not enough rain, still extremely dry

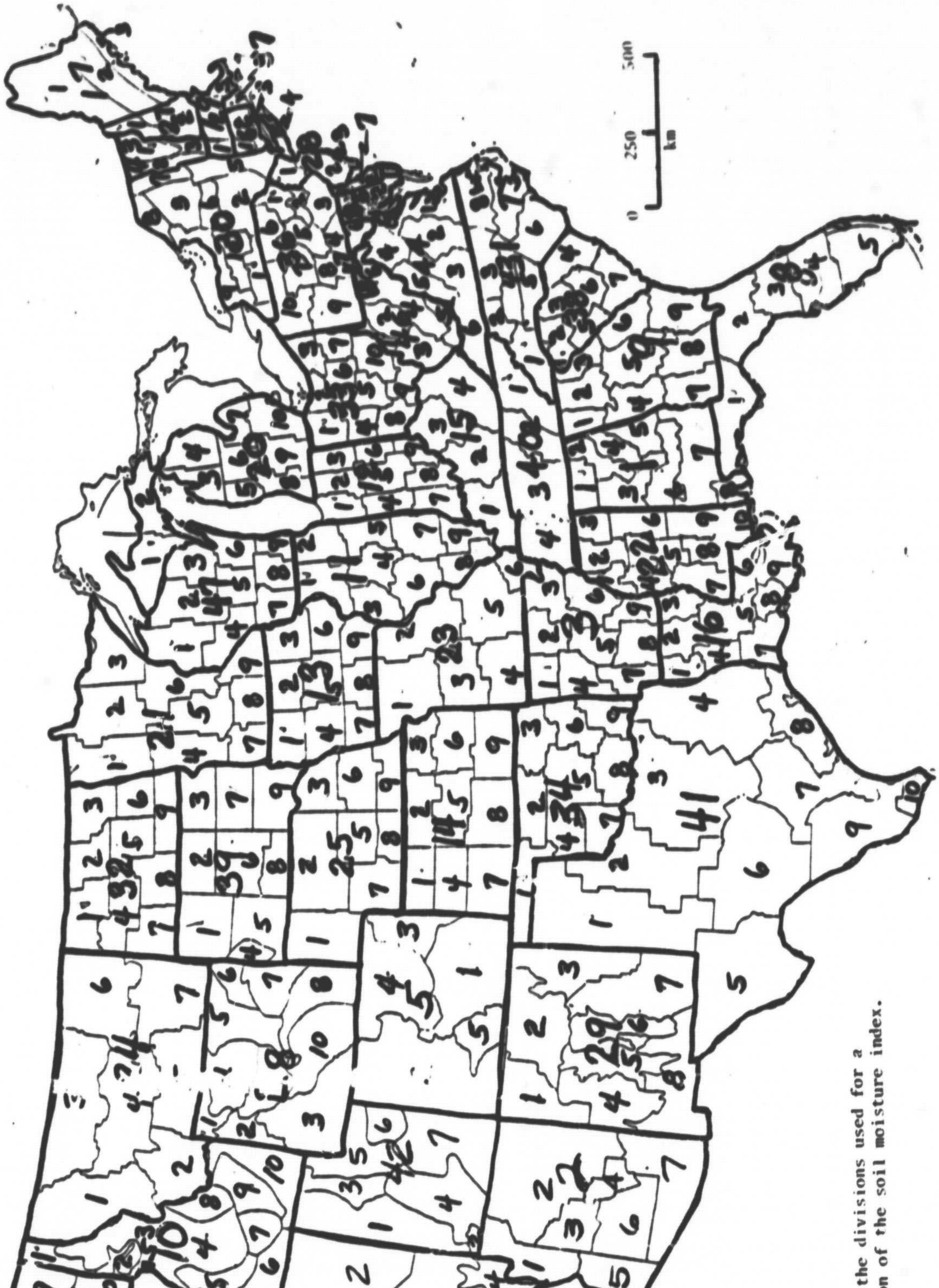


Figure 4-2 Map showing the divisions used for a determination of the soil moisture index.

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All the soil moisture information utilized by these various agencies is currently derived from precipitation reports or on-site direct measurements. Average spatial scale of the precipitation reports is 50 km or more. Direct measurements are usually carried out only for particular sites and the reports are less regular.

The Large Area Crop Inventory Experiment (LACIE) was performed by NASA in conjunction with NOAA and USDA to evaluate vegetative moisture stress using Landsat digital data (Thompson and Wehmanen, 1979). The remote sensing method showed a high degree of agreement with the CMI model. In the LACIE program, moisture condition was evaluated from vegetative stress rather than soil moisture.

4.2 Future Applications and Improvements of Soil Moisture Information

It is generally accepted that soil moisture estimates can improve crop yield and hydrological models. It was recognized at a Soil Moisture Workshop (NASA, 1978) that there are many potential users for soil moisture information. Once routine soil moisture information becomes available, operational programs would likely go through a period of development and evaluation of the new types of data.

Models using soil moisture budgeting should be a better predictor of crop yield than direct use of climatological data. Baier and Robertson (1968) claim higher correlation coefficients, lower coefficients of variation, and lower standard of errors of estimate for their soil moisture model versus models relying only on daily temperature and monthly rainfall.

Improvement of precipitation monitoring on a finer scale is another key to improving the accuracy of crop yield and hydrological models. Current soil moisture resolution over large areas is dependent upon the resolution of the climatological data. This study shows that the centers of maximum precipitation can occur within a 10-km diameter. Consequently, the incorporation of a dense rain-gage network could result in improved soil moisture information, and this would be of value for generating more accurate crop-yield models and forecasts.

Both soil moisture and watershed models also require accurate prediction of evapotranspiration. It is recognized that the accuracy of the Thornwaite equation for evapotranspiration is an inherent problem in the Crop Moisture Index (Denny, 1979). The potential evapotranspiration is usually calculated using the actual long-term mean monthly climatic temperatures. It is adjusted by the actual mean temperature and mean duration of sunlight of the past 10 to 30 days. Better accuracy of the climatological and meteorological information can certainly improve the estimate of the evapotranspiration.

The above summarizes the required improvements for soil moisture information. Soil moisture budgeting takes into account the soil texture and its capacity for holding water. Improvement of precipitation information leads to better input on the value of soil moisture. Evapotranspiration information plays a crucial part as a source of "depletion" of soil moisture. Among these factors, only precipitation information requires a fine spatial resolution of the order of 10 km. Present resolution of the order of a hundred kilometers for the other factors seem to be adequate for all users.

A satellite sensor system with a resolution of 10 km will be highly desirable for soil moisture monitoring. This is compatible with the ground information and meets the requirements of most users. A sensor with a resolution of 1 km would generate 100 times as many scenes for processing; other than specific interest groups which may have an interest in small areas, users of this fine-scale data cannot be easily identified.

Some of the government agencies that would benefit from a satellite sensor capable of detecting soil moisture on a 10-km resolution scale (NASA, 1978) include:

1) NOAA, for improving flood and water level forecasts

2) SRS (Statistical Reporting Service, or ESCS of USDA), for expanding areas for estimating and forecasting crop yields as present information is limited to specific research sites;

3) SCS (Soil Conservation Service) of USDA, for monitoring drought conditions and probable future moisture availability; and

4) AID (Agency for International Development), for anticipating drought and desertification in developing countries.

