35

Research Report No. 10

CORRELATION BETWEEN SUMMER HAIL PATTERNS IN ILLINOIS AND ASSOCIATED CLIMATOLOGICAL EVENTS

by

P. A. Huff

Illinois State Water Survey
Urbana, Illinois

Prepared for

Crop-Hail Insurance Actuarial Association
209 West Jackson Boulevard
Chicago 6, Illinois

December 15, 1961

TABLE OF CONTENTS

CORRELATION BETWEEN SUMMER HAIL PATTERNS IN ILLINOIS AND ASSOCIATED CLIMATOLOGICAL EVENTS

by

Floyd A. Huff

INTRODUCTION

An investigation was made of the correlation between the areal distribution of hail in summer in Illinois and the distribution patterns of related climatological factors. This study was undertaken in an effort to obtain basic information which could eventually lead to a better definition of the spatial distribution of hail, and, consequently, facilitate the determination of hail insurance rates throughout the state. Furthermore, it was anticipated that the study might, to some small extent, contribute to better understanding of the interrelationship of atmospheric events which produce our weather and climate. Because of the primary interest of the contractor in hail distribution during the period when crops are most susceptible to damage, the correlation study was restricted to the summer season, defined here as the months of June through August. Correlations were made between the distributions of hail and thunderstorms, rainfall, air temperature, dew point temperature, and synoptic weather fronts.

DATA USED

The summer hail distribution pattern obtained by Huff and Changnon, based upon a 50-year sampling period from 1901 through

1950, was used in the correlation analyses. This pattern is illustrated in Figure 1, which shows the number of days with hail in an average 10-year period. Two peaks are indicated, one in northwestern Illinois and the other in the west-southwestern part of the state. Minimum occurrences are indicated along the upper portion and west of the central portion of the Illinois River Valley, and in the extreme southern part of the state.

Figure 2 shows the average number of days with thunderstorms in summer, based upon all available records of the U. S. Weather Bureau from 1901 through 1954. An increase in thunderstorm frequency is indicated westward and southward from a minimum in northeastern Illinois. In Summer, nearly all hailstorms occur in conjunction with thunderstorms; thus, the inclusion of thunderstorm days in the correlation analyses appeared necessary.

Normal rainfall for the June-August period is shown in Figure 3, based upon the 50-year period, 1906-1955. Peaks are indicated in northwestern Illinois and in the Shawnee Hills of southern Illinois. Minimum rainfall regions are indicated in the extreme southern part of the state and east of the Illinois River Valley from the vicinity of Chicago to Springfield. However, extreme differences do not appear within the state, most of which lies within the rainfall range from 10.0 to 11.5 inches. Since most of the summer rainfall in Illinois is convective in nature and hail is a product of strong convection in the atmosphere, selection of rainfall as one of the correlating factors appeared desirable.

