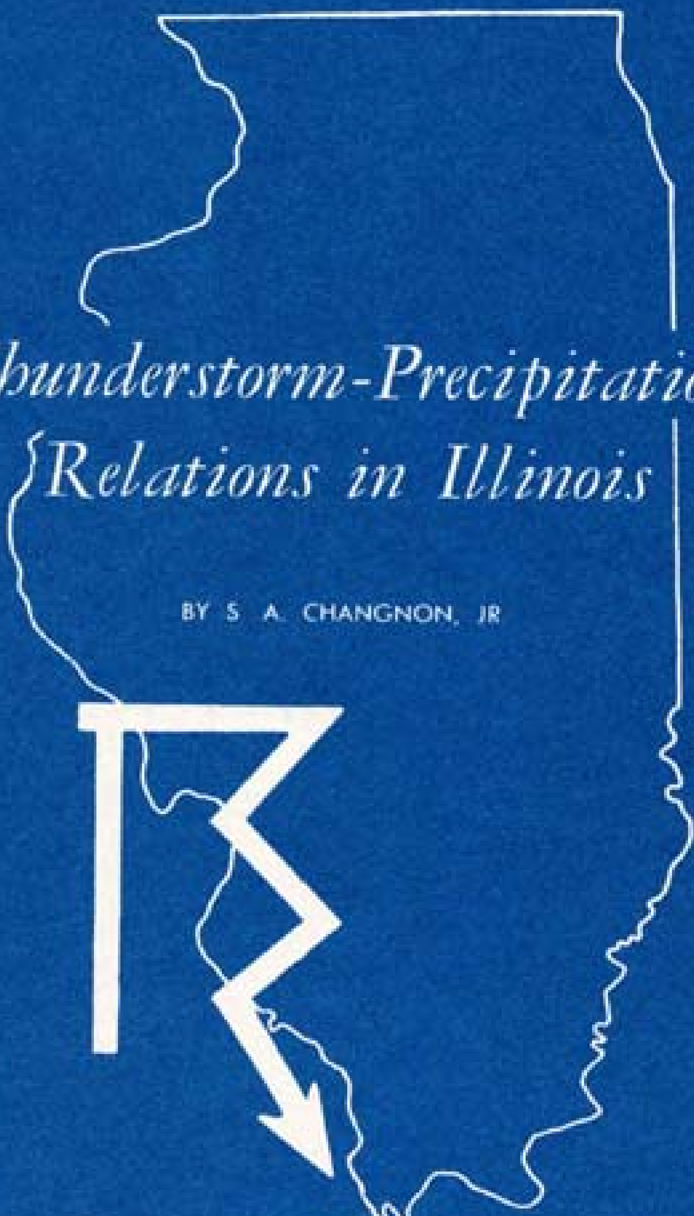
REPORT OF INVESTIGATION 34

STATE OF ILLINOIS
WILLIAM G. STRATTON, Governor

DEPARTMENT OF REGISTRATION AND EDUCATION
VERA M. BINKS, Director

Thunderstorm-Precipitation Relations in Illinois

BY S. A. CHANGNON, JR



ILLINOIS STATE WATER SURVEY
WILLIAM C. ACKERMANN, Chief

URBANA
1957

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THUNDERSTORM-PRECIPITATION RELATIONS IN ILLINOIS

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SUMMARY

First-order stations in Illinois are too few in number to yield thunderstorm data sufficient for depicting areal variations in detail. For this reason data from cooperative substations were evaluated for the present study, and results indicated that this information can be utilized by including those thunderstorms having an associated rainfall of more than 0.09 inch per day.

The annual geographic distribution of thunderstorms in Illinois exhibits a decrease from south to north and is controlled by three factors. The altitude of the sun and moisture source are the more important factors, and nocturnal advection of warm air during the warmer half-year is of secondary importance.

The occurrence of nocturnal thunderstorms in western Illinois causes the northwestward bending of isoceraunic lines (lines of equal thunderstorm frequency) away from east-west latitudinal positions. A latitudinal orientation of isoceraunic lines with a northward decrease is present in all months except June and July, when the lines assume a north-south orientation with occurrences decreasing eastward across Illinois.

Southern and western Illinois have more thunderstorms than eastern and northern Illinois, and the former areas also receive more thunderstorm precipitation. Over 42 percent of the normal annual precipitation in southern and western Illinois results from thunderstorms. The percentage of normal precipitation due to thunderstorms decreases from west to east, whereas the number of thunderstorms and amount of thunderstorm precipitation decrease from south to north.

Thunderstorm occurrences and thunderstorm precipitation are highest in Illinois during June, but the percent of normal precipitation due to thunderstorms has a statewide maximum in July. December has the fewest number of thunderstorms and the lowest monthly amount of thunderstorm precipitation.

INTRODUCTION

The purpose of this study is to describe thunderstorms in Illinois as a climatological factor with specific reference to precipitation relationships. Increasing scientific interest and knowledge of the physical characteristics of thunderstorms [1] have indicated the importance of thunderstorm rainfall within the hydrologic cycle. Thunderstorms have great hydroclimatic significance in the continental climate of the Middle West principally because of their associated precipitation. Therefore, detailed knowledge of the distribution of thunderstorms and thunderstorm rainfall in Illinois is essential in the understanding of the rainfall distribution and water resources of Illinois.

The analysis in this study was accomplished using climatological data entered on IBM punch cards, as this procedure permits rapid processing of voluminous data. [2,3]

Since thunderstorms are weather phenomena of relatively small areal extent and exist in one location for only a short period, two major analytical problems resulted. The first was obtaining a network of climatological stations which would accurately represent the areal and seasonal variations in thunderstorm occurrences. The second was determining from daily climatic records the amounts of precipitation resulting from thunderstorms and being usually of only a few hours duration.

There are six U. S. Weather Bureau first-order stations in Illinois, but only four of these and one adjacent Missouri station had records available on IBM cards. To obtain the areal detail required, records from 20 U. S. Weather Bureau cooperative substations in Illinois, which had been entered on IBM cards, were included in the analyses.

Including the substation data created two problems. First, the substations differ from first-order stations in methods of observation and data collection. Secondly, first-order stations are operated by the U. S. Weather Bureau personnel on a 24-hour basis; and therefore, recordings of thunderstorms are more complete and more frequent than at substations where a volunteer observer reports thunderstorms on his own initiative. Thus, statistical methods were necessary to adjust substation records of thunderstorm occurrences. Since substation data were recorded only once a day, the standard period of comparative analysis for thunderstorm occurrences and precipitation was restricted to a 24-hour minimum, and a more desirable hourly base for analysis was impossible to obtain.

ACKNOWLEDGMENTS

The material herein is based on a thesis submitted in partial fulfillment of the requirements of a Master of Science degree in Geography at the University of Illinois. Dr. John L. Page of the University of Illinois Department of Geography is acknowledged for his aid and guidance in the development of the thesis.

The summary of the thesis was prepared under the direction of William C. Ackermann, Chief, Illinois State Water Survey, and under the supervision of Glenn E. Stout, Head of the Meteorology Section. Portions of the drafting were done by John Wesselhoff.

Paul Sutton, formerly U. S. Weather Bureau State Climatologist of Illinois, gave advice concerning the reliability of past weather records of Illinois and the solution of some analytical problems. Leonard Staugas of the University of Illinois Statistical Service Unit provided suggestions concerning the methodology of IBM card analyses.

ANALYTICAL PROCEDURES

Source of Data

All stations used in the analyses had approximately 54 years of available records, 1901-1954, as shown in Table 1. [2,3] Stations are located as shown in Figure 1.

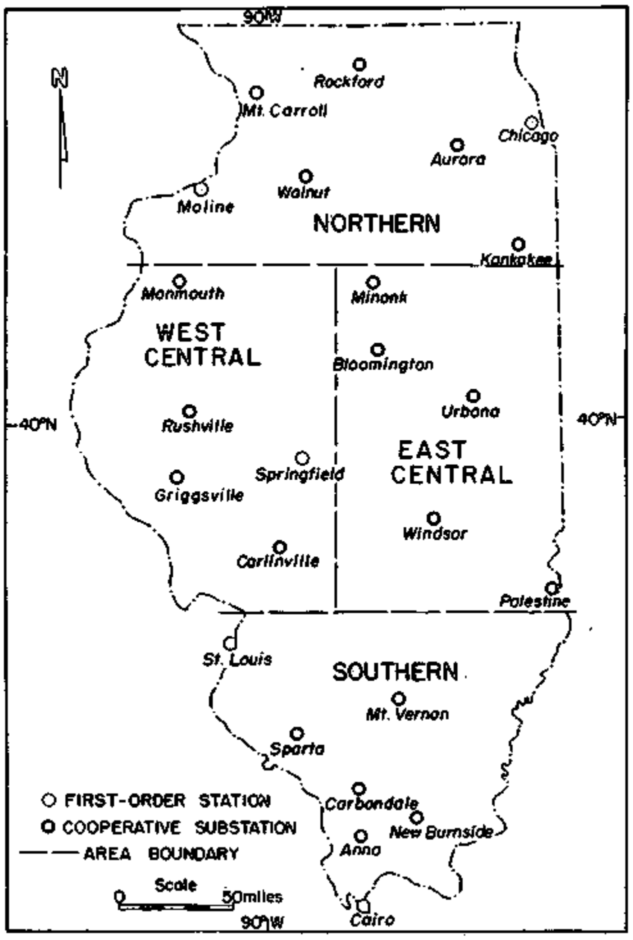


FIGURE 1. REFERENCE MAP OF CLIMATOLOGICAL DATA STATIONS AND ANALYSIS AREAS

Thunderstorm Occurrences

The thunderstorm records from first-order stations were accepted as reliable, but the thunderstorm data from the cooperative substations were not considered entirely reliable. The lack of continuous observations throughout each 24-hour period and of volunteer observer interest at substations, together with frequent observer changes during 50 years of station operation, resulted in some questionable substation records.

The acceptable thunderstorm records for substations were determined first by evaluating the annual totals of thunderstorms in relation to the various observers throughout the total record. Observers who recorded very few thunderstorms were ascertained and their years of records were eliminated as unreliable. The annual thunderstorm totals from the remaining years were next compared to those of the nearest first-order station as shown in Figure 2. A quasi-constancy ratio, developed between the first-order station record counts and the best years of record from each substation, was employed to evaluate the remaining questionable years. By this method, the total acceptable years were ascertained for each substation.