As can be seen, the capability of improving the monitoring of crop yield and drought/wetland areas from satellite microwave sensors on a 10-km resolution can benefit many major government agencies. Due to the current lack of data, applications and users for sensors of a 1-km resolution may appear once a system with a 10-km resolution is developed. Some of the potential users of data down to a 1-km resolution include:

1) USGS in their various water resource investigations;

2) ARS (Agricultural Research Service, or SEA) of USDA in local requirements of irrigation, drainage needs, and erosion;

3) the U.S. Water and Power Resources Service (formerly the Bureau of Reclamation) in their Irrigation Management Services Program; and

4) the U.S. Army Corps of Engineers in monitoring or predicting trafficability and mobility of military vehicles.

In general, these are operations and problems limited to local areas. As a result, data management and cost of operating a satellite sensor would be quite different from that of a system designed to monitor regional characteristics.

5. CONCLUSIONS

The intent of this study was to examine the usefulness of soil moisture observations at a 10-km and a 1-km resolution. Basic to this examination was an assessment of the problems inherent in the remote sensing of soil moisture by means of satellite-borne microwave radiometers.

The first item investigated was the rainfall amount patterns in the central regions of the U.S. The basic data were obtained from three networks of rain gages and the gages were separated by about 5 km. With this spacing it was not possible to obtain any useful information on scales of less than 5 km. However, from the correlation analysis of storm rainfall amounts, several previous investigators have demonstrated that the rainfall amounts at gages separated by about 5 km are correlated at the 0.9 level or higher. Thus, for the storm total rainfall amounts or the daily amounts used in this study, the patterns obtained from the networks having gage spacing of about 5 km are considered to be representative of the actual patterns with the exception that peak amounts and the gradients near the peak will generally be underestimated. Near the center of some storms where the gradients in rainfall amount are largest, a sensor with a 10-km resolution may underestimate the true value by about 20%. Beyond 5 km from the storm center, however, a 10-km resolution would lead to a good representation of the patterns for all the categories of storms.

The second item studied was an assessment of the problems associated with the remote sensing of soil moisture by means of a satellite-borne microwave radiometer. It has been shown in this study that the physical characteristics of the land features in the mid-western portions of the U.S. are such that microwave radiometers with resolutions on the order of 10 km can obtain representative and useful soil moisture measurements. This results was obtained from a combined analysis of the land features and the response to these land features by a 10-km resolution microwave radiometer.

The third major topic covered in the study was an assessment of the current uses of soil moisture information. Soil moisture information is essential for the generation of accurate results from crop yield and hydrological models. At present, soil moisture values are usually being derived from temperature and precipitation reporting stations which are separated by distances on the order of 100 km. Since considerable variability in soil moisture can occur on scales of less than 100 km, crop yield and hydrological models would be improved with data having a finer resolution. The immediate users of soil moisture at scales of 10 km include agencies which are concerned with the prediction of crop yields at a regional or local level and for hydrologists responsible for the prediction of run-off on relatively small basins. Information at a 1-km resolution would be valuable in those areas which are dominated by small ponds or land features which have areas of less than about 25 km^2. However, users of this very fine resolution data are likely to be confined to a small number of specific interest groups who are concerned with the details of soil moisture over very small regions.

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APPENDIX A

FORMAT FOR THE INFORMATION EXTRACTED FOR EACH STORM CELL AND LISTING OF THE CELL DATA

VAR	DESCRIPTION	NO. DIGITS	FORMAT	INCLUSIVE COLUMNS	EXAMPLE
SITE	1=OK; 2=TX; 3=KS	1	F1.0	1	1
DATE	YYMMDD	6	F6.0	2-7	770704
CID	CELL ID NUMBER	4	A4	8-11	C112
SFC	SFC WX TYPE[1]	2	1X, F1.0	12-13	2
kPa50	500 mb WX TYPE[2]	2	F2.0	14-15	03
MAXP	MAX PRECIP[3]	4	1X, F3.2	16-19	1.30
VAR7	5 km (360)[3]	4	1X, F3.2	20-23	.50
VAR8	5 km (90)	3	F3.2	24-26	.40
VAR9	5 km (180)	3	F3.2	27-29	.30
VAR10	5 km (270)	3	F3.2	30-32	.20
VAR11	10 km (360)	4	1X, F3.2	33-36	.10
VAR12	10 km (90)	3	F3.2	37-39	.06
VAR13	10 km (180)	3	F3.2	40-42	.04
VAR14	10 km (270)	3	F3.2	43-45	.02
VAR15	STORM DURATION(min)	5	1X, F4.0	46-50	1440

Sites include:
1 Oklahoma
2 Texas
3 Kansas

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[1] Code for Surface Weather Types
1 AIRMASS
2 UPSLOPE
3 SQUALL LINE
4 SQUALL ZONE
5 COLD FRONT
6 WARM FRONT
7 SFC HIGH
8 SFC LOW
9 STATIONARY FRONT
0 NONE OF ABOVE

[2] Code for 500 mb Types
1 TROF W
2 TROF E
3 RIDGE
4 SWLY FLOW
5 SELY FLOW
6 W FLOW
7 NW FLOW
8 LOW
0 NONE OF ABOVE

[3] Maximum precipitation and values at 5 and 10 km are in units of 0.01 inches.

EXAMPLE:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	7	7	0	7	0	4	C	1	1	2		2	0	3		1	3	0			5	0		4	0

27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
	3	0		2	0		0	1	0		0	6		0	4		0	2		1	4	4	0						

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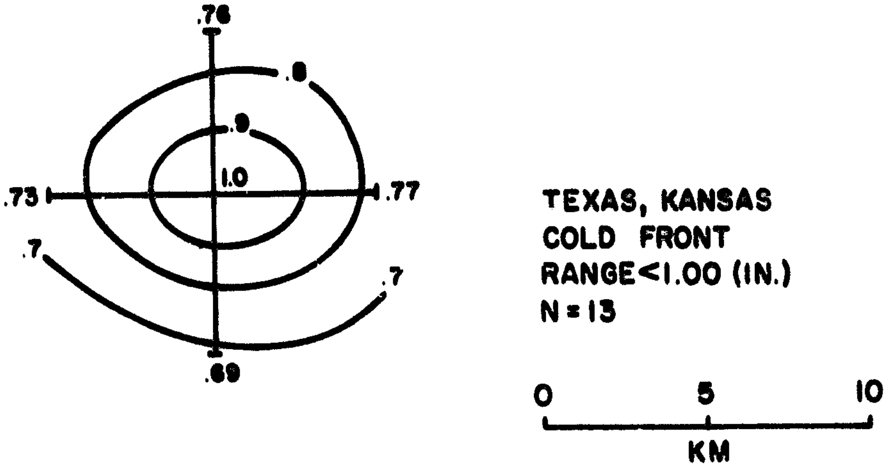
APPENDIX B

NORMALIZED RAINFALL AMOUNT PATTERNS

APPENDIX B

The 22 patterns in this appendix are the result of separating the storms by four synoptic types and various storm-center rainfall amount categories for the rain gage network in Oklahoma and the networks in Kansas and Texas. The range of the maximum storm rainfall amounts included in each pattern is indicated to the right of the pattern. The patterns have been normalized to the rainfall amount of the gage showing the maximum for the storm. The number of storms in each of the categories is indicated by the letter N. The direction of storm motion, as indicated by the 700 mb wind, is in the vertical upward direction for all patterns.



