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Dry Periods in Illinois
A Climatological and Meteorological Analysis

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PART FOUR: METEOROLOGICAL ANALYSES OF DRY PERIODS

PART ONE: INTRODUCTION

Stanley A. Changnon

An extensive analysis of dry periods in Illinois was accomplished to address several objectives. The goal was to obtain a very detailed meteorological and climatological description of dry period events and their causes.

The first and principal objective of the research of dry periods concerned the potential for rainfall modification. Extensive prior research had evaluated the impacts of enhanced summer rainfall due to cloud seeding, revealing that enhanced rainfall in July and August, on the average, would be beneficial (Swanson et al., 1971). However, recent extensive field studies done on agricultural experimental plots of the University of Illinois in central Illinois provided important and somewhat different results. These also showed that the effects of altering summer rainfall led to increased yields of corn and soybeans, but primarily only in the drier and near normal rainfall growing seasons (Hollinger and Changnon, 1993). Assessment of these findings, in light of a simulated operational cloud seeding project (to enhance summer rainfall) for central Illinois, revealed that financial benefits, weighed against the cost of project operations, would largely only accrue in the drier third of the summers (Changnon and Shealy, 1993). Subsequent research (Hollinger and Changnon, 1995) has shown that in summers with near normal rainfall, rainfall applied at discrete time periods during crop growth would result in minor yield increases. However, these are typically short, 1- to 2-week periods. Costly cloud seeding operations established for an entire summer could not justify, in a benefit-cost analysis, the slight income increases realized by these relatively minor yield increases.

The summation of these economic benefit-weather modification studies over the last 25 years showed that as an economic investment, weather modification, having a capability of producing rainfall increases of 10 percent up to 25 percent in Illinois' summer rainfall, can only achieve a meaningful benefit-cost ratio in the drier 30 to 35 percent of the summers. Further, it should be noted that capabilities to produce such rainfall increases have yet to be scientifically demonstrated through research of the Illinois State Water Survey.

A second objective for conducting an extensive analyses of warm-season dry periods in Illinois relates to global climate change, the subject of great state, national, and international interest for the past 15 years. The potential exists for a shift to a warmer and drier climate in the Midwest. This would be due to the effects of an enhanced greenhouse influence in the atmosphere caused by ever-increasing amounts of trace gases released to the atmosphere. In 1994, Changnon and Wendland (1994) made an in-depth assessment of what is known about the science of climate change in Illinois. This study presented what has been learned about the potential effects of global warming on various activities including crop production (Easterling and Changnon, 1993) and water resources (Changnon, 1989). The Changnon-Wendland study also presented the results of four widely-accepted global climate models (GCMs) and their best estimates of the potential future climatic conditions in Illinois under a doubling of carbon dioxide in the atmosphere. The outputs of these four GCMs showed the change from today's average May-September precipitation (Table 1-1).

Table 1-1. Projected changes in May-September rainfall in Illinois under 2 X CO_2 atmospheric concentrations, as estimated by four global climate models.

Source of Model	Percent of Normal (Today's) Rainfall
Oregon State University	101
Goddard Institute	94
Princeton GFDL	104
United Kingdom	107

Two of the four models show near normal rain (101 and 104 percent) and the others show decreases ranging between 6 and 19 percent of the normal summer rainfall, falling within the definition of "summer dry periods." Future climate change may present Illinois with an average climate that is not terribly different than exists in its current "dry summers." Thus, a more complete definition of summer dry period conditions would serve as useful input in attempts to model the influence of an altered climate on various Illinois activities which require detailed information on rainfall conditions.

A third objective for a thorough investigation dry periods related to the value of such information in the future design and operation of water management systems, including irrigation and drainage systems. It has been shown that the use of irrigation in Illinois to enhance crop production has been growing (Bowman and Collins, 1987). A better understanding of the precipitation conditions during dry seasons when irrigation would be most profitable should be a beneficial.

Approach to Defining Dry Periods and Droughts

The delineation of a summer (June-August) or an annual dry period was based on a straightforward definition of seasonal and monthly precipitation conditions. A precipitation departure approach was needed to match dry period conditions with those due to enhanced greenhouse effect (as derived from the GCMs), and to match dry period findings with past calculations of effects of additional summer rainfall due to cloud seeding.

Past studies showed that approximately one-third (30 to 35%) of all summer periods were sufficiently dry to justify the cost of cloud seeding projects (Changnon and Shealy, 1993) and irrigation (1969). Thus, a summer, growing season, or annual dry period was defined as those years with sizable portions of Illinois (> 10 percent) receiving precipitation in the lowest 35 percent of the years during the past 95-year period.

Droughts, which are a part of dry periods, are much more severe, and have been defined in different ways. Droughts, whether they relate to agricultural impacts (seriously reduced crop yields), or hydrologic droughts (seriously reduced water supplies), are generally defined through such impacts. However, Huff and Changnon (1963) also defined historical droughts in Illinois based on their precipitation deficiencies. Assessment of past droughts in Illinois, qualifying on an agricultural, precipitation, or hydrologic basis, shows that they occur in approximately 10 percent of all years (Easterling and Changnon, 1987). This is compared to 35 percent of the years qualifying as dry periods. The droughts which exist in 10 percent of the months, were included in the dry periods identified and studied. Further information on the specific definition of dry periods is presented in the sections addressing summer and annual dry periods.

The major goal of this study was to derive and provide the best possible description of the meteorological conditions that cause dry periods, and further to define and describe the various climatological conditions associated with these events. Important in satisfying this objective was the fact that there had been several previous Water Survey studies of droughts. Therefore, useful drought information existed, but it was scattered amongst many research reports and scientific papers. For example, there have been two major studies of the climatological aspects of Illinois drought (Huff and Changnon, 1963; Easterling and Changnon, 1987). In addition, there have been in-depth case studies of specific droughts in 1952-1955 (Hudson and Roberts, 1955), in 1980-1981 (Changnon et al., 1982), and in 1988 (Angel et al., 1991). Other studies have focused on the detection of incipient droughts (Changnon, 1987), on the aspects of droughts related to weather modification applications (Huff and Vogel, 1977); and on the impacts of droughts (Changnon and Easterling, 1989).

Scope of the Investigations

Certain sections of this report are summaries based on the review and assessments of the key findings from past drought-related studies. These sections attempt to bring the relevant meteorological and climatological findings forward, and this information is presented in Section Two.

The third major section of the report presents a series of findings about the climatological aspects of dry periods. For example, the information is presented about the temporal distribution of wet and dry months during dry periods, the frequency of rain events, the areal extent of deficient rainfall, and the frequency of thunderstorms and convective entities. Results relating to the relationship of rainfall deficiencies to soil moisture are also included in the climatic investigations.

The fourth major section of this report is based on investigations of the meteorological aspects of dry periods and embraces "causative" investigations. These include analyses of the atmospheric conditions (surface and upper air) associated with dry periods, how these conditions relate to the actual rain areas and their structure, and the characteristics of cells and rain entities produced during dry periods. In many instances, the dry period conditions are compared with those during near-normal and wet summers to illustrate the differences present in dry periods. Included in these causative analyses are assessments of atmospheric moisture, atmospheric instability, and the influence of surface conditions on the development and intensity of dry periods.

The research in this extensive two-year study of dry periods, including a review of key findings for droughts, has embraced the efforts of several investigators. These included Stanley Changnon, Floyd Huff, Kenneth Kunkel, Robert Scott, and Nancy Westcott. The sections of the report that each has authored are so labeled. References cited in all sections of the report are found at the end of the report. Tables and illustrations are numbered according to the four major sections of the report. That is, Figure 2-2 is the second figure appearing in the second major section of the report, and table 3-4 is the fourth table in the third section.

PART TWO: REVIEW OF RELEVANT FINDINGS ABOUT ILLINOIS DROUGHTS

Floyd A. Huff

Introduction

During a 30-year period, 1957-1987, several Water Survey hydroclimatic studies yielded information that is pertinent in assessing the potential for using weather modification to alleviate water shortages (agricultural and public water supplies) in moderate to severe droughts. Results from these are briefly described in this section. This information has been compiled as a guide in future research planning by pointing out what we know about the drought problem, and where more future research effort is needed if cloud seeding during droughts appears to be feasible and helpful to society. Furthermore, the previous research has yielded valuable information concerning the climatological characteristics of midwestern droughts of various intensity and areal extent. This information has application in various endeavors affected by dry-period conditions, such as the pollution of surface-water supplies, aquatic biology, and evaluation of climate change. Detailed description of the various studies are contained in the references cited under each subject in the review.

Macroscale Synoptic Conditions

Huff and Changnon (1963) made an analysis of synoptic weather conditions associated with a 12-month drought in 1953-54 which was the most severe in history in south-central Illinois. At the same time, the northern part of the state experienced normal precipitation. Analysis of the 50 heaviest rainstorms in the 1953-54 drought region showed that 32 of these storms (64%) were associated with cold fronts occurring in conjunction with low centers which passed across southern Canada or the northern boundary states. In these 32 storms, wave formations on trailing cold fronts intensified the storms over Illinois in 14 cases.

It was found that the frequency of cold fronts in Illinois during the drought period was 89% of the normal frequency established by Chiang (1961). Furthermore, the frequency of all fronts combined (cold, warm, stationary, and occluded) was 98% of normal. Actually, the frontal frequency in the severe drought region was even greater than the state averages (93% for cold fronts and 100% for all fronts combined). Thus, one must conclude that this particular drought, at least, was not produced by a deficiency of frontal passages.

Huff and Vogel (1977) analyzed the synoptic conditions of 492 storms associated with 35 July-August droughts of various size and intensity during 1900-1974. These were considered agricultural droughts and included all dry periods in which the two-month rainfall was <50% of normal over substantial portions of Illinois. Storms were classified according to whether they were associated with fronts, pre-frontal squall lines, low center passages, or non-frontal air mass activity. Analyses showed that cold fronts and pre-frontal squall lines were the major rainfall contributors of rainfall in the 35 summer droughts. They were associated with 61% of the drought rainfall occurrences compared with a normal Illinois frequency of 46%. Conversely, the frequency of air mass storms decreased from 30% under normal conditions to 11% in July-August droughts. Cold fronts produced 65% of the total drought rainfall, whereas their normal contribution is 39%. Air mass storms contributed only 6% of the drought rainfall compared with 17% under normal weather conditions.

A similar study was made for May-September (warm season) droughts. The synoptic relations departed only slightly from the July-August findings, except that cold fronts were even more outstanding in their contribution to the total rainfall. The cold front rainfall averaged 90% of normal and these storms accounted for 63% of the storm occurrences compared with a normal frequency of 36%. The Huff-Vogel findings essentially agree with those obtained in the earlier Huff-Changnon study. That is, cold fronts and their associated pre-frontal squall lines offer the greatest potential for successful rain enhancement by cloud seeding in droughts of various intensity and areal extent.

Changnon (1982) made a study of a 12-month drought that extended over the southern two-thirds of the state and was the most severe Illinois drought since the early 1950s. Although the analysis procedures varied somewhat from the previous studies, the total frequency of frontal passages was found to be near normal. There were 76 cold frontal passages compared with 30 for warm fronts and 17 for stationary fronts. Thus, their findings also suggest that cold frontal systems offer the best potential for rainfall enhancement by cloud seeding.

Clouds and Atmospheric Moisture

Only limited information is available on precipitation-producing clouds during Illinois droughts. Changnon and Huff (1957) made a study of the climatological distribution of the frequency and amount of various cloud types over Illinois. Based upon this study, Huff and Changnon (1963) determined that the percent of convective clouds during the severe 1953-54 drought was approximately 90% of normal.

They also found that precipitable water was only slightly below normal, and that its vertical distribution was near normal. Semonin (1960) in a study of Illinois dry periods of five days or longer found that both the total amount and vertical stratification of atmospheric moisture is near-normal during such dry periods. However, the air is abnormally dry, so that the humidity is low even with normal atmospheric moisture content. Furthermore, the atmosphere is so abnormally stable that vertical development of clouds and subsequent rainfall initiation is unlikely most of the time.

In a later study of the 1953-54 drought, Huff and Semonin (1975) used a one-dimensional cloud model (Hirsch, 1972) to examine precipitation potential in the drought region, based on available radiosonde data. Results indicated that about 1 day in 10 might be suitable for seeding in a 1953-54 type of drought, but that about 70% of these would occur in summer when crop requirements maximize.

Moderate to Severe Summer Droughts

Huff and Vogel (1977) investigated the distribution of moderate to severe droughts in Illinois for July-August, which is the most critical weather period for the major crops (corn and soybeans). These were droughts in which substantial areas experienced total rainfall that was equal to or less than 12.5 mm (0.50 in.). The area-depth relations for individual dry periods developed in this study were used to determine the areal extent of moderate to severe droughts for June-August using the Huff-Aogel definition. Qualifying dry periods were defined as those in which the area-depth relations indicated rainfall less than 50% of normal over contiguous areas of 2600 km^2 (1000 mi^2) or larger. Results are summarized in Table 2-1.

In this table, the frequency distribution is shown for the area enveloped by the 12.5-mm isohyet in the June-August dry periods used in the ongoing study. Values are shown for total area and for the percent of the total state area affected for each of the selected frequency intervals. Reference to Table 2-1 shows that the area enveloped by moderate to severe drought conditions increases from approximately 2% of the state at the 2-year frequency interval to 11%, 24%, 41%, and 50%, respectively, at the 5-, 10-, 25-, and 50-year recurrences. The foregoing results provide useful estimates of the frequency with which moderate to severe drought conditions occur and their areal extent. Although the findings are for Illinois, the warm season climate is similar in the surrounding midwestern states and dry-period occurrences should be similar.

Table 2-2 provides additional information on the distribution of moderate to severe drought conditions. In this table, the qualifying droughts have been grouped according to areal extent during the 93-year sampling period. The first column shows the selected groups that experienced moderate to severe droughts. Columns 2 and 3 show the range of areas for each of the district groups. Column 4 indicates the number of cases (qualifying droughts) for each group.

Table 2-2 shows a total of 45 qualifying droughts in the 93 years. However, only 5 (8%) involved over one third of the state. The majority of the moderate to severe drought occurrences involved only a small portion of the state. Thus, 21 (47% of the cases) included less than 5% of Illinois. These findings provide additional important information for users of drought information, especially those involved in agriculture and water supply activities.

The foregoing analyses have dealt with the frequency and areal extent of moderate to severe drought conditions, but do not define the rainfall deficiency at the core of these events. Information on this subject was also developed from the area-depth relations for 1901-1993 droughts. In doing this, the rainfall deficiency in the 2600 km^2 and 5200 km^2 (1000 and 2000 mi^2)

immediately surrounding the drought center was determined. Results are summarized in Table 2-3.

In this table, the frequency distribution of percent of normal rainfall is shown for each of two central areas in those droughts that qualified as being moderate to severe. Thus, at the very center of these events (2600 km^2), the rainfall deficiency was 44% or less of normal at the 2-year recurrence interval and decreased gradually to 22% at the 50-year interval. Moving outward to the 5200 km^2 area, the corresponding rainfall values were 49% and 24%, respectively. The 5-year recurrence interval is frequently used as the level at which the drought consequences become serious (Huff and Vogel, 1977). In Table 2-3, the 5-year values are 36% and 39%, respectively, at the 5-year level.

Table 2-1. Frequency Distribution of the Areal Extent of Moderate to Severe Summer Droughts.

Frequency (years)	Areal Extent km^2	Areal Extent mi^2	Percent of State
2	3,055	1,180	2
3	5,025	1,940	3
5	16,575	6,400	11
10	34,710	13,400	24
25	59,050	22,800	41
50	76,405	29,500	50
100	90,650	35,000	62

Table 2-2. Moderate to Severe Summer Droughts
Grouped by Areal Extent.

Group	km^2	mi	Number	Cumulative % of State
1	>51,800	>20,000	5	>35
2	25,900-51,800	10,000-20,000	7	18-35
3	12,950-25,900	5,000-10,000	7	9-18
4	7,700-12,950	3,000-5,000	5	5-9
5	3,885-7,770	1,500-3,000	15	3-5
6	<3,885	<1,500	6	<3

Table 2-3. Frequency Distribution of Rainfall Deficiency (%)
at Center of Droughts.

Frequency (years)	Drought Center Area	
	2600 km^2	5200 km^2
2	44	49
3	41	45
5	36	39
10	28	32
25	23	26
50	22	24

Precipitation Characteristics in Moderate to Severe Droughts

From various Illinois-focused hydroclimatic studies, it appears that drought severity is strongly related to (1) major deficiencies in days having 12.5 mm (0.5 in.) or more rainfall, and (2) a below average frequency of thunderstorms (strong convective forces). For example, in the 1953-1954 drought, the number of 12.5 mm (0.5 in.) or more days was less than 50% of normal in the drought region of south-central Illinois, but near to above-normal in northern Illinois where normal precipitation occurred. The frequency of thunderstorms was substantially below normal not only in the drought region but also south and west of this region where major breeding areas for the drought region storms are located. In general, the climatic studies indicate that within drought regions, relatively small areas frequently receive modest amounts which might be intensified and increased in areal extent by seeding.

Potential Benefits of Cloud Seeding for Surface Water Supplies

Huff (1973a) made an investigation of the potential benefits of seeding-induced increases in runoff on alleviation of surface water shortages in Illinois. Runoff and weather data for 14 basins of various sizes and locations and with records of 30 years or longer were used to develop basin equations relating runoff to antecedent runoff indices, various precipitation parameters, and mean temperature. Hypothetical seeding-induced increases in precipitation were then used with the appropriate basin equation to obtain an estimate of average runoff increases in the cold season (October-March), the warm season (April-September), and two subseasons, December-March and July-August. This was done for all seasons combined, seasons having near-normal to below-normal runoff, and seasons with below-normal streamflow. Results indicated that seeding could result in substantial increases in runoff during near-normal to slightly below-normal years. However, substantial runoff would be difficult to achieve in drought years unless exceptional rainfall increases could be achieved. Previous hydrologic studies at the Water Survey (Stall, 1964) indicated that major benefits to water supply in Illinois would only result if substantial rain increases could be achieved in moderate to severe drought conditions. Consequently, it was tentatively concluded that the major beneficiary of weather modification in Illinois would be agriculture, and that future efforts should be concentrated primarily on weather modification applications in the growing season (Changnon, 1973).

The conversion of precipitation to runoff in below-normal rainfall years is small, averaging only 10-13%, and large seeding-induced increases in precipitation would be required to obtain substantial alleviation of water-supply deficiencies. This would be difficult to achieve with the atmospheric conditions (unusually above normal temperatures with low humidities) that exist in moderate to severe drought conditions. Thus, only 7% to 10% of the natural precipitation is converted to runoff in a typical 10-year drought. This percentage lowers to 3 to 5% in 25-year droughts and to a range of 2 to 4% in a 50-year drought.

However, the possibility that seeding may be of assistance during temporary breaks in *light to moderate droughts* in the Midwest cannot be eliminated. This is certainly true where shortages become very acute, in which case even a small contribution from seeding would be usually helpful and economically acceptable. This is most likely to occur in small communities where reservoir storage facilities are inadequate or where water is being taken directly from a small stream for municipal usage.

Potential for Hydrologic Drought Alleviation

Under the Illinois rain enhancement research program, Huff (1973b) made a study of the potential of weather modification in alleviating surface water supply problems in moderate to severe droughts. Using 1906-55 data, he determined that temporary breaks in 12-month or longer droughts do occur. It was found that consecutive 2- to 3-month periods of near- to above-normal rainfall occurred over 90% to 100% of the affected area in droughts of 5-year recurrence (moderate drought). Furthermore it was found that 90% or more of normal rainfall can be expected over approximately 50% of the affected area in 25-year drought recurrences. About 20% to 30% of the affected area in a 25-year drought can be expected to experience three consecutive months with 90% normal rainfall. Examination of droughts of 24-month durations provided similar evidence of substantial breaks of near average precipitation during which seeding might be potentially useful.

Special attention was given to the very severe 12-month drought of 1953-54. Results showed that large monthly differences sometimes occurred within the drought region. Areas of above-normal monthly rainfall did occur within the drought region, and it is conceivable that seeding could have induced additional precipitation in these situations, and, possibly extend the area affected by the ongoing storm systems. Examination of rain days showed six months in which one-third or more of the drought area had rain days of 12.5 mm (0.5 in.) or more.

Analysis was also made of the 48 heaviest storms in the state during the 12-month drought. Isohyetal maps drawn for these storms showed that it was not unusual for certain portions of the drought region to receive moderate to heavy rainfall, whereas other parts received little or none. These produced 83% of the total precipitation in the drought region. It was assumed these major storms would be more productive from a seeding standpoint. Moderate seeding-induced increases would be large enough to be useful in alleviating agriculture deficiencies and, possibly, some small reservoir inadequacies. Some of these major storms lasted 2-3 days. They were predominately cold frontal storms, which again indicates that this type would probably be the system most likely to yield substantial precipitation increases in severe drought regions.

A fuller description of the research pertaining to hydrologic-oriented studies of Illinois droughts is provided later in this report.

Potential for Agricultural Drought Alleviation

A comprehensive study of the potential of weather modification for alleviating water shortages during agricultural droughts was made by Huff and Vogel (1977). The general conclusions reached from this study are summarized below. Long-term climatic data, data from the METROMEX program (Changnon et al. 1977), and findings from earlier studies were used in the study. Major emphasis was on agricultural droughts, and the key findings are summarized below.

> Results described the natural rainfall distribution in droughts of various severity in Illinois. Information was provided for relationships 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 were also investigated. This information can be used to evaluate weather modification potential and to plan cloud seeding operations in droughts, provided that the enhancement capabilities, under various combinations of natural weather conditions, can be specified, and that the economic benefits that would be derived from the specified enhancement can be defined.

Climatological analyses of rainfall characteristics during growing season droughts indicated that opportunities for alleviating agricultural water shortages through planned weather modification 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 crop 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, those encompassing areas of less than 5000 km^2, 50% of the storms during drought 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 July, August droughts. In these warm season droughts, measurable rainfall was found to extend over approximately 70% of the drought area in 50% of the storms for large drought areas exceeding 80,000 km^2. In smaller drought area (encompassing less than 50,000 km^2), 50% of the storms produced measurable rainfall over approximately 90% of the drought region.

If weather modification success is dependent largely upon enhancing rain from ongoing rainstorms, substantial increases in the natural rainfall are more 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 within the overall drought region.

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

Analyses of the METROMEX data provided additional evidence that weather modification should be successful to some degree, at least, in dry summers when agricultural water shortages develop. Analyses of urban modified rainfall characteristics in the network of 225 recording raingages in 5200 km^2 showed that the patterns of raincell initiations, raincell mergers, and surface rainfall are similar in dry, wet, and moderate rainfall periods. Further, that the inadvertent influences on atmospheric processes are as active proportionally in dry as in wet periods. Dry periods appeared to be caused to a large extent by a decrease in frequency of the more intense types of synoptic systems.

Key Findings for Weather Modification in Droughts

- Water Survey hydroclimatic studies of droughts indicate that alleviation of agricultural droughts is potentially feasible by cloud seeding in some areas experiencing extensive drought. Intensification and/or extension of existing areas of ongoing rainstorms by cloud treatment of these storms is likely the best approach.

- Treatment of precipitation systems associated with cold fronts and pre-frontal squall line or areas offers the most promise, both from the standpoint of frequency of occurrence and precipitation production. Other synoptic types were found to be largely deficient in both frequency and rain production in drought situations.

- Significant increases in runoff in moderate to severe hydrologic droughts do not appear feasible with present expectations for precipitation enhancement (10 to 25%). Very large increases in rainfall (>50%) would be needed in moderate to severe droughts to achieve substantial increases in runoff, and consequently, in surface water supplies. This also is likely to apply to shallow groundwater supplies (Changnon et al., 1982).

- However, some increases in runoff may be economically acceptable and technically feasible in minor drought situations. The main benefactors are likely to be communities operating small-capacity reservoirs, or where water is being drawn from small streams. Stall (1964) has shown that reservoir capacity in most large communities is generally adequate to withstand a 10-year drought and some can handle a 25-year drought (runoff deficiency) adequately.

- In all cases, it is likely that successful seeding can only significantly alleviate drought problems on a localized basis (relatively small or scattered areas) within large-scale severe droughts. This is especially true for moderate to severe droughts.

- Operational seeding capability must include night operations to be successful in Illinois and the Midwest where a large portion of the precipitation in droughts occurs between 1800 and 0600 CST.

- The greatest existing need in evaluating the potential of successful cloud seeding in droughts (light, moderate, severe) is a thorough study of the climatology of convective clouds. This should include their time and space distribution under the normal weather conditions, and their departures from normal in various types of drought conditions.

- Expansion of the studies of synoptic weather conditions during droughts and their departure from normality would be desirable. This was only accomplished on a limited scale in the previous hydroclimatic studies of the Water Survey, but they have provided useful information for evaluating existing seeding potential and for planning possible future research on this subject.

PART THREE: CLIMATOLOGICAL ANALYSES OF DRY PERIODS

TEMPORAL CHARACTERISTICS OF SUMMER DRY PERIODS

Stanley A. Changnon

Introduction

The temporal characteristics of dry periods occurring during the summers (June-August) of 1896-1990 were investigated. To qualify as a dry period, a summer had to have two or more of the nine crop reporting districts (CRDs) in Illinois in the top 30 rank positions as driest as based on the summer rainfall of 1896-1990. Furthermore, July of those summers had to have below normal rainfall in two or more CRDs. To illustrate the choices, let us examine the summer of 1906. Five of the nine crop districts in Illinois (see Figure 3-1) had summer rainfall amounts that were ranked among the top 30 (driest) for each crop reporting district. Furthermore, July was ranked as "dry" in all five crop reporting districts. Thus, 1906 qualified as one of the "dry summers" of the 95-year period under study.

Results

The analysis of the temporal distribution showed that 31 of the 95 years qualified as having summer dry periods. These years are listed in Table 3-1. The dry districts in each of the years are indicated, and the numbers and their locations are shown in Figure 3-1. Also indicated in Table 3-1 are the driest months, defined as departures greater than 25 percent below average.

Indicated in Table 3-1 is a mean rank of the year based on averaging the rank values of the nine crop reporting districts. That is, each qualifying dry summer in each district was assigned a rank from 1 (lowest) to 30. That rank in 1906 for each of the five districts that qualified was 21 (Table 3-1). This process of ranking the individual summers does not produce a rank 1 because that would have required that all nine districts be the driest together. Examination of Table 3-1 shows that the summer drought of 1936 with a rank 4 was the most severe. The mean rank of 4 was based on the ranks of all nine districts and as shown, all three summer months were dry.

Also shown in Table 3-1 are the number of years between the dry summers. For example, the time between 1896 and the 1901 dry year was five years as shown. The time between 1901 and 1906 was 4 years.

Further assessment of the 31 dry periods focused on the rank, or severity, of the rainfall departures. Table 3-2 presents two different rankings of the summer dry periods during 1896-1990. The rank values on the left of the table are based on the mean ranks of the qualifying districts. This shows that the rank 1, or most severe (lowest), value occurred in 1936, rank two

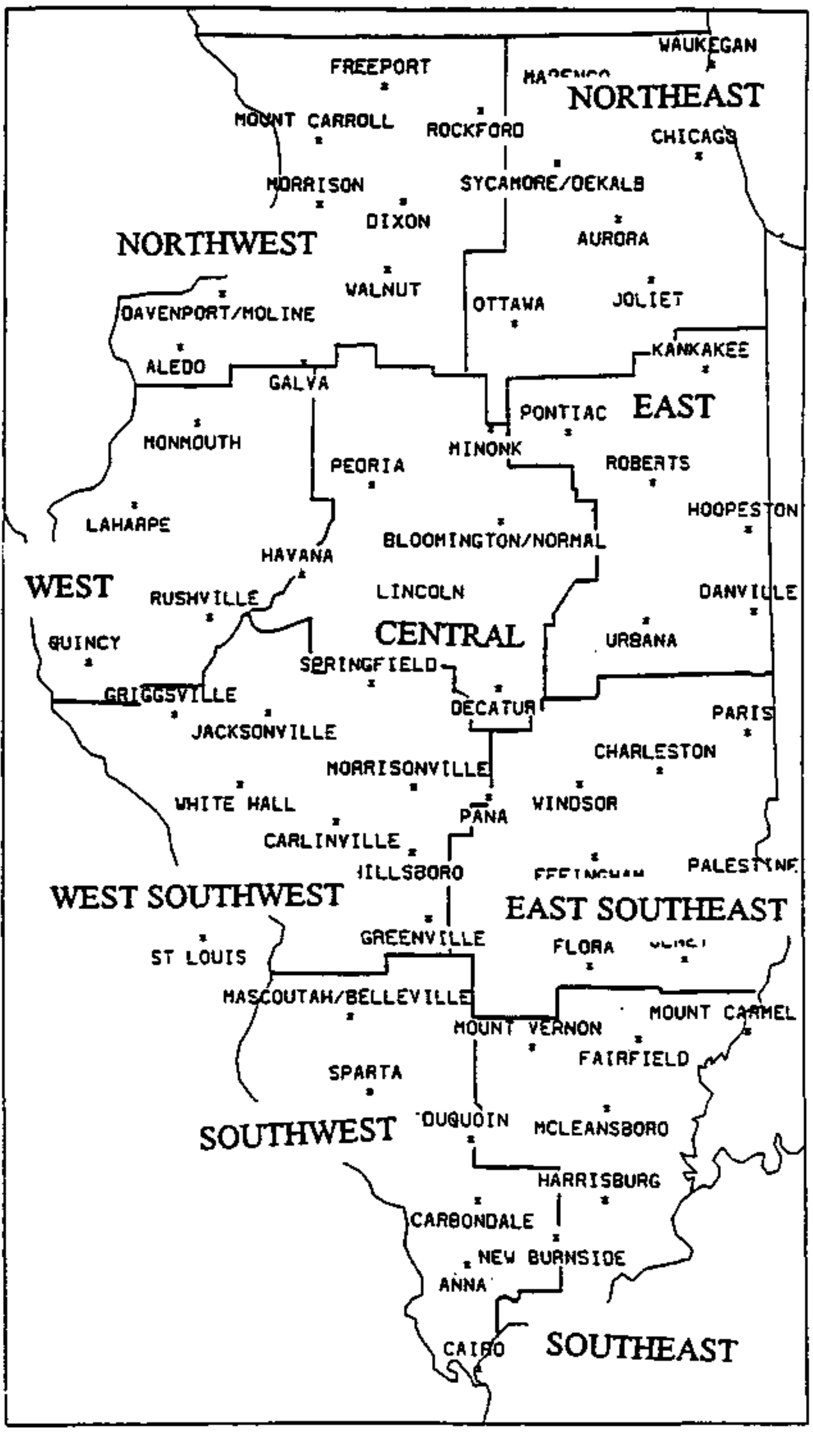


Figure 3-1. The nine crop reporting districts in Illinois and the weather stations used to calculate district values.

was 1933, etc. On the right side of the table are the ranks of the dry summers based on the statewide mean rainfall, not on the crop reporting district ranks. This shows that 1936 again qualified as the worst or most dry of the dry summers. However, 1988 replaced 1933 as rank 2, and there are some other differences in the ranks. However, the dry summers of the 1930s were high ranked amongst all the 31 years that qualified as dry.

Analysis of the time periods between the dry summers was done using the values expressed in Table 3-1. The resulting frequency of the various time durations between the dry summers is shown in Table 3-3. Thirteen times, one dry summer followed another. In other words, there was no summer in between them. In eight occasions, there was only one year in between. This reveals that 21 of the 31 dry periods occurred within a year or less of each other, showing a tendency to group. Also note in Table 3-3 that 11 of the occasions with no time between dry summers occurred before 1950. Conversely, the longer time periods between dry summers, defined as 6 to 10 years without a dry summer, have occurred S times over the 95-year period. Furthermore, 4 of these 5 events have occurred since 1950. These results, along with an examination of Table 3-1 reveal the paucity of dry summers since 1960.

Analysis of the Table 3-1 values show that there were three periods with several dry summers. The first of these was 1906-1922. This 17-year period had 11 dry summers. The next run of dry summers occurred in the 7-year period of 1930-1936 with six dry summers out of seven possibilities. Then, the six-year period of 1940-1945 had five dry summers. These results show a tendency of these events to cluster in time. Table 3-4 shows the temporal distribution of the dry summers by decades. As expected, these show the relatively high frequency during the first five decades of this century. Very few dry summers occurred in the 1960-1971 and 1971-1980 period.

Another examination of the distribution of dry periods, done on a regional basis across Illinois, appears in Table 3-5. The frequency of crop districts qualifying as dry was shown for three discrete 30-year periods. For example, the northwest district of Illinois had 10 dry periods in 1901-1930, five in 1931-1960, and five in 1961-1990, for a total of 20 dry periods. Clearly, the first 30 years of the century had the greatest number of dry periods in all but one district. The west-southwest district of Illinois had ten dry summers during the 1931-1960 period, the only time that a value exceeded the early 30-year value. The 1931-1960 era showed quite a bit of spatial difference across the state, with as few as five dry summers in the northwest, up to as many as 10 in the west-southwest. During the last 30-year period, 1961-1990, the values in all crop reporting districts were about the same values. The totals shown in Table 3-5 reveal the spatial differences across the state with a preference for dry summers to appear most often in the south-central part of the state, with values of 24 occurrences in the 90-year period. Other districts, particularly in the extreme south and extreme north, have fewer qualifying dry summers.

Further spatial analysis of the dry summers of 1896-1990 was pursued. The frequency of dry summers to qualify based on the number of districts dry is shown in Table 3-6. For example, five of the dry summers qualified based on having two districts defined as dry, and two of the dry summers qualified with three districts. This shows furthermore that 10 of the 31 dry summers qualified by having 9 districts, all of the state, dry. The median value of summer dry periods in Illinois shows that 7 of the 9 districts qualified with an average of 6.3 districts and a mode at 9. This reveals that most often, dry periods of the summer season encompass more than half of the state 80 percent of the time.

In an effort to assess intensity and location of dry summers, The three top ranked dry summers in each crop district was listed and compared. Table 3-7 shows these top ranked values for the 9 crop reporting districts in Illinois. For example, in the southeast district, the 1930 rainfall was the lowest, achieving rank 1, followed by 1936, and then 1953. Examination of the worst, most severe, dry periods reveals that 5 years of the 90-year period were most often top ranked. For example, 1988 achieved rank one or driest rank in 3 districts, and achieved third rank in another district (west).

Conclusions

The spatial and temporal distribution characteristics of dry summers in Illinois were assessed in most of these dry summers, the dry areas cover at least SO percent of the state and in a third of them (10 of 31), the entire state is classified as dry. The dry areas occur most often in the south-central portions of Illinois and are least prevalent in the extreme north and extreme south, but only slightly less prevalent.

Many of the most severe dry summers in Illinois' history occurred during the 1930s with three of the worst in that decade. In the more recent years, the dry summers of 1983, 1984, and 1988 rank relatively high.

The temporal distribution of the dry periods shows this prevalence for dry summers during the 1911-1920 and 1931-1940 decades. Only one dry summer occurred in the decade of 1961-1970, and only one in 1971-1980. Clearly, dry summers in Illinois were much more prevalent in the early 50 years of this century than in the last 40 years. Three distinct periods with a large number of dry periods were evident. They included 1906-1922, 1930-1936, and 1940-1945. The preponderance of dry summers in the early 30 years of the decade was seen in all crop reporting districts, with a diminishing frequency by district with time such that the 1961-1990 period had the fewest number of dry summers in all crop districts. Time between dry summers varies considerably. Two-thirds of the dry summers that have occurred in Illinois had only 1 or no summer between occurrences. Five times there was between 6 and 10 years between dry summers, and 4 of these have occurred since 1950.

Table 3-1. Assessment of Dry Summers, 1896-1990[1]

Year	Number of Districts	Mean[2] Rank	Number of Years Between Dry Summers	Dry Districts[3]	Driest Months
1901	9	13	5	all	7,8
1906	5	21	4	2,3,4,5,6	7
1908	7	13	1	1,2,4,5,7,8,9	6,8
1910	5	9	1	1,2,3,4,5	all
1911	7	23	0	1,3,4,5,6,7	7
1913	8	7	1	1,3,4,5,6,7,8,9	6,7,8
1914	9	12	0	all	6,7
1916	2	24	1	1,3	7
1918	5	23	1	5,6,7,8,9	7
1919	5	20	0	2,4,5,7,9	7,8
1920	9	11	0	all	6,7,8
1922	9	8	1	all	6,7,8
1930	9	5	8	all	7,8
1931	3	18	0	1,6,8	6,7
1933	9	4+	1	all	6,7
1934	2	16	0	2,6	7
1935	2	21	0	6,7	7,8
1936	9	4	0	all	6,7,8
1940	7	16	4	3,4,5,6,7,8,9	6,7
1941	2	13	0	2,8	7,8
1943	3	20	1	4,6,9	7,8
1944	8	15	0	all but 1	6,7
1945	4	21	0	1,2,3,5	7
1953	6	9	8	1,3,6,7,8,9	6,7,8
1954	2	22	0	7,9	6,7
1959	5	12+	5	3,4,5,6,7	6,7
1966	9	12	7	all	6,7,8
1976	7	13-	10	all but 8 and 9	7,8
1983	7	11+	7	all but 2 and 5	7,8
1984	9	10	0	all	6,7,8
1988	9	7+	4	all	6,7
Total	31				

[1] 1) Two or more CRD in top 30 driest ranks for summer rainfall in 1896-1990, and 2) July with below normal rainfall in 2 or more CRDs.

[2] Rank 1 = driest, based on mean of the values of the 9 CRDs.

[3] Districts:NW-l;NE = 2;W = 3;C = 4;E = 5;WSW = 6;ESE = 7;SW = 8;SW = 9

Table 3-2. Two rankings of summer dry periods, 1896-1990.

Rank based on mean ranks of qualifying districts	Rank based on mean statewide rainfall
#1 - 1936	#1 - 1936
#2 - 1933	#2-1988
#3 - 1930	#3 - 1930
#4-1913	#4 - 1933
#5 - 1988	#5-1913
#6 - 1922	#6 - 1984
#7-1910	#7-1966
#8 - 1953	#8 - 1914
#9-1984	#9 - 1920
#10-1983	#10- 1901
#11-13 (tie) -1914, 1966, 1959, 1920	
#14-17 (tie)-1901, 1908, 1941, 1976	

Table 3-3. Distribution of time periods between dry summers.

Non-dry years between qualifying years	Frequency
0 (no time in between)	13 times
1 year	8 times
2 to 5 years	5 times
6 to 10 years	5 times

Table 3-4. Temporal distribution of dry summers.

1901-1910 = 4

1911-1920 = 7

1921-1930 = 2

1931-1940 = 6

1941-1950 = 4

1951-1960 = 3

1961-1970 = 1

1971-1980 = 1

1981-1990 = 3

Table 3-5. Frequency of Crop Districts qualifying as dry per 30-year periods.

District	1901-1930	1931-1960	1961-1990	TOTAL
NW	10	5	5	20
NE	9	6	4	19
W	10	7	5	22
C	11	6	5	22
EC	12	6	5	23
WSW	9	10	5	24
ESE	10	9	5	24
SW	8	6	4	18
SE	10	7	4	21

Table 3-6. Size of dry areas in dry summers.

Number of Districts	Number of dry summers
2 districts	5
3 districts	2
4 districts	1
5 districts	5
6 districts	1
7 districts	5
8 districts	2
9 districts	10

Median = 7 districts
Average = 6.3 districts
Mode = 9 districts

Table 3-7. Primary dry summers in each district.

District	Rank#l	Rank #2	Rank #3
NW	1988	1976	1910
NE	1910	1933	1934
W	1936	1983	1988
C	1988	1933	1936
E	1988	1933	1922
WSW	1936	1933	1914
ESE	1930	1984	1922
SW	1936	1930	1913
SE	1930	1936	1953
1910	1	0	1
1930	2	1	0
1933	0	4	0
1936	3	1	1
1988	3	0	1

SPATIAL CHARACTERISTICS OF SUMMER DRY PERIODS

Floyd A. Huff

Introduction

Several spatial characteristics of dry periods were investigated including their frequency, intensity, and areal extent. The analytical unit employed was the mean summer precipitation for each of the nine crop reporting districts in Illinois during 1900-1993. There were 61 stations with complete records for the 93-year period. These provided an average sampling density of approximately one observation for each 2360 km^2 (920 mi^2). District areas ranged from 11,250 to 20,000 km^2 (4585 to 7815 mi^2). The 9-district average was 15,960 km^2 (6225 mi^2).

Qualifying dry periods were determined by district, as in the previous section on temporal characteristics. All summers were included in which the mean rainfall in one or more districts was among the lowest one-third recorded in the district(s) during the sampling period. The resulting samples included dry periods that ranged in areal extent from only one district in the state (18 cases) to 10 cases that affected all nine districts (entire state). A large proportion of the summers had two or more separated dry areas. An area was considered independent if all bordering districts were non-qualifiers. Thus, in a particular summer, there might be a qualifying dry area in northern Illinois and another in southern Illinois, but none in the central part of the state. Such two qualifying areas were treated as separate dry-period samples. Based on this approach, there were a total of 68 qualifiers in the 93-year sampling period.