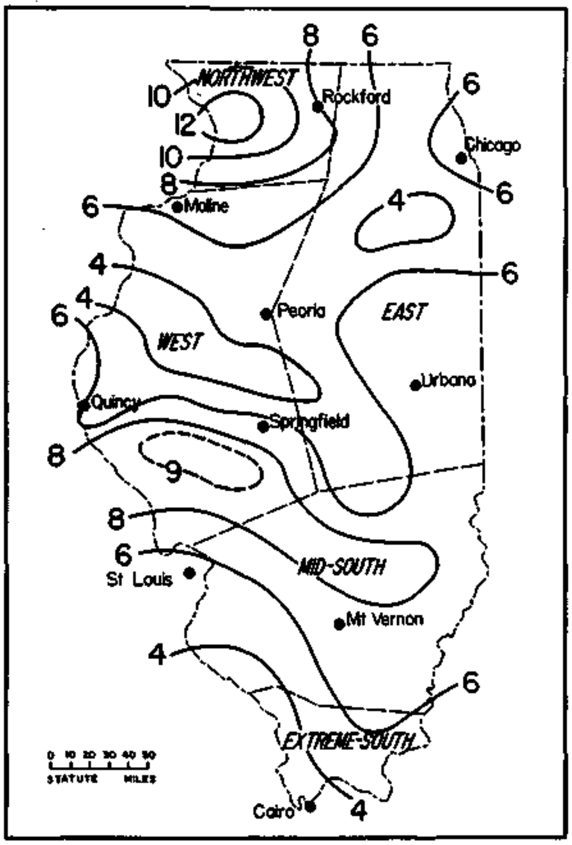

FIG. I SUMMER AVERAGE HAIL DISTRIBUTION EXPRESSED AS NUMBER OF DAYS WITH HAIL PER 10-YEAR PERIOD

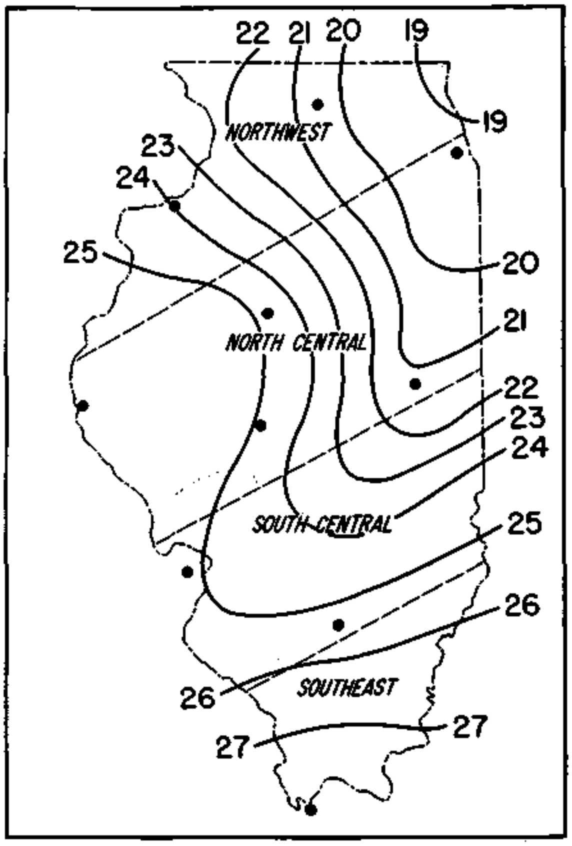

FIG. 2 AVERAGE NUMBER OF DAYS WITH THUNDERSTORMS IN SUMMER

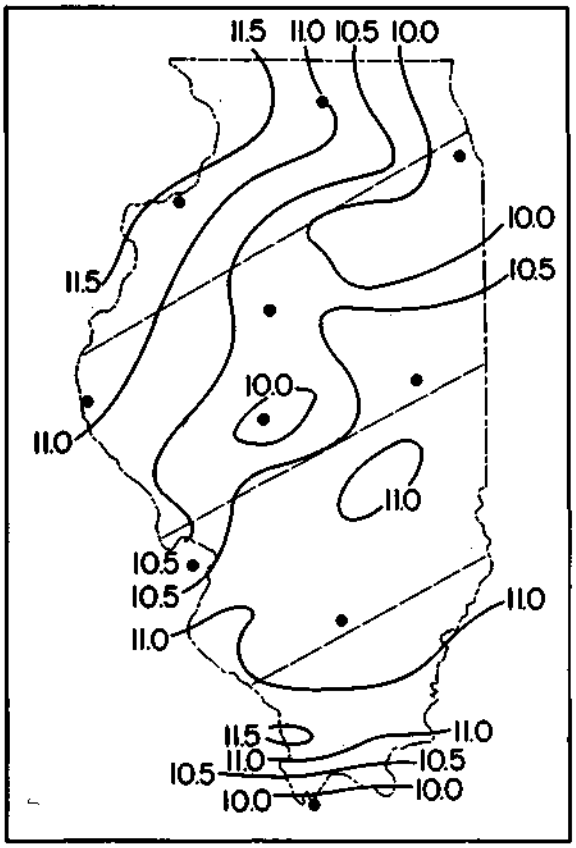

FIG. 3 NORMAL RAINFALL (IN.) IN SUMMER

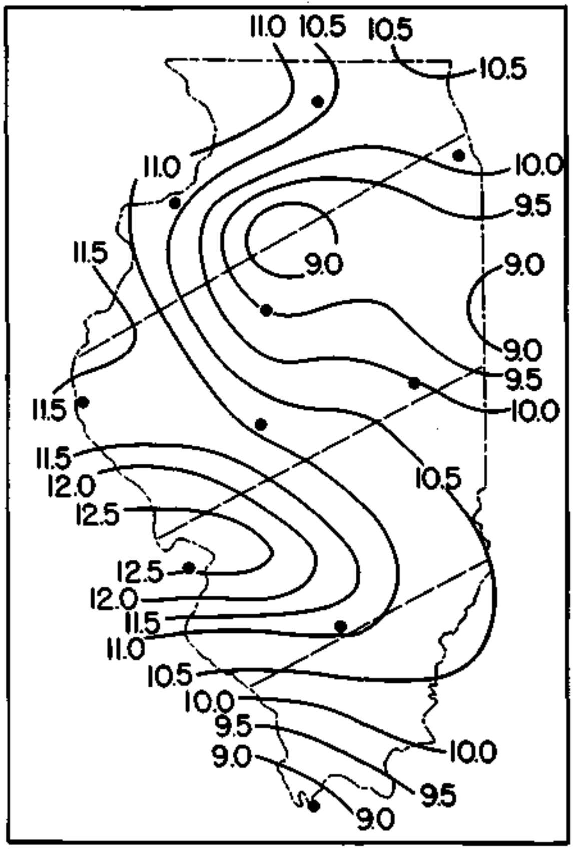

FIG. 4 DISTRIBUTION OF FRONTS IN SUMMER (BASED ON LOCATIONS AT 0030 CST, 1945-59)

The distribution of fronts in Illinois, based upon a study by Chiang, is shown in Figure 4. This distribution includes all types of fronts and was obtained from the daily weather maps printed by the U. S. Weather Bureau during the 15-year period, 1945-1959. The results are based upon data for 0000 CST, and the lines are labeled in terms of total number of frontal occurrences during the 15-year sampling period. Figure 4. shows a maximum frequency of fronts in southwestern Illinois, eastward from St. Louis. This maximum region results largely from the tendency of cold fronts to slow down or stagnate in this area. Minimum frontal occurrences are in north central to east central Illinois and in the extreme southern portion of the state, according to Figure 4. In a study of widespread hailstorms in Illinois, Huff[3] found that 86 percent of these storms occurred in conjunction with fronts. He also found that, on the average, 81 percent of all hail occurrences at a given point occur in conjunction with fronts. Consequently, it was deemed desirable to include the frequency distribution of fronts in the correlation study.