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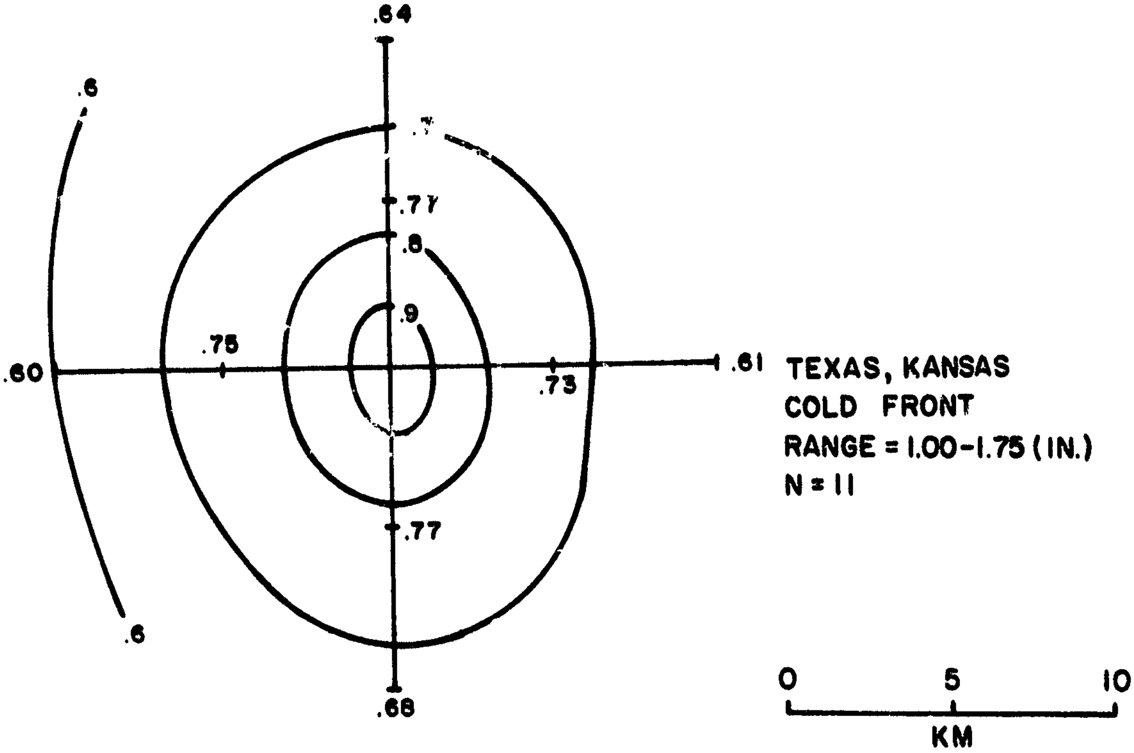

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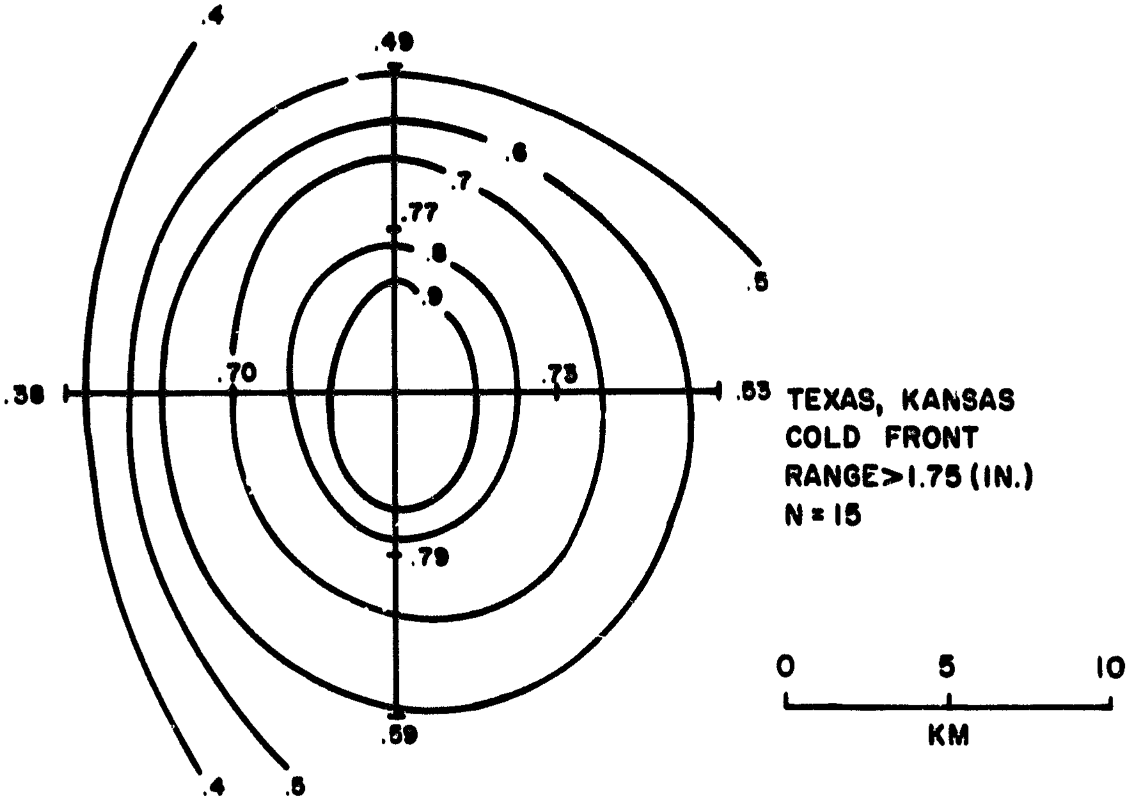

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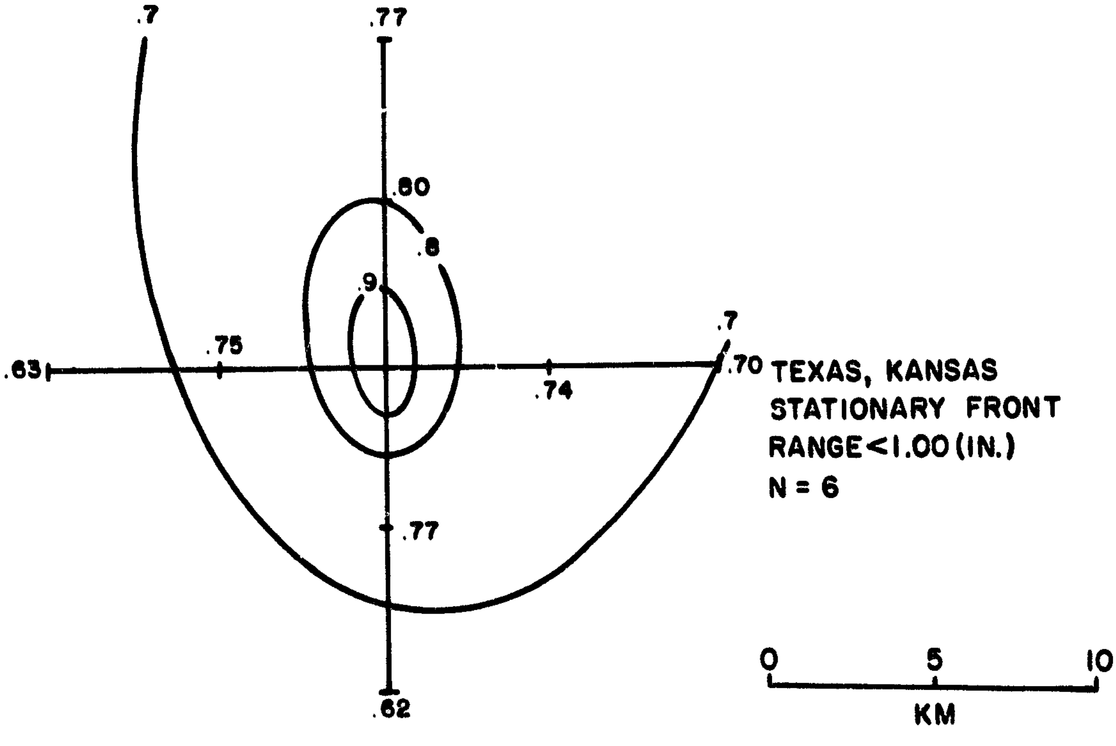

