Illinois State Water Survey
at the
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Urbana, Illinois

ASSESSMENT OF WEATHER MODIFICATION IN ALLEVIATING AGRICULTURAL WATER SHORTAGES DURING DROUGHTS

by

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ACKNOWLEDGMENTS

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INTRODUCTION

Purpose and Scope of Research

The research discussed in this final report under NSF/RANN Grant No. ENV74-24367 was undertaken to assess the potential utility of weather modification in stimulating crop production during droughts of various-severity in the Midwest. This was done through application of existing knowledge on hydroclimatic conditions during such events. This assessment was considered especially pertinent at this time in view of: 1) the world-wide food shortages which are predicted to worsen with time, 2) the major role that the United States must play to alleviate this problem, and 3) the fact that the Midwest is the nation's primary agricultural region but is subject periodically to the. ravages of drought. It is believed that the results of this research will provide useful input into future decision-making pertaining to the use of weather modification for alleviating agricultural droughts. Findings should also prove useful in establishing the limitations of weather modification in agricultural applications, and should assist in determining the scope and direction of future research in weather modification.

In the present research, analyses have been limited to Illinois which in climate, soils, and crop production is typical of much of the Midwest. Furthermore, previous agro-climatic studies by the Illinois State Water Survey have provided methods and techniques, background information, and certain types of processed data which are necessary to this research and which have permitted its undertaking on the limited budget allotted for the work.

Two time periods have been used in evaluating agricultural droughts. The first is the 2-month period of July and August which earlier studies had shown is the most critical period in the relationship between crop production and precipitation for two major midwestern, crops, corn and soybeans

(Changnon and Neill, 1967; Huff and Changnon, 1972b). The second analytical period spans the growing season from May through September which includes much of the planting, all of the plant growth, and major portions of the harvesting in the Midwest for most crops.

Investigation was made of July-August droughts in which portions of Illinois experienced 2-month rainfalls that were 50% or less of the normal precipitation. This provided a sample of 35 droughts in the 75 years of records (1900-1974) used in the agro-climatic research. For the growing season, analyses were made of droughts in which the 5-month rainfall was less than 70% of normal. By this definition, a sample of 14 outstanding droughts was obtained for detailed meteorological analyses. The 35 July-August droughts provide a sample of events that occur approximately once in two years, on the average. The 14 May-September droughts sample 5-year average occurrences. A larger sample of July-August dry periods was selected for study because of the more critical need for plentiful rainfall in this period to insure good crop yields.

The drought samples incorporated a wide variety of conditions and included 1) widespread severe droughts often involving several states such as occurred in the early 1950s, 2) moderate droughts which usually persist for one or two growing seasons over portions of one or more states, and 3) spot droughts which frequently occur over isolated areas of several contiguous counties or a region of the state, and which are surrounded by areas of near-normal or above-normal rainfall.

Data Used in Research

Precipitation data for the period 1900-1974 were used to determine storm, monthly, and seasonal rainfall amounts. In those analyses requiring hourly rainfall, analyses had to be limited to the period since 1940 when a major increase in the number of recording raingages was initiated. Prior to that time, only a few tipping bucket recording gages, usually located at first-order stations, were available. Of course, analyses utilizing METROMEX data had to be limited to the 1971-1975 operational period. Data for the Whitetop cloud seeding project (Braham, 1966), used in one phase of the study, were available for the 1960-1964 period. Cloud analyses were performed for the 14-year period, 1951-1964, when suitable data were available in Illinois. Thermodynamic analyses for comparing wet and dry periods were made for 1958-1962 and 1971-1975. Data for 1963-1970 were not used because the RAOB humidity measurements were subject to significant errors. The locations of meteorological stations used in the various studies are shown in Fig, 1,

Normality of rainfall was based upon averages for the 50-year period 1906-1955 which spanned most of the drought sampling period. Furthermore, this 50-year period was used in earlier drought studies at the Illinois State Water Survey. The period included two major droughts and two outstanding wet periods, and should be representative of long-term averages. Average rainfall for July-August and May-September, the two periods under investigation, are shown in Figs. 2 and 3.

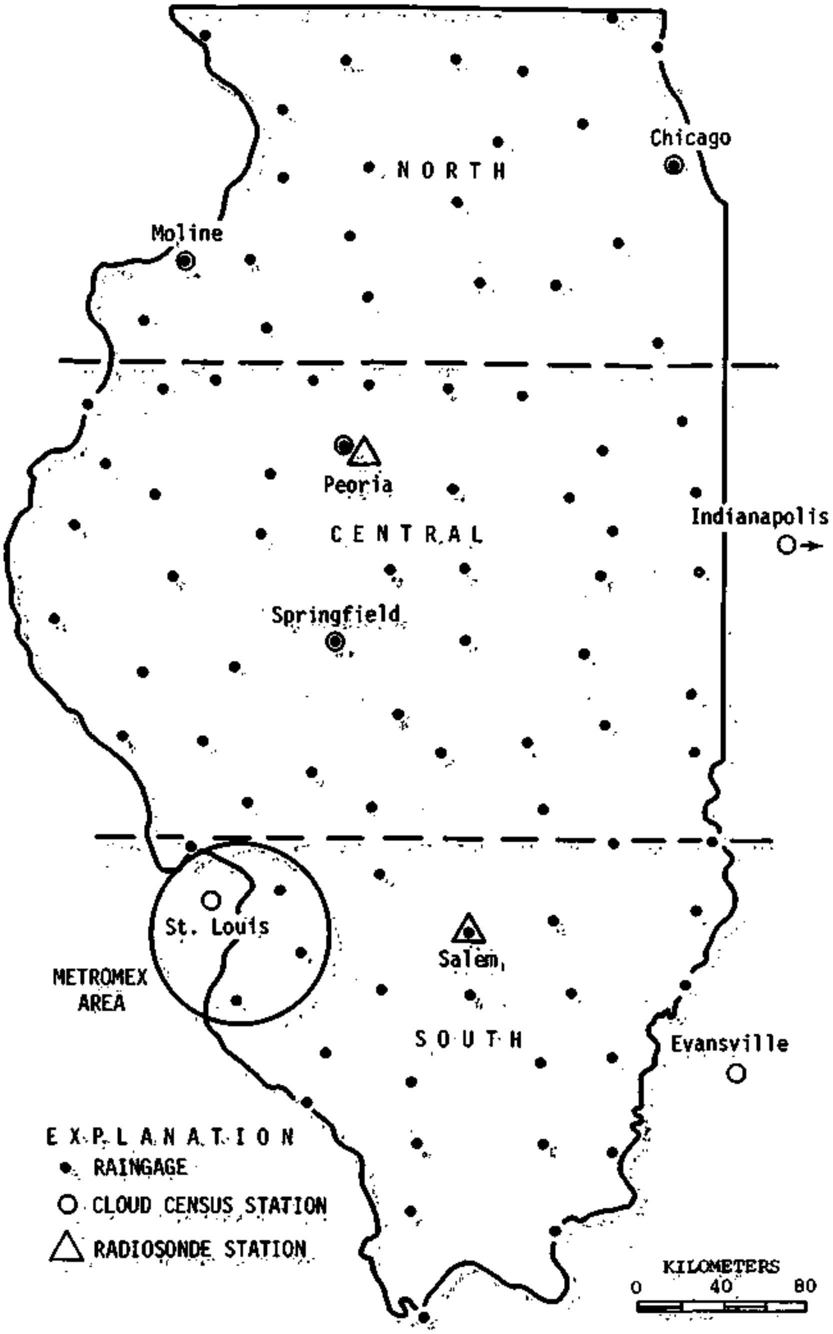


Figure 1. Meteorological Stations and State Divisions.

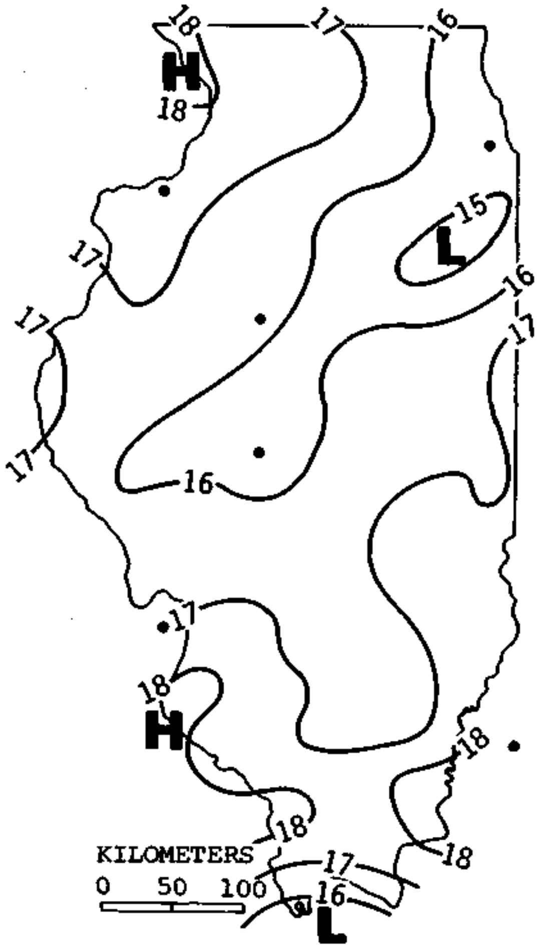


Figure 2. Normal Rainfall (cm) for July-August in Illinois.

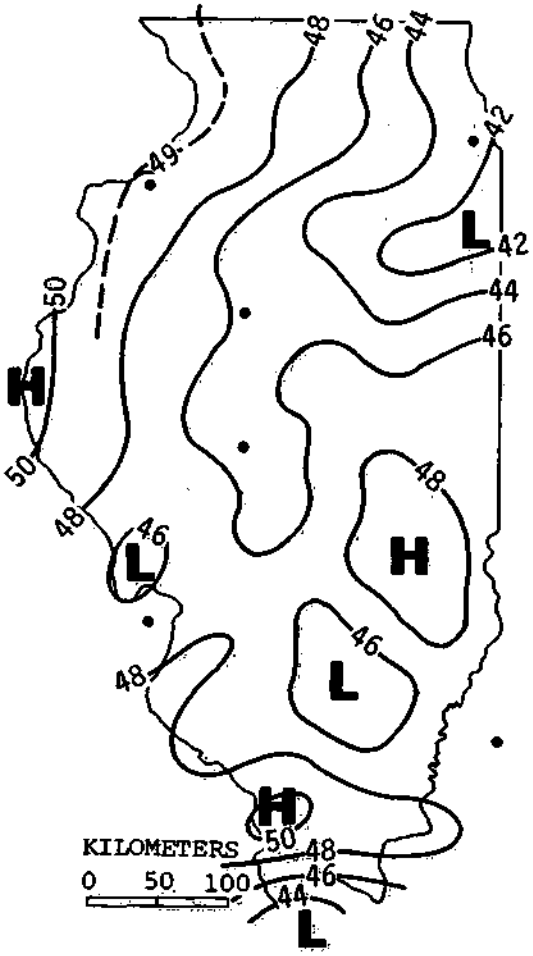


Figure 3. Normal Rainfall (cm) for May-September in Illinois.

The July-August normal pattern (Fig. 2) is flat with no major differences from north to south or west to east within the state. The state average for the 2-month period was approximately 16.5 cm (6.5 in.). The May-September pattern (Fig. 3) is also quite flat with most stations having 50-year means from 42 cm to 49 cm. The state average was 45,2 cm (17.8 in.). The major features are a low extending SW from the northeastern to central part of the state and highs over western Illinois and the Shawnee Hills in the southern part of the state.

Approach to the Problem

In making the assessment of the potential of weather modification for alleviating agricultural drought conditions, numerous types of meteorological-climatological analyses were made in each of the selected droughts. These included:

1. Means, medians, and maxima of rainfall in each selected drought
2. Spatial distribution of rainfall in each drought as portrayed by area-depth curves constructed from the precipitation data
3. Frequency and areal extent of daily rainfalls of various intensities during droughts and their departure from normal
4. Percentage of drought area experiencing various degrees of normal rainfall during drought periods
5. Percentage of the drought area with two consecutive months of near or above normal rainfall (important in evaluating seeding potential)
6. Identification of all storms producing significant amounts of rainfall within each drought area, their intensity (mean rainfall) and areal extent
7. Determination of the rainfall contribution in each drought from various types of storms (cold front, squall line, air mass, etc.)

For those droughts after 1940 when recording raingage data became more plentiful, analyses were made of the diurnal distribution of rainfall during growing season droughts and its variance (if any) from the normal diurnal distribution. The frequency distribution of various cloud types was computed during wet and dry periods, along with their departure from the normal or average distribution. Thermodynamic characteristics of air masses predominating in selected wet and dry periods were also studied.

Data from the NSF-funded METROMEX project at St. Louis during 1971-1975 (Changnon et al., 1971) were used to investigate raincell initiations and mergers in wet, dry, and moderate rainfall months with respect to location and frequency. The METROMEX data were used also in a detailed analysis of the 1971 summer drought in and adjacent to the 5200-km^2 raingage network.

In seeking additional information on the potential of weather modification for alleviating agricultural drought conditions, a re-analysis was made of available Whitetop data for 1960-1964 (Braham, 1966; Decker and Schickedanz, 1966) to evaluate possible differential seeding effects in wet and dry months.

In evaluating results of the various climatological analyses throughout this report, the assumption is made that weather modification can be applied to increase the rainfall output in synoptic situations that are favorable for the production of natural rainfall. Most weather modification experiments reporting success in the past have been limited to the seeding of individual convective clouds, usually in non-frontal situations commonly referred to as air mass convective activity. As will be brought out later in this report, the most frequent opportunities for seeding in drought conditions appear to be associated with cold frontal or frontally related activity. Thus, this poses a question as to the efficacy of cloud seeding in frontal situations. However, results of the METROMEX research (Huff, 1976b) on inadvertent weather modification indicate that the urban-related increase in summer precipitation in the St. Louis area is produced largely in organized convective activity such as cold fronts and squall systems.

PREVIOUS STUDIES OF ILLINOIS DROUGHTS

Huff and Changnon (1963) made a study of the climatology of Illinois droughts having durations of 3 to 60 months. Of particular interest were the analyses of the very severe drought of 1953-1954 when a large area in the south central part of the state had less than 50% of normal precipitation over a 12-month period. Analyses indicated that the major portion of the precipitation deficiency was caused by the lack of heavy rain days, defined as those producing daily totals of 12.5 mm (0,50 in.) or more. The zone of heavy rain deficiency corresponded almost exactly with the region experiencing less than 50% of normal precipitation, Analyses of hourly rainfall data showed a major deficiency in the number of hours with 2,5 mm (0.10 in.) or more. Thunderstorm and convective cloud frequencies were well below normal. However, the average depth of precipitable water in the atmosphere was found to be only slightly below normal with near normal vertical stratification.

The below-normal cloud frequencies and near-normal precipitable water agreed well with earlier findings of cloud and moisture conditions during short dry periods in Illinois. Thus, Changnon and Huff (1957) studied cloudiness during dry periods of five days or longer, defined as those having no measurable precipitation. This was done for four first-order stations in Illinois during 1951-1955. Results indicated a large deficiency in low clouds during the 5-day dry periods. For example, the median percent of normal was 40% in summer for the four stations combined, and cumulonimbus occurrences averaged only 3% of normal.

Table 1 shows an average frequency distribution of low clouds in summer derived from data for the four Illinois stations combined. The frequency of low clouds in the 5-day dry periods was less than 50% of the 1951-1955 average in 75% of the cases and less than 66% of normal in 90% of the dry periods. Thus, opportunities for successful seeding in no-rain dry periods appear very limited and lead to the conclusion that seeding-induced increases must be derived largely, if not entirely, from enhancement of ongoing rain systems.

Table 1. Average Frequency Distributions of Low Clouds in Dry Periods of 5 Days or Longer during Summers of 1951-1955, Based on 4 First-Order Stations

Cumulative Percent of Dry Periods	Maximum Percent of Normal *	Cumulative Percent of Dry Periods	Maximum Percent of Normal *
5	5	60	43
10	10	70	47
20	15	80	53
30	25	90	66
40	32	95	116
50	40		

*Percent of normal based on 1951-1955 averages; values determined from average daily cloudiness.

Semonin (1960) pursued the dry period study further. He studied 31 dry periods during 1953-1955. A dry period was defined as at least five consecutive days with less than 10% of normal rainfall over an area surrounding a RAOB station (Chanute Air Force Base) in east-central Illinois. He found near-normal water vapor in the atmosphere during a majority of the dry periods, but a definite deficit in the frequency of low clouds.

Analyses of frontal passages in the 1953-1954 drought showed these to be near normal also. Analyses of the 50 heaviest rainstorms in the 12 months indicated that the majority were associated with wave formations on trailing cold fronts. Although the near-normal frequency of fronts in this severe drought seemed surprising initially, further investigation showed that it was not. The rapid movement of low centers across southern Canada and the northern border states, typical of this and many other drought situations, resulted in the passage of a relatively large number of trailing cold fronts across northern United States with frequent penetration of the trailing end into Illinois.

Huff (1961) in a study of frontal passages at Urbana, Illinois, from 1951-1960 found a tendency for an inverse relation between frontal frequency and annual precipitation. He related this tendency to the prevalence of relatively large, strong, slow-moving systems (low index situations.) ;in wet years, in contrast to relatively weak, frequent, rapidly moving storms (high index flow) in dry years.

A basic finding relevant to weather modification was the relatively heavy rainfall production by cold fronts in the 1953-1954 drought. This led to further study of the synoptic weather-rainfall relations in this drought (Huff, 1973a) in the interest of evaluating the potential for weather modification during excessively dry periods. Results indicated that conditions occasionally prevailed during which successful cloud seeding might have provided temporary relief over portions of the extensive drought region, especially with respect to providing agricultural relief. A companion study indicated that it is extremely doubtful that municipal water supplies can be increased significantly in severe drought conditions in Illinois (Huff, 1973b).

Synoptic analyses further verified the importance of cold fronts in producing the 1953-1954 rainfall in drought. The various findings for the 1953-1954 drought indicated a need to investigate a large number of droughts in a similar manner to evaluate the potential for modification of agricultural drought conditions. This led to the proposal which has resulted in the present research under NSF grant ENV74-24357.

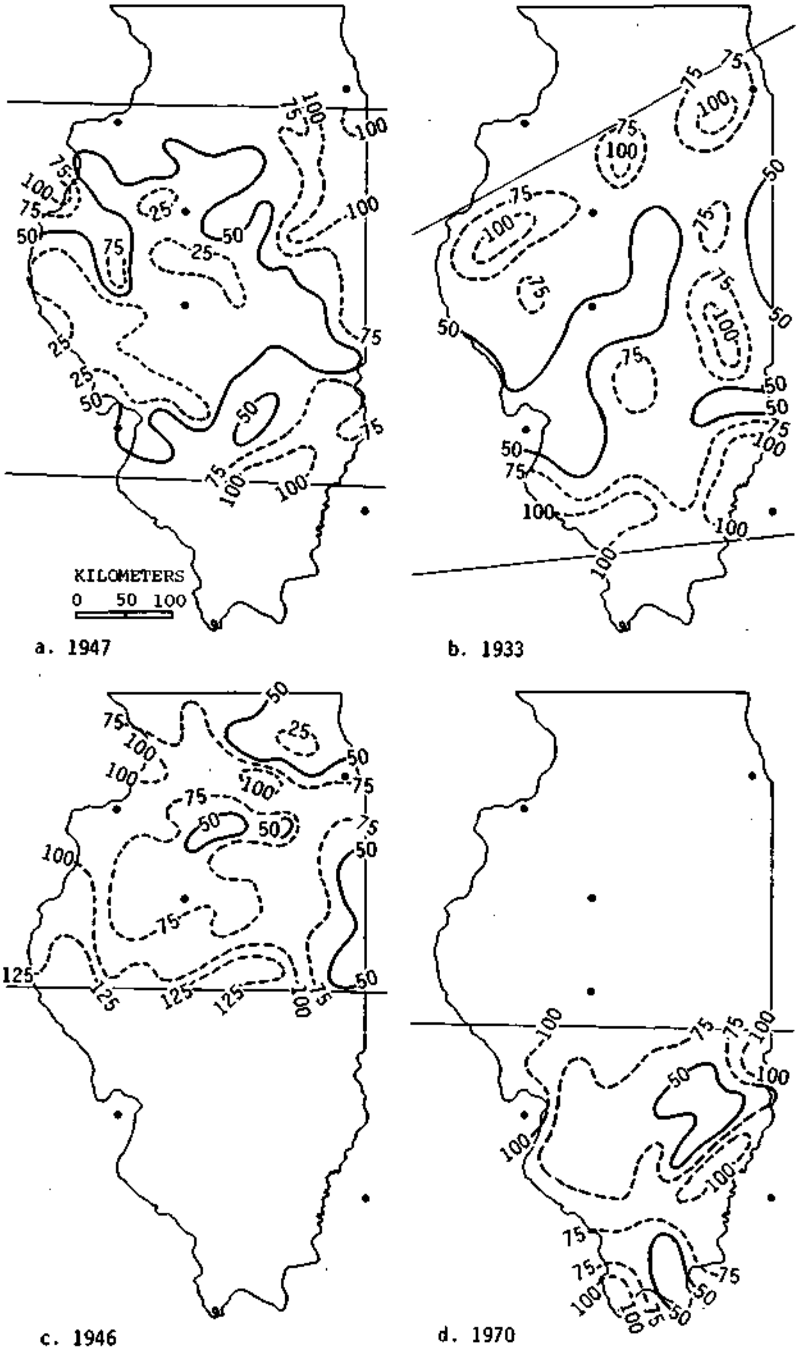
EXAMPLES OF DROUGHTS ANALYZED IN STUDY

July-August

Examples of the droughts analyzed in conjunction with the Illinois research are shown in Figs. 4 and 5, in which the spatial pattern has been expressed in percent of normal rainfall. Figure 4a to 4d shows four typical July-August droughts. The drought of 1947 extended over 52,000 km^2 in the central part of the state and resulted in a disastrous crop yield for corn and soybeans which are the primary crops. During July (the most critical month), the drought area had an average of 28% of normal rainfall and this increased to 34% in August. The 2-month period experienced 32% of normal rainfall.

Figure 4b shows the rainfall deficiency pattern in the July-August drought of 1933. This drought encompassed approximately 22,000 km^2 in which total rainfall was equal to or less than 50% of normal. It was also centered in the central part of the state. The 2-month total was 39% of normal with the greatest deficiency in July when the average monthly rainfall was 30% of normal in the drought area.

The July-August drought of 1946 which extended over 11,000 km^2 had several centers in the northeastern to east-central parts of the state (Fig. 4c). The average percent of normal rainfall in these scattered centers was 40%, but was



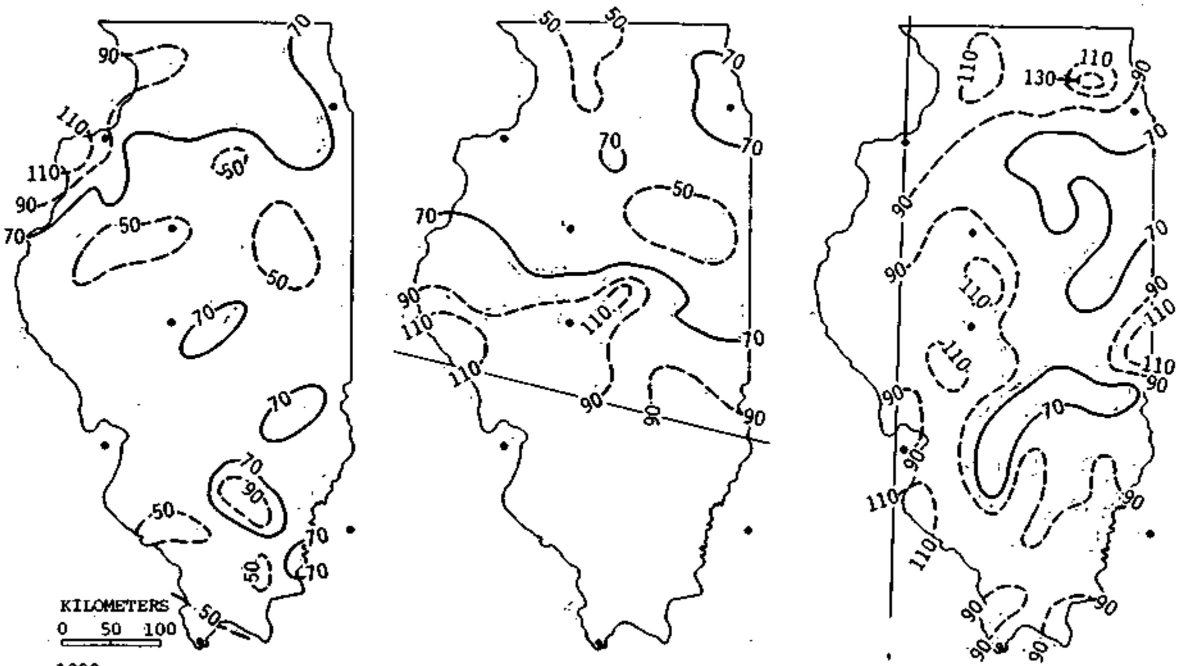
a. 1947

b. 1933

c. 1946

d. 1970

Figure 4. Examples of Typical July-August Drought Patterns.



a. 1930 b. 1920 c. 1925

Figure 5. Examples of Typical May-September Drought Patterns.

only 19% in July and increased to 57% in August. However, near-normal rainfall occurred in the vicinity of these centers, and the potential for enhancing natural rainfall would seem to be favored in these situations with scattered drought centers implanted within regions of near-normal precipitation.

Figure 4d shows the 1970 drought which extended over a relatively small area of 7500 km^2 within two centers in the southern part of the state. Average rainfall was 45% of normal for the two months and varied from 33% in July to 56% in August. Near-normal rainfall occurred within 40 km of both drought centers. This is another example of a relatively small drought area which might be helped by seeding if cloud treatment could extend the duration and/or areal extent of natural storms in the vicinity of the drought centers. The potential for such type of enhancement is suggested by the METROMEX research which indicates a major effect from inadvertent weather modification at St. Louis is the production of relatively large raincells (convective entities) with subsequent longer durations and path lengths than in the surrounding rural areas (Changnon et al., 1977)

May-September

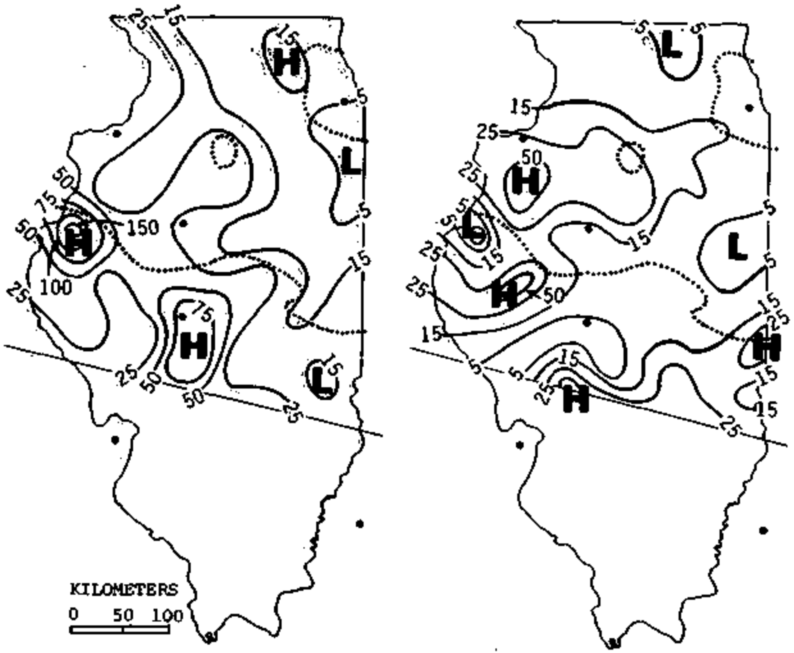
Three typical droughts of May-September are illustrated in Fig. 5a to 5c. The drought of 1930 encompassed approximately 110,000 km^2 in Illinois with 5-month total rainfall equal to or less than 70% of normal. This drought and many others used in the Illinois research extended into one or more of the bordering states. The 5-month average in the Illinois drought area was 59% of normal with individual months ranging from a low of 31% in July to a near-normal 91% in September. Unfortunately, the most severe portion of the drought came in the month which shows the highest correlation between rainfall and crop yield in Illinois (Changnon and Huff, 1971).

Figure 5b shows the spatial pattern of drought in 1920. This drought extended over 63,000 km^2, and was restricted mostly to the northern part of the state. The average rainfall was 58% of normal, and had a range from 50% in July to 76% in May.

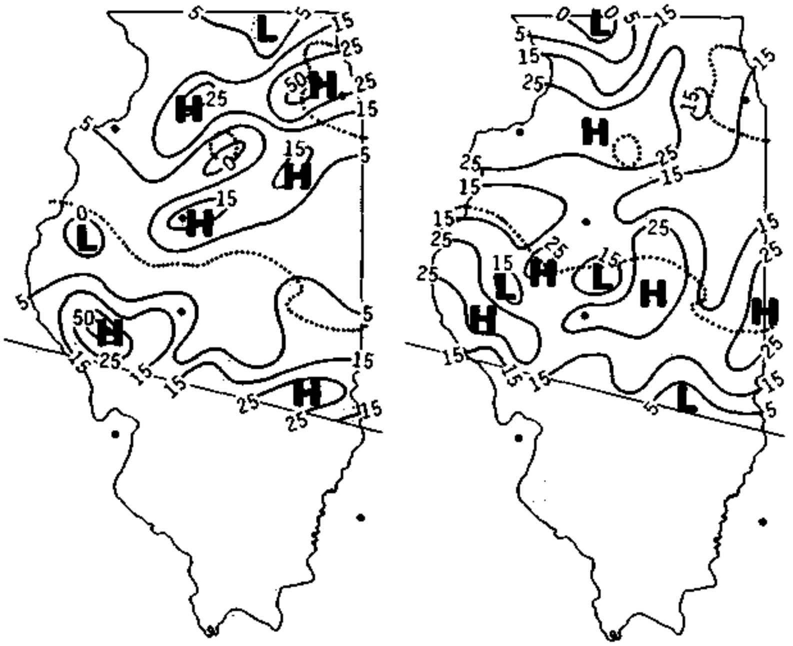
The May-September drought pattern in 1925 is shown in Fig. 5c. This drought included approximately 20,000 km^2, and the total rainfall for the 5 months averaged 62% of normal. The lowest rainfall, 21% of normal, occurred in the planting month of May, and increased to an average of 54% for the July-August period. The drought had two centers and the rainfall in the near vicinity of these centers was 80 to 100% of normal. Because of the smaller drought areas and the proximity of near-normal rainfall, this type of drought is another example of the type that would have better than average potential for rain enhancement from cloud treatment over and in the vicinity of the water deficit regions.

Typical Rainfall Patterns in Droughts

Figures 6 to 8 illustrate typical rainstorm patterns that are observed druing droughts. Figure 6 shows four storms selected from the May-September

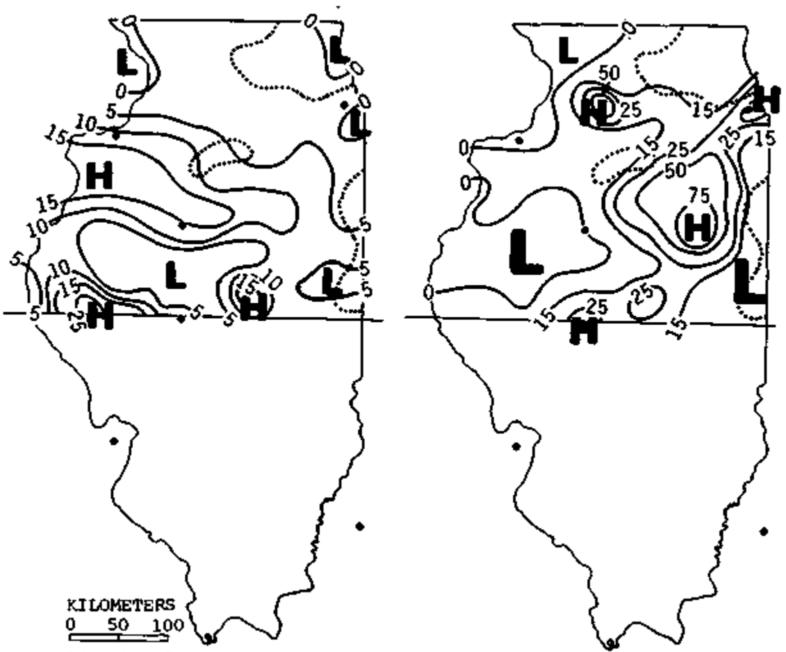


a. JUNE 1-2, 1920 b. July 5-6, 1920



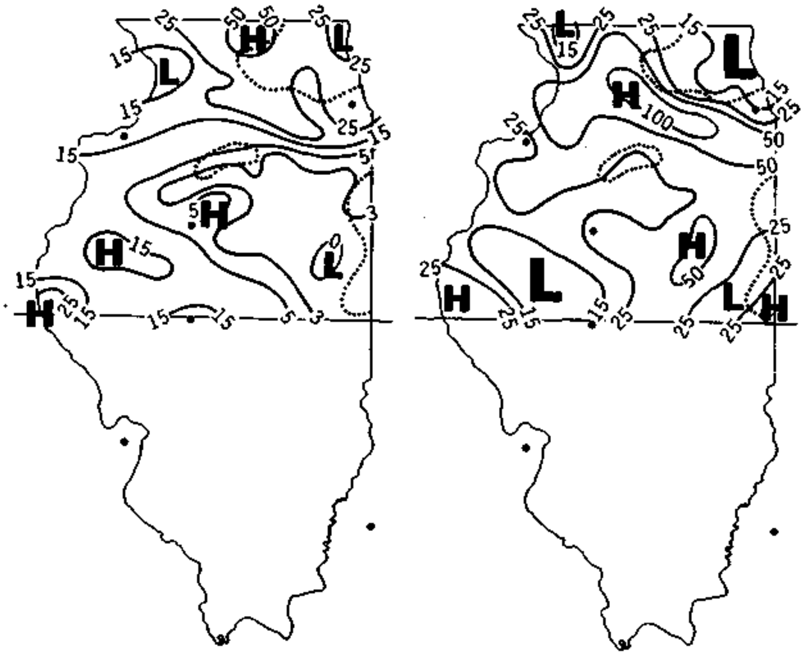
c. AUGUST 20-21, 1920 d. SEPTEMBER 26-27, 1920

Figure 6. Typical Patterns of Storm Rainfall (mm) in Drought of 1920.



a. JULY 24-25, 1946

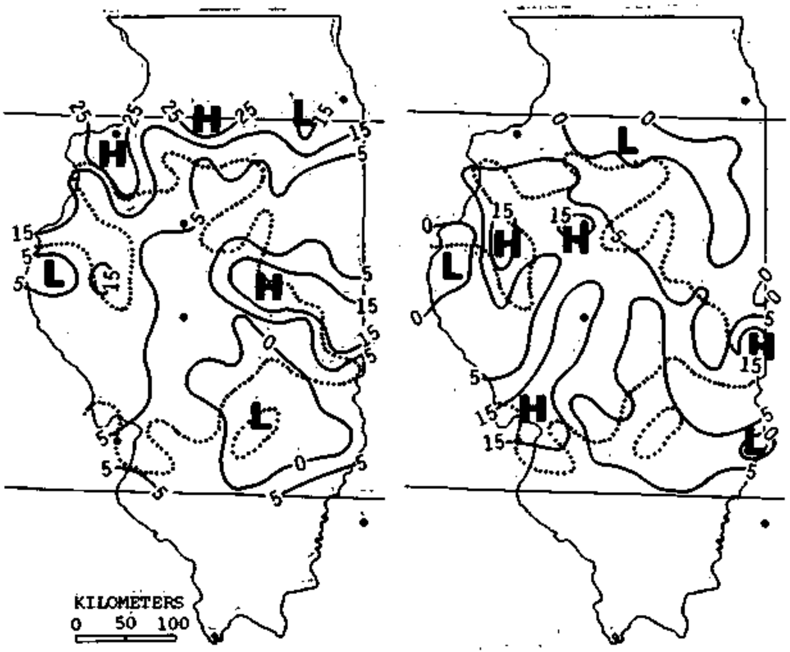
b. JULY 9-11, 1946



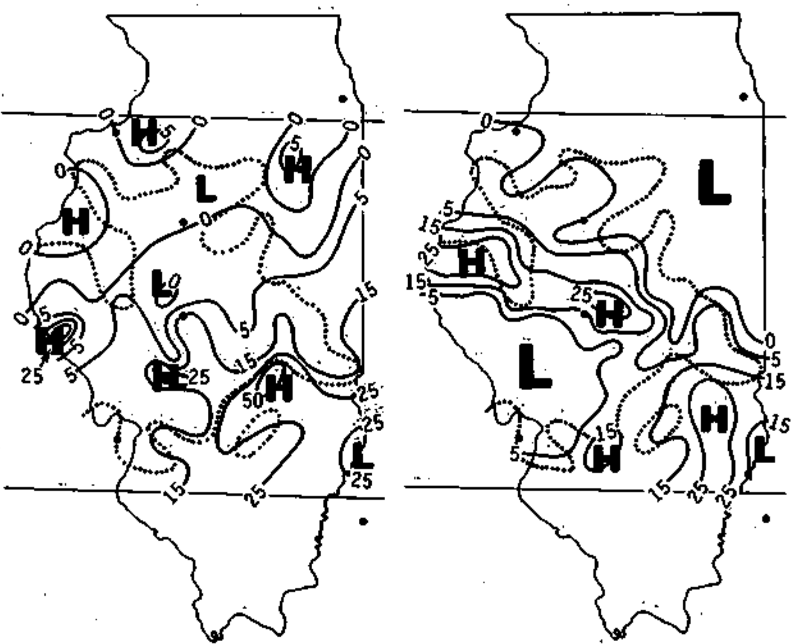
c. AUGUST 8-9, 1946

d. AUGUST 16-17, 1946

Figure 7. Typical Patterns of Storm Rainfall (mm) in Drought of 1946.



a. JULY 5-6, 1947 b. JULY 20-21, 1947



c. AUGUST 14-15. 1947 d. AUGUST 31, 1947

Figure 8. typical Patterns of Storm Rainfall (mm) in Drought of 1947.

drought of 1920 which extended over northern and central Illinois. Note that rainfall was widespread and heavy in some areas. Occasional storms of the types shown here are not uncommon to warm season droughts in Illinois. Moisture-stability conditions in these storms should be favorable for enhancement from cloud seeding in some cases, at least.

Figure 7 is an example of four storms from the July-August drought of 1946, and further illustrate the substantial rainstorms which can occur during general drought conditions. Figure 8 shows storms associated with the July-August drought of 1947 which was more widespread and had greater precipitation deficiencies than the 1946 drought. Rainstorms tended to be more spotty and to seldom produce heavy amounts, such as shown in some of the examples in the previous two figures.