Figure 5 shows the pattern of daily mean maximum temperature for the summer season, based upon U. S. Weather Bureau normals for the period 1931-1952. Temperature provides a measure of the magnitude of the daily solar heating of the ground surface and the moisture capacity of the air, both of which are intimately linked to the precipitation process, and, consequently, to the development of hailstorms, heavy rainstorms, and other severe weather events. Therefore, the inclusion of maximum temperature distribution in the correlation study appeared logical. Maximum temperature was chosen instead of daily mean temperature because hail occurs most frequently during and shortly after the period of maximum diurnal heating.

Figure 6 shows the distribution of mean noon dew point temperature for the June-August period,, Dew point temperature provides a readily available measure of the low-level moisture content of the atmosphere, and since moisture content is necessary to develop and sustain precipitation, the dew point distribution was included In the list of correlating factors. Noon and mean daily dew point data were available from previous studies by the Marley Company[4] and from unpublished studies of the Illinois State Water Survey. Because the noon dew point represents a measurement near the time of most frequent development of hailstorms, it was considered a more appropriate parameter than the mean daily value.

Reference to Figures 1-6 indicates that simple correlation of the hail distribution pattern with each of the five selected climatological factors will not produce high correlation coefficients. However, one purpose of the study was to obtain a mathematical measure of the degree of relationship, regardless of its significance. Furthermore, the primary objective was to determine multiple correlation coefficients from various groupings of the Independent variables, and the multiple correlation relationship is seldom obvious from a cursory examination of the data.