Area-Depth Analysis of Dry Periods

Analytical Approach. In this study, dry period characteristics were evaluated through use of seasonal (June-August) area-depth envelope relations. This type of area-depth relation is based on analysis of the total area enclosed by rainfall isohyets of various magnitude. In the standard area-depth curves described earlier in this report, average rainfall was used instead of enveloping rainfall to describe spatial distribution characteristics of storm rainfall. The standard type of curve is appropriate for most hydrological applications, but enveloping rainfall is better for describing the areal distribution and intensity of seasonal drought. An example of the area-depth envelope curve is provided in Figure 3-2 which shows the relation obtained for the summer dry period of 1911.

After an area-depth curve was derived for a qualifying dry period, a second curve we derived from the information furnished by the first curve. The second curve provided a relation between area and percent of normal rainfall; that is, percent of normal replaced actual rainfall values. This was done to normalize the area-depth data so that it could be used in analyses that required grouping of the data in various combinations. The 30-year normals for 1960-1990, published by the National Weather Service, were used for the percent-of-normal conversions.

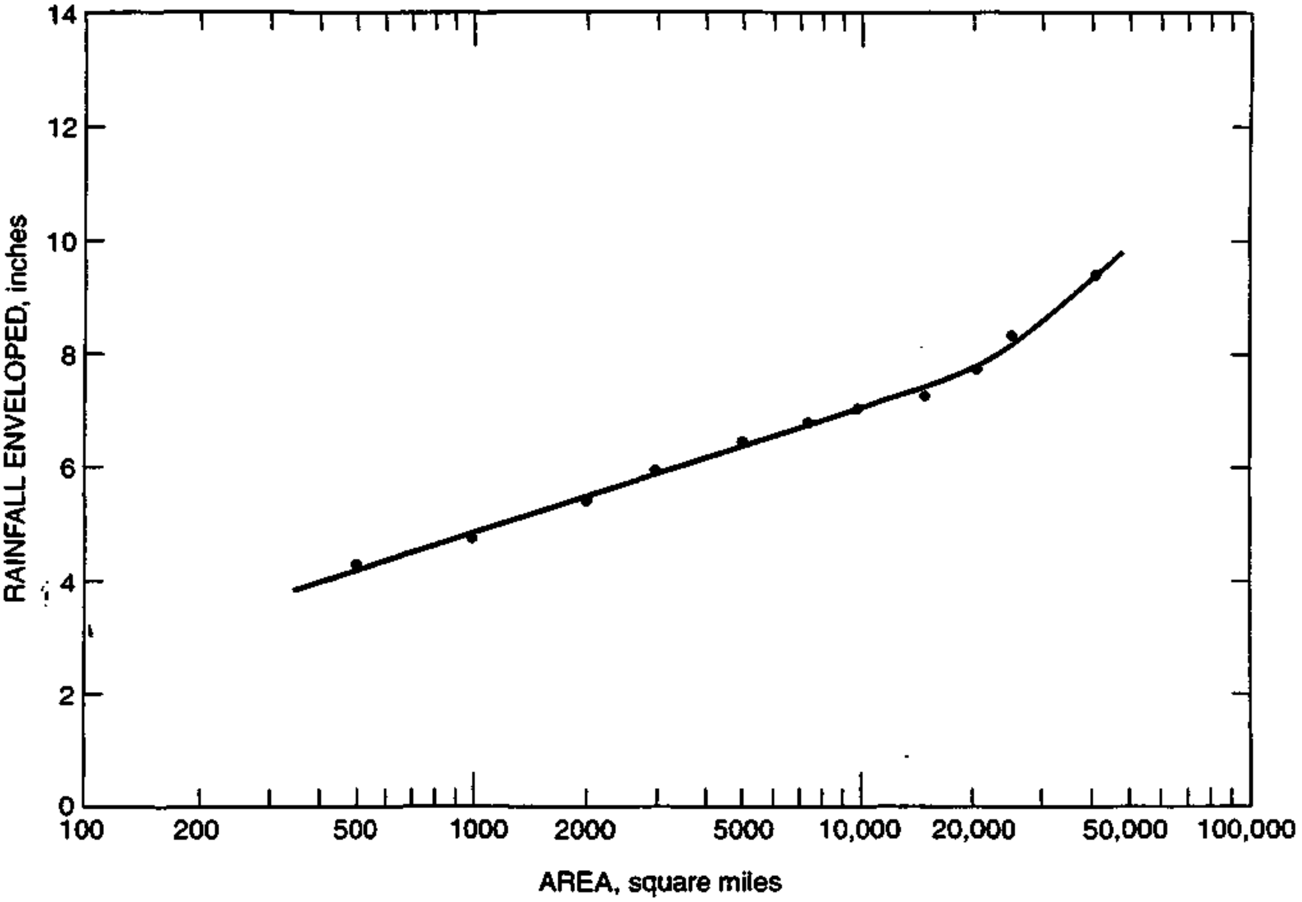


FIGURE 3-2. Area-depth curve for summer 1911 in crop districts #3 through #9.

An example of the two types of area-depth curves is illustrated in figures 3-2 and 3-3 for the summer of 1911. Figure 3-2 shows a graphical plot of the area-depth curve. Total rainfall amount (cm) enveloped with increasing distance from the drought center is related to the total area enveloped at corresponding distances. Thus, Figure 3-2 shows that within the 2,500 km^2 (1000 mi.^{2}) about the drought center, the rainfall <12.4 cm (4.9 in.) The rainfall amounts enveloped increase gradually to 12.4 cm (6.4 in.) at 12,500 km^2 (5000 mi^2) and to 17.8 cm (7.0 in.) at 25,000 km^2 (10,000 mi^2). Figure 3-3 shows figure 3-2 but with rainfall amount replaced by percent of normal rainfall. Thus, the rainfall of 12.4 cm at 2,500 km^3 in figure 3-2 is shown to represent 43% of the normal summer rainfall in the drought area. Similarly, the 16.3 cm at 12,500 km^2 represents 57% of normal, and the 17.8 cm at 25,000 km^2 in figure 3-2 is 63% of normal.

9-District Dry Periods. The ten dry periods that affected all nine districts were analyzed initially. In the first step, median area-depth curves of the types illustrated in Figures 3-2 and 3-3 above were derived from the data. These are shown in Figures 3-4 and 3-5. Table 3-8 summarizes information from the curves. It shows how rainfall and percent of total rainfall vary from the center of the median dry area to its outer extremities of Illinois, 140,000 km^2 (56,000 mi^2). As shown at the bottom of the table, normal summer rainfall for Illinois is 29.0 cm (11.4 in.). Assuming the median curve is typical of widespread dry periods in the state, Table 3-8 values imply that typical conditions would include 6,250 km^2 (2500 mi^2), at the dry area's center, having rainfall equal or less than 30% normal. Similarly, the median values show rainfall equal or less than 50% normal over 42,500 km2 (30% of state), and equal or less than 70% normal over 100,000 km^2 (71% of state).

Single-District Dry Periods. In grouping the summer dry periods according to areal extent, isolated dry periods were analyzed in which only one climatic district was affected. The sample consisted of 27 cases. Of these, 18 were occurrences in which only one district in the state met the criteria for inclusion in the study. The other 9 cases were those in which a single district was isolated with respect to contiguous districts, but there were one or two other districts in the state that qualified.

Similar to other groups, area-depth envelop curves were derived for each case with respect to rainfall and percent of normal rainfall, and results entered into the computer for further analyses. Figure 3-6 shows the area-depth relation obtained from the medians for selected subareas within the area-depth curves for the 27 cases. The median curve in figure 3-6 was calculated from values for percent of normal rainfall, which is employed in the study to normalize the data derived from districts having variable mean rainfalls and areal size. As indicated, the curve was found to closely fit a square-root distribution. Actual values of area (km^2) have been shown or selected subareas to facilitate reader interpretation.

As another phase of the analyses, the frequency distribution of district mean rainfall during dry periods was determined. The frequency distribution for the single-district data was determined to correspond closely with a log normal distribution. The values in Table 3-9 were obtained from fitting percent of normal rainfall to this distribution. Values in Table 3-9 indicate that the average percent of normal rainfall decreases gradually from 82% for a 5-year return period to 55% for a 100-

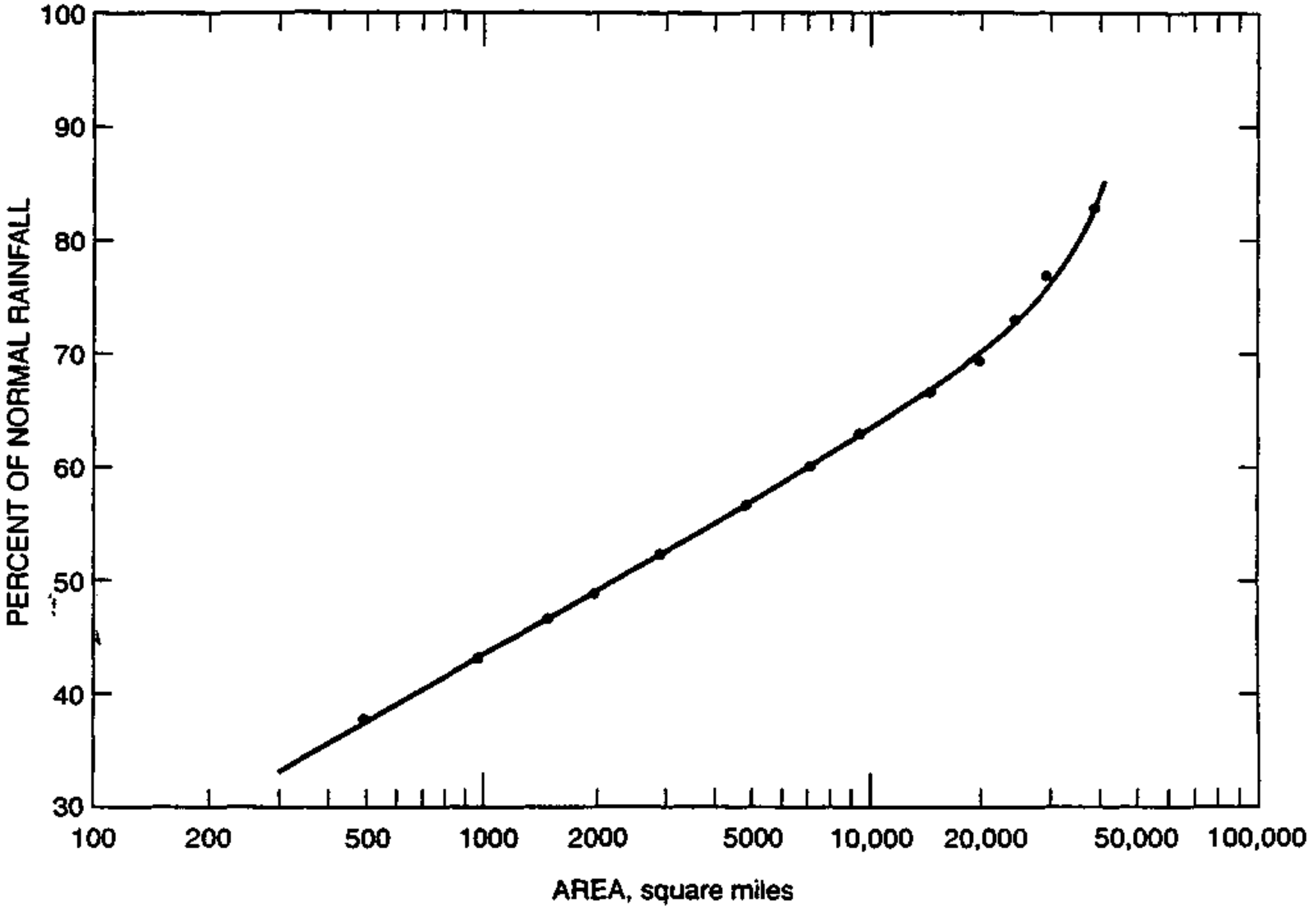


FIGURE 3-3. Area-depth curve for summer 199 (Fig. 3-2) converted to percent of normal rainfall

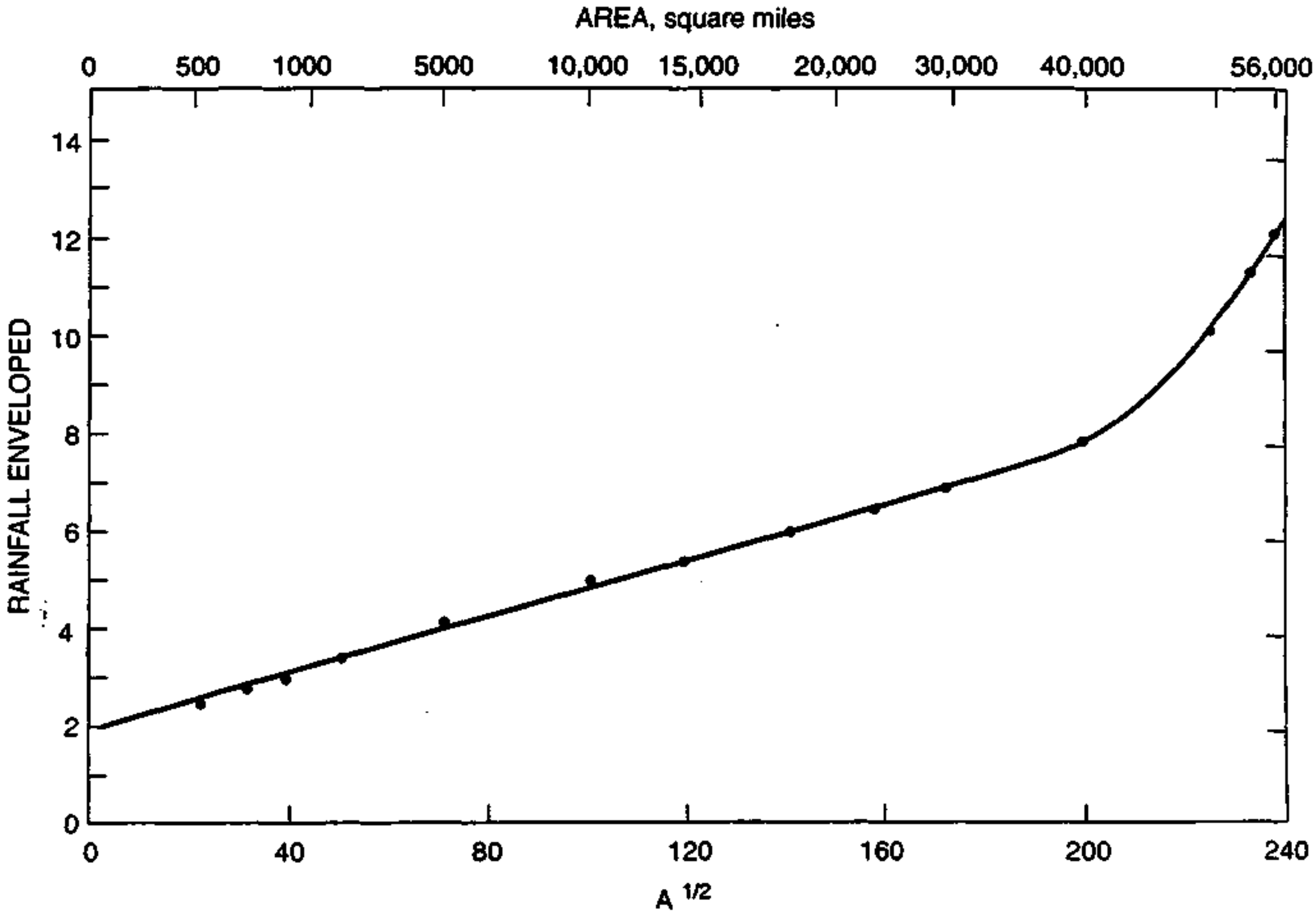


FIGURE 3-4. Median rainfall for dry periods affecting all nine crop districts (all of Illinois).

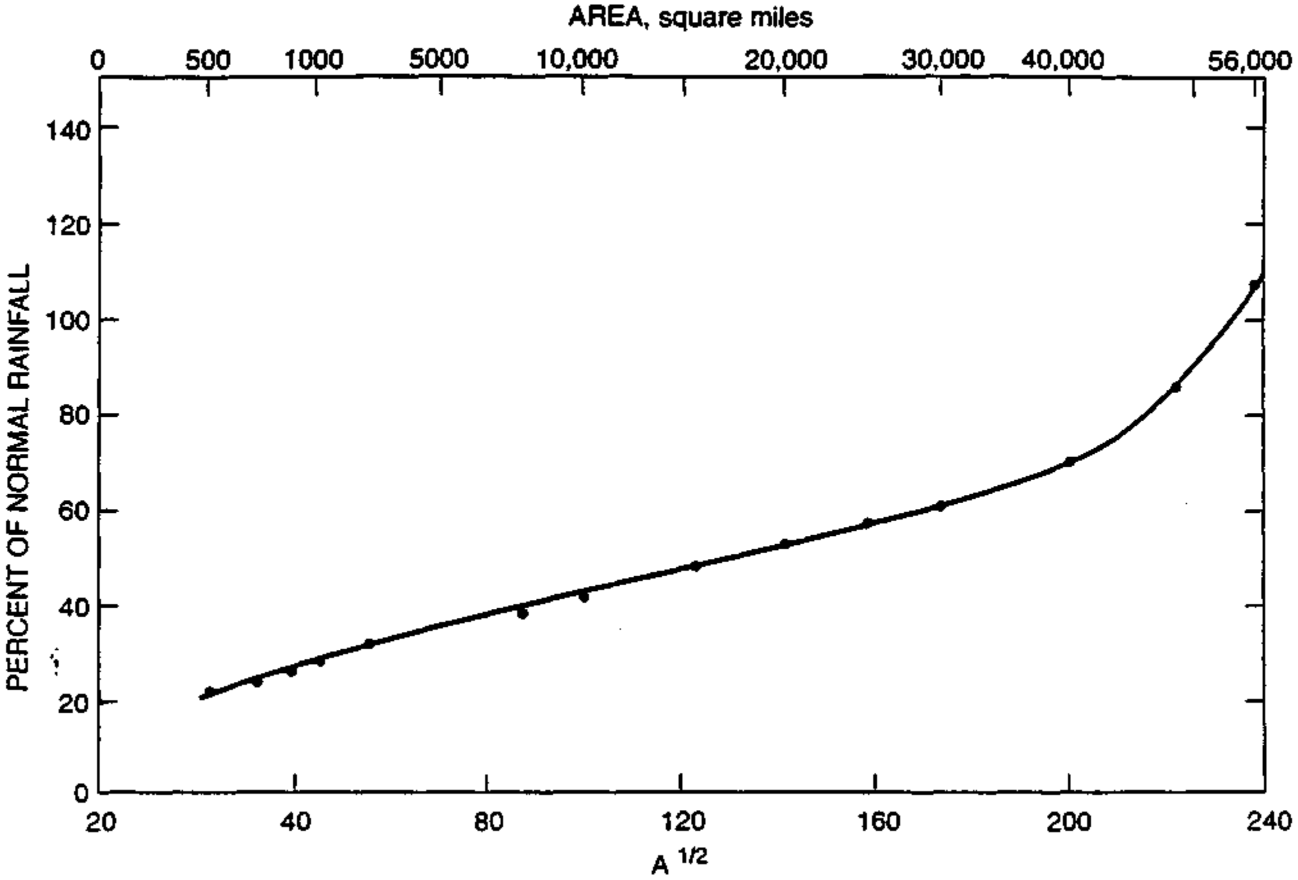


FIGURE 3-5. Median percent of normal rainfall in summer dry periods encompassing Illinois.

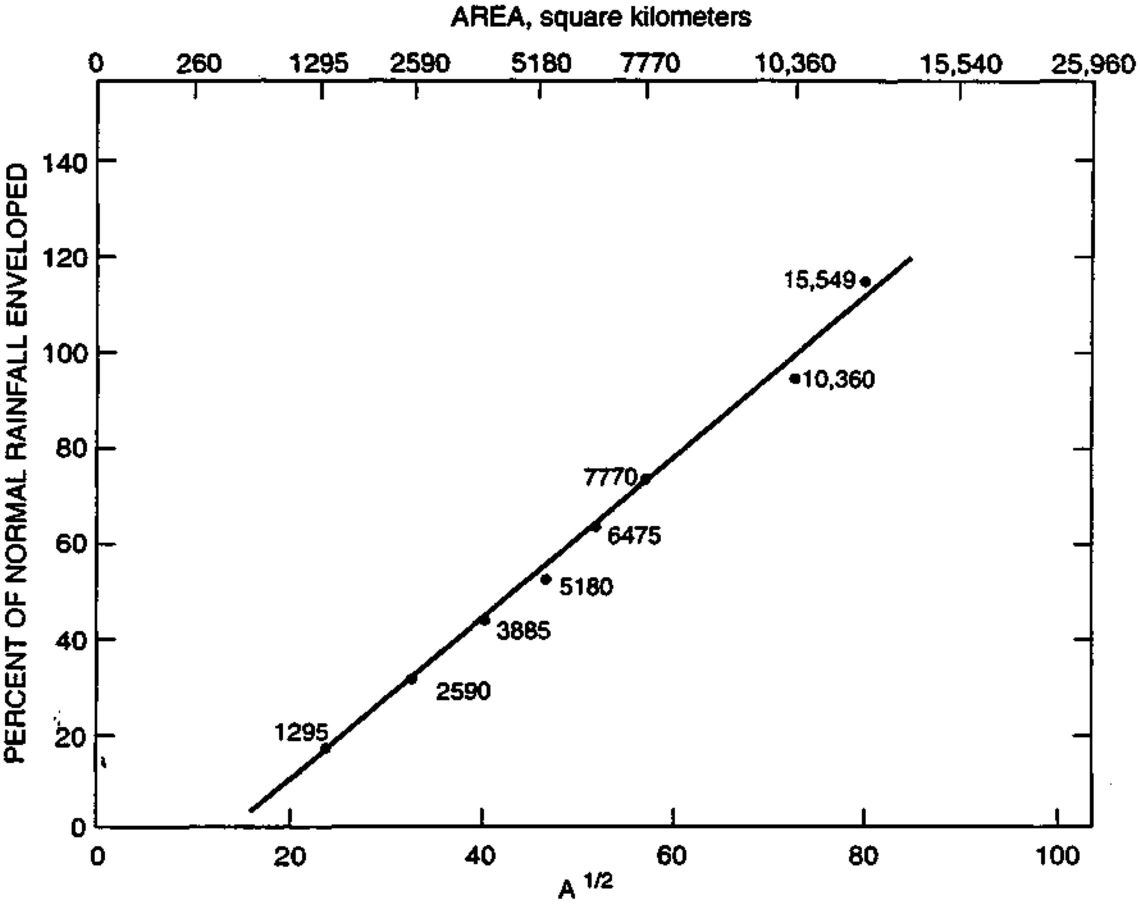


FIGURE 3-6. Area-depth envelope relation for single-district occurrences of summer dry periods.

year occurrence. However, the values for 50-year and 100-year return periods should be used with caution because of sample size (27 cases in 93-year period).

Areal Extent of Dry Periods

The areal extent of summer dry periods was determined for a 90-year period (1897-1987). The number of occurrences of dry periods was tabulated for each summer in which a dry period extended over one or more of the nine climatic districts in Illinois (Fig. 3-1) and the results are summarized in Table 3-10.

Table 3-10 shows that there were no dry periods in 28 years (31%). There were 50 years (56% of total) that had dry periods extending over two or more districts. Similarly, there were 36 years (40% of total) with dry conditions encompassing four or more districts; 19 years (21%) enveloping six or more dry (approximately two-thirds of the state); and 9 years (10%) in which all districts experienced drought conditions of some level of intensity.

Table 3-11 provides further information concerning the areal extent of the dry periods. This tabulation shows the number of times each district was part of a dry period enveloping two or more districts. The results indicate that differences in frequencies among the various districts are small. The values do not show any geographic trend and differences are most likely related to natural variability in precipitation distribution. Therefore, combining districts in defining the dry period characteristics in the study should be valid.

Table 3-8. Median Area-Depth Envelop Relations in Dry Summers Incorporating all 9 Districts (partially or completely)

Enveloped Area (km^2)	Enveloped Rainfall (cm)	Percent* ofNormal
1,250	6.3	22
2,500	7.1	24
3,750	7.6	26
5,000	8.1	28
7,500	9.1	32
12,500	10.4	36
25,000	12.2	42
37,500	14.0	48
50,000	15.2	53
62,500	16.5	51
75,000	17.5	61
100,000	20.3	70
125,000	25.7	89
135,750	29.0*	100
140,000	30.5	107

*1961-90 normal = 29.0 cm (11.43 in.)
≤30% of normal = 6,250 km^2
≤40% of normal = 20,875 km^2
≤50% of normal = 42,500 km^2
≤70% of normal = 100,000 km^2
≤100% of normal = 135,750 km^2

Table 3-9 Frequency Distribution of Percent of Normal Rainfall in Dry Summers Involving Single-District Occurrences.

Frequency (years)	Percent of Normal
5	82
10	73
15	69
25	64
50	59
100	55

Table 3-10. Areal Extent in Illinois.

Number of Districts	Number of Occurrences
0	28
1	12
2	13
3	1
4	9
5	8
6	1
7	6
8	3
9	9

Table 3-11. Number of Times Each District was Part of a Dry Period Enveloping Two or More Districts.

District	Occurrences
NW	26
NE	31
West	30
Central	33
East	28
WSW	38
ESE	28
SW	30
SE	31
Median	30
Mean	30

SOIL MOISTURE IN DRY PERIODS

Floyd A. Huff

The soil moisture conditions during dry periods was investigated. Analyses of precipitation-soil moisture relations were performed for each of the state's nine climate districts. Average monthly and seasonal rainfall values were calculated for each division during the peak growing season periods of June-August. Soil moisture averages for the first 50 cm below the surface was the moisture parameter selected. Analyses were limited to the 1949-1993 period because soil moisture estimates were not available prior to 1949. Although analysis focused on dry periods having recurrence intervals of 5 years or longer, those having recurrence intervals of 3 years or more were evaluated and some attention was given to all rainfall conditions associated with below-average soil moisture conditions.

Analyses were based on soil moisture averages for July-August and rainfall for July-August and for June-August. In this analysis, rainfall was expressed as percent of normal (average) rainfall for the 45-year sampling period. The soil moisture measure used was an index value related to the difference between existing soil conditions and field capacity.

Rainfall-Soil Moisture Relations in Moderate to Severe Dry Periods

The relations between total rainfall and soil moisture conditions in those dry periods which had a recurrence interval of five years or longer were assessed. This corresponds approximately to the relations in the nine most severe soil moisture deficiencies in the 45-year sampling period. Results of this analysis are summarized in Tables 3-12 and 3-13. These tables show comparisons between soil moisture ranks 1-9 and the corresponding total rainfall for July-August and June-August in each Illinois climate district. They also show the total range of rainfall values among the nine most severe soil moisture deficiencies, along with the ranges that incorporate 90% and 67% of the rainfall values.

A weak trend is indicated in the rainfall values in Table 3-12 in progressing from rank 1 to rank 9 of soil moisture in the July-August period. For example, the nine-division median rainfall for rank 1 of soil moisture is 47% of the average rainfall. This increases to 66% among the rank 5 rainfalls (approximately a 9-year recurrence), but then increases only to 72% at rank-9 (approximately five-year recurrence).

Values in Table 3-13, which shows the relationship of June-August rainfall to July-August soil moisture conditions, do not produce any major improvement in the rainfall-soil moisture relationship. Division median for rainfall associated with rank-1 soil moisture is 46% of average rainfall. This increases to 63% at the rank-5 level, and to 86% at the rank-9 level of soil moisture. The June-August trend in rainfall appears to be somewhat stronger based on the foregoing calculations. However, the median range of values in the districts (calculated from the table statistics) is nearly identical for June-August and July-August. For June-August, it is 44%-89%, compared with 42%-

88% for July-August.

Similar analyses (not shown here) were made for rainfall associated with the 15 driest July-August periods as measured by soil moisture conditions. Results were similar to those in Tables 3-12 and 3-13, except for the expected increase in the rainfall ranges for these lesser drought conditions which represent approximately the average three-year recurrence interval.

Comparison Between Rainfall Frequency and Soil Moisture Deficiencies

The 1949-1993 data were analyzed to determine average soil moisture conditions associated with below-average rainfall in each of the nine climatic districts for the July-August period. Rainfall was again expressed as the percent of average rainfall. These percentages were then used to derive a frequency distribution for the lowest 50% of the July-August rainfalls. For each rainfall value in the distribution, the soil moisture index was determined for the surface-50 cm layer.

Results are summarized in Table 3-14 for each climatic district. Column 1 shows the percent of average rainfall at selected levels in the frequency distribution. Column 2 shows the rainfall range associated with the frequency level in column 1. Column 3 indicates the corresponding values of soil moisture. For example, the table indicates that the lowest 10% of the 2-month rainfalls recorded in District 1 included rain amounts that ranged from 35% to 55% of average. Similarly, column 3 indicates soil moisture ranged from 14% to 35% of the 45-year average (55%). Statistics follow for rainfalls that incorporated the driest 20%, 25%, 30%, 40%, and 50% of the 45-year sample of rainfall for July-August. The average soil moisture index is shown below the statistical summary for each climate division.

Table 3-14 indicates that if the driest 25% of the July-August rainfalls are selected from the long-term sample (1901-1993), most of the soil moisture conditions that are below normal in the near-surface layer (50 cm) will be included. In the test samples described above, the lowest 25% of the rainfalls are all equal to or less than 80% of the average division rainfalls. The 25% limiting value agrees closely with Changnon's earlier estimates (25% to 30%).

Table 3-15 provides further support for the above findings. This table shows the frequency distribution of July-August rainfall amounts associated with the nine largest soil moisture deficiencies (approximate five-year recurrences). All nine climate districts have been combined in this analysis. Thus, four of the low soil moisture values occurred with rainfall that was only 30%-39% of average. Nearly 60% of the moisture deficiencies occurred with rainfall that was less than 70% of average, and 80% were associated with rainfalls below 80% of average. Values in Table 14 suggest that if all July-August rainfalls producing less than 80% of the long-term average were selected for study, most of the important agricultural dry periods in Illinois would be included in the sample. If the lower 30%-35% of years were included, all dry periods of any significance would be included.

Table 3-12. Percent of Average July-August Rainfall Associated with Ranks 1 to 9 of Soil Moisture Index for July-August 1949-1993, Illinois Climate District.

Soil Moisture Rank	Percent of Average Rainfall District 1	District 2	District 3	District 4	District 5	District 6
1	58	46	46	44	47	69
2	38	78	46	72	53	42
3	47	79	38	89	67	50
4	58	85	50	50	58	58
5	49	66	70	58	59	65
6	80	61	67	67	88	40
7	65	54	75	88	70	78
8	60	94	81	76	78	72
9	72	67	81	52	82	42
Total Range	38-80	46-94	38-81	44-89	47-88	42-78
8/9 (90%)	38-72	46-85	38-81	44-88	47-82	42-72
6/9 (67%)	38-60	46-78	38-75	44-72	47-70	42-65

Soil Moisture Rank	District 7	District 8	District 9
1	58	47	53
2	75	84	35
3	64	67	61
4	55	75	68
5	83	73	98
6	76	93	67
7	65	31	72
8	69	83	79
9	60	90	113
Total Range	55-83	31-93	35-113
8/9 (90%)	55-76	31-90	35-98
6/9 (67%)	55-69	31-83	35-72

Table 3-13. Percent of Average June-August Rainfall Associated with Ranks 1 to 9 of Soil Moisture Index for July-August, 1949-93, Illinois Climate Districts.

Soil Moisture Rain	Percent of Average Rainfall in Each District.								
	1	2	3	4	5	6	7	8	9
1	44	40	60	35	35	58	46	53	56
2	46	60	47	55	42	58	57	03	44
3	49	77	44	88	51	50	56	61	56
4	73	89	69	64	57	59	63	61	69
5	63	63	56	58	59	58	70	65	84
6	77	63	84	55	81	62	69	71	65
7	73	61	71	88	64	71	83	56	73
8	71	82	67	78	88	63	61	61	74
9	80	86	79	99	108	90	69	82	88
Total Range	44-80	40-89	44-84	35-99	35-108	50-90	46-83	53-93	44-88
8/9 (90%)	44-77	40-86	44-79	35-88	35-88	50-71	46-69	56-82	44-84
6/9 (67%)	44-77	40-77	44-69	35-78	35-64	50-62	46-69	56-65	44-73

Table 3-14. Soil moisture comparisons in Illinois rainfall for July-August dry periods during 1949-1993.

District 1

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range (%)
10	35-55	14-36
20	≤65	≤48
25	≤69	≤51
30	≤80	≤70
40	≤89	≤70
50	≤95	≤83

Soil Moisture Average = 55%

District 2

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range (%)
10	46-64	7-40
20	≤77	≤45
25	≤78	≤45
30	≤86	≤58
40	≤86	≤64
50	≤93	≤83

Soil Moisture Average = 49%

District 3

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range (%)
10	38-50	9-28
	≤75	≤31
25	≤77	≤51
30	≤80	≤51
40	≤82	≤61
50	≤90	≤82

Soil Moisture Average = 52%

District 4

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range *(%)*
10	44-61	3-30
20	≤72	≤61
25	≤74	≤61
30	≤88	≤61
40	≤90	≤61
50	96	≤65

Soil Moisture Average = 55%

District 5

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range (%)
10	47-58	4-34
20	≤70	≤53
25	≤71	≤53
30	≤75	≤60
40	≤88	≤60
50	≤97	≤71

Soil Moisture Average = 55%

District 6

Percent of Rainfalls	Rainfall Range Percent of Average	Corresponding Soil Moisture Index Range (%)
10	40-61	15-17
20	≤73	≤59
25	≤77	≤59
30	≤81	≤59
40	≤90	≤73
50	≤97	≤73

Soil Moisture Average - 46%

July-August Data, 1949-1993, Rainfall-Soil Moisture Comparisons

District 7

Percent of Area Rainfalls	Rainfall Range in Percent of 45-Year Average	Soil Moisture Index Range (%)
10	50-59	11-54
20	≤69	≤54
25	≤76	≤54
30	≤83	≤54
40	≤96	≤56
50	≤101	≤59

Soil Moisture Average = 45%

District 8

Percent of Area Rainfalls	Rainfall Range in Percent of 45-Year Average	Soil Moisture Index Range (%)	
10	31-67	14-49	(14-19)
20	≤73	≤49	
25	≤75	≤49	(≤40)
30	≤83	≤49	(≤40)
40	≤88	≤49	(≤40)
50	≤95	≤49	(≤40)

Soil Moisture Average = 42%

District 9

Percent of Area Rainfalls	Rainfall Range in Percent of 45-Year Average	Soil Moisture Index Range (%)
10	35-64	8-28
20	≤72	≤40
25	≤77	≤56
30	≤80	≤56
40	≤90	≤73
50	≤98	≤73

Soil Moisture Average= 47%

Table 3-15. Frequency of July-August Rainfall Amounts Associated with 9 Lowest Soil Moisture Indices Among Illinois Climate Districts.

Rainfall (Percent of Average)	Frequency of Qualifying Soil Moisture Values	
	Number of Occurrences	Cumulative Percent of Occurrences
30-39	4	5
40-49	11	19
50-59	15	37
60-69	18	59
70-79	17	80
80-89	11	94
≥ 90	_5	100
Total	81	

DRY PERIODS IN AN AREA WITH INADVERTENT PRECIPITATION MODIFICATION

Floyd A Huff

Introduction

Dry period analyses using METROMEX data were performed as part of three Water Survey studies in the late 1970s. The Metropolitan Meteorological Experiment (METROMEX) was an extensive 5-year (1971-1975) field project conducted in the St. Louis area to define the existence and causes of urban-induced changes in precipitation. One study of dry periods was part of the initial overall analyses of the METROMEX program data (Changnon et al., 1977). The second was a project dealing with assessing weather modification potential for alleviating water shortages during droughts (Huff and Vogel, 1977). The third was a further study of urban effects on precipitation during the transition seasons (Changnon et al., 1985).

Precipitation data were from a recording raingage network of 225 gages installed in a circular area of approximately 5200 sq km (2000 sq mi) centered on St. Louis. Complete data from the 225-gage network were available for the summers (June-August) of 1971-1975, and with a reduced gage density (120 gages) during the three transition seasons (fall, winter, and spring). Data used in these dry period analyses consisted of monthly and seasonal totals. These data were analyzed in various combinations of months and seasons to maximize the information available for comparisons of dry, near-normal, and wet periods. The primary objective was to determine the potential for weather modification in dry periods when agricultural and municipal water supplies are inadequate. However, the information should be useful also in other applications of climatic data (climate change, water pollution, industrial cooling process, etc.).

The approach to the problem was to study the effectiveness of inadvertent weather mechanisms during dry periods compared with those in near-normal and wet periods. The hypothesis was that the characteristics of the inadvertent mechanisms in various combinations could provide a measure of the potential effectiveness of cloud seeding in dry periods. Two types of inadvertent weather conditions were present in the sampling area. The primary mechanism was urban-induced rainfall which was largely restricted to intensification of on-going storm systems. A secondary effect on the natural distribution of summer rainfall was local topographic factors. These included the Ozark foothills which penetrated the SW quadrant of the raingage network; a hilly region located in the extremity of the SE quadrant of the network; bluffs along the Mississippi River; and bottomlands (moisture source) located in the NW quadrant near the confluence of the Mississippi, Missouri, and Illinois Rivers.

Results of Dry Period Rain fall Analyses

Figure 3-7 shows the isohyetal pattern of the 5-summer total rainfall on the METROMEX network. The 5-summer rainfall distribution characteristics were the basis of comparison in evaluating dry-period rainfall with respect to pattern configuration and effectiveness of the inadvertent weather mechanisms. As shown in Figure 3-7, the 5-summer pattern exhibited a strong high centered NE of the city found to be urban related (Changnon et al., 1977). Topographic effects were associated with the secondary highs in the NW, SW, and SE quadrants (Huff and Vogel, 1978).

As mentioned above, various combinations of months and seasons were used to evaluate similarities and differences between dry, normal, and wet weather conditions. In one combination, the 15 sample months were ranked and divided into five groups of three months each. These were designated dry, moderately dry, near normal, moderately wet, and wet periods. Another analysis involved comparison of the three driest and three wettest months in the five years. A third investigation was a comprehensive evaluation of the summer 1971 rainfall which was a dry period having a 3-month total of only 63% of normal. A fourth analysis involved comparison of the total rainfall for the five June months (67% of normal) with the five August totals (99% of normal). These analyses provided a comparison between dry and normal periods of precipitation with respect to pattern configuration and magnitude of inadvertent weather effects.

Figure 3-8 shows the isohyetal patterns for the dry summer of 1971 (63% of normal), and the 5-year June total (67% of normal). Both maps indicate similar pattern configurations when compared with the total 5-summer rainfall in Figure 3-7. In general, highs and lows were in the same locations among the three isohyetal patterns. In both dry-period maps, the major high was in the region of the major urban-induced high in Figure 3-7. All three maps indicate the urban-induced high was more pronounced than the topographic-related highs.

The relative strength of the urban-induced high northeast of St. Louis is brought out further in Table 3-16, based on results of a special study of the nocturnal high observed in the METROMEX network (Changnon et al., 1985). For each of the six anomaly areas (shown in Figure 3-9), the ratio of average rainfall in each area to the network average rainfall is shown, along with the time (CST) that the anomaly maximized, for the following data groups:

1. Total summer rainfall for 1971-1975 (93% normal);
2. June rainfall for 1971 -1975 (dry period, 67% normal);
3. August rainfall for 1971-1975 (normal 99%).