Storm rainfall will be analyzed in more detail later in this report. The illustrations here are intended only to show that substantial storms can occur in droughts. Enhancement of these through seeding could alleviate agricultural water shortages on a temporary basis and stimulate crop production over portions of extensive drought regions, depending upon the magnitude of the enhancement and when it is produced in the crop growing cycle.

AREAL EXTENT AND NORMALITY OF TOTAL RAINFALL IN JULY-AUGUST DROUGHTS

Analyses of the 35 selected droughts for July-August, which include only those in which rainfall was 50% or less of normal, showed drought areas ranging from 8,550 to 95,800 km^2 (330 to 37,000 mi^2) within Illinois. The median was 9,583 km^2 (3,700 mi2) which encompasses less than 7% of the state. Most of these droughts in the 75-year sample were not widespread areally. Only 20% exceeded 26,000 km^2 (10,000 mi^2) and 30% encompassed less than 5,200 km^2 (2,000 mi^2).

Table 2 shows the distribution of areas within the 2-month droughts taken from a frequency distribution curve derived from the 35 occurrences. Calculations in this and following tables were made originally in English units and converted to the metric system. Table 2 clearly indicates that most July-August droughts do not extend over a large portion of the state. Thus, only once in 6 years, on the average, does a drought occur that encompasses 10% or more of Illinois, and more than 50% of the state is involved only once in 50 years. Of the 35 July-August droughts during 1900-1974, over 50% covered less than 10,000 km2 (3,860 mi2). The relatively small size of most of these droughts should be favorable from the standpoint of rain modification potential.

The 35 July-August and 14 May-September droughts were examined for normality of rainfall in several ways. Consideration was initially given to analyzing the drought periods on a monthly basis, especially the July-August period which is most critical for the two major Illinois crops, corn and soybeans. However, examination of the data did not indicate any strong trend for one. month to. bes drier than, another, on the average, in the various drought periods. One exception was a slight: trend for May rainfall to be closer to normal than the other months, but this was not considered sufficient to undertake a very time-consuming month-to-month analysis of each period.

Table 2. Frequency Distribution of Areas in July-August Droughts of Moderate to Severe Intensity in Illinois

	Area Equalled or Exceeded.		
Frequency (years)	km^2	mi^2	Percent of State
2	1,550	600	1
3	4,660	1,800	3
5	11,650	4,500	8
10	25,900	10,000	18
25	51,800	20,000	35
50	77,700	30,000	53

Normality of Total Rainfall

The 35 July-August droughts were divided into six groups according to their areal extent. These are listed in Table 3. The average percent of normal rainfall for the 2-month period was then determined for each drought, based on all observations within the area having less than 50% of normal rainfall. The median percent of normal was also determined. Results are summarized in Table 4.

Table 3. July-August Droughts Grouped by Areal Extent

	Area Encompassed by Given Group		
Group	km^2	mi^2	Number of Cases
1	>51,800	>20,000	3
2	25,900-51,800	10,000-20,000	5
3	12,950-25,900	5,000-10,000	5
4	7,770-12,950	3,000- 5,000	6
5	3,885- 7,770	1,500- 3,000	8
6	<3,885	<1,500	8

Table 4. Average Percent of Normal Rainfall in 35 July-August Droughts

Drought Rank	Year	Area Enveloped (km^2)	Percent of Normal	
			Mean	Median
1	1930	95,830	33	34
2	1936	63,455	31	30
3	1947	52,320	33	31
Group Average			32	32
4	1913	41,960	36	39
5	1953	39,110	34	33
6	1920	31,080	41	43
7	1945	28,360	34	37
8	1943	27,970	39	40
Group Average			37	38
9	1914	25,900	38	37
10	1933	21,755	39	40
11	1974	17,610	40	42
12	1966	15,800	41	43
13	1925	13,985	35	36
Group Average			39	40
14	1940	12,175	40	42
15	1946	11,395	40	40
16	1935	11,135	40	43
17	1957	10,880	43	43
18	1910	9,195	46	47
19	1934	8,545	39	40
Group Average			41	42
20	1970	7,510	45	48
21	1922	7,510	46	46
22	1968	6,215	46	48
23	1960	5,830	43	43
24	1955	4,920	44	43
25	1971	4,505	43	45
26	1952	4,145	36	36
27	1959	3,885	38	39
Group Average			43	44

Table 4. (Continued)

Drought Rank	Year	Area Enveloped (km^2)	Percent of Normal Mean	Percent of Normal Median
28	1964	3,625	39	39
29	1941	3,495	45	44
30	1944	2,745	49	49
31	1937	2,720	44	44
32	1948	2,720	34	34
33	1949	2,200	40	40
34	1973	1,970	44	44
35	1962	855	42	42
Group Average			42	42

Table 4 shows a substantial increase in percent of normal in progressing from the large-area drought of Group 1 to the small-area (spot) droughts of Groups 5 and 6. Thus, the mean percent of normal increases from 32% for Group 1 to 42-43% for the small groups, which corresponds to an increase of approximately 30-35% in the mean rainfall for the drought areas. Thus, as expected, the small-area droughts tend to be less severe. The means and medians are generally close together, indicating a nearly normal distribution of the percentages within the drought areas.

The primary purpose of Table 4 is to provide a quantitative measure of the severity of the precipitation deficiency in the critical crop-growing months of July and August, and, thereby, provide information relevant to evaluation of cloud seeding potential. Thus, Table 4 shows that, on the average, successful seeding operations would have to produce useful amounts of rainfall in situations when the drought-stricken areas are usually receiving only 30 to 40% of normal rainfall in large-area droughts and 40 to 50% in the small, spot droughts extending over areas less than 4000 km^. From this particular climatological analysis, there is obviously no way in which seeding potential under such conditions can be evaluated, Its purpose is to define quantitatively the natural rainfall conditions under which weather modification must be conducted in Illinois, the Midwest, and other areas of similar precipitation climate. These are the average conditions under which the cloud seeder must operate.

The foregoing statistics provided information on the average rainfall deficiency in the immediate drought areas. It is also useful to examine the level of rainfall deficiency in the areas surrounding the drought region. With less severe rainfall deficiency and more frequent and/or heavier storms, seeding could conceivably be quite useful in these areas, and, perhaps cause additional rainfall to extend into the more severe drought areas. For each of the 35 July-August droughts, the average percent of normal in the surrounding region was determined. Table 5 summarizes the results through a comparison of the percent of normal in each of the six drought groups listed in Table 3.

Table 5. Comparison between Mean Rainfall in and Surrounding July-August Droughts

Drought Group	Area Inside of Drought	Area Surrounding Drought	Ratio of Mean Rainfall Surrounding to Inside Drought
	Percent of Normal		
1	32	73	2.28
2	37	84	2.27
3	39	80	2.05
4	41	86	2.10
5	43	90	2.09
6	42	91	2.17

Table 5 shows that, in general, the rainfall is below normal in the region surrounding a drought center, but the deficiency is not exceptionally severe, particularly in the smaller area droughts. The last column in Table 5 shows that the surrounding areas have over twice the average 2-month rainfall in the drought area. Thus, alleviation of water shortages in the areas surrounding the major drought centers appears to be much more feasible than in the drought cores, and the possibility for extension of seeding-enhanced rainfall into the fringes of the drought center may also be feasible.

Huff (1973a) determined the frequency with which monthly rainfalls equalled or exceeded 80, 100, and 120% of normal in the 10 most severe 12-month droughts of 1906-1955. He found that nearly all of the drought areas had at least one month among the 12 with 80% or more of normal rainfall, and 70 to 100% of the drought areas had one month with 100% or more of normal rainfall. Among the 10 droughts, the percent of the area with one month having rainfall equalling 120% or more of normal ranged from 40 to 90%.

This same analysis was performed on the 35 July-August droughts. Results showed that 80% of normal except on small portions of the drought areas was unusual in either July or August. Thus, there were 11 out of a possible 70 months in the 35 droughts with monthly rainfall equalling 80% or more of normal within the drought areas. However, the percent of area having this much rainfall ranged only from 4 to 37% with a median of 9% among the 11 cases. Only 5 of the 70 drought months had any area with 100% of normal and these were all less than 20% with a median of 5% for the 5 cases.

Thus, the inevitable conclusion is that only small portions of the drought areas in July-August have near normal rainfall in either month. Except for. occasional spat's, the. entire drought areas tend, to have much below normal rainfall throughout the 2-month periods. This situation does not appear particularly favorable for seeding. However, this problem will be treated in more detail later in the discussion of storm rainfall characteristics.

Area-Depth Relations

Preceding discussions have been concerned with mean and median values of rainfall normality within the July-August drought areas. An even more important question relative to the potential for weather modification in these situations is the distribution of total rainfall amounts within the drought areas. This distribution was investigated by deriving average relationships between area and amount of rainfall within the 35 droughts through computation of individual area-depth curves for each. Area-depth curves are constructed by planimetering isohyets or ranking the rainfall values from high to low (or vice versa) and then constructing an envelope curve showing rainfall plotted against area enveloped (Huff, 1968). Examples of this type of curve are shown in Fig. 9 for two outstanding droughts.

Curves such as those in Fig. 9 were drawn for each drought. The curve values of rainfall were then converted to percent of normal rainfall and combined into the six area groups listed in Table 3. From these combinations, the relationships summarized in Fig. 10 were derived. These curves show the percent of normal rainfall for partial areas within the enveloping isohyet corresponding to 50% of the normal rainfall for July-August. Average or typical relationships are shown for the entire spectrum of droughts in the 75-year sample.

For example, in the 1000 km^2 (386 mi^2) with the least rainfall (core of drought), the percent of normal increases from 8% in the large-area droughts 90,000 km^2) to 43% in the small, spot droughts encompassing 2000 km^2. The area-depth relations illustrated in Fig. 10 are pertinent to evaluation of weather modification potential. In severe droughts which extend over large areas, the rainfall deficiency becomes critical over relatively large areas in the Midwest. Thus, the 43% of normal for 1000 km^2 in the 2000 km^2 spot drought is likely to extend over approximately 70,000 km^2 in a large-area drought enveloping 90,000 km2.

Table 6 illustrates the actual magnitude of rainfall to be expected over partial areas of various sizes within the overall drought area. In Table 6, this has been done for a large, extensive, drought of 75,000 km2 and for progressively smaller droughts. These span the areal extent of major July-August droughts in Illinois during 1900-1974. Rainfall amounts were calculated by multiplying the percentages of Fig. 10 by 16.51 cm (6.50 in.), which is the average July-August rainfall in Illinois. The smaller droughts, frequently referred to as spot droughts, would be most amenable to seeding, since departures from normal are not nearly as severe within their confines as

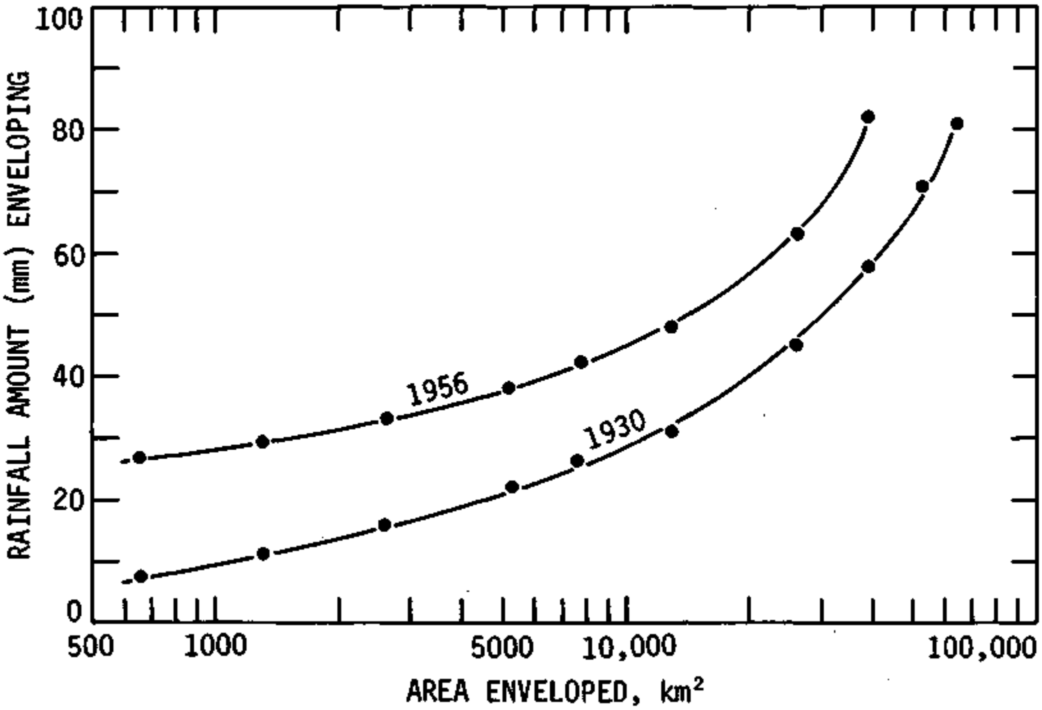


Figure 9. Area-Depth Envelope Curves for Two Outstanding July-August Droughts.

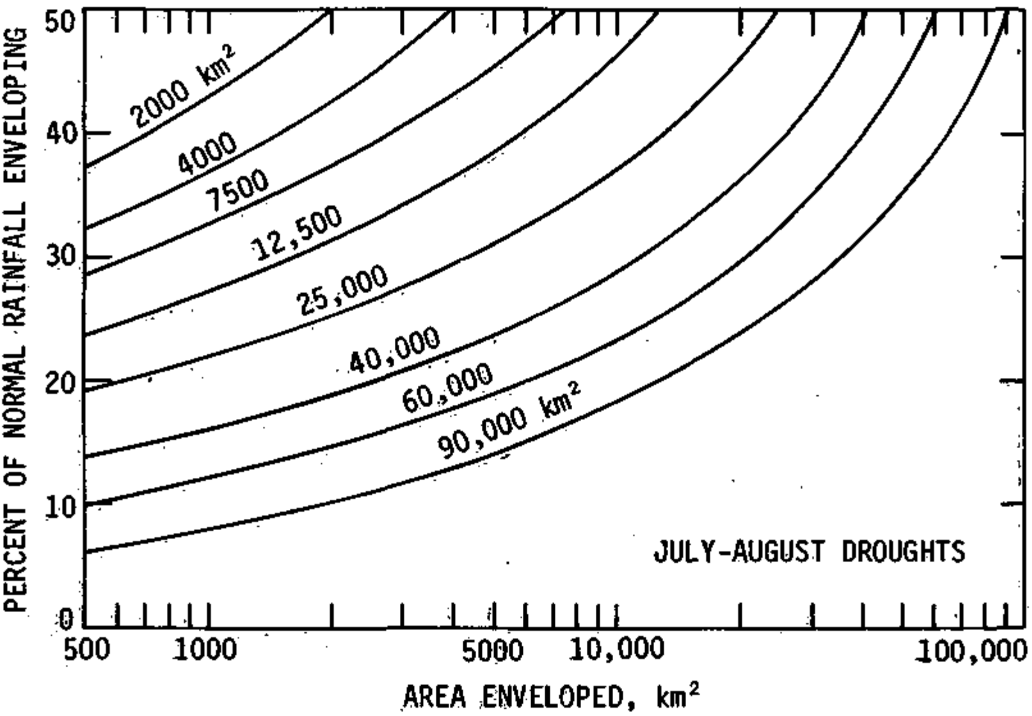


Figure 10. Typical Spatial Distribution of Rainfall in July-August Droughts.

Table 6. Typical Area-Depth Relations during July-August Droughts in Illinois

Enveloping Rainfall (mm) Within Given Partial Areas (km^2)

500	1000	2000	5000	10,000	15,000	20,000	25,000	30,000	40,000	50,000	60,000	75,000
61.1	71.0	82.5										
50.0	57.7	66.0	82.5									
42.9	48.7	56.1	68.5	82.5								
36.3	41.2	47.8	58.5	71.8	82.5							
31.4	36.0	41.6	51.1	61.1	69.3	76.4	82.5					
19.8	22.8	27.6	35.3	43.4	49.5	54.8	59.9	64.4	73.4	82.5		
13.2	17.2	20.8	27.2	33.8	38.8	43.2	47.4	51.2	57.8	64.4	73.4	82.5

within relatively large areas of widespread droughts. Figure 10 and Table 6 provide a measure of the severity of rainfall deficiencies in drought regions of various sizes in Illinois and the Midwest, and provide basic information needed in evaluating the feasibility and potential benefits of weather modification in agriculture under various degrees of drought severity.

AREAL EXTENT AND NORMALITY OF TOTAL RAINFALL IN MAY-SEPTEMBER DROUGHTS

Although July and August are the most critical of the crop growing months in Illinois, the entire growing season from May to September requires adequate soil moisture to bring the plants from seeding through germination and growth to harvesting. Therefore, investigation was made also of the potential for weather modification during the entire growing season, as revealed by climatological analyses of rainfall characteristics in this 5-month period.

Investigation showed 14 outstanding May-September droughts during the 75-year sampling period (1900-1974) in Illinois, Drought area was defined as that region within which the 5-month rainfall was less than 70% of normal. The reason for selecting this level is that mean rainfall does not tend to be as deficient over periods of 5 consecutive months as in the two midsummer months of July and August. For example, only 8 of the 14 May-September droughts had any area with rainfall less than 50% of normal which was used as the boundary for the July-August droughts, Among these 6 to 23% of the total area had rainfall less than 50% of normal, and the average was 16%. The area encompassed by the 14 droughts ranged from less than 1000 km2 to nearly 110,000 km^2, and 50% of them exceeded 60,000 km^2. The 14 occurrences were divided into the three groups shown in Table 7 for further analysis.

Table 7. May-September Droughts Grouped by Areal Extent

Group	Area Encompassed by Given Group km^2	 mi^2	Number of Cases
1	>77,700	>30,000	3
2	51,800-77,700	20,000-30,000	5
3	<51,800	<20,000	6

Normality of Total Rainfall

Average and median percents of normal for the 14 May-September droughts are shown in Table 8. All droughts had means in the range from 58 to 70% of normal, and the medians ranged from 56 to 69% of normal. Most values were in the relatively narrow range of 60 to 69% of normal. Thus, the growing season droughts in Illinois tend to be similar in their severity. However, Table 8 does show a tendency for the severity to lessen as the size of the drought area decreases. Thus, the average for Group 1 is 60% compared with 65% for Group 3. The less severe nature of the growing season droughts makes them potentially a more favorable target for weather modification. During the 5-month periods, opportunities for enhancing on-going storm systems would be more frequent and the probability of occasional widespread storms of moderate intensity would be much greater. Breaks in the drought are likely to be experienced several times in a 5-month period. This will be discussed later.

Table 8. Average and Median Percents of Normal Rainfall in 14 May-September Droughts

Drought Rank	Area Enveloped (km^2)	Year	Percent of Normal Mean	Percent of Normal Median
1	109,350	1930	59	59
2	83,400	1922	61	59
3	82,405	1913	61	62
Group Average			60	60
4	77,620	1953	60	60
5	77,570	1940	60	60
6	69,800	1914	63	64
7	62,835	1920	58	56
8	58,845	1936	60	60
Group Average			60	60
9	19,995	1925	62	62
10	18,210	1954	64	66
11	14,635	1910	63	65
12	10,645	1956	64	66
13	6,294	1962	67	67
14	725	1933	70	69
Group Average			65	67

Examination of the average percent of normal in the region surrounding the 14 droughts showed values ranging from 83 to 101% of normal, with averages of 86, 86, and 95% of normal, respectively, for Groups 1, 2, and 3. Thus, similar to the situation with the July-August droughts, the surrounding area tends to be below normal, but much less so than the major drought region. Average ratios of areal mean rainfall for the surrounding area to the drought area were 1.43, 1.43, and 1.46, respectively, for Groups 1, 2, and 3. These were considerably smaller than the July-August ratios shown in Table 5. The near-normal rainfall that tends to occur in the region surrounding the May-September droughts is also indicative of greater seeding opportunities than in July-August, and. the possibility of extending seeding effects from the surrounding region into the more severe drought area.

Following the procedure used with the July-August droughts, analyses were made to determine the percent of the drought area experiencing monthly rainfall equal to or exceeding 80, 100, and 120% of normal during May-September. Results are summarized in Table 9 for each of the three groups of Table 7. There was a wide variation in areal coverage for the three selected percents of normal among individual months, and this is reflected in considerable variation between the means and medians in some months in Table 9.

Table 9. Average Percent of Drought Area Having Monthly Rainfall Equalling or Exceeding 80, 100, and 120% of Normal in May-September Droughts

	80%		100%		120%	
Month	Mean	Median	Mean	Median	Mean	Median
			Group 1 Averages			
May	12	10	10	12	3	4
June	26	25	7	7	1	1
July	29	16	15	12	8	5
August	10	11	4	4	2	1
September	39	47	22	26	10	7
Group 1 Mean	23	23	12	12	5	4
			Group 2 Averages			
May	26	35	9	12	3	1
June	17	15	4	7	0	0
July	11	12	5	3	3	0
August	42	33	18	3	6	0
September	30	9	22	0	14	0
Group 2 Mean	25	21	12	5	5	0
			Group 3 Averages			
May	41	30	34	25	24	11
June	15	4	1	0	0	0
July	26	4	21	4	17	4
August	41	41	25	25	10	6
September	43	29	9	0	7	0
Group 3 Mean	33	21	18	11	12	4

Examination of the 70 months sampled in the 14 droughts showed a range from 0 to 100% coverage for months equalling or exceeding 80% of normal, and an overall average of 27% areal coverage. Similarily, a range from 0 to 90% coverage was obtained for months equalling or exceeding 100% of normal, and the overall average was 14%. A range of 0 to 70% coverage and an average of 7% was obtained for percent areal coverage with rainfall equal to or exceeding 120% of normal.

Table 9 indicates that 20 to 30% of a May-September drought area with a monthly rainfall equalling or exceeding 80% of normal is not uncommon. This suggests that breaks do occur in these droughts where portions of the drought area are experiencing considerable rainfall, and these situations could conceivably be seeded to enhance the natural rainfall output substantially. At least, the possibility is much stronger than with the July-August droughts.

There is a contradiction suggested by statements earlier about the lack of rainfall equalling or exceeding 80% of normal in the July-August droughts and the indication of substantial percentage coverages in the May-September statistics of Table 9. However, this is caused by the much smaller, more severe drought conditions in the July-August periods in which rainfall equal to or less than 50% of normal was required to qualify, as opposed to 70% of normal in the May-September droughts. For example, the median area encompassed by the 35 July-August droughts was 9,195 km^2 compared with 60,440 km^2 in the May-September droughts.

Table 9 indicates that the percent coverage decreases rapidly in proceeding from 80% of normal to 100 and 120% of normal. Above-normal rainfall in any of the 5 months in unusual. Other analyses showed that 38 of the 70 months had no area receiving 120% of normal and 28 months had no area receiving 100% of normal rainfall. Only 14 months (20%) did not have some portion of the drought area with 80% of normal precipitation.

Seasonal Area-Depth Relations

Area-depth relations were determined for each of the May-September droughts in the same manner described earlier for the July-August droughts. These were used to develop the average relationships shown in Table 10 for drought areas of 77,700 km^2 (30,000 mi^2), 51,800 km^2 (20,000 mi^2), 25,900 km^2 (10,000 mi^2), and 12,950 km^2 (5,000 mi^2). Enveloping values of percent of normal rainfall are shown progressing outward from the most severe portion of the drought (smallest percent of normal) to the drought boundary of 70% of normal. For example, the Illinois data indicate that in an average spatial distribution for a drought encompassing 51,800 km^2 (20,000 mi^2), rainfall will be equal to or less than 32% of normal in the core of the drought, increasing to 44% or less within the driest 2,590 km^2, a maximum of 53% at 12,950 km^2, and 59% or less in the driest 25,900 km^2 (10,000 mi^2).

Table 10. Average Spatial Distributions of Rainfall in May-September Droughts of Various Sizes

Enveloping Percent of Normal Rainfall for Partial Areas in Droughts

260	650	1295	2590	5180	7770	12,950	25,900	38,850	51,800	64,750	77,700	(km^2)
100	250	500	1000	2000	3000	5,000	10,000	15,000	20,000	25,000	30,000	(mi^2)
29	33	37	40	43	45	49	55	59	63	66	70	
32	37	40	44	47	50	53	59	65	70			
42	45	48	51	54	57	61	70					
52	54	56	58	62	65	70						

Table 10 provides a measure of spatial variability in May-September droughts which should be useful in evaluating and/or planning weather modification operations for agricultural purposes, Comparing Table 10 with Fig. 9 clearly shows the much greater severity of the 2-month midsummer droughts. For example, in an average July-August drought extending over 25,000 km^2 (10,000 mi^2), the percent of normal rainfall is less than 20% at the drought center compared with 40 to 45% in a May-September drought of similar areal extent. Thus, as pointed out earlier, it is likely that seeding operations would have a greater opportunity for success over the 5-month total growing season than in the more critical July-August period of crop growth.

INTENSITY OF DAILY RAINFALLS IN JULY-AUGUST DROUGHTS

Tables 11 and 12 provide another measure of the rainfall distribution in July-August droughts. The 35 droughts have been divided into 6 groups in column 1, based upon areal extent of the individual droughts. Then, for each group of droughts the percent of the area having various frequencies of daily rainfall is shown for three selected levels of daily rainfall amounts. The selected levels are amounts equalling or exceeding 0.25 mm (0,01 in,), 12.7 mm (0.50 in.), and 25.4 mm (1.00 in.). Table 11 shows average monthly statistics within the drought areas, and Table 12 provides similar information outside the drought regions for comparison purposes. The outside area was taken as the remaining area within the section of the state (north, central, and south) in which the drought occurred. If the drought spanned two or three sections, the outside area was that remaining after eliminating the drought area in which rainfall was equal to or less than 50% or normal.

Table 11 provides an estimate of the frequency and areal extent of natural rainfalls of various magnitude during droughts of different sizes. This provides one of several guiding statistics for evaluating cloud seeding potential. Thus, Table 11 indicates that there will nearly always be at least 2 days per month with measurable rainfall throughout drought areas in the July-August period. However, this is not much when one considers that the normal July-August frequency is 9 days with measurable precipitation at all points in a given area. Table 11 indicates an average of only 4% of the drought areas with 10 days per month of measurable rainfall, and this increases to an average of 20% of the area having 8 days with measurable rainfall. Approximately 50% of the drought areas would have 6 days per month of measurable rainfall.

Table 11 indicates that on the average only 18 to 20% of the Illinois drought areas would have 2 days per month with rainfall of 12.7 mm (0.50 in,) or more. These storms normally produce approximately 70% of the total growing season rainfall (Huff and Schickedanz, 1970) and have an average point frequency of 2 days per month. As pointed out above, only a small percentage of the drought areas achieve this normal frequency. No strong trend is indicated in Table 11 for the percent of area having a given frequency of rain days to increase with decreasing size (areal extent) of the droughts. Such a trend was anticipated, but apparently frequency is poorly correlated with drought extent.

Table 11. Average Percent of Area Having Daily Rainfalls Equal to or Exceeding 0.25, 12.7, and 25.4 mm within July-August Droughts of Various Areal Extent

Parameter												
Daily Rainfall	**≥0.25 mm (0.01 in.)**					**≥12.7 mm (0.50 in.)**				**≥25.4 mm (1.00 in.)**		
Number of Days Per Month	**2**	**4**	**6**	**8**	**10**	**1**	**2**	**3**	**4**	**1**	**2**	**3**
	Percent of Area for Given Drought Size											
>51,800 km^2 (30,000 mi^2)	97	69	32	10	2	43	11	2	<1	13	0	0
25,900 to 51,800 km^2	97	77	36	13	2	55	11	3	<1	13	<1	0
12,950 to 25,900 km^2	99	84	43	13	1	63	16	2	0	10	0	0
7,770 to 12,950 km^2	94	88	54	26	10	60	20	3	0	22	1	0
3,885 to 7,770 km^2	97	92	67	29	9	63	22	4	0	16	0	0
<3,885 km^2 (1,500 mi^2)	100	97	49	29	0	70	31	0	0	7	0	0
Mean	97	85	47	20	4	62	18	2	0	13	0	0
Median	97	86	46	20	2	62	18	3	0	13	0	0

From Table 11 it is evident that the frequency of very heavy rain days (25.4 mm or more) are scarce in the July-August drought areas, and it is seldom that more than one such day per month is experienced within the confines of the drought. An average of 13% of the drought areas had one such day per month, whereas 100% of the areas (all points) would experience one day per month in July-August in a perfectly normal year (which never occurs, of course, in reality).

In earlier studies where the major emphasis was on droughts having durations of 12 months and longer (Huff and Changnon, 1963; Huff, 1973a), the frequency of days with measurable precipitation was usually found to be only slightly below normal, and the major precipitation deficiency resulted from a lack of days with moderate to heavy rainfall. However, in the hot dry periods of midsummer, Table 11 indicates that the frequency of days with measurable rainfall is also considerably below normal over much of the drought areas. On the basis of earlier Illinois studies (Changnon and Huff, 1957; Semonin, 1960), it appears most likely that any significant rain increases from cloud seeding during summer droughts would have to be accomplished during natural rainfall occurrences. That is, seeding would have to enhance on-going rain processes. Table 11 indicates that opportunities would be much below average in the July-August droughts. This implies a need to increase the natural rainfall by very large percentages when it is raining to produce major alleviation of water shortages over the confines of the drought area. However, this does not necessarily mean that small areas within a major drought region could not be helped significantly. In fact, Table 11 shows that small portions of the moderate to severe drought areas receive the normal frequency of light, moderate, and heavy storms. These storms in which natural precipitation processes are functioning to some degree of effectiveness are potential targets for enhancement. This subject will be examined in more detail later in this report in discussing storm rainfall characteristics in these droughts.

Table 12. Average Percent of Area Having Daily Rainfalls Equal to or Exceeding 0.25, 12.7, and 25.4 mm in Region Surrounding July-August Droughts of Various Areal Extent

Parameter												
Daily Rainfall	**≥0.25 mm (0.01 in.)**					**≥12.7 mm (0.50 in.)**				**≥25.4 mm (1.00 in.)**		
Number of Days Per Month	**2**	**4**	**6**	**8**	**10**	**1**	**2**	**3**	**4**	**1**	**2**	**3**
	Percent of Area for Given Drought Size											
>51,800 km^2 (30,000 mi^2)	100	93	56	26	9	81	52	22	7	52	13	2
25,900 to 51,800 km^2	98	93	64	31	10	86	58	27	8	52	19	2
12,950 to 25,900 km^2	99	92	69	34	10	89	56	26	5	49	13	3
7,770 to 12,950 km^2	99	92	71	37	18	90	61	30	11	56	16	2
3,885 to 7,770 km^2	100	94	82	40	7	89	58	28	12	60	17	3
<3,885 km^2 (1,500 mi^2)	100	96	76	44	18	94	67	32	12	61	18	4
Mean	99	93	70	35	12	88	59	28	9	55	16	3
Median	99	93	70	36	10	89	58	28	10	54	17	3

INTENSITY OF DAILY RAINFALLS IN MAY-SEPTEMBER DROUGHTS

Tables 13 and 14 are analogous to Tables 11 and 12 discussed earlier in conjunction with July-August droughts. These tables provide measures of the characteristics of the daily rainfall distributions in drought situations and, consequently, should provide useful information in evaluating cloud seeding potential during periods of agricultural stress. The 14 May-September droughts were divided into the three groups shown in Table 8. For each group, the percent of the drought area having various frequencies of daily rainfall has been shown for three selected levels of daily rainfall amounts. Table 13 shows statistics within the drought areas, and Table 14 in the area immediately surrounding the drought area which is enclosed by 70% of normal rainfall.

Table 13 provides a measure of the frequency and areal extent of daily rainfalls of various intensity in the 5-month drought areas. Comparing this table with Table 11 for the July-August droughts, it is apparent that a larger percentage of the area in 5-month droughts has normal to near-normal frequencies of daily rainfall than occurs in the 2-month dry periods. In turn, this implies a greater number of opportunities per month to enhance natural rainfall processes through cloud seeding. Under normal conditions, all points would average 9 days per month with measurable rainfall, 2 days with amounts exceeding 12.7 mm, and 1 day with amounts of 25.4 mm or more in a normal month of the warm season in Illinois.

Table 14 shows average daily rainfall distributions in the area surrounding the May-September droughts. Relatively large portions of these surrounding regions have moderate to heavy daily rainfall amounts. Thus, the 14 droughts had about two-thirds of their areas, on the average with 2 days or more of 12.7-mm storms and over 50% of their areas had the normal 1 day per month with 25.4-mm amounts. The surrounding areas with relatively light drought conditions would then offer quite frequent opportunities for enhancement of natural rainfall, and this enhancement could perhaps be extended into the outer portions of the major drought region in such cases.

DIURNAL DISTRIBUTION OF RAINFALL IN DROUGHTS

A study of the diurnal distribution of rainfall in the July-August and May-September droughts was made for the period 1940-1974 when the number of recording gages became sufficient to permit such analyses. During the 35-year sampling period, 17 of the 35 July-August droughts and 4 of the 14 growing season droughts used in the study were recorded. The primary purpose of the study was to determine whether the diurnal distribution in drought periods tended to differ significantly from the average distribution for Illinois. If so, the differences should be taken into account in planning weather modification operations during droughts. Furthermore, the diurnal

Table 13, Average Percent of Area Having Daily Rainfalls Equal to or Exceeding G.25, 12,7/ and 25.4 mm within May-September Droughts of Various Areal Extent

Drought Area	Rainfall ≥ 0.25 mm					Rainfall ≥ 12.7 mm				Rainfall ≥ 25.4 mm		
	Given Number of Days											
	2	4	6	8	10	1	2	3	4	1	2	3
	Percent of Area for Given Drought Size											
>51,800 km^2 (30,000 mi^2)	99	92	72	37	13	76	48	16	6	35	4	1
25,900 to 51,800 km^2	99	91	59	23	4	78	41	11	2	29	5	0
<25,900 km^2 (10,000 mi^2)	99	95	76	41	10	77	44	11	2	31	3	0
Mean	99	93	69	34	9	77	44	13	3	32	4	0
Median	99	92	72	37	10	78	44	11	2	35	4	0

Table 14. Average Percent of Area Having Daily Rainfalls Equal to or Exceeding 0.25, 12.7, and 25,4 mm Surrounding May-September Droughts of Various Areal Extent

Drought Area	Rainfall ≥ 0.25 mm					Rainfall ≥ 12,7 mm				Rainfall ≥ 25,4 mm		
	Given Number of Days											
	2	4	6	8	10	1	2	3	4	1	2	3
	Percent of Area for Given Drought Size											
>51,800 km^2 (30,000 mi^2)	100	95	77	46	19	94	66	32	13	58	19	3
25,900 to 51,800 km^2	100	94	75	50	21	90	64	32	13	55	15	3
<25,900 km^2 (10,000 mi^2)	99	97	84	61	26	92	71	40	17	53	23	3
Mean	100	95	79	52	22	92	67	35	14	55	19	3
Median	100	95	77	50	21	92	66	32	13	55	19	3

distributions are useful, in general, for planning the time and duration of weather modification activities to maximize contributions from seeding efforts.

No major differences were found in the diurnal distributions during drought situations and average weather conditions. This is illustrated in Table 15 where the average percent of total rainfall has been tabulated by 3-hour and 6-hour periods for 1) the July-August and May-September drought periods, and 2) average summer distributions in Illinois, based upon an earlier Water Survey study (Huff, 1971). The Illinois averages are based upon 30 recording raingage stations in and adjacent to Illinois during the 10-year period, 1948-1957.

Table 15. Diurnal Distribution of Summer Rainfall in Illinois during Drought and Average Rainfall Conditions

	Percent of Total Rainfall		
Time	July-August	May-September	1948-57
0000-0300	12	15	14
0300-0600	11	12	14
0600-0900	13	13	13
0900-1200	8	9	10
1200-1500	14	11	12
1500-1800	16	13	13
1800-2100	15	14	12
2100-2400	11	13	12
0000-0600	23	27	28
0600-1200	21	22	23
1200-1800	30	24	25
1800-2400	26	27	24
0600-1800	51	46	48
1800-0600	49	54	52

The 3-hour distributions in Table 15 indicate the least rainfall occurring during the late forenoon. The Illinois averages indicate the highest percentages late at night (0000-0600), but no major differences from the late afternoon and evening hours. The 6-hour Illinois averages indicate only small percentage differences with the maximum at 0000-0600 CST. The Illinois averages show a slightly greater percentage of the total rainfall (52%) during the evening and night hours (1800-0600) than in the daytime hours (0600-1800) when 48% of the rain occurred in the 1948-1957 period. At this time, it should be pointed out that the diurnal distribution does show variability within the state that is obscured by the state averages. In the northern two-thirds of the state, the maximum amount of rainfall tends to occur in the 0000-0600 period, whereas in southern Illinois there is a distinct afternoon maximum. However, the minimum occurs in late forenoon throughout the state.

The 3-hour and 6-hour averages for the growing season droughts (May-September) are very similar to the Illinois averages. The July-August drought distributions vary somewhat more from the Illinois averages. Reference to the 6-hour percentages shows a tendency for a considerably greater percentage of the rainfall to occur in the afternoon (1200-1800) than indicated by the Illinois summer averages, and this is balanced by less rainfall late at night (0000-0600) in the July-August droughts.

Examination of 3-hour and 6-hour averages for individual months in the July-August and May-September droughts did not show any trend for the diurnal distribution to progressively change from May to September. Rather, the month-to-month variations in percentages for each 3-hour and 6-hour period were quite random with respect to percent of total rainfall. Examination of the 17 July-August droughts for which hourly rainfall data were available indicated that the maximum amount of rainfall occurred most frequently in the period from 1500-2100. The maximum occurred during this 6-hour period in 10 of the 17 (59%) droughts.

These analyses of the diurnal distributions in droughts and under average conditions indicate that the diurnal percentage distributions of total rainfall do not depart substantially from the average during droughts. Thus, the total amount of rainfall is much less during droughts, but diurnally it is divided very much like it is under normal conditions.

Both the average and drought distributions show that substantial percentages of the total rainfall in the growing season occur throughout the day and night. This stresses the need to carry out weather modification operations on a 24-hour basis to take maximum advantage of seeding opportunities during drought conditions. Most operations in the past have been restricted to daylight hours. However, this study shows that in Illinois at least 50% of the total rainfall occurs in the evening to early morning hours (1800-0600) and that approximately 25% of the total occurs from midnight to 0600. On the basis of frequency of maximum rainfall amounts in droughts, the greatest number of seeding opportunities is likely to occur from 1500 to 2100. This assumes, of course, that seeding will be most productive under synoptic conditions favorable for the natural development of precipitation.