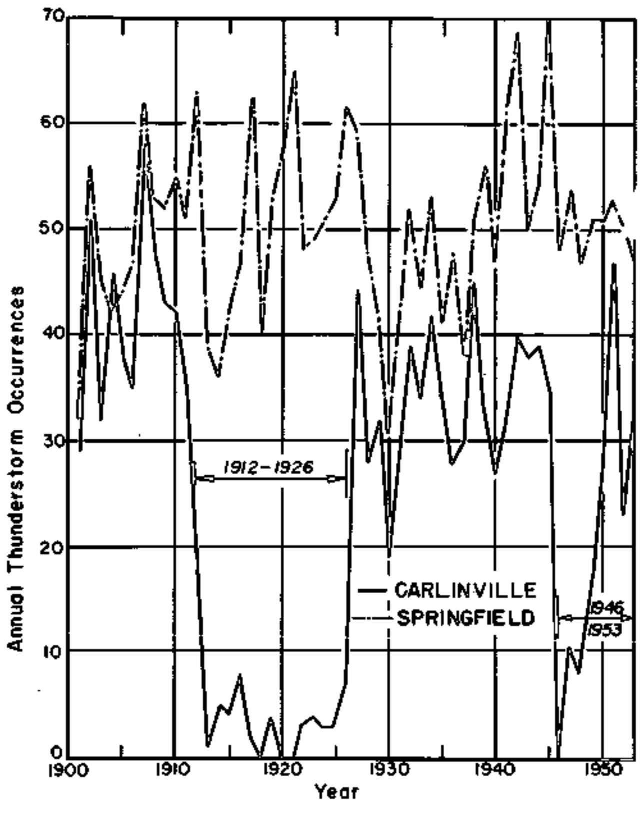


FIGURE 2. GRAPHICAL COMPARISON OF ANNUAL THUNDERSTORM OCCURRENCES AT SPRINGFIELD AND CARLINVILLE

Due to inaccuracies in observation, most of the substations had considerably less than 54 years of acceptable thunderstorm records. Therefore, it became necessary to ascertain the shortest period of acceptable thunderstorm records that would be sufficient to give climatological reliability. Tests using moving averages were employed for periods of 5, 10, 20, and 30 years to determine the minimum period required to obtain a representative sample. It was found that a minimum of 20 years was required, but that no single continuous period could be less than 6 years. A 30-year period was slightly better, but not enough better to eliminate the gain in additional data by using 20 years. The acceptable number of years of record for each station is listed in Table 1. Only one station with card records, Danville, had too few acceptable years to be used in the analysis.

TABLE I

STATION DATA AVAILABLE ON IBM CARDS

Stations (a)	Periods of Card Records	Total Years Acceptable Thunderstorm Records
First-Order Stations (No. 3 cards)		
Cairo	1908-1952	45
Chicago	1901-1953	53
Moline	1901-1953	53
St. Louis, Mo.	1908-1952	45
Springfield	1901-1953	53
Cooperative Substations (No. 1009 cards)		
Anna	1901-1954	20
Aurora	1901-1954	51
Bloomington	1901-1954	39
Carbondale	1910-1954	37
Carlinville	1901-1954	30
Danville	1901-1903, 1910-1954	11
Griggsville	1901-1954	21
Kankakee	1917-1954	22
Minonk	1901-1953	23
Monmouth	1901-1953	40
Mt. Carroll	1901-1954	25
Mt. Vernon	1901-1953	20
New Burnside	1901-1954	36
Palestine	1901-1954	20
Rockford	1905-1954	22
Rushville	1901-1954	21
Sparta	1901-1954	25
Urbana	1903-1954	43
Walnut	1901-1954	42
Windsor	1904-1954	30

(a) All stations in Illinois unless otherwise indicated.

To obtain data concerning the areal probability of thunderstorm occurrences on each day also required the use of the substation records, and again questionable reliability was a problem. To eliminate possible errors because of unrecorded thunderstorm occurrences, even from acceptable substation records, a station-to-station method of comparison was not used. The state was divided into four, approximately equal areas. A count of an areal occurrence was based upon the reporting of a thunderstorm from at least two stations in an area. These state divisions are shown in Figure 1 and are labeled northern, west central, east central, and southern. The two east-west boundaries nearly coincide with similar climatological boundaries used by the U. S. Weather Bureau.

Thunderstorm Precipitation

At a first-order station, the daily summary of precipitation amount and thunderstorm occurrence is made at midnight. In this analysis, thunderstorm precipitation was initially classified as the total daily precipitation occurring on the same day with the thunderstorm. However, substation daily observations of precipitation and thunderstorms are generally made at two different times, with the precipitation being recorded usually at about 5 p. m. and the thunderstorm occurrence at the end of the day. Therefore, a time discrepancy in recording often occurs at the substations. To evaluate the effect of this discrepancy, the percentage of all thunderstorms that occur in the period from 6 p. m. to midnight was determined at 4 first-order stations used in this study. As shown in Table 2, nearly 27 percent of all thunderstorms occur between 6 p.m. and midnight.

TABLE 2

PERCENT OF THUNDERSTORM OCCURRENCES BETWEEN 6 PM AND MIDNIGHT AT FOUR FIRST-ORDER STATIONS, 1906-1925

Seasons	Station Percentages				Combined Seasonal Percentages
	Chicago	Springfield	St. Louis	Cairo	
Winter	23	27	43	30	31
Spring	33	30	28	29	30
Summer	28	25	22	22	24
Fall	29	34	30	29	31
Annual	29	28	26	26	27

Therefore, in this study, a method had to be devised to associate the rainfall reported on the day following a day with a thunderstorm. Furthermore, it was necessary that this method correctly include the rainfall on the day of the thunderstorm occurrence.

From case studies, the method of best estimation was ascertained to be that which included total rainfall on the day of a thunderstorm as well as the rainfall on the following day. The validity of this method was tested by comparing the thunderstorm precipitation amounts and their percentage of normal at substations with comparable data from nearby first-order stations. A sample of this analysis for the year 1945, as shown in Table 3, reveals that precipitation data at five of the substations more nearly agree with the data from first-order stations when the precipitation is included from days following thunderstorms reported at substations. In this particular year, two of the substation values were not improved by including precipitation from the days following thunderstorms. These reversals at Carbondale and Kankakee are a result of regional differences in thunderstorm frequency in relation to the nearby first-order stations.

TABLE 3

THUNDERSTORM PRECIPITATION AT SELECTED SUBSTATIONS COMPARED WITH NEAREST FIRST-ORDER STATIONS, 1945

Stations	Number of Thunderstorms	Total Annual Precipitation	Annual Precipitation on Thunderstorm Days		Annual Thunderstorm Precipitation[a]	
			Total Amount	Percent of Total[b]	Total Amount	Percent of Total[b]
Chicago*	44	37.46	17.26	46	--	--
Rockford	37	43.59	18.50	42	19.61	45
Aurora	25	39.85	11.91	30	16.30	41
Kankakee	36	37.57	17.32	46	19.10	50
Springfield*	71	43.40	27.25	62	--	--
Rushville	30	41.51	18.32	44	21.01	52
Carlinville	35	54.08	27.57	51	31.65	58
Cairo*	63	61.98	41.01	66	--	--
New Burnside	44	71.34	33.50	47	41.67	59
Carbondale	62	74.50	49.58	66	55.74	74

[a] Substation precipitation from thunderstorms computed by using the total daily precipitation on day of thunderstorm and the day following.

[b] Total indicates total annual precipitation.

* First-order stations.

A second evaluation was accomplished by testing the records from two randomly selected years, 1931 and 1945. This test revealed that by eliminating all thunderstorm occurrences having daily precipitation amounts of 0.09 inch or less from the substation and the first-order station records, the number of thunderstorm occurrences reported by the two types of stations more nearly agreed, as shown in Table 4.

This analysis indicates that thunderstorms producing only small amounts of precipitation were not always recorded at the substations. Conversely, the frequent observations made at the first-order stations resulted in more frequent observations of distant thunderstorms which produced little or no precipitation at the station. It was concluded that the computation of thunderstorm precipitation at substations using the precipitation on the day of thunder and the day following was

TABLE 4

STATION COMPARISON OF TOTAL ANNUAL THUNDERSTORM OCCURRENCES AND ANNUAL THUNDERSTORM OCCURRENCES WITH ASSOCIATED DAILY PRECIPITATION GREATER THAN 0.09 inch, 1931

Stations	Total Annual Thunderstorm Occurrences	Total Annual Thunderstorm Occurrences With Precipitation Greater Than 0.09 Inch
Springfield	41	25
Carlinville	29	27
Chicago	43	24
Aurora	32	23
St. Louis	52	32
Carbondale	30	29

an acceptable method. Furthermore, a satisfactory comparison of thunderstorm occurrences between the substations and first-order stations could be made if all thunderstorm days with total amounts less than 0.10 inch were eliminated from the totals for both types of stations.

Methods for computing thunderstorm precipitation described above result only in the total precipitation on the calendar day of thunderstorms for first-order stations and on the thunderstorm day and day after for substations. Because precipitation of non-thunderstorm origin may occur on days with thunderstorms, the methods described above do not compute the actual thunderstorm precipitation. Therefore, it was necessary to analyze thunderstorm and precipitation data recorded more frequently than once daily.

It has been found [4] that the average duration of rain from a thunderstorm is one hour at one location. Substation data were not recorded more than once in 24 hours, and therefore, no station-to-station evaluation of the actual thunderstorm precipitation based on hourly data could be made. However, first-order station hourly data for Chicago, Springfield, and Moline were available and were used to calculate the actual thunderstorm precipitation. The amounts were calculated by manual editing of each daily record to ascertain the thunderstorm precipitation for each hour. The ratios of the actual thunderstorm precipitation to the total precipitation on the day of thunderstorms, computed on a monthly basis for Chicago, Springfield, and Moline are presented in Table 5.

TABLE 5

PERCENT OF MONTHLY PRECIPITATION
ON DAYS OF THUNDERSTORMS WHICH
IS ACTUAL THUNDERSTORM PRECIPITATION
AT CHICAGO, SPRINGFIELD AND MOLINE

Months	Chicago (1926-1948) %	Springfield (1926-1943) %	Moline (1926-1948) %
January	41	38	43
February	67	65	64
March	68	68	66
April	64	67	65
May	74	82	73
June	81	83	84
July	90	92	92
August	87	85	85
September	76	77	74
October	77	76	71
November	51	54	50
December	19	43	40
Annual	77	78	76

The percent of monthly and annual precipitation, as computed from these three first-order stations, was used to correct the computed thunderstorm precipitation totals of the substations and of the other two first-order stations. Table 5 shows that the only months when the station percentages differed significantly were May and December. In all months except these two months the Springfield percentages were used as the correcting multiplier for all the Illinois stations. For May and December the Springfield percentages were used as the multiplier for central and southern Illinois stations while the Moline percentages were used for the northern Illinois stations. This method of arriving at the monthly average thunderstorm precipitation cannot be assumed to be entirely accurate for the monthly data for each substation. However, the close association in the percentages of the three first-order stations indicates no significant deviation could be expected to occur elsewhere in Illinois.