For the five summers combined, the nocturnal anomaly was strongest in the Edwardsville and Granite City-Edwardsville areas, where it maximized at 2100-2400 CST. Effect area/network ratios were 1.58 and 1.49, respectively. For the June rainfalls, the same ratios were 2.13 and 1.77, considerably greater than the total summer ratios. For the August rainfalls, the ratios were 1.06 and 1.16, considerably smaller than those for the other two groups. For all three groups, the anomaly maximized at 2100-2400 CST. The time of maximization was consistent for Wood River Refineries

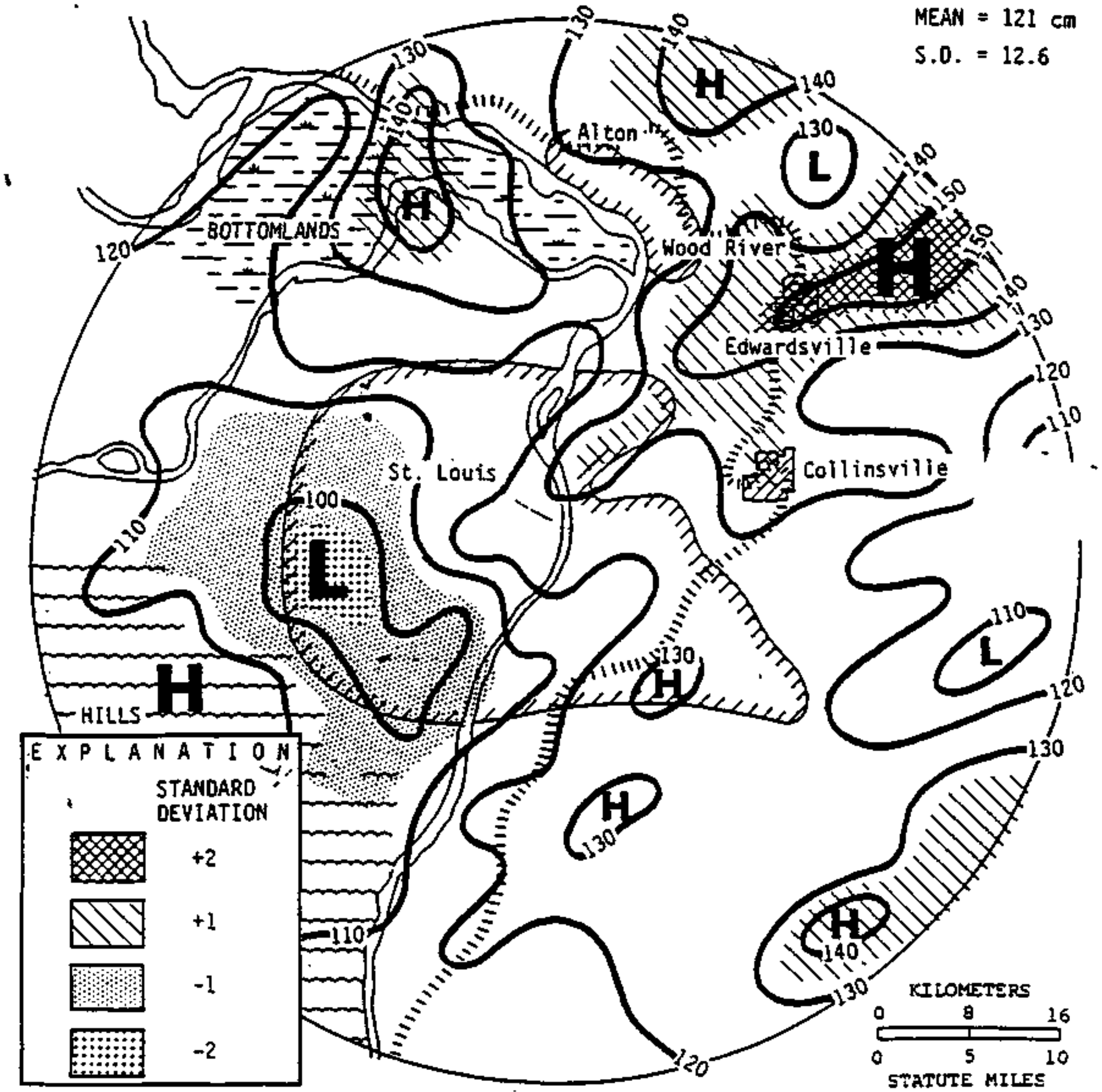
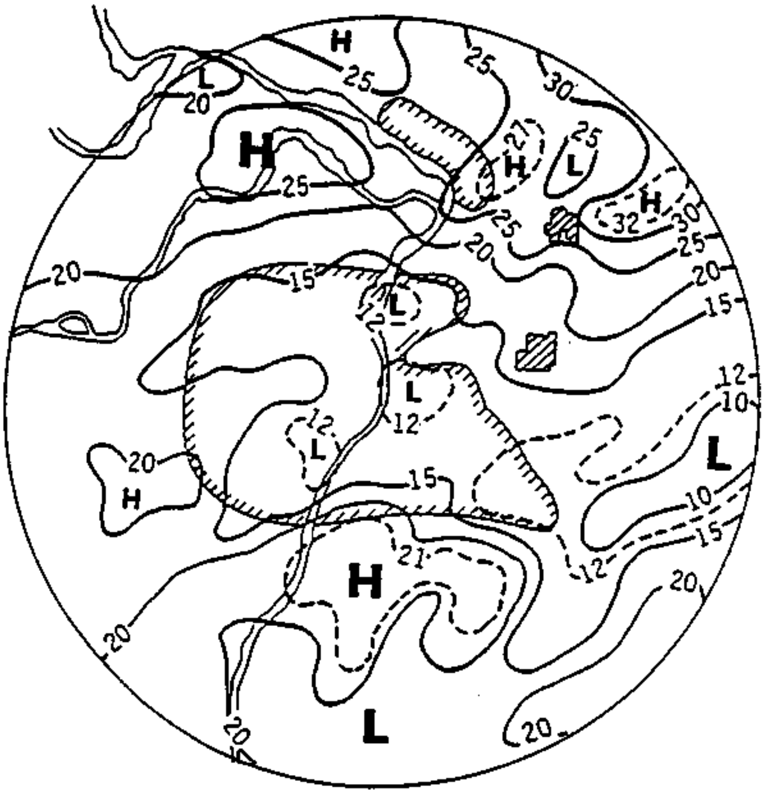
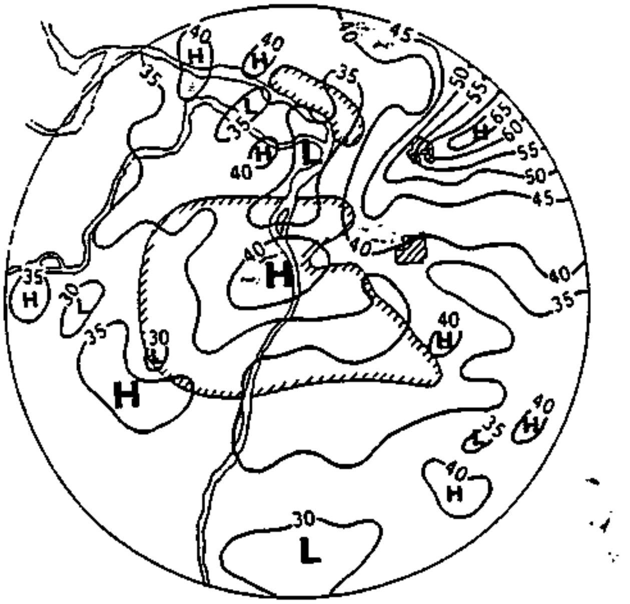


FIGURE 3-7. Total summer (June-August) rainfall (cm) for 1971-1975 period in St Louis area.



June-August, 1971



June, 1971-1975

FIGURE 3-8. Total rainfall (cm) in St Louis area for dry summer of 1971, and for Junes from 1971 to 1975.

and the Bottomlands also, but varied in the other two groups. Processed data were not available in the METROMEX computer files to assess the diurnal relations further with respect to their variation between normal, dry, and wet periods.

In general, the analyses of relatively dry, moderate, and wet periods indicated that both the urban and topographic factors were affecting precipitation under all types of precipitation regimes. During dry months, a trend was noted for rainfall to occur more frequently along the river valleys, in hilly regions, and in the vicinity of the heavily industrialized urban areas of St. Louis and Alton-Wood River.

At the center of the major urban-induced high NE of St. Louis the rainfall was relatively greater in dry periods than in moderate to wet periods.. When the rainfall of the six driest months on the METROMEX network were compared with that from the six wettest months, the rain in the NE of St. Louis high exceeded the network average by 74% in the relatively dry months as compared with 20% greater in the wettest months. The total amount of excess rainfall (departure from network mean) in the Edwardsville high averaged 9.55 cm (3.76 in.) for the six dry months and 6.50 cm (2.56 in.) for the six wettest months. Thus, the results of the dry period rainfall analyses at St. Louis suggest there could be weather modification potential during these drier periods.

Convective Rain Elements

Raincell initiations during relatively wet, near-normal, and dry periods were analyzed in conjunction with the METROMEX summer sampling program (Huff and Vogel, 1978). Rain cells were defined by closed contours displayed in the 15-minute rainfall maps. The sample consisted of rain cells during six dry months (21 to 68% of normal rainfall), three near-normal months (80 to 104% of normal), and during six wet months (105 to 155% of normal). Results indicated that the initiations of rain cells were concentrated in and downwind of the urban-industrial regions of St. Louis and Alton-Wood River in wet, near normal, and dry months. Topographic influences on raincell initiations were also indicated, but were not as pronounced as urban influences. The above average frequency of cell initiations occurred along the major river valleys and in the Ozark foothills in the southwestern part of the raingage network. Although urban and topographic effects were present in months of below-normal, near-normal, and above-normal rainfall, the effect relative to the rest of the network appeared to be slightly greater in dry months. The results of this analysis provide additional evidence that the potential for modification of convective rainfall is present in relatively dry periods.

Raincell mergers were also identified when two ore more surface raincells grew together. Such merging of convective elements have been associated with intensification, areal growth, and duration of convective entities. Therefore merged storm elements are an important contributor to storm total rainfall production. Huff and Vogel (1977) made a study of the characteristics of METROMEX raincells, with particular emphasis on those in wet and dry periods. In the dry months, 32% of the total number of cell mergers occurred over, east, and northeast of St. Louis in the region

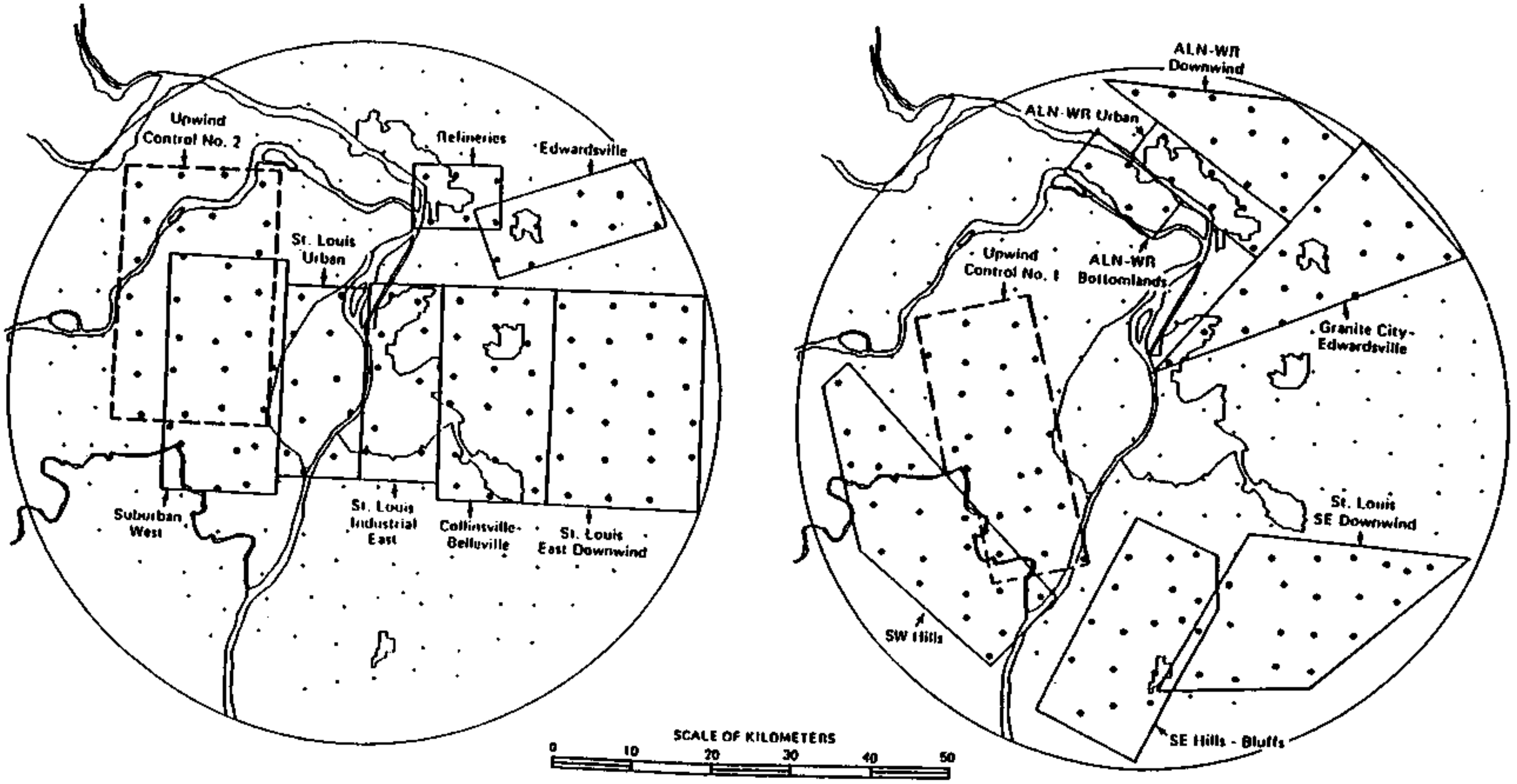


FIGURE 3-9. Subareas used in evaluating possible urban effects on rainfall at St. Louis.

of maximum urban effect. In comparison, 25% occurred in this region in months of near-normal rainfall, and 28% in the wet months. This indicates that the merger-related dynamic processes, which are closely related to the rain enhancement processes, are active in dry as well as wet periods, and are apparently stimulated by urban influences on atmospheric mechanisms. This is another favorable finding from the standpoint of planned weather modification; that is, there is an indication that there is the potential to stimulate rain production under some conditions during dry periods.

Synoptic Weather Conditions

Synoptic conditions were analyzed in conjunction with a detailed study of the dry summer of 1971 on the METROMEX network (Huff and Vogel, 1977). The synoptic weather differences between dry (1971) and wet periods (1975) is provided by the tabulations in Table 3- 17a, abstracted from Changnon et al. (1977). Comparisons are shown for the four major rain-producing synoptic types on the 1971-1975 METROMEX summer network. These four types were associated with 94.5% of the total network rainfall in the five summers. Squall lines were associated with 50.5% of the total rainfall, followed by squall zones with 25.0%, cold fronts with 12.4%, and stationary (static) fronts with 6.6%.

During 1971, the largest deficiency (compared with the average) was in the frequency of squall lines, the most prolific rain producer during summer. Squall zones occurred with an average frequency in 1971. Together, squall lines and squall zones accounted for 75.5% of the 1971-1975 rainfall. There was a slight deficiency in cold fronts during 1971. During 1975 (wettest summer), above average frequencies occurred with all but static fronts.

The foregoing comparisons indicate that the dry summer was largely due to a deficiency in the frequency of squall lines which were associated with over 50% of the 5-summer rainfall. The wet summer was associated with generally above-average frequencies in the major storm types.

Tabulations shown in Table 3-17b are similar to those in Table 3-17a in basic format. For each synoptic type, the total rainfall (cm) and percentage of total rainfall are shown for the dry summer (1971), the wet summer (1975), along with the summer averages for 1971-1975. Comparison of the rainfall amounts, shows that squall-line rainfall was three times greater in the wet summer (1975) than in the dry summer (1971). The squall line contribution to the seasonal rainfall was considerably below average in the dry summer and considerably above the 5-summer average in the wet summer. Rain totals did not vary significantly with squall zones between the dry and wet summers, but the percentage contribution to total summer rainfall was much above average in 1971 and near average in 1975. The contribution of cold and static fronts was below average in both the dry and wet summers. Much above average rainfall for these two types occurred in 1974, and this resulted in 5-year averages being dominated largely by the 1974 data.

The tabulations of synoptic types with respect to frequency of occurrence and total summer rainfall (Tables 3-17a and 3-17b) indicate that the dry summer (1971) was caused primarily by a substantial below normal occurrence in both the frequency and total rainfall output for squall lines. Similarly, the wet summer (1975) was associated with strongly above-normal occurrences in the frequency of squall lines and in the total rainfall produced by this synoptic storm type.

Overall, the outstanding finding was that the 1971 dry summer was similar to other wetter summers with respect to (1) monthly and seasonal rainfall patterns; (2) distribution of highs and lows; (3) initiation and merger regions; (4) heavy rainstorm patterns; and (5) the major urban-effect anomaly in the Edwardsville (EDW) area being produced largely in a relatively few storms. The major difference, and one that helps explain the relatively light rainfall in 1971 (63% of normal), was that the major rain producer in the St. Louis area storm systems, squall lines, occurred with only 50% of normal frequency in 1971. The findings of this 1971 drought study suggest that when rain occurs 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.

Transition Seasons

A study of the inadvertent weather effects on precipitation in the St. Louis area during the transition seasons (fall, winter, spring) was made using data from the METROMEX network for 1971-1975 (Changnon et al., 1985). In one analysis, potential inadvertent effects on precipitation were investigated during months of light, moderate, and heavy precipitation. Grouping was done by ranking the months from high to low by season. The upper third was then defined as heavy precipitation months, the middle third as moderate, and the lower third as light.

The ratio of total precipitation in selected effect areas in and around St. Louis was divided by that in Upwind Control-1 to obtain a measure of the potential inadvertent effect (locations of the subareas are shown in Figure 3-9). Results are summarized in Tables 3-18 through 3-20. In these tables, the ratios of precipitation in each potential effect area to that in the no-effect control area are shown for the light, moderate, and heavy categories.

In evaluating the findings, it has been assumed here (as a first approximation) that all ratios of 1.10 or greater are indicative of a potential inadvertent-induced increase. Values of 0.91 to 1.09 have been considered insignificant (due likely to sampling variations), and ratios equal to or less than 0.90 have been assumed to be indicative of a potential negative effect on precipitation.

In the fall analysis, all light precipitation ratios in Table 3-18 were in the insignificant to potentially negative ranges. The moderate precipitation ratios equaled or exceeded 1.10 in the major urban-effect areas defined by Huff and Vogel (1978). In Figure 3-9, these include EDW, GRC-EDW, STL Industrial, COL-BLV, and STL Downwind. The SW Hills had a ratio of 1.10, but the other topographic-effect areas were in the insignificant range, as were the ALN-WR industrial regions. Most ratios were in the insignificant range for heavy monthly precipitation.

Table 3-19 indicates that all the light precipitation ratios during winter were in the insignificant range, except for ALN-WR Bottomlands. In the moderate category, as in fall, the five major urban-effect areas had ratios of 1.10 or greater, indicating a likelihood of an urban-induced increase in precipitation. Except for ALN-WR Urban (1.10), all other ratios for moderate precipitation were in the insignificant range. In the heavy precipitation group, all ratios were in the insignificant range (similar to fall). Thus, the winter statistics support those for fall; that is the greatest inadvertent effects appear to be associated with moderate precipitation months.

In the light precipitation group during spring (Table 3-20), ratios of 1.10 or greater occurred in two of the urban-effect areas (COL-BLV and STL Downwind) and one topographic-effect area (SE Hills-Bluffs). Surprisingly, in view of the fall-winter findings, all precipitation ratios were in the insignificant range for moderate precipitation months. However, the heavy category, which was in the insignificant range in fall and winter, indicated ratios of 1.10 or greater for all the potential urban-effect areas. Except for ALN Bottomlands, the topographic-effect areas were in the insignificant range. More of the total spring rainfall is produced by convective elements than in fall or winter, suggesting that the marked urban influence on summer convective rainfall is more evident in spring than the other two seasons.

The relatively strong urban-effect ratios in spring are indicative of the gradual change to summer weather conditions as spring processes. The largest seasonal ratios in both the urban-effect and topographic-effect areas occurred in summer during the 5-year METROMEX sampling program. In both spring and summer, the largest inadvertent effects were most frequently associated with relatively heavy rainstorms (Huff and Vogel, 1978). Thus, planned weather modification appears to be most favored in the warm seasons when agricultural and municipal-industrial water supply shortages occur most often.

Table 3-16. Comparison of Nocturnal Anomaly in Dry and Near-Normal Rainfall.

Effect Area	Summer, 1971-1975		June 1971-1975		August 1971-1975	
	Ratio*	Time	Ratio	Time	Ratio	Time
Edwardsville (EDW)	1.58	21-24	2.13	21-24	1.06	21-24
Granite City-EDW	1.49	21-24	1.77	21-24	1.16	21-24
Wood River Refineries	1.44	20-23	1.44	20-23	0.87	20-23
Alton-Wood River Bottomlands	1.50	18-21	1.79	18-21	1.30	19-22
Alton-Wood River Urban	1.33	20-23	1.33	18-21	0.99	19-22
Alton-Wood River Downwind	1.48	20-23	1.56	18-21	1.24	18-21

*Ratio = Effect Area/Network Mean

Table 3-17a. Synoptic Type Comparisons in METROMEX Storms.

Synoptic Type	1971-1975 Average	1971 (Driest)	1975 (Wettest)
Squall Lines	10	5	13
Squall Zones	17	17	20
Cold Fronts	9	7	12
Static Fronts	4	5	2
Total	40	34	47

Table 3-17b. Rainfall Amounts in Average, Dry, and Wet Summers.

Synoptic Type	1971-1975 Average		1971 Total		1975 Total	
	cm	%	cm	%	cm	%
Squall Lines	11.40	50.0	6.22	38.0	18.59	64.4
Squall Zones	5.64	25.0	7.82	47.8	7.65	26.5
Cold Fronts	2.80	12.4	0.46	2.8	1.80	6.2
Static Fronts	1.48	6.6	0.66	4.0	0.43	1.5

Table 3-18. Estimated Inadvertent Effect on Precipitation During Months of Relatively Light, Moderate, and Heavy Precipitation in <u>Fall</u> on the METROMEX Network.

	Ratio, Subarea to Control Area are Mean		
Subarea	Light	Moderate	Heavy
EDW	0.90	1.12	1.06
GRC-EDW	0.91	1.11	1.02
WR Refineries	0.89	0.98	1.03
STL Urban	1.02	1.03	1.02
STL Industrial	0.90	1.13	0.98
COL-BLV	0.86	1.18	0.99
STL East Downwind	0.93	1.13	1.04
SE Hills-Bluffs	0.94	1.07	1.10
STL Suburban West	0.99	0.99	1.00
ANL-WR River Urban	0.91	1.01	1.06
ANL-WR Downwind	0.89	1.01	1.01
ANL-WR Bottomlands	0.89	0.95	1.14
SW Hills	1.08	1.10	1.08

Table 3-19. Estimated Inadvertent Effect on Precipitation During Months of Relatively Light, Moderate, and Heavy Winter Precipitation on 1971-1975 METROMEX Network.

	Ratio, Subarea to Control Area are Mean		
Subarea	Light	Moderate	Heavy
EDW	1.03	1.16	1.08
GRC-EDW	0.99	1.13	1.05
WR Refineries	0.92	1.06	1.00
STL Urban	0.99	1.01	1.00
STL Industrial East	1.03	1.10	1.04
COL-BLV	1.05	1.10	1.05
STL East Downwind	1.09	1.11	1.08
SE Hills-Bluffs	0.95	1.04	1.01
STL Suburban West	1.00	0.99	1.00
ANL-WR Urban	0.94	1.10	1.02
ANL-WR Downwind	0.93	1.07	1.01
ANL-WR Bottomlands	0.87	1.06	0.98
SW Hills	1.07	1.00	1.03

Table 3-20. Estimated Inadvertent Effect on Precipitation During Months of Relatively Light, Moderate, and Heavy Precipitation in Spring on the METROMEX Network.

	Ratio, Subarea to Control Area are Mean		
Subarea	Light	Moderate	Heavy
EDW	1.06	1.08	1.23
GRC-EDW	1.09	1.08	1.20
WR Refineries	0.94	0.97	1.19
STL Urban	1.08	1.02	1.13
STL Industrial	1.09	1.09	1.13
COL-BLV	1.13	1.09	1.15
STL East Downwind	1.20	1.07	1.11
SE Hills-Bluffs	1.10	1.00	0.96
STL Suburban West	0.97	1.01	0.98
ANL-WR Urban	0.94	0.98	1.25
ANL-WR Downwind	0.97	0.98	1.18
ANL-WR Bottomlands	0.95	0.98	1.18
SW Hills	1.04	1.06	0.98

FREQUENCY OF RAIN DAYS IN SUMMER DRY PERIODS

Floyd A. Huff

An examination of the frequency distribution of rainy days during the 93-year sampling period was made. Tables 3-21 and 3-22 briefly summarize the results of this analysis. Table 3-21 shows how the number of days with rainfall varied in dry, normal, and wet summers in each district. A slight trend is indicated for the frequency to decrease from north to south during dry periods. The opposite trend is indicated for wet summers when the frequency of rainy days is slightly larger in the northern than in the southern part of the state. Overall, the departures from normal are similar in dry and wet summers. The state averages indicate a departure of -18% in dry years and +14% in wet periods.

In Table 3-22, the mean frequency of rainy days is shown for dry summers grouped by areal extent and daily amounts. The area grouping is the same as used throughout this report. The table indicates a general trend for the number of rainy days to increase with decreasing drought area in each rainfall category and for all rain days combined. The trends are as expected. The value of Tables 3-21 and 3-22 is that they provide quantitative estimates of the rainy day distribution in dry periods. This is an important factor in considering the potential for alleviating water shortages by cloud seeding in dry periods.

Further information on rain days in dry periods can be found in Tables 4-7 and 4-8.

Table 3-21. Frequency (%) of Days with Measurable Precipitation in Dry, Wet, and Normal Summers.

Districts	Dry	Normal	Wet
1	25	30	35
2	25	29	34
3	23	27	32
4	23	28	33
5	24	28	32
6	22	28	32
7	22	28	32
8	22	28	31
9	22	22	11
Average	23	28	32
Median	24	28	32
Range	22-25	27-30	31-35

Table 3-22. Mean frequency of rainy days in dry summers grouped by areal extent and daily amounts.

	Frequency (%) of summer days having; given amounts (mm)						
Area (km^2)	0.0-2.5	<2.5-6.3	>6.3-12.7	>12.7-25.4	>25.4	All rain days combined	N
>52,000	7.3	4.3	3.2	2.7	1.6	19.1	5
26,000-52,000	8.2	4.5	3.7	3.2	1.8	21.4	6
13,000-26,000	8.5	4.8	4.0	3.5	1.9	22.7	7
7,700-13,000	8.1	5.1	4.5	3.7	2.0	23.4	5
3,885-7,770	9.7	5.6	4.9	4.0	1.9	26.1	13

AREA-DEPTH RELATIONS FOR STORMS DURING DRY AND NORMAL SUMMER MONTHS

Floyd A. Huff

Introduction

An area-depth analysis was used to investigate potential differences between storm characteristics in dry periods and those in normal rainfall periods of summer (June, July, and August). Storm area-depth curves provide a method of investigating the spatial characteristics of rainfall. The curve intercept provides an estimate of the maximum point rainfall, the slope indicates the mean rainfall gradient in the storm, and the endpoint of the curve shows the storm mean rainfall in the sampling area. Points along the curve show the mean rainfall in subareas within the total sampling area. As part of previous Water Survey research, area-depth curves were determined for all storms in which the areal mean rainfall ≥ 1.25 cm on two dense raingage networks operated in Illinois during the period 1955-1966. This cutoff occurred because the previous research had been oriented to hydrologic needs.

Huff and Vogel (1977) have shown that the major source of rainfall in moderate to severe droughts results from occasional storms producing rainfall >1.25 cm. These storms accounted for 40% of the total rainfall measured on the raingage networks during the dry periods used in the present study. The two networks consisted of the East-Central Illinois network (ECI) and the Little Egypt network (LEN), located in southern Illinois. Both networks provided measurements over areas of 1000 km^2 (400 mi^2) in which raingages were spaced at approximate intervals of 5 km. Processed rainfall data were available from ECI for 1955-64 and from 1956-1966 for LEN.

Analysis Procedures

The first step was to develop average (normal) area-depth relations on the two networks. For this purpose, it was necessary to convert the standard area-depth curves to area-depth ratio curves. These curves are obtained by dividing the maximum point rainfall and subarea means (points along the curve) by the sampling area mean. The data were divided into two groups: those incorporating storms having means of 1.25 to 2.50 cm, and those with means >2.50 cm. Mean and median curves were then derived for each network.

Examination of the two network results showed only insignificant differences between their curves. Therefore, data from the two networks were combined to obtain relations from a larger sample. The combined network samples consisted of 194 storms (rain events) in the 1.25-2.50 cm group, and 101 storms in the >2.50 cm category. Median curves are shown for the combined networks for each of the two storm categories in Figure 3-10. As expected, the slope of the lighter rainfall curve is greater; that is, the spatial relative variability is greater. This is a common

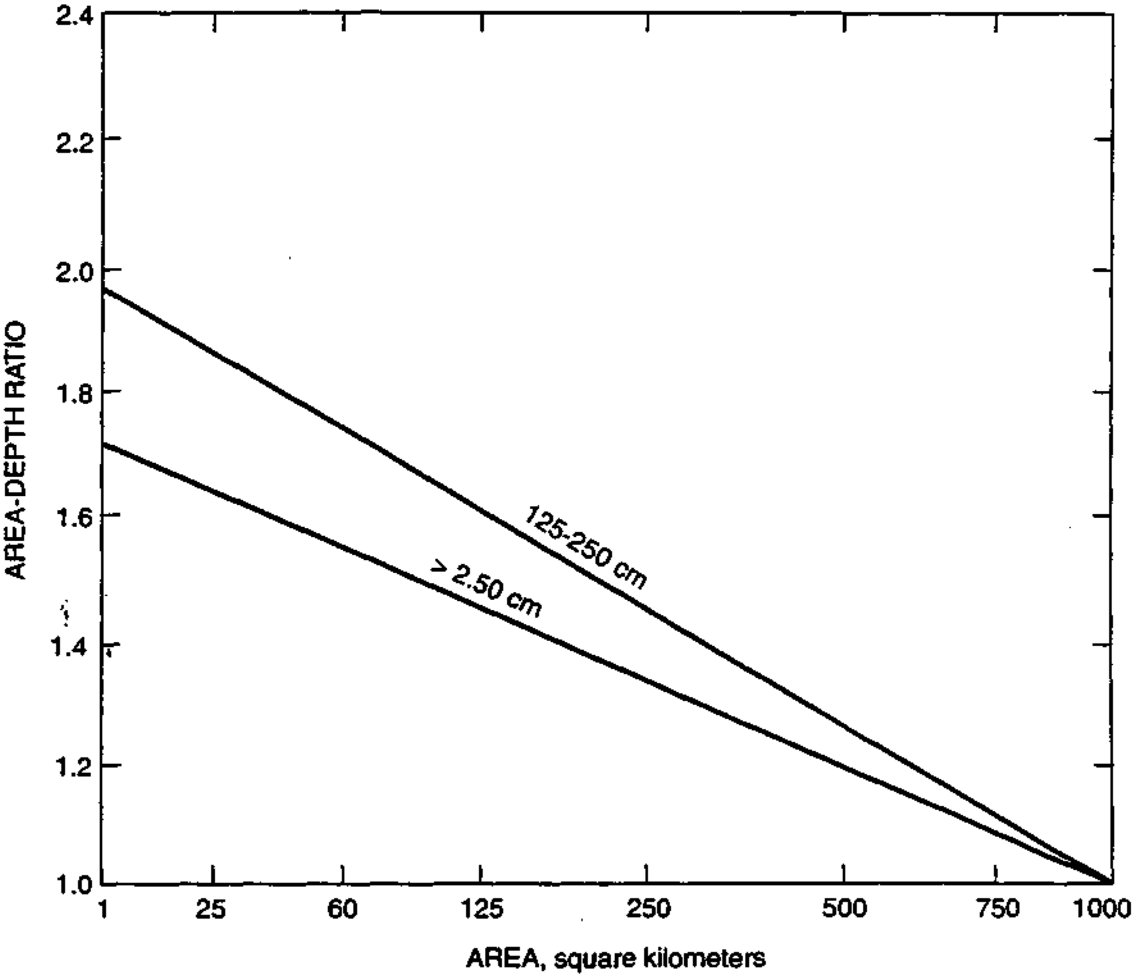


FIGURE 3-10. Area-depth ratio relations for rains at two levels (125-250 cm, >250 cm) across 1,000-^{km} reengage networks in Illinois.

characteristic which has been observed in previous Water Survey studies (Huff, 1967; 1968), and is related to rain duration, synoptic storm type, and other meteorological variables. The curves in Figure 3-10 conform to a cube-root distribution. Grouped area-depth relations in Illinois storms have been found to conform most frequently to square-root or cube-root transformations (Huff, 1993).

Dry Periods

In compiling the dry period samples, the summer months in which rainfall was below normal were selected on each network. These cases were then examined for the presence of days having network mean rainfall ≥ 1.25 cm. This provided a total of 35 cases which consisted of 22 days in the 1.25 to 2.50 cm group and 13 in the >2.50 cm category. Area-depth ratio curves were then determined for each storm, and median curves derived for each storm group. Median curves were considered preferable to average curves because of the small sample sizes. Of the 35 cases, 6 (17%) occurred during months that were < 50% of normal (relatively severe drought conditions); another 21 (60%) were associated with months that were 51%-70% of normal (moderately dry); and 8 (23%) occurred in months having rainfall 81%-90% of normal (slightly dry conditions). The dry period median curves were then compared with those for the total sample curves (Figure 3-10). Results are summarized in Table 3-23.

Comparison of the normal curve values in Table 3-23 show a steeper slope (rainfall gradient) in the lighter storm category, and this is primarily due to average relative variability being greater in the lighter storms (as indicated earlier). However, in the dry-period storms, the slope was greater in the heavier storm group than in the lighter storm category (opposite of the normal outcome). As a result, larger differences were observed between the normal and dry period curves in the heavier storm group, compared with the lighter category.

This reversal from the average distributions indicates a basic difference in the spatial distribution characteristics of rainstorms in dry periods. The weaker rain systems tend to have shorter durations, smaller areal extents, and a more rapid decay of rainfall rate with distance from the rainstorm center. These conditions probably result from less adequate moisture input and\or less efficient processing of available moisture in the dry-period storms.

The dry-period results in Table 3-23 are based on a relatively small sample that could be affected by natural temporal variability in the spatial distribution of convective rainfall. Consequently, they should be considered a first approximation of dry-period effects on the spatial distribution characteristics of summer rainfall. Assuming results in Table 3-23 are representative of normal and dry-period conditions, an implication for weather modification is that cloud seeding would be less effective during dry periods than during normal weather conditions for increasing rainfall from on-going storm systems. This is a consequence of the more rapid decay of rainfall with distance from the storm center in the dry-period storms.

Synoptic Storm Types

As part of this study, the dry-period storms were classified by synoptic type which indicates the macroscale storm system with which the rainfall was associated. No subtyping of the frontal systems was done. Thus, cold fronts included rainfall associated with prefrontal squall lines or areas, the frontal passage, and post-frontal activity. Results were compared with the average distribution of synoptic storm types during summer in Illinois provided by Huff and Vogel (1977). These comparisons are shown in Table 3-24, in which synoptic storm systems have been divided into six categories.

Results indicate an increase in the percentage frequency of cold fronts during dry periods and a decrease in air mass storms compared with average conditions. Otherwise, only small differences occurred. This agrees with findings by Huff and Vogel (1977) in studies of widespread moderate to severe droughts in Illinois during summer.

An analysis was made also of the distribution of total rainfall according to synoptic type in the dry period storms. Results, summarized in Table 3-25, show comparable values similar to those for rainfall frequency in Table 3-24. The normal distribution was obtained from Huff and Schickedanz (1970). Table 3-25 shows that cold fronts and air mass (non-frontal) storms were the major rain producers in the dry period storms. Their percentage of total rainfall was also substantially above average. The other major rain producers, warm and static fronts, were below average during the dry periods.

Table 3-23. Comparison of Median Area-Depth Ratio Relations in Dry Periods with those in Average Weather Conditions.

	Ratio for given area (km^2) Storms = 1.25 to 2.50 cm						
	25	62	125	250	500	750	1000
Average	1.75	1.69	1.57	1.44	1.25	1.11	1.00
Dry	1.94	1.84	1.72	1.56	1.33	1.16	1.00
Difference	0.15	0.15	0.15	0.12	0.08	0.05	0.00
Ratio	1.08	1.09	1.10	1.08	1.06	1.05	1.00
	Storms <2.50 cm						
Average	1.59	1.51	1.41	1.32	1.19	1.08	1.00
Dry	1.99	1.88	1.75	1.58	1.35	1.17	1.00
Difference	0.40	0.37	0.34	0.26	0.16	0.03	0.00
Ratio	1.25	1.25	1.24	1.20	1.19	1.08	1.00

Table 3-24. Comparison of Distribution of Synoptic Types in Network Dry Periods and Average Weather Conditions in Summer.

	Dry Period		
Storm Type	Number	Percent	Average Percentage
Cold Front	19	54	46
Warm Front	3	9	8
Static Front	5	14	13
Occluded Front	0	0	1
Air Mass	6	17	30
Low Center	2	6	2

Table 3-25 . Relation Between Total Storm Rainfall and Synoptic: Storm Types on Networks in Dry Period Storms.

Synoptic Type	Rainfall Total (cm)	Percent of Total	Normal Percentage
Cold Front	72.3	48	39
Warm Front	14.2	9	14
Static Front	19.9	13	21
Occluded Front	6.0	4	2
Air Mass	36.6	24	17
Low Center	3.4	2	7

12-MONTH DRY PERIODS

Stanley A. Changnon

Introduction

The characteristics of 12-month dry periods, based on defining them by the amount of precipitation deficiency, were investigated (Changnon, 1987). The definition of a 12-month period as a "dry period" was based on averaging the values of 61 weather stations across Illinois. The statewide precipitation values of all possible 12-month periods from 1901-1990 were assessed. Based on this review, dry periods were defined as a 12-month period when 80 percent or less of the statewide precipitation occurred.

Temporal Distribution

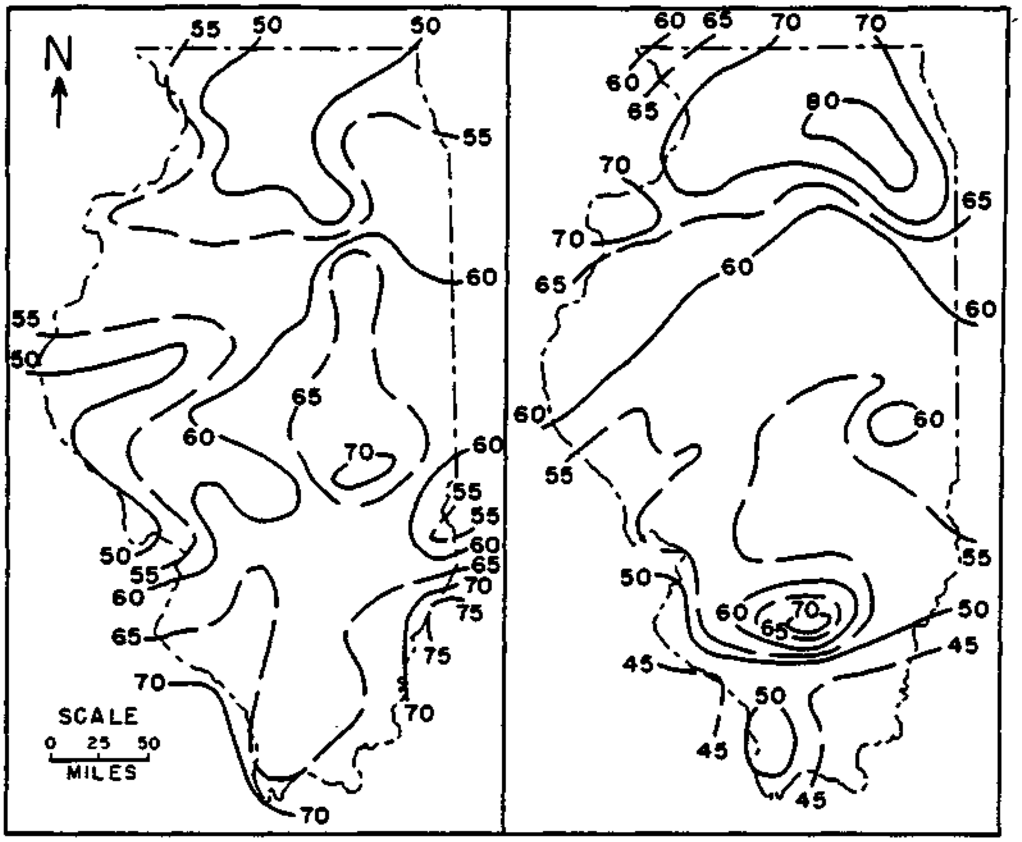
Analysis of the 12-month dry periods during the 90-year period revealed that 16 events, approximately 18 percent of the time, qualified as dry periods. Their distribution by decade is shown below.

1901-1910=1
1911-1920 = 2
1921-1930 = 2
1931-1940 = 4
1941-1950 = 1
1951-1960 = 2
1961-1970=1
1971-1980 = 1
1981-1990 = 2

All decades except 1930s had one or two 12-month dry periods. The 1930s are anomalous with four dry periods. The greatest departure, or most severe dry period, occurred in the June 1933-May 1934 period when the statewide precipitation averaged 58 percent of normal. The second most severe dry period occurred in 1930-1931 with a statewide average of 61 percent. The 12-month dry periods of 1935-1936 and 1953-1954 had statewide values that tied at 70 percent of the normal.