DISTRIBUTION OF STORM RAINFALL IN JULY-AUGUST DROUGHTS

It has been assumed in this research that the potential for alleviating agricultural water shortages during droughts is dependent upon the frequency of synoptic weather conditions favorable for natural precipitation, as reflected in the surface rainfall distribution. Under this assumption, frequency, intensity, and areal extent of precipitation are the parameters which can be used as indices of the potential for augmenting rainfall during droughts.

Limitations of Storm Rainfall Data

In the storm rainfall analyses described in this section, isohyetal maps were drawn for each storm and planimetered to determine areal mean rainfall and area-depth (spatial distribution) relationships. The climatic network data of the National Weather Service were used for this purpose. Because of raingage densities employed in this network, it is to be expected that the maximum values in individual storms will frequently be underestimated (Huff and Neill, 1957), and that appreciable sampling errors may occur occasionally in computations of areal mean rainfall. However, when large groups of storms are combined to obtain average relationships, the results should be reasonably accurate, and provide a satisfactory approximation of spatial distribution characteristics of rainstorm events in droughts. Consequently, emphasis has been placed upon deriving average relationships in the storm analyses.

In the following discussion, daily rainfall and storm rainfall are used interchangeably. Daily rainfall usually includes only one basic synoptic event during the warm season, although several individual showers or thunderstorms may be involved. Furthermore, most of the daily rainfall totals in summer are for storms of only a few hours duration, usually less than 12 hours and frequently less than 6 hours (Huff and Neill, 1959).

Frequency and Intensity of Storms Grouped by Areal Extent

The first step undertaken in evaluating storm rainfall characteristics in droughts was to obtain the mean rainfall in each storm producing measurable rainfall within the boundaries of each drought. In the 35 July-August droughts, 492 storm days had areal mean rainfall of 0.01 inch (0.25 mm) or more. The 35 droughts were divided into six groups, depending upon their areal extent. Then, the frequency distribution of areal mean rainfalls was determined for the total sample of storm days included in each group. Table 16 summarizes the results of this analysis. This table was extracted from frequency distribution curves for each group and shows the mean rainfall equalled or exceeded for given percentages of the total number of storms.

The table shows a trend for the small area droughts to have heavier mean rainfall than the larger droughts. Thus, in droughts of very small areal extent encompassing less than 5,000 km^2 (1,900 mi2), approximately 5% of the storm days show mean rainfall exceeding 18.5 mm (0.73 in.). This decreases gradually to 10.4 mm (0.40 in.) for the equivalent frequency in droughts extending over areas in excess of 50,000 km^2 (19,000 mi2). Similarly, 30% of the storms in small drought areas of 5,000 km^2 or less had areal mean rainfalls of 7.0 mm (0.28 in.) or more, and this decreased gradually to 5.0 mm (0.13 in.) for the large area droughts covering over 50,000 km2.

Table 16, provides a measure of the frequency of storm mean rainfalls of various intensities over drought areas of various sizes. Not unexpectedly, the analysis shows that relatively heavy storms tend to occur more frequently in small-area than in large-area droughts. However, the most important information provided by Table 16 is the quantitative estimates of the storm rainfall distributions in droughts in Illinois, which is a typical midwestern corn belt state with respect to growing season climate.

Table 16. Distribution of Storm Mean Rainfall in July-August Droughts of Various Areal Extent

Drought Area (km^2)	Storm Mean Rainfall (mm) Equalled or Exceeded for Given Percent of Storms										
	5	10	20	30	40	50	60	70	80	90	95
>50,000	10.4	7.5	6.0	5.0	4.5	2.5	2.3	1.3	0.8	0.4	0.2
10,000-50,000	14.5	10.0	7.5	5.5	4.7	2.8	2.4	1.4	0.8	0.4	0.2
5,000-10,000	16.0	13.5	9.5	6.7	5.0	3.0	2.5	1.5	0.8	0.4	0.2
< 5,000	18.5	15.5	11.0	7.0	5.0	3.0	2.5	1.5	0.8	0.4	0.2

Area-Depth Relations for Storm Rainfall in July-August Droughts

The spatial distribution of storm rainfall with respect to intensity and areal extent in droughts is extremely important to the planning and accomplishment of weather modification. This is especially true in moderate to severe droughts, since it appears extremely likely that any substantial alleviation of water shortages in these droughts must be accomplished through stimulation of the atmospheric precipitation processes during those periods when natural rainfall is being produced. That is, the productivity of the precipitation process must be increased by increaing the number, intensity, and areal extent of convective entities during synoptic conditions favorable for natural rainfall.

A convenient method of evaluating the spatial distribuion characteristic of natural rainstorms is through the computation of storm area-depth curves (Huff, 1968). Therefore, area-depth curves were computed for all 492 storms among the 35 July-August droughts. The curves were then grouped according to areal extent of the droughts. From these groups of storm area-depth relations, median curves were derived for six drought groups as shown in Fig. 11.

These are envelope curves. For example, the curve for areas of 12,500 to 25,000 km^2 indicates that 20% of such drought areas will have storm rainfall amounts that equal or exceed 5.6 mm (0.22 in.), on the average. When the 40% of the area with heaviest rainfall is included, the enveloping isohyet (rainfall amount) decreases to 2.4 mm (0.09 in.). These area-depth curves provide the user with quantitative measures of the rainfall distribution in average or typical storms occurring in droughts of various areal extent under midwestern climatic conditions.

As a further guide in the evaluation of weather modification potential in moderate to severe droughts, the area-depth relations for the 492 storms were used to develop a technique for computing the average spatial distribution of

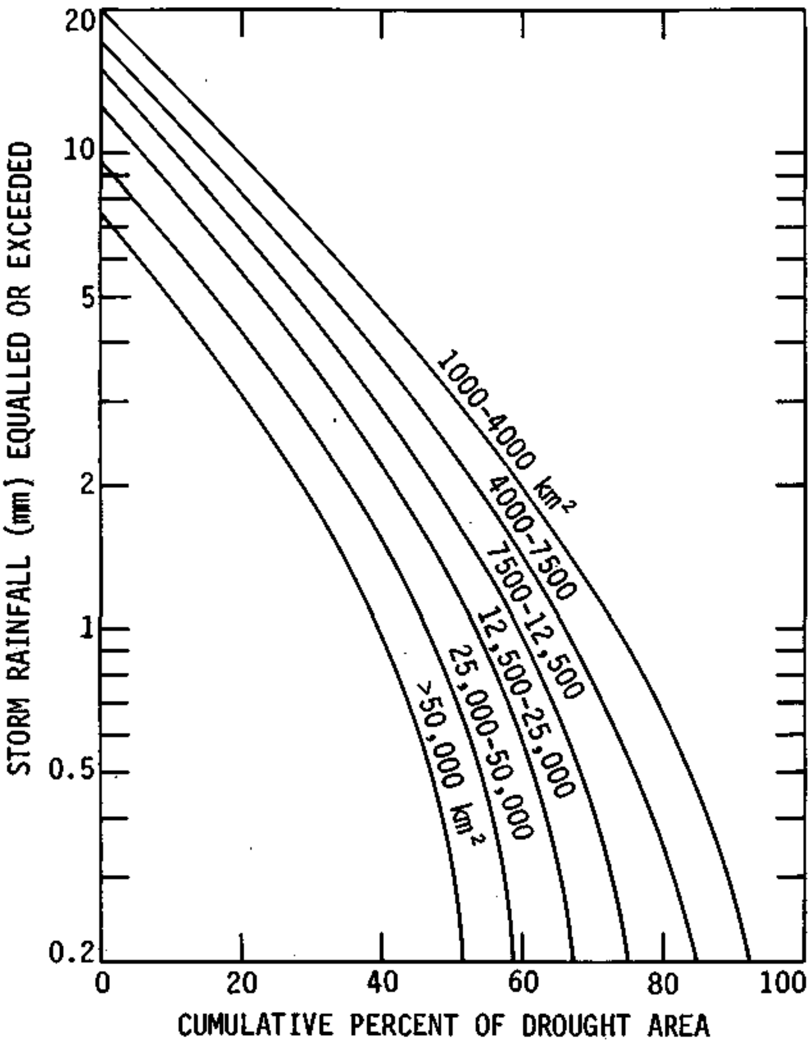


Figure 11. Median Area-Depth Envelope Curves of Storm Rainfall in July-August Droughts of Various Sizes.

rainfall in storms of any given intensity (areal mean rainfall) over a wide range of areas in July-August droughts. The nomogram (Fig. 12) is used in combination with the frequency distribution of storm mean rainfalls in Table 16. The nomogram is non-dimensional and should be applicable as a first approximation, in the Midwest and other areas of similar precipitation climate. It consists of a family of curves for various sizes of droughts in which ratios of maximum rainfall amounts enveloped to the areal mean rainfall are shown on the ordinate and cumulative percent of drought area on the abscissa.

The use of the nomogram of Fig. 12 and Table 16 is illustrated in Fig. 13 in which average area-depth envelope curves have been computed for a drought extending over 20,000 km^2 and for four different areal mean rainfalls. The storm mean rainfalls were selected from Table 16 and correspond to those equalled or exceeded in 10, 30, 50, and 70% of the storms on drought areas of 20,000 km^2. The nomogram ratios for areas of 20,000 km^2 were then used to compute the rainfall (mm) that would be equalled or exceeded on various subareas of the 20,000 km^2 drought region, and curves constructed for each storm mean rainfall as shown in Fig. 13.

These curves then provide the user with quantitative estimates of the spatial distribution characteristics of rainfalls of various magnitude on the given drought area. The expected percentage increases from weather modification can be applied along the distribution curves to arrive at seeding-modified distribution curves. In turn, these should be very useful in assessing the expected results and potential benefits from cloud treatment under any given set of drought conditions.

A more detailed description of the rainfall distribution in storms associated with the July-August droughts is provided in Tables 17-19. Table 17 shows median area-depth relations for each of the 35 July-August droughts. These tabulated values were taken from the individual storm curves, and provide further information on the spatial distribution characteristics. The area-depth relations have been listed by droughts in decreasing order of areal extent, and the number of storms used in determining each mean curve is shown in the second column of the table. Rainfall values have been omitted at the upper ends of the distribution in some cases, especially in the smaller area droughts. This was done because raingage density was not adequate to extrapolate the curves further into the drought center.

Table 17 provides quantitative measures of the areal extent and rain intensity within storms associated with July-August droughts in Illinois. It also shows how storm intensity and areal extent vary between droughts of the same general size and between relatively large and small droughts. Thus, storms tend to cover a greater percentage of the drought area in the relatively small droughts and also tend to produce heavier rainfall.

Table 18 provides still another view of the areal extent and intensity of storm rainfall in droughts, which is so important in evaluating weather modification potential. Here, all 492 storms have been used to arrive at storm intensity-areal extent relations in droughts of various sizes. That is, all storms in each size group were ranked to derive the spatial frequency relations in Table 18, where rainfall depth has been shown for selected

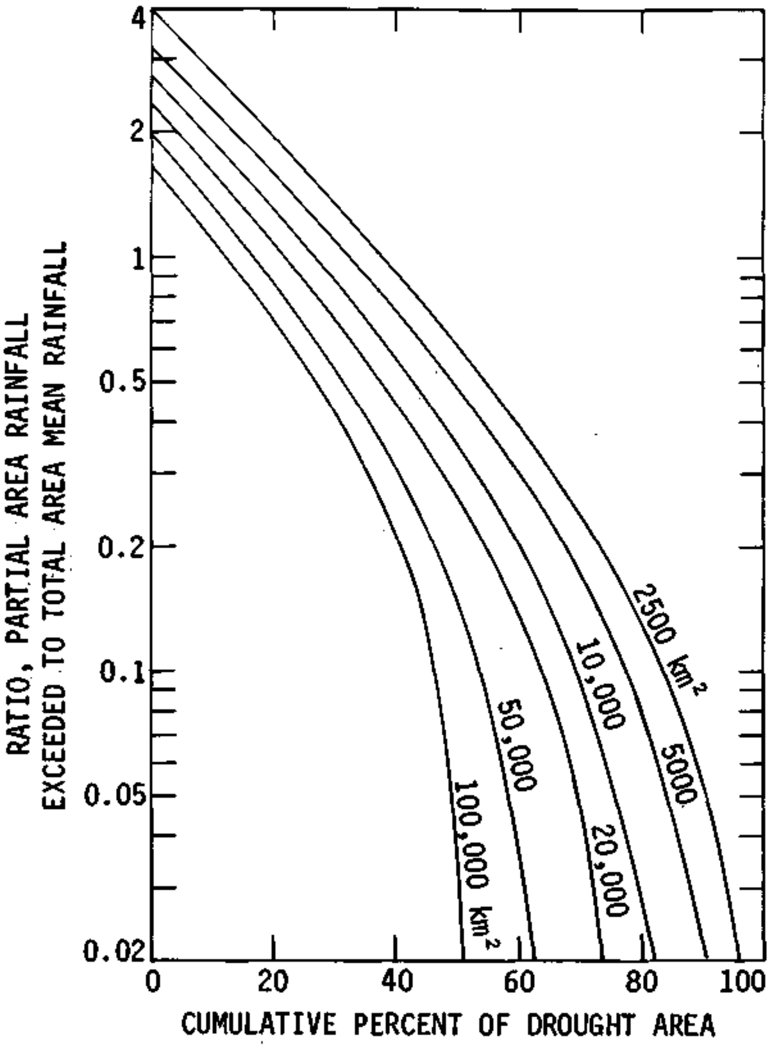


Figure 12. Nomogram for Estimating Spatial Distribution of Storm Rainfall in July-August Droughts of Various Areal Extent.

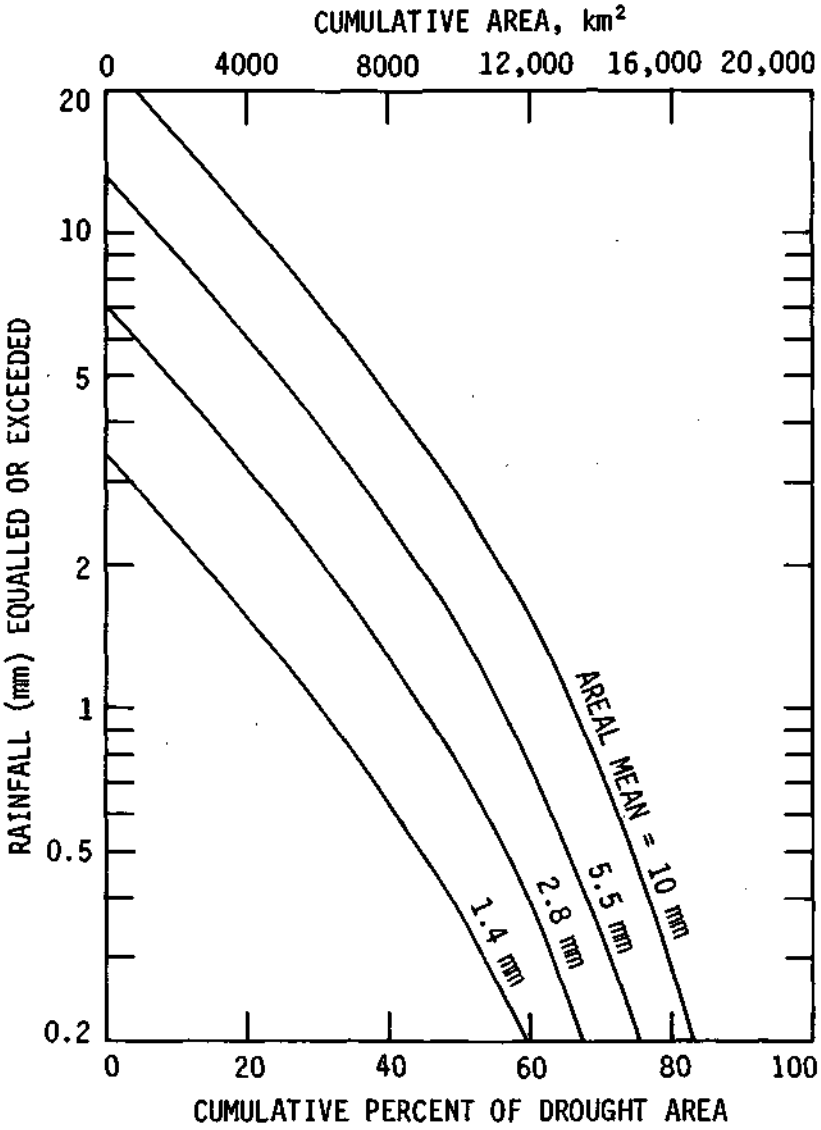


Figure 13. Example of Storm Area-Depth Relations Computed from Table 16 and Nomogram of Fig. 12 for Drought Area of 20,000 km^2 and Selected Areal Mean Rainfalls.

Table 17. Median Area-Depth Relations for Storm Rainfall in Each of 35 July-August Droughts

Year	N	Area (km^2)	Rainfall (mm) Equalled or Exceeded for Given Percent of Drought Area 5	10	20	30	40	50	60	70	80	90	100
1930	10	95,800	19.8	13.5	7.1	4.6	2.8	1.8	1.0	0.5	0	0	0
1936	15	63,400	16.5	9.9	4.6	0.5	0.3	0	0	0	0	0	0
1947	15	52,400	15.0	8.6	4.1	1.5	1.0	0.5	0	0	0	0	0
1913	17	42,000	20.3	11.7	6.1	2.8	0.3	0	0	0	0	0	0
1953	12	39,100	13.2	7.4	4.6	2.3	0.5	0	0	0	0	0	0
1920	17	31,100	15.5	8.6	5.1	2.8	2.0	1.0	0.3	0	0	0	0
1945	12	28,300	14.5	13.0	7.9	4.8	2.8	0.5	0	0	0	0	0
1943	17	28,000	17.5	10.4	2.0	0.5	0	0	0	0	0	0	0
1914	19	25,900	10.2	7.1	3.3	2.8	2.0	1.0	0.3	0	0	0	0
1933	10	21,800	----	17.5	11.9	8.1	6.6	3.3	1.8	0.8	0.3	0	0
1974	16	17,600	----	10.7	5.6	5.1	2.5	2.0	1.0	0.8	0	0	0
1966	17	15,800	----	11.9	7.1	3.6	2.8	0.8	0	0	0	0	0
1925	13	14,000	----	10.4	9.4	7.6	4.1	1.3	0	0	0	0	0
1940	15	12,200	----	9.4	8.9	3.6	1.8	1.0	0	0	0	0	0
1946	16	11,400	----	5.8	4.3	1.8	1.3	1.0	0.3	0	0	0	0
1935	17	11,100	----	----	11.7	7.9	2.8	2.0	1.8	0	0	0	0
1957	11	10,900	----	18.0	14.2	7.6	4.8	3.0	2.8	2.3	1.5	0.8	0
1910	15	9,200	----	----	5.6	4.6	2.5	2.5	1.8	1.5	1.5	1.0	0
1934	15	8,500	----	----	3.0	3.0	2.0	0.8	0.8	0.3	0	0	0
1970	16	7,500	----	11.9	10.4	6.6	2.0	0.8	0.3	0	0	0	0
1922	12	7,500	----	11.4	10.9	8.4	6.9	4.3	2.8	1.5	1.0	0.5	0
1968	15	6,200	----	8.6	7.9	6.4	5.1	2.5	1.5	1.0	0	0	0
1960	14	5,800	----	9.7	9.1	6.9	3.6	2.5	2.5	1.5	0.5	0.3	0
1955	15	4,900	----	----	11.1	5.8	4.3	2.0	1.5	0	0	0	0
1971	16	4,500	----	----	7.4	5.8	4.6	2.0	1.5	1.3	1.0	0.5	0
1952	12	4,100	----	----	----	9.7	7.9	5.3	4.3	2.0	1.3	0.8	0
1959	15	3,900	----	----	3.8	3.3	1.8	1.3	0.8	0.5	0.3	0.3	0
1964	11	3,600	----	----	----	6.1	3.3	3.0	2.3	1.8	1.0	0.8	0.5
1941	13	3,500	----	----	----	5.3	3.8	2.0	1.3	1.0	1.0	0.3	0
1944	15	2,700	----	4.6	2.3	0	0	0	0	0	0	0	0
1937	9	2,700	----	----	----	----	----	11.4	9.3	7.1	4.9	2.8	0.5
1948	12	2,700	----	----	----	4.1	3.8	3.6	3.3	3.0	2.3	0.8	0.3
1949	18	2,200	----	----	----	7.6	6.1	3.3	0.8	0.8	0.5	0.3	0
1973	13	2,000	----	----	9.7	7.6	5.1	3.0	2.0	0.5	0	0	0
1962	7	800	----	----	----	----	----	17.5	16.1	14.3	12.5	10.7	8.9

Table 18. Spatial Distribution of Rainfall Intensities within Storms during July-August Droughts

Percent of Drought Area	Rainfall (mm) Equalled or Exceeded in Given Percent of Storms									
	10	20	30	40	50	60	70	80	90	100
Drought Areas ≧ 50,000 km²										
10	26.2	17.5	11.4	7.6	4.8	3.0	1.8	1.0	0.5	<0.3
30	16.5	9.9	6.1	3.6	2.0	1.0	0.5	0.3		
50	9.4	4.8	2.3	1.0	0.3					
70	4.1	1.3	0.3							
90	0.2	<0.1								
Drought Areas of 25,000 - 50,000 km²										
10	30.0	21.1	14.5	9.9	6.6	4.3	2.8	1.8	1.0	1.0
30	18.0	10.9	7.6	4.8	3.0	1.8	1.0	0.5	<0.3	
50	9.7	5.3	2.8	1.5	0.8	0.3				
70	5.1	2.3	1.0	0.3						
90	0.9	<0.1								
Drought Areas of 12,500 - 25,000 km²										
10	31.2	23.1	17.0	12.4	9.1	6.4	4.6	3.0	1.8	0.8
30	19.1	13.5	9.1	6.4	4.1	2.5	1.5	0.8	0.3	
50	10.7	6.4	3.8	2.0	1.0	0.5	<0.1			
70	5.6	2.5	1.0	0.3						
90	2.4	0.7	0.2	<0.1						
Drought Areas of 7,500 - 12,500 km²										
10	32.3	23.9	17.8	13.0	9.7	6.6	4.8	3.3	2.0	1.0
30	22.1	16.0	11.2	7.9	5.1	3.0	1.5	0.8	0.3	
50	12.5	7.1	4.3	2.5	1.3	0.5	0.3			
70	6.9	3.6	1.8	7.6	0.3					
90	3.8	1.5	0.5	<0.1						
Drought Areas of 4,000 - 7,500 km²										
10	33.0	25.4	19.8	15.2	11.9	9.1	6.6	4.6	2.8	1.3
30	23.9	17.0	11.9	8.4	5.8	3.6	2.3	1.3	0.5	<0.3
50	15.5	9.7	6.6	4.3	2.5	1.5	0.5	<0.3		
70	8.9	5.1	3.3	1.8	0.8	0.3				
90	5.1	2.5	1.0	0.3						
Drought Areas of 1,000 - 4,000 km²										
10	35.1	27.9	21.8	16.8	13.0	9.7	7.1	5.1	3.3	1.8
30	24.9	18.0	13.0	9.1	6.4	4.1	2.8	1.5	0.5	<0.3
50	18.3	12.2	8.4	5.3	3.6	2.0	1.3	0.5	<0.3	
70	12.2	7.4	4.3	2.5	1.3	0.5	<0.3			
90	7.9	4.3	2.0	1.0	0.3					

percentages of the drought areas in various percentages of the storm occurrences. Thus, on drought areas exceeding 50,000 km^2 during July-August, it was determined that 10% of these drought areas would experience rainfalls of 26.2 mm or more in 10%, of the storms during the 2-month period. Similarly, rainfall would equal or exceed 11.4 mm in 30% of the storms and 4.8 mm in 50% of the storms over the 10% of the drought area with heaviest storm rainfall. Table 18 provides the user with detailed background information on the climatology of drought rainstorms which can be and should be used in assessing weather modification potential. These data which have been compiled for Illinois can be readily computed for other areas of the country through use of published climatological data.

An example of how Table 18 can be used follows. Assume the user concludes that cloud seeding is likely to be effective only in those storms in which 5 mm (0.20 in.) or more of rainfall is being produced naturally, and that he is concerned with a drought extending over 20,000 km^2 in Illinois. In what percentage of the storms is he likely to have seeding opportunities and over what percentage of the drought area?

Referring to the relations for droughts encompassing 12,500 to 25,000 km^2 in Table 18, it is seen that 10% of this drought area can be expected to have 5 mm or more in approximately 68% of the storms. The 5 mm value will be equalled or exceeded over 30% of the drought area in 46% of the storms. Similarly, 50% of the drought area can expect 5 mm or more in 26% of the storms, and 12% of the area in 70% of the storms. Approximately 20% of the storms will not produce 5 mm amounts over any portion of the drought area. The conclusion reached from this example and examination of Table 18 is that in most drought-associated rainstorms there is some portion of the area that is likely to be amenable to cloud seeding and, in some storms, a major portion of' the drought area may be helped by seeding.

Table 17 shows that an average of 15 storms can be expected to affect some portion of the area in droughts of the size used in the above example. Therefore, the 10% values of Table 18 correspond to those expected to be equalled or exceeded in 1 or 2 storms in a 20,000-km^2 drought. Similarly, the 30%. values include those equalled by the 4 or 5 heaviest storms in the 2-mpnth drought, and the 50% values encompass the heaviest 7 or 8 storms during July and August.

Table 19 shows the area-depth relationship for the heaviest storm that occurred in each drought. These storms have been presented to provide the interested reader and potential user with an estimate of the heaviest intensities, as measured by total rainfall, that can be expected to occur in individual rainstorms associated with July-August droughts of various areal extent.

Relations between Synoptic Weather and Drought Rainfall

Huff (1973a) in a study of the severe 12-month drought of 1953-1954 found that approximately 60% of the total rainfall was associated with cold frontal

Table 19. Area-Depth Relations in Heaviest Storms of July-August Droughts

		Rainfall (mm) Equalled or Exceeded for Given Percent of Drought Area									
Year	Area (km^2)	10	20	30	40	50	60	70	80	90	100
1930	95,800	26.7	18.0	13.7	11.2	7.9	4.6	3.3	2.0	0.3	0
1936	63,400	28.2	19.8	14.0	8.4	5.1	2.5	0	0	0	0
1947	52,400	10.7	8.9	7.1	4.8	3.6	2.8	2.0	1.0	0	0
1913	42,000	11.2	7.9	4.3	3.6	3.0	2.5	1.3	0	0	0
1953	39,100	37.3	31.5	24.4	19.1	15.5	14.0	10.4	7.6	6.6	2.3
1920	31,100	39.6	18.0	15.0	13.5	12.2	10.7	8.1	6.6	5.6	0
1945	28,000	35.3	19.1	13.2	11.9	10.9	10.4	9.4	7.9	5.8	2.5
1943	28,000	36.3	32.5	27.7	25.7	24.1	19.3	18.0	12.4	6.4	2.0
1914	25,900	24.4	16.5	14.2	10.4	9.1	5.8	2.5	1.8	1.5	0.5
1933	21,800	31.0	22.1	21.1	18.8	17.8	11.7	9.7	4.6	2.3	0
1974	17,600	19.1	17.0	13.5	10.7	9.9	8.9	5.1	2.5	1.3	0
1966	15,800	28.7	23.9	21.8	21.1	19.8	13.7	3.8	1.8	1.8	0
1925	14,000	37.1	27.9	18.5	13.7	11.4	11.4	10.4	8.6	6.1	0
1940	12,200	27.7	26.9	24.6	19.1	13.0	9.9	8.6	3.0	0.8	0
1946	11,400	40.1	34.0	31.8	31.2	26.7	25.1	15.7	12.2	10.4	9.9
1935	11,100	----	16.8	16.8	16.5	15.7	12.2	8.6	6.6	5.8	5.1
1957	10,900	37.6	36.8	35.3	22.4	14.0	10.4	4.6	2.5	1.5	0.8
1910	9,200	----	29.2	29.0	28.4	26.9	24.9	18.3	9.4	5.6	0
1934	8,500	----	37.3	36.6	33.0	30.5	24.4	16.5	13.0	10.7	7.4
1970	7,500	41.7	32.5	23.4	21.1	14.7	14.5	13.7	10.2	6.1	3.3
1922	7,500	37.6	36.3	32.3	27.7	22.9	18.5	15.7	7.4	3.6	1.8
1968	6,200	16.0	15.0	11.9	9.9	8.9	7.9	5.6	2.8	1.8	1.0
1960	5,800	28.4	27.7	25.7	21.8	19.1	14.0	8.9	8.4	7.9	7.4
1955	4,900	----	36.8	35.1	33.0	30.5	28.7	24.9	18.5	15.5	12.2
1971	4,500	----	31.2	28.7	28.4	27.7	24.1	21.8	21.3	18.0	11.9
1952	4,100	----	25.0	20.5	15.2	12.2	11.9	10.9	10.7	8.4	5.8
1959	3,900	----	33.5	29.5	21.1	17.0	11.4	8.4	4.3	3.0	0.3
1964	3,600	----	20.3	19.3	19.1	18.8	18.5	17.8	16.3	15.0	12.7
1941	3,500	----	27.2	25.7	24.4	23.4	14.2	9.9	5.3	3.8	3.3
1944	2,700	30.5	26.4	22.4	21.3	20.3	20.1	19.6	17.8	15.5	13.2
1937	2,700	----	44.5	41.4	38.4	35.6	31.2	27.2	23.1	19.1	15.2
1948	2,700	----	27.9	24.4	21.8	19.3	17.0	14.5	13.7	12.7	11.9
1949	2,200	----	37.8	29.7	21.8	14.0	5.8	5.6	4.1	2.3	0.5
1973	2,000	33.0	31.0	30.0	28.2	26.2	24.1	23.1	21.3	19.8	17.8

activity, and that these storms came the closest of all basic synoptic types in producing normal amounts of rainfall. In view of these findings, a study of the relationship between synoptic weather conditions and rainfall was made for all droughts in the July-August and May-September periods included in this research.

The basic synoptic types used in the study are shown in Table 20 where the normal percentage distribution of each type is shown for Illinois during July-August. These normals were derived from earlier studies by Hiser (1956) and Huff and Schickedanz (1970). For some phases of the analyses, cold frontal storms were subdivided into prefrontal squall lines, fronts with waves, and frontal passages.

Table 20. Normal Percentage Distribution of July-August Rainfall in Illinois by Synoptic Type

Synoptic Type	Percent of Storm Days	Percent of Total Rainfall
Gold Front	46	39
Warm Front	8	14
Stationary Front	13	21
Occluded Front	1	2
Low Centers	2	7
Air Mass Storms (Non frontal)	30	17

From Table 20, it is evident that cold frontal activity is the major producer of summer rainfall in Illinois, and this distribution should be generally typical of the Midwest corn belt. The normals in Table 20 are based on the entire state. In the drought analyses, computations were made oh a sectional basis. However, in summer in Illinois, the percentage distributions of Table 20 vary only slightly throughout the state.

Table 21 shows the average percent of normal rainfall according to synoptic type for droughts in each of four section combinations used in classifying drought locations for the research. Thus, in the North Section (see location in Fig. 1), cold fronts produced 63% of their normal summer rainfall in the 8 July-August droughts located in this region of the state. Warm fronts were much less efficient, since they produced only 11% of their normal summer rainfall in the 8 droughts in the North Section.

Further inspection of Table 21 shows that cold fronts came closer to producing their normal rainfall output in all sections than did any other synoptic type, except lows in the North Section and occluded fronts in the three multiple section droughts. However, as shown in Table 20, both low centers and occluded fronts are normally small producers of summer rainfall. Therefore, it is obvious that in all sections cold fronts were the major contributor of the rainfall recorded in the moderate to severe midsummer droughts of 1900-1974 in Illinois.

Table 21. Average Percent of Normal Rainfall in July-August Droughts Grouped by Synoptic Type and Section of Illinois

Synoptic Type	Percent of Normal Rainfall for Given Storm Type North Section	Central Section	South Section	Multiple Section	Combined Sections
Cold Front	63	59	73	65	65
Warm Front	11	8	4	1	6
Static Front	48	32	23	19	30
Occluded Front	15	0	0	120	13
Air Mass	9	9	22	0	13
Lows	86	31	51	43	50
Number of Droughts	8	12	12	3	35
Number of Storms	127	166	157	42	492

From the standpoint of weather modification, it is apparent from Table 20 and 21 that the greatest contributions to alleviating agricultural water shortages would come from successful treatment of cold frontal storms. Conversely, enhancement of nonfrontal storms (air mass) would normally contribute little additional precipitation during drought periods. For example, Table 20 (last column) shows that air mass storms normally contribute 17% of the July-August rainfall. However, in droughts, they average only 13% of their normal production. Average July-August rainfall in Illinois is approximately 16.5 cm (6.5 in.), and air mass storms would normally produce 2.8 cm (1.1 in.). Multiplying the normal by 13%, only 0.36 cm (0.14 in.) would occur, on the average in droughts. If one enhanced the air mass rainfall by 50%, the July-August average in droughts would only be 0.54 cm (0.21 in.) during the two months. The increase of 0.18 cm (0.07 in.) by seeding would have an insignificant effect on crop production.

Normally, cold fronts produce 39% of the 16.5-cm total in an average July-August. This amounts to 6.44 cm. If 65% of this is produced in drought periods as indicated in Table 21, the drought total would be 4.18 cm compared with the 0.36 cm in air mass storms. A 5% increase in cold frontal rainfall would then contribute more than a 50% increase in air mass rainfall (0.20 cm) under drought conditions.

Moderate increases of 20% through seeding would increase the cold front total in average drought conditions to 5.01 cm which is 78% of the summer normal. A 50% increase in cold frontal rainfall would increase its 2-month total to 6.27 cm, or 97% of its normal contribution. The foregoing examples emphasize the need to treat cold frontal storms successfully, if substantial contributions are to be made in alleviating agricultural water shortages during midsummer droughts in Illinois and adjacent corn belt states, which are the nation's major producers of corn and soybeans that are vital to world food supplies.

An investigation was made of the frequency distribution of synoptic weather types stratified according to the areal extent of droughts. This was done to determine whether the frequency of any particular storm type tended to dominate more in large droughts than in small droughts. Since cold fronts have been shown to be the primary precipitation producer in droughts, their relative frequency in droughts of various sizes provides useful information in evaluating the potential of weather modification in different drought conditions. Results of this investigation are summarized in Table 22, in which the percent of total storms has been shown for the six classifications of July-August droughts used in this study. Percentages are also shown at the bottom of the table for all droughts combined, along with the normal percentages derived from Hiser (1956) and Changnon et al. (1977).

Table 22. Percentage Distribution of Synoptic Weather Types in July-August Droughts of Various Areal Extent

	Percent of All Storms in Given Drought Areas					
Drought Area (km^2)	Cold Fronts	Warm Fronts	Stationary Fronts	Occluded Fronts	Low Centers	Air Mass Storms
>51,800	60	5	13	0	15	7
25,900-51,800	55	4	23	0	4	14
12,950-25,900	68	3	17	0	8	4
7,770-12,950	67	7	12	0	6	8
3,885-7,770	55	0	16	2	10	17
< 3,885	66	1	17	1	6	9
Areas Combined	61	3	16	1	8	11
Normal Percent	46	8	13	1	2	30

Inspection of Table 22 shows no pronounced trend for any of the synoptic frequencies to increase or decrease as drought areas change in size. However, a major trend for cold fronts to increase substantially in relative frequency during droughts is indicated. Thus, the average drought frequency is 61% compared with an average of 46% in Illinois. A major decrease in relative frequency of air mass storms from 30% under average conditions to 11% in droughts is indicated in Table 22. Other percentage changes between average and drought conditions are not as outstanding. Thus, Table 22 provides further evidence that cold fronts offer the greatest opportunity for rainfall enhancement in moderate to severe drought conditions.

Table 23 provides a convenient summary of the frequency distributions of storm occurrences and total rainfall in the 35 July-August droughts. The number of storms in each synoptic class, total rainfall contributed by each storm type, percent of all storm occurrences, and percent of total rainfall are shown. This table further emphasizes the dominant role of cold fronts in producing drought precipitation, especially when compared with the average distributions of synoptic types presented in Table 20.

Table 23. General Relationships between Storm Rainfall and Synoptic Weather Conditions in 35 July-August Droughts

Synoptic Type	Number of Storms	Percent of all Storms	Total Rainfall (cm)	Total Rainfall (in.)	Percent of Total Rainfall
Cold Front	304	61	147.0	57.88	65
Warm Front	14	3	5.2	2.04	2
Static Front	80	16	37.9	14.91	17
Occluded Front	3	1	1.5	0.61	1
Lows	38	8	20.6	8.12	9
Air Mass	53	11	13.5	5.30	6

Table 24 provides a more detail description of the rainfall distribution with the various synoptic storm types during drought conditions. The table was developed from frequency distribution curves for each synoptic storm type and shows areal mean rainfall equalled or exceeded in various percentages of the storm occurrences. Cold fronts have been divided into three groups in this table to examine their drought characteristics in more detail. Also, warm and occluded fronts have been combined because of their small frequency and similar rainfall distributions. All storms in the 35 droughts were used in deriving the mean rainfall frequency relations.

Reference to the median values in Table 24 shows that the heaviest rainfalls tend to occur with waves on cold fronts and with prefrontal squall lines. Rainfall associated with cold front passages was not particularly heavy in the 35 droughts. Lightest rainfalls tend to occur in the nonfrontal air mass storms. Rainfall amounts at the upper end of the distribution also indicates that the extreme values at the 5 and 10% levels tend to be largest with cold frontal squall lines. This table is still another indication of the extreme importance of cold frontal precipitation in establishing the rainfall distribution in midsummer droughts. Approximately 15% of the squall lines had relatively heavy mean rainfalls of 12.5 (0.50 in.) or more, and over 40% of the squall lines and cold front waves had moderate rainfalls of 6 mm (0.25 in.) or more.

Table 24. Frequency Distribution of Areal Mean Rainfall Associated with Various Synoptic Storm Types in July-August Droughts

	Areal Mean Rainfall (mm) Equalled or Exceeded for Given Percent of Storms										
Storm Type	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**N**
Cold Fronts	13.2	9.9	7.4	5.6	3.8	2.8	2.0	1.3	0.8	0.3	201
Cold Front Waves	16.8	11.7	8.9	7.9	6.4	4.8	3.6	2.3	1.3	0.8	42
Cold Front Squall Lines	19.3	16.3	10.2	7.6	6.6	4.6	3.6	2.5	1.3	0.8	61
Static Fronts	16.3	11.2	7.6	5.8	4.1	3.0	1.8	1.3	0.8	0.5	80
Warm + Occluded Fronts	15.2	12.2	7.4	5.1	3.0	2.3	1.8	1.5	1.0	0.3	17
Lows	18.1	14.5	11.7	6.4	4.6	2.0	1.8	1.3	1.0	0.8	38
Air Mass Storms	11.4	7.4	4.3	2.8	1.8	1.3	1.0	0.8	0.5	0.2	53
All Cold Fronts	15.2	11.7	7.9	6.1	4.6	3.3	2.5	1.5	0.8	0.5	304

DISTRIBUTION OF STORM RAINFALL IN MAY-SEPTEMBER DROUGHTS

The same analyses described in the last section for the July-August droughts were repeated for the May-September dry periods. There were 14 droughts subjected to analyses, and 462 rain days were associated with these droughts, or an average of 33 storms per drought.