THUNDERSTORM OCCURRENCES IN ILLINOIS

The distribution of thunderstorms in the Middle West is associated with latitude or the altitude of the sun. The average annual frequency of thunderstorms decreases northward from the Gulf of Mexico east of the 100th meridian. Other factors, including the availability of moisture and the positions of the Bermuda High and the polar fronts, affect the distribution and tend to align themselves with the latitudinal orientation. Due to its location, Illinois reflects the general decrease northward in the thunderstorm activity. An area of concentrated nocturnal thunderstorm activity in the warmer half-year is located in the Iowa-Nebraska region (5) and influences the distribution of thunderstorms in Illinois. The monthly variation in thunderstorm occurrences, in general, corresponds to the monthly variation in the altitude of the sun.

Annual Thunderstorm Occurrences

The average annual occurrences of thunderstorms in Illinois based on first-order station data are presented in Figure 3. Although isoceraunic lines for every two occurrence intervals were drawn, the first-order stations were too sparsely located to permit accurate plotting. However, the data from the first-order stations show, in general, the annual thunderstorm distribution in Illinois.

To obtain more detailed isoceraunic lines, data from substations were incorporated using totals only for thunderstorms producing precipitation greater than 0.09 inch per day. The average annual occurrences of thunderstorms with associated precipitation greater than 0.09 inch per day are presented in Figure 4. The isoceraunic pattern of this map, although more detailed, compares favorably with the pattern on Figure 3. The differences in the pattern and in the number of occurrences at each station are attributed to areal climatic differences in the frequency of thunderstorms with daily precipitation amounts less than 0.10 inch.

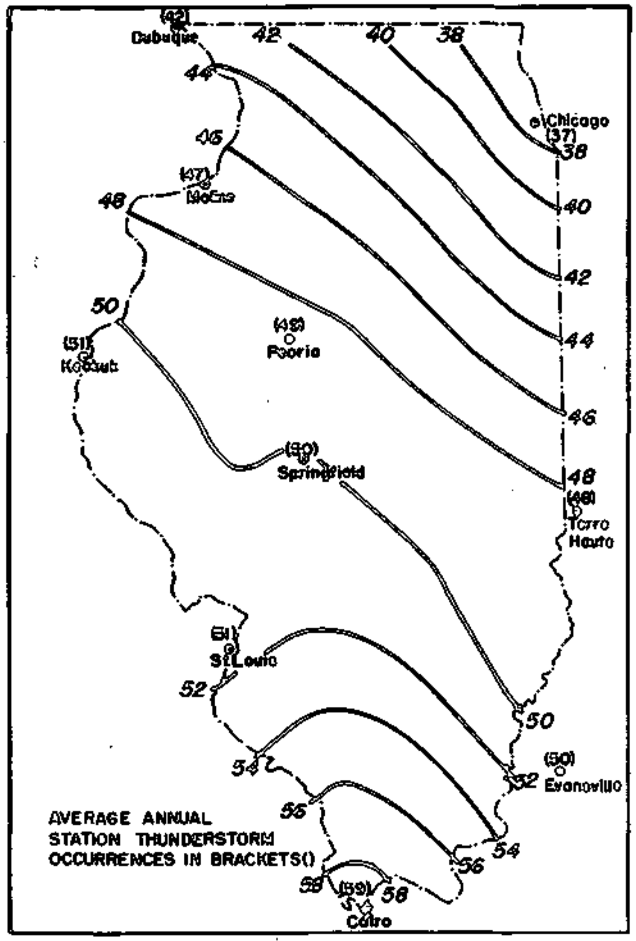


FIGURE 3. AVERAGE ANNUAL THUNDERSTORM OCCURRENCES

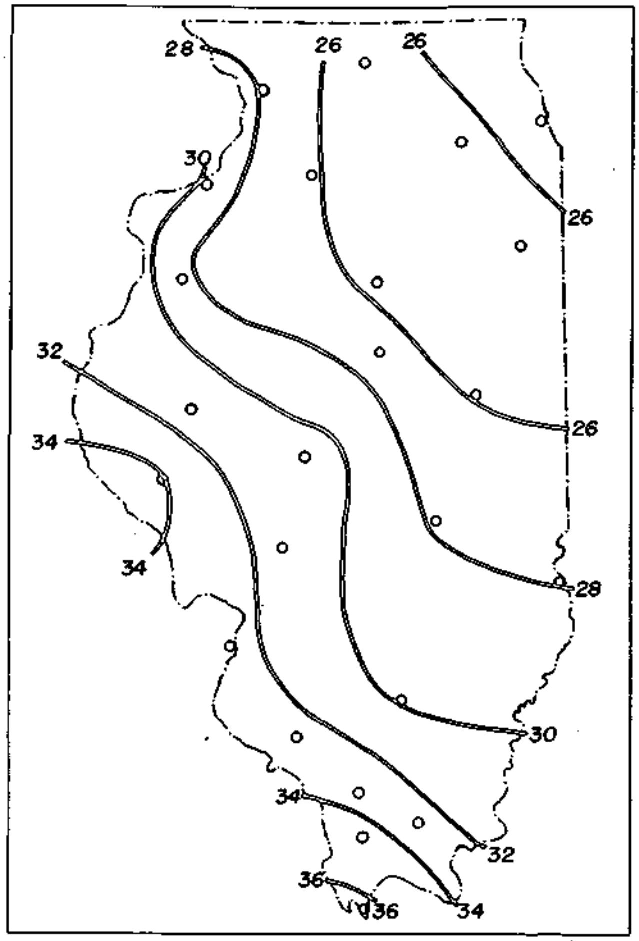


FIGURE 4 AVERAGE ANNUAL OCCURRENCES OF THUNDERSTORMS WITH A RESULTING PRECIITATION GREATER THAN 0.09 INCH, 1901-1954

The occurrences on days of greater than 0.09 inch decrease northward, from 36 at Cairo to 25 at Rockford and Aurora. However, the isoceraunics have a northwest-southeast orientation, indicating the influence of nocturnal thunderstorms in western Illinois.

Monthly Occurrence Distributions

Thunderstorm occurrences in December, January, and February (Fig. 5) show isoceraunics lying generally in an east-west orientation. This orientation reflects the dominating influence of latitudinal position on the frequency of thunderstorms in the winter season. The winter thunderstorms in Illinois are primarily the result of frontal activity. The proximity of southern Illinois to the warm moist Gulf of Mexico air and the generally higher temperatures in the area cause this part of Illinois to be most favorable for thunderstorm development. The movement northward of the 0.4 isoceraunic line in Figure 5 (maps a, b, and c) indicates the gradual northward penetration of the warm moist air and the gradual increase of surface heating in Illinois.

The March occurrence map (Fig. 5d) reflects the same latitudinal isoceraunic pattern, as thunderstorm development in Illinois still relies mainly on frontal activity. Thunderstorms in April and May result from conditions other than frontal action. With considerable warming in southern Illinois, insolational air mass thunderstorms also begin to occur.

The maximum area of thunderstorm occurrence in the United States during spring is in Arkansas and southern Missouri where maximum insolational and convergent activity are occurring. [4] The decrease northeastward from the Arkansas peak area is reflected in the high occurrence areas in southern and southwestern Illinois and in the northwest-southeast orientation of the April and May isoceraunic lines. Furthermore, the increasing southerly flow of warm, moist air is often orographically lifted by the Shawnee Hills in southern Illinois, resulting in more frequent thunderstorm development there.

In the summer months (Fig. 6) frontal activity and isolation are important as thunderstorm development factors in all of Illinois. Convective instability, created

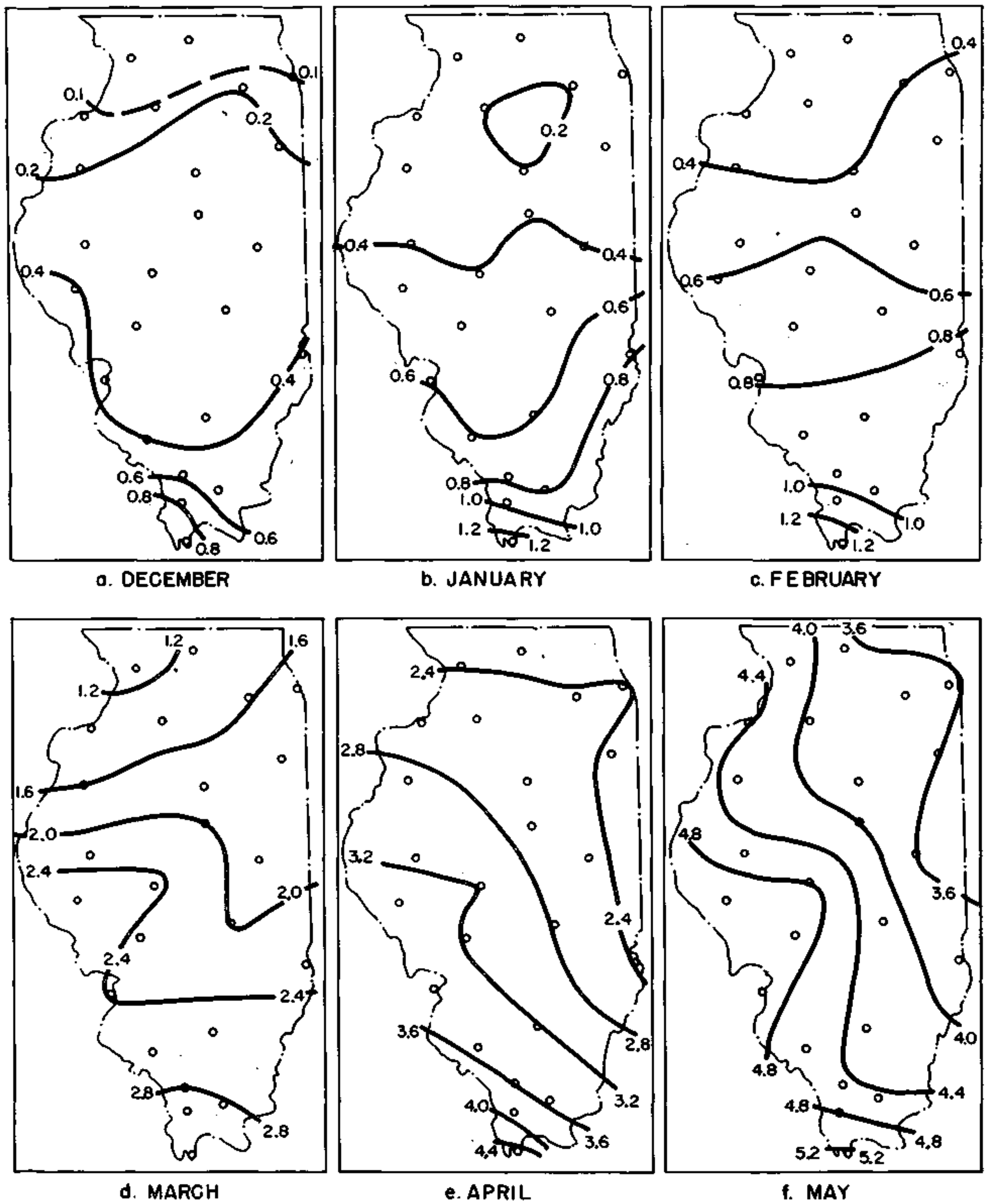


FIGURE 5. AVERAGE OCCURRENCES OF THUNDERSTORMS WITH A RESULTING PRECIPITATION GREATER THAN 0.09 INCH, WINTER AND SPRING, 1901-1954