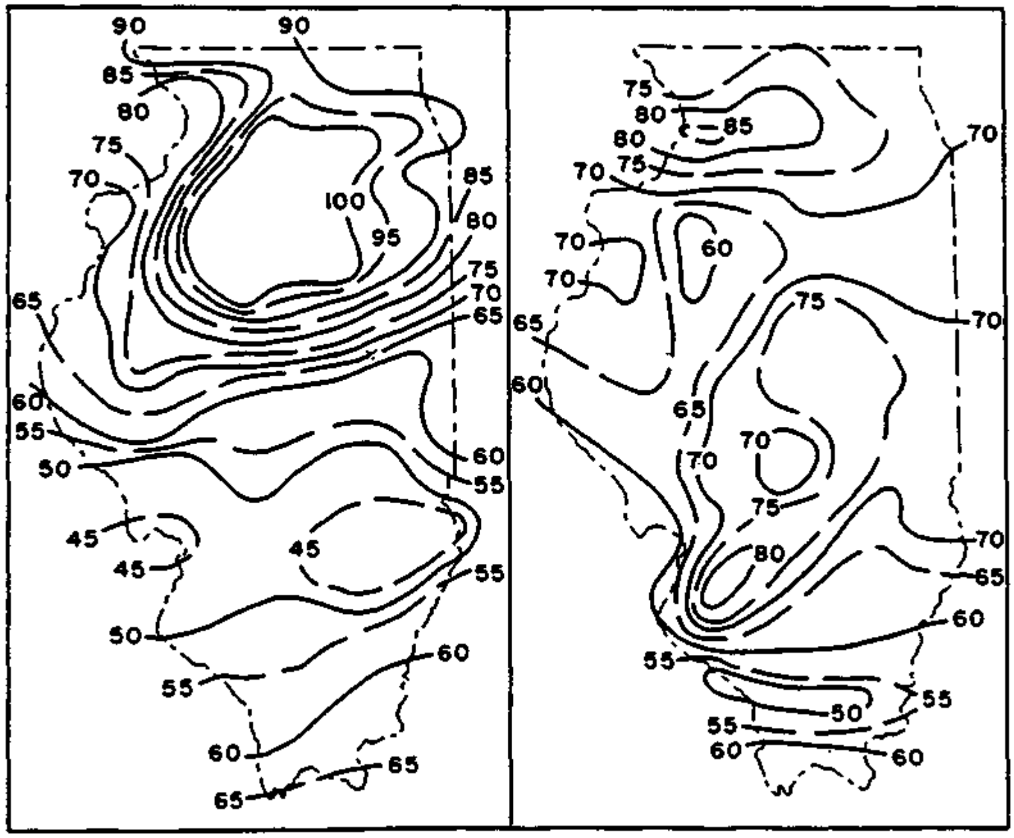
Patterns of Dry Periods

Maps of the precipitation in the four most severe 12-month dry periods, with precipitation expressed as a percent of the 90-year average, are shown in figure 3-11. Their precipitation patterns vary considerably with several high and low precipitation areas found across the state. However, in



a. FIRST RANKED, ENDING IN MAY 1934

b. SECOND RANKED, ENDING IN FEBRUARY 1931



c. THIRD RANKED, ENDING IN JULY 1954

d. FOURTH RANKED, ENDING IN AUGUST 1936

FIGURE 3-11. Four most severe 12-month droughts based on rank and month/year of end of drought

all four periods, extremely dry conditions could be found in southern Illinois. Also note that in the 1953-1954 dry period, a large portion of northern Illinois had above average (>100 percent) precipitation.

The 12-month dry periods were further analyzed for the frequency distribution of their precipitation amounts. The amounts of precipitation at each of the 61 stations was assessed, and return interval values for 5,10,25, and 50 years were developed. The resulting pattern showing the precipitation departure from average appear in figure 3-12, along with the actual precipitation amounts for those recurrence intervals at selected stations. The patterns displayed in figure 3-12 indicate, that for a given recurrence interval, dry periods are relatively more severe in the southwestern and extreme southern portions of Illinois, and they are least severe in the northeastern section. In general, the severity of 12-month dry periods decreases northward and eastward across Illinois. Also note that the differences in severity increase with increasing recurrence interval.

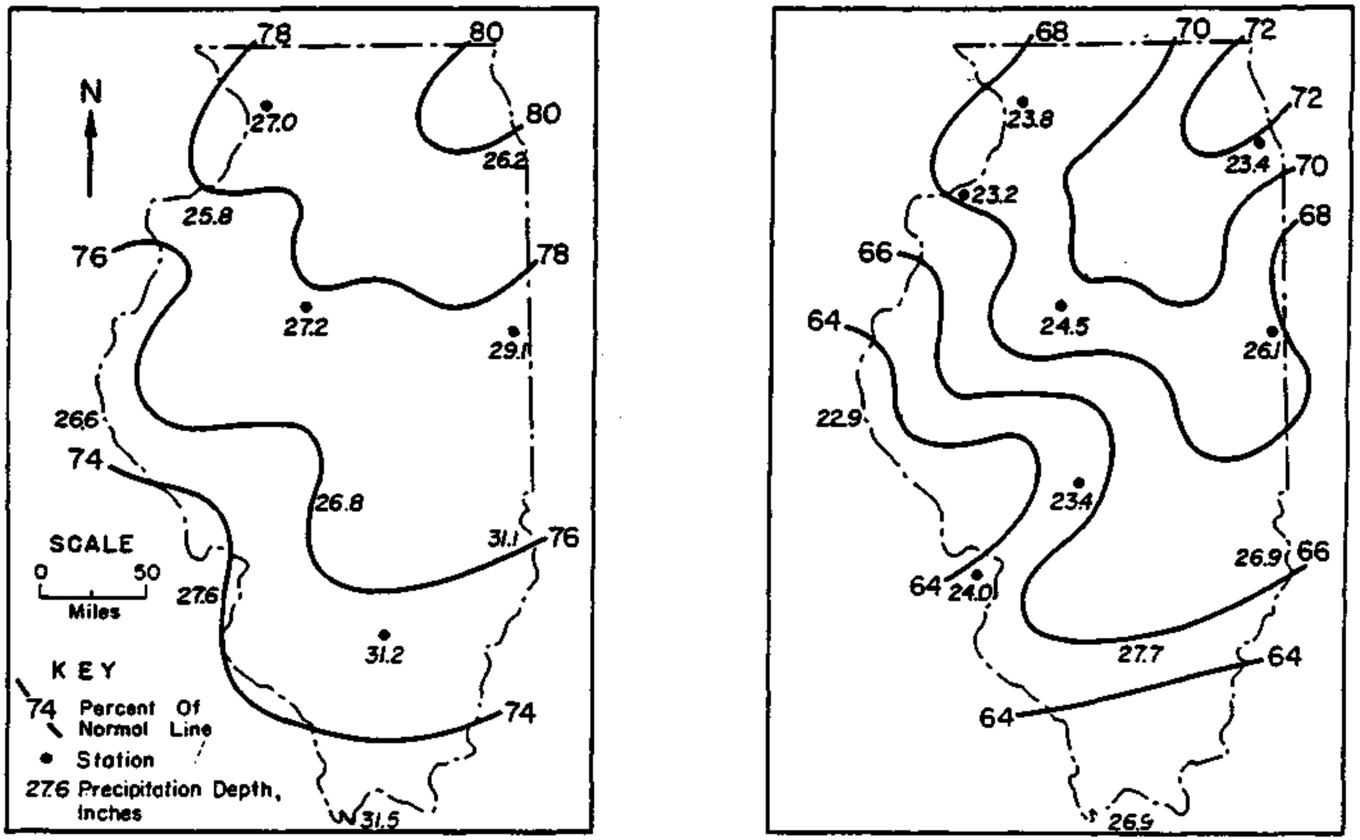
Time Between Dry Periods

An important issue relating to dry periods of any duration is the time separating these events, and hence the likelihood of one developing after one has terminated. Since there is no scientific capability to do this type of long-range forecasting of dry periods, a climatological analysis of the temporal distribution of the 12-month dry periods was accomplished on a statewide basis. The duration of time between each of the 16 dry periods was the basis for this analysis. The resulting values were plotted and their distribution was found to fit a log-log distribution. The resulting curve, figure 3-13, based on the time distributions between dry periods, shows the probability that a given dry period will begin within a specific time after one has terminated. For example, there is a 20 percent chance of a 12-month dry period beginning 5 to 6 months after one ends. There is an 80 percent chance that one will begin within 120 months (10 years) after one has finished. In lieu of forecasts of drought, these climatic probabilities are the best information available.

The 1953-1954 Dry Period

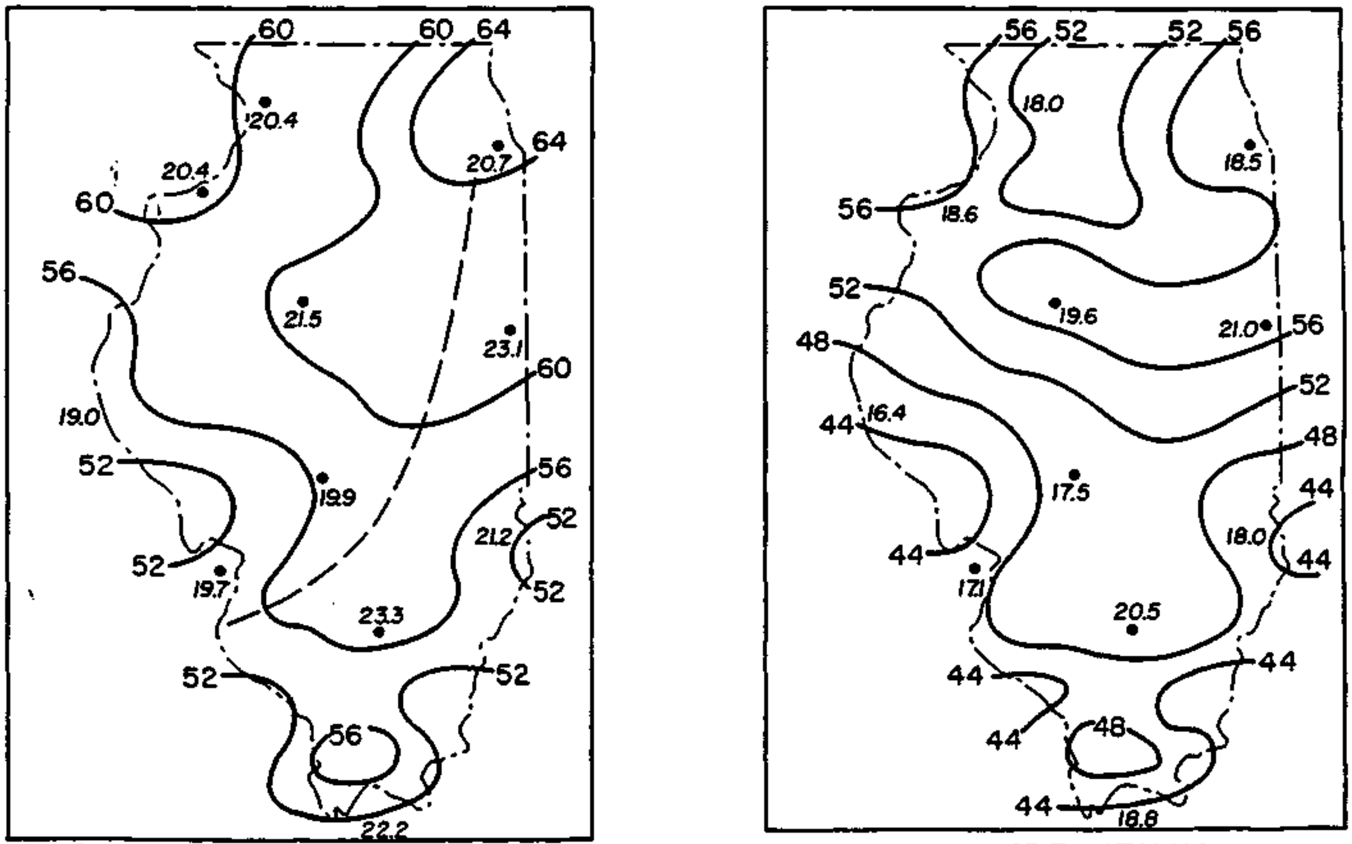
The characteristics of one of the more recent severe dry periods, that of 1953-1954, were investigated. Analysis of the hourly precipitation data for the 10-year period (1948-1957) which embraces this drought, was made for the weather stations in the regions of the most severe dryness (south-central Illinois). The data was divided into two parts: 1) the dry years of 1952-1954, and 2) the normal to wet years, 1948-1951 and 1955-1957.

A seasonal and annual comparison was made of the frequency of hours with measurable precipitation (>0.01 inch or more) in the dry years and the non-dry years. Results are summarized in Table 3-26 showing the mean number of seasonal and annual occurrences for a point in the dry area, the difference in frequency between dry and non-dry years, the ratio of the average frequency in dry years to that in non-dry years, and the annual ratios. The number of hours with measurable



a. 5-YEAR FREQUENCY

b. 10-YEAR FREQUENCY



c. 25-YEAR FREQUENCY

d. 50-YEAR FREQUENCY

FIGURE 3-12. Frequency of 12-month drought periods expressed as percent of average annual precipitation.

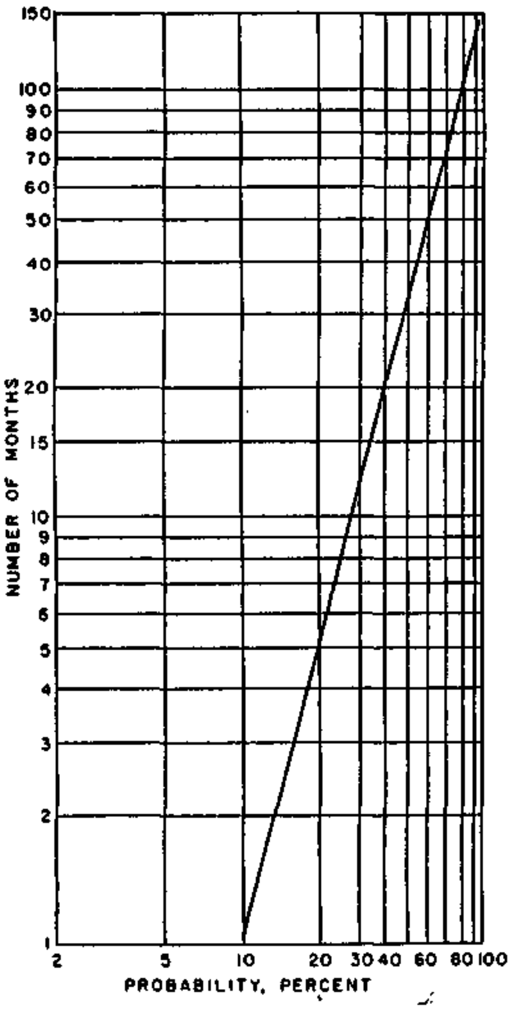


FIGURE 3-13. Probability that a 12-month dry period will occur within a given number of months after a 12-month drought ends.

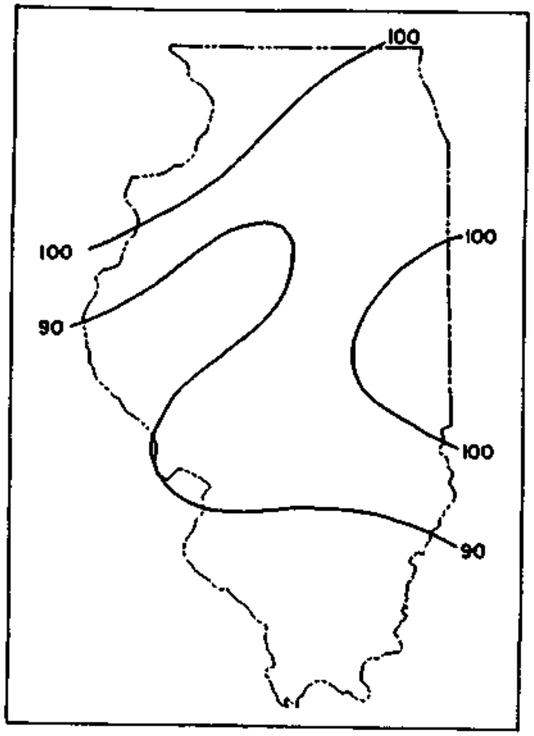


FIGURE 3-14. Percent of normal number of convective clouds during dry period of August 1953-July 1954.

precipitation in the dry years was only about one-third the number in the normal years, as indicated by the average annual ratio of 0.34. Seasonally, the dry period severity is portrayed by the dry to non-dry ratios, was greatest in the fall and winter, and least in spring.

Table 3-27 presents a comparison based on the frequency of hours with precipitation in excess of 0.1 inch. The purpose was to determine whether the frequency of relatively heavy rain amounts was greater than that of the lighter amounts. Comparison of the values in the two tables shows the heavier rain to be more scarce than the lighter rainfalls in these dry periods. The annual average ratio dropped from 0.34 for all measurable amounts to 0.3 for the amounts exceeding 0.10 inch.

To obtain a generalized assessment of the causes of this particular 1953-1954 dry period, related information concerning cloud and convective conditions were analyzed. Comparison of the percent of normal frequency of convective clouds (Figure 3-14) with the precipitation departure map (Figure 3-11c), reveals that the areas with the greatest precipitation deficiencies, those greater than 65 percent, were generally those where convective clouds were below 90 percent of normal during this 12-month period.

Figure 3-15 presents the frequency of days with more than 0.5 inch of precipitation during this 12-month dry period, expressed as percent of normal number of these heavy rain days. This pattern shows a close relationship to the total precipitation map (Fig. 3-1 lc) with less than 50 percent of these heavy rain events in the heart of the dry area of southern Illinois.

Figure 3-16 presents the map of thunderstorm frequencies for the 12-month period also expressed as a percent of normal. It shows reasonable agreement with total precipitation departure.

These three expressions of convective activity reveal that this 12-month dry period occurred largely because of the lack of strong convection. Convective cloud values were only 5 to 10 percent below normal, but the departures in moderate to heavy rains and in thunderstorms were much greater, 10 to 50 percent below average.

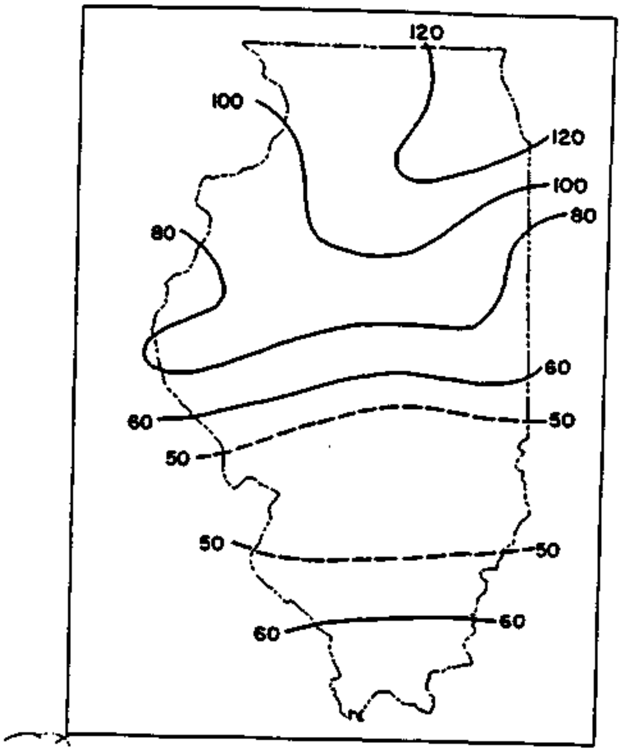


FIGURE 3-15. Percent of normal number of days with precipitation ≥ 0.5 inch, during August 1953-July 1954.

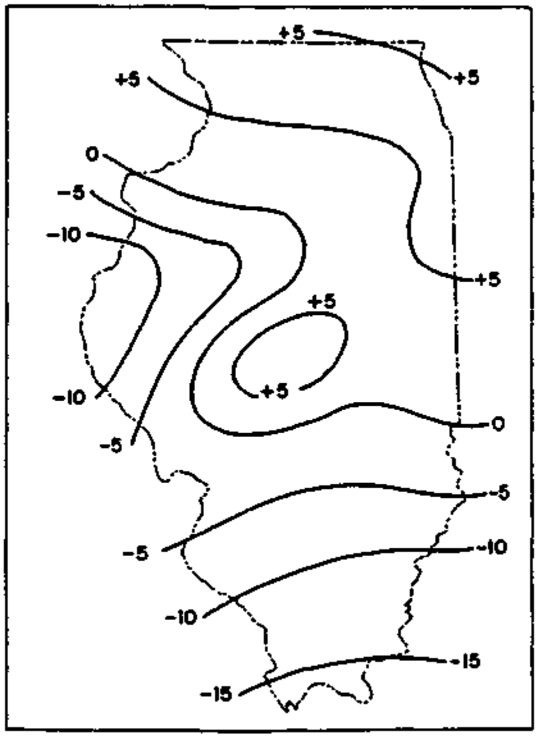


FIGURE 3-16. Departure from average number of thunderstorm days during August 1953-July 1954.

Table 3-26. Comparison of Frequency of Hours with Measurable Precipitation in Dry and Normal to Wet Periods.

	Dry Period (1952-1954)					Normal to Above Precipitation (1948-1951, 1955-1957)				
	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
Average frequency	93	120	58	68	339	305	285	174	234	998
Average difference	212	165	116	166	659					
Average ratio, dry to normal years	0.30	0.42	0.33	0.29	0.34					

Table 3-27. Comparison of Frequency of Hours with 0.11 Inch or More Precipitation in Dry Years and in Normal Precipitation Year

	Dry (1952-1954)					Normal to Above Normal (1948-1951, 1955-1957)				
	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Annual
Average frequency	9	22	15	12	58	48	48	46	50	192
Average difference	39	26	31	38	134					
Average ratio, dry to normal years	0.19	0.40	0.33	0.24	0.30					

REVIEW OF STUDIES OF IMPACTS OF ILLINOIS DROUGHTS

Floyd A. Huff

Along with agriculture, public water supplies are a major victim of precipitation drought. Several studies have been made in the Water Survey relating to this problem. Hudson and Roberts (1955) made an extensive study of the 1952-1955 drought in south-central Illinois, with special reference to impounding reservoir design requirements that were revealed by the consequences of this severe drought. As part of a meteorological study of the drought climatology of Illinois, Huff and Changnon (1964) investigated the relation between precipitation deficiency and low streamflow (surface water supplies). Stall (1964) made a comprehensive study of low flows in Illinois streams with emphasis on requirements for impounding reservoir design. In conjunction with a research contract with the Bureau of Reclamation, Huff (1973a) made an evaluation of the potential benefits of weather modification on water supply. Changnon et al. (1982) investigated the 1980-1981 drought in Illinois with respect to causes, occurrences, and impacts on agriculture, hydrology, and other fields. Changnon et al. (1987) made a comprehensive study of the physical and social dimensions of Illinois droughts. Easterling and Changnon (1987) summarized the climatology of precipitation droughts in Illinois based on water supply problems. Changnon and Easterling (1989) studied drought impacts in Illinois on surface water and shallow groundwater supplies. Changnon et al. (1988) investigated relations between precipitation and shallow groundwater in Illinois.

Precipitation Deficiency and Low Streamflow

Huff and Changnon (1964) made a study to determine whether low-flow frequency distributions in Illinois could be reliably estimated from meteorological data and geologic factors. This study was undertaken because of the general lack of long-term streamflow records needed to estimate the frequency, intensity, and location of drought conditions producing major shortages in surface water supplies. Use was made of 50-year records from 62 precipitation stations and data from 12 streamgaging stations with 45-year or longer records.

When the state was divided into six different geomorphic regions, it was found that the low flow frequencies for any basin in each region could be reliably estimated by the precipitation frequency distribution with a geomorphic index. The regional geomorphic indices were developed through use of data from the 12 basins with long streamflow records. The method developed is applicable for basins of any size, for recurrence intervals of five years or longer, and for drought durations of 12 months or longer. Although developed from Illinois records, the method is considered applicable, in general, to Midwest and other regions of similar precipitation climatology.

Potential Benefits of Weather Modification on Water Supply

With financial support from the Bureau of Reclamation, an investigation was made of the potential benefits of seeding-induced increases in runoff on alleviation of surface water shortages in Illinois (Huff, 1973b). Runoff and weather data for 14 basins of various sizes and locations having records of 30 years or longer were used to develop basin equations relating runoff to antecedent runoff indices, various precipitation parameters, and mean temperature. Hypothetical seeding-induced increases in precipitation were then used with the appropriate basin equation to obtain an estimate of average runoff increases in the cold season (October-March), the warm season (April-September), and two subseasons, December-March and July-August. This was done for all seasons combined, seasons having near-normal to below-normal runoff, and seasons with below-normal streamflow. Particular emphasis was placed upon the southern and central parts of the state where surface waters are the primary sources of water supply.

The net result of the investigation was that seeding to increase surface water supplies would be desirable in near-normal to slightly below-normal years for those midwestern communities where additional storage is available in such periods. Existing constraints would usually be too great to undertake seeding in above normal years, the need would rarely exist for additional water supplies, and seeding to suppress precipitation would be the most frequent need in such weather conditions. The conversion of precipitation to runoff was found to be small in below-normal years, averaging only 10% to 13%, so that large seeding-induced increases in precipitation would be needed to obtain substantial alleviation of water supply deficiencies. This would be difficult to achieve with the atmospheric conditions (usually hot with low humidities) that exist in moderate to severe drought conditions. In an earlier study, Huff and Changnon (1963) found that only 7% to 10% of the natural precipitation is converted to runoff in a typical 10-year drought, and this percentage lowers to 3% to 5% in 25-year droughts, and to a range of 2% to 4%t in a 50-year drought.

However, this study also indicated a possibility that seeding may be of some assistance during temporary breaks in light to moderate Midwest droughts in which storages have become very acute. In this case, even a small contribution would usually be helpful and economically acceptable, especially in small communities where reservoir storage facilities are inadequate, or where water is being taken directly from small streams for municipal usage.

Overall, this investigation of potential seeding-induced increases in runoff from cloud seeding indicated that substantial gains in streamflow could be achieved in near-normal to slightly below-normal years. However, other studies carried out by hydrologists indicated that weather modification would not provide a major source of water supply in Illinois (and the Midwest), unless it could provide substantial additions in relatively severe drought periods. Stall (1964) showed that, most impounding reservoirs in Illinois can withstand a 25-year drought. A few communities would have problems in a drought of 15-year to 20-year frequency according to the Stall study. Conversely, a few communities could operate a 50-year drought. Potential benefits from seeding in augmenting shallow groundwater supplies are estimated to be small by Survey hydrologists. Thus, results of this study indicate that agriculture would be the primary beneficiary of successful cloud seeding in Illinois and the Midwest.

Relation Between Precipitation Characteristics and Water Supply Problems

Although drought starts with a reduction in precipitation, different kinds of precipitation deficiency episodes (duration, intensity, and areal extent) create varying problems for drought sensitive activities. Thus, an agricultural drought typically is not a water supply drought. In this study, Easterling and Changnon (1987), focused on surface water supplies, seeking to identify shared characteristics of precipitation drought and water supply system droughts. They then used the shared features to characterize precipitation droughts in Illinois.

Results of analysis suggested that precipitation droughts persisting for periods of 12 to 24 months, and with return periods of 5 years (moderate drought) and 20 years (severe drought) elicit drought response adjustments in surface water-dependent water supply systems. Furthermore, the 5-year return periods correspond to precipitation deficiency episodes averaging 78% of normal precipitation for 12-month droughts and 90% of normal precipitation for 24-month droughts. The 20-year return periods correspond to 65% of normal precipitation for 12-month droughts and 77% of normal for 24-month droughts.

A number of generalizations were found relating to the spatial and temporal characteristics that qualify as water supply droughts (moderate and severe combined). These include:

(1) Droughts are most likely to begin in warm season months when water use requirements and evaporative losses are normally greater.

(2) The shorter the drought duration, the more widespread are precipitation deficiency extremes; and for any drought period, between 75% and 85% of the state can be expected to experience water supply drought conditions.

(3) The more severe the statewide precipitation deficiency of a drought, the more widespread are drought conditions.

(4) Precipitation droughts tend to be more frequent and severe in the central third of Illinois than in remaining portions of the state, especially for 12-month droughts.

(5) Illinois tends to emerge from droughts with much above normal precipitation in the immediate post-drought month, but then recesses back to near normal conditions. Frequencies of heavier precipitation days reflect this tendency also.

In conclusion, the primary significance of these findings is that they reflect characteristics of precipitation deficiency that are in step with water supply drought. These results should be more useful to drought mitigation planning efforts by water resources managers than the results of traditional drought climatologies. The results also indicate how precipitation deficiency periods in a humid climate qualify them as "drought" based on surface water criteria (Changnon and Easterling, 1989).

Droughts in Illinois—Physical and Social Dimensions

This study incorporated all pertinent information available on agricultural and water supply droughts and their impacts in Illinois (Changnon et al., 1987). The investigation involved several scientists and engineers from the Atmospheric Sciences and Hydrology Sections of the Water Survey, and others from the Illinois State Geological Survey and the Natural History Survey.

This comprehensive study utilized information from past studies and from new research carried out in conjunction with the project. New in-depth research had to be carried out because several major impacts had not been quantified adequately in past research studies. These included impacts related to soil moisture, runoff, shallow groundwater supplies, water quality, and erosion. The major output from this interagency undertaking was a drought decision model. This model incorporates climatological, hydrologic, physiologic, and human components. Models were developed for different areas of Illinois, because of regional differences in climate, soils, and other impacted conditions.

Relations Between Precipitation and Shallow Groundwater in Illinois

In this study by Changnon et al. (1988), the statistical relationship between monthly precipitation and shallow groundwater levels was determined for 20 wells scattered across Illinois. Data for 1960-1984 were used, and the relations defined by using autoregressive integrated moving average (ARIMA) modeling. The objectives of this study were threefold. The first was to measure the statistical relationship between monthly precipitation and shallow groundwater (water table) levels. The second was to compare the resulting relationships with physiographic divisions, major soil types, parent soil materials, and aquifer types to discern the most meaningful physical expression that would be useful in defining discrete regions. These regional definitions of precipitation-groundwater relations were desired as input for a study of the effects of Illinois droughts on various components of the hydrologic cycle. The third objective was to develop equations for each region that used precipitation values in droughts to estimate shallow groundwater levels in the state. These would be useful in future drought monitoring.

This study first examined the statistical relationship between monthly precipitation and shallow groundwater levels in the 20 well sites across Illinois using ARIMA modeling. The best temporal relationship was found to be a lag of one month followed by a 2-month lag. Regional analyses suggested a two-area spatial division (north and south) for Illinois that reflect the influence of two major soil orders in the state on the precipitation-shallow groundwater relationship. The analyses also indicated a relatively strong relation between precipitation and shallow groundwater that was related to loess thickness across the state from west to east.

The above findings were applied in developing equations to allow groundwater levels to be estimated anywhere in the state using soil information and precipitation values which are widely available. These regional equations were based on data from all wells in each area for 1960-1979. Tests were made of the equations using data from the 1980-1981 drought. Results indicated that differences between actual and estimated values were largely less than one standard deviation. The indicated accuracy is satisfactory for making estimates of groundwater levels in drought situations throughout the state. The number of usable wells is inadequate for this purpose. Since the major parent soil materials in Illinois are found in many other areas of the Midwest, the methodology applied here should be widely applicable.

PART FOUR: METEOROLOGICAL ANALYSES OF DRY PERIODS

EFFECTS OF DRY CONDITIONS ON THE SURFACE ENERGY BUDGET

Kenneth E. Kunkel

Introduction

The potential effects of extreme dry periods on the land surface and the possible feedback effects on the atmosphere were investigated. Research was based on field observations during the 1988 and 1991 droughts and on a diagnostic analysis of radiosonde data. This research addressed an old question: "does drought beget drought?"

The possible effects of soil moisture on the near-surface climate can be identified by examining a simplified energy budget of the earth's surface, given by

$$S(1-a) + I_a - L_s = H + LE + G \qquad (1)$$

where S = incoming solar radiation, a = albedo (reflectivity) of the surface, I, = long-wave (infrared) radiation from the atmosphere, I_s = long-wave radiation from the surface, H = sensible heat flux (heating of the near-surface air), LE = latent heat flux (evaporation), and G = soil heat flux. All terms on the left hand side of (1) are electromagnetic forms of energy. They are often combined into a single term, called net radiation, defined as

$$R_n = S(1-a) + I_a - I_s \qquad (2)$$

Soil moisture deficits do not directly affect values of S or I,. The albedo can change slightly as vegetation wilts and soils dry. Also, I_s can increase as soils and vegetation warm. These effects can be large for bare soils, but they are relatively small for vegetated surfaces. Also, for typical mid-summer conditions with vegetated surfaces, values of G are rather small and are not affected much by soil moisture deficits. Based on the above observations, the total amount of energy (Rn-G) available either to heat the near-surface atmosphere (H) or to evaporate water (LE) does not change greatly with variations in soil moisture when the surface is vegetated. However, the partitioning between H and LE is affected. When soil moisture deficits are present, the availability of water is limited and LE is restricted. A much greater proportion of the available energy is used to heat the lower atmosphere. As a result, the lower atmosphere is relatively warmer and drier.

1988 Observations

The drought of 1988 provided an opportunity to monitor the effects of a severe drought on the surface energy budget of the central United States. To this end, an experiment was conducted in a corn field in east-central Illinois. The purpose of this experiment was to quantify the changes in sensible and latent fluxes which occur in a major drought and estimate the possible impact on mid-summer precipitation (Kunkel, 1989).

The 1988 drought was by most measures the worst in the midwestern United States since the 1930s (Kunkel and Angel, 1989). The total economic losses from this drought are estimated at close to $40 billion (Riebsame et al., 1991). There has been considerable work concerning its causes. Trenberth et al. (1988) speculated that the northward displacement of the Intertropical Convergence Zone (TTCZ) in the eastern Pacific in early 1988, caused by the formation of abnormally cold water in the tropical Pacific (the La Nina phase of the Southern Oscillation), was responsible for the anomalous circulation pattern at mid-latitudes. Lau and Ping (1992) confirmed that an upper level high pressure system over North America can be forced by the northward displacement of latent heating in the eastern equatorial Pacific to north of 10°N. Trenberth and Branstator (1992) demonstrated that atmospheric heating anomalies forced by the sea surface temperature anomalies could account for the drought, and that the circulation anomalies were not generated solely by mechanisms internal to the atmosphere. They also argued that positive feedback caused by soil moisture anomalies could not have been a primary cause of the drought circulation. However, they also showed that low-level heating produces a strong local response in the upper troposphere. Atlas et al. (1993) performed a series of sensitivity experiments with a General Circulation Model and found that soil moisture deficits in 1988 probably contributed significantly to the maintenance of hot and dry conditions in the central U.S.

The 1988 field site was located near Champaign, Illinois, at 40°6'N, 88° 14'W with an elevation of 228 m, about 600 m from a National Weather Service cooperative observer climatological station (Urbana). The dimensions of the field were 400 m (east-west) by 320 m (north-south). The experimental equipment was located 190 m from the east edge and 190 m from the south edge. This position in the middle of this mainly level field provided good fetch conditions for all wind directions.

Measurements of sensible and latent heat fluxes were obtained using the eddy correlation technique. Vertical wind, temperature, and water vapor fluctuations were measured using a sonic anemometer, fine-wire thermocouple, and Krypton hygrometer, respectively, manufactured by Campbell Scientific, Inc. A number of other meteorological variables were measured including incoming solar radiation, temperature, relative humidity, precipitation, wind speed and direction, and soil heat flux. The eddy correlation sensors were sampled at a frequency of 5 Hz and measurements were averaged over ten minute intervals. In addition, neutron probe measurements of soil moisture were made once a week at the location of the eddy correlation equipment.

The eddy correlation sensors were placed at a height of 2.4 m above ground level. The height of the corn canopy varied from 1.0 m at the beginning of the experiment (June 30) to 1.4 m at the end (August 18). The leaf area index in the vicinity of the equipment varied from 1.0 at the beginning of the observational period to 1.7 at the end. Typically, a mature corn crop will reach leaf area index values of 3 or more. The unusually slow corn growth reflected the effects of the drought. Data were obtained on a total of 17 days and were usually restricted to daytime hours.

Table 4-1 shows the Urbana monthly precipitation and temperature data for the period January-August 1988 compared with the climatological averages. During a critical part of the growing season (April-August), the total precipitation of 211 mm was only 43% of the normal for that period. Temperatures were 1.1°C above normal. Daily maximum temperatures exhibited larger departures, averaging 2.8C above normal.

The measurements of sensible (H) and latent (LE) heat fluxes were used to calculate the Bowen ratio (B = H/LE). In addition, a potential Bowen ratio (B_p) i.e., that which would occur if evaporation occurred at the maximum rate, was calculated following Thorn (1976):

$$B_p = \frac{r_{st} + r_a - r_i}{(\Delta/\beta) r_a + r_i} \tag{3}$$

where

$$r_i = \frac{c_p}{\beta} \frac{e_s(T) - e}{(R_n - G)} \tag{4}$$

$$r_a = \frac{[\ln(z-d)/z_o]^2}{k^2 U} \tag{5}$$

r_{st} = stomatal resistance (a constant value of SO s m^{-1} was assumed)
c_p = heat capacity of air at constant pressure
Δ = slope of the saturation water vapor pressure vs. temperature curve
ß = psychrometric constant
e_g (T) = saturation vapor pressure at air temperature T
e = water vapor pressure
R_n = net radiation
G = soil heat flux
z = height
d = displacement height = 1.1 m
z_o = roughness height = 0.07 m
U = wind speed
k = von Karman constant

R_n was estimated from the solar radiation measurements following the approach of Weiss (1983), which treats the individual components of the radiation budget separately and then combines them. The albedo was set equal to 0.23.

Figure 4-1 shows the diurnal changes in sensible and latent heat fluxes for a 4-day test period near the end of July. This period was preceded by the largest rainfall event of the summer (52 mm) and illustrates what would be the situation during a normal summer. During the daytime hours, latent heat flux is 3-5 times greater than sensible heat flux. By contrast, Figure 4-2 shows similar data for a test period in mid-August. During the daytime hours, sensible heat flux is actually greater than latent heat flux. This latter example is more typical of the 1988 summer.

Table 4-1. 1988 monthly total precipitation (mm) and mean temperature (°C) compared with the climatological averages for Urbana climatological station

Month	1988 Precipitation (mm)	1951-1980 Average Precipitation (mm)	1988 Temperature (°C)	1951-1980 Average Temperature (°C)
January	55	50	-4.6	-4.1
February	33	48	-4.4	-1.5
March	64	84	4.2	3.9
April	38	98	10.8	11.3
May	39	91	18.6	17.1
June	8	100	23.0	22.2
July	93	111	25.6	24.0
August	33	93	25.0	22.9

Figure 4-3 shows daily precipitation, maximum temperature, minimum temperature, and average water vapor pressure at the Urbana climatological station for the period June 15 - August 25. During this period, there were only 2 days on which more than 10 mm of rain fell. Daily maximum temperatures reached or exceeded 35 °C on 21 days. During the early part of this period, both water vapor content and daily minimum temperatures were unseasonably low, but more seasonable values of both variables were experienced during the latter two-thirds of this period.

Figure 4-3 also shows a plot of B and B_p averaged over the midday period of 0800-1600 CST on measurement days and the weekly soil moisture measurements for three layers (0-15 cm, 15-50 cm, and 50-100 cm). These measurements are expressed as a percentage of the plant available soil moisture. At the beginning of the experiment, soil moisture was very low in the top layer with no

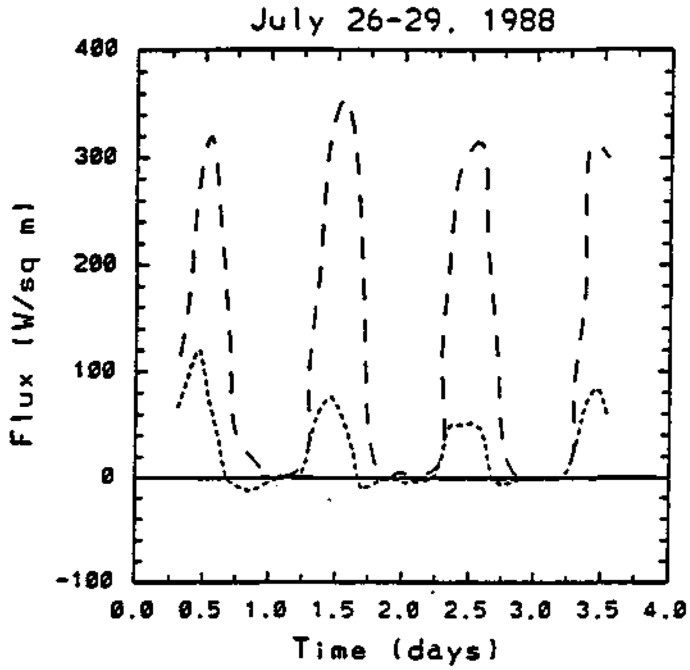


FIGURE 4-1. Diurnal changes in latent heat (long-dashed) and sensible (short-dashed) heat fluxes for July 26-29,1988. The time scale begins at midnight, July 26.