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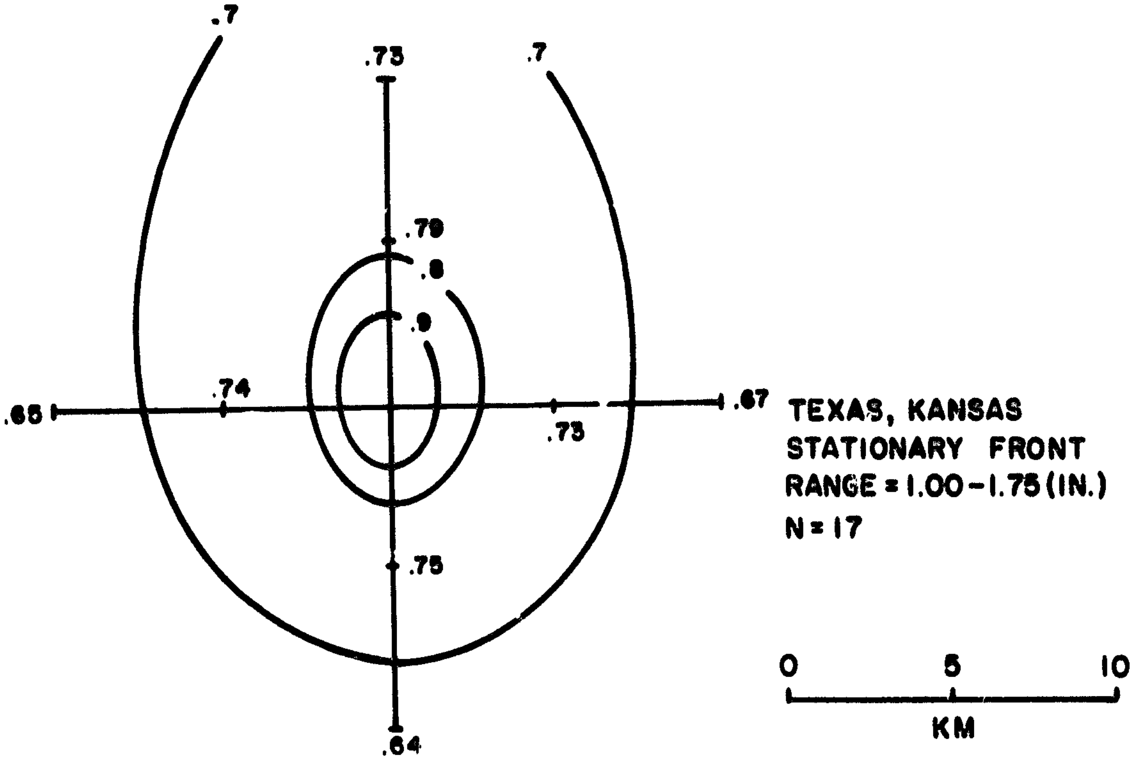

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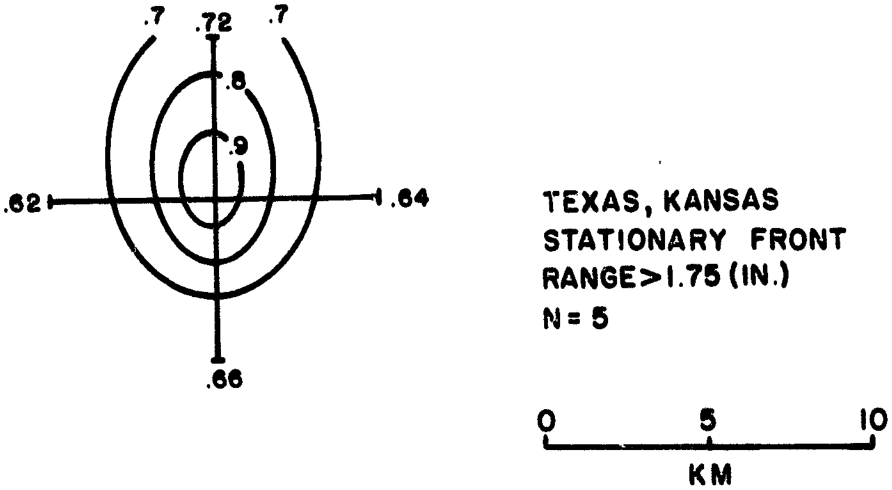

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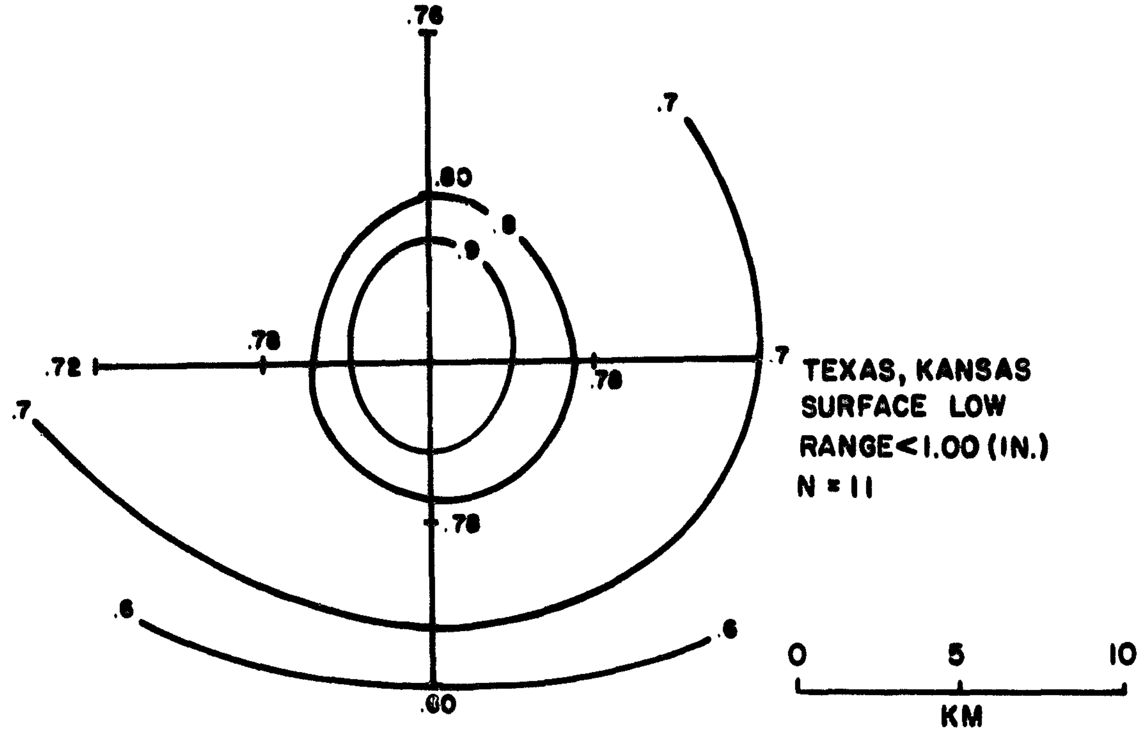