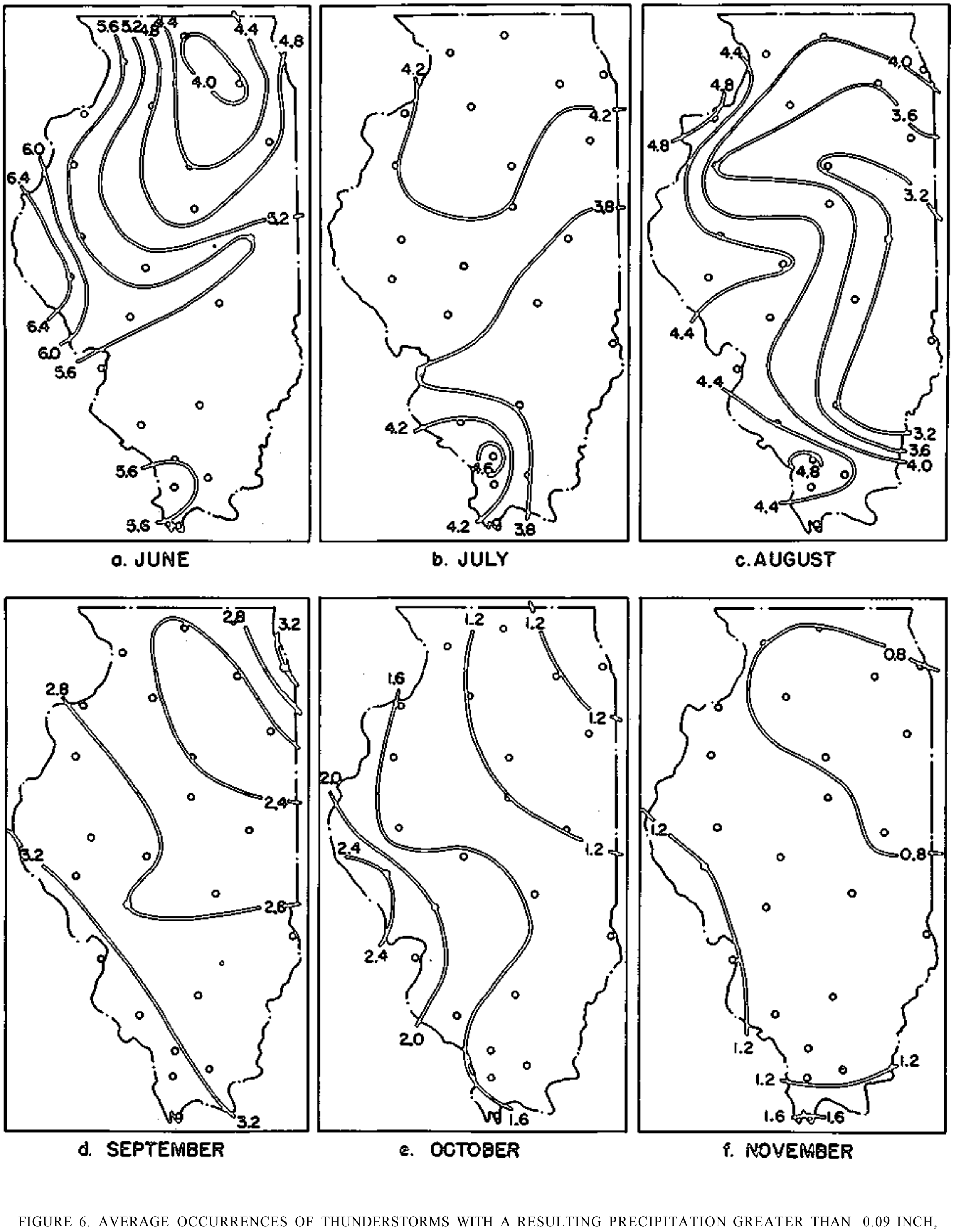


FIGURE 6. AVERAGE OCCURRENCES OF THUNDERSTORMS WITH A RESULTING PRECIPITATION GREATER THAN 0.09 INCH, SUMMER AND FALL, 1901-1954

by the southern Illinois Shawnee Hills, continues to contribute to thunderstorm development in that area and is probably responsible for the high number of occurrences in the Anna-Carbondale-New Burnside region during June, July, and August.

During the summer, nocturnal thunderstorms, which become predominant in western and northern Illinois, are created by nighttime advection or horizontal transport of the warmer air in the lower layers of the atmosphere creating instability. [5] Since in this season the maximum area of advection in the United States is centered in Iowa and Nebraska, the strength of this center decreases eastward and southeastward with western Illinois having the greatest advective activity in Illinois. The effect of this eastward decrease across Illinois creates the general north-south isoceraunic orientation in central and northern Illinois (Fig. 6a, b, c). The Illinois stations have their greatest monthly frequency of thunderstorms in June (Fig. 6a). In July the frequency of thunderstorms decreases as the flow of moist air over Illinois decreases. A high-level anticyclone frequently develops over the Mississippi Valley, forcing much of the moist air westward away from Illinois. [4] In August the delimiting effect of the high-level anticyclone is still present, but increasing nocturnal thunderstorm activity to the west keeps occurrences frequent in the extreme western and southwestern area.

In the fall thunderstorm activity begins to contract gulfward, as both insolation and the northward flow of moist air decrease. However, a rapid decrease is prevented by three conditions. In September (Fig. 6d) an increase in frontal activity [4] throughout Illinois and the persistence of nocturnal thunderstorm activity in the western area [5] maintain the comparatively high frequency area in western Illinois. In late September, October, and November the center of thunderstorm activity in the central United States occurs in the Missouri-Arkansas area because this area is the center of strong continental convergent activity. The associated thunderstorm activity decreases northeastward into Illinois (Fig. 6d, e, f).

Areal Probability of Daily Thunderstorm Activity

The areal probability of daily thunderstorm activity in Illinois was analyzed by dividing the state into four areas, as shown in Figure 1. An areal occurrence was based upon a reporting of a thunderstorm from at least two stations in an area. The four years analyzed in this study, 1941-1944, had 544 days of thunderstorms, and they were selected because more of the substations had acceptable records during this period than at any other time between 1901 and 1954. To obtain sufficient thunderstorm days to provide statistically significant results, all data were summarized into seasonal rather than monthly periods. The total daily occurrences in each area are presented by seasons in Table 6. Fall was the only season when the Southern Area did not rank first in number of thunderstorms.

TABLE 6

NUMBER OF DAILY OCCURRENCES OF THUNDERSTORMS IN EACH AREA PER SEASON, 1941-1944

	Winter					Spring				
	S[a]	W[b]	E[c]	N[d]	Total	S	W	E	N	Total
Number	22	15	14	9	60	115	109	79	90	393
Percent of Total Number	37	25	23	15	--	29	28	20	23	---

	Summer					Fall				
	S	W	E	N	Total	S	W	E	N	Total
Number	170	146	108	120	544	49	68	47	46	210
Percent of Total Number	31	27	20	22	---	23	33	22	22	---

a. S-Southern Area
b. W-West Central Area
c. E-East Central Area
d. N-Northern Area

From the areal data, probabilities that on a day when thunderstorms occur in one area, thunderstorms would also occur in the other three areas were calculated. Simultaneous daily occurrences in all areas were at a maximum in the spring season when 20 percent of all daily thunderstorms occurred in all four areas. Seasonal probabilities for each area to have a simultaneous daily occurrence in any of the other areas are shown in Table 7.

TABLE 7

PROBABILITY OF THUNDERSTORMS IN ONE AREA OCCURRING ON THE SAME DAY IN OTHER AREAS OF ILLINOIS, 1941-1944

	Southern Area				West Central Area			
Season	W[a]	E[b]	N[c]	S[d] only	W-only	E	N	S
Winter	45	41	27	45	20	60	47	67
Spring	68	52	47	23	12	57	55	72
Summer	62	47	46	21	8	57	57	73
Fall	67	47	41	20	10	54	53	49

	East Central Area				Northern Area			
Season	W	E-only	N	S	W	E	N-only	S
Winter	64	21	43	64	78	67	11	67
Spring	78	6	61	76	60	48	18	54
Summer	78	6	59	74	69	53	14	66
Fall	77	15	49	49	80	50	13	53

a. W-West Central Area
b. E-East Central Area
c. N-Northern Area
d. S-Southem Area

In all seasons the West Central Area had the highest probabilities of having a thunderstorm when one was occurring in southern Illinois. During the winter, spring, and summer seasons the Southern Area had the highest probabilities of having a thunderstorm on the same day as they occurred in West Central Illinois. However, in the fall the highest probability for another area occurrence shifted to the East Central Area.

The Northern Area thunderstorms had the greatest probability of simultaneous daily occurrences in the West Central Area during all seasons, and the highest percentage occurred in the fall.

The East Central Area occurrences had their greatest association with occurrences in the West Central Area because of their similar latitudinal positions.

These statistical findings substantiate the occurrence data shown in Figure 4, with the Southern Area predominating in thunderstorm occurrences followed in order by the West Central Area, East Central Area, and Northern Area.

THUNDERSTORM PRECIPITATION IN ILLINOIS

Average Annual Precipitation From Thunderstorms

The annual thunderstorm precipitation isohyetal lines tend to have an east-west orientation, as shown in Figure 7. The percentage of normal annual precipitation due to thunderstorms shows a range from 37 to 50 (Fig. 8), and the annual average thunderstorm precipitation values range from less than 13 inches per year in northeastern Illinois to more than 19 inches per year in southern Illinois. As expected, the average annual precipitation pattern (Fig. 9) has a greater similarity to the thunderstorm rainfall pattern than to the percent of normal annual rainfall pattern. Data in Figure 8 illustrate that thunderstorm precipitation contributes more significantly to the total annual precipitation in western and southern Illinois than in northern and eastern Illinois.