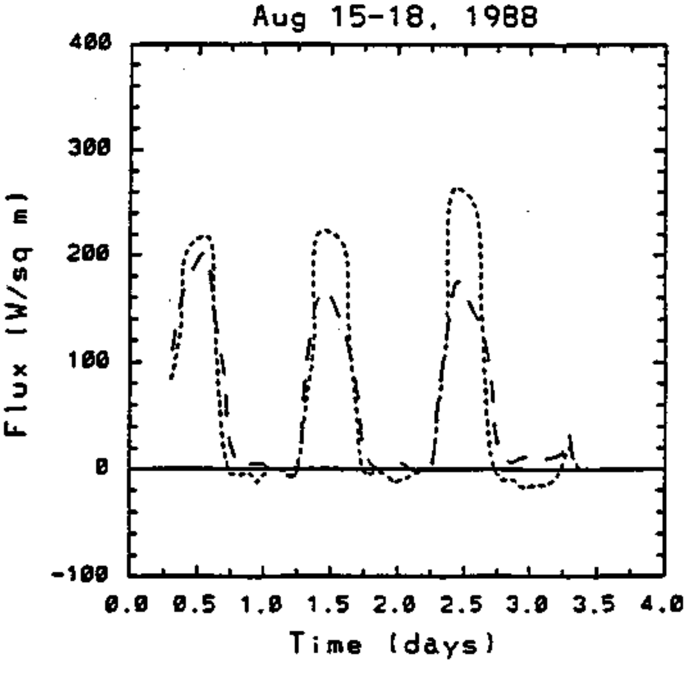


FIGURE 4-2. Diurnal changes in latent (long-dashed) and sensible (short-dashed) heat fluxes for August 15-18,1988. The time scale begins at midnight, August 15.

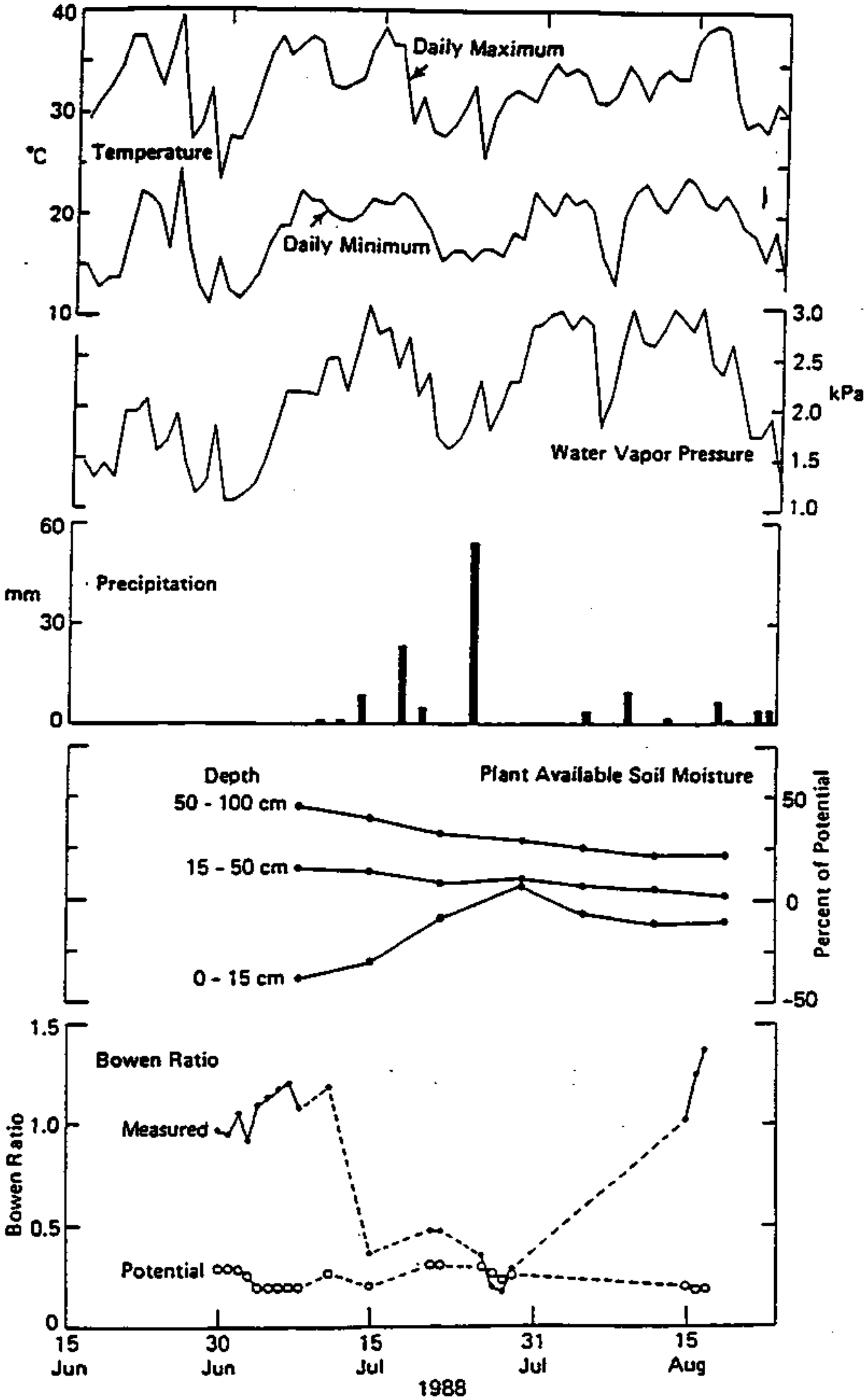


FIGURE 4-3. Daily values of maximum temperature, minimum temperature, water vapor pressure, soil moisture content, measured daytime Bowen ratio, and calculated values of the daytime potential ratio. Dashed lines indicate that there were missing days between measurements. Soil moisture is expressed as a percent of the plant available soil moisture where 100% represents the drained upper limit and 0% represents the wilting point

available water for plants. The values rose in response to the July rains, but fell again in August. In the lower two layers, soil moisture was also low and fell continually with little available by the end of the period.

During the first half of July, measured Bowen ratio values were much higher than the potential values, indicating higher sensible heat and lower latent heat fluxes than would be expected over a well-watered surface. The rain in late July lowered the Bowen ratio to near the potential value during the last week of July (although $B < B_p$, this may be the result of uncertainties in the measurements of B or in the calculation of B_p). However, the dryness after July 25 resulted in an eventual return to high Bowen ratios as measured in mid-August. During both the early July and mid-August periods, the corn was severely wilted, indicating moisture stress.

Measurements of the infrared temperature of the canopy were taken using a Model 110 infrared thermometer, manufactured by Everest Interscience. Reliable data were obtained on 10 days. Figure 4-4 shows a comparison between the (canopy-air) temperature difference and the Bowen ratio during early afternoon, around the time of maximum temperature. With the exception of two days, there is an approximate linear relationship between these two variables. Thus, for this field site, it appears that the changes in the surface energy budget are reflected in the remotely sensed data.

It is interesting to consider the impact of this change in the surface energy budget on the overlying atmosphere. The difference between the measured and the potential evaporation was integrated over the daytime period. During the first half of July and the middle of August, the calculated differences are the equivalent of about 2.5 mm/day or 75 mm/month. This value is about two-third's as large as the long-term average precipitation rate for July (see Table 4-1) and is about half of its potential evaporation.

A similar calculation was made for the sensible heat flux, integrating the differences between measured and potential values over the daytime period. Again focusing on early July and mid-August, the calculated differences represent an excess local atmospheric heating rate of about 4 $MJ/m^2/day$. Assuming that this energy is uniformly distributed over a mixing depth of 2 km (e.g., Kaimal et al., 1976), this represents a temperature increase of about 2°C/day in excess of normal heating.

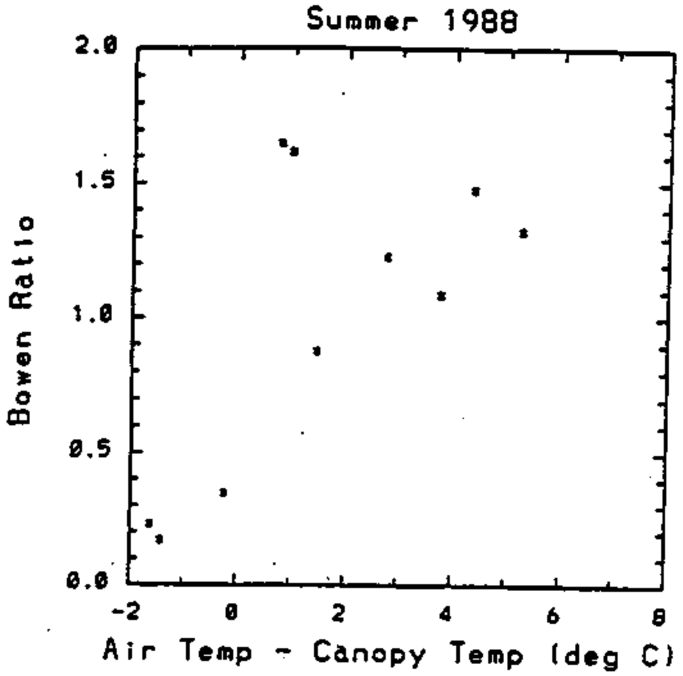


FIGURE 4-4. Early afternoon difference between the air temperature and the canopy IR temperature vs. the Bowen ratio. Each point represents a single day.

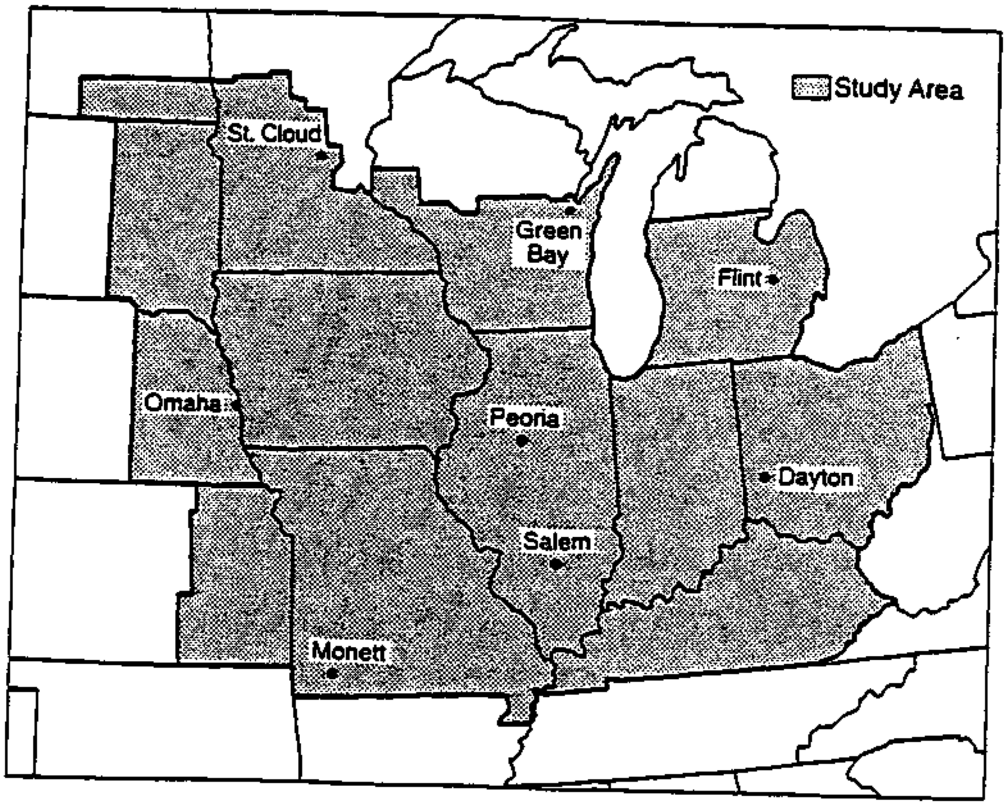


FIGURE 4-5. Location of radiosonde stations where long-term data records are available which were used in this study.

1991 Observations

Similar measurements were made in east-central Illinois at a field site just to the north of Champaign during the 1991 summer drought. It was much less extensive than the one in 1988, but was just as meteorologically severe in some locations in northeastern Illinois. Table 4-2 shows the monthly precipitation at the field site. Although adequate precipitation fell during the spring, precipitation during the summer months of June, July, and August was only 26% of the normal with a total deficit of 236 mm. Measurements of sensible and latent heat flux were made using the eddy correlation technique, as in the 1988 drought. Table 4-3 gives values of the mid-day Bowen ratio measured over a corn field at the site on sunny or mostly sunny days. As in 1988, Bowen ratios of -0.9 or greater were measured during mid- to late summer, indicating a substantial effect of the drought on the surface energy budget.

Table 4-2. Monthly precipitation during 1991 at field site near Champaign, EL.

Month	Precipitation (mm)	1961-1990 normal (mm)
Jan	37	46
Feb	19	50
Mar	88	84
Apr	75	100
May	143	101
Jun	21	103
Jul	20	113
Aug	41	102

Table 4-3. Midday (1000-1600 LST) Bowen ratio during 1991 at Champaign, IL field site.

Date	Bowen Ratio	Date	Bowen Ratio
7/22	0.9	8/3	1.3
7/23	0.9	8/4	1.5
7/24	0.9	Experiment suspended temporarily	
7/25	1.2	8/12	0.8
7/26	1.0	8/13	0.9
7/27	0.9	8/14	1.3
7/28	1.0	8/15	1.5
7/29	1.0	8/16	1.1
7/30	1.1	8/17	1.2
7/31	1.3	8/18	1.4
8/1	1.2	8/19	1.5
8/2	1.0	8/20	1.8

__Evidence in the Climate Record__

The measured changes in the surface energy budget are large and should have a detectable influence on the surface climate. In particular, the increased sensible heating should result in a warmer boundary layer. To investigate this, radiosonde data from the following locations were analyzed: Peoria (1957-1989), Omaha (1957-1989), Flint (1957-1989), Dayton (1957-1989), St. Cloud (1957-1989), Green Bay (1957-1989), Salem (1970-1988), and Monett (1971-1989). The locations of these are shown in Figure 4-5. The analysis was limited to the 7-week mid-summer period of July 1-August 18. June was not included because soil moisture stress on vegetation is uncommon, even during a drought, as the result of soil moisture reserves accumulated during the preceding cool season. The latter part of the summer was excluded because more intense autumn-like circulation patterns become more frequent. The above period was subjectively judged to be the optimum period to detect a surface feedback signal.

The Midwestern Climate Center's operational soil moisture model (Kunkel, 1990) was used to categorize each day according to the estimated soil moisture in the top 1 m of the soil, expressed as the percent of potential plant available water (PPAW), defined as PPAW = M_{UL}- M_{LL} where M_{UL} = soil water content at the drained upper limit and M_{LL}= soil water content at the lower limit of plant available water. The four categories are: <25% PPAW, 25 to 50% PPAW, 50 to 75% PPAW, and >75% PPAW.

A simple budget method is used to determine boundary layer heating, similar in many ways to the "slab" approach (Brutsaert, 1988). We assume that the late afternoon boundary layer can be represented as a perfectly mixed slab of depth h with a vertical distribution of the potential temperature 6 that is nearly uniform with height. Assuming that internal heating due to radiative flux divergence and water phase changes can be neglected, the change in 6 can be expressed as (Estoque, 1973)

$$\partial\theta/\partial t + \vec{V}\cdot\nabla\theta = -\partial/\partial z\ \overline{(w'T')} \qquad (6)$$

where

$\vec{V}$ = velocity vector,

$\overline{w'T'}$ = vertical eddy flux of temperature.

By restricting the analysis to low-wind cases, it will also be assumed that advection can be neglected. Then

$$\partial\theta/\partial t = -\partial/\partial z\ \overline{(w'T')} \qquad (7)$$

Integrating from the surface to z = h gives the net boundary layer heating, defined as

$$\int_0^h \partial\theta/\partial t \; dz = \overline{(w'T')}_{z=0} - \overline{(w'T')}_{z=h} \tag{8}$$

Past experiments have suggested a good relationship between the surface sensible heating $(wT)_{z=o}$ and entrainment at the inversion, $(wT)_{z=h}$. The following simple relationship will be used (Brutsaert, 1988):

$$\overline{(w'T')}_{z=h} = -A\overline{(w'T')}_{z=0} \tag{9}$$

where A is a constant with a value between 0.2 and 0.3. Using a value of 0.2 and substituting in (8), the following relationship for the surface sensible heat flux is obtained.

$$H = \rho c_p \overline{(w'T')}_{z=0} = \rho c_p \left(\int_0^h \partial\theta/\partial t \; dz\right)/1.2 \tag{10}$$

The rawinsonde data were obtained from the Data Support Section of the National Center for Atmospheric Research where quality control, including a check for hydrostatic balance, had been performed. Those soundings failing this check were excluded from the analysis. We interpolated temperature in each sounding to every 10 mb using all available mandatory and significant level information. Next, by substituting the maximum temperature of each day for the temperature of the lowest level of the 0000 UTC sounding, we calculated the surface-based maximum potential temperature θ_{maod} assuming that the airmass in place over the rawinsonde site did not change between the time of maximum surface temperature and the time of the 0000 UTC sounding. Work by Scott and Czys (1992) support this assumption for summertime conditions over the Midwest. In subsequent discussion, the levels are numbered with level 1 being the surface and layer 1 representing the layer between levels 1 and 2.

This analysis was restricted to days with daily average surface wind speeds of less than 4 ms^{-1} to minimize advective effects and daily solar radiation greater than 23 MJ $m^{-2}d^{-1}$ to identify sunny days with maximum boundary layer heating. The boundary layer depth h was estimated from the 0000 UTC sounding as the height z of the lowest level meeting the criteria:

$$\theta(z=h) > \theta_{max} + 1.0K$$

The net daytime boundary layer heating was estimated from the temperature change between the

0000 UTC sounding and the prior early morning 1200 UTC sounding as

$$\int_{o}^{h} \partial\theta/\partial t\,dz = \frac{1}{\Delta t}\sum_{i-1}^{N=1}\left[\bar{\theta}_{i,0000\ UTC} - \bar{\theta}_{i,1200\ UTC}\right](z_{i+1} - z_i) \qquad (12)$$

where N = level number of the inversion height, $\Delta t = 12$ h, z_i = height of pressure level i, and θ = layer average potential temperature = $(\theta_i + \theta_i)/2$.

The average temperature difference profile is shown in Figure 4-6. This profile, representing an average of all qualifying days for all stations, exhibits the expected decreasing difference (heating) with height. There is an identifiable difference in the heating rate based on soil moisture category with greater heating observed for the drier soil moisture cases. Interestingly, the heating rate remains positive through the middle portion of the troposphere (not entirely shown). This non-zero heating above the boundary layer could be due to absorption of solar radiation, but more likely is caused by subsidence warming. Since the analysis has been restricted to sunny to mostly sunny "fair weather" days, it is very likely that an average downward vertical motion is present. The average vertical potential temperature gradient above the boundary layer for these days is 0.005 $\mathrm{Km^{-1}}$. A downward vertical motion of 0.5 cm $\mathrm{s^{-1}}$ would be required to produce the observed heating of 1 K in a 12-hour period.

The scaling in Figure 4-6 makes it difficult to distinguish the differences due to soil moisture. Figure 4-7 shows the profile of the difference between the dry (<25% PPAW) and wet (>75% PPAW) soil moisture categories. Greater heating is observed throughout the lower 1 km for the dry soil moisture days, with the greatest difference of nearly 2 K observed at the surface.

The difference profile reverses sign between 1500 and 2500 m. Although the values are small and could be attributed to statistical sampling, another possibility is that this is due to latent heating from fair weather cumulus formation at the top of the boundary layer, occurring preferentially on days with high soil moisture. This was investigated by increasing the daily solar radiation threshold to 28 MJ $\mathrm{m^{-2}\ d^{-1}}$. The majority of days are then eliminated from the sample, leaving a small subset of days with very low cloudiness. The positive differences in the lower boundary layer (Fig. 4-8) remain, but the negative differences are almost completely eliminated. This provides some support for the above explanation.

The estimates from eq. (12) were used to calculate H from eq. (10). Averaging over all stations, the difference in H between the dry and wet soil moisture categories was 17 $\mathrm{Wm^{-2}}$ (65 $\mathrm{Wm^{-2}}$ vs. 48 $\mathrm{Wm^{-2}}$), a significant amount that leads to the 2K greater heating observed at the surface.

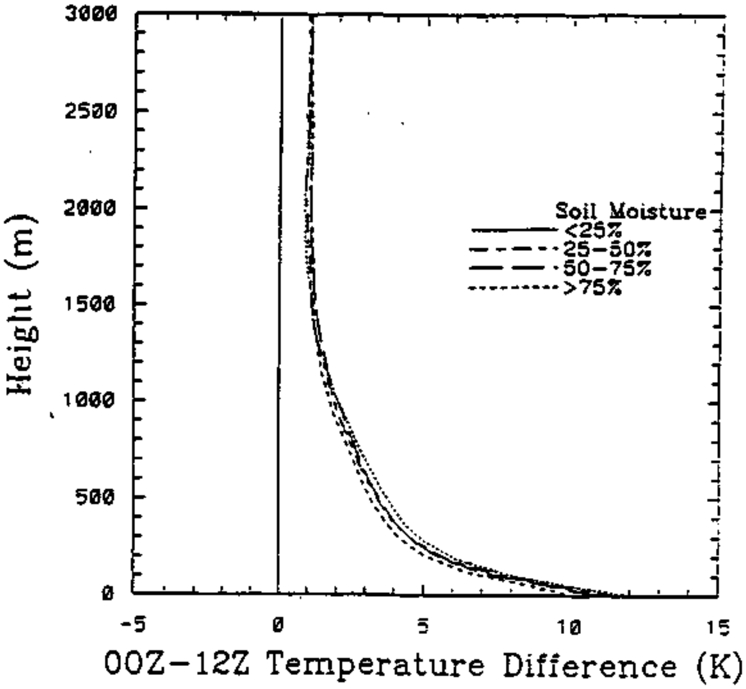


FIGURE 4-6. Vertical profile of the difference between late afternoon (00Z) and the prior early morning (12Z) vertical temperature profiles categorized by soil moisture for the period July 1-August 18. These are averages of all qualifying soundings from the eight radiosonde sites.

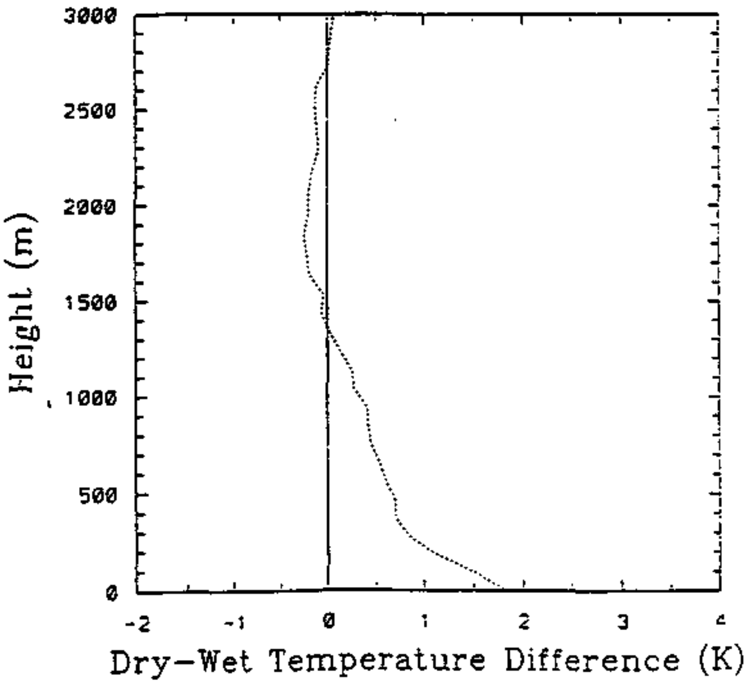


FIGURE 4-7. Vertical profile of the difference between the day (<25% PPA W) and wet (>75%) profiles in Figure 6.

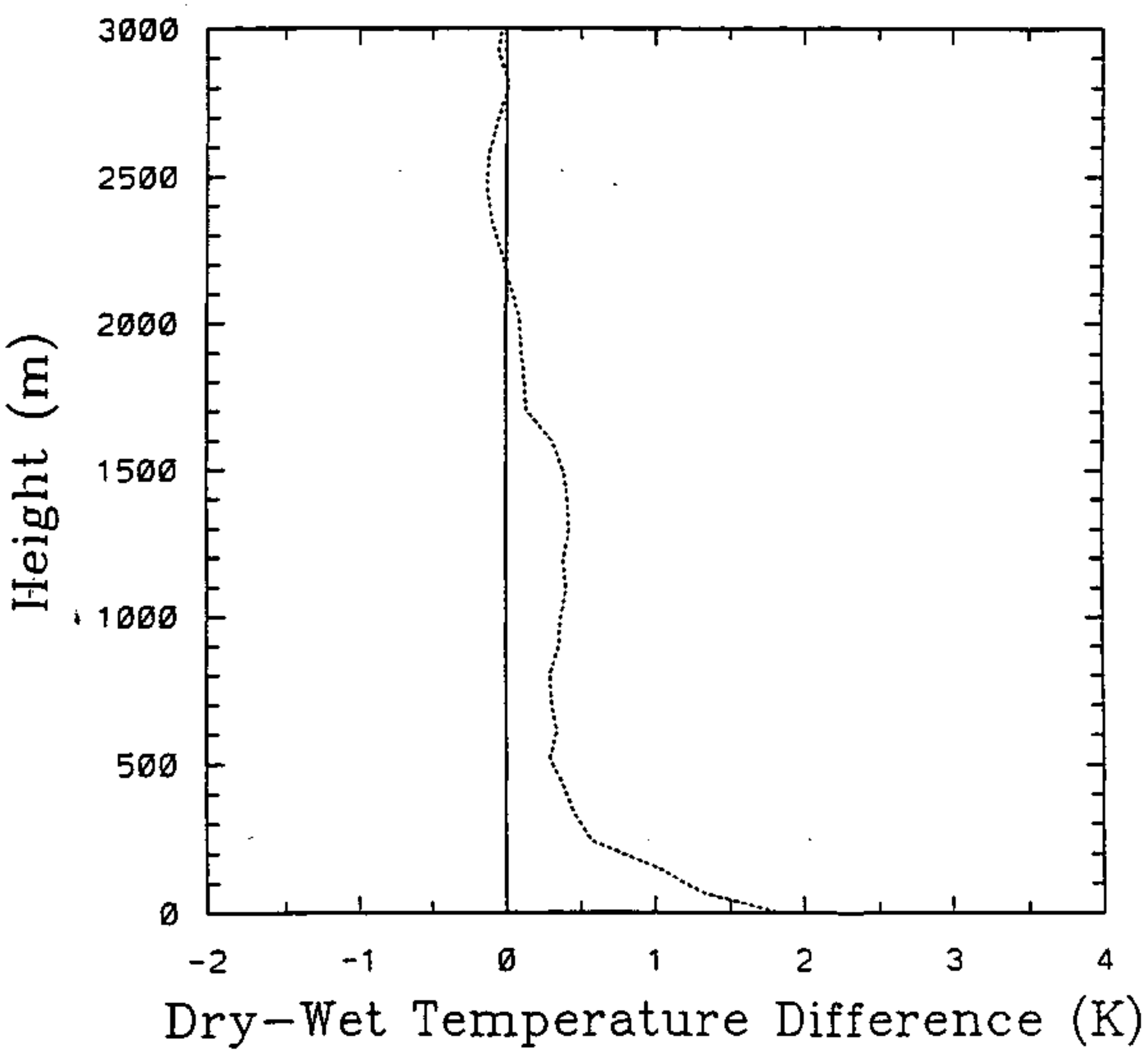


FIGURE 4-8. Same as Figure 7 except that the analysis was limited to days with daily solar radiation totals exceeding 28 MJm^{-2}.

Satellite Observations

Kogan (1990a) used a variation of the Normalized Difference Vegetation Index (NDVI) to investigate the intensity of the 1988 drought. He compared the satellite data with Illinois county corn yields and found good qualitative agreement. The objective of this study was to explore the use of satellite data for monitoring the status of soil moisture through its effects on vegetation. Four data sets were available for this analysis: a) the eddy correlation measurements mentioned above which were available for 17 days during the period June 30-August 17; b) semi-monthly soil moisture measurements at depths of 0-15 cm, 15-50 cm, and 50-100 cm; c) weekly model soil moisture estimates for several layers to a depth of 2 m; and d) weekly NDVI measurements. Because the soil moisture measurements were only available for Illinois, this study is mostly limited to Illinois.

The Water Survey obtained semi-monthly measurements of soil moisture under grass at 18 sites in Illinois using the neutron probe technique (Hollinger and Isard, 1994). The soil moisture model of Kunkel (1990) was used to estimate soil moisture at an additional 101 sites in Illinois where complete daily precipitation data for 1988 were available. These estimates assumed corn as the cover crop. The NDVI measurements were available at a 16 km x 16 km resolution and were normalized relative to the range of their change for each location during the period of available satellite records (Kogan, 1990b); this modified NDVI is named the Vegetation Condition Index (VCI) and has a range of 0-100%. Approximately 60% of the state's area is covered by corn and soybeans. Therefore the VCI data are expected to generally be representative of those crops. Since grass will begin transpiring in early spring while corn and soybeans will not emerge (and therefore begin transpiring) until mid to late spring, the early summer soil moisture depletion as indicated by the under-grass soil moisture measurements is expected to be earlier than under corn and soybeans. The VCI may also lag the change in soil moisture due to a lag in the response of the vegetation to soil moisture changes.

Figure 4-9 shows the time dependence of all four data sets at the one common site, Champaign. The soil moisture data are expressed as percent plant available water, defined as 100% $(SM-M_{LL})/PPAW$ where SM = soil moisture measurements/estimates. The behavior of all four are generally consistent. The model soil moisture estimates and the VCI decrease rapidly over the same time period. As expected, the decrease in the soil moisture measurement data occurs earlier. The midday Bowen ratio measurements are already high at the onset of their availability, consistent with the plant stress suggested by the VCI and soil moisture data. The temporary decease in the Bowen ratio during mid-late July in response to a few rain events is reflected by small increases in the soil moisture data, but not in the VCI.

Figure 4-10 shows the time dependence of the soil moisture values and the VCI averaged over all available stations and pixels in Illinois. Once again, very similar behavior is observed. The rapid early summer decrease in the soil moisture estimates and the VCI occur simultaneously. The decrease in the soil moisture measurements is similar, but begins earlier. The widespread coverage of low soil moisture/NDVI values indicated by Figure 4-10, of a magnitude similar to that observed at Champaign, would suggest that the evaporation decreases measured at Champaign were also widespread and of similar magnitude throughout the state. Table 4-4 shows the distribution of

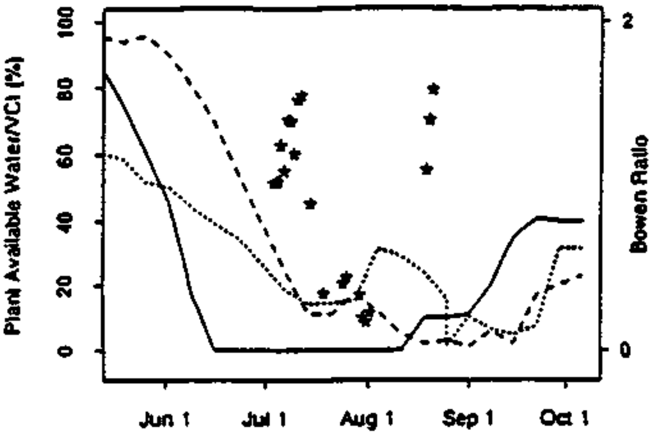


FIGURE 4-9. Temporal behavior during 1988 of the following data at Champaign, Illinois: a) model soil moisture estimates (dashed line), b) by soil moisture measurement (dotted line) c) VCI (solid line), d) Bowen ratio measurements (asterisks).

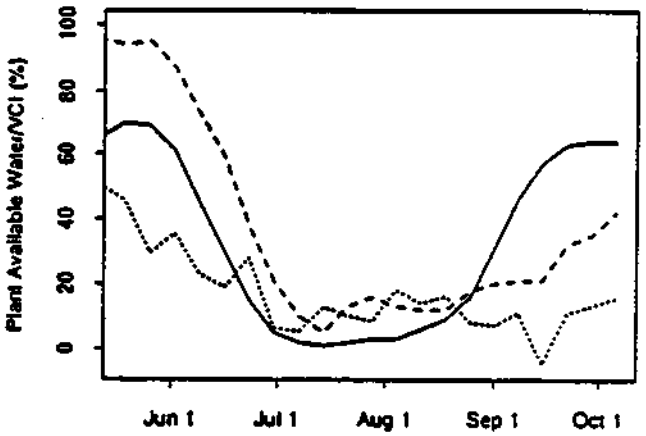


FIGURE 4-10. Temporal behavior during 1988 of modeled soil moisture estijates (short dashed line), soil moisture measurements (dontted line), and VCI (solid line) for Illinois averaged over all available stations or pixels.

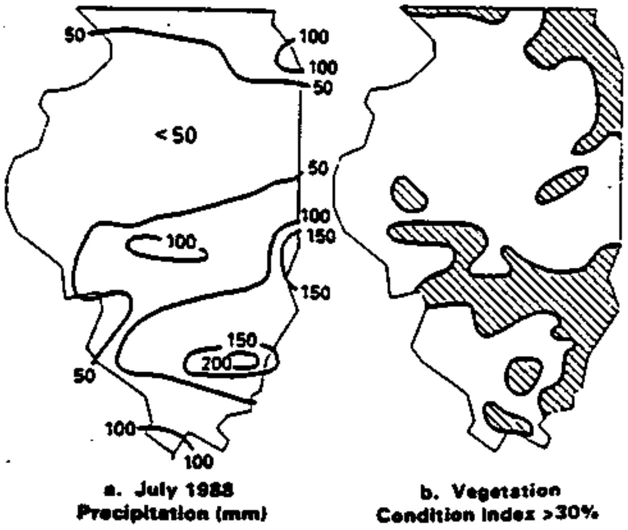


FIGURE 4-11. Total July precipitation (mm) in Illinois, b) smoothed V.I. distribution with shaded areas indicating values greater than 30%.

measured VCI values for the four weeks of July 1988. About 92% of the pixel-weeks were in the lowest category, further indication of the severity and areal coverage of vegetation under severe stress.

In a slightly different vein, we investigated the response of the VCI to short-term soil moisture recovery. Significant precipitation occurred in southern Illinois during the last two weeks of July. Amounts at some locations exceeded 100 mm. The resulting response of the VCI lagged the precipitation by about 3-4 weeks and was not entirely coincident with the areal coverage. Figure 4-11 compares the July precipitation patterns with the VCI distribution for week 34 (late August). The east-west strip of higher VCI across south-central Illinois coincides with a portion of the significant precipitation area. However, the significant precipitation in extreme southern Illinois is not entirely reflected in the VCI pattern. We can only speculate on the reason for this mixed behavior. That region of Illinois has a much higher proportion of forested land than the rest of the state; the location of these coincide in a general way with those areas in which the VCI did not respond. Perhaps trees were unable to take significant advantage of the recovery of near-surface soil moisture supplies because of their deep root systems. The terrain in this area is also rather hilly which may result in increased runoff from these rain events (which were quite heavy and occurred in very short time periods) and less soil moisture recharge. By contrast, the area to the north and east where the VCI did respond is flat, generally planted in corn or soybeans, and characterized by soils with poor drainage (an advantage in this situation). The lag in response of the NDVI has also been observed in the Sahel (Kerr et al., 1989). In that study, they found a lag of about 2 weeks.

Table 4-4. Frequency of occurrence of VCI pixel values in Illinois for weeks 27-30. A total of 714 pixels were available for this analysis.

VCI (%)	Frequency (%)
0-10	91.7
10-20	2.3
20-30	1.3
30-40	1.3
40-50	1.3
50-60	0.4
60-70	0.5
70-80	0.4
80-90	0.2
90-100	0.6

This study also indicated that the soil moisture changes (and presumably changes in evaporation rates) can be monitored remotely by satellite NDVI data, as expressed in the VCI. Short-term shallow soil moisture recovery may not be detectable under some circumstances.

SYNOPTIC AND THERMODYNAMIC CONDITIONS DURING DRY PERIODS

Robert W. Scott

Introduction

The frequency of precipitation-producing events during droughts was reduced in all types of synoptic-scale weather systems, especially air mass convection (Huff and Vogel, 1977). As summarized in Table 3-24, the frequency of rain days due to air mass convection during a variety of case studies of "dry" periods occurring during July and August in the years 1944 to 1966 was substantially smaller compared to the normal synoptic values for these crop-interest months. As a consequence, a concomitant increase occurred in the frequency of days with rain generated by cold frontal passages.

Rainfall production in summer dry periods is reduced substantially as well (Tables 3-24 and 3-25). Huff and Vogel (1977) found that daily rainfall totals generated by cold fronts during droughts were only 65 percent of cold front production during normal summers. Rain production on days of air mass storms totaled just 13 percent of normal. Nevertheless, 50 percent of rain occurring during July and August produced areas of measurable precipitation that covered about 50 percent of the region of large droughts (areal extents > 50,000 km^2*)*, and up to 90 percent of areas experiencing smaller-scale drought conditions (areas < 5,000 km^2). Thus, significant precipitation events do occur in dry summers, although synoptic conditions that are appropriate for generating rainfall are less frequent (Huff and Vogel, 1977).

As stated in Part 1 of this report, weather modification research in Illinois over the past 25 years have been designed to evaluate the impacts of increased rainfall on crop yields (Changnon, 1973). Average statewide rainfall during June, July, and August totals 293 mm (11.54 in). *Total* rainfall in many summers may be sufficient for most of the state's agricultural and water resource needs and, thereby, reduce or eliminate the desire for precipitation enhancement in these summers. Nevertheless, the spatial and temporal distribution of rainfall can be far from ideal, even in wet summers (Hollinger and Changnon, 1996). Regardless, rainfall augmentation is certain to have a more substantive effect on crop yields during dry summers (when even small increases in rainfall can be quite valuable) than in years when precipitation is generally plentiful (Hollinger and Changnon, 1993).

Thus, the question remains as to the extent of meteorological differences present during dry summers compared to summers with greater (normal or above) precipitation. The objective of this research was to conduct a climatological investigation of the summertime meteorological conditions during dry summers to define the prevailing meteorological patterns which result in conditions of low precipitation. This included an investigation of summertime thermodynamic conditions observed aloft over central Illinois, compared to seasonal rainfall conditions, to determine differences that existed in dry, near normal, and wet summers.

Precipitation Analysis

Daily rainfall measurements during June, July, and August at 61 long-term precipitation-measuring sites across Illinois for the years 1901 - 1993 were averaged by occurrence within the nine climatological districts of the state (Figure 3-1). Due to the small number of sites in Districts 3, 4, and 6, selected sites very close to these borders but actually located in an adjacent district were included to increase the number of sites within these districts.

The data from all stations within each district (totaling between 6 and 9 sites each) were categorized by rainfall intensity, and a frequency distribution of daily rainfall totals was generated. Results shown in Table 4-5 indicate that throughout the 93-year period, the occurrence of days without measurable precipitation is slightly higher at sites in the southern districts. That is, on average, dry days occur just over 73% of the time in the southernmost part of the state, and likewise, about 70% of the time in the far north. Most of this difference is due to a higher frequency of light daily rainfall totals (amounts < 6.4 mm) in northern districts. As daily precipitation totals increase, the frequency of occurrences expectedly decrease, but the differences in the frequencies of occurrence between districts decrease as well. That is, days with the heaviest rain intensities (greater than 25.4 mm) occur approximately 3.3% of the time statewide.

Table 4-5. Percentage of days with precipitation during summer in Illinois, categorized by daily rainfall totals, for 1901-1993.

	precipitation categories (mm)						
District	0.0	0.1-2.6i	2.7 - 6.4	6.5 - 12.7	12.8 - 25.4	>25.4	>0.0
1(NW)	70.3	9.8	6.1	5.3	4.9	3.6	29.7
2(NE)	70.5	10.3	6.0	5.4	4.6	3.2	29.5
3(W)	72.5	8.4	5.6	5.2	4.8	3.5	27.5
4(C)	71.7	9.8	5.6	5.0	4.5	3.2	28.3
5(E)	71.6	9.6	5.8	5.2	4.7	3.2	28.4
6(WSW)	72.8	9.0	5.4	4.9	4.6	3.2	27.2
7(ESE)	72.8	8.4	5.5	5.2	4.8	3.3	27.2
8(SW)	73.4	8.9	5.2	4.7	4.5	3.3	26.6
9(SE)	73.5	8.1	5.5	5.1	4.6	3.3	26.5

Average summertime rainfall for each year was computed for each district by using all daily site amounts within each district. The seasonal averages were then ranked and divided into terciles (each 31 years in length), creating categories of "wet", "normal", and "dry" seasons for each district. In other words, dry periods were defined as those summers whose precipitation was in the lowest third of all years of summertime rainfall totals. Daily amounts were grouped once again by precipitation categories within each tercile (Table 4-6). Although the individual years defined as dry in this manner are not the same for every district, results show that only a small variability exists between districts. Within each district, however, some notable distributions are found.