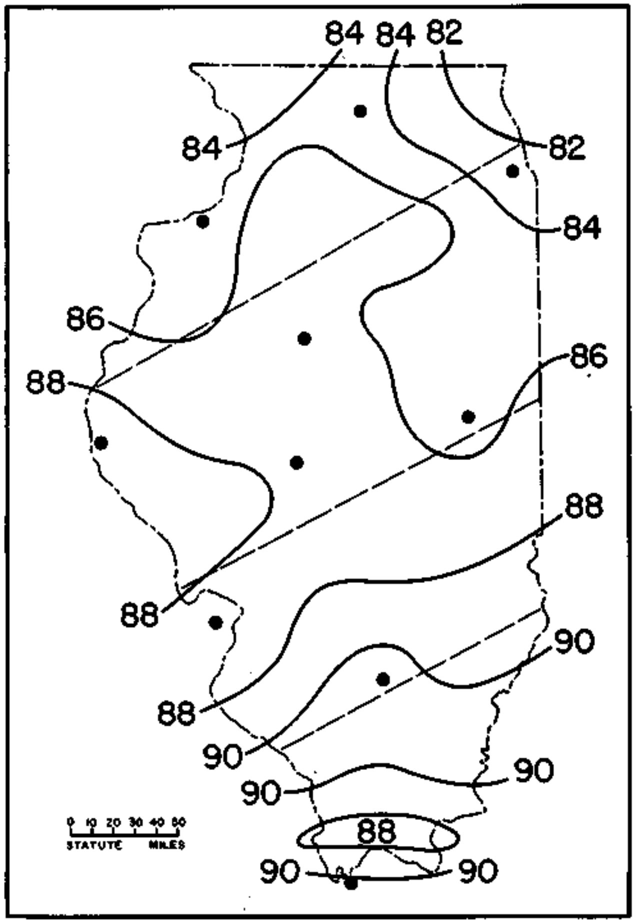

FIG. 5 DAILY MEAN MAXIMUM TEMPERATURES (° F) IN SUMMER

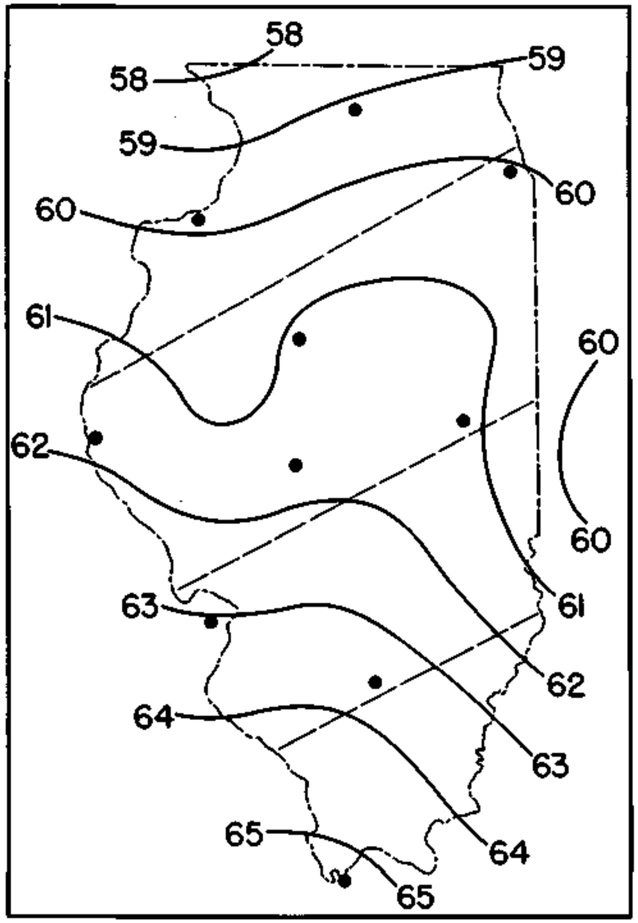

FIG. 6 AVERAGE NOON DEW POINT (° F) IN SUMMER

ANALYTICAL PROCEDURE

The patterns shown in Figures 1-6 were assumed to portray accurately the distribution patterns of the various climatological factors used in this study. It is recognized that some of the variables are based upon longer or different periods of record than others and that the number of sampling points varies among the six elements. However, these are the best estimates of the statistical population presently available for study, and it is believed that they are closely representative of the true distributions. Fortunately, the most variable of the elements, hail, thunderstorms, and rainfall, are based upon 50-year records at a relatively large number of sampling points.

In order to obtain a mathematical definition of each of the climatological patterns of Figures 1-6 for correlation analysis, a grid overlay with squares 15 miles by 15 miles (225 sq. mi.) was placed over each map. Values were recorded at the center of each grid square and this provided a total of 268 points to define the distribution pattern of each element. As stated above, the purpose of this procedure was merely to define the pattern for mathematical analysis, based upon the assumption that each pattern is closely representative of the true distribution. It is not implied that observations were available at 268 points.