In most areas the annual thunderstorm isohyetal lines are in good agreement with the annual isoceraunic lines (Fig. 4). In the southern half of Illinois the iso-

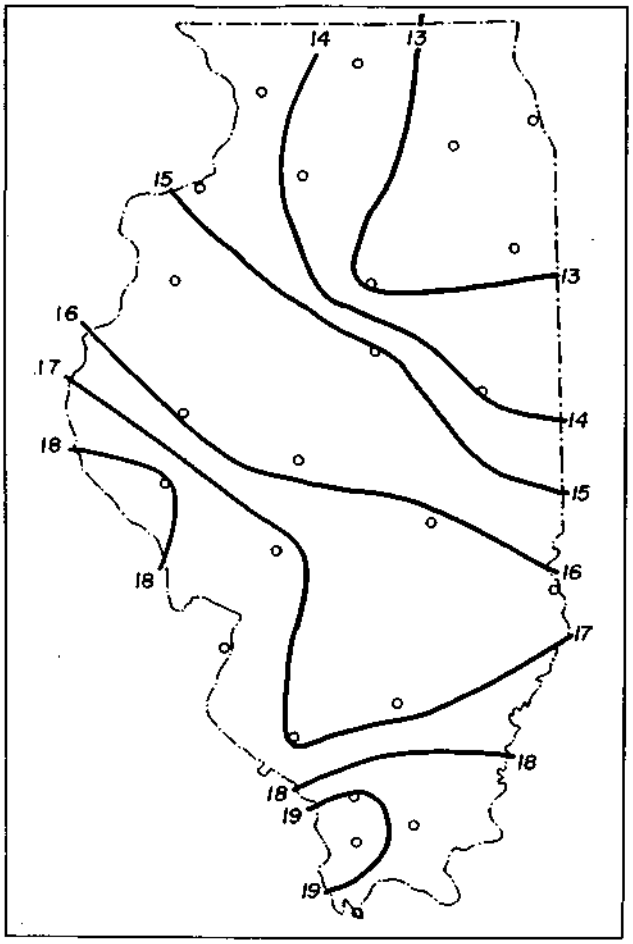


FIGURE 7. AVERAGE ANNUAL THUNDERSTORM PRECIPITATION IN INCHES, 1901-1944

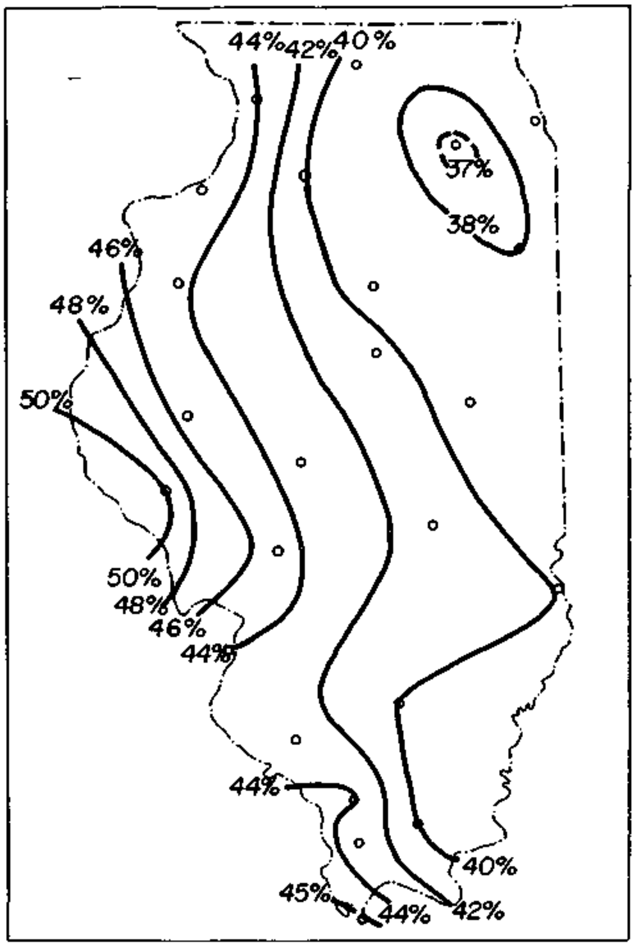


FIGURE 8. AVERAGE PERCENT OF NORMAL ANNUAL PRECIPITATION FROM THUNDERSTORMS

ceraunic pattern is in better agreement with the isopercental than the isohyetal pattern. Western Illinois has percentages equivalent to or greater than those in southern Illinois, but thunderstorm occurrences in the southern area are considerably more frequent than in the western area. As seen in Figure 7, the southern area also averages more thunderstorm precipitation than the western area. Therefore, this equivalence in percentages was due to the greater normal annual precipitation in the southern area (Fig. 9). The significance of the rapid decrease in percentages eastward across Illinois can be best realized by comparing these results to the annual average precipitation pattern (Fig. 9). A percentage decrease of thunderstorm precipitation in relation to the total normal precipitation can be interpreted as either a decrease in thunderstorm precipitation or an increase in non-thunderstorm precipitation.

To attempt a better estimate of the relationship between thunderstorm occurrences and thunderstorm precipitation, annual thunderstorm data for a 23-year period at Chicago were analyzed (Fig. 10). The correlation coefficient of 0.28 indicates that no close relationship existed between the annual number of thunderstorms and the annual amount of thunderstorm precipitation. An even poorer correlation, 0.10, was obtained between the number of thunderstorms and the total annual precipitation.

Average Monthly Precipitation From Thunderstorms

The winter months, Figures 11 and 12, have isohyetal and isopercental lines oriented east-west in patterns similar to the isoceraunic line patterns for the same months. The northward increase in the monthly thunderstorm precipitation can be followed by tracing the northward progression of the 0.1-, 0.2-, and 0.3-inch isohyetal lines in December, January, and February. December thunderstorm precipitation was the lowest of any month as were the percentages which are shown in Figure 12a.

The northward latitudinal increase in thunderstorm precipitation continues in March, April, and May, as shown in Figure 11d, e, f. The largest state-wide monthly increase is from April to May with only a slight increase occurring between March and April, mainly in southern Illinois.

The isohyetal patterns of the spring months differ in orientation from the isoceraunic patterns. However,

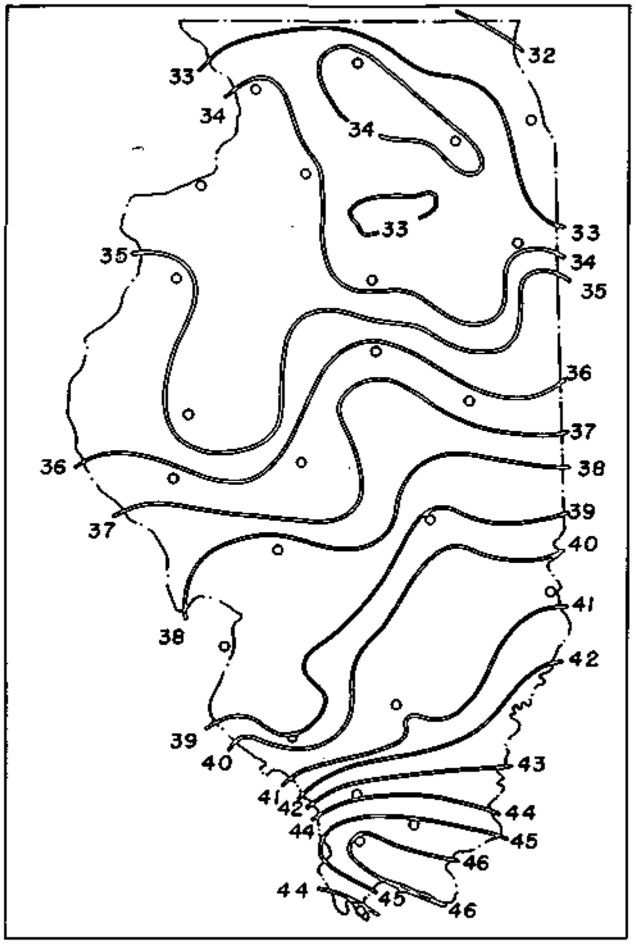


FIGURE 9. AVERAGE ANNUAL PRECIPITATION IN INCHES, 1901-1944

the isohyetal patterns have some similarity to the March, April, and May isopercental patterns (Fig. 12). The northward increase in percentage on a latitudinal basis continues in the spring months (Fig. 12d, e, and f) with the 35 isopercental line having some local irregularities in March and April. The April 1.2-inch isohyet is positioned in the state almost exactly as the April 35 isopercental line. In May the 2.3-inch and 2.5-inch isohyetal lines are in close agreement with the 55 and 60 isopercental lines, respectively.

The isohyetal lines in June and July (Fig. 13) differ in orientation with both isoceraunic and isopercental lines. In summer (Fig. 14) the orientation of the isopercental lines changes from east-west to northwest-southeast. The strong influence of the nocturnal thunderstorm activity in northern and western Illinois is responsible for this new alignment. Withinsolatibnal, nocturnal, and frontal activity all serving as development factors in different state areas, the resulting thunderstorm precipitation patterns are varied in orientation and intensities. June, which had on the average more thunderstorm occurrences than any other month, also led all months in the amount of thunderstorm precipitation, although July (Fig. 14b) led in the percentage of total monthly precipitation from thunderstorms.

The isopercental pattern in August indicates a closer relation to the isoceraunic pattern (Fig. 6c) than does the June or July patterns. The 70 isopercental line in August closely approximates the 4.0 isoceraunic line position. In August and September, the high precipitation in southwestern and western Illinois is indicative of the large amounts contributed by nocturnal thunderstorms in those areas.