During dry seasons, there is a much larger frequency of days without measurable precipitation compared to the frequency of these days in wet summers. In District 4, for example, days without precipitation occur nearly 77 percent of the time in seasons categorized as dry, whereas only 67 percent of the time in seasons considered to be wet. Summers considered to produce normal precipitation show days without rainfall at a 72 percent rate.

Trends consistent with this result exist for all rainfall intensities. That is, regardless of the daily rainfall amount, days with precipitation always occur less frequently during dry summers than in normal or wet summers. Furthermore, as daily rainfall totals increase, the difference between the frequencies of occurrence of precipitation in dry and wet seasons also increase. For example, in District 4, days with just light rainfall (measurable totals less than 6.4 mm) occur in dry summers only about 85 percent as often as they do in wet summers. This relationship decreases to nearly 62 percent on days with moderate precipitation and to only 42 percent with heavy rainfall (daily totals in excess of 25.4 mm).

Table 4-6. Percentage of days with precipitation during summer in Illinois (1901 - 1993) within rainfall categories, stratified by dry, normal, and wet summers. N represents the number of non-missing station-days within each season type.

District 1

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	75.3	9.2	4.9	4.5	3.9	2.3	24.7	25452
normal	70.1	10.1	6.5	5.3	4.7	3.3	29.9	25053
wet	65.5	10.2	6.9	6.1	6.2	5.1	34.5	25082

District 2

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	75.0	9.5	5.6	4.6	3.4	1.9	25.0	18551
normal	71.1	10.2	5.8	5.1	4.8	3.0	28.9	19203
wet	65.6	11.2	6.6	6.3	5.7	4.6	34.4	19324

District 3

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	77.1	7.9	5.1	4.2	3.6	2.0	22.9	17051
normal	72.6	8.8	5.4	5.2	4.7	3.3	27.4	16957
wet	67.8	8.5	6.3	6.2	5.9	5.3	32.2	16987

District 4

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	76.6	9.0	5.1	3.9	3.5	1.9	23.4	19604
normal	71.6	10.0	5.7	5.0	4.4	3.2	28.4	19443
wet	67.0	10.5	6.0	6.1	5.9	4.5	33.0	19594

Table 4-6. (continued)

District 5

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7 - 6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	75.7	9.5	5.1	4.5	3.4	1.8	24.3	14718
normal	71.6	9.6	5.9	5.1	4.9	3.0	28.4	15916
wet	67.6	9.6	6.3	6.0	5.8	4.7	32.4	14941

District 7

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	77.6	7.6	4.8	4.1	3.7	2.2	22.4	19841
normal	72.2	8.7	5.7	5.2	5.1	3.2	27.8	19473
wet	68.5	8.9	6.1	6.1	5.8	4.6	31.5	19650

District 8

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7 - 6.4	6.5 - 12.7	12.8 - 25.4	>25.4	>0.0	N
dry	78.1	8.2	4.5	3.8	3.5	2.1	21.9	18637
normal	73.0	9.1	5.4	4.9	4.6	3.0	27.0	18307
wet	69.0	9.4	5.8	5.5	5.6	4.7	31.0	18306

District 9

	precipitation categories (mm)							
season	0.0	0.1-2.6	2.7-6.4	6.5-12.7	12.8-25.4	>25.4	>0.0	N
dry	78.5	7.2	4.6	4.1	3.6	2.0	21.5	16680
normal	73.0	8.5	5.8	4.9	4.4	3.3	27.0	16732
wet	69.0	8.4	6.2	6.3	5.7	4.4	31.0	16984

Thus, dry summers have two characteristics: (1) there is a reduction in the total number of rain days when compared to normal or wet summers, and (2) these reductions are greater on days with larger rainfall totals. These results are not unexpected, but they lead to an important question asked from a weather modification perspective. Are the general atmospheric conditions during dry summers in Illinois sufficient for the development of convective rain-making systems that are suitable for weather modification activities to be attempted? Summers with plentiful intrinsic rainfall are typically seasons when cloud intervention, used to augment precipitation, has a limited beneficial effect on the water resources of Illinois (Changnon and Hollinger, 1993). However, during summers that are dry, the impact of successful rain enhancement can be quite substantial.

Investigations of Synoptic Weather Conditions

Investigations of seasonal synoptic weather types are frequently performed to help differentiate patterns in precipitation frequency and intensity. Due to the space and time scales involved, these relationships are best used over limited intervals of each. Relating daily rainfall amounts to synoptic forcing over Illinois is complicated due to the state's size and long (615 km) north-south extent. That is, there are frequently days on which more than one synoptic type is concurrently present over different regions of the state. However, conclusions from the previous section indicate that there are no large regional variations in summer precipitation statistics across the state. Thus, it was assumed that relationships between synoptic conditions and precipitation data within District 4 (Figure 3-1) were likely representative for the entire state.

Surface synoptic charts were obtained for the United States from the Daily Weather Map Series. Although charts are available since 1899, only the period from 1957 - 1993 was used so as to be consistent with an analysis of upper air data across central Illinois as part of a climatological investigation of thermodynamic conditions, described in a following section.. Prior to 1967, two surface charts were available each day, at 0600 and 1800 UTC. From that year forward, only a single (1200 UTC) surface chart was provided. Throughout the period of investigation, just one daily upper air chart (500 mb) was available for analysis. Thus, the large spatial and temporal intervals between charts placed limitations on these data to define and resolve short-term features, and therefore, the choice of synoptic types was limited to six. These included: cold front, warm front, static front, occluded front, low pressure, and air mass convection. Important precipitation-related features of smaller scales, such as a squall line or a zone of squall activity, were occasionally indicated on the synoptic charts, but these were classified, in general, with one of the six synoptic feature based on the one that likely generated the activity (usually frontal), even though this feature may have been a substantial distance from the state. In addition, there were a few days on which it was obvious that two synoptic features were responsible for the precipitation conditions over District 4. In each case, these were a combination of warm and cold frontal passages on the same calendar day, cases when it was impossible to differentiate the precipitation attributed to the individual fronts. These were all classified as cold front since in general they are the more dominant feature in precipitation production.

Seasonal rainfall in the district was computed for each of the 37 (1957-1993) summers from an average of precipitation using all district sites. These amounts were once again ranked and apportioned into terciles as either "dry", "normal", or "wet". That is, the driest 12 summers in the 1957-1993 period were assigned as dry, and the next 13 and 12 summer seasons, in order of ascending rainfall amounts, were defined within the normal and wet precipitation group, respectively. A synoptic type was determined for each day on which measurable precipitation was observed based on rainfall values from Decatur, Springfield, and Peoria that were averaged. Only these sites were chosen to link daily synoptic types with rainfall since their times of observation for 24-hour precipitation amounts were consistently at midnight throughout the period of investigation.

The distribution of each synoptic type for each year is shown in Table 4-7. On the whole, summertime precipitation in Illinois is largely influenced synoptically by the presence of cold fronts. Precipitation due to the presence of static fronts or to air mass conditions conducive to convective rainfall has substantial frequencies of occurrence in some years. However, the presence of warm fronts and low pressure centers are far less frequent, while days with precipitation from occluded fronts are highly infrequent.

Table 4-7 also shows the precipitation rankings of each summer season. As revealed earlier, days with rainfall are substantially reduced during those summers classified as dry compared to years considered having normal or wet summer rainfall totals. The number of rain days during the 12 dry summers ranged from 26 to 44 days with a median of 33.5. Rain days during summers with normal rainfall ranged from 32 to 56 with a median of 43 days. Wet summers had rain day totals ranging from 38 to 63 days with a median of 47.

Thus, these data further reveal decreased precipitation opportunities during dry summers. This result is largely unchanged by summing the seasonal synoptic type totals in Table 4-7 within the dry, normal, and wet season rankings, once more arranging within precipitation categories (Table 4-8). Considering first all rain days (those with precipitation > 0.0 mm), rainfall generated by cold fronts, static fronts, and air mass convection dominate on 79% to 85% of rain days, regardless of the seasonal rainfall trends. Second, a higher frequency of days with cold fronts and air mass conditions exists during dry summers (compared to wet seasons) due to a concomitant drop in days with warm fronts and passages of low pressure centers. Thus, although all synoptic types show a decrease in occurrences during dry summers, the greatest changes take place in the number of days when warm fronts and low pressure centers cross the region, down nearly 40% to 50% respectively. Decreases in the number of days with cold fronts (24%) and static fronts (28%) may indicate a change in cyclone frequencies, being down by roughly one-fourth, and perhaps more cyclones are located further to the north and not tracking over the state.

Table 4-7. Distribution of various synoptic types on rain days during summers 1957 - 1993.

Year	Cold	Static	Warm	Occlude	Low	Air	Total	Rankin
1957	17	10	3	0	2	9	41	Normal
1958	24	9	4	0	2	9	48	Wet
1959	12	7	3	0	1	12	35	Dry
1960	15	10	1	1	5	7	39	Wet
1961	14	13	1	0	2	7	37	Normal
1962	10	10	3	1	3	4	31	Dry
1963	12	4	1	0	3	12	32	Normal
1964	9	5	4	1	4	8	31	Dry
1965	25	5	9	0	2	2	43	Wet
1966	15	5	5	0	2	6	33	Dry
1967	18	12	1	0	2	9	42	Normal
1968	15	7	3	0	3	5	33	Normal
1969	14	12	7	0	3	11	47	Normal
1970	19	9	1	0	5	12	46	Normal
1971	17	9	2	0	2	10	40	Dry
1972	16	9	1	0	3	14	43	Normal
1973	16	12	2	0	3	10	43	Wet
1974	18	7	0	0	4	11	40	Normal
1975	17	13	3	0	3	14	50	Wet
1976	17	3	3	0	1	10	34	Dry
1977	21	7	5	0	2	17	52	Wet
1978	19	5	6	2	2	13	47	Normal
1979	13	13	5	0	3	10	44	Dry
1980	11	12	9	0	2	12	46	Normal
1981	19	8	4	0	6	15	52	Wet
1982	21	7	8	0	4	16	56	Normal
1983	13	5	1	0	2	10	31	Dry
1984	20	5	4	0	1	12	42	Dry
1985	18	8	3	1	8	18	56	Wet
1986	15	8	5	0	2	8	38	Wet
1987	19	8	7	0	4	8	46	Normal
1988	16	5	0	0	0	5	26	Dry
1989	11	9	3	0	5	7	35	Dry
1990	13	11	7	0	9	6	46	Wet
1991	14	6	3	0	2	7	32	Dry
1992	16	5	8	0	4	10	43	Wet
1993	18	19	12	0	8	6	63	Wet
Average	16.1	8.4	4.0	0.2	3.2	9.8	41.7	

Table 4-8. Total occurrence and frequency distribution of synoptic types on rain days during summers 1957 - 1993, stratified by dry, normal, and wet seasons.

	Cold Front		Static Front		Warm Front		Occluded Front		Low Pressure		Air Mass		Total
precipitation (mm) > 0.0													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	167	40.3	82	19.8	36	8.7	2	0.5	26	6.3	101	24.4	414
Normal	213	38.3	115	20.7	48	8.6	2	0.4	39	7.0	139	25.0	556
Wet	217	37.9	115	20.1	63	11.0	2	0.3	54	9.4	122	21.3	573
Total	597	38.7	312	20.2	147	9.5	6	0.4	119	7.7	362	23.5	1543
0.0 < precipitation (mm) s;2.6													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	68	35.2	29	15.0	16	8.3	0	0.0	12	6.2	68	35.2	193
Normal	83	35.2	42	17.8	19	8.1	2	0.8	14	5.9	76	32.2	236
Wet	65	31.6	28	13.6	22	10.7	1	0.5	20	9.7	70	34.0	206
Total	216	34.0	99	15.6	57	9.0	3	0.5	46	7.2	214	33.7	635
2.6 < precipitation (mm) s;6.4													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	39	35.8	30	27.5	10	9.2	2	1.8	8	7.3	20	18.3	109
Normal	57	46.3	18	14.6	9	7.3	0	0.0	9	7.3	30	24.4	123
Wet	54	42.2	25	19.5	11	8.6	0	0.0	8	6.2	30	23.4	128
Total	150	41.7	73	20.3	30	8.3	2	0.6	25	6.9	80	22.2	360
6.4 < precipitation (mm) ≤ 12.7													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	34	53.1	9	14.1	7	10.9	0	0.0	4	6.2	10	15.6	64
Normal	40	38.1	26	24.8	12	11.4	0	0.0	7	6.7	20	19.0	105
Wet	34	31.8	27	25.2	18	16.8	1	0.9	13	12.1	14	13.1	107
Total	108	39.1	62	22.5	37	13.4	1	0.4	24	8.7	44	15.9	276
12.7 < precipitation (mm) ≤ 25.4													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	22	59.5	9	24.3	2	5.4	0	0.0	1	2.7	3	8.1	37
Normal	26	40.0	19	29.2	6	9.2	0	0.0	4	6.2	10	15.4	65
Wet	46	51.6	20	22.0	10	11.0	0	0.0	7	7.7	7	7.7	91
Total	95	49.2	48	24.9	18	9.3	0	0.0	12	6.2	20	10.4	193
precioitation (mm^{1}) > 2 5 4													
Season	N	%	N	%	N	%	N	%	N	%	N	%	N
Dry	4	36.4	5	45.5	1	9.1	0	0.0	1	9.1	0	0.0	11
Normal	7	25.9	10	37.0	2	7.4	0	0.0	5	18.5	3	11.1	27
Wet	17	41.5	15	36.6	2	4.9	0	0.0	6	14.6	1	2.4	41
Total	27	35.4	30	38.0	5	6.3	0	0.0	12	15.2	4	5.1	79

Thereby, the numbers of warms fronts and low pressure centers are affected in two ways. The 17% drop in air mass convection frequency likely indicates less ambient moisture in the region between cyclones, consistent with conditions during severe droughts of large persistent high pressure subsidence.

Comparison of the frequency of rain events by synoptic type (Table 4-8) for dry and normal summers is instructive as to what rain-producing conditions are absent (and how often) in dry summers. Comparisons based on all measurable rain days shows for cold fronts, 167 days in dry compared with 213 days in normal summers. The difference is 46 days, an average of 4 per summer less in dry periods. Similar comparisons reveals, on average, 3 fewer static front days, 1 fewer warm front day, 1 less day with a low pressure center, and 3 fewer air mass days for a total difference of 12 rain days in dry verses normal summers.

Comparison of dry summers and normal summers for moderate to heavy rains is also informative. The differences for the synoptic classes are: cold front - 7 less in dry summers (about 0.5 per year), static front - 15 (1 day less per year), warm front - 5 days less (about 0.5 per year), low pressure 7 days (0.5 per year), and air mass - 10 fewer days (about 1 day per year). The total difference is 44 days, nearly 4 per year with the largest losses on days with static fronts and air mass convection. All synoptic conditions producing rain in dry summers in Illinois are fewer in dry periods than normal rain summers.

A final analysis of the data in Table 4-8 concerns the trend of synoptic type frequency with increasing daily rainfall totals. With light precipitation (totals ≤ 2.6 mm), days with both cold fronts and air mass convection occur with equal frequency. However, as daily rainfall increases, the frequency of cold front days increases while air mass days decrease as a percentage of all synoptic types. On days with moderate precipitation (totals ranging between 12.7 and 25.4 mm), cold fronts are the synoptic type in control nearly 50% of the time, while air mass rainfall dominates on just over 10% of the days. Static fronts meanwhile show a smaller increase in frequency while the other synoptic types maintain frequencies similar to those shown with light precipitation. On days with the heaviest rainfall (totals > 25.4 mm), static fronts become as important as cold fronts, and the frequency of precipitation due to nearby low pressure centers increases considerably. However, the occurrence of air mass storm days continues to decrease.

Similar results are seen when considering just dry summers. After being nearly of equal occurrence with light precipitation, days with cold fronts dominate air mass days by more than 7 to 1 with moderate precipitation. On days with heaviest rainfall during dry summers, there is a nearly complete dominance by cold and static fronts while air mass day occurrence actually goes to zero. However, the small number of days in this category (11) is likely an important factor for this very low percentage. Unexplained are the numerous occurrences throughout the rainfall rankings for highest frequencies of static fronts and air mass conditions during years with normal precipitation.

One final point should be made. Research by Changnon and Shealy (1993) indicated that the most economically efficient days on which to conduct weather modification operations were those days on which the expected rainfall totals would exceed 25.4 mm. Data here indicate that over an area the size of a climatological district in Illinois, these are relatively rare events, only 11 occurrences in the 12 years of dry summers, about one a year. Days with at least moderate rainfall have occurred on only 47 days during same this period, barely 4 times each dry summer. Considering that at least half of these rain periods likely occurred at night, substantial planning would need to be undertaken to maximize the potential benefits from weather modification activities on days with the heaviest precipitation during dry summers.

Thermodynamic Studies of Upper Air Conditions

A climatological investigation of the summertime thermodynamic conditions, derived from the daily 0700 UTC sounding at Peoria, was performed using the past 37 years of rawinsonde observations (1957 - 1993). Comparison of upper air conditions with precipitation measurements (from the average of three sites in central Illinois) was conducted. The stations included Peoria, Decatur (located approximately 110 km to the SE of Peoria), and Springfield (95 km south of Peoria).

A variety of thermodynamic diagnostic and quasi-prognostic parameters were selected and tested for quantifiable differences between days without precipitation and on days with varying amounts of rainfall. Data were again stratified by dry, normal, and wet summers. Average conditions for all 37 summers are shown in Table 4-9; those for dry, normal and wet summers individually are shown in Tables 4-10 to 4-12, respectively.

As expected, results indicate large differences between days with no rain and those with rain, regardless of the wetness or dryness of the season as a whole. Days with rain show substantially more positive thermodynamic conditions towards the formation of clouds, and thus, opportunities for convection, than those days on which no precipitation fell. For example, in Table 4-9, the temperature of the convective condensation level (TCCL), which can represent cloud base temperature, is much warmer on days with rain. Therefore, on rain days during summer in central Illinois, less mechanical lifting would be required to initiate cloud formation. Cloud bases would be lower, and depths of clouds with temperatures greater than 0° C would be larger. This would allow more time for warm rain processes (coalescence) to be active and efficient (an important part of the natural summertime rain-making formula). Likewise, precipitable water (PW), a measure of the total amount of water mass in a column of the atmosphere, is larger on days with observed precipitation. Thus, more moisture is available allowing for heavier rainfall to occur.

Table 4-9. Average thermodynamic conditions from the 1200 UTC sounding at Peoria, Illinois during all summers (1957 - 1993) related to categorical average precipitation observed at Decatur, Springfield and Peoria, Illinois.

	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip	(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.0	17.0	14.4	33.6	13.2	2623.	9.5	4282.	5929.	821.	2.5
0.1 -2.5	18.1	15.9	31.2	14.6	2179.	11.6	4183.	5912.	868.	3.0
2.6 - 6.4	19.1	17.0	31.1	15.8	2037.	13.0	4265.	5984.	847.	3.3
6.4 - 12.7	19.2	17.3	31.1	15.4	1990.	13.4	4295.	6042.	882.	3.5
12.8 - 25.4	19.9	18.1	30.2	16.1	1781.	14.5	4327.	6056.	867.	3.6
>25.4	19.1	17.5	30.5	16.4	1888.	13.8	4314.	6145.	908.	3.7
>0.0	18.8	16.7	31.0	15.5	2050.	12.7	4246.	5981.	867.	3.3

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.0	4.4	14.4	20.2	12.9	107.	413.	303.	83.	2.6	2.1
0.1 -2.5	2.9	22.3	27.8	11.3	140.	420.	316..	61.	0.8	2.5
2.6 - 6.4	1.8	25.1	30.6	10.6	158.	374.	371.	49.	0.7	3.1
6.4 - 12.7	1.7	27.8	32.9	9.8	171.	381.	352.	50.	0.3	3.1
12.8 - 25.4	0.9	29.3	34.8	9.6	175.	398.	362.	33.	-0.9	3.0
>25.4	2.5	31.0	35.3	9.0	182.	415.	248.	19.	-1.3	2.4
>0.0	2.2	25.2	30.6	10.6	156.	399.	337.	51.	0.4	2.8

Key:

SFCT = surface temperature
SFCD = surface dew point temperature
CNVT = convective temperature
DBAR = dew point temperature (lowest 50 mb)
TCCL = convective condensation level temperature
HCCL = convective condensation level height
HGT = height of 0° C and -10° C levels
DH38 = depth of layer between -3° C and -8° C
PW = precipitable water
LI = lifted index
KI = K-index
MKI = modified K-Index
MSH = modified Showalter index

SWT = sweat index
PTOP = top of positive energy region on sounding
CAPE = convective available potential energy
BRI = bulk Richardson number
ICA = index of coalescence activity
PB = potential buoyancy

Table 4-10. Same as Table 4-9, except only for dry summers. Statistical comparisons (shading) are with identical parameters in Table 4-12.

	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip	(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.0	17.2	14.4	34.0	13.2	2675.	9.4	4308.	5937.	815.	2.6
0.1 -2.5	18.6	16.3	31.6	15.0	2181.	12.0	4240.	5933.	862.	3.1
2.6 - 6.4	19.7	17.5	31.2	16.5	1967.	13.8	4387.	6094.	830.	3.4
6.4 - 12.7	18.9	17.0	30.6	16.0	1952.	13.3	4330.	6045.	833.	3.4
12.8 - 25.4	20.4	18.8	28.9	17.8	1539.	15.9	4361.	6111.	890.	3.8
> 25.4	19.4	18.6	29.1	17.2	1626.	15.1	4348.	6243.	1004.	3.7
> 0.0	19.1	17.0	31.1	15.8	2123.	13.0	4304.	6030.	855.	3.3

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.0	4.2	15.5	21.0	12.6	111.	393.	324.	89.	3.2	2.3
0.1 -2.5	2.5	22.7	28.2	11.3	142.	390.	341.	77.	0.7	2.6
2.6 - 6.4	1.2	26.7	32.2	10.4	159.	356.	385.	54.	-0.1	3.1
6.4 - 12.7	2.3	27.7	32.8	10.3	164.	427.	242.	28.	-0.2	2.8
12.8 - 25.4	0.1	31.3	36.6	9.2	188.	423.	405.	39.	-2.1	2.9
> 25.4	1.7	33.0	37.3	9.0	186.	408.	245.	15.	-2.0	2.7
> 0.0	1.9	25.5	30.8	10.7	155.	390.	340.	59.	0.0	2.8

Table 4-11. Same as Table 4-9, except only for normal summers.

	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip	(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.0	16.9	14.4	33.2	13.2	2584.	9.5	4247.	5908.	825.	2.6
0.1 -2.5	18.0	15.6	31.6	14.4	2259.	11.3	4220.	5930.	854.	3.0
2.6 - 6.4	18.8	16.7	31.8	15.6	2129.	12.7	4247.	5961.	844.	3.2
6.4 - 12.7	19.2	17.2	31.5	16.2	2034.	13.3	4337.	6106.	905.	3.6
12.8 - 25.4	19.8	17.9	30.2	16.7	1815.	14.3	4273.	6030.	870.	3.5
> 25.4	19.3	17.0	30.8	16.6	1911.	13.9	4291.	6119.	954.	3.7
> 0.0	18.6	16.5	31.4	15.4	2121.	12.4	4257.	5990.	868.	3.2

Precip	LI (C)	KI (C)	MKI (C)	MSH (C)	SWT (C)	PTOP (mb)	CAPE (J/Kg)	BRI	ICA	PB (C)
0.0	4.4	13.3	19.3	13.1	106.	423.	296.	90.	2.4	2.1
0.1 -2.5	3.1	21.4	26.7	11.4	138.	426.	320.	62.	1.0	2.4
2.6 - 6.4	2.1	23.9	29.3	10.6	157.	351.	409.	56.	1.4	3.3
6.4 - 12.7	1.9	27.2	32.4	9.5	169.	377.	366.	56.	0.4	3.2
12.8 - 25.4	0.8	29.8	35.0	9.3	175.	374.	363.	32.	-0.6	3.0
>25.4	1.9	32.6	36.6	8.5	193.	368.	306.	36.	-0.5	2.8
>0.0	2.3	24.5	29.8	10.5	155.	392.	352.	55.	0.7	2.9

Table 4-12. Same as Table 4-9, except only for wet summers.

Precip	SFCT (C)	SFCD (C)	CNVT (C)	DBAR (C)	HCCL (m)	TCCL (C)	HGT (m) 0°C	HGT (m) -10°C	DH38 (m)	PW (cm)
0.0	16.9	14.6	33.4	13.2	2605.	9.5	4293.	5944.	825.	2.5
0.1-2.5	18.0	15.9	30.2	14.5	2085.	11.6	4082.	5834.	893.	3.0
2.6 - 6.4	18.7	16.9	30.4	15.3	2005.	12.6	4184.	5920.	862.	3.2
6.4 - 12.7	19.4	17.5	31.0	16.3	1968	13.6	4228.	5971.	888.	3.5
12.8-25.4	19.7	18.2	30.6	16.85	1850.	14.3	4353.	6054.	856.	3.6
>25.4	18.8	17.7	30.5	16.0	1942.	13.3	4322.	6140.	853.	3.8
>0.0	18.7	16.9	30.5	15.5	1999.	12.7	4192.	5936.	876.	3.3

Precip	LI (C)	KI (C)	MKI (C)	MSH (C)	SWT (C)	PTOP (mb)	CAPE (J/Kg)	BRI	ICA	PB (C)
0.0	4.7	14.3	20.3	13.3	104.	425.	286.	68.	2.2	2.0
0.1 -2.5	3.0	23.1	28.8	11.2	141.	440.	288.	45.	0.8	2.3
2.6 - 6.4	1.9	25.0	30.6	10.8	157.	410.	323.	39.	0.5	2.9
6.4 - 12.7	1.2	28.5	33.5	9.8	176.	358.	404.	56.	0.6	3.4
12.8 - 25.4	1.3	28.2	33.8	10.0	170.	406.	344.	30.	-0.6	3.1
>25.4	3.2	29.3	33.9	9.4	172.	450.	207.	8.	-1.7	2.0
>0.0	2.2	25.7	31.2	10.5	158.	414.	321.	41.	0.3	2.8

Similar results can be found through an examination of the remaining parameters or through a select subset of the parameters displayed graphically in Figures 4-12 through 4-21. For example, surface temperatures (Figure 4-12) averaged about 17.0° C on days without rain (symbol "8") but were nearly 2ºC warmer on days with rain (symbol "0"). A perusal of each figure and table shows that similar relationships exists with each parameter. All of these results were anticipated and have been quantified here.

Of significance is the comparison of stratifications of summers among the wet, normal and dry classes. Some noticeable differences in individual thermodynamic conditions appear to depend on the raininess of summers. Values are sufficiently high on all rain days to aid in the production of precipitation. However, for days with the heaviest rainfall production (points 4 and 5 in the figures), the precipitation potential during dry summers tends to exceed that measured in summers that are wet. For example, convective temperatures for dry summers shown in Figure 4-13 are lower when compared to values for wet summers, the surface layer average dew point temperature (Figure 4-14) is larger, and the TCCL (Figure 4-15) is higher, all indications of greater convective rainfall potential. In addition, the lifted index (Figure 4-16), modified K-index (Figure 4-17), and CAPE (Figure 4-18) show larger instabilities. Even the index of coalescence activity (Figure 4-20; Mather; 1986, Czys and Scott; 1993), provides for the highest potential of large drop sizes during dry summers. (Given the observed thermodynamic structure, negative values of this parameter are necessary theoretically for a dynamic seeding process to be effective.) The trends with surface temperature (Figure 4-12) and potential buoyancy (Figure 4-21) are weaker. Only, the amounts of available water mass (precipitable water, Figure 4-19) indicate essentially no change between wet and dry summer on days with heavy rainfall.

Statistical testing shows these differences to be significant for several of the parameters. Thermodynamic conditions during dry summers (Table 4-10) shown with light shading are significantly different at the 10% level of probability compared with the same conditions in wet summers (Table 4-12) as indicated by the /-test, Wilcoxon test, or both. Those shown with medium shading are significant to the 5% level, while those with the heaviest shading show statistical difference in values between dry and wet years at the 1 percent level. Once again, days with heavy precipitation are those which Changnon and Shealy (1993) state may best justify weather modification efforts from an economical viewpoint. Thus, a determination of the reasons for higher thermodynamic potential on heavy rain days during dry summers deserves consideration.

One speculation is that the above conditions may be generated by differences between synoptic types. These are displayed for each type in Tables 4-13 to 4-17. (Occluded fronts were excluded since their numbers were too small to be useful.) An examination of nearly all parameters indicates that, in general, conditions present on days with frontal activity are more positive towards convection than are the conditions observed with the presence of low pressure systems or air mass convection, especially with lighter daily rainfall amounts. As precipitation totals increase, however, differences between synoptic types tend to decrease. Nevertheless, cold and static fronts continue to show the most positive values compared to other synoptic types on days with heaviest rain. For example, the TCCL ranges from about 15°C on days with moderate precipitation (12.8 - 2S.4 m) due to cold and static fronts to just over 12° C on air mass days. Likewise, the average surface layer dew point temperature ranges from 17.3°C to 15.0°.

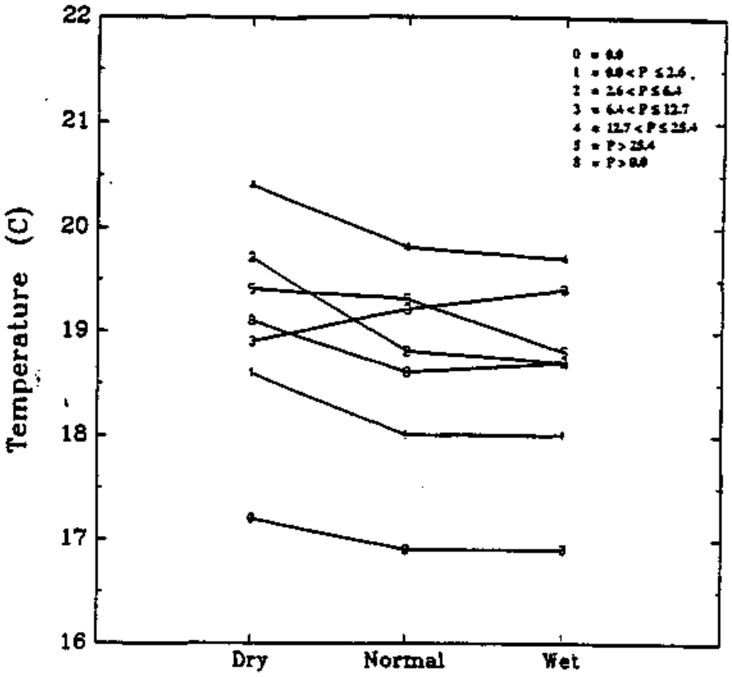


FIGURE 4-12. Average surface temperature (°C) at Peoria, Illinois during June, July, and August, 1957-1993 as measured by the 1200 UTC rawinsonde sounding. Data are stratified into terciles of inter-seasonal precipitation and within rainfall categories defined by the average precipitation (P; in mm) at Decatur, Springfield, and Peoria.

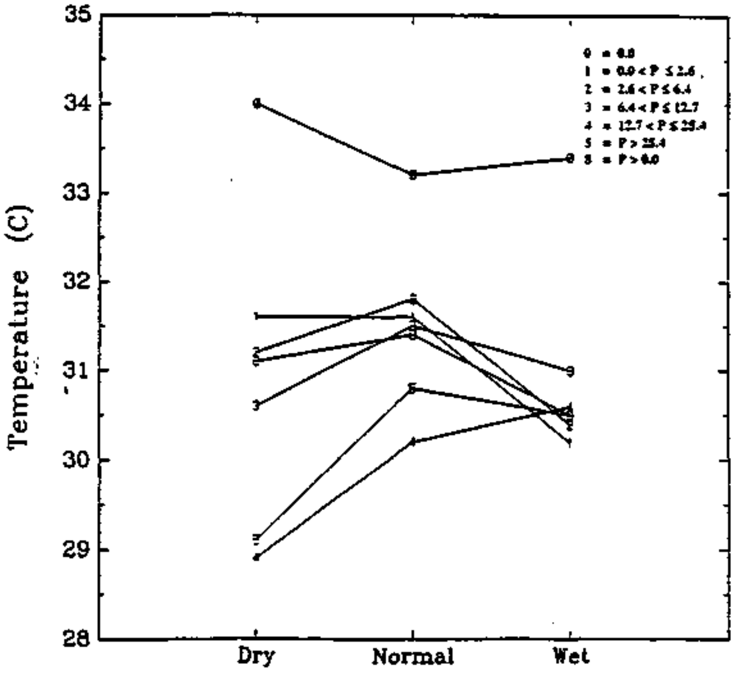


FIGURE 4-13. Same as Figure 4-12 except for convective temperature (°C).

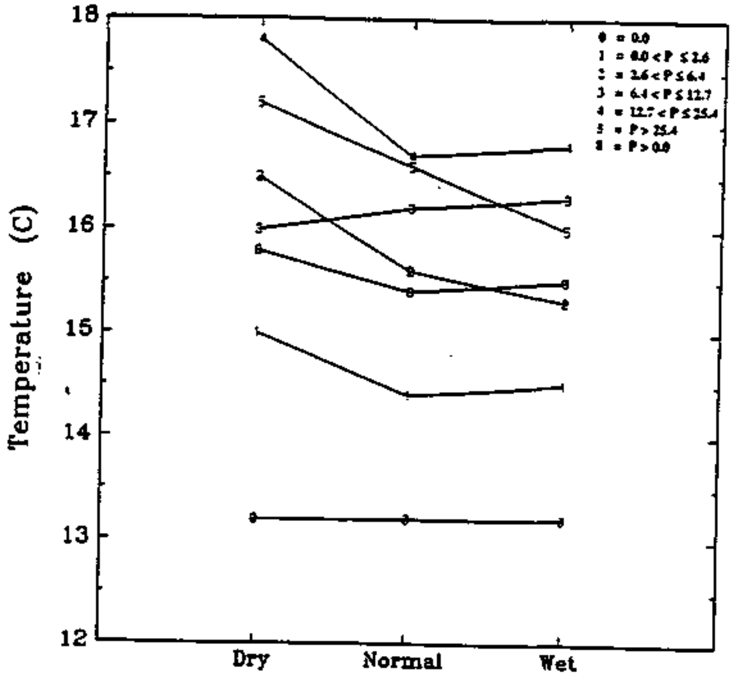


FIGURE 4-14. Same as Figure 4-12, except for average dew point temperature (°C) in the SO mb layer nearest the surface of the earth.

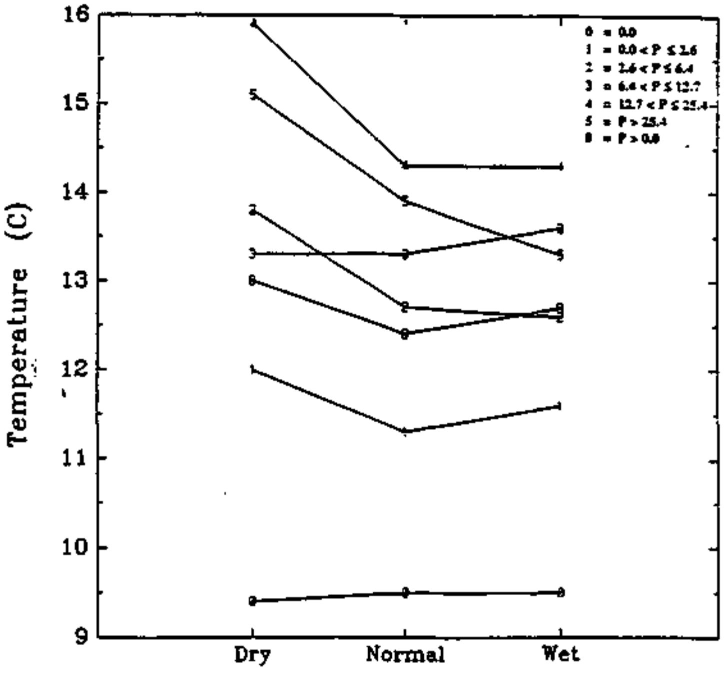


FIGURE 4-15. Same as Figure 4-12, except for temperature (°C) of the convective condensation layer.

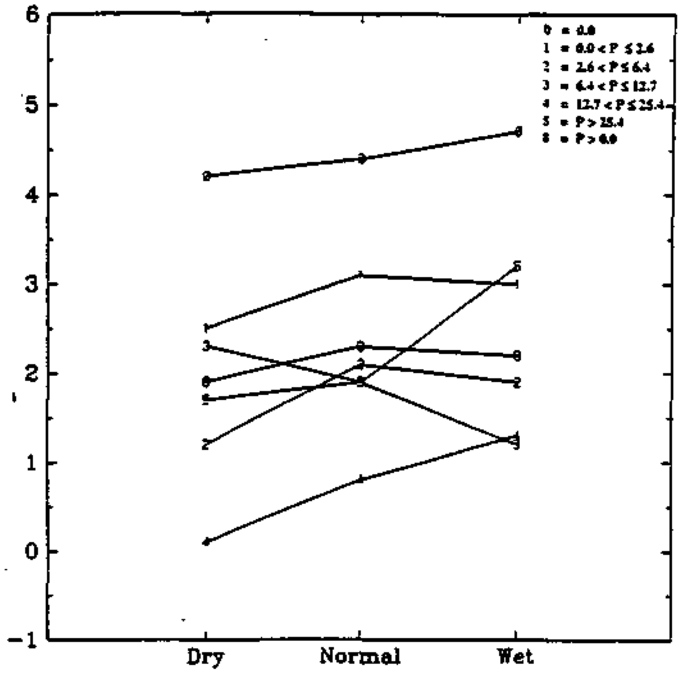


FIGURE 4-16. Same as Figure 4-12, except for lifted index (°C).

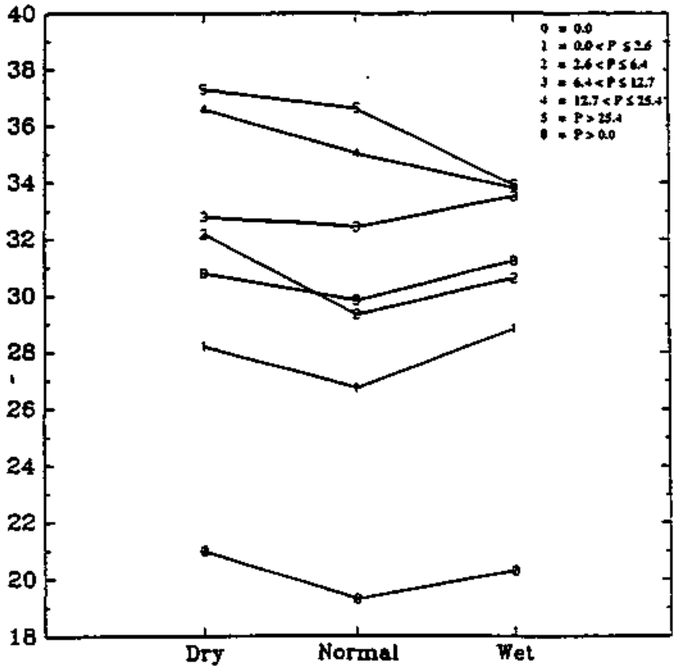


FIGURE 4-17. Same as Figure 4-12, except for modified K-index (°C).

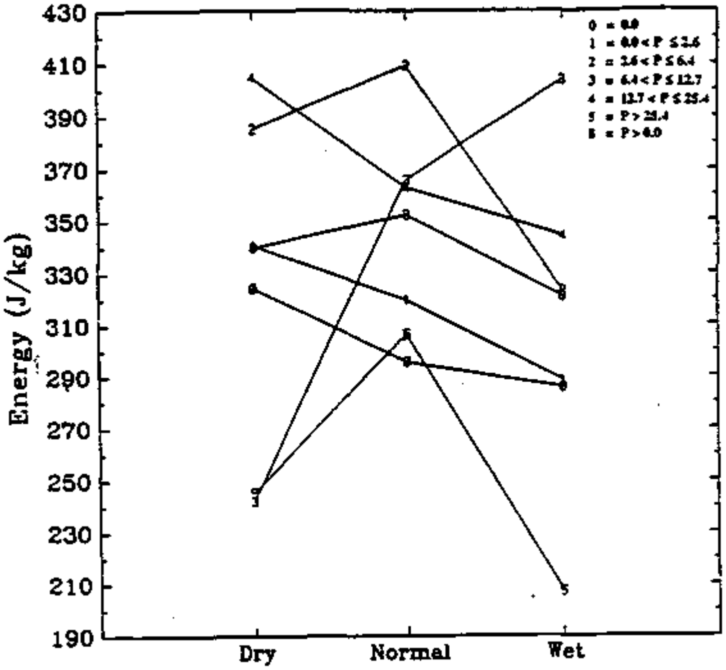


FIGURE 4-18. Same as Figure 4-12, except for convective available potential energy (J kg^{-1}).