Frequency and Intensity of Storms Grouped by Areal Extent

The 14 droughts were divided into three groups, based upon their areal extent. Frequency distributions of areal mean rainfalls was then determined for each group. Results summarized in Table 25 were extracted from frequency curves for each group. None of the 14 droughts encompassed areas of 20,000 to 50,000 km^2, hence, the gap in areas in Table 25.

A trend for storm mean rainfall to increase with decreasing size of drought is indicated. That is, heavier storms tend to occur in the smaller area droughts. Comparison with the equivalent table for July-August droughts (Table 16) shows considerably heavier rainfalls in the May-September droughts, although on the average their areal extent is greater. For example, the median of the mean rainfalls for July-August droughts was 2.5 to 3.0 mm compared with 5.3 to 6.6 mm in the growing season droughts.

Water yields from enhancement of storm rainfall by cloud treatment, on the average, would tend to be larger in the May-September droughts. Thus, assuming an average increase of 20% from cloud seeding in all storms, the median storm in May-September would yield an additional 1.1 mm of rain on the drought area compared with 0.6 mm in the July-August droughts. Table 25 provides the user with quantitative estimates of the frequency distribution of storm mean rainfalls in the May-September droughts. These estimates are pertinent to evaluating weather modification potential under typical growing season drought conditions in the Midwest.

Table 25. Distribution of Storm Mean Rainfall in May-September Droughts of Various Sizes

Drought Area (km²)	Storm Mean Rainfall (mm) Equalled or Exceeded for Given Percent of Storms										
	5	10	20	30	40	50	60	70	80	90	95
>80,000	20.1	16.8	10.9	7.6	6.1	5.3	3.8	2.5	1.5	0.8	0.3
50,000-80,000	21.8	17.3	12.2	8.9	7.1	5.3	4.1	2.5	1.5	0.8	0.3
≤20,000	23.6	19.3	15.0	11.4	8.9	6.6	4.8	3.8	2.3	1.0	0.3

Area-Depth Relations for Storm Rainfall in May-September Droughts

Figure 14 shows area-depth envelope curves for the three drought groups of Table 25. As discussed in the previous section, these provide a measure of the spatial distribution of rainfall in drought conditions, and when used in conjunction with the frequency distributions of storm mean rainfall provide very useful background information for evaluating weather modification potential and for planning modification activities.

Figure 15 is analogous to Fig. 12 for July-August droughts, but could not be defined in as much detail because of the smaller sample size. This non-dimensional nomogram can be used in conjunction with Table 25 to provide spatial distribution curves for various storm mean rainfalls and different drought areas. Its use was illustrated in the previous section dealing with the July-August analyses.

Table 26 provides median area-depth envelope relations for each of the 14 separate droughts. These provide a measure of the variability in spatial distributions between droughts, and illustrate further the trend for storm

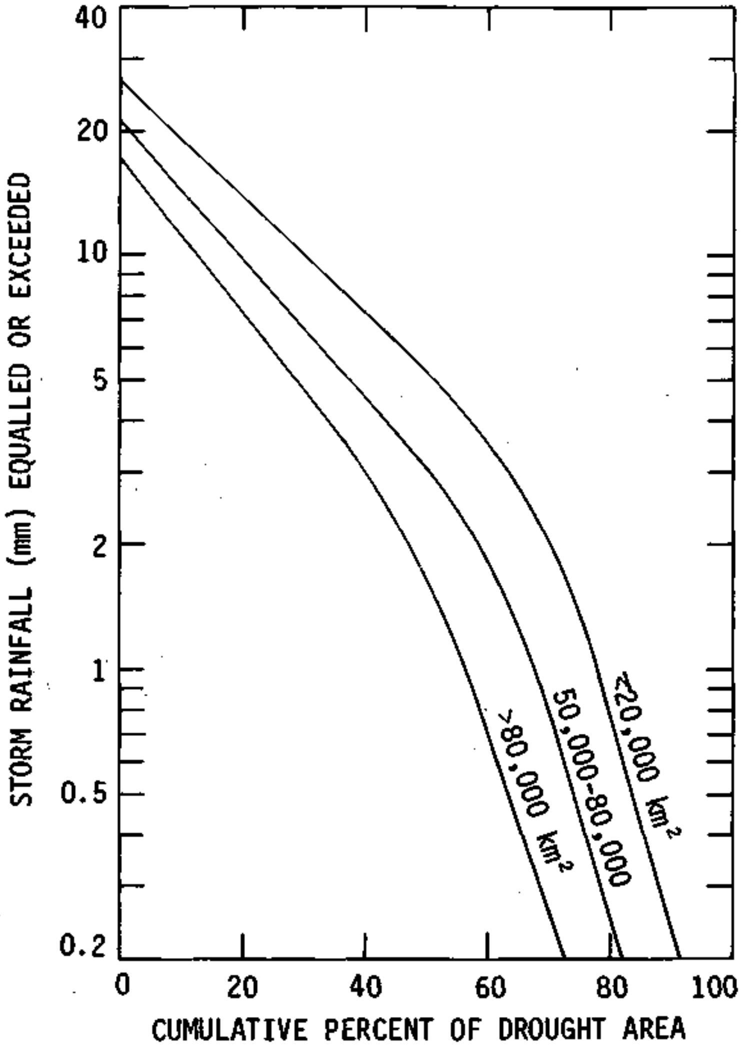


Figure 14. Median Area-Depth Envelope Curves of Storm Rainfall in May-September Droughts of Various Sizes.

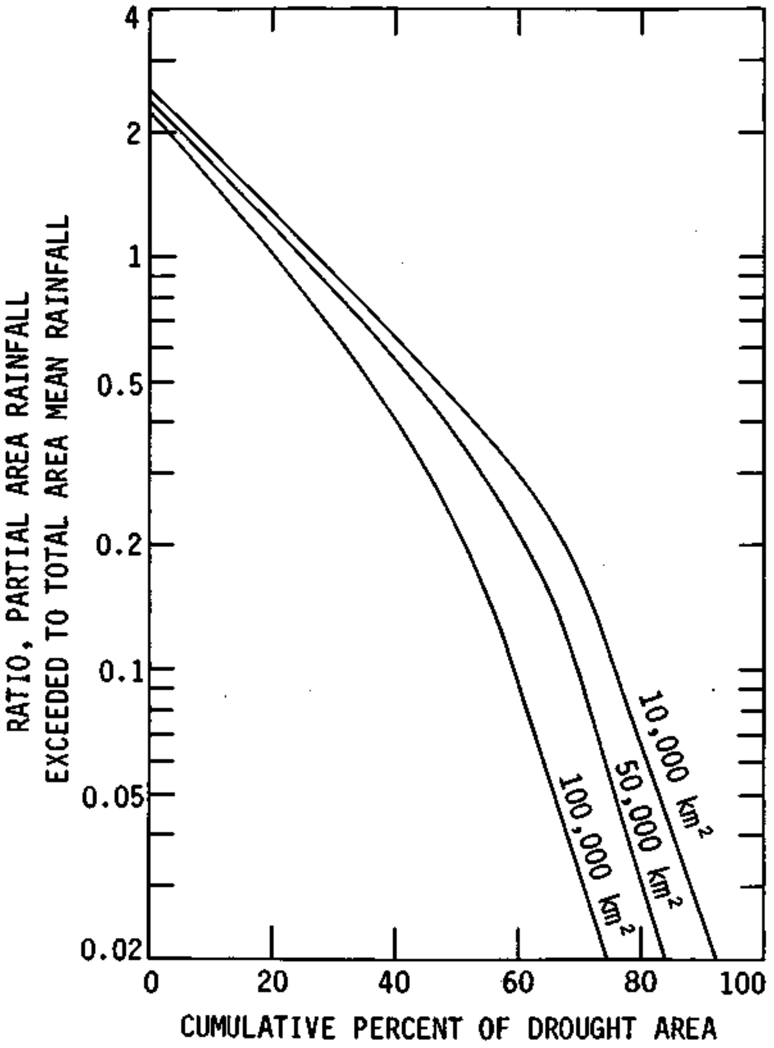


Figure 15. Nomogram for Estimating Spatial Distribution of Storm Rainfall in Mag-September Droughts of Various Areal Extent.

means to increase with decreasing extent of drought conditions. Table 27 is analogous to Table 18 for July-August droughts, and provides more detailed background information on the intensity and areal extent of storms in May-September dry periods. It provides the user with guidance in evaluating the potential benefits from weather modification in warm season droughts (see previous section for example of application). Table 28 presents the area-depth relation in the heaviest storm of each drought, and shows that relatively heavy storms do occur occasionally in droughts. Thus, all of these storms had rainfall that equalled or exceeded 19 mm (0.76 in.) over 50% of the particular drought area, and this is relatively heavy rainfall under normal weather conditions.

Table 26. Median Area-Depth Relations for Storm Rainfall in Each of 14 May-September Droughts

			Rainfall (mm) Equalled or Exceeded for Given Percent of Drought Area										
Year	N	(km^2)	5	10	20	30	40	50	60	70	80	90	100
1930	29	109,400	25.7	19.8	11.7	8.1	6.4	4.1	2.3	1.3	0.3	0	0
1922	41	83,400	18.8	12.4	8.1	5.1	3.6	2.5	0.5	0	0	0	0
1913	43	82,400	24.4	13.7	6.9	4.3	1.5	0.8	0	0	0	0	0
1953	33	77,600	21.6	15.5	10.2	7.1	4.3	2.5	2.0	0	0	0	0
1940	31	77,600	24.9	20.1	11.9	8.9	4.1	2.8	1.0	0.3	0	0	0
1914	35	69,800	25.4	16.5	11.7	6.4	3.3	1.0	0	0	0	0	0
1920	36	62,800	18.3	13.2	8.1	5.1	3.8	2.0	0.3	0	0	0	0
1936	33	58,800	26.9	19.1	8.6	5.6	2.8	1.5	1.0	0.3	0	0	0
1925	35	20,000	—	19.8	10.2	6.9	4.3	2.5	1.3	0.8	0.3	0	0
1954	30	18,200	--	23.4	15.0	9.9	5.6	3.8	3.0	2.3	1.3	0.5	0
1910	32	14,600	—	20.8	14.2	10.7	8.4	5.6	4.8	3.3	1.3	0	0
1956	26	10,600	—	20.3	15.7	9.4	7.9	5.8	3.6	1.8	1.0	0.3	0
1962	28	6,300	—	19.3	17.3	11.9	10.7	6.1	4.6	2.3	1.0	0	0
1933	30	700	—	26.0	21.9	17.7	13.2	9.7	8.0	6.4	4.8	3.3	1.5

Relation between Synoptic Weather and Drought Rainfall

The same basic synoptic types were used as in the analysis of the July-August droughts in the previous section. The normal percentage distributions of storm days and total rainfall by synoptic type during May-September are shown in Table 29. They differ only slightly from the July-August distributions.

Table 30 corresponds to Table 21 for July-August and shows the average percent of normal rainfall in May-September droughts grouped by synoptic type

Table 27. Spatial Distribution of Rainfall Intensities within Storms During May-September Droughts

% of Drought Area	Rainfall (mm) Equalled or Exceeded in Given Percent of Storms									
	10	20	30	40	50	60	70	80	90	100
Drought Areas > 80,000 km^2										
10	36.1	29.7	24.1	19.6	15.5	11.7	8.4	5.3	2.0	0.3
30	19.1	14.2	10.4	7.6	5.1	3.0	1.5	0.3	<0.3	
50	11.4	7.6	4.8	3.0	1.8	0.8	<0.3			
70	5.3	2.8	1.3	0.5	0.3	<0.3				
90	1.5	0.5	0.3	<0.3						
Drought Areas 50,000 - 80,000 km^2										
10	37.3	31.2	25.9	23.6	16.8	12.7	9.1	5.8	2.0	0.3
30	22.1	16.5	12.2	8.9	6.1	3.8	2.0	0.5	<0.3	
50	14.5	9.7	6.4	3.8	2.0	1.0	<0.3			
70	8.6	5.1	2.8	1.0	0.3	<0.3				
90	3.3	1.0	0.3	<0.3						
Drought Areas < 50,000 km^2										
10	46.2	38.9	32.3	26.7	21.6	17.5	13.7	10.4	7.4	2.5
30	27.4	21.3	16.8	13.0	9.9	7.1	5.1	3.3	1.5	0.3
50	18.5	14.0	10.4	7.6	5.3	3.6	2.0	1.0	0.3	<0.3
70	12.4	8.4	5.8	3.8	2.3	1.0	0.3	<0.3		
90	7.4	4.1	2.0	0.8	0.3	<0.3				

and section of the state. Cold fronts are even more outstanding in their drought contribution to total rainfall than in the July-August droughts. In fact, cold frontal rainfall approached normality in all sections, and averaged 90% of normal for all sections combined. Conversely, air mass storms were the most inefficient during the growing season droughts, since they averaged only 10% of their normal rainfall. Lows produced near-normal rainfall also, but their total contribution is small compared with cold fronts. The major conclusion is the same as reached in the July-August analyses; that is, successful treatment of cold frontal storms is a necessity for substantial increases in storm water yield during growing season droughts.

Table 28. Area-Depth Relations in Heaviest Storms of May-September Droughts

Year	Area (km²)	Rainfall (mm) Equalled or Exceeded for Given Percent of Drought Area 10	20	30	40	50	60	70	80	90	100
1930	109,400	38.1	31.0	26.7	23.9	20.3	14.7	11.2	8.4	5.8	1.3
1922	83,400	48.3	39.6	32.3	25.1	19.8	15.7	12.2	6.4	2.0	0
1913	82,400	38.6	27.2	23.6	21.1	16.5	9.4	6.4	2.3	0	0
1953	77,600	43.4	28.4	25.7	22.4	21.3	19.8	16.5	14.7	9.9	5.3
1940	77,600	46.7	40.6	33.5	30.5	20.8	19.1	10.7	5.6	2.3	1.5
1914	69,800	43.4	37.3	24.6	20.3	19.3	17.3	15.5	12.4	4.8	0
1920	62,800	61.5	51.8	47.8	44.7	42.2	39.4	38.4	31.0	23.9	5.8
1936	58,800	67.6	56.1	48.8	43.9	42.2	36.0	32.5	29.2	25.1	9.6
1925	20,000	47.0	36.8	36.8	36.3	35.3	20.3	9.9	8.9	8.6	1.3
1954	18,200	54.4	46.7	39.6	38.1	35.1	31.8	27.2	22.1	0.5	0
1910	14,600	40.4	35.8	30.7	27.7	25.4	22.6	19.1	16.8	15.7	8.1
1956	10,600	58.9	44.7	42.2	31.2	28.2	24.1	19.1	18.8	15.0	0
1962	6,300	43.2	40.6	33.5	29.5	24.9	20.8	12.7	4.8	0.8	0
1933	700	81.3	80.0	77.5	73.7	70.0	64.8	59.7	54.6	48.8	45.0

Table 29. Normal Percentage Distribution of May-September Rainfall in Illinois by Synoptic Type

Synoptic Type	Percent of Storm Days	Percent of Total Rainfall
Cold Front	36	39
Warm Front	11	14
Stationary Front	17	21
Occluded Front	2	2
Low Centers	8	7
Air Mass Storms (Non frontal)	26	17

Table 30. Average Percent of Normal Rainfall in May-September Droughts Grouped by Synoptic Type and Section of Illinois

	Percent of Normal for Given Storm Type				
Synoptic Type	North Section	Central Section	South Section	Multiple Section	Combined Sections
Cold Front	81	100	88	83	90
Warm Front	32	22	18	20	23
Static Front	30	33	45	42	38
Occluded Front	211	74	49	0	67
Air Mass	5	6	21	8	10
Lows	85	102	74	96	92
Number of Droughts	2	5	3	4	14
Number of Storms	68	179	101	114	462

Table 31. Percentage Distribution of Synoptic Weather Types in May-September Droughts of Various Areal Extent

	Percent of All Storms in Given Drought Areas					
Drought Area (km^2)	Cold Fronts	Warm Fronts	Stationary Fronts	Occluded Fronts	Low Centers	Air Mass Storms
>80,000	74	4	12	0	8	2
50,000-80,000	55	7	15	2	11	10
<50,000	62	5	14	2	14	3
Areas Combined	63	5	14	2	11	5
Normal Percent	36	11	17	2	8	26

Inspection of Table 31 shows no pronounced trend for any of the synoptic frequencies to increase or decrease as drought areas change in size. However, a major trend for cold fronts to increase substantially in relative frequency during droughts is indicated. The average drought frequency for cold fronts is 63% compared with a normal frequency of 36% in Illinois. A major decrease in relative frequency of air mass storms from a normal of 26% to 5% during droughts is indicated in Table 31. Other percentage changes between average and drought conditions are not as outstanding. Thus, Table 31 provides further evidence that cold fronts offer the greatest opportunity for rainfall enhancement in moderate to severe droughts.

Table 32 illustrates the general relationships between storm rainfall and synoptic weather conditions in the May-September droughts. It provides a convenient summary. The relationships are very close to those for July-August droughts in Table 23.

Table 32. General Relationships between Storm Rainfall and Synoptic Weather Types in 14 May-September Droughts

Synoptic Type	Number of Storms	Percent of all Storms	Total (cm)	Rainfall (in.)	Percent of Total Rainfall
Cold Front	290	63	227.4	89.52	63
Warm Front	24	5	20.4	8.02	6
Static Front	64	14	52.9	20.82	15
Occluded Front	8	2	8.6	3.46	2
Lows	53	11	41.9	16.49	11
Air Mass	23	5	11.1	4.34	3

Table 33 provides a more detailed description of the rainfall distribution associated with various types of synoptic weather conditions during the May-September droughts. This table indicates that the reason for the large percentage contribution of total drought rainfall from cold frontal storms is largely their greater frequency rather than greater intensity. Except for air mass storms, there is only small differences among the mean rainfall values for given percentages of all storms in each synoptic group. However, there are many more rain producers among the cold frontal storms.

Table 33. Frequency Distribution of Areal Mean Rainfall Associated with Various Synoptic Storm Types in May-September Droughts

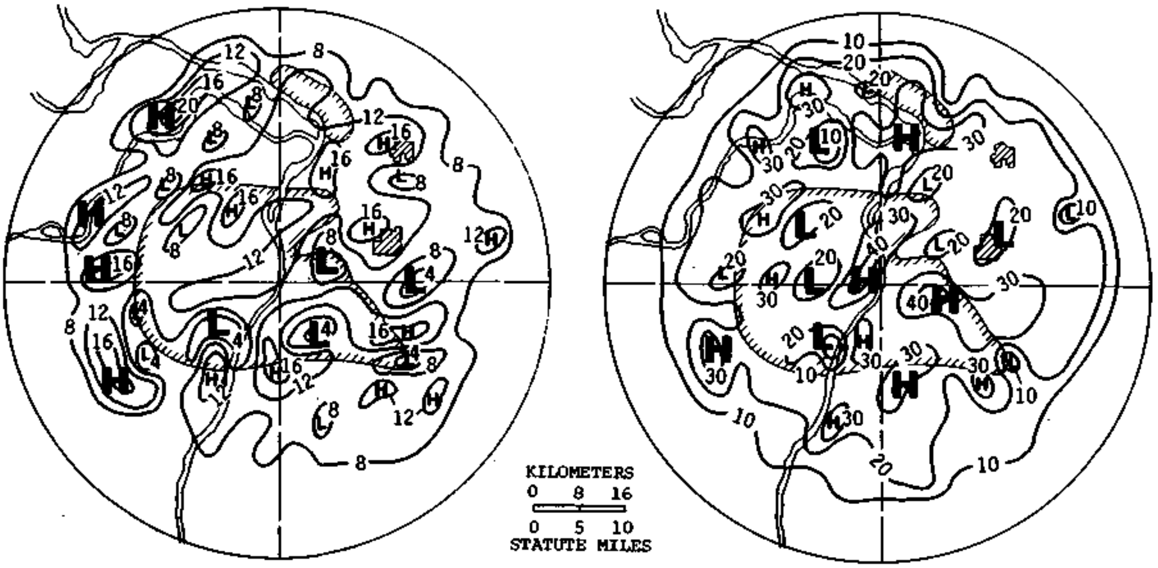
Storm Type	Areal Mean Rainfall (mm) Equalled or Exceeded for Given Percent of Storms										
	5	10	20	30	40	50	60	70	80	90	N
Cold Fronts	19.6	17.3	11.4	8.6	6.6	5.3	3.8	2.5	1.8	0.8	176
Cold Front Waves	24.1	22.6	17.5	11.7	8.1	6.6	5.3	3.8	1.8	0.8	82
Cold Front Squall Lines	23.9	19.3	14.2	11.4	9.1	8.4	6.1	4.3	3.6	2.3	32
Static Fronts	25.7	20.1	13.0	9.4	7.1	4.8	4.3	3.8	2.5	0.8	64
Warm + Occluded Fronts	27.7	18.0	16.3	11.9	8.9	7.9	5.6	4.8	3.3	1.0	32
Lows	22.0	16.3	11.9	10.2	8.1	6.6	5.6	4.1	3.3	1.3	53
Air Mass Storms	21.1	13.7	8.6	6.9	4.3	3.0	1.5	1.0	0.8	0.5	23
All Cold Fronts	22.4	18.5	13.0	9.6	7.4	5.8	4.3	2.8	1.8	1.0	290

RAINFALL INITIATIONS IN WET AND DRY PERIODS

Valuable information pertaining to rainfall characteristics during warm season droughts was obtained from analyses of raincell data obtained from the METROMEX Network of 225 recording raingages for the summers of 1971-1975. These data were analyzed to determine the characteristics of raincell initiations and mergers in wet, dry, and moderate precipitation conditions. Major emphasis was placed upon dry period conditions and observed differences in the distribution characteristics between wet and dry months. Of particular interest was whether inadvertent weather modification occurred during below normal rainfall periods and, if so, how the magnitude of this effect compared with similar effects in normal to above normal rainfall periods. Findings relative to raincell initiations are summarized in the following paragraphs. Raincell mergers are discussed in the next section of this report.

Spatial Patterns of Initiations

The 15 months in the METROMEX sample were divided into three groups that included six months with network mean rainfall varying from 21 to 68% of normal, three near normal months (80 to 104% of normal), and six relatively wet months with network mean rainfall ranging from 105 to 155% of normal. The frequency of raincell initiations in the relatively dry and wet months is shown in Fig. 16. The outer band of raingages in the research circle was not used in the pattern analysis, since it cannot be determined whether a raincell first detected over these gages initiated there or moved



a. Dry months

b. Wet months

Figure 16. Spatial Patterns of Raincell Initiations in Relatively Dry and Wet Months during Summers of 1971-1975.

on to the network. This is especially a problem in the W, SW, and NW parts of the network, since most convective entities move from these directions.

The dry period pattern in Fig. 16a shows indications of both topographic and urban-induced increases in the frequency of raincell initiations. Thus, relatively high frequencies are indicated along the Missouri River in the western part of the network, in the Ozark foothills in the southwestern part of the network, and to some extent along the Mississippi River. The relatively hot and sometimes swampy lowlands of the river valleys are a potential heat and moisture source that would be conducive to convective development. Similarly, the hills are also likely regions of convective development.

Figure 16a also shows relatively high frequencies E and NE of the St. Louis urban-industrial region which could be related to urban-related mechanisms that stimulate convective developments (Changnon et al., 1976). Thus, Fig. 16a indicates that external forces, such as topographic barriers and urban areas, are operating in relatively dry periods during the summer and are stimulating convective developments. If so, this is indirect evidence that similar (if not more pronounced) effects could be induced from planned weather modification operations, whenever natural conditions are capable of supporting convective activity.

Figure 16b shows the raincell initiation pattern in the six relatively wet months. Naturally, the frequency of initiations is much greater than in the dry months, but the spatial distribution is quite similar. The wet month pattern also shows relatively high frequencies in some areas along the river valleys and in the Ozark foothills. High frequencies also occurred over and E of St. Louis, and to a lesser extent SE of the city and in the Wood River industrial area in the northern part of the network. The raincell initiation pattern in the three near normal months (not shown) also indicated relatively high frequencies in the region from St. Louis to Wood River and SE of the city.

The three driest months of the five summers had network mean rainfall ranging from 21 to 32% of normal. When these were separated from the dry sample of Fig. 16a, relatively high frequencies were still found in the vicinity of the Missouri River, in St. Louis, Wood River, and downwind (E-SE) of St. Louis. The three wettest months with rainfall varying from 125 to 155% of normal also showed high frequencies in the region from St. Louis to Wood River and SE of St. Louis. Thus, the inadvertent weather processes generated by the urban area appear to be active in a wide range of precipitation conditions, which is the conclusion reached in various rainfall analyses performed on the METROMEX project (Changnon et al., 1977).

Comparison of Initiations by Network Quadrant

The NE quadrant of the METROMEX Network is the region of maximum urban-induced enhancement of summer rainfall (Changnon et al., 1977). The SE quadrant is exposed to both urban and topographic influences. The only major external force in the SW quadrant is the Ozark foothills, since this region is rarely downwind of the urban area immediately prior to or during precipitation. The NW quadrant may be subjected to topographic effects (river bottomlands) and urban effects, if low-level flow is from the SE quadrant.

The frequency of raincell initiations was determined for each quadrant in the dry, wet, and near normal months. Results have been summarized in Table 34, where the percent of total network occurrences has been shown for each quadrant after normalizing for differences in gage density among the quadrants. A total of 1819 initiations were identified in the six dry months, compared with 4044 in the six wet months and 1108 in the three near normal months. Table 34 shows the greatest percentages in the NE and NW quadrants during dry periods, and the smallest percentage in the SW quadrant that is rarely subjected to urban effects. Except for the SW quadrant, there is little difference among the quadrants in the wet months, and practically no variation among the four areas in the near normal months.

Table 34. Percentage Distribution of Raincell Initiations during Months of Below Normal, Near Normal, and Above Normal Rainfall in Summers of 1971-1975 on METROMEX Network

Network Quadrant	Below Normal	Near Normal	Above Normal
	Percent of Total Initiations		
Northeast	28	25	27
Northwest	28	25	26
Southeast	23	24	25
Southwest	21	26	22
Total number of initiations	1819	1108	4044

Comparing the NE quadrant which is subjected only to urban influences and the SW quadrant which is usually exposed only to topographic effects, there is evidence that the urban effect on raincell initiations is considerably greater than the hill effect in relatively dry periods. This provides additional evidence that weather modification (inadvertent in this case) may be feasible in relatively dry periods when conditions are occasionally favorable for convective developments.

General Conclusions

Results of the analysis of raincell initiations during the summers of 1971-1975 on the METROMEX Network indicate that raincell initiations are most concentrated in and downwind of the source of inadvertent weather modification, that is, the urban-industrial areas of St. Louis and Wood River in both relatively wet and dry months. Topographic influences were also indicated with an above normal frequency of initiations along the river valleys, especially the Missouri River, and in the Ozark foothills in the southwestern part of the network. Although urban and topographic effects are present in months of below normal, near normal, and above normal rainfall, the effect relative to the rest of the network appears to be slightly greater in relatively dry months. Thus, the inadvertent modification by the city and topographic factors is apparently present in relatively dry months. This is evidence that weather modification potential is present in relatively dry periods, and that some success in alleviating agricultural water shortages might be achieved during drought conditions.

SURFACE RAINCELL MERGERS

Analyses were made of the characteristics of raincell mergers in the METROMEX Network during 1971-1975. A limited sample of radar data had indicated that radar echo mergers tend to occur more frequently in and immediately east of St. Louis. Mergers of convective clouds and rain systems have been shown to be associated with rain intensification (Huff, 1967; Simpson *et al.*, 1972). Mergers would likely be favored in a region of urban rainfall enhancement, since the major cause of enhancement appears to be growth in raincell sizes in the St. Louis area (Changnon *et al.*, 1977).

Therefore, it was considered pertinent to pursue evaluation of the merger phenomena further through use of the larger sample of surface raincell data. Particular attention has been given to the comparative frequency of mergers and the enhancement of rainfall following mergers during relatively dry, wet, and near normal periods. This was done to determine whether mergers and, consequently, rainfall enhancement are more frequent in regions of topographic and urban effects during dry periods. If so, this would provide useful background information both for evaluating the potential of weather modification to alleviate droughts, and for planning modification operations, if deemed desirable.

Method of Analysis

A merger was defined as the joining of two surface raincells which had been at least 8 km (5 mi) apart initially, and these cells must have existed for at least 10 minutes prior to merger. Qualification also dictated that the merged entity exist for at least 10 minutes following merger. In order to eliminate numerous mergers of very light raincells which contribute insignificantly to storm totals, it was required that the maximum intensity in one of the two merging cells (or both) must be 6 mm/hr (0.25 in./hr) or more prior to merger. This limited the sample to those convective entities which could contribute significantly to urban and topographic anomalies and, also, to rain entities of significance from the standpoint of planned weather modification. The above definitive criteria yielded a sample of 325 mergers during the five summers.

Initially, a problem arose in assignment of cell area within a complex storm system where the individual cells were not isolated from surrounding precipitation. It was decided to define cell area as the area included in closed isohyets directly associated with a particular cell. This procedure separated the cell rainfall (rain intensity center) from the lighter background rainfall of the parent storm system.

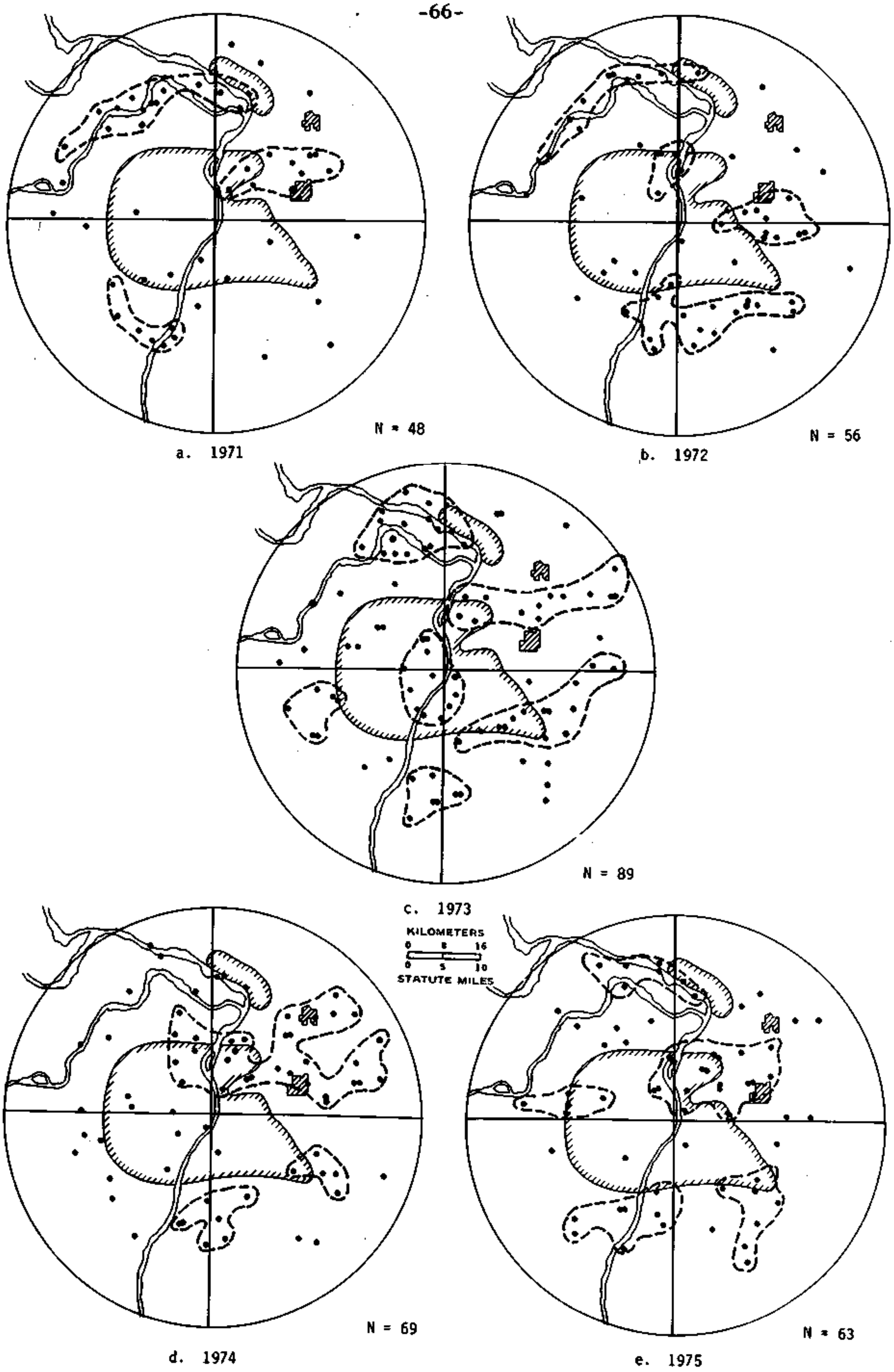
Analyses were performed for each storm day to determine the number of mergers meeting the definitive criteria, their location in the network, changes in cell intensity and area following merger, and duration of cells prior to and following merger. The merger was assigned to the raingage nearest to which it occurred. This provided a convenient means for comparison of frequency of mergers in different parts of the network. The merger data were then summed over monthly and seasonal periods, and were stratified also into three monthly groups classified below normal, near normal, and above normal. The separation by normality of rainfall was made to investigate differential effects and, thus, to help evaluate the urban and topographic effects and the potential for planned weather modification. Mergers were also stratified according to synoptic type, storm mean rainfall, and diurnal occurrence.

Seasonal Spatial Distributions

1971. Summer 1971 was the driest in the 1971-1975 period. The network averaged 54% of normal in June. This increased to 115% in July and dropped to only 21% of normal in August. The 3-month period was 63% of normal. Mergers were concentrated downwind of St. Louis (STL) in the Granite City-Collinsville (GRC-CLV) area (Fig. 17a) and along the Missouri River and the Meramec River which is downwind of the Ozark foothills. This pattern suggests that the mergers were stimulated by environmental influences, including river bottomlands (heat-moisture source), the STL urban area, and possibly the Ozark hills. The greatest number of mergers was in the NE quadrant of the network, and all were in the vicinity or downwind of urban-industrial areas at STL and Alton-Wood River (ALN-WDR).

1972. Summer rainfall averaged 69% of normal with a range from 32% of normal in June to 80% in July and 104% in August. The most mergers occurred in the SE quadrant (Fig. 17b) where 36% of the total occurred. This quadrant is subject to both urban and hill effects, depending upon storm movement and low-level winds. Figure 17b shows a concentration E of STL which was likely urban-related, and others S to SE of the city where both topographic and urban effects could have been involved.

1973. Average rainfall was slightly above normal (103%) for the summer with a large positive departure of 125% of normal in June followed by 101%



a. 1971

b. 1972

c. 1973

d. 1974

e. 1975

Figure 17. Distribution of Raincell Mergers in Each of 5 Summers.

in July and 78% in August. Approximately 50% of the mergers (Fig. 17c) occurred within or a few miles downwind of the urban-industrial areas in this nearly normal summer. A preferential area was indicated also in the bottomlands in the NW quadrant. In all, 89 mergers were identified compared with 48 and 56 in the dry summers of 1971 and 1972.

1974. This was a moderately below normal summer (81%) with 61% of normal in June, 31% in July, but a heavy 156% in August. The greatest concentration of mergers was in the NE quadrant with 41% of the network total (Fig. 17d). These were all in locations where they could have been urban-related. There was no particular concentration along the river valleys, NW bottomlands, or hills. Of the 69 mergers, 22% were in the immediate urban areas of STL and ALN-WDR, and 19% were downwind (E or NE) of the urban-industrial areas.

1975. Summer rainfall was near normal (101%), and ranged from 68% of normal in June to 109% in July, and a heavy 139% in August. Again, the most obvious concentration of mergers was in the urban-industrial areas or within a few miles downwind of them (Fig. 17e). Of 63 mergers, 48% were within or downwind of the urban-industrial areas, particularly in the STL-CLV-EDW area. There were slight indications of preferential regions associated with bottomlands and hills.

Summer 1971-1975. Figure 18 shows the spatial distribution of all 325 mergers during the 5-summer period. For easier interpretation, totals are shown for grid squares of 93 km^2 (36 mi^2).

The average frequency was 6 with a standard deviation of 4. Mergers occurred most frequently in the GRC-CLV region and in the bottomlands of the NW quadrant of the network. Frequencies in these areas were two to three times the network mean and over two standard deviations above the mean. Thus, the greatest frequencies were in areas subject to urban and topographic effects. Above-average frequencies also occurred in the southern part of the network where storms may be affected by movement across the Ozark foothills and the river bluffs. Frequencies over the western suburbs was below average, and this is a region of minimum urban effect.

In general, there appears to have been a tendency for mergers to occur most frequently in a major urban-effect area E and NE of STL and in regions under topographic influences. Thus, Fig. 18 provides support for other analyses which indicate that convective entities tend to develop more frequently or become enhanced over the urban-industrial region, which then leads to mergers and rain intensification downwind of the city (usually NE, E, or SE of urban area). The bottomlands are believed to be a favored region of convective development in which both topographic and urban factors are involved, and this too should favor merger or consolidation of clouds.