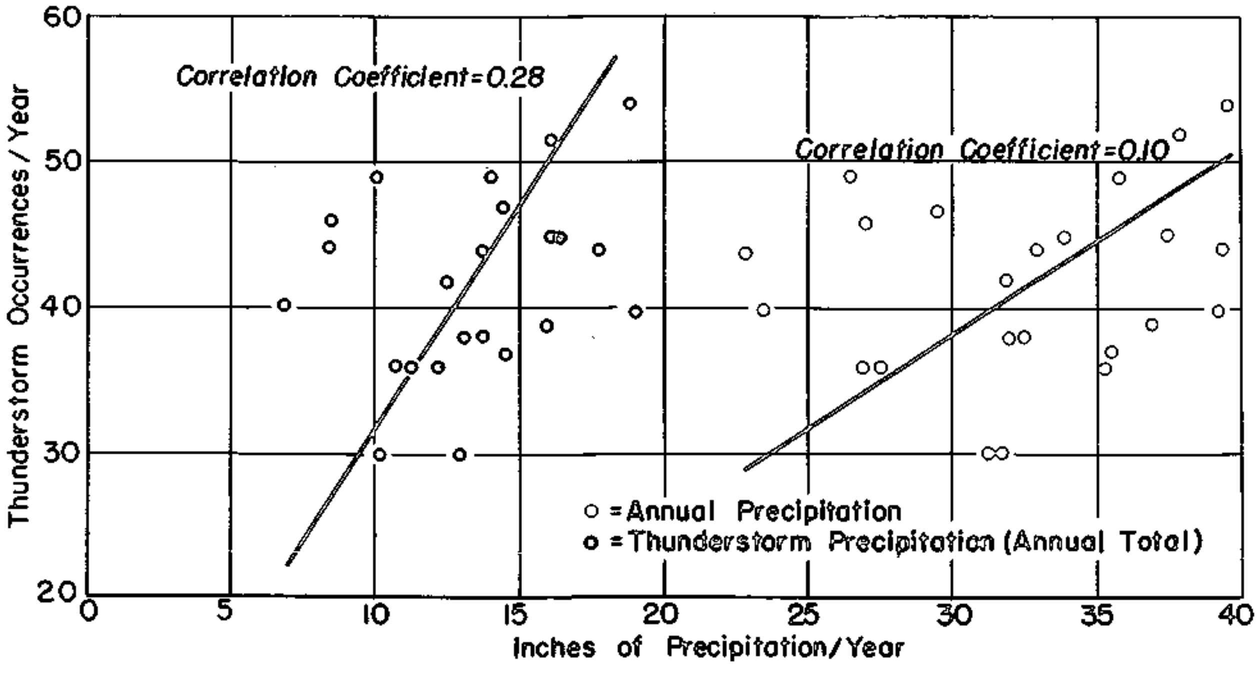


FIGURE 10. RELATIONSHIPS BETWEEN ANNUAL THUNDERSTORM OCCURRENCES AND PRECIPITATION TOTALS AT CHICAGO, 1926-1948

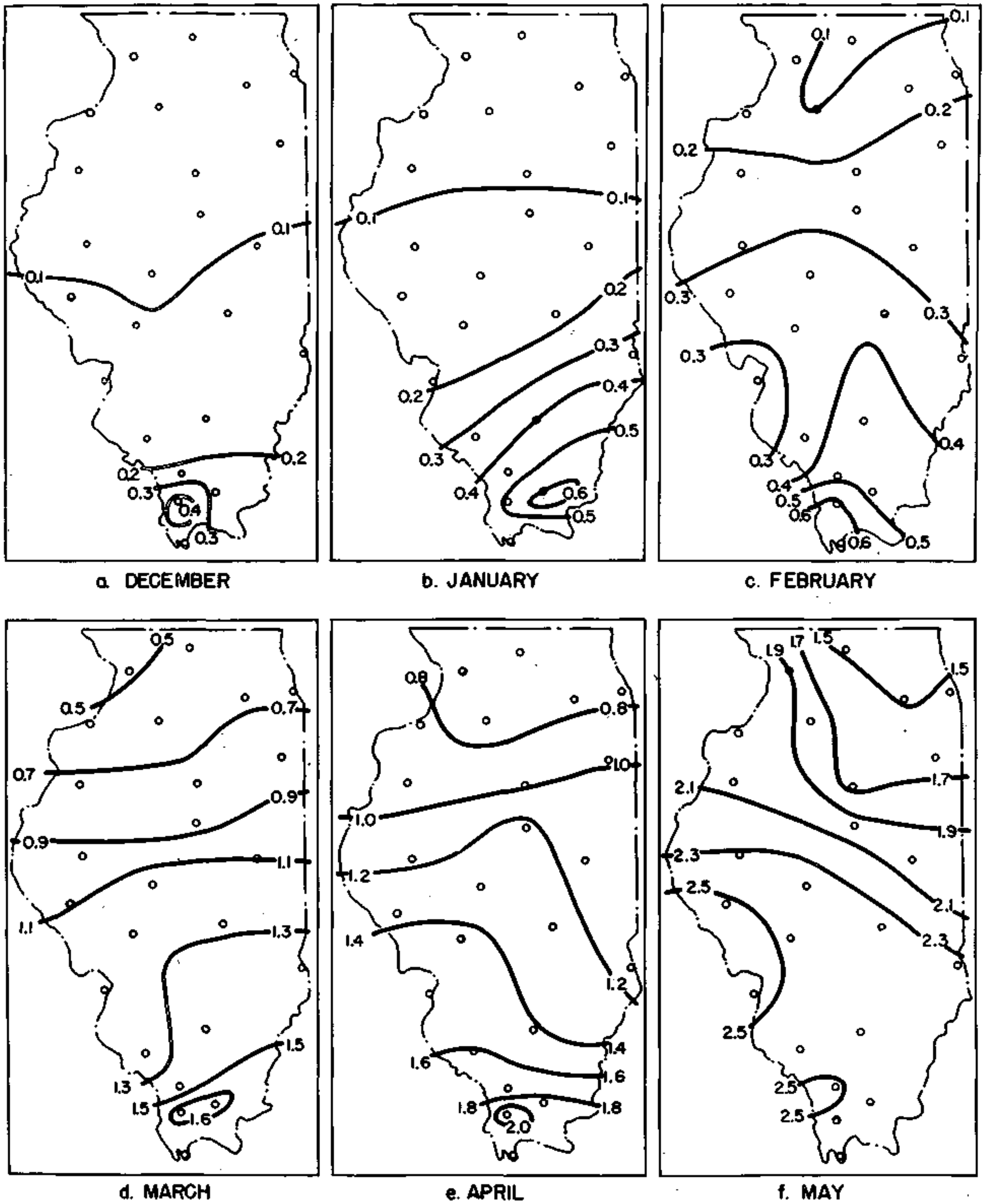
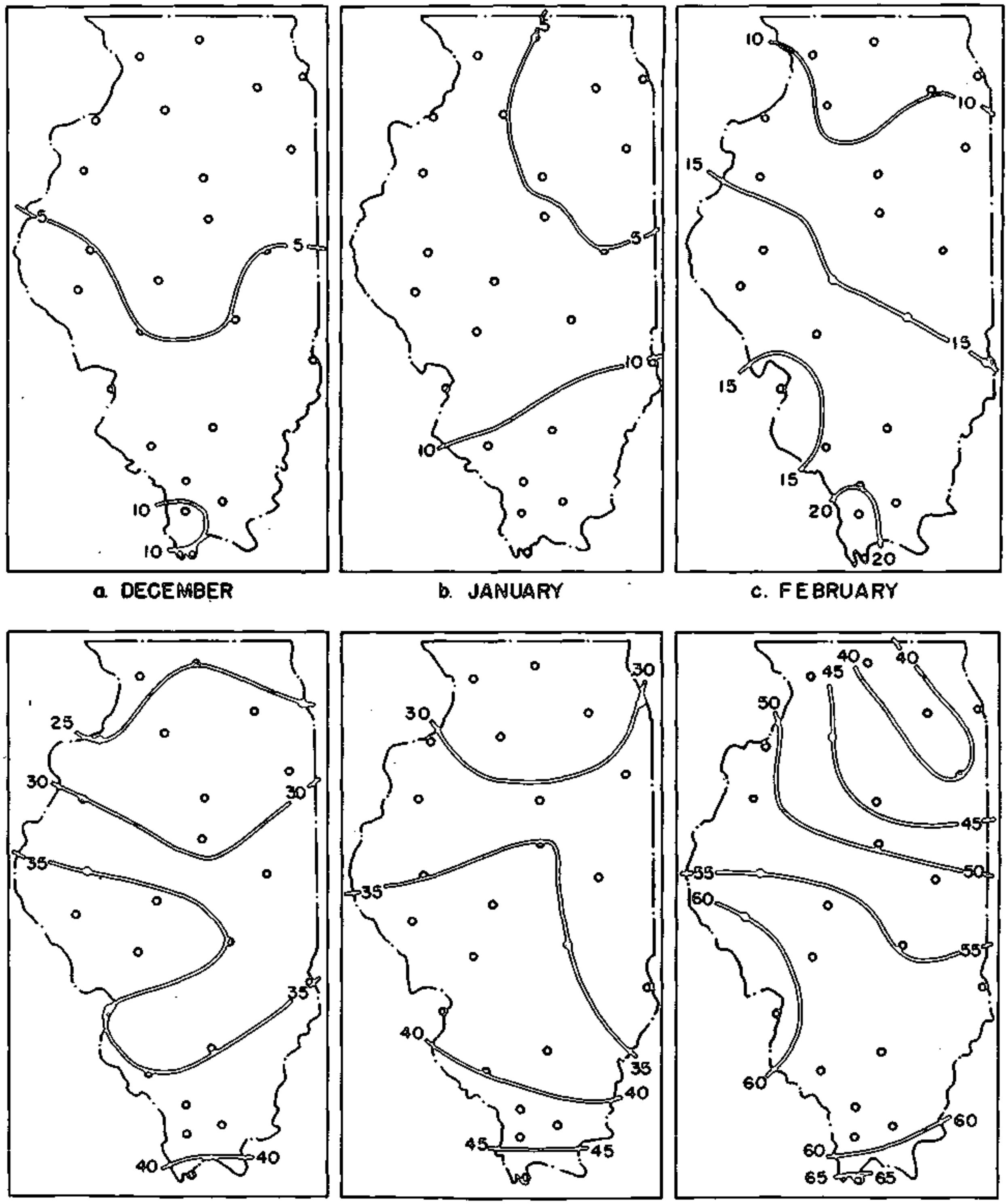