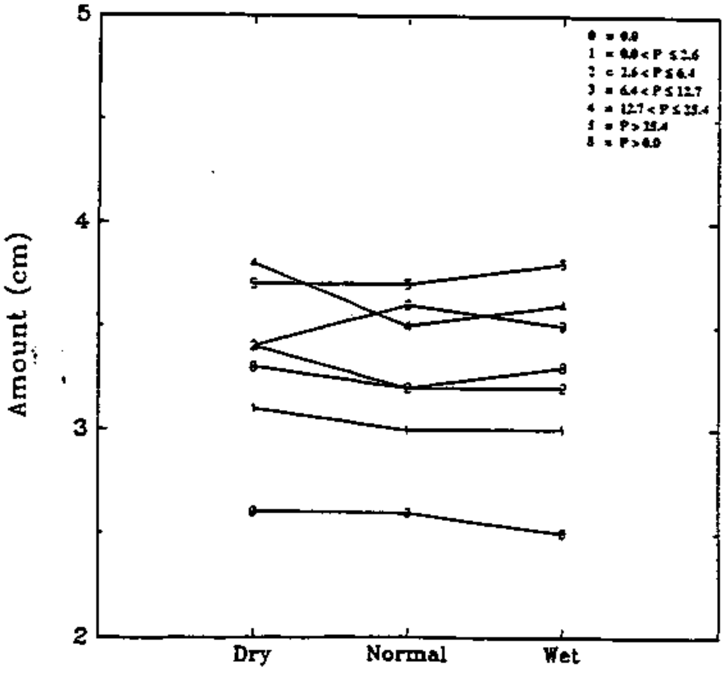


FIGURE 4-19. Same as Figure 4-12, except for precipitable water (cm).

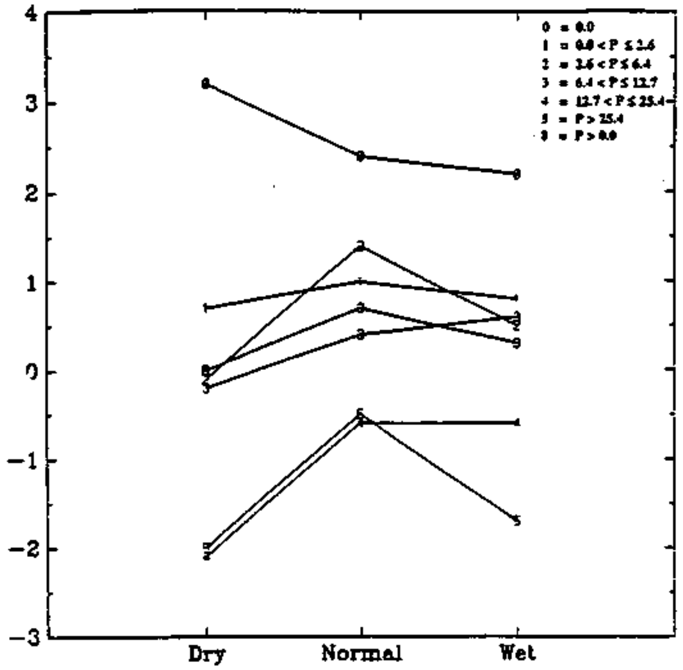


FIGURE 4-20. Same as Figure 4-12, except for index of coalescence activity.

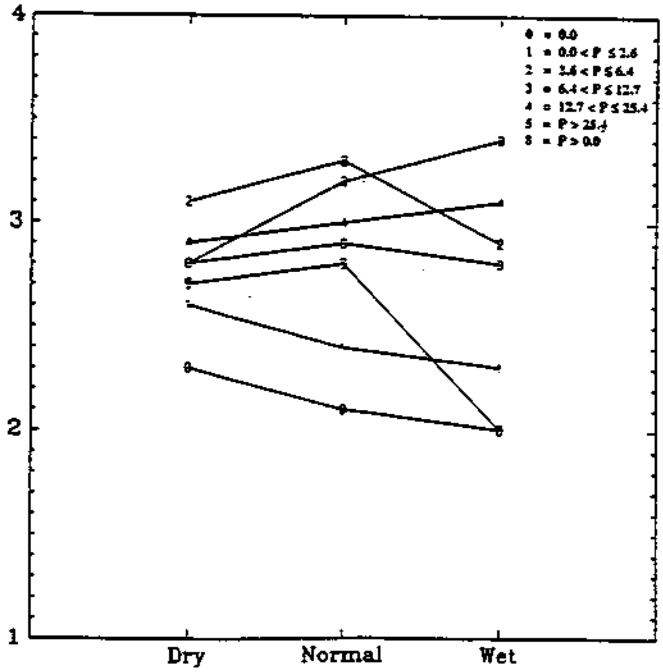


FIGURE 4-21. Same as Figure 4-12, except for potential energy (°C).

Table 4-13. Average thermodynamic conditions from the 1200 UTC sounding at Peoria, Illinois during all summers (1957 - 1993) related to categorical average precipitation at Decatur, Springfield and Peoria, Illinois on days with cold fronts. The number of days for each precipitation category (N) has been added from Table 4-8.

	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip (mm)		(9	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.1 -2.5	216	19.1	17.0	31.8	15.7	2124.	12.8	4201.	5935.	866.	3.1
2.6-6.4	145	19.9	18.0	30.8	16.8	1883.	14.3	4303.	6007.	839.	3.4
6.4 - 12.7	108	19.9	18.0	31.1	16.7	1927.	14.1	4288.	6025.	882.	3.5
12.8 - 25.4	91	20.0	18.5	29.5	17.3	1658.	15.2	4288.	6023.	900.	3.6
>25.4	27	19.3	18.0	30.3	16.7	1818.	14.3	4286.	6075	893.	3.9

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip (mm)	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.1 -2.5	1.6	23.7	29.3	10.8	152.	380.	397.	143.	1.4	3.2
2.6-6.4	0.5	26.1	31.8	10.3	174.	362.	419.	117.	0.1	3.3
6.4 - 12.7	0.9	28.1	33.4	9.6	172.	382.	376.	61.	0.1	3.2
12.8 - 25.4	0.5	28.8	34.5	9.9	176.	425.	350.	30.	-1.6	2.9
>25.4	1.7	31.1	35.5	9.3	219.	401.	303.	11.	-1.2	2.6

Table 4-14. Same as Table 4-13, except on days with static fronts.

	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip (mm)		(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.1 -2.5	98	18.9	17.0	31.8	15.7	2130.	12.8	4280.	6001.	866.	3.1
2.6 - 6.4	72	19.7	17.9	31.5	16.9	1952.	14.2	4286.	6078.	898.	3.6
6.4 - 12.7	61	20.1	18.0	31.0	17.2	1857.	14.7	4320.	6091.	869.	3.9
12.8 - 25.4	47	20.5	18.6	31.2	17.3	1861.	14.8	4363.	6105.	853.	3.9
>25.4	28	19.6	18.5	30.4	16.8	1842.	14.3	4339.	6172.	897.	3.9

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip (mm)	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.1 -2.5	2.0	23.7	29.1	10.8	147.	391.	368.	420.	0.5	2.7
2.6 - 6.4	1.1	28.2	33.2	9.8	173.	334.	449.	47.	0.1	3.3
6.4 - 12.7	0.7	32.0	36.8	9.4	185.	350.	407.	46.	-0.5	3.3
12.8 - 25.4	0.7	31.3	36.4	9.1	193.	355.	411.	34.	-0.7	3.2
>25.4	2.0	30.3	35.6	8.9	173.	394.	258.	23.	-2.5	1.8

Table 4-15. Same as Table 4-13, except on days with warm fronts.

	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT(m)		DH38	PW
Precip(mm)		(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10ºC	(m)	(cm)
0.1 -2.5	57	18.3	15.8	33.8	14.7	2478.	11.2	4287.	5978.	869.	3.1
2.6-6.4	31	18.6	16.7	31.8	15.5	2142.	12.5	4210.	5945.	857.	3.4
6.4 - 12.7	35	19.5	17.9	31.9	17.0	1997.	14.2	4382.	6114.	841.	3.8
12.8-25.4	15	19.4	17.4	31.8	16.4	2030.	13.6	4343.	6140.	867.	3.6
>25.4	3	18.1	15.8	31.0	15.1	2120.	12.1	4366.	6352.	1138.	4.0

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip(mm)	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.1 -2.5	3.0	23.3	28.6	10.4	141.	360.	375.	78.	2.9	3.2
2.6-6.4	2.3	27.1	31.3	10.0	164.	352.	321.	22.	1.5	3.2
6.4 - 12.7	1.2	30.3	34.6	8.9	194.	322.	445.	54.	0.4	3.5
12.8 - 25.4	2.0	26.9	33.1	8.9	145.	358.	357.	21.	-0.1	2.9
>25.4	6.0	32.7	35.7	11.7	213.	522.	67.	1.	-4.0	-0.3

Table 4-16. Same as Table 4-13, except on days with low pressure centers located nearby.

	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip (mm)		(C)	(C)	(C)	(C)	(m)	(C)	0ºC	-10ºC	(m)	(cm)
0.1 -2.5	44	17.1	15.3	27.3	14.0	1788.	11.7	3887.	5669.	853.	2.9
2.6 - 6.4	22	17.5	14.7	29.7	13.5	2130.	10.5	3925.	5776.	908.	3.0
6.4 - 12.7	24	17.5	16.0	28.8	15.4	1816.	12.9	4071.	5759.	804.	3.3
12.8 - 25.4	12	18.7	17.3	29.4	16.4	1706.	14.2	4224.	5957.	845.	3.5
>25.4	11	17.3	16.2	30.9	14.9	2125.	11.8	4224.	6059.	851.	4.0

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip (mm)	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.1 -2.5	3.7	21.7	27.2	12.2	168.	531.	188.	38.	-1.7	0.8
2.6 - 6.4	4.1	23.2	28.5	11.1	129.	469.	186.	19.	0.0	1.1
6.4 - 12.7	2.0	26.7	31.3	10.3	160.	407.	249.	13.	-0.5	2.2
12.8 - 25.4	1.4	29.5	34.1	9.7	173.	418.	287.	29.	-1.6	2.3
>25.4	5.3	33.5	36.4	8.3	182.	479.	144.	4.	-0.9	1.3

Table 4-17. Same as Table 4-13, except on days with air mass convection.

	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	HGT (m)		DH38	PW
Precip (mm)		(C)	(C)	(C)	(C)	(m)	(C)	0°C	-10°C	(m)	(cm)
0.1 -2.5	215	17.0	14.4	30.3	13.1	2257.	10.0	39%.	5765.	899.	2.8
2.6-6.4	79	17.4	15.1	31.5	13.6	2328.	10.4	4048.	5799.	870.	2.8
6.4 - 12.7	42	16.9	14.8	31.9	13.1	2435.	9.6	4132.	5844.	928.	2.9
12.8-25.4	19	19.1	16.3	30.3	15.0	2021.	12.3	4077.	5893.	923.	3.4
>25.4	4	19.6	12.7	30.2	16.5	1852.	14.0	4208.	6181.	948.	3.8

	LI	KI	MKI	MSH	SWT	PTOP	CAPE	BRI	ICA	PB
Precip (mm)	(C)	(C)	(C)	(C)	(C)	(mb)	(J/Kg)			(C)
0.1 -2.5	4.5	20.0	25.7	12.2	121.	465.	224.	159.	0.5	1.1
2.6-6.4	4.1	20.2	26.2	12.0	139.	412.	289.	43.	1.4	1.8
6.4 - 12.7	5.2	19.8	25.6	11.7	131.	460.	191.	106.	1.4	1.4
12.8 - 25.4	2.2	28.7	33.5	9.8	156.	369.	346.	52.	0.0	2.1
>25.4	1.8	28.0	30.2	9.0	170.	394.	222.	51.	-2.3	1.8

Thus, substantial differences exist in thermodynamic conditions on days with different synoptic types. However, a further stratification between just dry and wet summers is less significant. Table 4-18 shows average thermodynamic conditions stratified by synoptic type for dry and wet seasons on days with precipitation totals in excess of 12.7 mm. Days with rainfall totals in the heaviest precipitation category (>25.4 mm) were to few in many of these stratifications to allow for quality testing of the data. This is also the case for some of the rows in this table, but all were shown for completeness.

Table 4-18. Average thermodynamic conditions during dry and wet summers in central Illinois on days with rainfall totals in excess of 12.7 mm.

Synoptic Type	Rain	N	SFCT	SFCD	CNVT	DBAR	HCCL	TCCL	DH38	PW
			(C)	(C)	(C)	(C)	(m)	(C)	(m)	(cm)
Cold Front	Dry	24	20.2	18.8	29.1	18.1	1531.	16.1	949.	3.8
	Wet	62	19.7	18.4	29.8	16.8	1754.	14.5	873.	3.6
Static Front	Dry	12	20.6	18.9	29.5	17.7	1622.	15.6	895.	3.8
	Wet	34	19.8	18.2	31.5	16.4	2006.	13.7	811.	3.8
Warm Front	Dry	3	20.3	19.4	29.8	18.1	1617.	15.9	977.	4.3
	Wet	7	19.4	16.8	32.1	16.3	2061.	13.5	824.	3.8
Low Pressure	Dry	2	18.2	17.0	24.5	15.4	1280.	13.9	792.	3.8
	Wet	13	17.8	16.9	31.5	15.8	2078.	12.8	881.	3.9
Air Mass	Dry	3	19.8	17.8	27.9	15.9	1648.	13.8	1041.	3.9
	Wet	8	19.3	17.4	29.7	16.3	1799.	13.9	955.	3.4

Synoptic Type	Rain	N	LI	KI	MKI	MSH	SWT	CAPE	ICA	PB
			(C)	(C)	(C)	(C)	(C)	(J/Kg)		(C)
Cold Front	Dry	24	0.3	31.0	35.8	9.7	191.	382.	-2.5	2.9
	Wet	62	1.2	27.9	33.7	9.9	181.	310.	-1.5	2.5
Static Front	Dry	12	-0.2	32.6	37.9	8.2	191.	425.	-1.9	2.9
	Wet	34	2.2	28.9	33.9	9.8	179.	317.	-1.3	2.2
Warm Front	Dry	3	2.0	32.0	37.3	10.0	186.	175.	-4.1	1.9
	Wet	7	1.9	28.1	33.7	8.7	152.	351.	0.7	3.3
Low Pressure	Dry	2	3.0	34.5	38.5	8.5	180.	14.	-5.5	-0.1
	Wet	13	3.8	32.5	35.6	9.0	184.	242.	-0.1	2.4
Air Mass	Dry	3	1.7	31.7	38.3	8.7	149.	469.	-3.7	0.8
	Wet	8	2.2	26.1	31.1	11.0	151.	250.	-2.6	1.5

Results indicate that most parameters of each synoptic type show thermodynamic conditions that are more positive towards convective rainfall in dry summers compared to the values during wet summers. However, testing performed on the days with cold and static fronts, show that few of the differences have any statistical significance. Again, light shading indicates parameters with statistical differences in their values between dry and wet summers at the 10% level as observed by the /-test, the Wilcoxon test, or both. Heavier shading shows significance at the 5% level. It is very likely that the small sample sizes in the groups was important here.

Nevertheless, the trend for higher values during dry summers exists. It may be that dry summers are so dominated by suppressing action of anticyclones that only the strongest of frontal activity can be influential on rainfall production while during summers with normal or wet precipitation, weak and marginally dynamic weather systems can generate rainfall. Thus, minimal thermodynamic conditions would be included during wet season averages, and thereby lower overall values in the parameters.

Summary

A climatological investigation of summertime meteorological conditions during dry summers was conducted to define what was different from conditions in near-normal or wet summers. Thermodynamic conditions observed over central Illinois were also quantified to determine differences, if any, that may help delineate differences among dry, normal, and wet summers. The results indicate that dry summers can be characterized in five ways.

1) Dry summers have 29% fewer days with measurable precipitation than wet summers,

2) Days with heavy precipitation are 62% fewer in dry summers than wet summers.

3) The relative frequency of days with precipitation due to cold fronts and air mass convection is greater in dry summers due to a concomitant reduction in the relative frequency of warm fronts and low pressure systems.

4) On days with moderate to heavy precipitation, many thermodynamic conditions of the upper air in central Illinois are more positive towards rain production in dry summers than is observed in wet summers.

5) Dry summers are more likely the result of fewer rainfall events than by an inadequacy of the atmosphere for rain production (on rain days).

In other words, results indicate that thermodynamic conditions in the atmosphere on naturally rainy days during summer in Illinois are substantially the same regardless of the macroscale synoptic conditions associated with seasons ranked as dry, normal, or wet. Clouds during dry summers have virtually the same potential of being modified successfully as those that occur during wet summers. Thus, during years when rain events are scarce and water resources are low, the opportunity for modification is present, albeit less frequent, providing a potential for substantial impacts to the region.

RAINSTORM PROPERTIES DURING DRY AND NORMAL PRECIPITATION PERIODS IN ILLINOIS

Nancy E. Westcott

This section examines possible differences in summertime storm characteristics during three summer seasons to evaluate the potential for cloud seeding opportunities under dry and near normal rainfall conditions. Radar echo characteristics of rain events occurring in east central Illinois during the drought summer of 1988, the normal-rain summer 1989, and a S week dry period in 1986 are evaluated.

Data and Analysis Procedures

Radar data were collected in east central Illinois during the summers of 1986, and 1988 and 1989 using the CHILL 10-cm radar in support of two projects: the Cloud Chemistry Cloud Physics Organization (3CPO), and the Precipitation Augmentation for Crops Experiment (PACE). Operations for both experiments generally were undertaken during daylight hours on days when rainfall was forecasted. Thus, the radar was operated when most cloud seeding opportunities would be expected. Radar data were recorded on 8 days from late July to late August in 1986, on 7 days during June and July 1988, and on 16 days from mid-May through July 1989.

The Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN) software package was employed to develop a climatology of summertime radar echo properties. The TITAN software identified storms in three-dimensions according to a prescribed minimum reflectivity threshold (35 dBZ used for this study) and volume threshold (30 km^3). The software then tracked the echoes in time and space (Dixon and Wiener, 1993). For echoes to be included in the sample, they had to be present for more than two consecutive volume scans. The echoes were identified as being either "simple" tracked or "complex" tracked entities. The simple-tracked echoes were ones which did not merge nor split during their lifetime whereas the complex-tracked echoes were ones which did merge or split. Only echoes within 120 km of the CHILL radar site were examined (Figure 4-22).

The height at which merging was identified was at the 4 km level for the days that were primarily convective in nature. The echo tops were typically lower on days with widespread stratiform rain. Thus, the merging level on days with widespread stratiform rain was identified at the 3 km level to avoid spurious counts of echoes due to the radar often topping the echoes in a ring pattern.

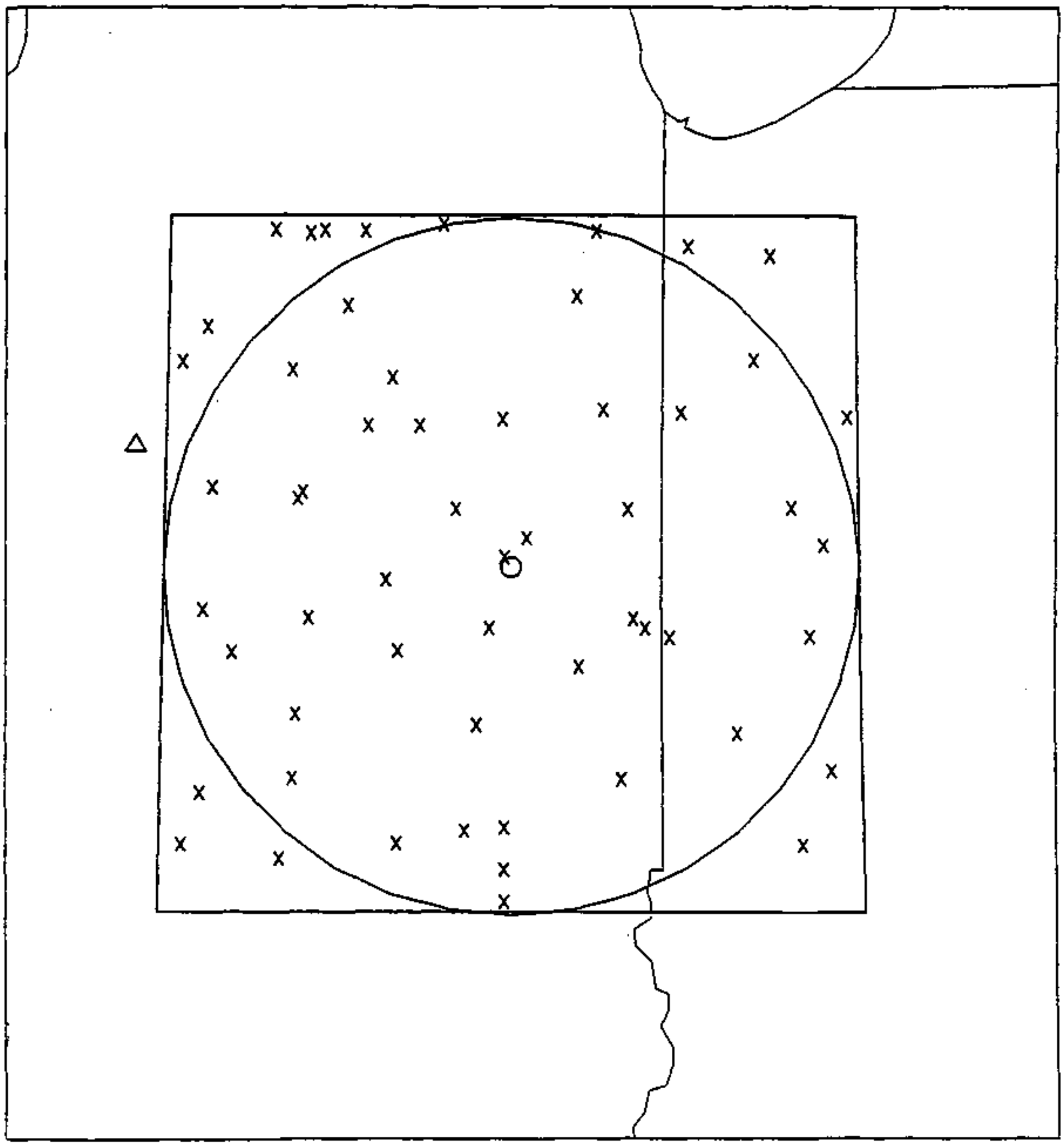


FIGURE 4-22. The Illinois-Indiana echo study area. The CHILL radar is the dot, and the 120-km raingage is shown. Raingage data stations are X, and the Peoria rawinsonde site is a triangle.

General Atmospheric Conditions

In the dry summer of 1988, only one of the seven days produced more than 0.63 cm (0.25 inch) of rain in the area covered by the radar, according to NWS cooperative observer daily raingage data (Figure 4-22). However, nearly half of the days in the wetter 1989 had an areawide average of at least 0.63 cm (Table 4-19a, b). Two of the 1989 days were characterized by widespread stratiform or embedded convective rain. On days with radar operations in 1986, only two days had rain greater than 0.63 cm. A larger percent of the days in 1986 had rain greater than .25 cm (0.1 inch) than in 1988.

Some of the indices computed from 1200 UTC soundings from Peoria, Ill. (PIA; see Figure 4-22) indicate that for the days studied, thermodynamic conditions were the most conducive to convection in the normal rain summer of 1989. For example, the dew point temperature (SdewT) in the lowest 50 mb was highest in 1989, indicating greater surface moisture availability, and potential buoyancy (PB; difference between the pseudoadiabat through cloud base and the environmental temperature at 500 mb) also were higher for the study days in 1989 (Table 4-19a). This suggests warmer cloud bases and potentially stronger vertical velocities. The temperature of the convective condensation level (TCCL), which can be equated with cloud base temperature, was warmer. The convective available potential energy (CAPE), which is related to cloud vertical velocity and depth), was also greater in 1989, particularly considering the median values. Little difference was found between 1989 and 1988, however, in terms of precipitable water (PW), and the modified K index (MKI is a measure of instability between the surface and 500 mb). CAPE and PB were slightly higher in 1988 than in 1986, but the other thermodynamic indices were slightly better for 1986 than for 1988.

Table 4-19a Summary of thermodynamic conditions at Peoria, Ill. (PIA) for project rain days without a predominance of stratiform rain or embedded convection for 1986, 1988 and 1989.]Daily median values are included for each year under "All".

Date	Average Areawide Rain (cm)	Synoptic Type	MKI (°C)	Sfc Layer Dew Point Temp (°C)	TCCL (°C)	CAPE (J Kg^{-1})	PW (cm)	Potential Buoyancy (C)
07-25-1986	0.36	Cold Frt	41	18.7	15.1	6%	5.1	5.4
07-31-1986	0.61	Cold Frt	40	17.4	14.1	346	5.0	4.0
08-06-1986	0.74	Low Pres	43	17.6	17.2	0	4.2	2.0
08-17-1986	0.03	Cold Frt	06	19.3	17.7	78	2.5	1.8
08-23-1986	0.00	Cold Frt	41	17.2	15.1	159	4.6	1.2
08-25-1986	0.33	Warm Frt	32	10.8	5.9	0	3.6	0.2
08-26-1986	0.66	Cold Frt	42	20.4	19.0	0	4.9	3.1
All 1986	0.36		41	17.6	15.1	78	4.6	2.0
06-02-1988	0.08	Cold Frt	37	12.7	9.5	234	2.7	1.8
06-15-1988	0.05	Cold Frt	37	15.4	12.6	321	3.1	2.5
07-10-1988	0.46	Cold Frt	32	17.7	15.6	431	3.8	3.3
07-12-1988	0.03	Static Frt	25	12.1	8.3	70	2.8	0.5
07-14-1988	0.23	Static Frt	47	23.1	20.6	1843	5.4	8.7
07-18-1988	0.99	Cold Frt	41	19.6	18.2	151	4.9	1.0
All 1988	0.16		37	16.6	14.1	278	3.5	2.2
05-24-1989	0.89	Warm Frt	38	16.3	13.8	936	3.2	5.6
05-30-1989	0.13	Cold Frt	41	17.5	15.6	223	4.2	1.8
06-01-1989	0.84	Cold Frt	43	19.8	18.5	831	4.4	6.8
06-03-1989	0.61	Cold Frt	M	M	M	M	M	M
06-12-1989	0.41	Cold Frt	40	16.6	16.1	0	3.8	-0.3
06-19-1989	0.25	Air Mass	23	15.6	13.7	0	3.1	-0.8
06-23-1989	0.38	Static Frt	31	19.0	16.7	838	3.2	5.6
07-02-1989	0.64	Low Pres	17	16.5	14.6	2	2.9	2.2
07-08-1989	0.10	Warm Frt	32	17.2	13.1	941	3.8	7.8
07-11-1989	1.04	Static Frt	37	21.4	19.1	1091	4.1	8.4
07-19-1989	2.18	Low Pres	41	17.3	16.6	197	3.8	2.8
07-23-1989	0.23	Air Mass	35	18.7	17.0	572	3.2	4.1
07-24-1989	0.20	Air Mass	37	20.3	19.1	561	4.2	4.1
07-25-1989	0.28	Air Mass	42	20.2	18.6	533	4.8	4.2
All 1989	0.40		37	17.5	16.6	561	3.8	4.1

Table 4-19b. Summary of thermodynamic conditions at PIA for project rain days with either stratiform rain or embedded convection for 1986,1988 and 1989.

Date	Average Areawide Rain (cm)	Synoptic Type	MKI (°C)	Sfc. Layer Dew Point Temp (°C)	TCCL (°C)	CAPE (J Kg')	PW (cm)	Potential Buoyancy (°C)
08-15-1986	0.13	Air Mass	37	17.7	15.5	468	4.2	4.5
06-08-1988	0.46	Cold Frt	16	14.0	10.1	440	2.4	3.8
05 19-1989	2.29	Low Pres	40	14.9	13.8	70	3.3	0.9
05 25 1989	2.29	Cold Frt	16	13.6	9.1	737	2.4	7.5

Earlier in this chapter, it was shown that during dry periods, the potential for convection was stronger particularly for heavy rain days (> 1.27 cm). In this study, there were few heavy rain days and all occurred only in the normal rain summer of 1989.

The thermodynamic values were quite variable on heavy rain days. The variability was especially large for the embedded convection and stratiform rain cases on both heavy rain and light rain days. For the embedded convection case in 1988, thermodynamic indices were similar or weaker than for the other 1988 cases. For the one embedded convection case in 1986, thermodynamic indices were similar or more conducive to rain than for the other 1986 cases. In 1989, one case had a large value of CAPE and another had a relatively small CAPE, but both produced the largest amounts of rain according to the daily rainfall data.

Echo Frequency

During the dry summer of 1988, there were about half as many days on which data for non-embedded convection were recorded than in 1989 (Table 4-20a). On many days in 1988, the rain periods were of shorter duration than those of 1986 and 1989. The median rain period duration was 2.5 hr in 1988, 3.5 hr in 1986, and 4.25 hr in 1989. There were 287 tracked echoes in 1988, 559 in 1986, and 975 in 1989. The large number of tracked echoes falling on 7 days in 1986 as compared to the number falling on 6 days in 1988, was largely because nearly half of the echoes in 1986 occurred on one day, August 26.

For all summers, when convection was present, similar numbers of echoes were observed during any given hour, 15/hour in 1986; 18/hour in 1988 and 16/hour in 1989. Similar numbers of larger complex tracked cores were also found for the three summers, 5, 6, and 5 per hour respectively in 1986, 1988 and 1989.

A similar proportion of simple-tracked to complex-tracked echoes also was found for all summers. There were about twice as many 35 dBZ echoes that never merged or split as ones that did merge and/or split (ratios of simple / complex = 1.7 in 1986, 2.1 in 1988, and 2.0 in 1989).

The time at which storms began differed during the three summer periods (Table 4-21). During 1989, the majority of the storms (10/14) began during the early afternoon hours (11:30- 14:30 CDT). During the drought of 1988, most (5/6) storms began close to or after 15:00 CDT. During the dry period of 1986, most storms (4/7) began or moved into the area in the early morning (07:00 - 09:30 CDT), or between 14:30 and 18:00 CDT. These times suggest that in 1986, external forcing and not solar heating played a large role in precipitation development. In 1988, a longer period of afternoon heating was required than in 1989 to initiate storms of 35 dBZ or greater.

Table 4-20a. Summary of rain periods with recorded radar reflectivity data from 1986, 1988 and 1989 on days; without a predominance of stratiform rain or embedded convection(omitting tracks with a maximum top height of < 4 km). Daily totals and daily mean values are included for each year under "All".

Date	Hours with Recorded Storms	Tracked Echoes	Number/ Hour	Simple-Tracked Echoes	Number/ Hour	Complex-Tracked Echoes	Number/ Hour
07-25-1986	3.5	40	11	22	6	18	5
07-31-1986	5.5	86	16	39	7	47	9
08-06-1986	10.0	154	15	102	10	52	5
08-17-1986	3.5	10	3	6	2	4	1
08-23-1986	2.5	8	3	7	3	1	0
08-25-1986	1.5	7	5	3	2	4	6
08-26-1986	11.5	254	22	173	15	81	7
All 1986	38.0	559	15	352	9	207	5
06-02-1988	2.5	41	16	30	12	11	4
06-15-1988	1.5	4	3	3	2	1	1
07-10-1988	1.5	52	35	39	24	13	9
07-12-1988	2.5	23	9	16	6	7	3
07-14-1988	4.5	85	19	56	12	29	6
07-18-1988	3.5	84	24	51	15	33	9
All 1988	16.0	289	18	195	12	94	6
05-24-1989	1.0	5	5	2	2	3	3
05-30-1989	5.5	20	4	15	3	5	1
06-01-1989	5.0	90	18	59	12	49	10
06-03-1989	4.0	97	24	64	16	33	8
06-12-1989	3.0	26	9	19	6	7	2
06-19-1989	4.0	45	11	35	9	10	3
06-23-1989	7.0	132	19	87	27	45	6
07-02-1989	2.5	76	30	50	20	26	10
07-08-1989	5.5	52	9	27	5	25	5
07-11-1989	5.0	84	17	61	12	23	5
07-19-1989	4.0	144	36	97	24	47	12
07-23-1989	5.0	71	14	48	10	23	5
07-24-1989	4.5	58	13	39	9	19	4
07-25-1989	4.0	57	14	45	11	12	3
All 1989	60.0	975	16	648	11	327	5

Table 4-20b. Summary of rain periods with recorded radar reflectivity data on days from 1986, 1988 and 1989 with a predominance of stratiform rain or embedded convection.

Date	Hours with Recorded Storms	Tracked Echoes	Number/ Hour	Simple-Tracked Echoes	Number/ Hour	Complex-Tracked Echoes	Number/ Hour
08-15-1986	5.5	31	6	19	4	12	2
06-08-1988	9.5	154	16	106	11	48	5
05 19-1989	7.0	210	30	137	20	73	10
05 25 1989	6.5	151	23	94	14	57	8

It is also interesting to note that in the dry 1988 season, a larger proportion of the observed echoes fell in the first hour of precipitation (Table 4-21), whereas in 1986 the heavier echoes were distributed over at least the first 2 hours, and in 1989, the heavier echoes were distributed over a number of hours. In fact, during 1988, more echoes were found during the first hour of the storms than in either 1986 or 1989. This is particularly true for the 1988 afternoon storms. Thus, once the atmospheric conditions were favorable for convection in 1988, a large number of storms was observed. For cloud seeding purposes during dry conditions, this suggests that storms may develop either early in the morning or later in the afternoon (after 14:30 CDT), and that it is crucial to treat the afternoon storms, in particular, as quickly as possible.

Widespread stratiform rain periods in 1988 and 1989 were often longer in duration than convective rain periods, as might be expected. Many more echo cores were tracked during the stratiform/embedded convection events during those two summers. The stratiform case in 1986, weakened as it moved through the area and produced little rain. With so few stratiform/ embedded convective days in the sample of these three years, and since these rain situations generally are not conducive for cloud seeding operations, further discussion concerning these cases is limited.

Table 4-21a. Summary of rain periods with recorded radar reflectivity data from 1986, 1988 and 1989 on days without a predominance of stratiform rain or embedded convection(omitting tracks with a maximum top height of < 4 km). Median values are included for each year under "All.

Date	Storm Begin Time (CDT)	Hours with Recorded Storms	Echoes in Hour 1	Complex Echoes in Hour 1	Percent in Hour 1	Complex Percent in Hour 1	Complex Percent in 1st 2 Hours
07-25-1986	!5:52	3.5	15	5	38	28	61
07-31-1986	07:15	5.5	75	39	87	83	98
08-06-1986	09:08	10.0	11	7	7	13	25
08-17-1986	14:33	3.5	5	2	50	50	100
08-23-1986	08:31	2.5	5	1	63	100	100
08-25-1986	17:55	1.5	7	4	100	100	100
08-26-1986	07:46	11.5	23	13	9	16	30
All 1986		5.5	11	5	50	50	98
06-02-1988	16:10	2.5	32	11	78	100	100
06-15-1988	15:13	1.5	5	1	100	100	100
07-10-1988	14:57	1.5	48	11	92	85	100
07-12-1988	15:40	2.5	17	7	74	100	100
07-14-1988	10:13	4.5	26	11	31	38	41
07-18-1988	16:21	3.5	46	17	55	52	78
All 1988		2.5	29	11	76	93	100
05-24-1989	17:22	1.0	5	3	100	100	100
05-30-1989	08:51	5.5	10	3	50	60	60
06-01-1989	12:38	5.0	34	18	38	37	43
06-03-1989	11:07	4.0	9	4	9	12	48
06-12-1989	14:04	3.0	14	4	54	57	71
06-19-1989	16:06	4.0	22	7	49	70	70
06-23-1989	11:50	7.0	9	4	7	9	22
07-02-1989	12:34	2.5	34	16	45	62	100
07-08-1989	14:16	5.5	24	10	46	40	52
07-11-1989	12:42	5.0	25	5	30	22	35
07-19-1989	11:52	4.0	42	20	29	43	60
07-23-1989	13:56	5.0	21	10	70	43	61
07-24-1989	13:15	4.5	22	10	38	53	68
07-25-1989	11:47	4.0	35	8	61	67	92
All 1989		4.3	22	8	46	48	60

Table 4-21b. Summary of rain periods with recorded radar reflectivity data on days from 1986, 1988 and 1989 with a predominance of stratiform rain or embedded convection.

Date	Storm Begin Time (CDT)	Hours with Recorded Storms	Echoes in Hour 1	Complex Echoes in Hour 1	Percent in Hour 1	Complex Percent in Hour 1	Complex Percent in 1st 2 Hours
08-15-1986	11:06	5.5	6	2	19	17	17
06-08-1988	09:32	9.5	3	2	2	4	6
05 19989	11:05	7.0	45	21	21	29	38
05 25 1989	11:04	6.5	20	11	13	19	30

Echo Properties

The median values of simple-tracked and complex-tracked echoes on days which were characterized by predominantly convective rainfall are presented in Table 4-22. The echo properties were examined for differences between years, their thermodynamic conditions, and the associated synoptic weather types.

a) Between year differences in echo properties

Median values of the echo properties from the three years are shown in Table 4-22a (simple track) and Table 4-22b (complex track). Comparison of the 1988 values for simple-tracked echoes shows that they were the largest of the three years. That is the dry summer simple-tracked echoes lasted longer (by 2 to 4 minutes), had higher near-top heights (0.3 to 0.7 km), larger areas (1.3 km^2), and greater radar estimated rain volumes (3.1 to 14.2 10^{-4} m^3). Comparison of the dry 1988 complex-tracked echoes showed that year's echoes values consistently ranked second behind those of 1989, but were greater than those of 1986.

The median values of the duration, dimension and rainfall properties of the echoes sampled in the drought year 1988 and the normal rain year 1989, however, were generally quite similar. P-values computed using the two-sided Wilcoxon Rank Sum non-parametric test indicated little difference between the medians at the 5 percent level, as shown in Tables 4-22a, b. During the dry 1986 season, the echoes were generally smaller and shorter-lived than during either 1988 or 1989. This may be due in part to time of day and to seasonal differences. The 1986 data were dominated by morning storms, and for the other two summer seasons by afternoon storms. Additionally, radar data were collected primarily in June and July for 1988 and 1989, and in late July and August in 1986. In the net, these results do not indicate that convective radar echoes in dry summers are much different than in summers with near average rainfall.

Table 4-22a. Simple Track Median Properties: Convective Days. RERvol refers the radar estimated rain volume.

Property	1986	1988	1989	1988-86 P-value	1988-89 P-value
Sample	352	195	648		
Duration (min)	13.9	17.9	16.1	0.000	0.083
Mean Top (km)	5.5	6.2	5.9	0.000	0.067
Max Top (km)	6.5	6.5	6.5	0.000	0.375
Mean Area (km^2)	17.7	19.0	17.7	0.036	0.192
RERvol (10^{-4} m^3)	12.4	26.6	23.5	0.000	0.123

Table 4-22b. Complex Track Median Properties: Convective Days

Property	1986	1988	1989	1988-86 P-value	1988-89 P-value
Sample	207	94	327		
Duration (min)	35.7	44.2	44.6	0.007	0.804
Mean Top (km)	6.3	6.5	6.8	0.034	0.525
Max Top (km)	7.5	7.5	9.5	0.195	0.086
Mean Area (km^2)	34.8	39.8	41.0	0.015	0.814
RERvol (10^{-4} m^3)	111.3	247.9	293.2	0.000	0.679

b) Daily differences related to thermodynamic conditions

For any given summer season, there was considerable variability in echo properties among the rain events (Table 4-23). For convective systems, the six days with the largest sample of tracked echoes (> 40) were in 1986 and 1989. The 12 days with less than 15 tracked echoes were distributed among the three years with proportionally more days from 1988. The days with the tallest echoes and ones with the largest radar-estimated rainfall were generally found in the normal rain summer of 1989. In terms of echo duration and area, little difference was observed in the distribution of daily values between years.

Plots were made comparing the 7:00 am PIA thermodynamic indices (Table 4-19a) with the daily median echo parameters (Table 4-23a), as well as with, raingage estimated areawide and storm rainfall. Only the plots for CAPE are included here (Figure 4-23a-g).