The next step was to divide the state into areas of approximate climatic homogeneity, based upon the meteorological elements involved in the study. No clear-cut division of the state was apparent for the combination of variable involved. Consequently, correlation analyses were made for each of four possible state divisions, selected after considerable evaluation of the various climatological factors involved in the study. As indicated earlier, correlation coefficients were then determined between the hail distribution and the distribution of each of the five independent variables. Next, multiple correlation coefficients were calculated between hail and various combinations of the five associated elements of Figures 2-6. Digital computer facilities at the University of Illinois were employed to facilitate the extensive calculations involved in pursuing the above procedure.

State divisions tested included;

1. Division of the state into two nearly equal parts, the northern one-half and the southern one-half.
2. Division of Illinois into two parts, the northern three-fourths and the southern one-fourth.
3. Grouping of the state into five sections, based upon similar surface characteristics. This division is illustrated in Figure 1, and was arrived at from consideration of topography, soil type and color, and land use (Table 1).
4. Division into four sections corresponding to those used by Huff and Neill[5] in a study of extreme rainfall events. This division, shown in Figure 2, was determined from statistical studies of severe rainstorm probabilities in Illinois.

TABLE 1

AREAS OP SIMILAR SURFACE CHARACTERISTICS

Area	Topography	Soil	Land Use
Northwest	Hill lands, steep slopes, mature dissection	Light to med. brown	Forests, pasture, minor cropping
East	Flat lands, no steep slopes	Dark brown to black	Mainly grain crops, very few forests
West	Flat to undulating	Medium brown	Grain farming, pasture, few valley bottom forests
Mid-South	Minor hill lands	Light to med. yellow	Mainly mixed farming (grains and garden crops), some valley bottom forests
Extreme South	Hilly, locally steep slopes, mature dissection	Med. gray and brown	Mostly forests and orchards, some pasture, minor cropping

RESULTS OF ANALYSES

Correlation Analyses

As one would expect from an examination of Figures 1-6, poor correlation was obtained, in general, between the hail distribution and each of the five individual independent variables employed in the study, when simple correlation analysis was employed. Furthermore, the simple correlation coefficients showed a rather erratic pattern between sections within each state division and between the several divisions tested. However, when multiple correlation of all the variables was applied, a great improvement was obtained in all divisions. Of the four division methods tested, the Huff-Neill method and the division based upon similar surface characteristics appeared superior. Further discussion of results will be restricted to these divisions.

Table 2 shows multiple correlation coefficients (R) and coefficients of determination (R2) for each section of the state division based on similar surface characteristics (Fig. 1). Table 3 shows similar data for the Huff-Neill division (Fig. 2). Table 2 shows correlation coefficients ranging from 0.73 to 0.96 with the highest correlations in the hill country of the Northwest and Extreme South Sections and the lowest correlation in the Mid-South Section. Table 3 shows the highest correlation coefficients in the Northwest and Southeast Sections, which include within their boundaries the Northwest and Extreme South Sections of Table 2. Correlation coefficients of 0.75 were obtained in the North Central and South Central Sections which include about 65 percent of the area of the state.

The results of the multiple correlation analyses presented in Tables 2 and 3 indicate little difference in the two methods of climatological division for the state. It was hoped that the grouping by topography, soil, and land use might materially Improve the correlations, but this did not happen. Therefore, the remaining discussion will be limited to the Huff-Neill classification which has been used in other State Water Survey studies.

Prom Table 3 it Is evident that the major portion of the variance in the hail distribution pattern in the Northwest and Southeast Sections, encompassing about 35 percent of Illinois, can be explained by consideration of the effects of the distributions

TABLE 2

MULTIPLE CORRELATIONS WITHIN AREAS OP SIMILAR SURFACE CHARACTERISTICS

Section	Multiple Correlation Coefficient	Coefficient of Determination (%)
Northwest	0.96	92
West	0.82	67
East	0.78	61
Mid-South	0.73	53
Extreme South	0.91	83

TABLE 3

MULTIPLE CORRELATIONS WITHIN FUFF-NEILL SECTIONS

Section	Multiple Correlation Coefficient	Coefficient of Determination (%)
Northwest	0.91	83
North Central	0.75	56
South Central	0.75	56
Southeast	0.95	90

of thunderstorms, rainfall, fronts, maximum air temperature, and dew point temperature. As indicated by the coefficients of determination, 83 percent and 90 percent, respectively, of the variance in the hail pattern in the Northwest and Southeast Sections are explained by the five independent variables. It seems quite possible that all or most of the remaining variance in these sections may be accounted for by sampling errors. In the North Central and South Central Sections, however, only 56 percent of the variance in the hail distribution has been explained by the independent variables used in this study. Thus, one must conclude that other factors important in establishing the hail pattern in these regions have not been taken into consideration.