FIGURE 11. AVERAGE MONTHLY THUNDERSTORM PRECIPITATION IN INCHES, WINTER AND SPRING, 1901-1944



a. DECEMBER b. JANUARY c. FEBRUARY

d. MARCH e. APRIL f. MAY

FIGURE 12. AVERAGE PERCENT OF NORMAL MONTHLY PRECIPITATION FROM THUNDERSTORMS DURING WINTER AND SPRING SEASONS

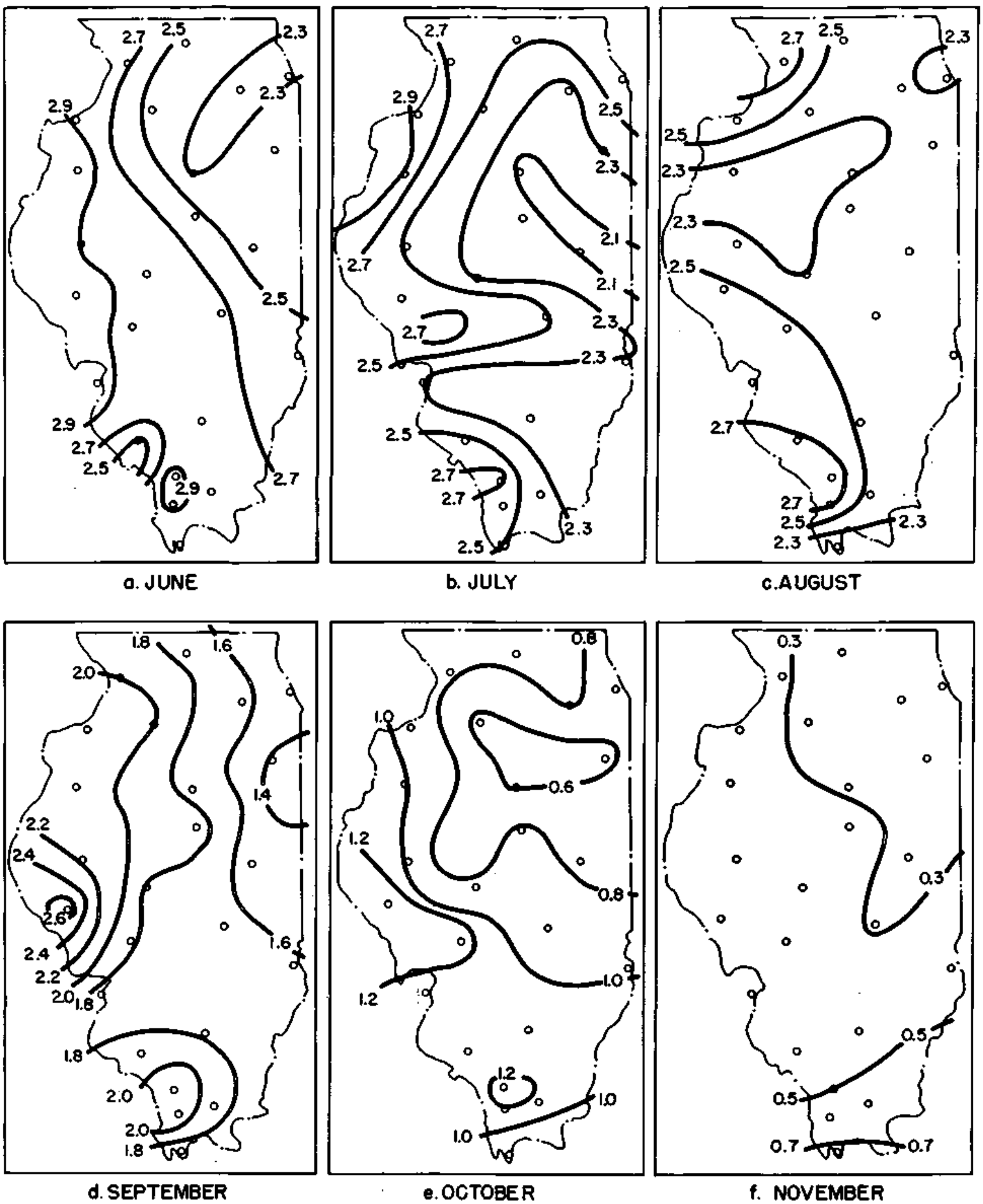


FIGURE 13. AVERAGE MONTHLY THUNDERSTORM PRECIPITATION IN INCHES, SUMMER AND FALL, 1901-1944

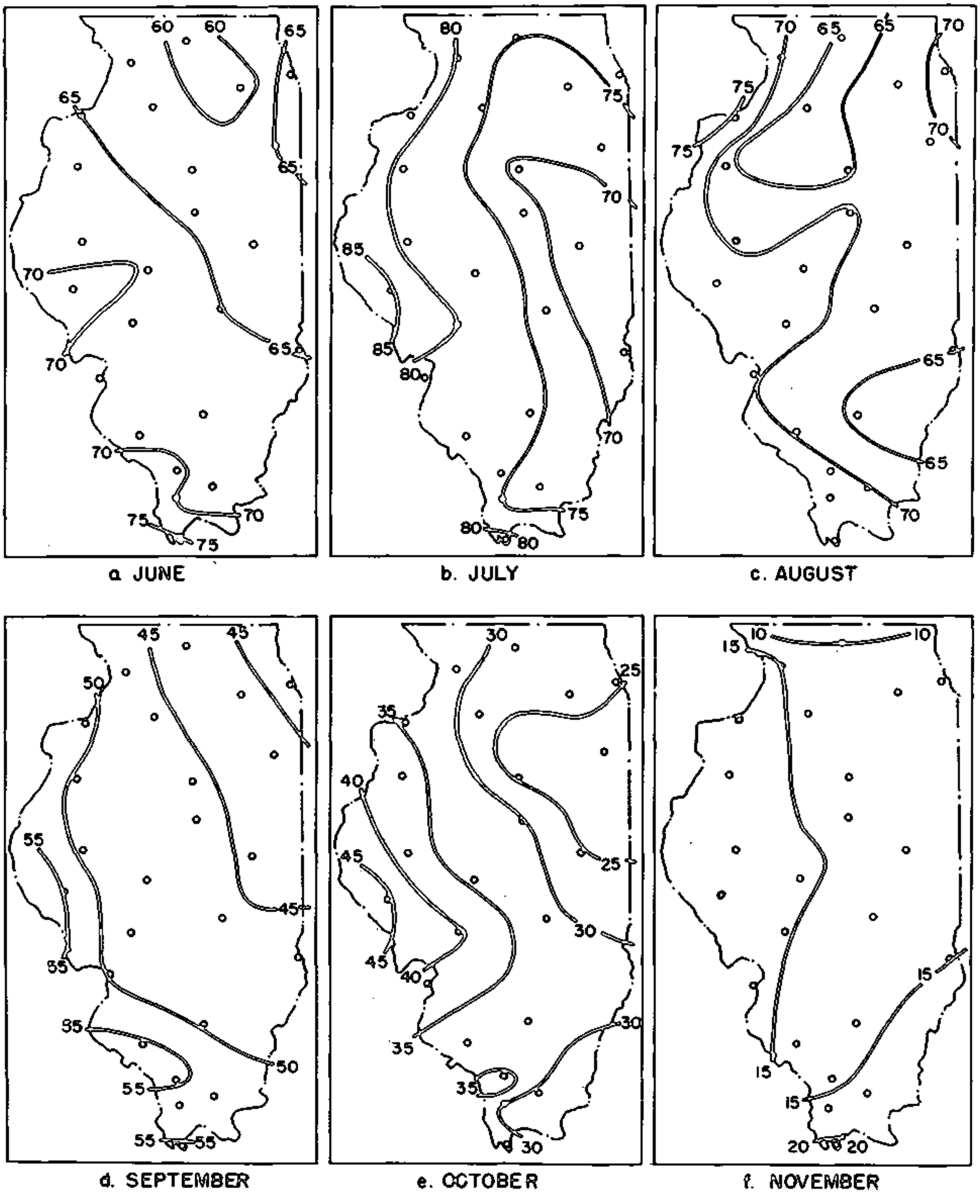


FIGURE 14. AVERAGE PERCENT OF NORMAL MONTHLY PRECIPITATION FROM THUNDERSTORMS DURING SUMMER AND FALL SEASONS

The isohyetal patterns of September, October, and November (Fig. 13) have no close associations with either the isopercental (Fig. 14) or the isoceraunic patterns in those months. However, in September the 45 isopercental line approximates the 2.4 isoceraunic line, and the 40 isopercental line in October approximates the 2.0 isoceraunic line. The recession of thunderstorm activity gulfward is reflected in October and November by the general east-west isohyetal orientation and the southward displacement of the isohyets in November.

Daily Thunderstorm Precipitation Amounts Sorted by Class Intervals

To ascertain the distribution of the daily thunderstorm precipitation amounts at each station and to examine these results for areal differences in Illinois, the daily amounts from the acceptable years of thunderstorm records of the stations were sorted into six intervals. The intervals in inches per day were 0.01-0.09, 0.10-0.25,0.26-0.49, 0.50-1.00, 1.01-2.49, and greater than 2.49. The occurrences in each interval were totaled and expressed as a percentage of the total daily thunderstorm precipitation amounts greater than a trace.

By comparing the interval percentages of the different stations, areal climatic differences in the average daily amounts can be illustrated, as well as relationships between thunderstorms and excessive 24-hour amounts. The areal percentages in each interval are presented cartographically in Figure 15. On the 0.01-0.09 inch interval map, a low percentage area based on Sparta and Mt. Vernon data is near the high percentage area of Carbondale, Anna, and Cairo. In the 0.10-0.25 inch interval (Fig. 15b) most of southern Illinois had slightly lower percentages than in the rest of the state. In the 0.26-0.49 inch interval a reversal of the southern area condition apparent in the 0.01-0.09 inch interval occurred. The Sparta-Mt. Vemon area had a higher percentage of occurrences in the 0.26-0.49 inch interval than did the Anna-Carbondale area. A random pattern was apparent in central and northern Illinois, with an unusually high percentage area in the Kankakee-Chicago area which was also evident in the 0.10-0.25 inch interval. In the 0.50-1.00 inch interval (Fig. 15d) the highest percentage area was found in south-central Illinois. The extreme southern area and the central Illinois area had lower percentages, similar to ranking in the interval from 0.26-0.49 inch. On the map for 1.01-2.49 inches (Fig. 15e), the percentages increased southward from northeastern Illinois to south-central Illinois. However, the extreme southern area had percentages lower than the area immediately north of it. The map (Fig. 15f) for amounts greater than 2.49 inches also reveals a southward increase in percentages from northeastern Illinois with the maximum area centered in the Shawnee Hill Region.

The results of this investigation of the areal distribution of daily thunderstorm precipitation amounts indicated that roughly there were five areas in Illinois each having a particular and homogeneous distribution. These approximate areas were northwestern, northeastern, central, south-central, and extreme southern Illinois.

Thunderstorms in northwestern Illinois tended to have a high percentage of amounts in the intervals between 0.26 and 1.00 inch. Thunderstorms in northeastern Illinois had a high percentage of amounts in the intervals between 0.01 and 0.49 inch.

In the central area, thunderstorms had a high percentage of amounts in the intervals from 0.01-0.25 inch. Thunderstorms in south-central Illinois had a greater percentage of higher amounts than in any other area. The south-central area had high percentages in all the intervals from 0.26 to 2.49 inches. In the south-central area, the high percentage of thunderstorm precipitation amounts in the larger amount intervals apparently causes the 17- and 19-inch isohyets (Fig. 7) to have an east-west orientation even though the isoceraunics in that area (Fig. 4) have a northwest-southeast orientation.

The extreme southern area differed significantly from the other areas, as it had high percentages in the 0.01-0.25 inch interval and in the interval greater than 2.49 inches. The southern area leads the state in the number of orographically initiated thunderstorms during the warmer half-year. These thunderstorms with their small average amounts are probably responsible for this area's abnormally high percentages in the two lowest amount intervals.

RELATIONSHIPS BETWEEN THUNDERSTORMS AND HAIL AND SLEET

Hail

Although the occurrence of hail is generally associated with the occurrence of thunderstorms, the geographic distribution of the two in the Middle West is not the same. [4] Therefore, it was necessary to investigate the thunderstorm-hail association in Illinois for areal variations. The results of this analysis, as shown in Figure 16, reveal that the isopercental association lines have an orientation similar to the isopercental lines in Figure 7 and the isoceraunic lines in Figure 4. The percentage of hail occurring with thunderstorms decreased from the south and west towards the north and east. This eastward decrease is also characteristic of the average distribution of hail occurrences in Illinois [6] with an eastward decrease from the area of maximum activity in Kansas and Nebraska.