The largest values of CAPE and the tallest echoes were generally found in the normal rain summer of 1989. For all years combined, the median daily maximum echo top height (Max Top) was positively correlated with CAPE (+0.67) in particular (Figure 4-23d), and to a lesser extent with SdewT (+0.36), TCCL (+0.25), and PW (+0.35). Figures for these are not shown. Max Top, however, was not well correlated with areawide rainfall (+0.05), and only marginally correlated with storm rainfall (+0.23). Little or no relationship was found between echo duration, area and radar-

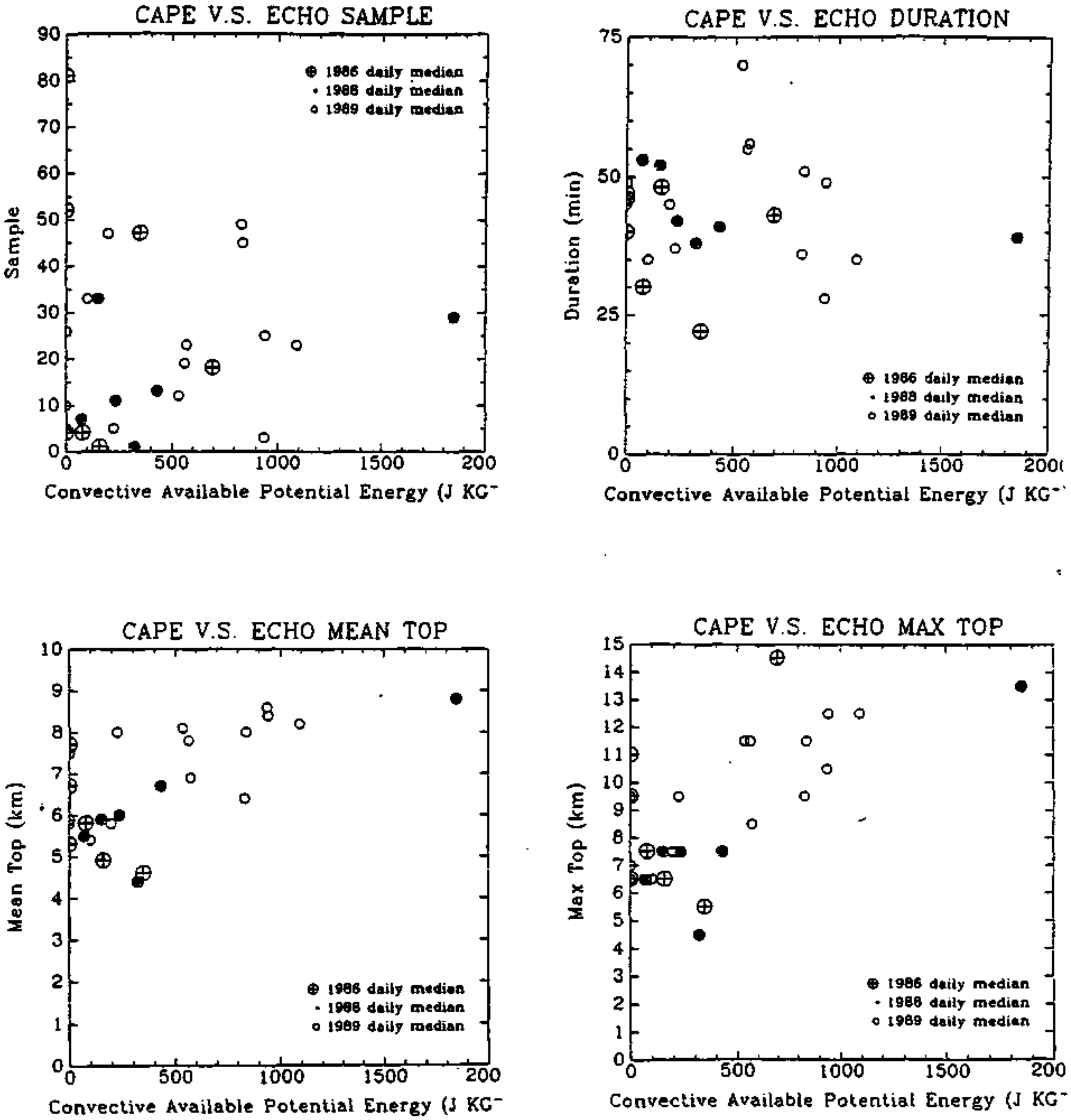


FIGURE 4-23. Relation of echo properties in 1986, 1988, and 1989, to various thermodynamic conditions.

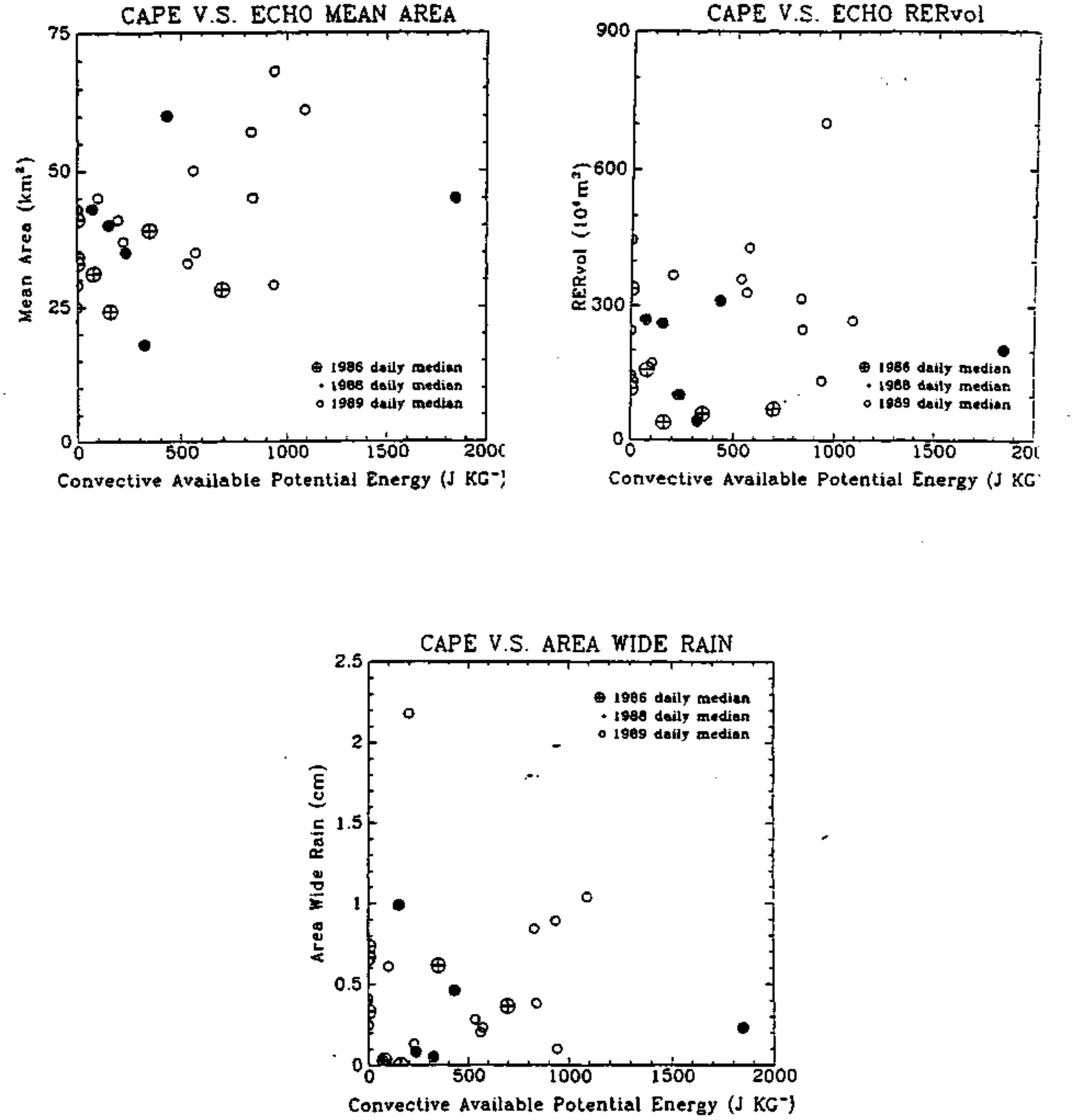


FIGURE 4-23. Relation of Echo Properties in 1986, 1988, and 1989 to Various Thermodynamic Conditions.

estimated-rainfall volume (RERvoI), and the thermodynamic indices.

little or no correlation was found between CAPE and areawide rainfall (+0.01; Figure 4-23g) and the correlation was small between CAPE and total storm rainfall (+0.16) for all years combined. When individual years were examined, likewise there was little correlation. This, in part, was due to one day in 1988, when a large CAPE was computed but little areawide rain was observed, and one day in 1989 with a small CAPE and a large areawide rain.

Table 4-23a Summary of daily median Complex-Tracked echo core characteristics from 1986,1988 and 1989 on days without a predominance of stratiform rain or embedded convection. Daily mean values are included for each year under "All". RERvol refers to the radar estimated rain volume.

Date	Sample	Duration (min)	Mean Top (km)	Max Top (km)	Mean Area (km^2)	RERvol (10^4 m^3)
07-25-1986	18	43.1	10.3	14.5	28.0	67.8
07-31-1986	47	22.0	4.6	5.5	37.8	57.6
08-06-1986	52	39.9	5.3	6.5	32.9	128.3
08-17-1986	4	30.1	5.8	7.5	31.2	155.0
08-23-1986	1	47.8	4.9	6.5	24.4	37.8
08-25-1986	4	46.8	7.7	11.0	41.3	336.3
08-26-1986	81	45.7	6.7	9.5	33.5	113.2
All 1986	207	39.3	6.5	8.7	32.7	128.0
06-02-1988	11	41.5	6.0	7.5	34.6	101.0
06-15-1988	1	38.4	4.4	4,5	17.6	42.6
07-10-1988	13	41.3	6.7	7.5	59.8	311.5
07-12-1988	7	52.7	5.5	6.5	43.0	268.3
07-14-1988	29	38.9	8.8	13.5	45.3	203.1
07-18-1988	33	52.2	5.9	7.5	40.0	259.6
All 1988	94	44.2	6.5	7.5	39.8	247.9
05-24-1989	3	27.6	8.6	10.5	28.9	133.1
05-30-1989	5	36.9	8.0	9.5	37.2	100.9
06-01-1989	49	35.9	6.4	9.5	56.7	315.7
06-03-1989	33	35.3	5.4	6.5	45.0	171.3
06-12-1989	5	46.3	5.8	6.5	25.4	244.4
06-19-1989	10	46.5	7.5	9.5	43.1	447.1
06-23-1989	45	50.5	8.0	11.5	45.1	247.1
07-02-1989	26	49.0	5.9	7.0	29.1	143.6
07-08-1989	25	48.7	8.4	12.5	68.0	702.6
07-11-1989	23	34.9	8.2	12.5	60.7	266.5
07-19-1989	47	44.7	5.8	7.5	40.7	368.0
07-23-1989	23	55.7	6.9	8.5	35.3	429.9
07-24-1989	19	54.7	7.8	11.5	50.1	329.8
07-25-1989	12	69.7	8.1	11.5	33.3	360.2
All 1989	327	44.6	6.8	9.6	41.0	293.2

Table 4-23b. Summary ofmedian Complex-Tracked echo core characteristics on days from 1986, 1988 and 1989 with a predominance of stratiform rain or embedded convection.

Date	Sample	Duration(min)	Mean Top (km)	Max Top (km)	Mean Area (km^2)	RERvol ($10^4 m^3$)
08-15-1986	12	37.0	5.4	6.5	52.0	379.4
06-08-1988	48	33.3	4.8	5.5	118.1	311.6
05 19-1989	125	41.1	4.8	5.5	44.5	120.5
05 25 1989	117	22.6	5.2	6.5	51.6	112.4

The thermodynamic parameters showed little correlation with areawide rain. While the presence of rainfall can be predicted using thermodynamic properties, these results, based on a limited number of cases, suggest that differentiating between heavy and light rainfall is not substantially enhanced by knowledge of thermodynamic indices. Thus, even if thermodynamic values were substantially different between normal and dry years, prediction of seasonal precipitation based on rainy day parameters would not be strongly related to those parameters.

c) Daily differences related to synoptic weather type

In the 37-year study of synoptic weather conditions, it was found that the relative frequency of cold fronts was larger, and the relative frequency of warm fronts and low pressure centers was smaller in dry periods (Tables 4-7 and 4-8). The frequency of storm types in the three seasons studied here generally agree. Approximately 50 % of the convective rain periods for the combined 3-years were on days influenced by cold fronts (Table 4-19a). The smallest percent of cold fronts was clearly observed in the normal rain year of 1989. In addition, warm fronts, low pressure centers, and static fronts were present in 1989. Low pressure centers, warms fronts, and cold fronts were present in 1986, and only cold fronts and static fronts were observed in 1988. As suggested in the prior study, this indicates that fewer cyclones passed through the region during dry periods, and that between cyclones there was less ambient moisture in the region, factors consistent with the presence of persistent high pressure subsidence during severe droughts. Radar data on days with isolated convection were recorded for airmass events only in the normal rain year of 1989.

The distributions of echo properties (Figure 4-24a-g) were similar for the three frontal types observed (cold, warm and static), although the static and warm fronts produced taller echoes. Low pressure centers generally produced the smallest echoes in terms of height and area, but had some of the greatest echo frequencies and areawide rainfall amounts. While airmass events produced the fewest number of trackable echoes, and produced the least amount of areawide rainfall, the echo properties of duration, height, area, and radar-estimated rain were similar to those from other weather types.

The echo property results stratified by synoptic type (Figure 4-24a-g) suggest that for days with rain, prediction of echo frequency and total area rainfall is aided most by knowing whether or

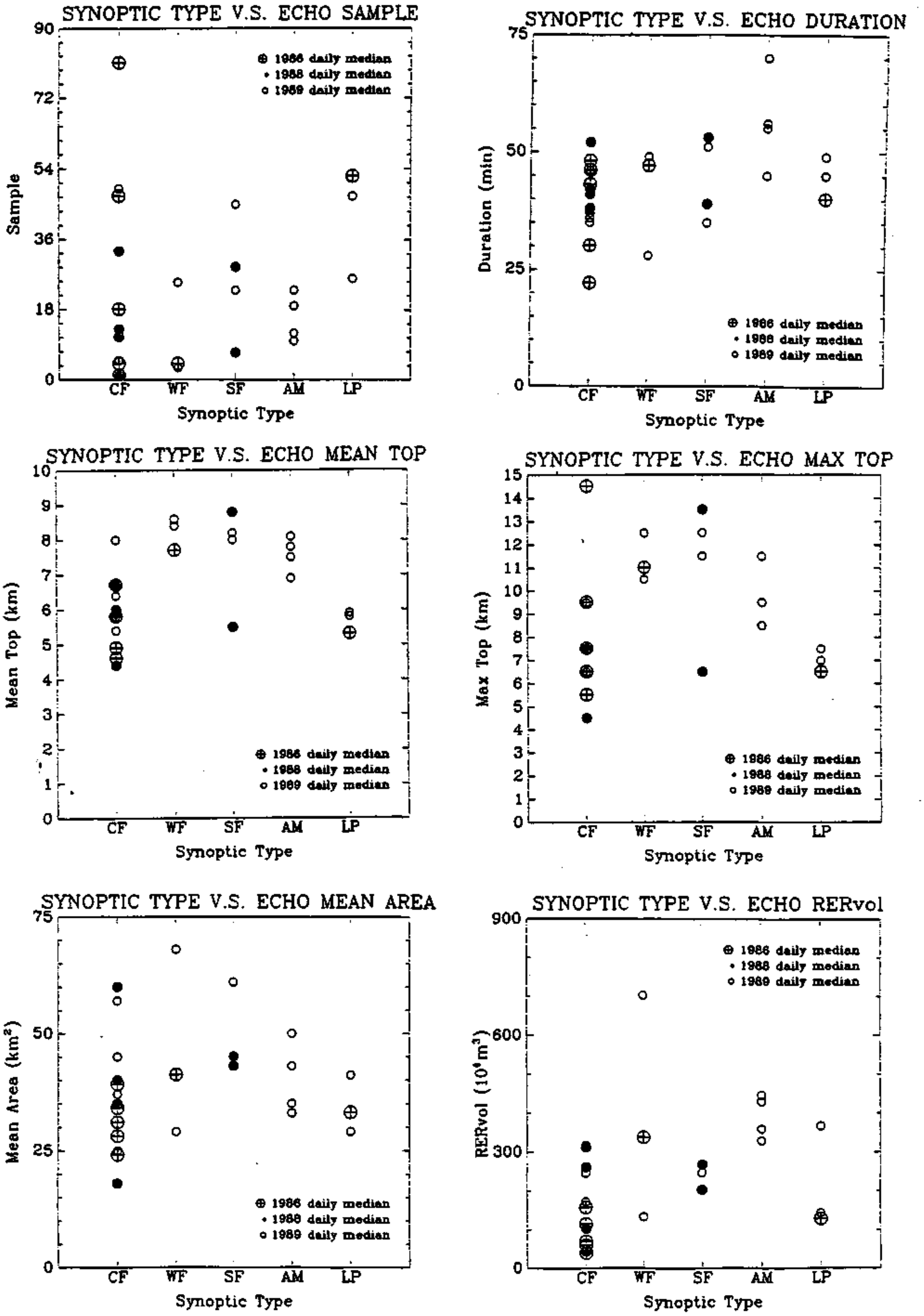


FIGURE 4-24. Relation of echo properties in 1986, 1988, and 1989, to synoptic weather types.

not there is an obvious trigger for convection, as airmass storms generally produce low amounts of rainfall areawide. Otherwise, it appears that prediction of all other echo properties on a daily basis *are not substantially aided by* knowing the synoptic type.

Summary

Study of three-dimensionally tracked echo data from a drought (1988) and a normal-rain summer (1989) indicates few differences in the duration, dimension and rainfall properties of the echoes between years. It appears that the major difference in echo properties was in their frequency of occurrence, both in terms of days with rain episodes, and in the number and duration of rain episodes. For all summers, however, when convection was present, on average similar numbers of echoes were observed during any given hour, and the echoes were similar in dimension, duration and rainfall. During dry periods, however, more echoes were observed during the first hour after storm initiation than during normal rain periods.

Examination of the 1986 dry season showed echoes that were generally smaller and shorter-lived than for both the normal rain summer of 1989 and for the drought summer of 1988. This may be related to both time of day and seasonal differences in storm characteristics (i.e. most 1986 data were collected during morning hours and in the late summer). There was little difference in median echo properties for the summers of 1988 and 1989 when most data were collected during the afternoon and from May through July.

For cloud seeding purposes, it might be expected that there will be fewer and shorter rain episodes during dry periods. On average during any given hour when convection is present, it is likely that there will be as many seeding candidates as during a "normal" rain season. However, it also appears from this small sample of data that afternoon storms during dry periods develop somewhat later than during the normal rain summer and importantly, a large fraction of seeding opportunities fell during the first hour of storm development.

PART FIVE: SUMMARY AND CONCLUSIONS

Temporal Characteristics of Summer Dry Periods

The temporal distribution of dry summers in Illinois was assessed using data for 1896-1990. Dry summers were much more prevalent in the early SO years of the century than in the last 40 years. Dry areas occurred most often in south-central Illinois, and were least prevalent in the extreme northern and southern sections. This results because the north experienced more rain-producing frontal passages in past summers than the rest of the state, and the extreme south was more subject to showers associated with tropical air masses from the Gulf of Mexico.

The time between successive dry periods was found to vary considerably. Two-thirds of the dry periods occurred with either one or no summers between occurrences. However, ten dry periods had intervals of 2 to 10 years between them. Four of the 5- to 10-year intervals have occurred since 1950, and this reflects the post 1950 decrease in the frequency of summer dry periods. There were 11 dry periods in 1906-1922 (17 years), 6 dry periods in 1930-1936, and 5 dry periods in 1940-1945. One occurred during 1961-1980, but three during the 1980s.

Spatial Characteristics of Summer Dry Periods

The areal extent of summer dry periods in Illinois was investigated through use of the mean summer precipitation for each of nine crop reporting districts for 1900-1993. Results showed that there were no dry periods anywhere in Illinois in 28 of the 90 years sampled. During 50 years (50% of total), dry periods extended over two or more districts. Similarly, there were 36 years (40% of total) with dry periods encompassing four or more districts, or about half the state. There were 19 years (21% of total) in which six or more districts (about 2/3 of the state) were enveloped by dry conditions, and in nine years (10% of total) all nine districts experienced dry period conditions.

Results further indicated that differences in the return frequencies of dry periods among districts was minimal. No geographic trend was indicated and combining districts to study dry period conditions is valid. The frequency distribution of mean rainfall for each district reveals the percent of normal rainfall decreases gradually from approximately 80 percent for a 5-year return period, to 55 percent for a 100-year return period.

Dry Periods and Soil Moisture

A study of precipitation-soil moisture relations for dry periods with 5-year or greater frequency was performed for each of the state's districts, and analyses were limited to 1949-1993 because moisture estimates were not available prior to 1949. Average monthly and seasonal rainfall values (and percent of average) were calculated for each district for the growing season (May-August), and soil moisture averages for the first 50 cm below the surface were analyzed. This parameter served as an index value relating the difference between existing soil conditions and field capacity.

Results provided comprehensive information. For example, the driest 25 percent of the July-August rainfall summers (critical crop development period) had soil moisture conditions that were below normal. The frequency of July-August rainfall amounts associated with the nine largest soil moisture deficiencies (approximately 5-year recurrences) was calculated for all nine districts. Four of the low soil moisture values occurred with rainfall that was only 30-39 percent of average; nearly 60 percent occurred with rainfall that was less than 70 percent of average; and 80 percent were associated with rainfalls below 80 percent of average. These results indicate that July-August rainfalls producing less than 80 percent of the long-term average rainfall include most of the important agricultural dry periods in Illinois (with respect to soil moisture deficiency).

Effects of Dry Conditions on the Surface Energy Budget

The potential effects of extreme dry periods on the land surface and the possible feedback effects on the atmosphere were investigated. Research was based on field observations during the 1988 and 1991 droughts and on a diagnostic analysis of radiosonde data.

Field observations and subsequent analysis of the relatively severe 1988 drought in Illinois indicated that the dry-hot soil produced temperature increases in the overlying atmosphere that were sufficient to contribute to drought intensity through intensification of evapotranspiration. Summer radiosonde data at selected midwestem stations for 1957-1989 were used to study the surface energy budget and how the increased sensible heating in dry periods affected the boundary layer conditions. Another study used 1988 (drought) satellite data to explore its effects on vegetation. Results indicated that soil moisture changes in dry seasons can be monitored successfully by satellite data.

Dry Periods in an Area with Inadvertent Weather Modification

Dry period analyses using data taken in the St. Louis area during 1971-1975 were performed based on data from prior studies that dealt with various aspects of the relationship between urban effects and rainfall. All studies were based on observations from the 5,200 km^2 network of 225 recording raingages centered on the St. Louis area.

Most of the analyses of dry, near-normal, and wet conditions were performed using monthly values to maximize the amount of dry period information available from only five years of data. The approach involved study of the inadvertent rainfall modification during dry periods (months) compared with that in near-normal periods and wet periods. Analyses addressed both urban-induced and topographic factors, but with major emphasis on urban influences.

In general, results indicated that both urban and topographic factors were affecting rainfall under all three classes of precipitation. During dry months, a trend was noted for rainfall to occur along the region's major river valleys, in nearby hilly regions, and in the vicinity of the heavily industrialized areas. The initiation of rain cells was concentrated in and downwind of the urban industrialized regions in all three conditions (wet, near-normal, and dry months). Topographic effects on raincell initiations were also indicated, but were less pronounced than the influence of urban effects. Some evidence was found suggesting the urban effects were relatively greater during dry periods than in wetter periods. Analyses of raincell mergers indicated that the merger-related dynamic processes, which are closely related to the rain enhancement processes, are active in both dry and wet periods, and are apparently stimulated by urban influences on atmospheric mechanisms.

Findings collectively suggest that when rain occurs, the basic precipitation processes are functioning similarly in relatively dry, near-normal, and wet conditions in a given area, but that the frequency of dry period storms are below average. Results indicate that weather modification potential exists under these conditions since rain was being enhanced by urban effects.

Area-Devth Regions for Storms during Dry and Normal Summer Months

Storm area-depth curves, which provide a method of investigating the spatial characteristics of rainfall, were used to evaluate potential differences between storm rainfall properties during dry and near-normal summer rainfall periods. Data from two dense raingage networks for the 1955-1965 period were used for this study, and both provided rainfall measurements over areas of 1,000 km^2. The data were divided into two groups which included those with 1) network means of 1.25 to 2.50 cm, and 2) those with means exceeding 2.50 cm. The sample consisted of 194 storms in the first category, and 101 storms in the second.

Results indicated a basic difference in the spatial distribution characteristics of rainstorms in dry periods. Their weaker rain systems tended to have shorter durations, smaller areal extents, and more rapid decay of rainfall rate with distance from the rainstorm center. These conditions probably result from less available moisture input, and/or less efficient processing of available moisture in the dry-period storms. An implication, with respect to weather modification, is that cloud seeding would be less effective in dry periods than during normal weather condition as a consequence of the more rapid decay of rainfall with distance from the storm center in dry-period storms.

12-Month Dry Periods

For this study, 12-month dry periods were defined as those during 1901-1990 in which statewide precipitation was 80% or less. The most severe 12-month droughts had a tendency to favor development in southern Illinois. A frequency distribution analysis indicated that for a given recurrence interval, dry periods were relatively more severe in the southwestern and extreme southern portions of the state, and were least severe in the northeastern section. In general, the severity of 12-month dry periods decreased northward and eastward across the state.

A climatological analysis of the temporal distribution of 12-month dry periods was made, based on the 16 events found in the 90-year sample. The resulting frequency curves, expressed as climatic probabilities, provide useful information. For example, the curves indicate a 20 percent probability that a 12-month dry period will be followed by another one in 5 to 6 months. Similarly, there is an 80 percent chance that one will not begin within 120 months (10 years).

The characteristics of one of the more recent severe droughts, one that occurred in 1953-1954, were analyzed as a part of the 12-month dry period study. Results provided information not previously available showing the diminishment of heavy rainfalls, reductions in thunderstorm frequencies, and fewer convective clouds.

Impacts of Illinois Dry Periods and Droughts

Several past studies provide useful information on droughts and dry periods in Illinois and their impacts on agriculture and water supply. The highlights of these studies were presented because they provide guidance on effects that are pertinent to hydrologists, climatologists, agriculturalists, and others who must deal with the problems created by precipitation deficiencies.

Among the important findings was the development of a general relationship between precipitation deficiency and low streamflow in Illinois. It was found that when the state was divided into six different geomorphic regions, that low flow frequencies could be reliably estimated for any basin by utilizing the precipitation frequency distribution with a geomorphic index. The relationship between low precipitation and shallow ground water supplies was also defined for various parts of Illinois, showing a 1- to 3-month lag depending on locale. Other studies evaluated the potential benefits of weather modification on water supply and an agriculture. Other studies treated the physical and social dimensions of Illinois droughts, including detailed analyses of the 1952-1955 severe drought in south-central Illinois, the 1980-1981 drought in southern Illinois, and the 1988 statewide drought. The primary impact of dry periods is on Illinois agricultural production, whereas droughts impact water supplies as well as agriculture.

Synoptic and Thermodynamic Conditions

The primary macroscale rain producer in dry summers was found to be cold frontal systems. Non-frontal air mass storms were least effective, and dry periods had sizably fewer storms from static fronts, warm fronts, and lows. Pre-frontal squall lines and squall areas, usually in association with cold fronts, were the mesoscale mechanisms most effective in generating substantial rainfall in dry periods. Summer dry periods in Illinois averaged 33 days with measurable rain, compared to 43 rain days in near-normal rain summers, and 47 rain days in wet summers. The biggest reduction occured in the number of rain days producing >12.8 mm of rain.

Thermodynamic conditions in the atmosphere on naturally rainy days in summer are substantially the same (1) regardless of the macroscale synoptic conditions, and (2) whether the season is wet, normal, or day. The convective potential and instabilities on rain days of dry summers was found to be slightly greater than in wet summers. The results suggest that strong anticyclonic conditions persist in dry summers such that relatively weak and marginal dynamic weather systems do not rain, but in wetter years, these marginal systems do produce rain. As a result, it appears that cumulus-type clouds developing during dry summers have virtually the same potential for rain, and for being modified successfully, as those that occur in wet summers. However, such clouds are much less frequent in dry periods, and usually occur with cold frontal systems and their related squall lines or squall areas.

Radar Studies

A study of the frequency, intensity, and areal extent of radar echoes over an area of 44,000 km^2 during the summers of 1986, 1988, and 1989, investigated the potential differences in echo properties between those in near-normal rainfall periods and those in dry periods. When echo properties were stratified by synoptic type, it was found that the type was useful in identifying the presence of a trigger for convection. Knowledge of the convective trigger is helpful in predicting echo frequency and areal extent of rainfall. Thermodynamic parameters showed little correlation with areawide differences in rain intensity. However, atmospheric indices were useful for predicting rain occurrence.

In general, significant differences were not found between echo characteristics of near-normal and those of dry periods. The echo research did discover that in this large area (central Illinois), the rain duration was much less during dry periods than in near-normal periods (2.5 to 3 hours in dry periods versus 4.2 hours in normal rain periods). Also, the daytime rain periods began earlier, by 1 to 3 hours, in the wetter periods than in dry periods.

Conclusions

This study has defined the atmospheric characteristics of dry periods in Illinois and contrasted these with the characteristics of wetter summers. The aim was twofold: 1) to assess the potential for purposeful rainfall modification in dry periods, and 2) to measure the conditions in what *could* become the typical, or average, future climate of the state, expected to be drier and warmer as a result of a potential greenhouse-induced change in the Midwestern climate.

The climatology of the past dry periods shows they have been unevenly distributed in time (many in 1901-1950), and few in 1951-1949. Further, when they occur, they tend to come in clusters of years. Dry periods tend to warm the soil, leading to higher air temperatures, which act to propagate the dry conditions through enhanced evapotranspiration. Spatially, the summer dry areas are large with most covering half or more of the state. Dry conditions have occurred slightly more often in south-central Illinois than elsewhere in Illinois.

The meteorological aspects of dry periods in Illinois reveal they have fewer rain events per unit area. The incidence of rain events was greatly curtailed with 25 percent fewer summers raindays than in the near-normal rain summers. Furthermore, most of the reduction in rain days occurs in events that produce ≥ 12.7 mm. These reductions are due to decreases in all types of weather conditions that produce rain, but the relative greatest dry period reductions are in the number of static fronts, warm fronts, and low pressure centers. Atmospheric stability and radar echoes in dry and wet summers are alike in rain events over a sizable area, but rain tends to develop later in the day in dry periods. Furthermore, rain periods in a 44,000 km^2 area during dry summers do not last as long those in wetter summers, having durations of 2 to 3 hours as opposed to 4 to 5 hours in wetter summers.

The primary cause of dry summers in Illinois is a lack of synoptic-scale rain-producing conditions. Dryness is also enhanced when rains occur in dry years because the rains over an area do not persist as long as those in normal conditions, resulting in less total rain and fewer heavier rainfalls over an area.

Certain findings are encouraging for cloud seeding. The St. Louis urban influences to increase in rain occurred in dry conditions. Also, when rains developed in dry summers, the instability was as high as that in wet summers, and echo characteristics (sizes, numbers, mergers) in dry summers were similar to those in wet periods. However, with 25 percent fewer rain days (per unit area) and shorter lasting rain periods, modification opportunities are curtailed.

References

Atlas, R., N. Wolfson, and J. Terry, 1993: The effect of SST and soil moisture anomalies on GLA model simulations of the 1988 U.S. summer drought. *J. Clint.*, 6, 2034-2048.

Bowman, J.A, and MA Collins, 1987: *Impacts of Irrigation and Drought on Illinois Ground-Water Resources,* 111. State Water Survey Report of Investigations 109, Champaign, IL, 31 pp.

Brutsaert, W., 1988: The parameterization of regional evaporation-some directions and strategies. *J. Hydrology,* 102,409-426.

Changnon, S.A., 1969: A climatological-technological method for estimating irrigation water requirements to maximize crop yields. *J. Soil and Water Conservation,* 24, 12-15.

Changnon, S.A., 1973: Precipitation enhancement program for Illinois. *J. of Irrigation and Drainage Div.,* ASCE, 99, 27-42.

Changnon, S.A., Jr., 1982: *The 1980-1981 Drought in Illinois: Causes, Dimensions, and Impacts.* Ill. State Water Survey, Report of Investigation 102, 78 pp.

Changnon, S.A., Jr., 1987: *Droughts in Illinois: Their Physical and Social Dimensions.* Ill. State Water Bulletin _, 318 pp.

Changnon, S.A., 1987: *Detecting Drought Conditions in Illinois.* ISWS Circular 169, 36 pp.

Changnon, S.A, 1989: Issues Related to Climate Change and Water Resources. *Proceedings Annual Conference of University Council on Water Resources,* 19-23.

Changnon, S.A., 1990: "Impacts and lessons taught by the 1988 drought." *Planning for Water Shortages.* Proceedings of the 1989 Annual Meeting, U.S. Committee on Irrigation and Drainage, St. Louis, pp. 263-270.

Changnon, S.A., Jr., and W.E. Easterling, 1989: Measuring drought impacts: The Illinois case. *Water Resources Bulletin,* American Water Resources Assoc, 25:1, 27-41.

Changnon, S.A, and S. Hollinger, 1993: The potential use of summer rainfall enhancement in Illinois. Part II: Integration of factors affecting enhancement projects and future research. *J. Appl. Meteor.,* 32, 455-461.

Changnon, S.A., Jr., and F.A. Huff, 1957: *Cloud Distribution and Correlation with Precipitation in Illinois.* Report of Investigation 33, Illinois State Water Survey, 83 pp.

Changnon, S.A., and R.T. Shealy, 1993: Value of summer season precipitation predictions in decision about use of precipitation modification. *J. Appl. Meteor.,* 32, 1774-1777.

Changnon, S.A., and W. Wendland, 1994: *What Is and Is Not Known About Climate Change in Illinois: The Scientific Perspective.* Misc. Pub. 156, Illinois State Water Survey.

Changnon, S.A., Jr., FA Huff, and C.-F. Hsu, 1988: Relations between precipitation and shallow groundwater in Illinois. *Journal of Climate,* Amer. Meteor. Soc, 1:12, 1248-1250.

Changnon, S.A., Jr., FA Huff, P.T. Schickedanz, and J.L. Vogel, 1977: *Summary of METROMEX, Volume 1, Weather Anomalies and Impacts.* Bulletin 62, Illinois State Water Survey, 260 pp.

Changnon, S.A., Jr., F.A Huff, S.Q. Kidder, and H.T. Wu, 1985: *Further Studies of Urban Effects on Precipitation at St. Louis.* Illinois State Water Survey Contract Report 372, Final Report to National Science Foundation, Grant ATM 83-05502, 165 pp.

Chiang, I.-Min, 1961: *An Analysis of Selected Synoptic Elements of the Climate of Illinois.* Master's Thesis, Southern Illinois University.

Czys, R.R, and RW. Scott, 1993: A simple objective method used to forecast convective activity during the 1989 PACE cloud seeding experiment. *J. Appl. Meteor.,* 32, 996-1005.

Dixon, M., and G. Wiener, 1993: TITAN: Thunderstorm Identification, Tracking, Analysis and Nowcasting - A radar-based methodology. *J. Atmos. Ocean. Tech.,* 10, 785-797.

Easterling, W.E., and S.A Changnon, Jr., 1987: Climatology of precipitation droughts in Illinois based on water supply problems. *Physical Geography,* 8:4, 362-376, ISWS Reprint 830.

Easterling, W.E., and S.A Changnon, 1993: *Farm-Level Adjustments by Illinois Corn Producers to Climatic Change.* Illinois State Water Survey, 43 pp.

Estoque, M.A., 1973: Numerical modeling of the planetary boundary layer. In *Workshop on Micrometeorology,* ed. D.A. Haugen, American Meteorological Society, Boston, 217-270.

Hirsch, J.G., 1972: A Numerical Cloud model - Its Use During Project Cloud Catcher. *Preprints, Third Conference on Weather Modification,* American Meteorological Society, 182-185.

Hollinger, S.E., and S.A. Changnon, 1993: *Response of Corn and Soybean Yields to Precipitation Augmentation, and Implications for Weather Modification in Illinois.* Bulletin 73, Illinois State Water Survey, Champaign, 95 pp.

Hollinger, S.E., and S.A. Isard, 1994: A soil moisture climatology of Illinois. *J. Clim.,* 7, 822-833.

Hollinger S.E., and S.A. Changnon, 1996: Timing rainfall increases to maximize corn response. *Preprint, 13th Conference on Planned and Inadvertent Weather* Modification, 76th AMS Annual Meeting, January 1996, Atlanta, GA, AMS, Boston, MA.

Hudson, H.E., and W.J. Roberts, 1955: *1952-1955 Illinois Drought with Special Reference to Impounding Reservoir Design*. Illinois State Water Survey Bulletin 43, Champaign, 52 pp.

Huff, F.A., 1967: Time distribution of rainfall in heavy storms. *Water Resources Research,* 3:4, 1007-1029.

Huff, F.A, 1968: Spatial distribution of heavy storm rainfall in Illinois. *Water Resources Research,* 4:1.

Huff, F.A., 1973a: *Evaluation of Potential Benefits of Weather Modification on Water Supply*. Technical Report 1, Illinois Precipitation Enhancement Program, Phase 1, to Dir. Atmos. Water Res. Management, Bureau of Reclamation, Contract 14-06-D-7197, 59 pp.

Huff, F.A., 1973b: *Potential of Precipitation Modification in Moderate to Severe Droughts*. Technical Report 2, Illinois Precipitation Enhancement Program, Phase 1 to Dir. Atmos. Water Res. Management, Bureau of Reclamation, Contract 14-06-D-7197, 26 pp.

Huff, F.A., 1993: *100-Year Rainstorms in the Midwest: Design Characteristics.* Circular 176, Illinois State Water Survey and Midwest Climate Center Research Report 93-01, 20 pp.

Huff, F A , and S.A. Changnon, Jr., 1963: Drought Climatology of Illinois. Bulletin 50, Illinois State Water Survey, 68 pp.

Huff, F.A., and S.A. Changnon, Jr., 1964: Relation between precipitation deficiency and low streamflow. *J. Geophys. Res.,* 69:4, 604-614.

Huff, F.A., and S.A. Changnon, Jr., 1972: Evaluation of potential effects of weather modification on agriculture. *Journal of Applied Meteorology*. 11:2, 376-384.

Huff, F.A., and R.G. Semonin, 1975: Potential of Precipitation Modification in Moderate to Severe Droughts. *J. Appl. Meteor., Vol. 14, No. 5,* 974-979.

Huff, F.A., and J.L. Vogel, 1977: *Assessment of Weather Modification in Alleviating Agricultural Water Shortages During Droughts*. Final Report to National Science Foundation, Research Applied to National Needs (RANN) Grant ENV74-24367, 133 pp.

Huff, F.A., and J.L. Vogel, 1978: Urban, topographic, and diurnal effects on rainfall in the St. Louis Region. *Journal of Applied Meteorology*, 17(5), 565-577.

Kerr, Y.H., J. Imbernon, G. Dedieu, O. Hautecoeur, J.P. Lagouarde, and B. Seguin, 1989: NOAA

AVHRR and its uses for rainfall and evapotranspiration monitoring. *Int. J. Remote Sensing,* 10, 847-854.

Kogan, F.N., 1990a: Monitoring the 1988 U.S. drought from satellite. *Proceedings of the Fifth Conference on Satellite Meteorology and Oceanography,* London, England, September 3-7.

Kogan, F.N., 1990b: Remote sensing of weather impacts on vegetation in non-homogeneous areas. *Int. J. Remote Sensing,* 11, 1405-1419.

Kunkel, KE., and JR. Angel, 1989: A perspective on the 1988 midwestern drought. *EOS,* 70, 817.

Kunkel, K.E., 1989: A surface energy budget view of the 1988 midwestern United States drought. *Boundary Layer Meteor.,* 48, 217-225.

Kunkel, KE., 1990: Operational soil moisture estimation for the midwestern United States. *J. Appl. Meteorol,* 29, 1158-1166.

Lau, K.-M., and L. Peng, 1992: Dynamics of atmospheric teleconnections during the northern summer. *J. Climate,* 5, 140-158.

Riebsame, W.E., S.A. Changnon, and T.R. Karl, 1991: *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-1989 Drought.* Westview Press, Boulder, 174 pp.

Scott, R.W., and R.R. Czys, 1992: Objective forecasting of some individual cloud characteristics in the 1989 Illinois Cloud Seeding Experiment. *J. Wea. Mod,* 24, 1-12.

Semonin, R.G., 1960: Artificial Precipitation Potential During Dry Periods in Illinois. *Proc. Conference on Physics of Precipitation, Monograph No. 5,* American Geophys. Union.

Stall, J.B., 1964: *Low Flows of Illinois Streams for Impounding Reservoir Design.* Ill. State Water Survey, Bulletin 51, Urbana, 396 pp.

Thorn, A S., 1976: Momentum, mass and heat exchange of plant communities, in *Vegetation and the Atmosphere,* Vol. 1, ed. J. L. Monteith, Academic Press, New York.

Trenberth, K.E., G.W. Branstator, and P.A. Arkin, 1988: Origins of the 1988 North American drought. *Science,* 242, 1640-1645.

Trenberth, K.E., and G.W. Branstator, 1992: Issues in establishing causes of the 1988 drought over North America. *J. Clim.,* 5, 159-172.

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