Spatial Patterns in Wet and Dry Periods

The spatial pattern of mergers was investigated for differences in relatively wet and dry periods. For this purpose, the 15-month sample was

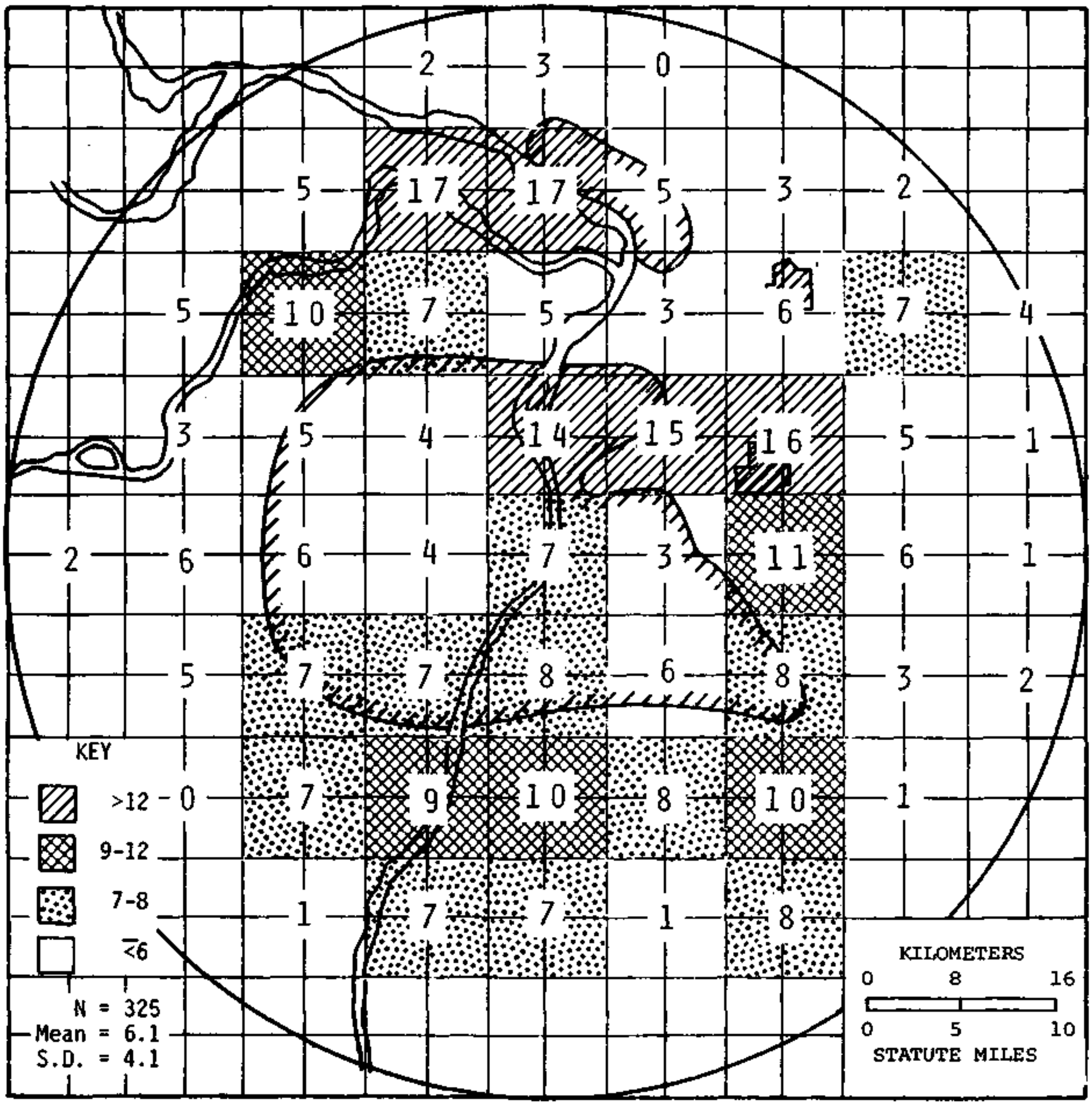


Figure 18. 5-Summer Pattern of All Raincell Mergers.

divided into six relatively dry, three near normal, and six relatively wet months. The dry months had rainfalls ranging from 21 to 68% of normal. The near normal months varied from 80 to 104% of normal, and the wet months from 105 to 155% of normal.

Spatial patterns for the three groups are shown in Fig. 19. The dry pattern of Fig. 19a shows the greatest frequency of mergers just east of STL in the GRC-CLV area. Other areas with above average frequency lie along the Mississippi and Missouri River valleys, including the NW bottomlands, and in the Ozark foothills. Only 26% of the total mergers occurred in the six relatively dry months compared with 48% in the six wet months.

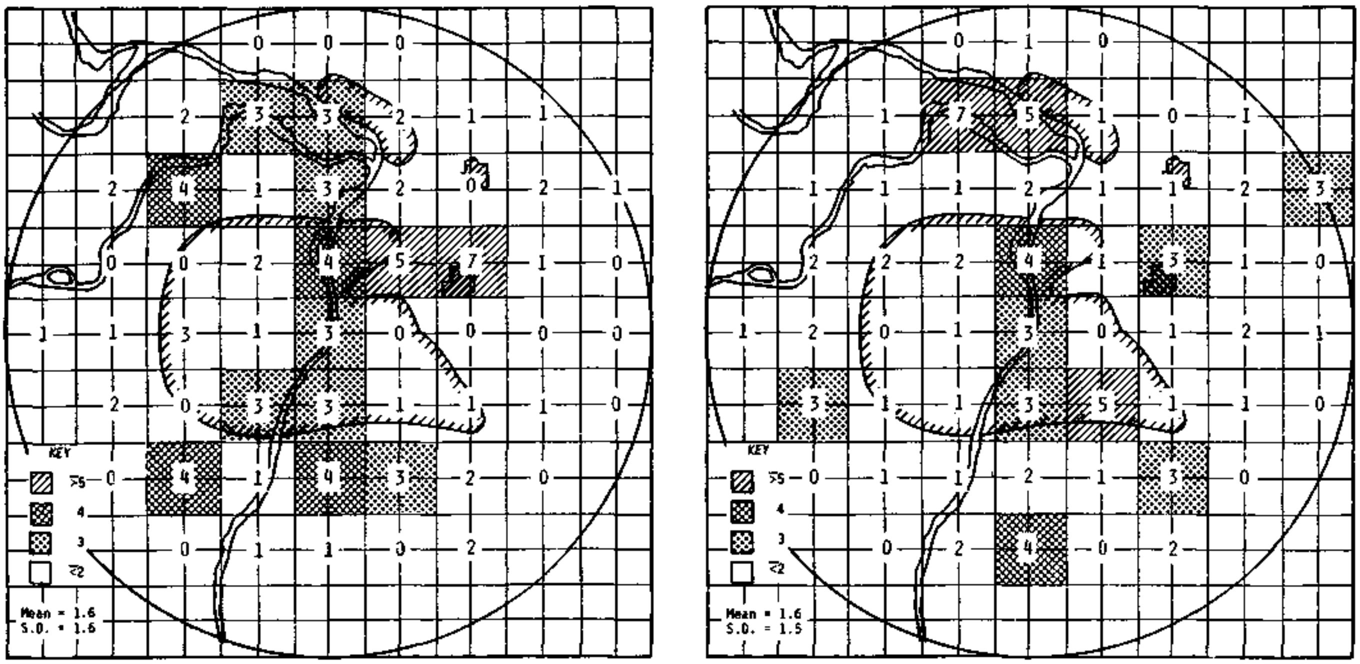
The wet month pattern of Fig. 19c shows relatively high areas east of STL in the regions of GRC-CLV and EDW-CLV-BLV, and in the confluence of the Missouri and Mississippi Rivers in the NW bottomlands. Relative high frequencies are also indicated again along the Missouri River, portions of the Mississippi, and the Ozark foothills. In general, the near normal pattern of Fig. 19b has relatively high areas in the same regions as the wet and dry months. Overall, there is a definite indication that mergers are favored downwind of urban-industrial areas, in river valleys, and hill regions, similar to findings for raincell initiations discussed in the previous section of this report. This is a factor that should be taken into consideration in the planning and operation of planned weather modification experiments, particularly in dry periods when the convective cloud population is relatively small.

Diurnal Distribution

The frequency of raincell mergers at 3-hour intervals was calculated for summers 1971-1975 to determine whether mergers occurred more often during the daytime. Since other analyses had shown that total rainfall maximized in the period from 1500 to 1800 CDT, it seems reasonable to expect mergers to maximize at approximately the same time. Sample size was not adequate to group diurnal mergers, further by individual month and year.

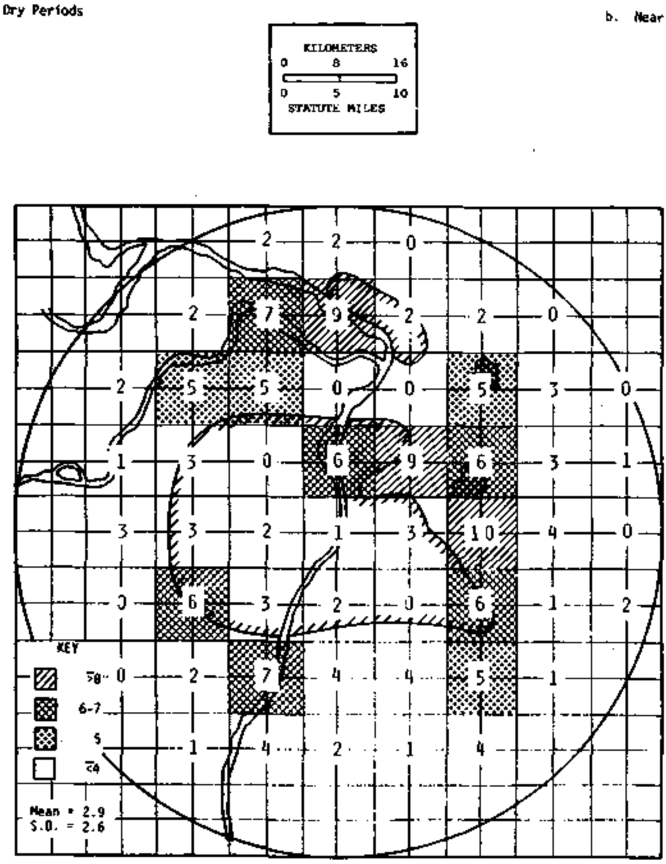
As expected, analyses indicated that 77 (24%) of the mergers occurred from 1500 to 1800, when approximately 20% of the network summer rainfall occurred. As shown in Fig. 20b, the mergers tended to cluster in the late afternoon over and east of STL. This is a logical sequence of urban initiation and enhancement of convective entities over the urban-industrial areas which would promote mergers (more and larger raincells) over and downwind of the city. That is, the mergers are clustering where expected in consideration of urban enhancement processes, storm motions, and maximizing of rainfall in late afternoon.

Figures 20a and 20c show the distribution of mergers at 1200-1500 and 1800-2100 which ranked next to 1500-1800 in merger occurrences. During 1200-1500, nearly 20% of all mergers occurred, and 58 (18%) were recorded at 1800-2100. The earlier pattern at 1200-1500 (Fig. 20a), preceding the



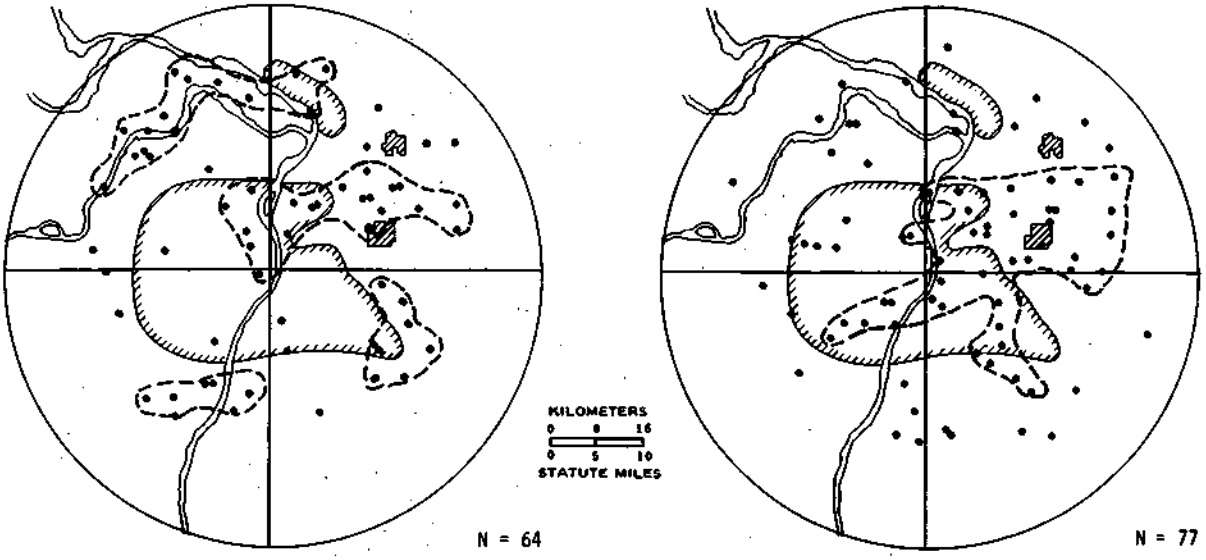
a. Relatively Dry Periods

b. Near-Normal Periods



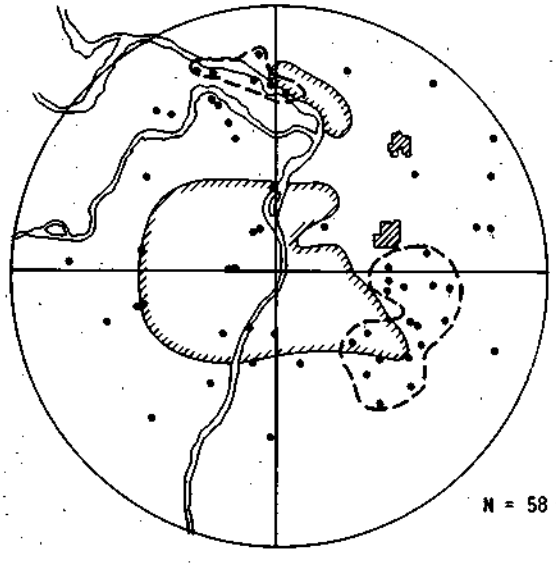
c. Relatively Wet Periods

Figure 19. Distribution of Raincell Mergers in Dry, Near Normal and Wet Periods, 1971-1975.



a. 1200-1500 CDT

b. 1500-1800 CDT



c. 1800-2100 CDT

Figure *20. Diurnal Distribution of Raincell Mergers.*

network maximum, shows major clusters extending eastward from STL and along the Missouri River valley into the bottomlands in the confluence of the Missouri and Mississippi Rivers. Reference to total rainfall patterns during this period does not show the strong correlation between mergers and rainfall that is apparent in the late afternoon patterns. These topographic-related convective entities apparently do not become as intense, on the average, as the urban-related entities.

The early evening pattern (1800-2100) in Fig. 20c, shows a major merger cluster E-SE of the city in the Belleville (BLV) area. The total rainfall pattern at that time also indicated a high in the BLV region. The maximizing of rainfall and mergers farther downwind of the city is reasonable considering most frequent storm movements (W-E). Storms forming in the peak rain period of 1500-1800 would often be centered farther eastward, but still in the network in the early part of the 1800-2100 period.

Mergers were least frequent from 0000 to 0600 when only 39 (12%) of the total were recorded. Approximately 16% occurred in the 0600-1200 period, 43% from 1200 to 1800, and 29% from 1800 to 2400. Thus, if a major goal of cloud seeding is to promote merger of convective entities, opportunities are greatest, on the average, in middle to late afternoon.

Distribution Grouped by Storm Mean Rainfall

The sample of 325 mergers was grouped according to storm mean rainfall to determine how the frequency of mergers was related to storm magnitude (intensity) and whether there were differences in the mean rainfall relation within the network. Storms were divided into four classes in which network mean rainfall was a trace, 0.25 to 2.30 mm (0.01-0.09 in.), 2.31-12.45 mm (>0.09 to 0.49 in.), and ≥12.45 mm (≥0.50 in.). Approximately 4, 20, 52, and 24%, respectively, fell into the above groups. Nothing of significance was discerned in this analysis. For example, the area E of STL and the NW bottomlands had the greatest frequencies in all of the three classes having significant rainfall amounts.

Distribution Grouped by Synoptic Storm Type

The 325 mergers identified in the summers of 1971-1975 were classified by the synoptic storm types used in the METROMEX studies (Changnon et al., 1977). Analyses showed that approximately 72% of the mergers occurred in squall systems Iquall lines and squall areas). Only 3% of the total occurred in non-frontal, air mass storms. These frequencies agree well with the total rainfall distribution, in that a majority of the summer rainfall occurred with squall activity and very little with air mass situations. Since so many mergers were associated with squall systems, the spatial distribution of their occurrences was similar to the total distribution pattern of Fig. 18. Thus, not unexpectedly, mergers are most likely to occur with organized, relatively large convective storm systems. This is another factor, therefore, that should be considered in the planning of cloud seeding operations to alleviate water shortages.

Effects of Mergers on Raincell Characteristics

If mergers of convective entities tend to intensify the rain production processes as indicated by several investigators (Huff, 1967; Simpson et al., 1972), then the rain intensity and/or areal extent of the rain-producing entities should tend to increase following mergers. Therefore, analyses were made to determine the characteristics of raincells prior to and following mergers, since merger effects are of concern in both planned and inadvertent weather modification. A general summary of the changes observed with mergers in the METROMEX sample of 325 mergers during 110 storm days is presented in Table 35.

Table 35 shows that most mergers were followed by an increase in both area and rain intensity. Thus, 78% of the mergers were followed by an intensity increase and 82% by an area increase. Conversely, only 14 and 10%, respectively, were followed by a decrease in intensity and area. This helps verify previous observations that the merger of convective entities tends to increase the total rain production from the raincells involved.

The duration statistics in Table 35 show that the merged cells had a median duration of 33 minutes following merger, and this exceeds the duration of either cell prior to the merger. Among the 325 mergers, the median of the maximum intensity change after merger was an increase of 27 mm/hr (1.08 in./hr) which is a relatively intense rate in itself. Similarly, the median of the maximum area change following merger was an increase of 90 km^2 (35 mi^2), and this also is a substantial change.

Table 35. Statistics of Raincell Mergers for Summers of 1971-1975.

Number and percent of mergers with intensity increase	254	(78)
Number and percent of mergers with no change in intensity	25	(8.)
Number and percent of mergers followed by intensity decrease	46	(14)
Number and percent of mergers followed by area increase	266	(82)
Number and percent of mergers followed by no area change	25	(8)
Number and percent of mergers followed by area decrease	34	(10)
Median duration of merger-involved cells		
Oldest cell prior to merger (min)	26	
Newest cell prior to merger (min)	13	
Merged cell (min)	33	
Median of maximum intensity change (mm/hr and %) after merger	27	(57)
Median of maximum area change (km^2 and %) after merger	90	(37)
Maximum intensity change (mm/hr) among all cases	190	
Maximum area change (km^2) among all cases	1119	

Summary and Conclusions

Analyses were made of the characteristics of raincell mergers with particular emphasis on wet and dry periods. Mergers of convective clouds and rain systems have been shown to be associated with rain intensification by previous investigators. It was hypothesized that mergers would be favored in a region of urban rainfall enhancement. Other METROMEX analyses have indicated the major cause of raincell enhancement in the STL area is growth in areal sizes plus development of new cells, both of which favor cell mergers. A merger was defined as the joining of two surface raincells which had been at least 8 km apart initially, were in existence for at least 10 minutes prior to merger, lasted for at least 10 minutes after merger, and one or both must have had a maximum intensity of 6 mm/hr or more prior to merger. This limited the analyses to those convective entities which could contribute significantly to urban or topographic anomalies and of significance from the standpoint of rain augmentation from weather modification operations.

Results indicated a relatively strong tendency for mergers to occur most frequently in a major urban-effect area E and NE of St. Louis, along river valleys, and, to a lesser extent, in the more hilly regions of the METROMEX experimental area. In general, there was strong association between the spatial distribution of mergers and total monthly and seasonal rainfall. Diurnally, the greatest frequency of mergers occurred in mid to late afternoon (1500-1800), and the greatest concentration of mergers at that time was over and E of St. Louis where mergers are favored by the urban enhancement of convective activity. The pattern of total rainfall for 1500-1800 closely resembled the merger pattern, and 25 to 35% of the total summer rainfall occurred in this 3-hour period in the region where the concentration of mergers was greatest (Changnon et al., 1977).

Synoptically, it was found that 72% of the surface raincell mergers were associated with squall systems (lines and areas), and only 3% with air mass storms. Thus, it is apparent that the merger process is much more likely to occur with organized storm systems. Changnon et al. (1977) has shown that approximately 75% of the total summer rainfall in 1971-1975 was associated with squall systems and only 2% with air mass storms. This is another indication of the strong relationship between mergers and rain production at the surface.

Analyses indicated that 78% of the mergers were followed by an increase in intensity and 82% by an area increase, whereas only 14 and 10%, respectively, were followed by decreases in intensity and area. This further verifies the important role of mergers in stimulation of the total rain production from convective cells.

Analyses of mergers in relatively dry, near normal, and wet periods indicated similar merger trends in the three groups. That is, mergers tended to be concentrated over and downwind of STL, along river valleys, and in the more hilly regions of the network.

Comparison of rainfall in regions of greatest merger concentrations indicated that the urban-related mergers tend to intensify the ongoing rainfall processes more than topographic-related mergers.

In the dry months, 32% of the total number of mergers occurred over and E of STL in the region from GRC-CVL-BLV-STL (Fig. 19), whereas 25% occurred in this region in the near normal months and 28% in the wet months. This indicates that the merger processes, which are closely related to the rain enhancement processes, are as active in dry as during wet months and are apparently stimulated by inadvertent weather mechanisms. This is a favorable finding from the standpoint of planned weather modification; that is, there is an indication that weather modification has potential to stimulate rain production under some conditions during dry periods when water shortages exist.

MESOSCALE COMPARISONS OF RAINFALL PATTERNS IN WET AND DRY PERIODS ON METROMEX NETWORK

Data for the summers of 1971-1975 from the METROMEX Network of 225 recording raingages in 5200 km^2 (Fig. 21) were analyzed to determine whether the spatial rainfall distribution varied significantly between wet, dry, and moderate rainfall periods. Analyses of raincell initiations and mergers on this densely gaged mesoscale network, discussed in the two previous sections of this report, indicated a preference for rain-producing convective clouds to develop and merge into larger and more intense convective entities under the influence of inadvertent weather mechanisms (urban areas and small-scale topographic features). The purpose of this analysis was to ascertain the extent to which the inadvertent weather influences are reflected in the end-product of most interest in this study, that is, the total rainfall at the surface.

For analysis, the 15 months in the 5-summer sample were divided into five groups of three months each. These were designated dry, moderately dry, near normal, moderately wet, and wet periods. Maps were then prepared showing the distribution of total rainfall and frequency of measurable rain days in each group.

Figure 22a shows the frequency distribution of rainy days for the dry period which consisted of August 1971, June 1972, and July 1974. The network average rainfall varied from 21 to 32% of normal in these three months. The frequency map shows a trend for rainfall to occur most often in exceptionally dry periods along the river valleys, in the vicinity of the urban area, and in the hill regions in the SW and SE parts of the METROMEX Network. The high in the SE part of the network is likely related to both hill and river valley (moisture source) effects, since the Kaskaskia River basin is located just off the SE part of the network.

Thus, inadvertent modification by the city and topographic factors are apparently present in relatively dry months, as indicated by the raincell initiation and merger analyses. This provides further evidence that the weather modification potential is present in dry periods, and that some success in alleviating water shortages might be achieved during drought conditions.

Figure 22b shows the frequency distribution of rainy days in the three months of heaviest rainfall. These included June 1973, August 1974, and August 1975. Monthly totals varied from 125 to 156% of normal in these three months with an average of 140%, The urban-induced high is not indicated in the heavy rain months, and the high and low areas have a more random distribution than in the dry months discussed above.

Examination of frequency maps for the other periods (not shown) indicated a pattern in the moderately dry months similar to that for the exceptionally dry months. The maps for near normal and above normal periods showed nearly random distribution of highs and lows.

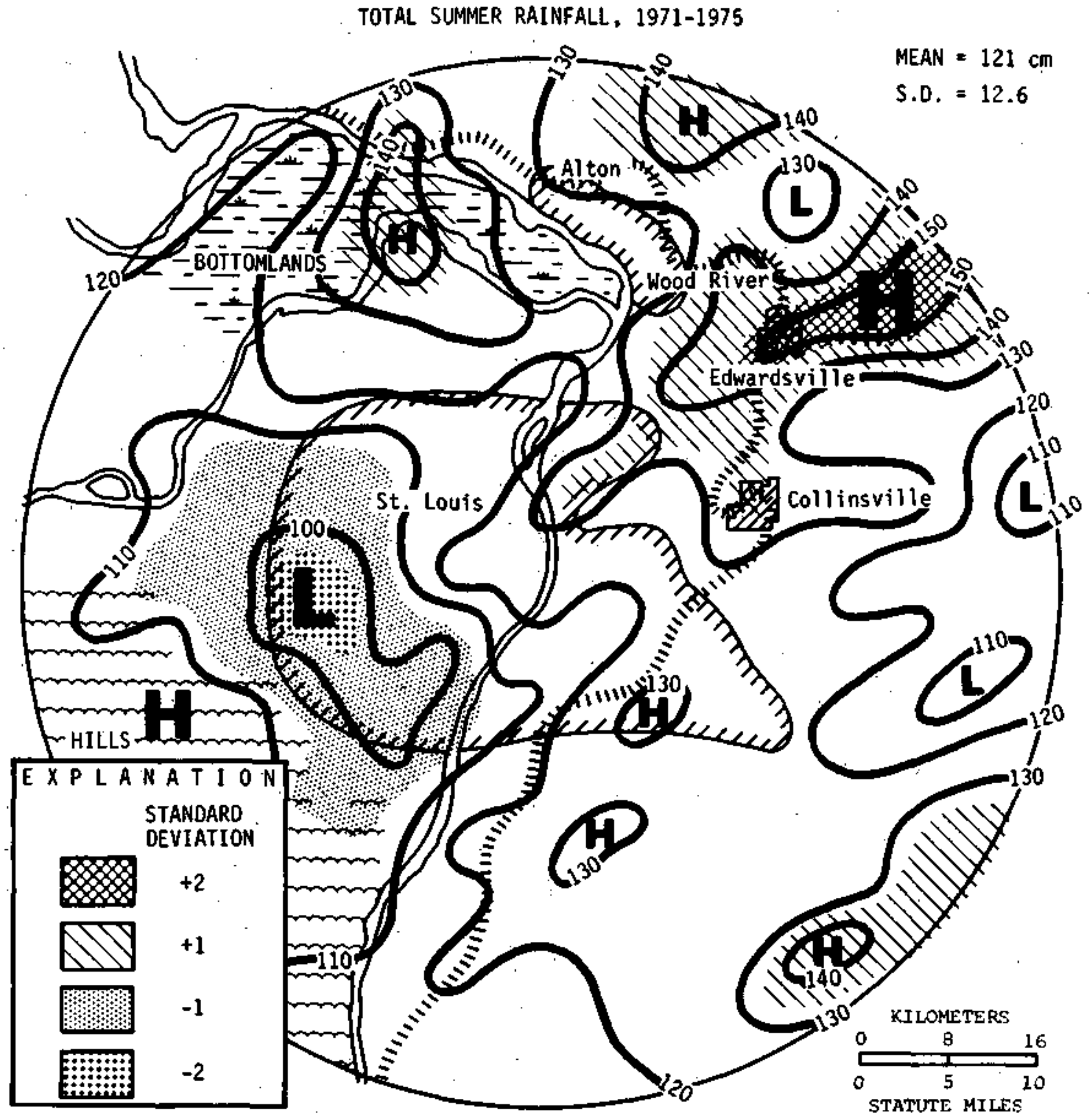
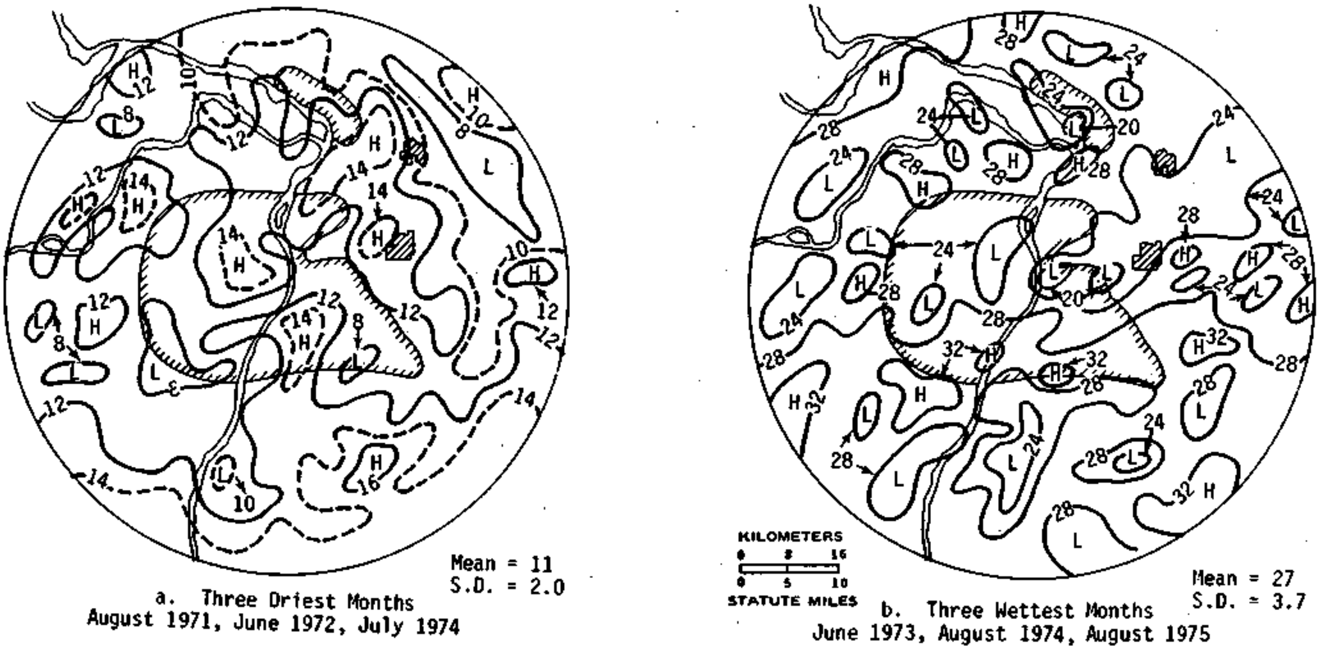


Figure 21. Total Summer Rainfall (cm) on METROMEX Network, 1971-1975.



a. Three Driest Months
August 1971, June 1972, July 1974

b. Three Wettest Months
June 1973, August 1974, August 1975

Figure 22. Frequency of Measurable Rainfall in Dry and Wet Months on METROMEX Network.

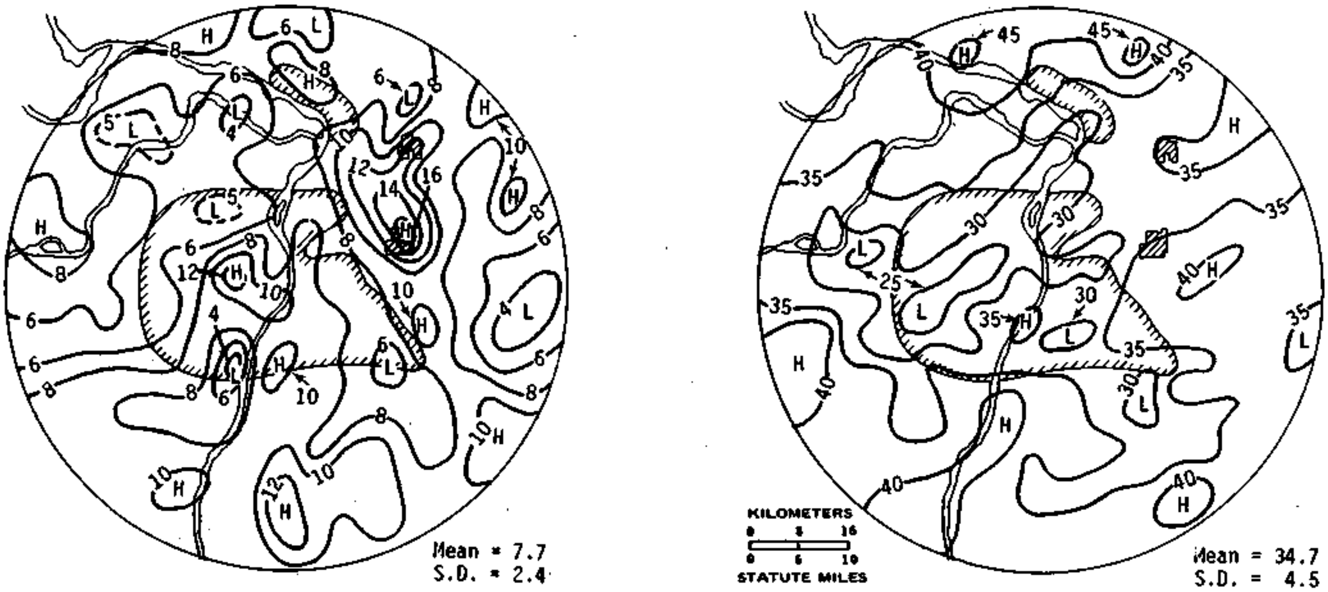
Fig. 23a shows total rainfall for the three dry months. The heaviest rainfall occurred along the Mississippi River Valley in and downwind (east) of the St. Louis urban area and in the SE quadrant of the network. Similar to the frequency distribution, there appears to be a tendency for urban and topographic effects to be operating in exceptionally dry periods, and this is favorable from the standpoint of the potential of weather modification in drought conditions. Fig. 23b shows the total rainfall pattern for the wet months which average 140% of normal. This map is similar in most areas to the total 5-summer map in Fig. 21, including the pronounced high extending NE from St. Louis to Edwardsville.

Computations were made of the rainfall excess in the Edwardsville high (EDW) of Fig. 21, by comparing the average rainfall in that region with the network average. This was done for each of the wet, dry, and moderate groups. Four gages (gages 38, 50, 51, and 52) were used to represent the core of the 5-summer EDW high. Results showed that the average rainfall in the dry period was 40% greater in the EDW high than over the network. Similarly, the 4-station mean was 88% greater in the moderately dry months, only 1% greater in the normal period, 32% more in the moderately wet months, and 10% greater in the wet months. Combining the six dry-type and the six wet-type months, it was found that rainfall in the EDW high exceeded the network average by 74% in the relatively dry months, compared with 20% in the relatively wet months. These computations indicate that the urban effect, which is primarily responsible for the EDW excess rainfall, is relatively stronger in dry periods. The total amount of excess rainfall (departure from network mean) in the EDW high averaged 9.55 cm (3.76 in.) for the six dry months and 6.50 cm (2.56 in.) for the six wet months.

In general, the analyses of relatively dry, moderate, and wet rain months indicated that the urban and topographic factors are operating under all types of precipitation climate. During dry months, a trend for rainfall to occur more frequently along river valleys, in hilly regions, and in heavily urbanized regions was noted. These findings are favorable from the standpoint of weather modification potential, particularly in drought conditions when water shortages are likely to become critical. The results suggest that certain topographic and land use features (river valleys, hills, urban areas) are favorable regions to initiate weather modification activities during dry periods.

CLOUD AND UPPER AIR CLIMATOLOGY

As part of the research under this grant, studies were made of the . climatology of low and middle clouds and of several upper air parameters in Illinois. The data in each case were stratified according to normality of monthly rainfall during the growing season. The primary purpose was to ascertain whether distinct differences occurred in the characteristics of clouds, temperature, and moisture conditions between dry and wet periods. Such information is relevant to evaluating the potential of weather modification in alleviating agricultural water shortages.



a. Three Driest Months,
August 1971, June 1972, July 1974

b. Three Wettest Months
June 1973, August 1974, August 1975

Figure 23. Total Rainfall in Dry and Wet Months on METROMEX Network.

In the cloud studies, the frequency and areal coverage of cumulonimbus were determined to provide an index of the convective activity under various degrees of normality of monthly precipitation. Analyses were based on data for 1951-1964 at six first-order stations situated in or close to Illinois. Monthly precipitation was determined from averages for six to eight stations within a 48-km radius of the cloud observation stations. Cumulus distributions were used as a measure of the low-level moisture conditions, and altocumulus and altostratus serve as an index of middle-level moisture conditions.

In Illinois, the cloud climatology showed that Cb activity tends to be greatest in all months (dry, wet, or moderate) in the western and southwestern parts of the state where potential enhancement of the natural precipitation processes by topographic features (Ozark foothills and Mississippi River) is present. The low-level moisture supply, as indicated by the Cu distribution, tends to be greatest in the eastern to southeastern parts of the state which are frequently downwind of the Ohio and Wabash River Valleys. Middle-level clouds during dry periods were found to be more plentiful over the central part of the state, but differences throughout the state were generally small.

Analyses of the diurnal distribution of cumulonimbus showed that rain-producing clouds occur more frequently during the night hours (1800-0600 CST) than during the daylight hours. This compares favorably with earlier findings (Huff, 1971) of the diurnal distribution of summer rainfall in Illinois, and stresses the need to conduct weather modification operations on a 24-hour basis in order to achieve maximum benefits. Details of the cloud climatology study are contained in Appendix A.

In the study of the upper air climatology, data were used for 1971-1975 from two RA0B stations in Illinois (Peoria and Salem). Analyses were based on soundings taken at 0600 and 1800 CST during the months of June, July, and August. Monthly precipitation was stratified into five classes of normality ranging from very dry (less than 50% of normal) to very wet (> 160% of normal), based upon all precipitation stations within 48 km of the radiosonde stations.

Analyses of temperature were made for each precipitation group in the layers from surface-850 mb, 850-700 mb, 700-500 mb, surface-700 mb, and surface-500 mb. Mean relative humidity, saturation deficit, mixing ratio, and precipitable water were computed for the same layers. For each precipitation class and each time (0600 and 1800 CST), frequency distributions were computed for the 500-mb temperature, surface to 850-mb temperatures, and surface to 850-mb relative humidity.

Although results of this study are interesting and useful from the climatological standpoint, no strong relationship was established between normality of precipitation and the various upper air parameters. However, the inconclusive results are not really surprising, and tend to support ,the premise that the synoptic and mesoscale dynamics of the atmosphere exert a strong control over the initiation and intensity of convective precipitation. A detailed description of the upper air climatology is provided in Appendix B.

THE SUMMER DROUGHT OF 1971 ON THE METRQMEX NETWORK

The first summer of the METROMEX Project (1971) was characterized by moderate drought conditions on the 225-gage network of 5200 km^2. The June-August mean rainfall on the network was 63% of normal. However, it ranged from 35 to 40% of normal over and E of St. Louis to 111% of normal in the NE part of the network near Edwardsville (EDW)» which is frequently downwind of storms moving across the urban-industrial area (Huff, 1976a). The June average was 54% of normal and August had only 21% of normal, which was the driest of the 15 summer months during the field project (1971-1975). However, July had mean rainfall that was 115% of normal. The monthly and seasonal rainfall patterns are shown in Fig. 24a to d. A detailed analysis was made of the 1971 METROMEX data in an effort to obtain further information on the characteristics of these relatively small-area droughts. Actually, the drought extended across eastern Missouri into southwestern Illinois, and was present also in scattered locations (spot drought conditions) throughout Missouri and Illinois.

Upper Air Circulation

The average monthly flow pattern at 700 mb provides an indication of the upper air dynamics and its influence upon precipitation. The upper air flow characteristics and their variations during the summer of 1971 are described in the following paragraphs to show the general intensity of the large-scale weather patterns over the METROMEX area.

According to Posey (1971) the June 700-mb pattern was characterized by a ridge from Iowa to Louisiana. Major troughs were situated off the east and west coasts of the United States with a minor trough from Colorado to the Texas Panhandle. The main position of the jet was over the northern tier of states and in southern Canada, about 5° to 10° north of its normal position.