Hail in Illinois is usually associated with frontal activity, the same as thunderstorms. During the spring the areas of hail and thunderstorm activity are quite similar; but in the winter and summer, hail occurs more frequently without thunder being reported. Results of the

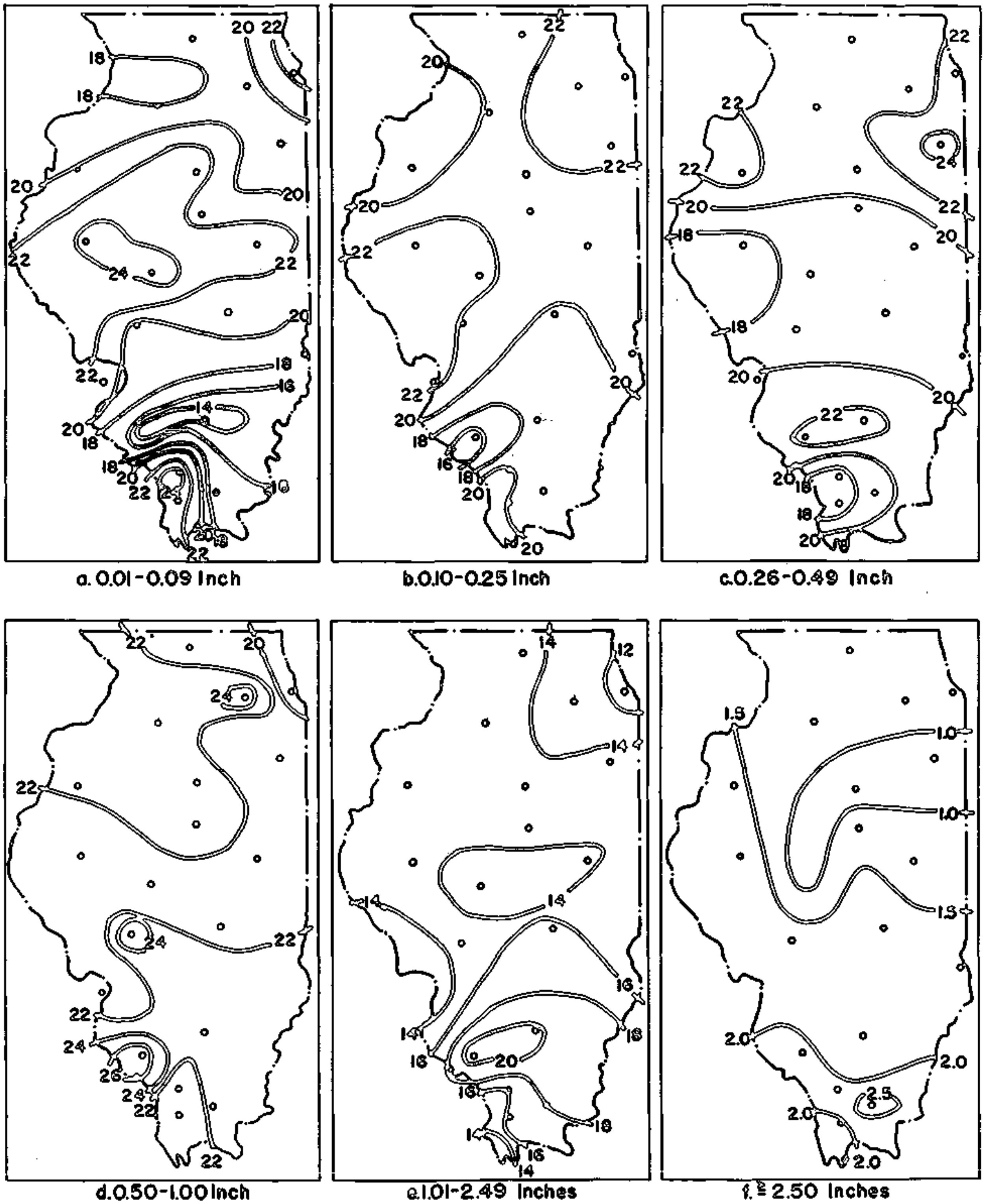


FIGURE 15. PERCENT OF TOTAL THUNDERSTORM PRECIPITATION AMOUNTS IN SIX INTERVALS

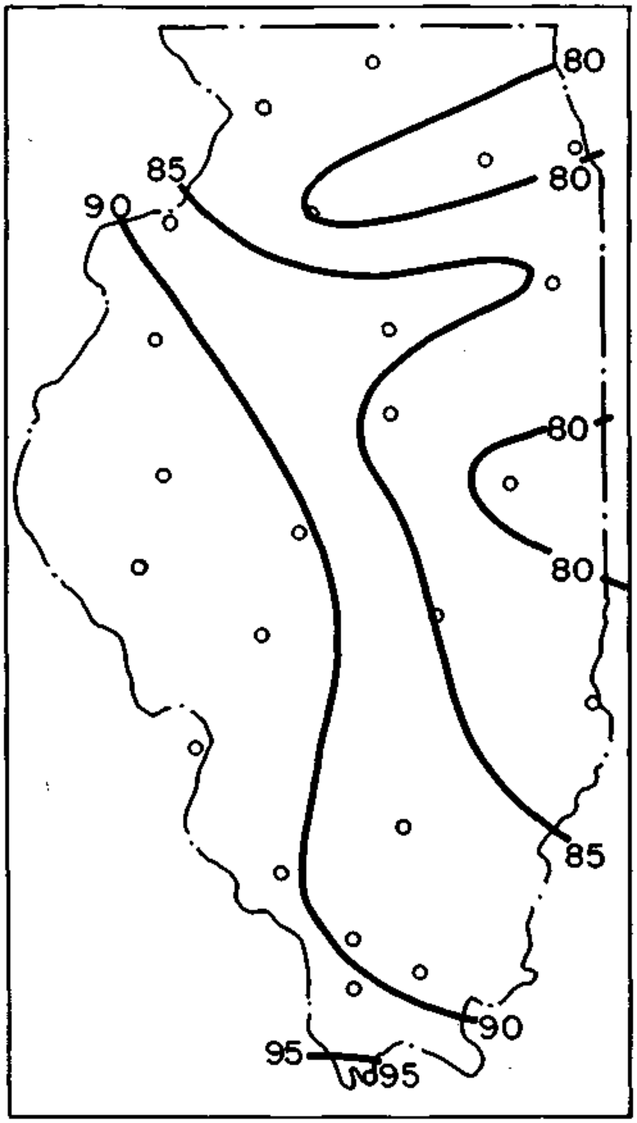


FIGURE 16. PERCENT OF HAIL REPORTED OCCURRING WITH THUNDERSTORMS, 1901-1954

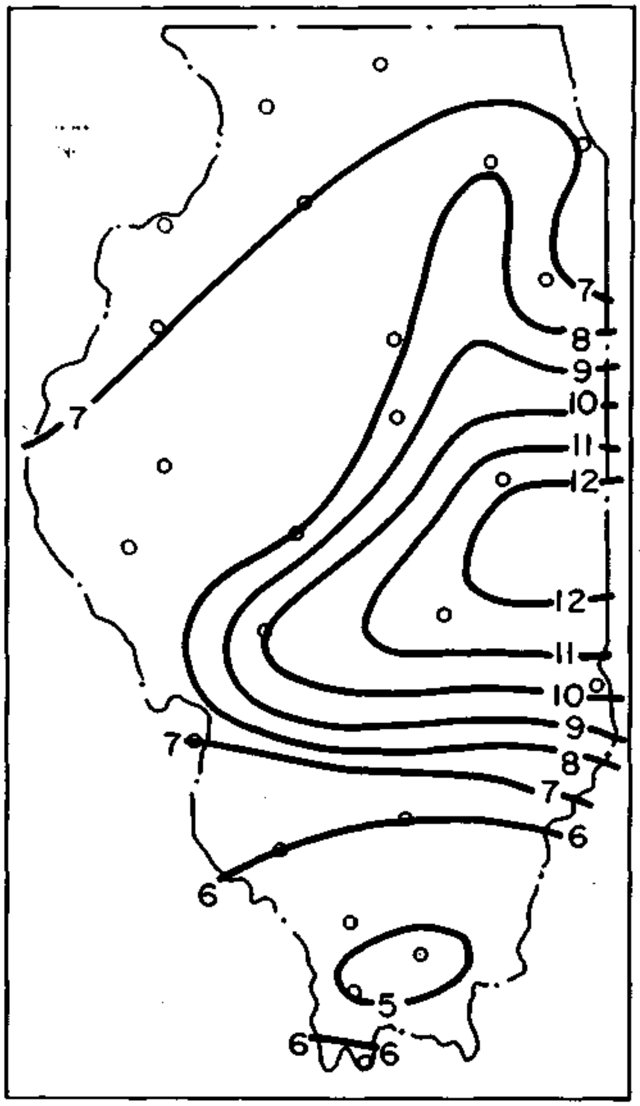


FIGURE 17. PERCENT OF SLEET REPORTED OCCURRING WITH THUNDERSTORMS, 1901-1954

study indicate that, in Illinois, 80 percent or more of all hail occurred with thunderstorms, and the frequency of simultaneous daily occurrences tended to increase in proportion with increasing thunderstorm occurrences.

Sleet

The occurrence of sleet is usually not considered to be directly associated with the occurrence of thunderstorms in the winter. However, the degree of association between the two phenomena and the areal variations of their association were investigated although reporting of sleet cannot be considered too accurate. Some frontal activity in the colder half-year produces thunderstorms and sleet on the same day.

The area of maximum simultaneous occurrences was in east-central Illinois, as shown in Figure 17. However, the highest percentage of sleet occurring on the same day with thunderstorms was 12 percent, which cannot be considered to be a close association between the occurrence of these two phenomena.

The area with the highest number of combined thunderstorm and sleet occurrences is east-central Illinois (Fig. 17). This location is indicative of two interacting winter climatic conditions. The first is the northward decrease of thunderstorms, and the second is the southward decrease of sleet occurrences. These conditions consequently are more likely to occur simultaneously in central Illinois. The areal associations between sleet and thunderstorms on the same day are considered to be more chance than a cause-and-effect relationship between the two events.

REFERENCES

1. Byers, H. R., and Braha m, R. R., The Thunderstorm, Washington, D. C: U. S. Government Printing Office, 1949.

2. Changnon, S. A., First Progress Report of the Illinois Cooperative Project in Climatology, Circular No. 50, Urbana, Illinois: Illinois State Water Survey, 1956.

3. Changnon, S. A., Second Progress Report of the Illinois Cooperative Project in Climatology, Circular No. 57, Urbana, Illinois: Illinois State Water Survey, 1956.

4. United States Department of Commerce, Weather Bureau, Thunderstorm Rainfall, Hydrometeorological Report No. 5, Vicksburg, Mississippi: 1947.

5. Means, L. L., The Nocturnal Maximum Occurrence of Thunderstorms in in the Midwestern States, Miscellaneous Report No. 16, Chicago: University of Chicago, 1944.

6. Harrison, H. T., A Re-Examination of Hail Patterns Over Western United States, UAL Meteorology Circular No. 35, Denver, Colorado: United Air Lines, Inc., 1950.