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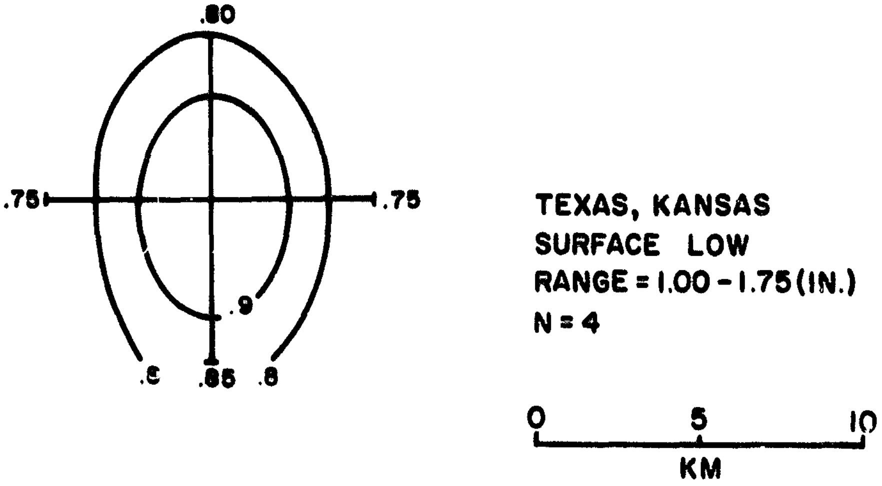