The average rainfall for June 1971 on the METROMEX network was 51% of normal. Most of this rain (91%) fell within the first 15 days. During this period, the mean 700-mb ridge was located east of St. Louis with a mean long-wave trough situated along a line from Idaho to Baja, California. After 15 June the upper-air flow pattern shifted, and generally flat height gradients were observed over all but the northern third of the United States. The trough to the west retrograded and was positioned off the west coast of the United States, while the ridge moved west into the Mississippi Valley. The upper-air pattern during the first 15 days of June was conducive to the formation of precipitation over the middle sections of the nation. After 15 June the upper-air pattern shifted. The pattern over the Midwest became more stagnant and stable, and was much less prone to the generation of major rainfall systems, especially over the Mid-Mississippi Valley.

The mean 700-mb flow pattern for July showed a major trough east of Missouri and Illinois which extended south from Hudson Bay to Mississippi, a trough was located off the West Coast, and a ridge persisted along the Continental Divide (Wagner, 1971). The mean jet axis was along the United States-Canada border, or very close to its mean position.

The rainfall within the METROMEX network during July was 115% of normal. During the first seven days, the mean upper-air flow was zonal across northern United States with an extension of the subtropical high over the southern third of thr nation. Only 17% of the monthly rainfall total was observed within the METROMEX network during this period. Cooler air advected into the central and northern sections of the United States after the first week of July. As a result, from 8 to 15 July the southern boundary of this colder air was situated across Missouri and Illinois, and the upper-air pattern was marked by zonal flow and a baroclinic zone across the central portions of the country. During this 7-day period, 47% of the monthly rainfall was recorded.

In the last half of the month there was a marked change in the upper-air pattern. The trough off the West Coast was replaced by a ridge and a deep trough was located from James Bay to Arkansas, just east of the METROMEX research area. During the last half of July a number of intense short waves were observed[1] to move across the region at both 700 and 500 mb. Thus, after the first week of July the upper-air flow was characterized by strong upper-air perturbations capable of producing major rain systems.

The mean August flow pattern at 700 mb showed troughs off the East and West coast and light anticyclonic flow over most of the United States (Green, 1971). The mean jet position was over central and southern Canada, some 3 to 8° north of the normal August jet axis. The August average rainfall in the METROMEX network was only 21% of normal, and was the lowest monthly rainfall observed during the five summers from 1971 to 1975. Lambert Field (St. Louis International Airport), the official National Weather Reporting station for the area, reported the second driest August on record. There was a persistent extension of the subtropical high pressure zone into the southern and central portions of the United States for the first three weeks of August. The last week was characterized by a major trough over NE United States and the Great Lakes and an anticyclone centered over Colorado. This put most of Missouri and Illinois in northwesterly flow. Thus, the synoptic-scale flow during Autust was characterized by light anticyclonic circulation which is detrimental to the development of rain system.

Spatial Characteristics of Network Rainfall

The June-August pattern of Fig. 24a is similar in shape to the dry season pattern identified by Huff and Changnon (1972a) in an earlier climatic study of seasonal rainfall patterns in the St. Louis area. This pattern consists of an approximate W-E high across the Alton (ALN) area in the northern part of the network, another W-E high of lesser extent across the southern part of the network a few miles S of St. Louis, and a W-E low extending from the urban area eastward.

Figure 24. Monthly and Seasonal Rainfall (cm) in 1971.

Examination of the monthly maps in Fig. 24 show that the EDW seasonal high resulted primarily from a pronounced peak in the network pattern during June when 12-18 cm of rain occurred in the EDW region, whereas most of the network recorded only 4-8 cm. The high in the NW quadrant of the network was produced largely in the relatively wet month of July, and the southern high was the result of relatively weak highs in all three months.

It is interesting to note that the 1971 seasonal pattern plus the June and July monthly patterns are similar in shape and general location of highs and lows to the 5-year patterns. This is another indication that the same processes are dominant over a wide range of rainfall conditions, as found in the analyses of raincell initiations and mergers discussed in previous sections of this report. That is, if external forces such as the regional topography and the urban environment are influencing the rainfall distribution in the St. Louis area, and this is supported by much evidence gathered in various METROMEX studies (Changnon et al., 1976), then these forces appear to be working equally well in dry, near-normal, and wet periods.

Diurnal Distribution of Cb Clouds

The Cb activity during June 1971 showed 73 hourly observations of Cb clouds at St. Louis, some 4.2% greater than the normal Cb hourly frequency during dry months. For the dry period from 16 June to 30 June, 41 hourly observations of Cb clouds were made. During this period, the Cb observations were nearly equally divided with 54% of the observations during the night hours and 46% during the day hours. However, many of these hourly observations, both at night and during the day, were of distant Cb clouds, so that they were not truly representative of the Cb population within the confines of the METROMEX network. Throughout most of this period a warm tropical air mass was evident over the Mississippi Valley and many smaller rain systems and air mass storms were observable. However, the opportunity for cloud seeding would appear to be about equally divided between day and night hours. The diurnal distribution of Cb clouds during June 1971 peaked during the late afternoon (1600 to 1800 CST) and in the early evening (2000 to 2200 CST).

Only 26 hourly observations of Cb clouds were made during August 1971, 2% less than the normal hourly frequency. All Cb activity was observed between the hours of 1000 to midnight CST, with maxima from 1400 to 1600 CST and at 2300 CST. Approximately 50% of the hourly observations were during the day (0600 to 1800 CST). During August and the last half of June, almost 50% of all the Cb clouds were observed during the night hours. These clouds are associated with the dominant precipitation process during the summer months. These 1971 findings further substantiate statements made several times in this report regarding the need to carry out weather modification operations on a 24-hour basis.

The hourly frequency of cumulus clouds observed during August 1971 was 126 hours (16.9% of all the hourly observations) which is 6% less than the normal frequency for dry months. This is an indication of the suppressed instability caused by the anticyclonic flow evident in the low and mid levels of the troposphere, or the lack of low-level moisture in the region. However, the mean monthly mixing ratio and relative humidity values in the layer from the surface to 850 mb for August 1971 were only slightly lower than average values for months with near-normal or greater precipitation. However, low-level and upper-level perturbations were insufficient to initiate very many raw systems because of the dominant anticyclone flow during the first three weeks of the month.

Raincell Initiations and Mergers

Examination of raincell initiations for summer 1971 showed an above-average frequency along the Missouri River valley, in the confluence of the Missouri and Mississippi Rivers in the NW part of the network, in the Ozark foothills in the SW part of the network, and over and E of the urban-industrial region. These relative highs indicate the likely presence of both topographic and urban influences, as discussed earlier in the section dealing with raincell initiations during wet and dry periods. The 1971 initiation maxima were in regions that coincide with or are frequently upwind of the highs in the summer rainfall pattern of Fig. 24a.

Plots of the location of raincell mergers, which are usually associated with intensification and horizontal growth of convective entities (see section on raincell mergers), also showed an above-average frequency of mergers in or upwind of the rainfall highs in Fig. 24a. With respect to the major high in the EDW area, the mergers occurred with relatively high frequency over and just E of St. Louis which is frequently upwind of EDW with storms and/or low-level winds moving from SW to NE. These conditions occur quite frequently in the summer.

Thus, both the distribution of raincell initiations and raincell mergers indicate that the spatial rainfall pattern for the relatively dry summer of 1971 was related to topographic and urban factors. Since the outstanding high was in the EDW area which is frequently downwind of the urban-industrial area but subjected to little, if any, topographic effect (Changnon et al., 1977), the data suggest that the urban environment was a stronger influence than the topographic forces. This conclusion is also strongly supported by various METROMEX results.

Distribution of Heavy Rainstorms

Huff (1977) has shown that the major portion of the EDW high is accounted for by excessive rainfall with respect to the network average in heavy rainstorms, defined as those producing rain amounts of 25 mm (1 in.) or more. Over the five summers, the EDW area experiences 20-23 occurrences per gage of these heavy storms, which was twice the network average of 11 occurrences. Examination of the frequency distribution of 25-mm storms in summer 1971 showed 4 to 6 occurrences in the EDW area compared with 0 to 2 over most of the network which has an average of 1.3 for the 225 recording gages (Fig. 25). Comparison with the 5-summer totals showed that the frequency of 25-mm storms in the EDW area during the dry summer of 1971 was near the 5-summer average. Since the relatively high frequency of these heavy storms in the EDW area is apparently related to urban effects, we have another indication

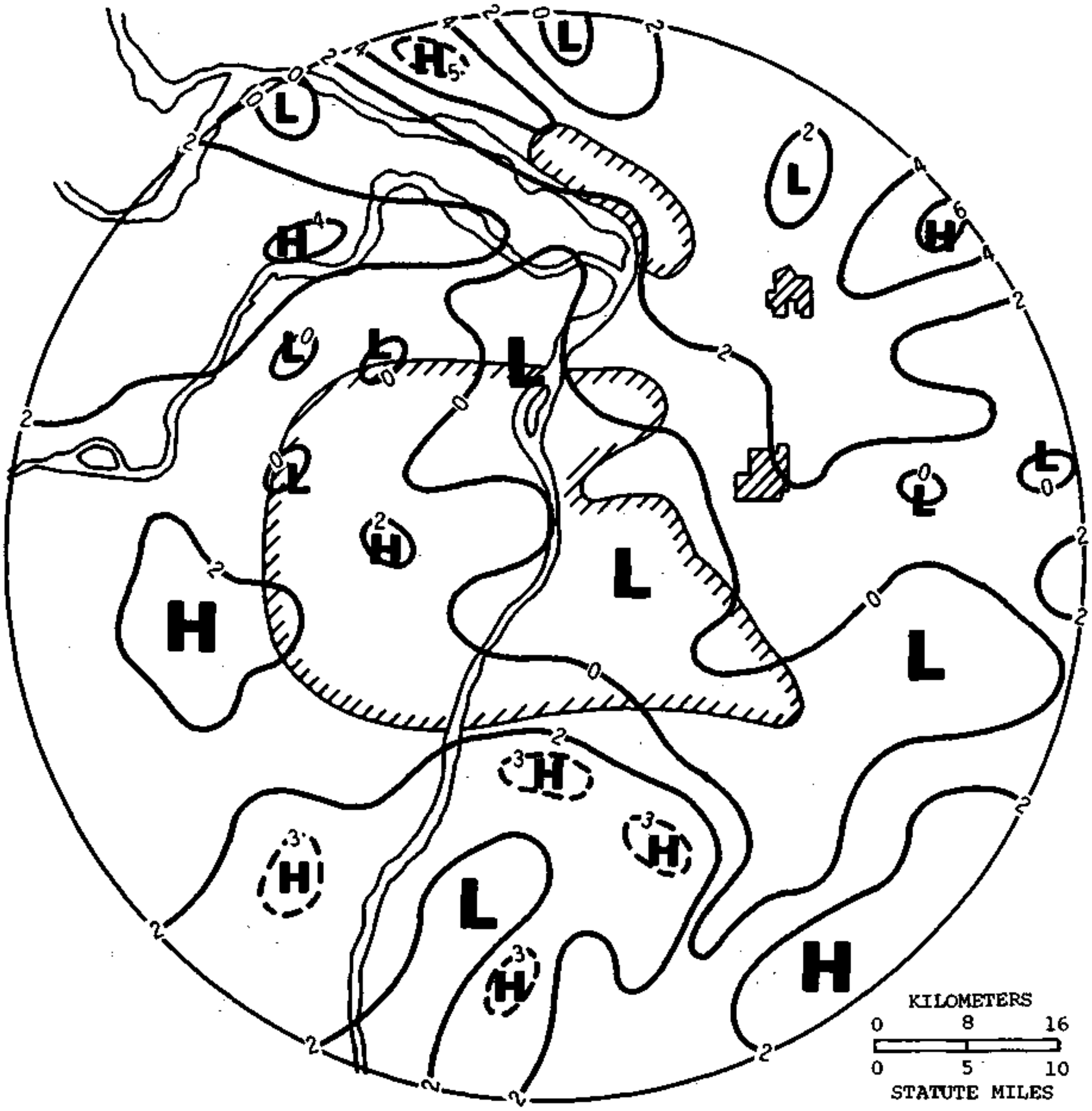


Figure 25. Frequency of 25-mm Storms in Summer, 1971.

that the urban environment was functioning as usual in its enhancement of precipitation during the 1971 dry period. Of the 4-6 heavy storms in the EDW region in 1971, three occurred in June when the network rainfall averaged only 54 percent of normal.

Storm Movements

Surface raincell data were used to determine the movement of storms on the METROMEX network. It was found that over two-thirds of the 1971 storms moved from the SW, WSW, or WNW. These predominating movements placed the high centers of Fig. 24a frequently downwind of 1) the major topographic features (hills, river bottomlands) where stimulation of convection is likely to occur, and 2) the urban-industrial area which is related to the EDW high. The distribution of storm movements in 1971 was quite similar to the 5-year average, and this is likely one reason that the 1971 rainfall pattern is similar to the 5-summer average distribution.

Analysis of storm movements provided more evidence that many basic storm characteristics in dry periods often do not differ substantially from those experienced in near normal or wet periods. The frequency, intensity, and areal extent of storms are normally less in dry periods, because favorable convective situations occur less frequently and the precipitation processes are not as productive, on the average.

Synoptic Storm Types

Synoptic weather types associated with the 1971 storms were classified and compared with the average distribution for the 5-summer experimental period on METROMEX. Results indicated that the rainfall deficiency in summer 1971 was caused largely by a below average frequency of squall lines. During the summers of 1971-1975, squall lines occurred, on the average, 10 times per season and produced slightly over 50% of the total network rainfall. In 1971, only five squall-line storms were recorded. The 1971 frequency of squall areas which are normally associated with 25% of the network rainfall was normal (17). Cold fronts which produce 12% of the network rainfall, on the average, occurred 9 times in 1971 and this is the normal frequency. The frequency of air mass storms were well below normal (6 vs normal of 18), but these only produce about 2% of the network rainfall under average conditions. The deficiency of prefrontal squall lines is indicative of relatively weak fronts and frequently unfavorable moisture-stability distributions in the warm sectors.

The Edwardsville Anomaly

A striking similarity between the rainfall spatial pattern in the relatively dry summer of 1971 and the total rainfall pattern for 1971-1975 is the location of the strongest high on the network in the EDW area in the NE quadrant (Figs. 21 and 24a). METROMEX studies have shown that the excess rainfall in the EDW high, as measured by its departure from the network mean rainfall, occurred mostly in a relatively few storms. During 1971-1975, over 80% of the EDW rainfall excess, obtained by summing the positive deviations from network storm means, could be accounted for in approximately 10% of the network storms. Investigation showed that five of these storms occurred in 1971, and that these storms produced enough rainfall excess to more than account for the EDW high.

In June, the EDW high, as measured by data from 9 raingages in the high rainfall region of approximately 300 km^2, had an average rainfall that was 4.51 cm above the network mean of 4.17 cm. Three storms in June (6/11, 6/12, 6/15) produced average rainfall in the EDW high that was 4.30 cm above the network mean for these storms, almost exactly the monthly difference. In July, the EDW area had average rainfall that was 4.21 cm greater than the network average. In two storms (7/4, 7/10), the EDW area received 4.32 cm more rain than the network. Thus, eliminating the excess in these two storms, there was no EDW excess in the June-July period. For the three months (June-August), the EDW area would have had an average rainfall slightly less than the network mean, if <u>no excess</u> had occurred in these five storms. It is interesting to note that the five 1971 storms represent approximately 11% of the total storms, which is nearly the same as the percentage that accounted for 83% of the EDW rainfall excess in the 5-summer period. That is, the percent of the storms with large positive deviations from the network mean was nearly the same in the dry summer as in the 5-summer period; the major difference was that only 47 storms having measurable rainfall occurred on the network in 1971 compared with a 5-summer average of 66 storms.

Examination of the synoptic conditions associated with the five 1971 storms showed that three occurred with squall lines which are the heaviest rain producers, on the average. Only five squall-line storms were recorded in this 3-month period. Storm movements were from the SW to WSW in all five of the 1971 storms, and these movements expose traveling storms to the urban-industrial area. Furthermore, the transport winds (surface to cloud base) were from the SW quadrant in four of the five storms. Therefore, low-level pollutants (heat, moisture, aerosols) would have been carried from the STL urban-industrial area toward EDW.

Analysis of storm rainfall in the 1971 storms showed that the five storms which were heavy contributors to the EDW high accounted for 50% of the total summer rainfall in that anomaly. Three of the five storms produced average rainfall in excess of 25 mm in the EDW high. Total summer rainfall in the EDW high was 81% of normal compared with 63% for the network. Thus, although storms were less productive than normal in the EDW region, the deficiency was much less than over the entire network. It is believed that this lesser deficiency was largely the result of urban-induced enhancement of ongoing storm systems (Huff, 1976a), that is, from an increase in productivity through inadvertent weather modification. This is still another indication of the potential for modest alleviation of water shortages during drought periods through cloud seeding operations.

Summary and Conclusions

Detailed precipitation data from the METROMEX network of 225 recording raingages in 5200 km^2 and synoptic weather information were used to study the characteristics of the rainfall distribution in the relatively dry summer of 1971. The network seasonal rainfall was 63% of normal with monthly percentages ranging from 21 in August to 54 in June and 115 in July. This was the driest of the five summers of the METROMEX experiment. Particular attention was given to determining differences in rainfall characteristics between this dry summer and the 5-summer average distribution.

Although differing in magnitude, it was found that the general shape and location of rainfall highs and lows in the spatial pattern for 1971 were similar to the 5-year mean distribution pattern. Similar to the 5-year pattern, the major high was located in the NE quadrant of the circular network in the vicinity of Edwardsville (EDW) and was produced to a large extent by excessive rainfall in June compared with the rest of the network. Thus, 1971 was quite normal with respect to spatial distribution characteristics, but was below normal with respect to rainfall amounts.

Analyses of raincell initiations and mergers in 1971 also showed a similar spatial distribution to the 5-summer pattern. Relatively high frequencies of initiation occurred along river valleys, in the Ozark foothills, and over and downward of the St. Louis urban-industrial area. Mergers, which are usually accompanied by increases in rain intensity and horizontal growth of the rain area, occurred most often in or upwind of highs in the rainfall pattern, and were apparently stimulated by both urban and topographic forces. The urban, however, appeared to be considerably greater.

The 1971 distribution of heavy rainstorms was also found to be similar to the 5-summer pattern, and these storms are largely responsible for the EDW anomaly in the 5-year pattern. Analyses of storm movements in 1971 showed dominant motions from the SW, WSW, and WNW, which again is in agreement with the 5-year averages. These motions result in the area NE to E of STL being frequently downwind of the urban-industrial area which has been shown to produce inadvertent enhancement of summer rainfall. Analyses of synoptic storm types indicated that the major cause of the dry summer in 1971 was a large deficiency of squall-line storms which produce 50% of the network rainfall, on the average.

Analyses of the causes of the EDW anomaly showed that the 1971 experience was similar to the 5-year average conditions. Thus, the EDW high was produced largely by approximately 10% of the summer storms, and the majority were associated with squall lines in which large positive deviations from the network mean rainfall occurred in the EDW region.

Overall, the outstanding finding of this study was that the dry summer was stikingly similar to other summers with respect to monthly and seasonal spatial patterns, distribution of highs and lows, initiation and merger regions, heavy rainstorm patterns, and the major anomaly at EDW being produced largely in a relatively few storms with the strongest effect in June. The major difference, and one that helps explain the relatively light summer rainfall in 1971, was that the major rain producer, squall lines, occurred with only 50% of normal frequency. However, squall lines were still the major contributor to the EDW anomaly. All these findings lead to the conclusion that the basic precipitation processes are functioning similarly in relatively dry, near normal, and wet periods in a given area, but the frequency and productivity of dry period storms are below average. This is encouraging from the standpoint of planned weather modification, especially since the urban inadvertent weather processes appeared to be working during the dry summer of 1971, but with lesser productivity. This finding is supported by comparative studies of wet and dry months from the METROMEX experiment, which were discussed in an earlier section of this paper.

COMPARISONS OF CLOUD SEEDING EFFECTS IN WET, MODERATE, AND DRY PERIODS DURING WHITETOP PROJECT

As another guide in evaluating the weather modification potential in drought periods, data from the Whitetop cloud seeding experiment were re-examined. This project was carried out during the summers of 1960-1964 within a circular experimental area of 97-km (60 mi) radius centered at West Plains, Missouri. These data were readily available in a usable form for the purposes of the drought study (Braham, 1966; Decker and Schickedanz, 1966). The limited study carried out here involved comparisons of rainfall recorded on seeded and unseeded days with the data stratified according to months which were relatively dry, wet, and near normal in precipitation within the experimental area. The major purpose was to ascertain whether the seeded-unseeded rainfall relations showed distinct differences in wet and dry periods. If so, this could shed further light on the potential for weather modification in drought situations.

Rainfall Comparisons Based on Seeding Plumes

The first analysis consisted of a comparison of the average daily rainfall 1) in and outside of the Chicago plume on days when cloud seeding took place, and 2) in the Chicago plume on days with and without seeding. The Chicago plume was defined by the most divergent winds between the seeding level and 14,000 ft (4270 m) MSL and restricted to the area within operating range of the project radar (Decker and Schickedanz, 1966). The second analysis involved a comparison of average daily rainfall in the Missouri plume on days with and without seeding. The Missouri plume was based upon winds at the seeding level and was not limited to the area within radar range.

In both plume analyses, the 15 summer months of operations were divided into three groups of five months that included the five driest, five wettest, and five months of moderate (near normal) rainfall in the Whitetop experimental area. Results of the two plume analyses are summarized in Table 36. The group of five dry months had average rainfall that was 63% of normal with a range from 46 to 73% among individual months. The moderate group had monthly rainfalls varying from 81 to 104% of normal with a mean of 91%. The wet months had an overall average of 142% of normal and a range from 106 to 195%. Thus, the 15 months included a wide range of rainfall experiences within the experimental area.

Table 36. Average Plume Ratios in Months of Relatively Light, Moderate, and Heavy Rainfall on Whitetop Experiment

Monthly Rain Group	Chicago Plume Average Ratios: Seed Day In/Out*	Chicago Plume Average Ratios: In-Plume Seed/No-Seed**	Missouri Plume (In-Plume Ratios) Seed/No-Seed
Dry	0.74	1.27	0.73
Moderate	1.09	0.31	0.21
Wet	1.00	0.73	0.77

* Rain ratio, in-plume/out-plume on seeded days

** Rain ratio, seed/no-seed days within specified plume

Comparisons between the relatively dry, moderate, and wet months did not provide evidence that seeding effects were significantly different under these three sets of rainfall conditions. Table 36 indicates that the Chicago out-plume rainfall was substantially larger than the in-plume rainfall on seeded days, on the average, during the relatively dry months. However, this variation reversed in the moderate months and showed no difference in wet months. During the dry months, the rainfall on seeded days exceeded the rainfall on unseeded days when the in-plume values were compared. However, a reversal occurred with moderate and wet months.

The Missouri plume summary (Table 36) shows substantially greater rainfall on the non-seeded days in all three classifications, and no established trend between the differences in proceeding from relatively dry to relatively wet conditions. Thus, the no-seed/seed ratio was nearly equal, on the average, for the wet and dry months, but was substantially different in the near normal rainfall months.

Overall, the Chicago and Missouri plume comparisons of rainfall in dry, wet, and moderate months proved inconclusive, and provided no assistance in evaluating weather modification potential in drought situations.

Rainfall Comparisons Over and Downwind of Experimental Area

Before closing out the re-examination of the Whitetop data, it was decided to make comparisons of rainfall over a much larger area than that encompassed by the Chicago and Missouri plumes. In this analysis, comparisons were made not only within the Whitetop research circle of 97-km radius, but were extended to incorporate possible downwind effects from the cloud seeding operations. In an earlier study, Huff and Schickedanz(1970) concluded there was no strong evidence of downwind effects in the Whitetop experiment. However, they did not stratify data according to relative intensity of precipitation as was done in the drought study.

The region used in the large-area comparisons is shown in Fig. 26. For these comparisons, the area was divided into grid squares of 160 x 160 km (100 x 100 mi) following the procedure of Huff and Schickedanz (1970). The study was carried out in the region that would normally be downwind of the seeding area in the vicinity of West Plains. As indicated in Fig. 26, the study region extended east of a N-S line through West Plains. There were 16 grid squares located in the region E of the N-S line within a radius of approximately 480 km (300 mi) of West Plains. In addition, two grid squares west of this line were incorporated into the study, so as to encompass the Whitetop research circle.

The published data (Decker and Shickedanz, 1966), were used to compute the average rainfall in each grid square for seeded and unseeded days in the three comparison groups. Rainfall assigned to each seed or no-seed day was the total rainfall recorded at raingaging stations in the 24 hours starting at 0700, in order to make use of non-recording rainfall data from National Weather Service (NWS) stations. The non-recording stations are the major source of rainfall in the NWS cooperative networks. This, of course, is not the best data to evaluate seeding effects, but it was the only means for obtaining a reasonable number of measurements for computing areal mean rainfall. If seeding was altering the rainfall distribution, this would provide a conservative estimate of the effect.

Table 37 shows the average ratio of areal mean rainfall on seeded days to no-seed days in each grid square used in the analysis. At the bottom of the table, the number of rainy days in each group is shown, along with median ratios and the range of ratios in each group. The median ratio was less than one for the dry and moderate months, which indicates less rainfall, on the average, on seeded days. This is a general finding which has been widely publicized and debated by others who have analyzed Whitetop data in the past. Whether this resulted from seeding effects or not has never been conclusively proven.

The median ratio in the wet months, however, indicates approximately 6% more rainfall on seeded than no-seed days over the experimental and downwind areas, and is a reversal from the dry-moderate month findings. Whether this is a sampling vagary or an indication of seeding enhancement in above-normal rainfall conditions cannot be established by the limited analysis performed here. It is interesting to note that all grid squares from 36-65 (see Fig. 26 for locations) indicate heavier rainfall on seeded days, and the average ratio for these 10 grid squares is a relatively large 1.33. In general, the grid squares within the research circle and those E and SE of it had positive deviations and those NE of the experimental area had negative deviations.

Schickedanz (1976) found that rainfall enhancement from irrigation (inadvertent weather modification) in the Great Plains tended to occur in the

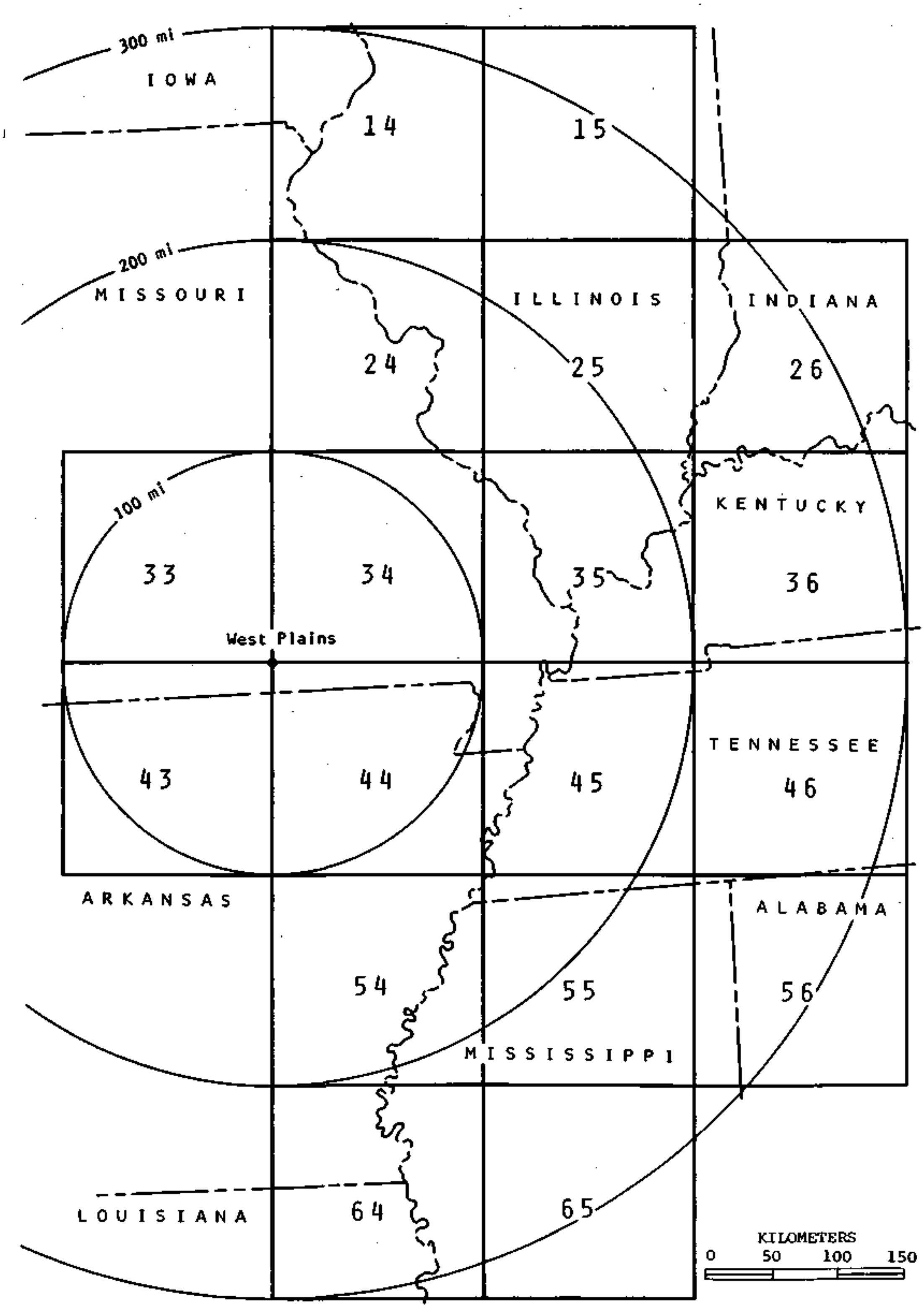


Figure 26. Grid Squares Used in Whitetop Rainfall Comparisons.

wetter months in the general study area. The above findings with respect to possible seeding effects in the wet months on Whitetop are in agreement with the Schickedanz findings in his irrigation study. Therefore, the possibility that the dry to wet reversal in the relationship between rainfall on seed and no-seed days in Table 37 cannot be dismissed as strictly a sampling vagary, however, time has not permitted further investigation of this possibility in this drought study. Accepted at face value, Table 37 does not provide support for successful cloud seeding in drought conditions. However, the evidence is too weak to have much weight in the overall evaluation of the problem.

Table 37. Comparison of Seed/No-Seed Ratios in and Downwind of Whitetop Experimental Area

Grid No.	Average Ratio, Seed/No-Seed Days Dry Months	 Moderate Months	 Wet Months
14	0.73	0.53	0.59
15	0.53	1.33	1.33
24	1.06	0.76	0.58
25	1.00	1.07	0.65
26	1.09	0.88	0.72
33	0.73	0.83	0.72
34	0.95	0.55	0.57
35	1.09	0.65	0.83
36	1.52	1.00	1.62
43	0.28	0.71	1.11
44	0.75	0.79	1.00
45	0.89	0.85	1.42
46	1.56	1.33	1.62
54	0.71	0.67	1.38
55	0.71	0.79	1.41
56	1.00	1.20	1.20
64	0.13	0.93	1.12
65	1.25	0.57	1.40
Number of Rainy Days	51	72	73
Median Ratio	0.95	0.81	1.06
Range of Ratios	0.13- 1.56	0.53- 1.33	0.57- 1.62

SUMMARY

The major objective of this research was to assess the potential utility of weather modification in stimulating crop production during droughts of various severity in the Midwest. A secondary objective was to develop techniques for applying precipitation climatology in assessing the feasibility and potential benefits of cloud seeding during growing season droughts. The present research was limited to Illinois which is typical of much of the Midwest in climate, soils, and crop production.

Analyses were performed on drought conditions in two time periods, July-August and May-September. July and August are the two most critical months of the growing season with respect to water needs for the two major Illinois crops, corn and soybeans. May-September includes the entire growing season from planting to harvest. Rainfall data for 1900-1974 were used in various studies of storm, monthly, and seasonal rainfall during droughts. Special precipitation studies were carried out with data from the METROMEX network of 225 recording gages in 5200 km^2 that was operated near St. Louis from 1971 through 1975. Limited analyses of cloud conditions and atmospheric moisture-stability conditions were performed also to help delineate weather modification potential during dry periods.

Analyses were concentrated on assessment of the distribution characteristics of natural rainfall in droughts. Previous studies in Illinois had indicated that significant seeding-induced increases in summer rainfall could only be achieved through enhancement of ongoing rain systems, and most of this would have to be produced in conjunction with organized storm systems. Previous cloud climatological studies also indicated too few low clouds (rain producers) present during dry periods to generate significant rainfall over the relatively large areas usually affected by drought conditions. Results of the present research are briefly summarized below.

Areal Extent of July-August Droughts

The droughts were grouped by areal extent as a measure of severity. Areas ranged from less than 1000 km^2 to nearly 100,000 km^2. July-August droughts were defined by the area within which the 2-month rainfall was equal to or less than 50% of normal. The droughts were divided into six areal groups (see Table 3). Average percent of normal rainfall was determined for each drought and each group of droughts to obtain a measure of the average intensity of droughts of various sizes. As expected, intensity (precipitation deficiency) increases as the areal extent increases (Table 4). Thus, average rainfall was 42% of normal in droughts encompassing areas less than 5000 km^2 compared with 32% for drought areas exceeding 50,000 km^2. These statistics indicate that enhancement opportunities are likely to be greater in the relatively small areal droughts compared with those extending over large areas of a state or several states.

Areas immediately surrounding droughts were usually below normal also, but the precipitation deficiency was not nearly as large (see Table 5). These areas tend to average over twice the rainfall in the adjacent drought area, so that possibility of seeding-induced enhancement is much better. Seeding of storms in these periphery areas would appear to offer an opportunity for extending the enhancement at least into the fringes of the major drought area by inducing larger and longer-duration convective entities.

Analyses were made of the frequency of months with 80, 100, and 120% of normal rainfall within the July-August droughts as another guide in assessing weather modification potential. Indications were that only small portions experience near normal rainfall in either of the two consecutive months. Only 11 of the 70 months in the 35 July-August droughts had any area with rainfall exceeding 80% of normal. Among these 11 months, the median was 9% of the drought area with a range from 4 to 37%. Thus, it tends to be very dry throughout the 2-month period. This is not a particularily favorable situation from the standpoint of seeding enhancement of ongoing storms, but does not preclude seeding success in drought situations.

Area-depth curves were derived for each drought to provide more detailed quantitative information on the spatial distribution characteristics than is provided by average rainfall statistics for these extreme events. As used here, these curves provide a measure of the minimum rainfall, rainfall gradient, and rainfall amounts enveloped within partial areas of droughts of various extent (severity). Quantitative estimates of the additional production of rainfall from weather modification operations should be more reliable if the spatial distribution characteristics of rainfall in droughts of various severity are better known. Thus, the area-depth relationships (see Table 6, and Fig. 10) provide basic information needed to help evaluate potential benefits of weather modification in agriculture in Illinois and areas of similar precipitation climate.

The area-depth curves provide further evidence that seeding opportunities are likely to occur more frequently in droughts of relatively small areal extent. Thus, the curves indicated that on the average, 50% of the area in droughts enveloping 4000 km^2 will have rainfall exceeding 43% of normal or more, compared with 37% of normal in droughts extending over 40,000 km^2, and 33% of normal in droughts encompassing 90,000 km^2.

Areal Extent of May-September Droughts

Findings relative to the May-September (growing season) droughts were in general agreement with those for the two critical months of July and August. Thus, the intensity, as measured by average percent of normal rainfall, tends to decrease as the areal extent of the droughts decreases.

Rainfall in the region immediately surrounding the droughts (areas enveloped by 70% or less of normal rainfall) was found to be frequently near normal and less deficient than the surrounding areas in the July-August droughts. Thus, seeding opportunities are likely to be more frequent within and surrounding the May-September droughts than in the shorter July-August droughts which tend to have greater precipitation deficiencies, on the average.

Analyses of the frequency of months with rainfall equalling or exceeding 80, 100, and 120% of normal were made. These showed that 20 to 30% of the drought areas with a monthly rainfall of 80% of normal or more is not uncommon (see Table 9). These results indicate that breaks do occur in the 5-month period when portions of the drought area is experiencing considerable rainfall, and these situations could conceivably be amendable to cloud seeding and substantial enhancement of the natural rainfall output. At least, the probability is much stronger than in the shorter July-August droughts.

The above conclusions were supported by area-depth relationships developed for the May-September droughts. That is, the 5-month droughts tend to be less severe throughout their area-of-effect, and, subsequently, offer a greater probability of seeding success. However, it must always be remembered that the major need for addtional water in the corn and soybean country of the Midwest is first in July and secondly in August, and precipitation enhancement is likely to be of minimal help in the other months of the growing season (May-September).

Intensity of Daily Rainfalls in July-August

Analyses were made to determine the frequency and areal extent of daily rainfalls equalling or exceeding 0.25 mm (0.01 in.), 12.7 mm (0.50 in.), and 25.4 mm (1.00 in.) in July-August droughts. The purpose was to obtain further information on the characteristics of droughts and the causes of their precipitation deficiencies. Results indicated that there are nearly always two days or more per month with measurable rainfall (0.25 mm) at all points within the drought areas of July-August, but this is only a small percentage of the normal frequency of 9 days. Approximately 50% of the drought areas were found to have 6 or more days with measurable rainfall, 20% experienced 8 days, and only 4% had 10 days (see Table 11). These statistics are indicative of the number of days with potential for seeding enhancement of natural rainfall. The opportunities are not too infrequent, but the natural rain area usually extends over only a small portion of the drought region.

Analyses indicated only 18 to 20% of the July-August drought areas have two or more days per month with rainfall of 12.7 mm or more, whereas normally the entire area should experience this number of moderate raindiys, Furthermore, only 14% of the drought areas, on the average, were found to have one day per month with rainfall exceeding 25 mm, whereas in a perfectly normal year this intensity would be experienced once at all locations.

In view of the small percentage of the July-August drought areas experiencing moderate to heavy rainfalls, natural rainfall would have to be increased by large percentages when seeding conditions are favorable to produce useful increases over more than a small percentage of the stricken area.

The areal extent of light, moderate, and heavy rainfall days in the area immediately surrounding the drought regions showed deficiencies in all categories but of a much lesser degree (see Table 12). Thus, on the average, there was 35% of the area with 8 days of measurable rainfall compared with 20% inside the drought area. Similarly, 59% of the surrounding area had 2 days per month with rainfall of 12.7 mm or more compared with 18% in the drought region, and 1 day with 55% coverage compared with only 13% inside the drought area. Thus, seeding opportunities are much more frequent in all categories in the sourrounding areas, and, if seeding can induce longer lasting and larger convective entities the prospects for alleviating the water deficiencies on the outer portions of drought areas would appear favorable.