After obtaining the above results, two modifications were attempted in an effort to improve the multiple correlations. First, a normalized frontal frequency pattern was substituted for the distribution shown in Figure 4. This normalized distribution was obtained by weighting the cold front, warm front and stationary front patterns of Chiang[2] according to the percentage frequency with which each front is associated with hailstorms, according to the study by Huff.[3] This produced a frontal frequency pattern dictated to a large extent by the cold front pattern, since over 70 percent of the frontal hailstorms occur with cold fronts. No significant improvement in the correlations was obtained with the normalized frontal pattern.

Next, the hail-thunderstorm ratio was correlated with the temperature, dew point, rainfall, and frontal distributions. Again, no significant improvement in correlation was obtained, as can be seen in Table 4 where multiple correlations are presented for the Huff-Neill sections.

TABLE 4

HAIL-THUNDERSTORM RATIO VS. TEMPERATURE, DEW POINT, RAINFALL AND FRONTS

Section	Multiple Correlation Coefficient	Coefficient of Determination (%)
Northwest	0.91	83
North Central	0.62	38
South Central	0.86	74
Southeast	0.98	96

Regression Analyses

As a final step in the study, regression equations were determined for each of the four sections of the state, and a map of summer hail distribution constructed from these equations. The sectional data were fitted to an equation of the form:

$$Y = a + bX_1 + cX_2 + dX_3 + eX_4 + fX_5$$

where Y is hail frequency, X_1 to X_5 represent the frequency distributions of thunderstorms, maximum temperature, mean rainfall, noon dew point, and fronts, and a, b, c, d, e, and f are regression constants. The regression constants for each section are shown in Table 5. The hail distribution map constructed from the sectional regression equations is shown in Figure 7.

Except for minor deviations, the computed hail pattern compares favorably with the hail distribution pattern of Figure 1, which is based on observed hail occurrences. The high center in northwestern Illinois is displaced a little northward from its

TABLE 5

SECTIONAL REGRESSION CONSTANTS.

Section	Regression Constants a	b	c	d	e	f
Northwest	+60.32	-0.52	+0.35	+2.92	-1.62	-0.06
North Central	-132.20	-0.77	+0.87	+0.73	+1.09	+0.06
South Central	+6.86	-0.52	+0.96	-0.33	-1.36	+0.14
Southeast	+33.09	+0.72	-0.31	-0.65	-0.57	+0.24

position in Figure 1 into the region of highest elevations in the state. The low center west of the Illinois River in Figure 1 has been displaced a few miles northward on the computed map of Figure 7, and the high center in west-southwestern Illinois has been displaced southwestward. The computed high center lies a few miles east and north of regions of steep topographic gradients, among the steepest in the state.

On Figure 7, the region of most frequent and least frequent occurrences of stagnating fronts in summer has been indicated, based on the Chiang study.[2] It is interesting to note that the high center in west-southwestern Illinois lies just to the north of the region of maximum frequency of stagnating fronts, which are the source of frequent wave action, and, consequently, represent a region of greater instability with respect to the surrounding area. The presence of the stagnating front maximum and unusually steep topographic gradients just south of the hail center may be primarily responsible for this anomaly in the hail distribution. Also, Figure 7 indicates that the region of minimum