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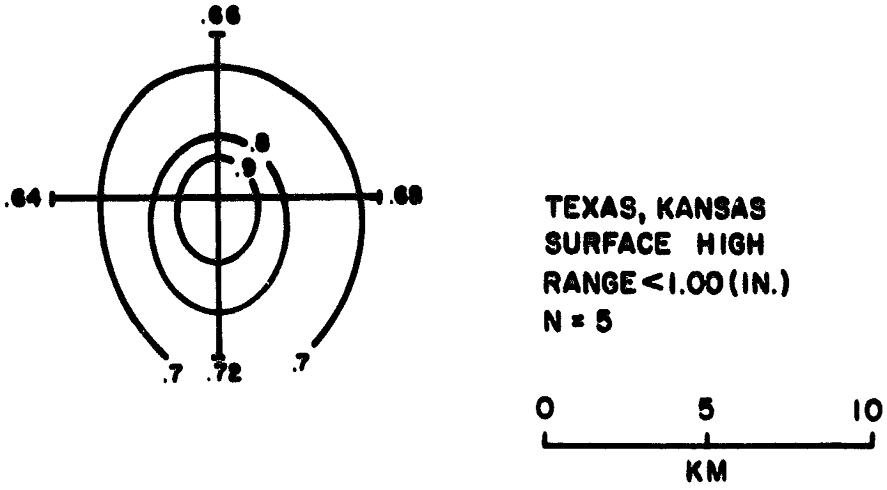
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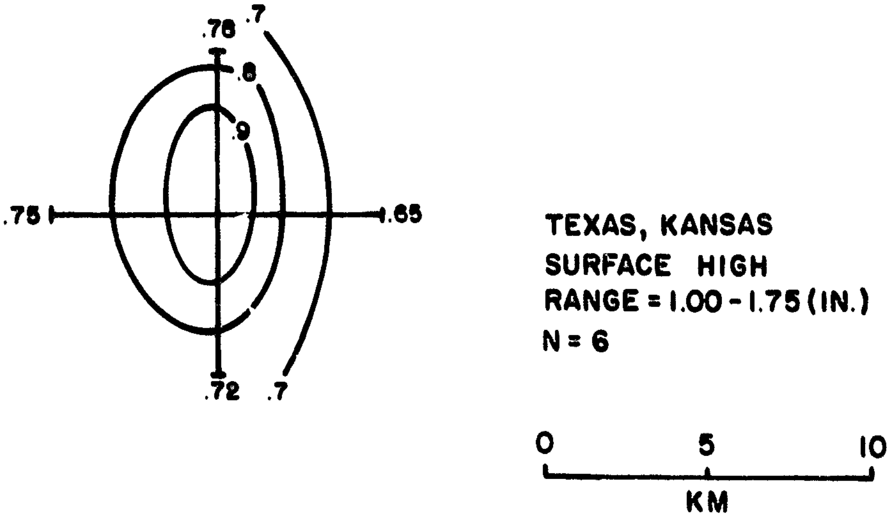
5
10
KM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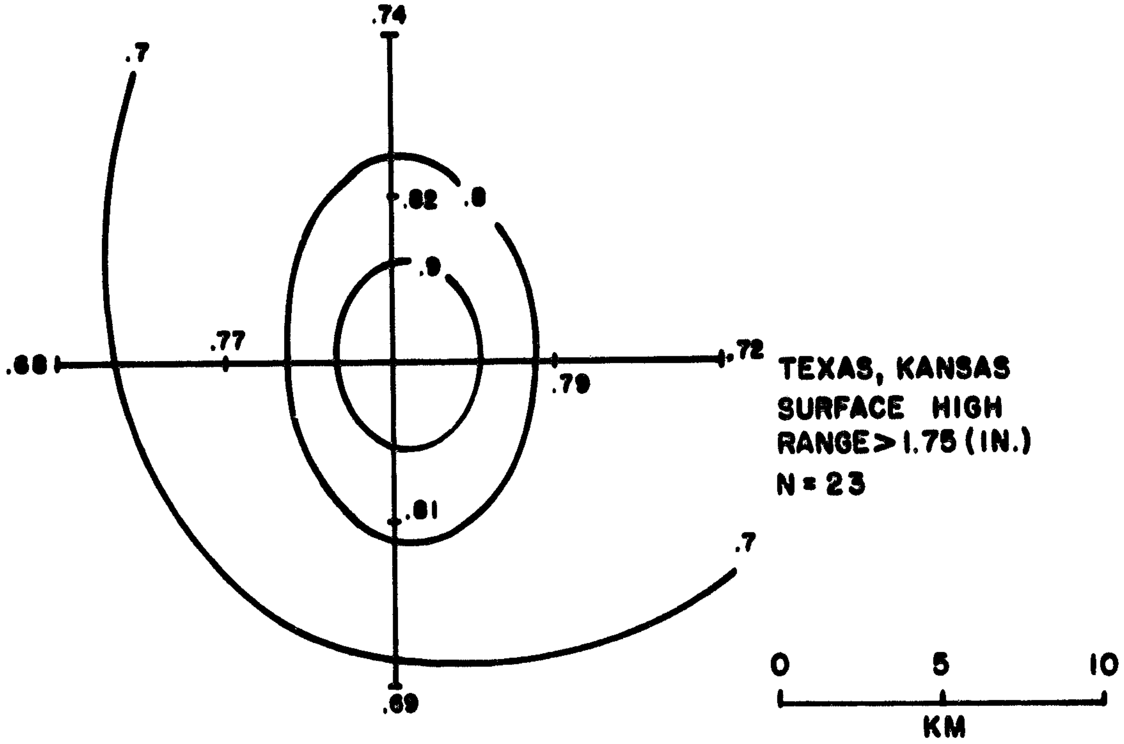
5
10
KM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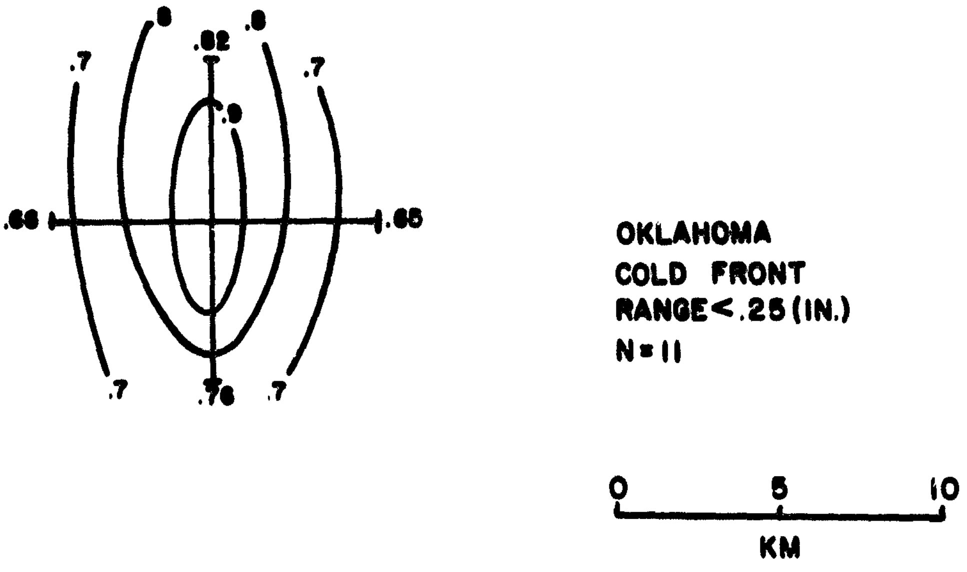
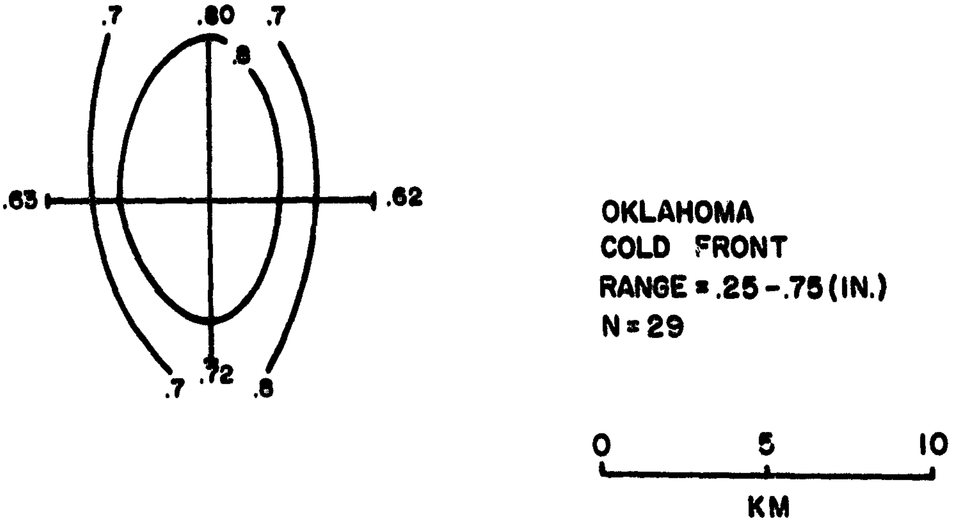
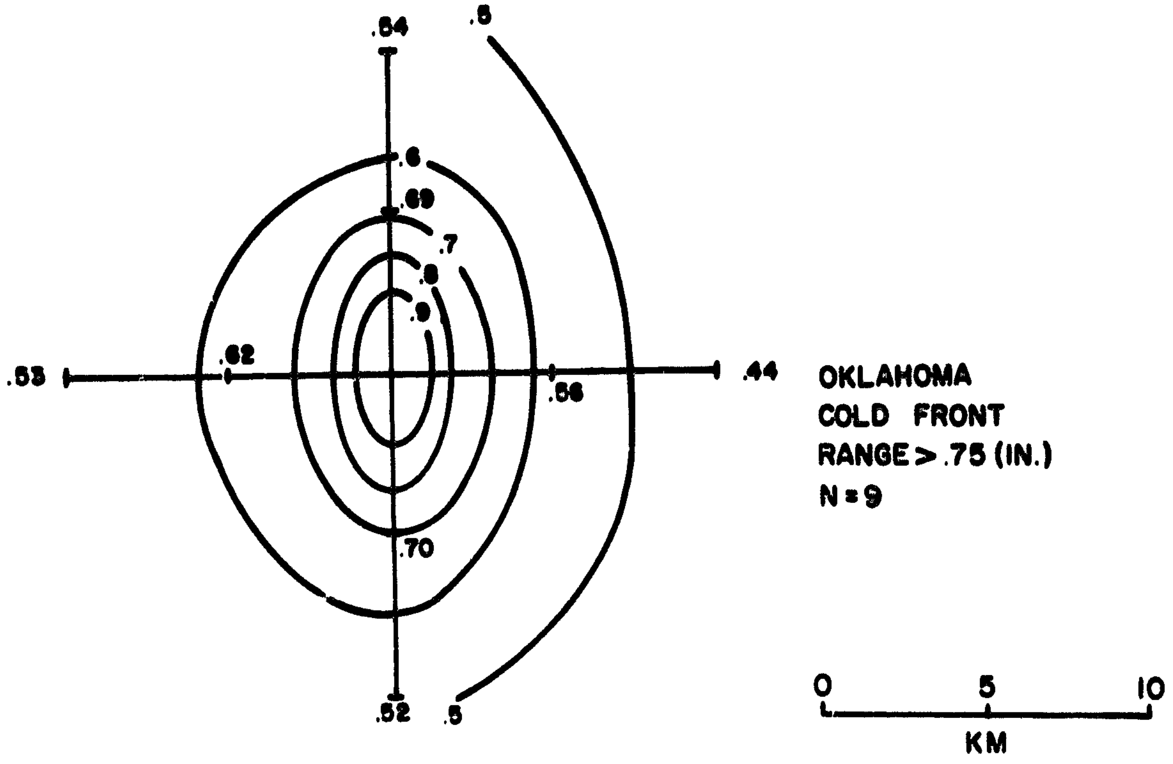
.7
.82
.8
.9
.68
.77
.72
.79
.81
.7
.69
TEXAS, KANSAS
SURFACE HIGH
RANGE > 1.75 (IN.)
N = 23
0
5
10
KM