Intensity of Daily Rainfalls in May-September

Similar conclusions were reached from analyses of daily rainfalls in and surrounding the May-September droughts. However, seeding opportunities, as indicated by the areal extent of light, moderate, and heavy daily rainfalls, are considerably greater than in the July-August droughts, which is in agreement with findings from various types of rainfall analyses performed in the research summarized in this final report.

Diurnal Distribution

Diurnal distributions should be considered in planning the time and duration of weather modification activities to maximize contributions from seeding effects. No major differences were found between the diurnal distributions during drought situations and average weather conditions (see Table 15). In the northern two-thirds of Illinois, the maximum amount of rainfall tends to occur in the early morning (0000-0600), whereas in the southern part there is a distinct afternoon maximum.

All diurnal analyses showed that substantial percentages of the total rainfall in the growing season occur throughout the day and night. This stresses the need to carry out weather modification operations on a 24-hour basis to take maximum advantage of seeding opportunities during droughts. At least 50% of the Illinois rainfall occurs from 1800 to 0600 CST, and approximately 25% from midnight to 0600. Based upon frequency of maximum rainfall amounts in Illinois droughts, the greatest number of seeding opportunities are likely to occur from 1500 to 2100. Studies of the diurnal distribution of cumulonimbus clouds in Illinois during 1951-1964 (Appendix A) provided further support for 24-hour weather modification operations to maximize seeding benefits.

Distribution of Storm Rainfall in July-August Droughts

Mean rainfall computations were made in each of 492 storms in the 35 July-August droughts studied in this research. From these computations, frequency distributions of mean rainfall were derived for droughts of various areal extent (see Table 16). These distributions were derived to provide a measure of the frequency of storm mean rainfalls of various intensities in droughts of various severity, as measured by area encompassed by the drought. Results showed that heavier storms tend to occur more frequently in small-area droughts. For example, storm mean rainfall equalled or exceeded 11 mm in 20% of the storms sampled on drought areas of less than 5000 km^2, whereas the equivalent mean rainfall was 6 mm in droughts extending over areas of 50,000 km^2. However, the most important contribution from this analysis is the quantitative estimates of storm mean rainfall distributions in moderate to severe midsummer droughts in Illinois and the Midwest. This information should be extremely useful in evaluating seeding potential in such situations, and consequently, in the planning of weather modification activities to alleviate agricultural water shortages.

The characteristics of drought-associated rainstorms were defined further through computation of area-depth relations for all 492 storms. Rainfall was accumulated from high to low amounts. These computations provided pertinent information on the spatial distribution of rainfall within storms. Droughts were again divided into six groups, based upon areal extent. For each drought group, median area-depth relations were developed to show the percentage of the drought area with storm rainfall amounts equalling or exceeding any chosen value (see Fig. 11). For example, in small droughts enveloping areas of 1000-4000 km^2, the median storm was found to have rainfall equalling or exceeding 10 mm over 20% of the area, 3 mm over 50% of the area, and 0.7 mm over 80% of the area. In droughts enveloping 50,000 km^2 or more, similar values were 5 mm, 0.3 mm and none. In addition to the group average relations, the median area-depth envelope relationship in each specific drought was computed and is presented in this report. Also, the area-depth relation for the heaviest storm in each drought is presented.

As another guide in the evaluation of weather modification potential in moderate to severe droughts, the area-depth relations for the 492 storms and the frequency distributions for storm mean rainfalls were used to develop a nomogram technique. This technique was used to compute the average spatial distribution of rainfall in storms of any given intensity (areal mean rainfall) over a wide range of areas (3000-75,000 km^2) in July-August droughts (see Fig. 12). This technique provides the user with a quantitative estimate of the average spatial distribution characteristics of storm rainfall in the area of interest under given conditions of drought areal extent and storm mean rainfall. This capability should be very useful both in evaluating the potential benefits of weather modification and in planning cloud seeding operations.

The nomogram technique was developed in non-dimensional terms, and is considered applicable in the Midwest, in general, and other areas of similar precipitation climate. The specific inputs required are the storm mean rainfall and size of area. These then determine the non-dimensional area-depth relation to be used for estimating the average spatial distribution of storm rainfall.

The culmination of the storm rainfall analyses was the development of relationships specifying the spatial distribution of rainfall intensities within storms during droughts of various areal extent (see Table 18). These relationships in conjunction with the number of storm occurrences per drought (also determined as a part of this study) can be used to quantitatively assess weather modification potential, provided that the user can specify his enhancement capabilities in natural storms of various intensity and area extent.

Distribution of Storm Rainfall in May-September Droughts

The computations made for the July-August droughts were repeated for the May-September droughts. Thus, the frequency distribution of storm mean rainfall was determined for the 462 storms sampled in the 14 droughts analyzed. This was followed by computations to define the spatial distribution characteristics of storm rainfall in the growing season droughts through use of area-depth relations. Finally, the frequency distributions of storm mean rainfall and the 462 storm area-depth relations were combined to provide a technique for estimating the average spatial distribution of storm rainfall given the storm mean rainfall and the areal extent of the droughts. Finally, relationships were developed for specifying the spatial distribution of rainfall intensities with respect to their frequency and areal extent in droughts of various sizes (see Table 27). All of the above analyses provide the user with valuable background information to evaluate weather modification potential benefits and to plan cloud seeding activities.

Relations between Synoptic Weather and Rainfall in July-August Droughts

The 492 storms associated with the 35 July-August droughts were classified into several basic synoptic types, depending upon whether the rainfall was associated with fronts (warm, cold, stationary, occluded), squall lines, low center passages, or non-frontal air mass activity. Analyses showed that cold fronts and prefrontal squall lines were the major contributors of the rainfall recorded in the midsummer droughts (see Tables 20, 24). These storms produced 61% of the total drought rainfall. Therefore, substantial alleviation of agricultural water shortages will be strongly dependent upon successful enhancement of the natural rainfall associated with these systems.

The frequency distribution of synoptic types was investigated for droughts stratified by areal extent to determine whether the cold front dominance persisted in all sizes of droughts. Results verified the importance of the frontal storms. No pronounced trend was found for any of the synoptic weather frequencies to increase or decrease their rainfall contribution as droughts became larger or smaller in their area of influences (see Table 22).

The relative importance of cold fronts was found to be greater in droughts than in average weather conditions. Thus, their average drought frequency was 61% of all storms, whereas their normal frequency in Illinois is 46%. Conversely, the frequency of air mass storms showed a pronounced decrease from 30% under normal conditions to only 11% in July-August droughts. This provides further evidence that cold fronts (and their pre-frontal squall systems) offer the greatest opportunity for rainfall enhancement in droughts. At the same time, indications are that seeding of unorganized air mass activity is likely to produce little enhancement over the drought areas as a whole, although it could help in isolated spots within the general drought area.

The importance of rainfall associated with cold frontal systems was brought out further in analysis of total rainfall contributions by synoptic types. Cold fronts normally contribute approximately 39% of the total rainfall during July-August in Illinois, but contributed 65% of the total in the 35 droughts studied. Air mass contribution decreased from an average of 17% normally to only 6% in droughts.

The frequency distribution of areal mean rainfall by synoptic type was determined to provide additional background information for use in assessment of weather modification potential (see Table 24). Results showed that the heaviest rainfalls tend to occur with cold front waves and with prefrontal squall lines. Stationary fronts, although relatively infrequent (16% of total occurrences), tend to produce relatively heavy areal mean rainfalls in midsummer droughts. As expected, air mass means tend to be light with their storm mean rainfalls being only about 25% of the average rainfall generated by cold front waves and squall lines.

Relations between Synoptic Weather and Rainfall in May-September Droughts

The same computations were performed as described above for the July-August droughts, and results were similar (Tables 29-33). Cold fronts were the major rain contributor in the May-September droughts, and produced total rainfall in the 14 droughts that averaged near normal for this storm type. Conversely, non-frontal air mass storms produced only 5% of the drought rainfall compared with 17% normally. Cold fronts were associated with 63% of the total drought rainfall. The relationship between drought rainfall and synoptic storm types provides another guide for use in assessing weather modification potential and in planning seeding operations.

Raincell Initiations in Wet and Dry Periods

Valuable information pertaining to rainfall characteristics during warm season droughts was obtained from analyses of raincell data obtained from the METROMEX network of 225 recording raingages for the summers of 1971-1975. These data were analyzed to determine the characteristics of raincell initiations and mergers in wet, dry, and moderate precipitation conditions. Major emphasis was placed upon dry period conditions and observed differences in the distribution characteristics between wet and dry months. Of particular interest was whether inadvertent weather modification occurred during below normal rainfall periods and, if so, how the magnitude of this effect compared with similar effects in normal to above normal rainfall periods.

Results of the analysis of raincell initiations indicate that initiations are most concentrated in and downwind of the source of inadvertent weather modification, that is, the urban-industrial areas of St. Louis and Wood River in both relatively wet and dry months (see Fig. 16). Topographic influences were also indicated with an above normal frequency of initiations along the river valleys and in the Ozark foothills. Although, urban and topographic effects are present in months of below normal, near normal, and above normal rainfall, the effect relative to the rest of the network appears to be slightly greater in relatively dry months. This provides positive evidence that convective activity can be stimulated to some extent by weather modification in dry periods. Success in alleviating agricultural water shortages would depend upon whether the increased number of raincells result in beneficial increases in surface rainfall. This cannot be determined from the raincell analyses performed here.

Surface Raincell Mergers

Analyses were made of the characteristics of raincell mergers in the METROMEX network during the summers of 1971-1975. Particular attention was given to differences in the frequency and locations of mergers in relatively wet and dry periods, since mergers are usually associated with increases in the intensity and areal extent of storm rainfall. It was of particular concern whether mergers were favored by inadvertent weather modification mechanisms, particularly urban influences, during dry periods (below normal rainfall). If so, this would provide further evidence of the feasibility of enhancing storm rainfall during drought periods.

Results indicated a relatively strong tendency for mergers to occur most frequently in a major urban-effect area E and NE of St. Louis, along river valleys, and, to a lesser extent, in the more hilly regions of the METROMEX experimental area (see Fig. 18). In general, there was strong association between the spatial distribution of mergers and total monthly and seasonal rainfall. Location of maximum activity did not vary significantly between dry, wet, and near normal months of rainfall.

Comparison of rainfall in regions of greatest merger concentrations indicated that the urban-related mergers tend to intensify the ongoing rainfall processes more than topographic-related mergers. A favorable finding from the standpoint of planned weather modification is that merger processes (which are closely related to the rain enhancement processes) were as active in dry as in wet months and are apparently stimulated by inadvertent weather mechanisms. That is, it indicates that weather modification may stimulate rain production under favorable conditions during periods of agricultural water shortages.

Comparison of Wet and Dry Period Patterns on METROMEX

Data for the summers of 1971-1975 from the METROMEX network of 225 recording raingages in 5200 km^2 were used to obtain very detailed comparisons of rainfall patterns in relatively wet, dry, and moderate rainfall periods. This was done to assess differential effects of inadvertent weather modification on surface rainfall during such periods, with major emphasis upon dry period effects. The 15 summer months were divided into groups of. three each to represent relative degrees of dryness and wetness, with the principle analyses performed on the three driest and three wettest months. Investigation was made of both the frequency of rainy days and total rainfall in the three groups of months.

In general, results showed that inadvertent weather mechanisms energized by the urban environment and certain topographic features are operating under all types of precipitation climate. During dry months, a trend for rainfall to occur more frequently along river valleys, in hilly regions, and in heavily urbanized areas was noted (see Fig. 22). The heaviest rainfall during dry months also tended to occur in and downwind (east) of the St. Louis urban area and near certain topographic features (see Fig. 23). These findings are also favorable from the standpoint of weather modification potential, since they indicate enhancement of the natural rainfall during dry periods by weather modification forces (inadvertent in this case). The results also suggest that certain topographic and land use features (river valleys, hills, urban areas) are favorable regions to initiate weather modification activities during dry periods.

Summer Drought of 1971 on the METROMEX Network

Detailed rainfall data from the METROMEX network were used to study the characteristics of the rainfall distribution in 1971 which was the driest of the five summers during the METROMEX project. Seasonal rainfall was only 63% of normal and monthly percentages ranged from 21 to 115% of normal.

Overall, the outstanding finding was that the dry summer was strikingly similar to other summers with respect to monthly and seasonal spatial patterns of rainfall, distribution of rainfall highs and lows, initiation and merger regions, heavy rainstorm patterns, and production of the major anomaly near Edwardsville in a relatively few storms. The major difference, and one that helps explain the relatively light rainfall in 1971, was that the most prolific rain producer, squall lines, occurred with only 50% of their normal frequency. All findings lead to the conclusion that the basic precipitation processes are functioning similarly in relatively dry, near normal, and wet periods in a given area, but the frequency and productivity are below average in dry periods. This is another encouraging finding from the standpoint of planned weather modification, especially since urban inadvertent weather processes appeared to be working during the dry summer of 1971.

GENERAL CONCLUSIONS

1. Analytical results have been presented which describe the natural rainfall distribution in droughts of various severity in Illinois, a typical midwestern state. Relationships have been provided between storm mean rainfall, areal extent of storm rainfall, rainfall intensity, and drought size (severity) on the basis of frequency of occurrence. Synoptic weather conditions under which drought rainfall occurs most frequently, its diurnal distribution, and other factors pertinent to planned weather modification have been discussed also. This information can be used to evaluate weather modification potential and to plan cloud seeding operations, provided that the weather modifier can specify his enhancement capabilities under various combinations of natural weather conditions, and that the agriculturist can define the economic benefits that would be derived from the specified enhancement.

2. Various climatological analyses of rainfall characteristics in growing season droughts indicate that opportunities for alleviating agricultural water shortages through planned weather modification do exist. Despite the large deficiencies in total rainfall in Illinois droughts, storms do occur that produce measurable rainfall on the average of once every four to five days.

During the most critical months of July and August, 50% of the drought-associated rainstorms produce measurable rainfall(0.25 mm or 0.01 in.) over approximately 50% of the drought areas in the larger, more severe droughts extending over 50,000 km^2 or more within the state. In spot droughts encompassing areas of less than 5000 km^2, 50% of the drought storms produce measurable amounts over approximately 90% of the drought area.

The May-September droughts (as defined in this study) tend to incorporate more area, but to have less deficient rainfall than the midsummer dry periods in July and August. In these droughts in Illinois, measurable rainfall was found to extend over approximately 70% of the drought area in 50% of the storms on large drought areas exceeding 80,000 km^2. In smaller area droughts encompassing less than 50,000 km^2, 50% of the storms produced measurable rainfall over approximately 90% of the drought region.

3. Assuming weather modification success is dependent largely upon enhancing ongoing rainstorms, substantial increases in the natural rainfall are most likely to be achieved through cloud treatment of organized storm systems, and in particular, cold frontal systems and their associated squall lines. These account for approximately two-thirds of the drought-period rainfall during July-August. Conversely, increases from treatment of non-organized air mass activity are likely to be negligible over an extensive drought region, although some minor alleviation might be accomplished in small spots (a few farms, perhaps) within the overall drought region.

4. Seeding should be conducted on a 24-hour schedule in the Midwest; otherwise, a large portion of the storm enhancement opportunities is likely to be missed. For example, in Illinois approximately 50% of the growing season rainfall occurs in the evening and night (1800-0600 CST) and 25% occurs from midnight to 0600 CST.

5. Analyses of METROMEX data provide additional evidence that weather modification should be successful to some degree, at least, in dry summers when agricultural water shortages develop. Analyses of inadvertent weather characteristics in the densely gaged network of 225 recording raingages in 5200 km^2 show that the spatial distribution patterns of raincell initiations, raincell mergers, and surface rainfall are similar in dry, wet, and moderate rainfall periods, and that the inadvertent processes are as active proportionally in dry as in wet periods. Dry periods appear to be caused to a large extent by a decrease in frequency of the more intense type of synoptic systems.

6. In evaluating the weather modification potential of cloud seeding operations, close attention should be given to the precipitation characteristics of the region to achieve realistic quantitative estimates. The use of the combination of storm mean rainfall probabilities and spatial distribution characteristics are especially helpful in making such estimates.

7. Precipitation climatological studies emphasizing those parameters which can be useful in the planning and evaluation of weather modification activities should be undertaken for various climatic regimes in the country.

APPENDIX A - CLOUD CLIMATOLOGY

The natural distribution of clouds associated with the occurrence of precipitation during the warm season and the critical crop-growth months of July and August was determined from hourly cloud observations. Such data provide pertinent background information regarding the availability of clouds for weather modification operations, plus valuable climatic data for various other uses. The cloud data was obtained from hourly observations of cloud type and cloud amount taken from 1951 to 1964. Between 1949 to 1951 and after 1964 such cloud data were available only every three hours. Chicago, Moline, Springfield, Indianapolis, St. Louis, and Evansville (all in or near Illinois) had such data for the 14-year period. Complete 24-hour observations did not begin at Peoria (PIA) until September 1956. The PIA cloud observations provided guidance and supplemented the analysis of cloud data from the other six stations.

The cloud data at each station were stratified according to the normality of monthly precipitation. Cloud observations at any observing site are generally representative of the cloud distribution in the region surrounding the observation point. Therefore, the average monthly precipitation was based upon six to eight stations within a 48-km radius of the surface observation point. Months with less than 80% of normal precipitation were classified as dry; moderate or near normal months included those having between 80 and 120% of normal precipitation; and when more than 120% of normal rainfall fell, the month was considered to be wet.

Only those clouds associated with the major precipitation process, and which are indicative of the low- and middle-level moisture patterns during the warm season were analyzed. During summer, the dominant precipitation process in Illinois is convective, and is associated with cumulonimbus (Cb) clouds (Changnon and Huff, 1957). The low-level moisture pattern on convective days is best described by cumulus (Cu) clouds, while altocumulus (Ac) and altostratus (As) clouds describe the middle-level moisture pattern. Since As clouds are often associated with Ac clouds it was decided to combine these two middle-level cloud types.

The data were limited by fixed surface observation points at each station; i.e., if the celestial horizon was obscured by the occurrence of fog or other surface-based phenomena, the ground observer was unable to determine if clouds were above the obscuration. Neither could the observer determine if Ac or As clouds were above an overcast layer of low clouds.

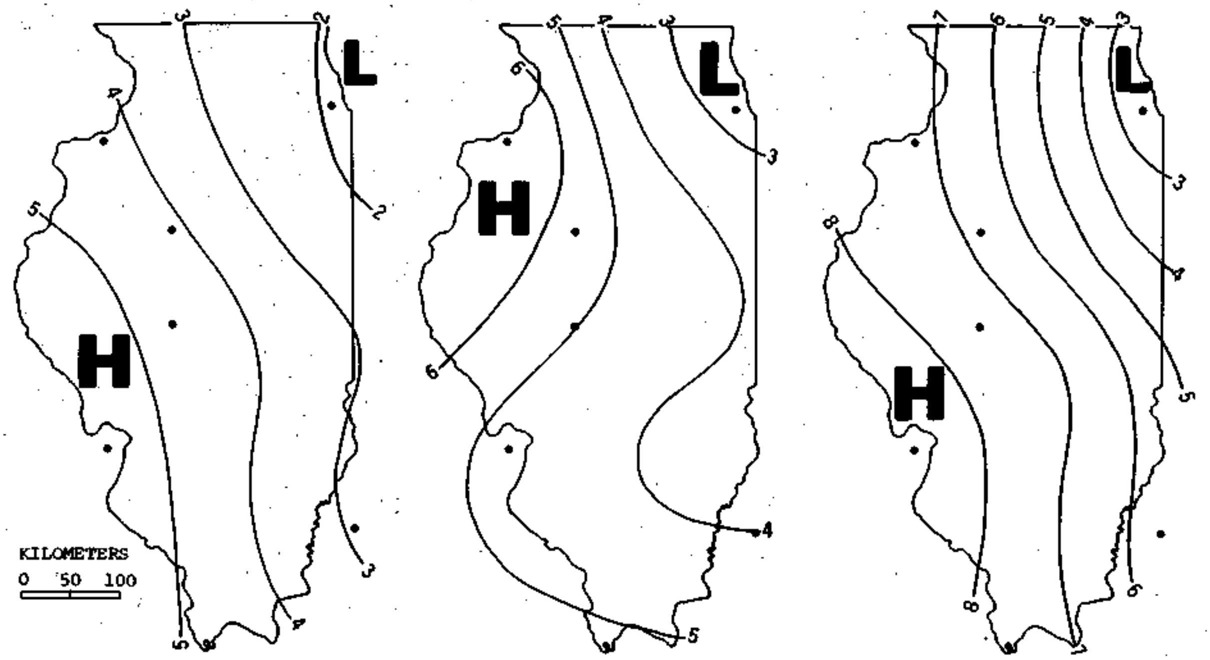
Other restrictions to the data set were the limitation of nighttime observations. After sunset the total sky cover and the cloud layer is difficult to measure or determine, especially if more than one cloud layer or cloud type exists. Another restriction occurred in the reporting of cloud types. The observer was instructed (Anom, 1951; Anom, 1955; Anom, 1961) to report the dominant cloud type. For example, if 0.2 of the sky cover was Ac and 0.4 was As, the dominant cloud type reported was As. An exception to this rule occurred in the reporting of Cb clouds. Regardless of what portion of the sky was covered with Cb clouds, it was reported as the dominant cloud type if the clouds had the same cloud base. For example, if 0.6 of the sky was obscured by Cu and a single Cb with the same base height, the dominant cloud type for this layer was reported as Cb. With these limitations, the data and analyses which follow are indicative only of the general climatic distribution of precipitation-associated clouds during the warm season.

Cloud Frequencies and Coverage

The monthly frequency of hourly observations of clouds and cloud amounts are presented for the July-August period in Figs. A-1 to A-6. The frequencies are given as the percent of total possible monthly hourly observations. For example, in a 30-day month, it is possible to observe each cloud type 720 times. If this cloud type was observed 72 times the percent of total possible observations would be 10%. The amount of cloud cover for each cloud type is expressed as the percent of total possible sky cover. Since the cloud amounts were recorded in terms of tenths of sky cover, in a month of 720 hourly observations it would' be possible to have 7200 tenths of cloud cover from a cloud type. If 720 tenths of cloud cover were observed within such a month, the coverage is expressed as 10%.

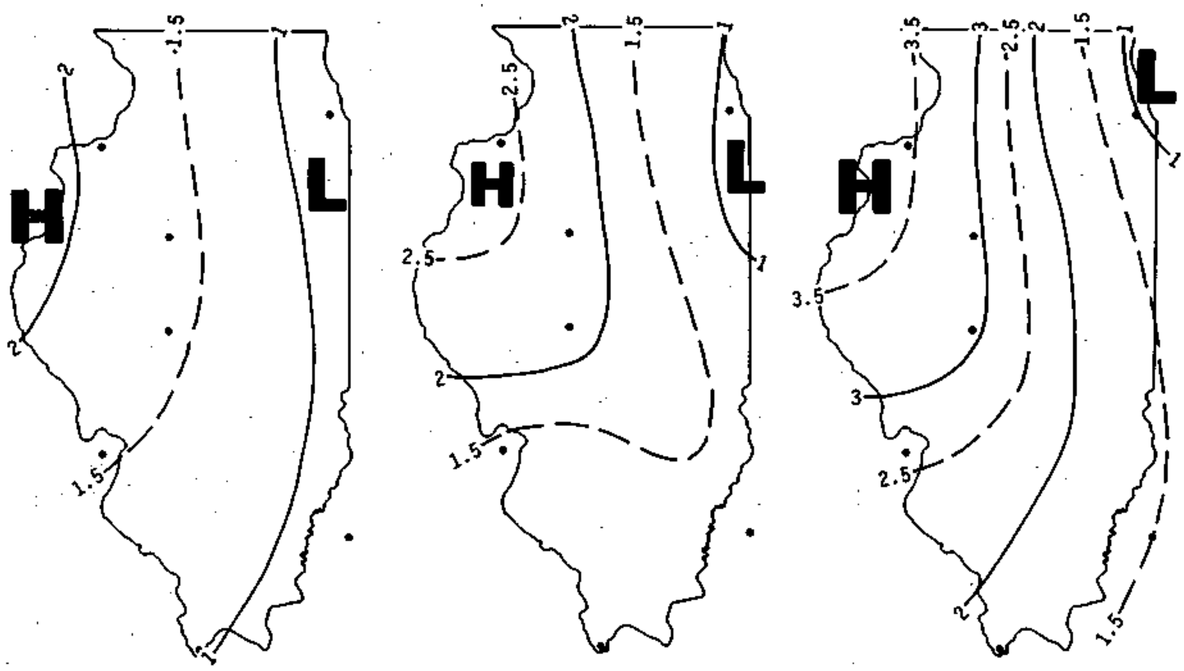
Figure A-l shows the spatial distribution of cumulonimbus over Illinois during the critical growing period of July and August for dry, moderate, and wet months. A general west to east decrease in the number of Cb observations for the three monthly types was found. The lowest frequency of observations for dry, moderate, and wet months was in the NE part of Illinois. This in part is a lake effect. During July and August, Lake Michigan is colder than the surrounding land surfaces for most of the day (Changnon, 1968). Consequently, the lake acts as a deterrent to the generation and maintenance of convective clouds during the warm months. In the dry and wet months, the maximum number of Cb observations was over SW Illinois. During moderate months the maximum frequency of Cbs shifted to west central Illinois. These areas are subject to topographic effects from the Mississippi River valley and the Ozark foothills. The average frequency of Cb clouds over Illinois varied from 3.6% in the July-August dry months to 5.8% in the wet months.

The July-August Cb sky coverage is shown in Fig. A2. A general west to east decrease in cloud coverage for all three monthly types is noted, similar to the frequency pattern shown in Fig. A-l. However, during dry and wet periods the maximum Cb cloud coverage occurred over west-central and NW Illinois, instead of SW Illinois. Also, during the dry months the Cb coverage is similar from N to S. During dry months, the Cb clouds observed over the northern part of Illinois are often associated with convective systems, such as cold fronts or squall lines. Over the southern part, more air mass storms and many isolated Cbs usually occur in dry periods. Cb coverage varied little over the eastern portion of the state from dry to wet months. The largest variation in Cb coverage was experienced over west Illinois, where the coverage at Moline (MLI) varied from 1.8% during dry months to 3.5% in wet months. During dry periods, Cb clouds are nearly twice as frequent in western Illinois as in eastern Illinois.



a. Dry months b. Moderate months c. Wet months

Figure A-1. Monthly Percentage Frequency of Cumulonimbus during July-August of 1951-1964.



a. Dry months b. Moderate months c. Wet months

Figure A-2. Monthly Percentage Frequency of Cumulonimbus Sky Coverage during July-August of 1951-1964.

The Cb frequency during the warm season has the same general pattern as July-August. The major difference was a maximum in wet months over west-central, instead of southwestern Illinois. The Cb frequency was somewhat less. Changnon and Huff (1957) have shown that Cb clouds in Illinois occur most frequently during June or July. The number of occurrences during August falls off slightly, but during May and September the Cb frequency was 40 to 60% of the maximum month.

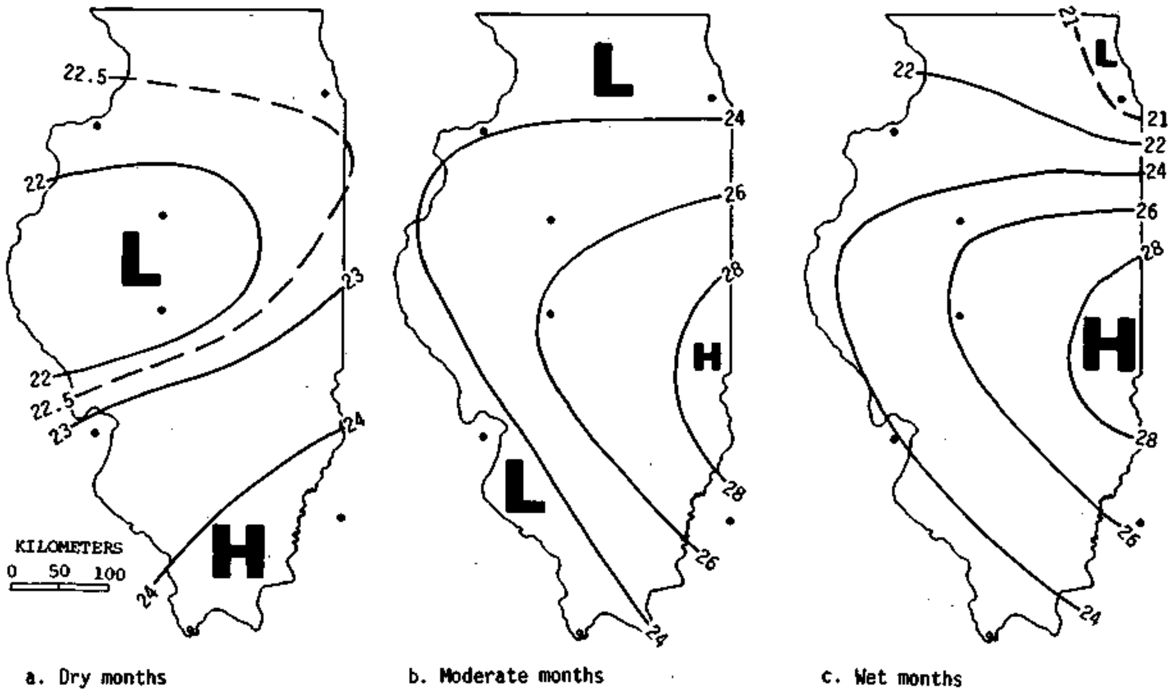
The amount of Cb sky coverage during the May-September period was nearly identical to that exhibited in Fig. A-2 for July-August. The same overall pattern for dry, moderate, and wet months was observed, with only minor variations in the percent of cloud coverage observed, usually less than 0.2%.

The frequency of Cu during the critical growing period of July-August is illustrated for Illinois in Fig. A-3. These clouds are indicative of the low-level moisture field on days when Cb clouds normally occur. The spatial pattern for the dry months indicated a minimum of occurrences over west-central and a maximum over southeastern Illinois. The average statewide coverage was 23%. During moderate and wet months, there was a general west to east increase of Cu with a maximum near the SE corner, and an average state coverage of 25%. Only minor differences in the frequency of Cu from moderate to wet years were indicated. Thus, the pattern of low-level moisture during moderate to wet months appears to be similar. The low-level moisture pattern in dry months over the southern third of the state does not appear to be markedly different in moderate, and wet months, but shows a decrease in the northern part in dry periods.

Figure A-4 presents the percent of possible Cu coverage for the critical growing period. During dry periods, a minimum was observed across the central Illinois, analogous to the dry period frequency pattern. Thus, there was a trend for less low-level moisture over central than over northern or southern Illinois during dry periods. The Cu pattern over the state was similar during moderate and wet months with only minor differences in the amount of sky cover.

During the dry months of May to September, Cu exhibited a minimum over NE and a maximum over SE Illinois with a general increase in frequency from N to S. The dry pattern showed only a slight N-S gradient over the southern two-thirds of the state. The Cu frequency pattern for moderate and wet months was quite similar to the July-August pattern. The statewide May-September Cu frequency for the May-September period varied from 19% in dry months to 21% in wet months, or a difference of only 14 hourly observations in each month. The pattern of percent of possible sky coverage for Cu clouds during the warm season was similar to the July-August pattern.

The frequency of Ac and As clouds during the critical growing period are shown in Fig. A-5. Dry, moderate, and wet months showed a maximum occurrence of middle clouds across central Illinois, with minima over the northern and southern parts of the state. The frequency of Ac and As clouds was 33% during dry months. The percent of possible occurrences was 3% higher for moderate months, and 5% for wet months. These clouds give indications of the amount of moisture which might be expected between 2.5 to 6 km.

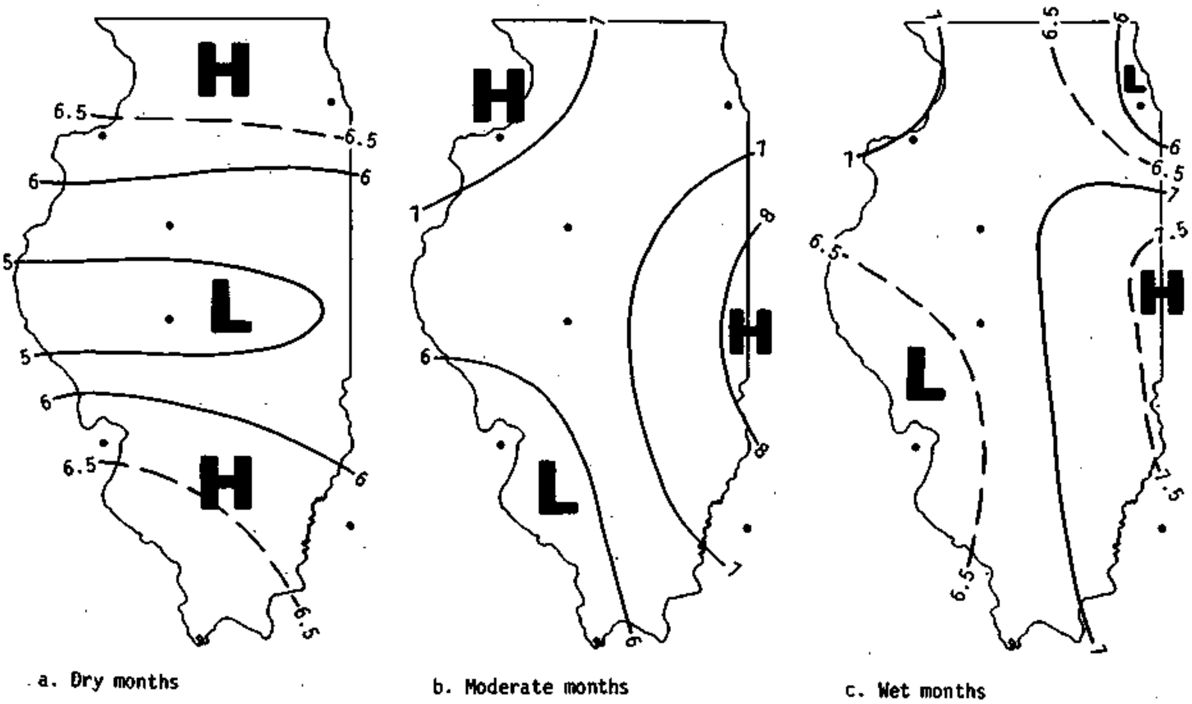


a. Dry months

b. Moderate months

c. Wet months

Figure *A-3. Monthly Percentage Frequency of Cumulus during July-August of 1951-1964.*

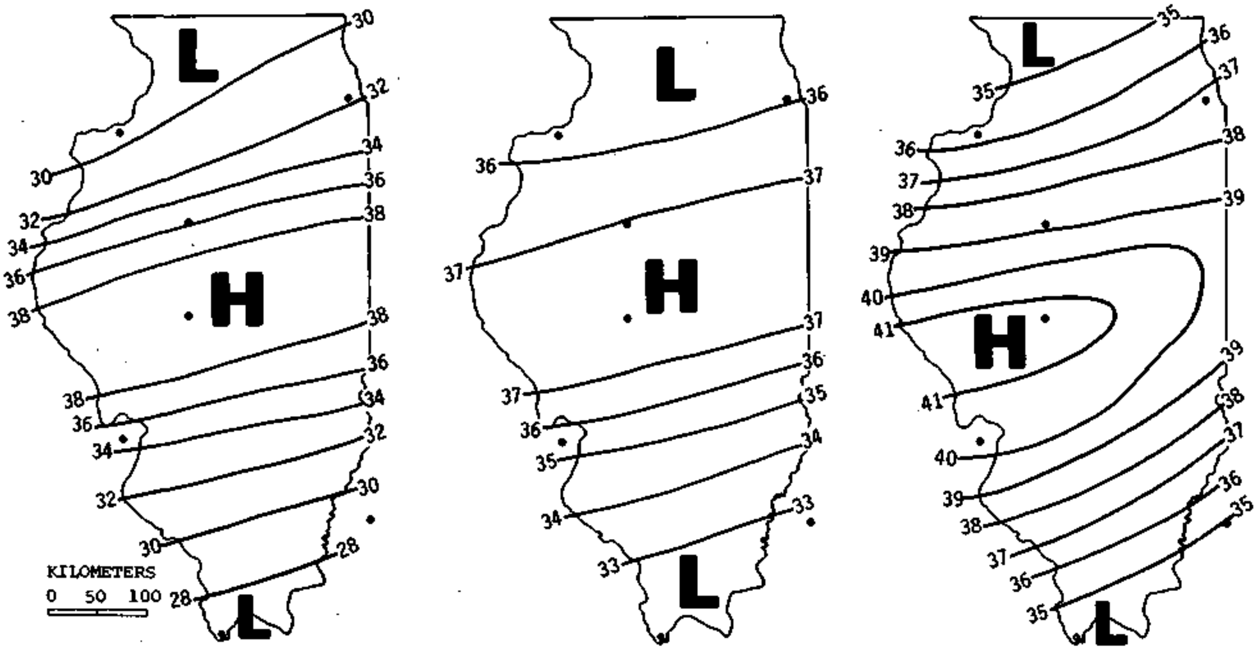


a. Dry months

b. Moderate months

c. Wet months

Figure A-4. Monthly Percentage Frequency of Cumulus Sky Coverage during July-August of 1951-1964.

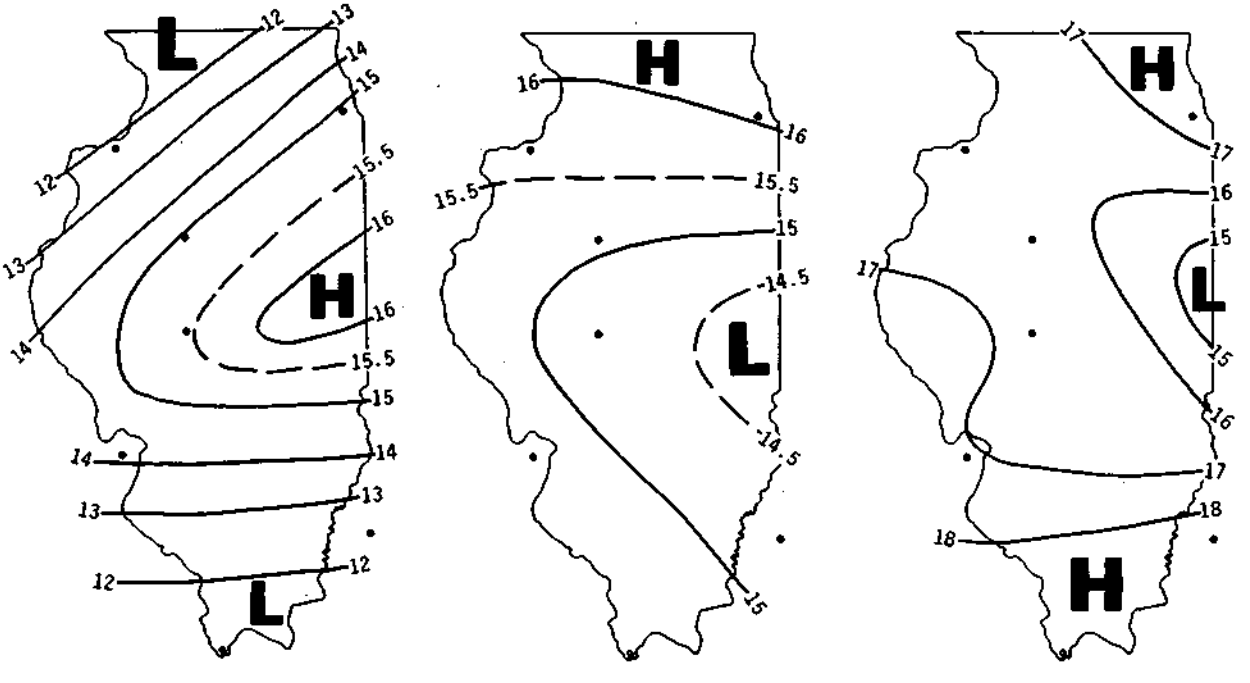


a. Dry months

b. Moderate months

c. Wet months

Figure A-5. Monthly Percentage Frequency of Middle Clouds during July-August of 1951-1964.



a. Dry months

b. Moderate months

c. Wet months

Figure A-6. Monthly Percentage Frequency of Middle Cloud Sky Coverage during July-August of 1951-1964.

The middle layer cloud coverage for July-August is illustrated in Fig. A-6. The dry period coverage indicated a maximum of middle-level coverage over east-central Illinois, agreeing well with the dry period frequency pattern. However, the middle-level coverage in moderate and wet periods showed a minimum across central Illinois, with maxima situated over N and S Illinois.

The Ac and As frequency pattern for May to September was similar to the July-August pattern, with maxima over central Illinois in dry, moderate and wet months. The middle-level sky cover during this period indicated a general maximum of cloudiness over the northern and southern parts of the state. There is general agreement in both the May-September and July-August periods of a frequency maximum across central Illinois, but the greatest Ac and As cloud coverage occurred over the northern part of the state.

Diurnal Distribution of Cumulonimbus Clouds

The dominant precipitation types during both July-August and May-September are convective showers and thunderstorms. Thus, it becomes important to identify the diurnal distribution of Cb clouds to determine climatologically the temporal variation in weather modification potential. The diurnal distribution for July-August and the growing season were determined for the six reporting stations in and near Illinois and stratified by dry, moderate, and wet months.

Figure A-7 presents the diurnal curve of Cb activity during July and August for dry, moderate, and wet periods at Springfield. The curves show the 3-hour moving average of the monthly Cb frequency for each hour. These curves are typical of data from other observing stations. There was a general decrease in the frequency of hourly Cb observations from west to east, otherwise, the curves showed little difference between stations. During the critical growing period of July-August the moderate and wet months exhibited similar characteristics with a minimum of Cb activity between 1000 to 1100 CST, followed by a rapid increase in activity and peaking in the late afternoon to early evening (1800 to 2100 CST). Secondary maxima were observed from midnight to 0700 CST. On the average, 64% of all July-August Cb activity during moderate and wet months occurred during the night hours from 1800 to 0600 CST.

During dry periods, the diurnal curves also has a late morning minimum (1000 CST), but the Cb activity tended to maximize 1 to 3 hours earlier during the mid-afternoon to early evening (1500 to 1900 CST). During dry periods, 53% of all Cb activity occurred during the night hours and 47% during the daytime. Thus, a majority of the convective cloud activity during July-August dry periods occurs during the night hours from 1800 to 0600 CST. Thus, cloud seeding operations after sunset are required to take advantage of those periods with the most frequent occurrence of atmospheric conditions favorable for rain production.

The Springfield Cb curve for May-September is shown in Fig. A-8. The curves during May-September were generally similar to those for July-August with mid-morning minima between 1000 and 1100 CST, and primary maxima during the mid- to late-

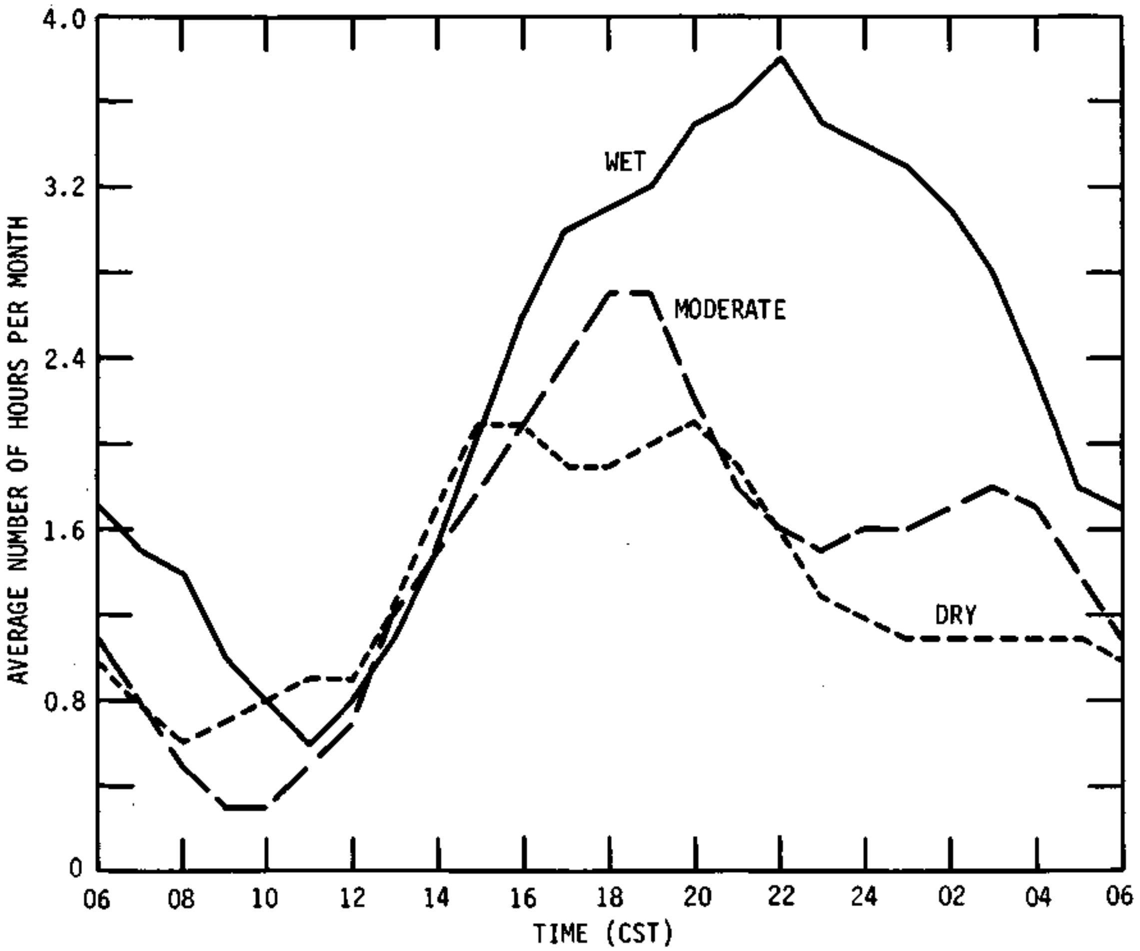


Figure A-7. Diurnal Frequency of Cumulonimbus Clouds at Springfield during July-August, 1951-1964.

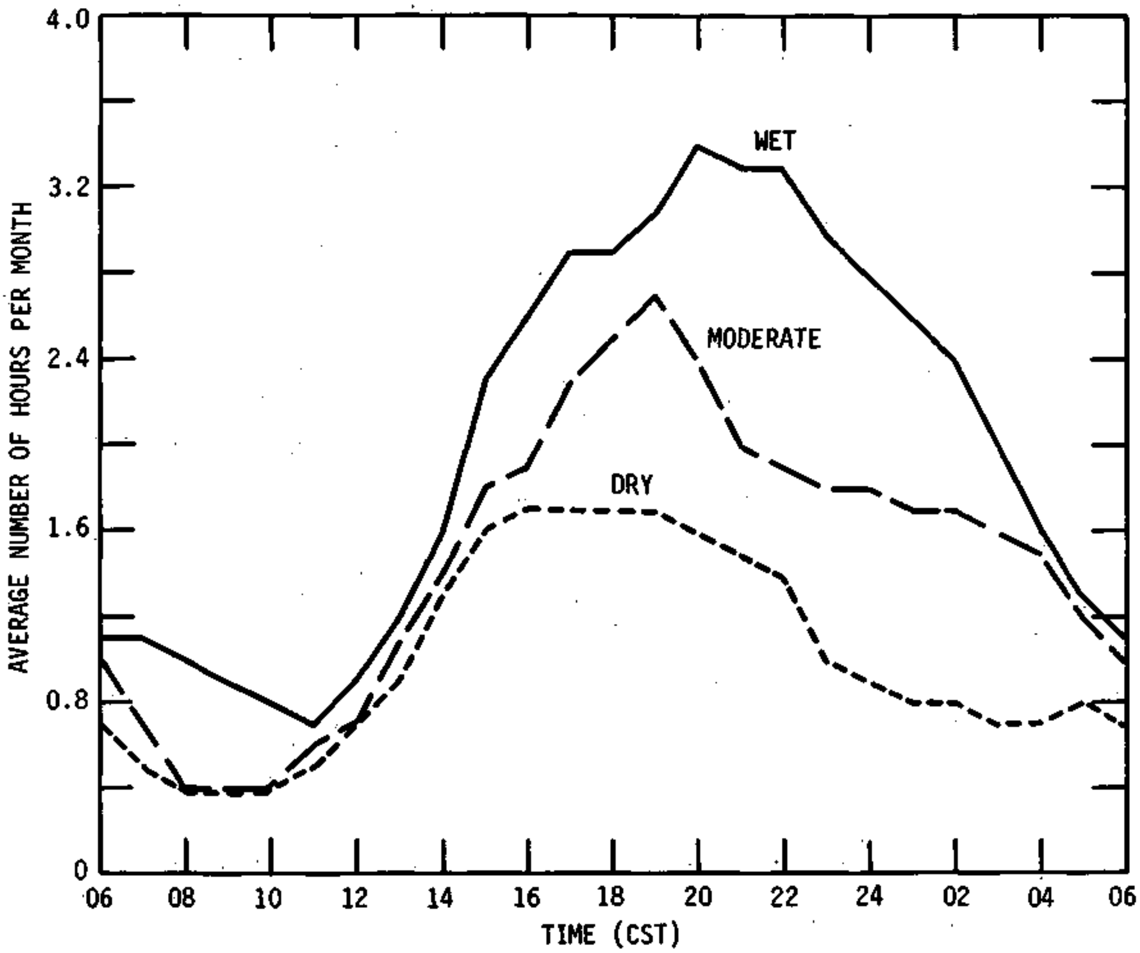


Figure A-8. Diurnal Frequency of Cumulonimbus Clouds at Springfield during May-September, 1951-1964.

afternoon in dry periods and during the evening hours in moderate to wet periods. In the moderate to wet periods, 62% of the Cb activity occurred during the night hours, and 58% of it occurred from 1800 to 0600 CST in dry months.

The diurnal frequency curves of Cb clouds agrees well with the diurnal frequency of thunderstorms over Illinois (Changnon, 1968). The diurnal trend in summer precipitation found by Huff (1971) for Illinois showed maxima in rainfall between midnight and 0800 CST and in the late afternoon to early evening hours. However, in all but extreme southern Illinois the primary rainfall maximum occurred in the early morning hours rather than the afternoon or evening. Also, Huff (1976c) determined that during the summer, cold fronts and all fronts maximized over east-central Illinois during the mid-morning (0700 and 0800 CST respectively), with a secondary maximum at 1900 CST. Since all of these weather phenomena are interrelated, the diurnal maxima of Cb clouds, thunderstorms, rainfall, and frontal passages are all closely related. The associated maxima of fronts and Cb clouds in the early morning and late evening help explain the primary and secondary rainfall maxima observed in the morning and evening hours across the state.

Organized weather systems are largely responsible for warm season rainfall in Illinois and these systems often have Cb clouds and thunderstorms associated with them. The maximum of Cb clouds during the late afternoon and early evening apparently results from a combination of unorganized air mass storms and organized weather systems (fronts, lows, etc.). The dry period Cb maximum in the mid-afternoon is probably produced largely by thermally induced air mass storms.

Summary

The climatological statistics of cloud frequency and coverage for a given region provide useful background information for evaluating the potential of planned weather modification. The statistics for dry periods are especially useful for this purpose. The Cb statistics indicate where the natural convective processes are most active. Thus, in Illinois it has been shown that Cb activity tends to be greatest in the western and southwestern parts of the state where potential enhancement by topographic features (hills and Mississippi River) is present. However, the low-level moisture supply, as indicated by the Cu statistics, tends to be greatest in the east to southeastern part of the state which is frequently downwind of the Ohio and Wabash River Valleys. The middle clouds provide a measure of the middle-layer moisture patterns, and are, therefore, helpful in evaluating relative differences in weather modification potential between different areas. Thus, in Illinois the statistics provided in this report show that the middle-layer clouds tend to occur most frequently over the central part of the state in dry, moderate, and wet months, and that total coverage maximizes also during dry periods in the central region. However, coverage is greater in the northern and southern regions of the state during moderate to wet months.

Analyses of the diurnal distribution of Cb clouds for 1951-1964 showed that rain-producing clouds occur more frequently in the night hours (1800-0600 CST) than in the daylight hours (0600-1800). This compares favorably with findings in earlier studies of the diurnal distribution of rainfall in Illinois, and stresses the need to conduct weather modification operations on a 24-hour basis to achieve maximum benefits from cloud seeding to alleviate surface water shortages.

APPENDIX B - UPPER AIR CLIMATOLOGY

Monthly Temperature and Moisture Characteristics

Analyses of the temperature and humidity characteristics of the lower troposphere were made to determine if significant differences existed in their average distribution among summer months having precipitation ranging from much below to much above normal. The lower layers of the atmosphere control the stability characteristics and serve as the moisture source for summer rain systems. Daily thermodynamic features are sometimes used in conjunction with one-dimension, steady state cloud models to determine the potential of cloud seeding within a given region (Simpson et al., 1971; Smith et al., 1974).

The thermal and moisture characteristics of the lower troposphere were determined at Peoria and Salem (see Fig. 1) for the period from 1971 to 1975. Soundings were taken twice a day at 0600 and 1800 CST. Humidity data from 1962 to 1970 was questioned because of possible bias toward lower humidity due to the incidence of solar radiation on the carbon humidity element (Morrissey and Brousaides, 1970). For this reason it was decided not to use these years. June, July, and August were chosen because during these months the frequency of cumulonimbus clouds maximize over Illinois (Changnon and Huff, 1957), and this is the type of cloud which is operationally seeded by weather modifiers. These three months display similar thermodynamic distributions, and two of the months are part of the critical period for agriculture in Illinois. The various analyses were stratified by the percent of normal precipitation which fell in a 48-km radius of each of the upper-air observing stations.

Months were classified as follows: Very dry if the average areal precipitation was equal or less than 50% of normal; moderately dry for 50 to 80% of normal; near normal if the precipitation was between 80 to 120% of normal; above normal if greater than 120% but less than 160%; and, much above normal if precipitation in excess of 160% of normal fell. The number of months Salem and Peoria experienced these rainfall types are given in Table B-1.

Table B-1. Salem and Peoria Rainfall Types by Months.

	Salem	Peoria
Very Dry	3	5
Moderately Dry	1	0
Near Normal	5	2
Above Normal	2	3
Much Above Normal	4	5

Monthly averages of temperature and humidity for various layers of the atmosphere from the surface to 400 mb were calculated. This was done to determine if a discernible difference in the moisture and temperature distribution could be detected in summer months which varied from very dry to very wet. Tables B-2 to B-4 present mean monthly average temperature and various measures of humidity for Salem and Peoria. These measurements were obtained for a number of layers from the 0600 and 1800 CST soundings. The five layers used in these computations for all parameters except precipitable water were 1) surface to 850 mb, 2) 850 to 700 mb, 3) 700 to 500 mb, 4) surface to 700 mb, and 5) surface to 500 mb. For precipitable water calculations the first three layers were the same, and the last two layers were the surface to 500 mb and the surface to 400 mb. This was done to indicate the mean depth of precipitable water available in the lower atmosphere.

Huff and Changnon (1963) have shown that severe three-month droughts in Illinois are associated with monthly surface temperature that are above normal. One would expect that during abnormally dry periods the temperature in the lower portion of the atmosphere would be relatively higher.

The mean monthly temperatures for the various layers at Salem and Peoria for both 0600 and 1800 CST showed only minor differences among months having very dry to much above-normal precipitation (Table B-2). At Peoria there was a trend for warmer temperatures during very dry months and cooler temperatures during much above-normal months. One would expect warmer temperatures during dry or drought periods, especially in the lowest layers of the atmosphere. Such a trend was not evident at Salem, while Peoria exhibited only slightly warmer temperature (1.3°C) in the surface to 850 mb layer. In the layers above 850 mb only minor temperature variations were noted with no discernable trend.

The mean monthly relative humidity (%) and saturation deficit (g/kg) are presented in Table B-3. The relative humidity at both Peoria and Salem in the surface to 850 mb layer exhibited little indication of any change during months with varying precipitation. Only a 4 to 5% difference in relative humidity was noted in the lowest layer, and the lowest relative humidity was not recorded during very dry months. The other layers at 0600 CST showed little difference in relative humidity.

Table B-2. Mean Monthly Temperatures at Peoria and Salem for 0600 and 1800 CST During June to August 1971 to 1975.

	Mean Temp (°C)				
	Sfc-850	850-700	700-500	Sfc-700	Sfc-500
Salem 0600 CST					
Very Dry	18.0	11.1	-0.9	14.5	8.2
Moderately Dry	18.3	10.5	-2.2	14.3	7.6
Near Normal	18.7	11.8	-0.3	15.1	8.1
Above Normal	18.5	10.7	-2.2	14.5	9.2
Much Above Normal	18.3	11.0	-1.3	14.6	8.1
Salem 1800 CST					
Very Dry	22.0	11.7	-0.3	16.9	10.0
Moderately Dry	21.3	11.0	-1.7	16.2	9.0
Near Normal	21.8	11.5	-0.7	16.7	9.7
Above Normal	22.1	12.4	0.3	17.3	10.4
Much Above Normal	21.3	11.7	-0.6	16.5	9.6
Peoria 0600 CST					
Very Dry	18.2	11.3	-1.4	14.6	8.1
Near Normal	17.5	10.0	-2.7	13.6	7.1
Above Normal	16.5	9.7	-2.4	13.0	6.7
Much Above Normal	17.5	10.3	-2.0	13.8	7.4
Peoria 1800 CST					
Very Dry	21.9	11.9	-0.6	17.0	9.9
Near Normal	20.7	10.5	-2.1	15.6	8.5
Above Normal	20.2	10.6	-1.4	15.6	8.6
Much Above Normal	20.6	10.8	-1.3	15.7	8.9

Table B-3. Mean Monthly Relative Humidity and Saturation Deficit at Peoria and Salem for 0600 and 1800 CST for June to August, 1971-1975.

	Mean Relative Humidity (%)					Mean Saturation Deficit (g/kg)				
	Sfc-850	850-700	700-500	Sfc-700	Sfc-500	Sfc-850	850-700	700-500	Sfc-700	Sfc-500
Salem 0600 CST										
Very Dry	68.0	51.0	35.0	59.7	49.7	4.8	5.3	4.0	5.0	4.6
Moderately Dry	67.0	54.0	49.0	61.0	56.0	4.9	4.8	3.0	4.9	4.1
Near Normal	72.4	57.2	41.2	55.6	55.6	4.3	4.7	3.5	4.4	4.0
Above Normal	70.5	54.0	38.5	52.0	52.5	4.8	5.3	4.2	5.0	4.6
Much Above Normal	71.8	52.0	38.3	62.0	56.5	4.3	5.3	3.8	4.7	4.3
Salem 1800 CST										
Very Dry	52.6	47.3	32.0	48.0	42.0	9.5	5.9	4.4	7.4	6.3
Moderately Dry	56.0	56.0	43.0	55.0	50.0	8.4	5.0	3.4	6.9	5.5
Near Normal	59.2	55.8	39.0	56.8	49.6	8.0	5.1	3.9	6.7	5.6
Above Normal	62.5	55.0	38.5	57.5	50.0	7.5	5.4	4.3	6.7	5.7
Much Above Normal	61.8	51.5	37.3	56.3	48.8	7.1	5.6	4.0	6.4	5.5
Peoria 0600 CST										
Very Dry	69.0	57.0	40.0	60.2	52.2	5.8	5.7	3.5	5.7	4.8
Near Normal	71.0	57.0	46.0	64.0	57.0	4.1	4.5	3.0	4.2	3.7
Above Normal	65.7	50.7	37.3	58.0	50.7	4.6	5.0	3.6	4.8	4.2
Much Above Normal	69.4	55.2	40.8	62.2	53.8	4.5	4.8	3.4	4.6	4.1
Peoria 1800 CST										
Very Dry	57.0	50.6	38.2	52.0	46.8	8.5	5.8	3.9	7.4	5.7
Near Normal	62.0	57.5	41.5	59.0	52.0	6.8	4.6	3.5	5.9	4.9
Above Normal	56.0	49.7	37.0	51.0	45.7	7.8	5.4	3.9	6.8	5.6
Much Above Normal	63.6	57.6	42.4	59.6	52.4	6.7	4.8	3.5	5.9	5.0

The soundings for 1800 CST at Salem showed higher relative humidities in the lowest layer in months having near normal to much above-normal precipitation. At all levels below 500 mb the lowest relative humidities was recorded in very dry months. At Peoria the lowest relative humidities at all levels below 700 mb occurred in months having above-normal rainfall. The relative humidity within the very dry months followed closely.

The saturation deficit is a direct measure of the amount of water vapor needed to produce saturation in the ambient atmosphere; that is, the drier the air the greater the saturation deficit. The morning sounding at both stations showed that the saturation deficit was relatively high from the surface to 700 mb (Table B-3). This same trend apparently held throughout the day. The evening soundings indicated that very dry months had the highest saturation deficit at all levels, and that more moisture was needed to bring the ambient temperature to saturation. Thus, to bring surface air parcel to the Level of Free Convection (LFC) more energy must be supplied dynamically to support convective storms. However, the saturation deficit values at Peoria were quite mixed with only minor differences between very dry and above normal months.

Table B-4 presents actual measures of the water vapor contained in the lower atmosphere; these are the mixing ratio (g/kg) and precipitable water depth (cm). The mixing ratio and precipitable water measurements at Peoria showed little difference between very dry, near-normal, and much above-normal months. The driest months at all levels were those with above-normal precipitation. These same months at Peoria had the lowest average relative humidity and some of the larger monthly saturation deficits.

At Salem, less precipitable water and the lowest mixing ratios were measured during the very dry months in both the morning and evening soundings. The highest water vapor measurements were recorded during the above-normal months. The most pronounced differences in actual water vapor content were measured in the lowest layer from the surface to 850 mb. The mixing ratios at 1800 CST for Salem during very dry and moderately dry months was 1 g/kg less than in months with near-normal or greater precipitation amounts. The precipitable water depths at 1800 CST were 0.2 cm less than in months with normal or greater precipitation.

The results from this set of data are mixed. At Salem there was little difference in the temperature structure between drier than normal months and those months with normal or greater precipitation. However, at Peoria the warmest temperatures were measured during the drier months, and there was a slight trend toward cooler temperatures as the monthly rainfall amounts became greater.

The moisture structure at Salem showed the lowest relative humidities and the largest saturation deficits during very dry and moderately dry months. At Peoria there was little difference between the very dry and above-normal months. The actual water vapor content at the two upper-air stations showed Salem having less water vapor available in the dry months and Peoria having more water vapor available during very dry months than during months with above-normal precipitation. The overall pattern from the monthly averages of temperature and humidity is quite mixed and not very well-defined.

Table B-4. Mean Monthly Mixing Ratio and Precipitable Water at Peoria and Salem for 0600 and 1800 CST for June to August, 1971 to 1975.

	Mixing Ratio (g/kg)					Precipitable Water (cm)				
	Sfc-850	850-700	700-500	Sfc-700	Sfc-500	Sfc-850	850-700	700-500	Sfc-500	Sfc-400
Salem 0600 CST										
Very Dry	9.9	5.7	2.2	7.8	5.7	1.5	0.9	0.4	2.8	2.9
Moderately Dry	9.9	5.8	2.8	7.9	5.9	1.5	0.9	0.6	3.0	3.1
Near Normal	10.7	6.3	2.6	8.5	6.2	1.6	0.9	0.5	3.1	3.2
Above Normal	11.2	6.3	2.5	8.7	6.4	1.8	0.9	0.5	3.2	3.3
Much above Normal	10.5	5.7	2.4	8.1	5.9	1.6	0.9	0.5	3.0	3.0
Salem 1800 CST										
Very Dry	9.7	5.6	1.9	7.5	5.4	1.5	0.8	0.4	2.7	2.8
Moderately Dry	9.8	6.1	2.6	7.9	5.8	1.5	0.9	0.5	2.9	3.0
Near Normal	10.9	6.4	2.5	8.6	6.2	1.7	0.8	0.5	3.1	3.2
Above Normal	11.0	6.7	2.7	9.0	6.6	1.8	1.0	0.5	3.3	3.4
Much Above Normal	10.9	5.9	2.7	7.9	5.9	1.7	0.9	0.5	3.0	3.2
Peoria 0600 CST										
Very Dry	10.0	5.7	2.4	7.8	5.8	1.5	0.9	0.5	2.9	3.0
Near Normal	10.0	5.9	2.7	8.0	5.9	1.6	0.8	0.6	3.0	3.1
Above Normal	8.7	5.1	2.1	6.9	5.1	1.4	0.8	0.4	2.6	2.6
Much Above Normal	9.7	6.0	2.5	7.7	5.7	1.5	0.9	0.5	2.9	3.0
Peoria 1800 CST										
Very Dry	10.4	5.9	2.5	8.1	5.9	1.6	0.9	0.5	3.0	3.1
Near Normal	10.8	6.2	2.5	8.4	6.1	1.6	1.0	0.5	3.1	3.2
Above Normal	9.4	5.2	2.2	7.3	5.3	1.4	0.8	0.5	2.7	2.8
Much Above Normal	10.7	6.2	2.7	8.4	6.2	1.7	0.9	0.5	3.1	3.2

The very dry months recorded during the sampling period could be classed as typical of spot or moderate drought months within Illinois. It is quite likely that during widespread droughts more discernible differences would be obtained within the temperature and humidity structure of the lower atmosphere. However, no suitable radiosonde data are available in Illinois to sample the large area droughts of the mid 1930s and 1953-1954. A radiosonde station was established at Rantoul during the latter drought. However, the station was not situated within the drought area. Other investigations (Huff and Semonin, 1975) have shown that during precipitation situations in 1953 to 1954, Rantoul was often imbedded in an air mass north of a static or cold front, so that the sounding was unrepresentative of the air mass within which the drought was occurring.

The mixed results from this set of data are believed related to the fact that the synoptic and mesoscale dynamics of the atmosphere exert strong control over the initiation of rainfall. As a result, the comparative analyses performed here do not permit reliable conclusions to be made regarding seeding-induced enhancement of natural rainfall during drought conditions.

Daily Distribution of Upper Air Parameters

The monthly mean values of temperature and humidity for various layers in the troposphere did not show any significant differences between months having below-normal to much above-normal precipitation. To determine if extreme daily thermodynamic values were being masked by the monthly means, daily distributions of several thermodynamic parameters were calculated. They were 1) the Showalter Stability Index (SSI), 2) precipitable water (surface to 500 mb), 3) 500-mb temperatures, 4) surface to 850-mb layer temperature, and 5) surface to 850-mb layer relative humidity.

The SSI is an objective measure of the static stability of the air mass. Generally, if the SSI is less than 3°C showers can occur; when the index is less than 0°C thunderstorms might be initiated; and, if the SSI is less than -3°C the atmosphere is quite unstable and severe thunderstorms are possible (Petterssen, 1956). When the SSI is greater than 3°C the sounding is considered to be stable. Generally, the soundings at 1800 CST were slightly less stable than those at 0600. This occurs because heating during the day destabilized the lower layers of the atmosphere.

A trend toward more stable or larger daily SSI values from above-normal to below-normal months of precipitation might be expected, if the static stability of the atmosphere dominated the development of showers and thunderstorms. However, the median 50% value of the SSI at both Peoria and Salem exhibited no detectable trend, and were generally stable. The Salem median value showed the two most stable values during very dry and very wet months. At Peoria, the most stable daily median value was found during above normal months. The distribution of unstable events at the upper 5% to 20% levels showed little difference between below-normal, near-normal, or above-normal months at either Salem or Peoria.

The median values of precipitable water depth at the two stations showed no overall tendency. Rather, the below-normal months and much above-normal months at Salem were similar. At Peoria during very dry months more precipitable water depth was recorded than during above-normal months, and the morning sounding (0600 CST) showed even more precipitable water during very dry months than much above-normal months. The results are not definitive. There is a tendency at both stations for higher precipitable water values with months of near-normal or greater precipitation at the 5 and 10% levels, but the daily distribution shows little overall difference for the remainder of the months.

The daily distribution of 500-mb temperatures can be used as an indicator of the strength of the dynamic forcing function generated by the mid-atmosphere. Relatively cold temperatures at this level are associated with strong upper-level troughs and perturbations, and these cold 500-mb temperatures can be utilized as indicators of the strength of the upper atmosphere. The median or 50% level of the 500-mb temperatures at both Peoria and Salem show little variation, with the temperature hovering between -8°C to -19°C with no discernible trend (Table B-5). Since heavy rain occurs less than 50% of the days in a month, the more significant portion of the daily frequency distribution should be concentrated in the colder temperatures. The 90 and 95% frequency levels at both Peoria and Salem indicates a tendency for colder 500-mb temperatures to occur during months with near-normal to much above-normal precipitation, especially at Peoria. Generally, the range of the 500-mb temperatures increased from months having below-normal to those with much above-normal precipitation. This is an indication of the more stagnant circulation pattern which prevailed during the drier months.

The daily distribution of the temperatures frequencies from surface to 800 mb for all types of monthly precipitation is similar at both Peoria and Salem (Table B-6) for the warmer temperatures. However, the distribution of the colder temperatures generally show the drier months to have warmer temperatures. Thus, there are more warmer days during the dry months near the surface. This data also indicates that the cold air masses which do move into the region in dry months are not as strong as during near-normal to above-normal months, and/or that after a cold frontal passage there is a rapid return to the warm-air sector.

The relative humidity distribution for surface to 850 mb at Salem and Peoria show little difference in the 0600 CST soundings (Table B-7). The 1800 CST soundings at Salem show a general increase in relative humidity from very dry to normal or greater rainfall months. At Peoria there are no indications of any noticable differences in the relative humidity distribution in very dry or above-normal months. Thus, there appears to be little difference in the distribution of relative humidity in the surface to 850-mb layer. Other analyses have shown that during dry months there are fewer occurrences of both cumulus and cumulonimbus clouds, It would appear that the frequency of occurrence of these summer low-level clouds is highly dependent upon the dynamics which exist in the troposphere, rather than the thermodynamics.

Table B-5. Frequency Distribution of SOO-mb Temperature at Salem and Peoria for Very Dry to Much Above Normal Months during Summers of 1971 to 1975 (500-mb Temperature (°C) Equalled or Exceeded for Given Percent of Observations).

SALEM 0600 CST

RAINFALL CLASSES	5	10	20	30	40	50	60	70	80	90	95
Very Dry	-7.0	-7.4	-7.9	-8.3	-8.6	-9.0	-9.3	-9.8	-10.5	-11.6	-12.7
Moderately Dry	-6.0	-6.6	-7.5	-8.2	-8.9	-9.7	-10.4	-11.4	-12.8	-15.0	-17.2
Near Normal	-5.8	-6.3	-7.2	-7.8	-8.4	-9.1	-9.7	-10.6	-11.7	-13.6	-15.4
Above Normal	-4.7	-5.4	-6.4	-7.1	-7.7	-8.0	-8.7	-9.3	-10.1	-12.0	-14.7
Much Above Normal	-6.3	-7.0	-7.8	-8.4	-8.9	-9.4	-9.9	-10.4	-11.1	-12.2	-13.6

SALEM 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	-6.4	-6.7	-7.2	-7.6	-8.0	-8.4	-8.9	-9.5	-10.2	-11.6	-12.9
Moderately Dry	-6.6	-7.3	-8.1	-8.7	-9.2	-9.6	-10.0	-10.7	-11.7	-13.3	-15.2
Near Normal	-5.2	-5.8	-6.6	-7.2	-7.8	-8.5	-9.2	-10.2	-11.3	-13.4	-15.5
Above Normal	-4.3	-5.0	-5.9	-6.6	-7.1	-7.7	-8.1	-8.6	-9.2	-11.2	-14.5
Much Above Normal	-5.4	-6.2	-7.2	-7.8	-8.3	-8.9	-9.5	-10.1	-10.7	-11.5	-13.3

PEORIA 0600 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	-6.9	-7.5	-8.2	-8.7	-9.2	-9.6	-10.1	-10.7	-11.3	-12.2	-13.3
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Near Normal	-5.8	-6.6	-7.7	-8.6	-9.4	-10.2	-11.0	-12.1	-13.4	-15.9	-18.7
Above Normal	-7.2	-7.8	-8.5	-9.2	-9.7	-10.3	-11.0	-11.8	-12.8	-14.8	-16.8
Much Above Normal	-5.8	-6.7	-7.6	-8.3	-8.8	-9.4	-10.1	-11.0	-12.4	-14.8	-16.8

Table B-5 Cont.

PEORIA 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	-6.3	-6.8	-7.4	-8.0	-8.4	-8.8	-9.3	-9.8	-10.5	-11.6	-12.5
Near Normal	-5.4	-6.3	-7.4	-8.3	-9.1	-9.9	-10.7	-11.8	-13.1	-15.7	-18.6
Above Normal	-6.0	-6.8	-7.7	-8.3	-8.9	-9.4	-9.9	-10.5	-11.7	-14.7	-18.2
Much Above Normal	-5.0	-5.8	-6.9	-7.8	-8.4	-9.1	-9.7	-10.3	-11.7	-14.3	-16.5

Table B-6. Frequency Distribution of Surface to 850-mb Temperatures at Salem and Peoria for Very Dry to Much Above Normal Months During Summers of 1971 to 1975

SALEM 0600 CST

RAINFALL CLASSES	5	10	20	30	40	50	60	70	80	90	95
Very Dry	22.3	21.8	21.1	20.5	19.8	18.9	17.8	16.5	15.0	13.0	11.3
Moderately Dry	22.6	21.9	21.1	20.6	20.1	19.3	18.3	16.9	15.3	13.3	11.5
Near Normal	22.9	22.2	21.2	20.6	20.0	19.4	18.4	17.2	15.7	13.6	11.8
Above Normal	23.2	22.5	21.7	21.1	20.6	20.1	19.6	18.9	17.6	15.2	13.2
Much Above Normal	22.7	22.1	21.1	20.3	19.6	18.8	18.1	17.2	16.0	14.3	12.8

SALEM 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	26.8	25.9	24.7	23.7	22.8	22.1	21.3	20.4	19.5	18.0	16.3
Moderately Dry	25.3	24.9	24.5	24.2	23.4	22.4	21.2	19.8	18.2	16.0	14.2
Near Normal	26.4	25.7	24.9	24.1	23.3	22.5	21.5	20.2	18.8	16.7	15.0
Above Normal	25.4	24.8	24.0	23.5	23.1	22.6	22.0	21.2	19.9	17.8	15.7
Much Above Normal	25.5	24.6	23.6	22.8	22.2	21.6	21.0	20.2	20.1	17.4	16.1

PEORIA 0600 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	23.1	22.1	20.8	19.9	19.2	18.4	17.6	16.8	15.8	14.2	12.8
	----	----	----	----	----	----	----	----	----	----	----
Near Normal	22.5	21.8	20.9	20.1	19.2	18.3	17.1	15.8	14.2	12.1	10.3
Above Normal	21.7	20.9	19.8	18.9	18.0	17.0	15.9	14.6	13.1	10.9	9.2
Much Above Normal	22.7	21.7	20.6	19.6	18.8	18.0	17.2	16.2	14.8	12.6	10.6

Table B-6 Cont.

PEORIA 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	27.3	26.1	24.7	23.6	22.7	21.9	21.1	20.2	19.2	17.7	16.5
	----	----	----	----	----	----	----	----	----	----	----
Near Normal	25.7	25.1	24.1	23.3	22.3	21.2	20.2	18.8	17.4	15.3	13.7
Above Normal	24.8	24.2	23.3	22.7	21.9	21.0	19.9	18.5	16.9	14.7	12.8
Much Above Normal	26.0	25.1	23.8	22.8	21.8	20.9	19.9	18.8	17.6	15.6	13.8

Table B-7. Frequency Distribution of Surface to 850-mb Relative Humidity at Salem and Peoria for Very Dry to Much Above Normal Months during Summers of 1971 to 1975

SALEM 0600 CST

RAINFALL CLASSES	5	10	20	30	40	50	60	70	80	90	95
Very Dry	88	85	80	76	73	69	66	62	57	50	45
Moderately Dry	93	87	81	76	72	68	64	59	54	47	41
Near Normal	89	85	82	78	76	73	70	67	63	57	51
Above Normal	88	84	80	76	73	70	67	64	61	56	52
Much Above Normal	90	87	82	78	75	72	69	65	61	56	51

SALEM 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	73	68	63	59	56	53	50	46	42	37	32
Moderately Dry	84	77	69	63	58	54	51	47	43	38	34
Near Normal	79	76	71	67	64	60	57	54	49	43	37
Above Normal	82	78	73	69	66	63	60	57	53	48	44
Much Above Normal	84	79	73	68	64	61	58	54	50	45	42

PEORIA 0600 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	87	83	79	75	72	70	67	64	61	56	52
	--	--	--	--	--	--	--	--	--	--	--
Near Normal	87	84	80	77	74	72	70	67	64	57	50
Above Normal	87	82	76	72	69	66	63	59	55	50	45
Much Above Normal	89	87	82	77	74	70	66	62	58	51	46

Table B-7 Cont.

PEORIA 1800 CST

	5	10	20	30	40	50	60	70	80	90	95
Very Dry	81	76	69	65	61	57	54	50	45	39	34
	--	--	--	--	--	--	--	--	--	--	--
Near Normal	85	80	74	70	66	63	59	56	51	45	40
Above Normal	77	73	67	63	59	56	53	49	45	40	35
Much Above Normal	88	83	76	71	67	63	60	55	51	44	38

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