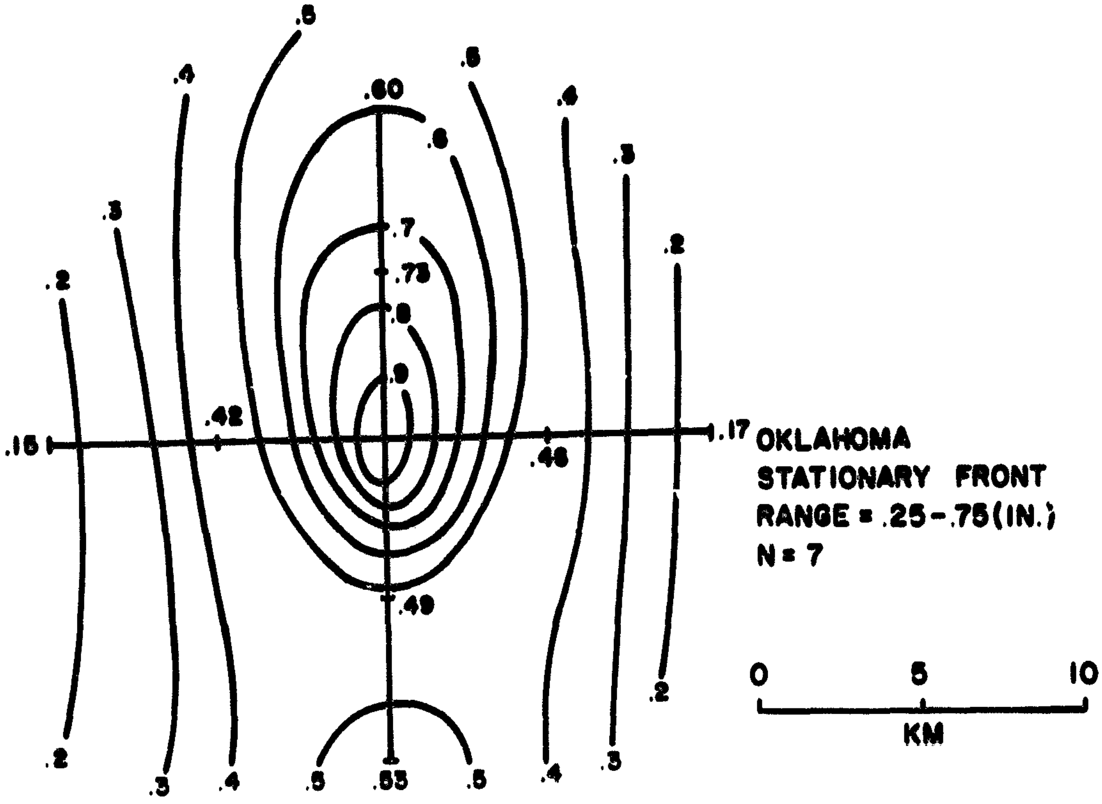
OKLAHOMA
COLD FRONT
RANGE<.25 (IN.)
N=11



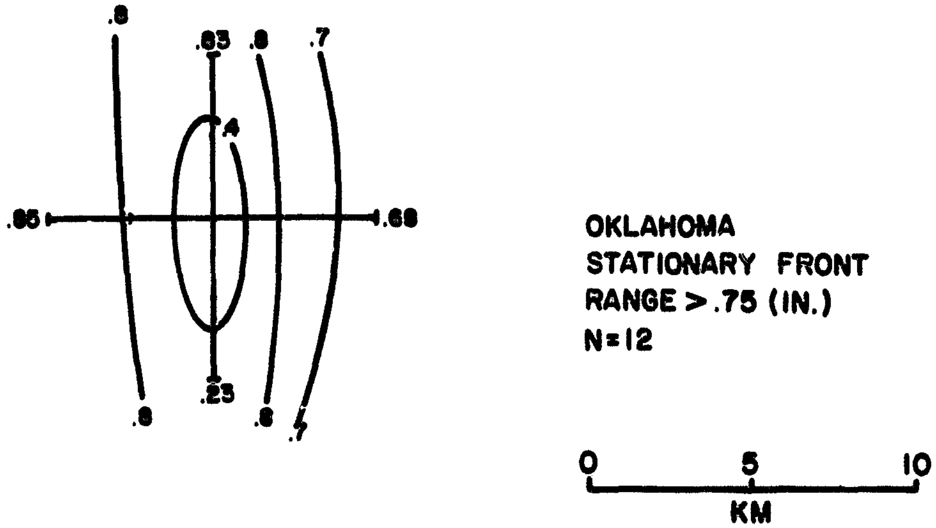
OKLAHOMA
COLD FRONT
RANGE = .25 – .75 (IN.)
N = 29



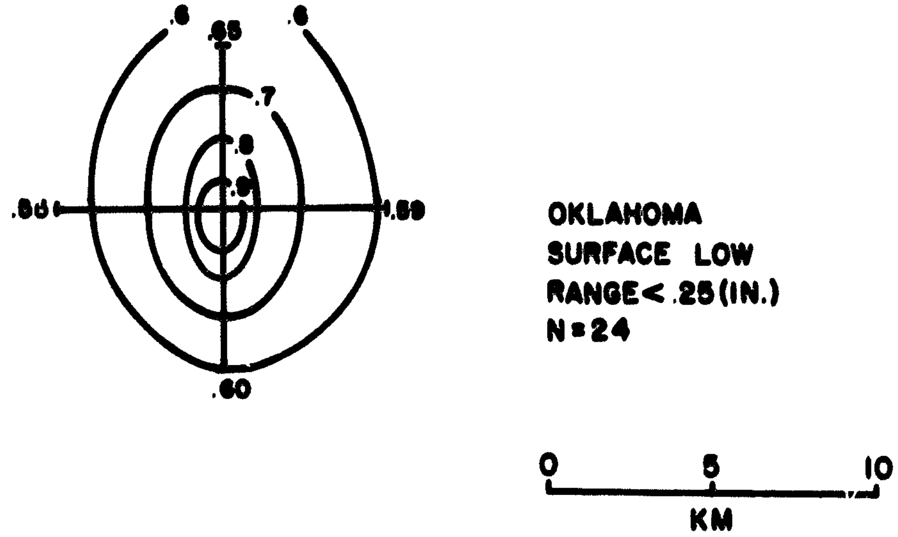
OKLAHOMA
COLD FRONT
RANGE > .75 (IN.)
N = 9



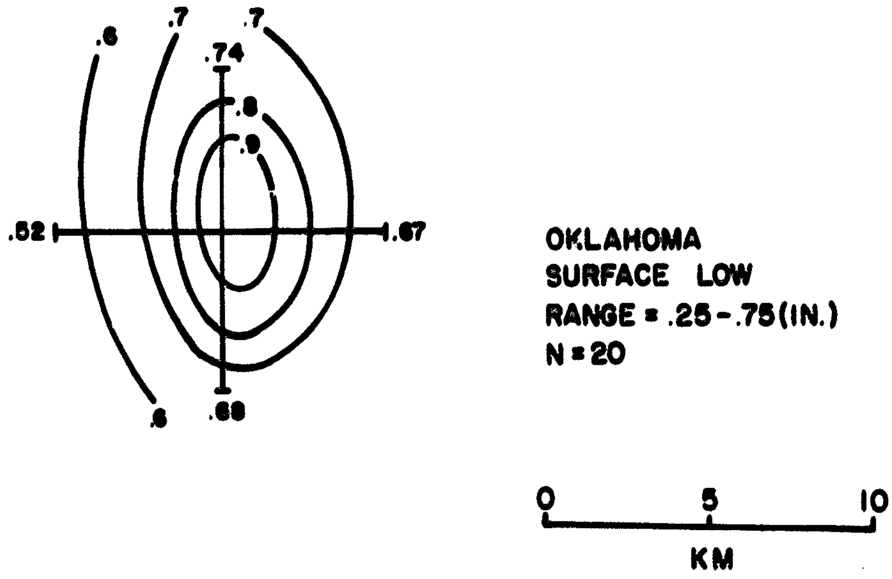
OKLAHOMA
STATIONARY FRONT
RANGE = .25 - .75 (IN.)
N = 7



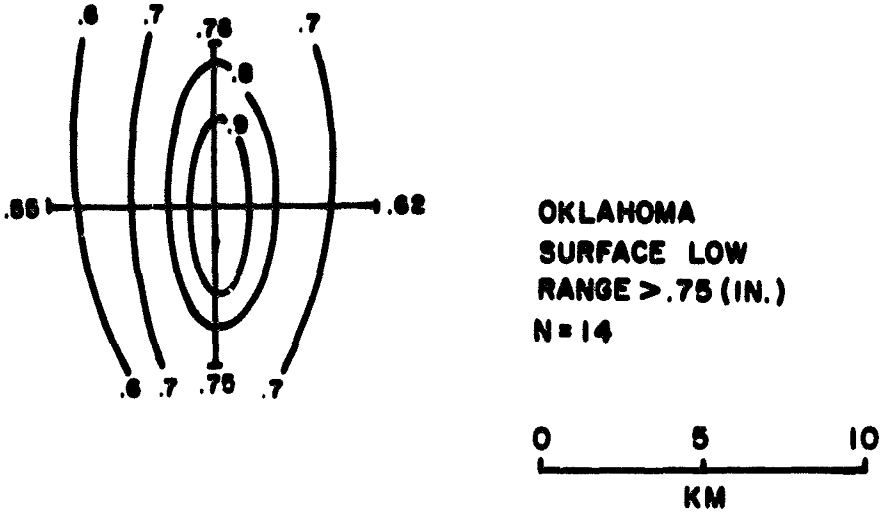
OKLAHOMA
STATIONARY FRONT
RANGE > .75 (IN.)
N=12



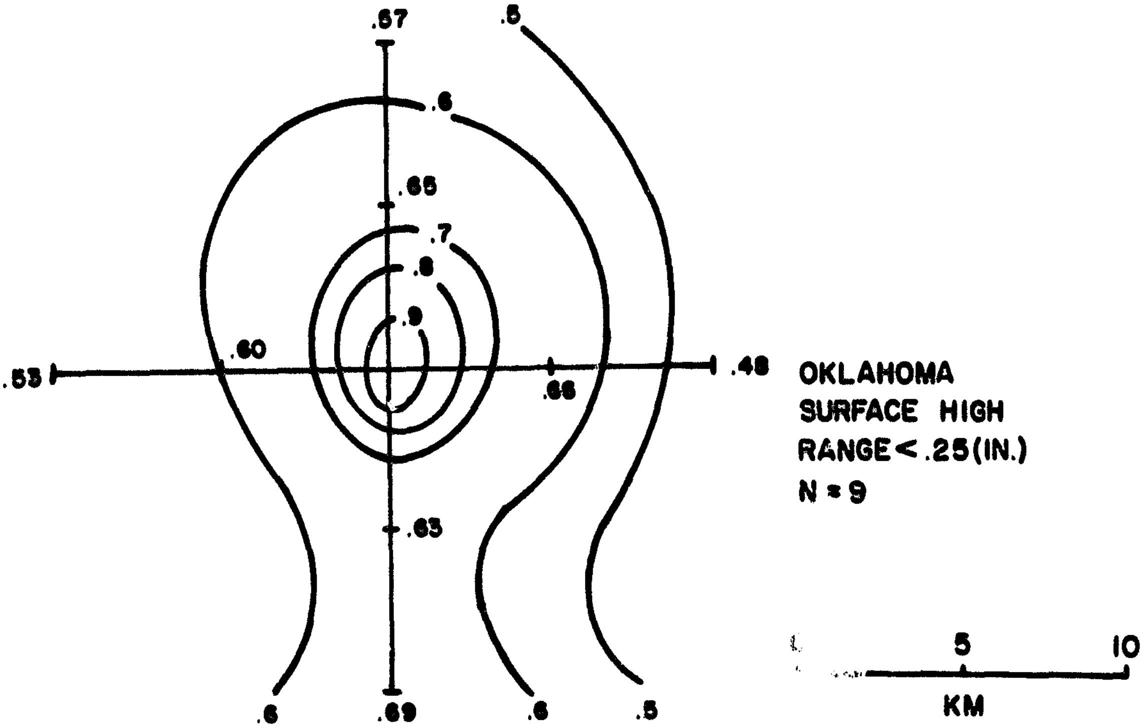
OKLAHOMA
SURFACE LOW
RANGE< .25 (IN.)
N=24



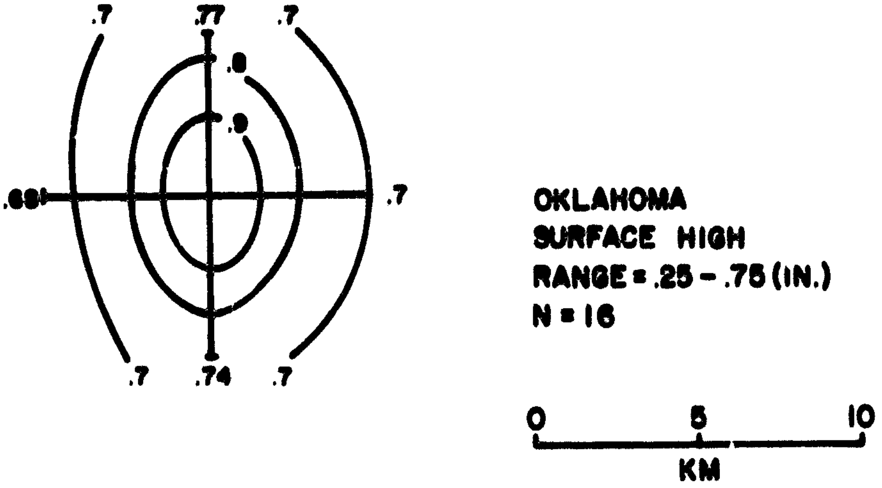
OKLAHOMA
SURFACE LOW
RANGE = .25-.75 (IN.)
N=20



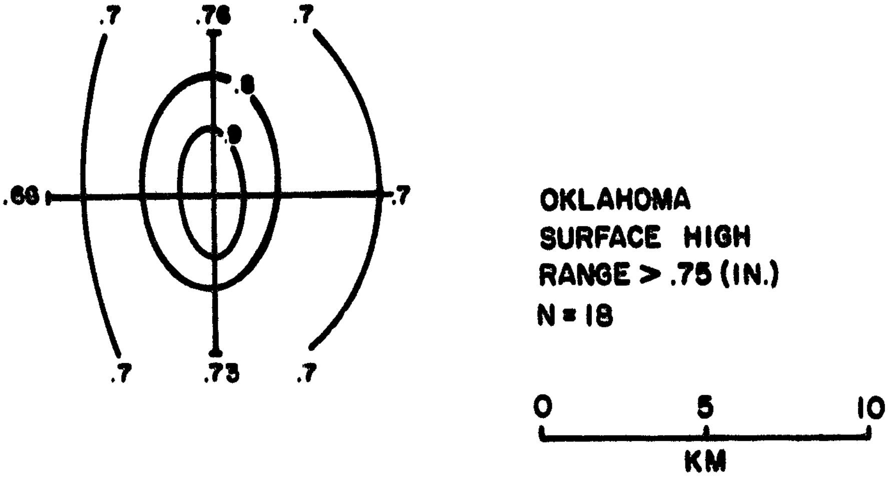
OKLAHOMA
SURFACE LOW
RANGE > .75 (IN.)
N = 14



OKLAHOMA
SURFACE HIGH
RANGE < .25 (IN.)
N = 9



OKLAHOMA
SURFACE HIGH
RANGE = .25 – .75 (IN.)
N = 16



OKLAHOMA
SURFACE HIGH
RANGE > .75 (IN.)
N = 18