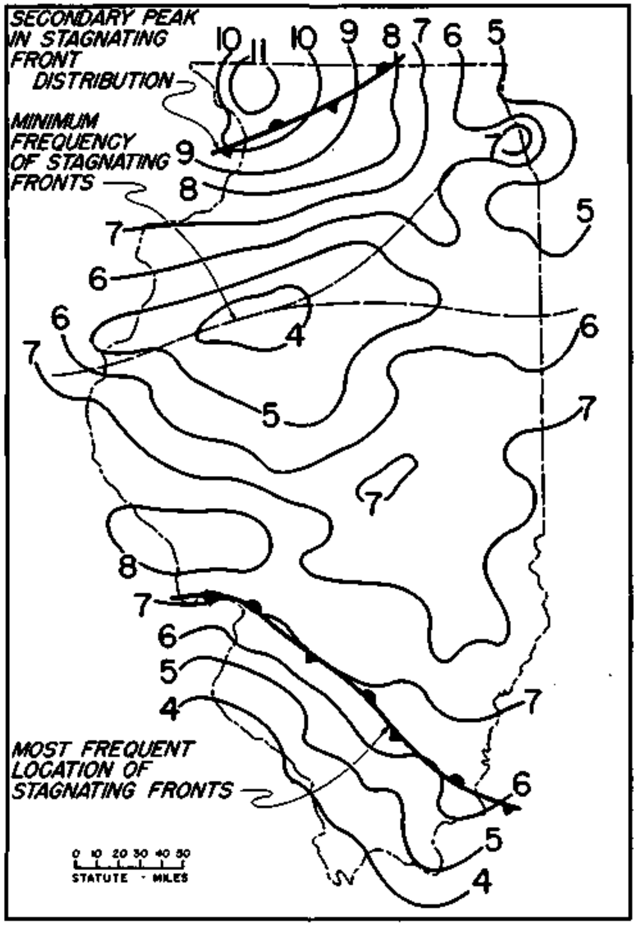

FIG. 7 SUMMER AVERAGE HAIL PATTERN COMPUTED FROM REGRESSION ANALYSIS (Expressed as Number of Days with Hail per 10-Year Period)

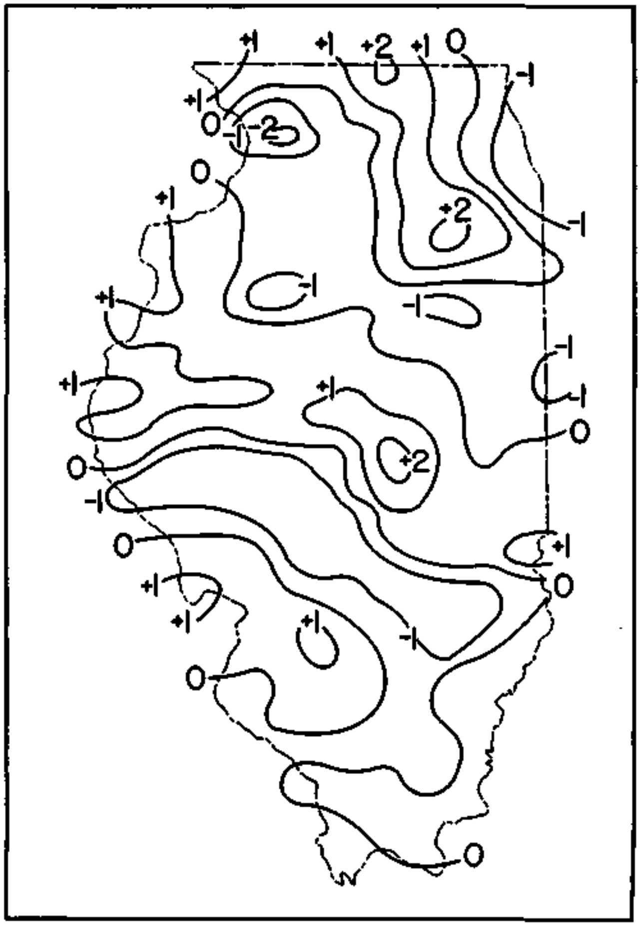

FIG. 8 DIFFERENCES BETWEEN OBSERVED AND COMPUTED SUMMER HAIL PATTERNS (Expressed as Number of Days with Hail per 10-Year Period)

frequency of stagnating fronts corresponds well with the region of minimum hail frequency, except for the Chicago region. A secondary maximum in the stagnating frontal distribution lies a few miles south of the hail maximum in the northwestern part of the state.

Figure 4 shows a similar relation between the frequency of all fronts and the zone of maximum hail frequency in west-southwestern Illinois in Figure 7° Also, Figure 4. shows close correspondence between the hail maximum in northwestern Illinois and a ridge in the frontal frequency pattern. The region of minimum frontal frequency in Figure 4 lies somewhat to the south of the minimum hail zone of Figure 7. In general, it appears that close association exists between the frontal frequency patterns of Figures 4 and 7 and the hail pattern of Figure 7 with respect to areas of maximum and minimum occurrences, particularly when sampling errors involved in the establishment of these patterns are considered.

In Figure 8, the differences between the observed and computed patterns of Figures 1 and 7 have been shown. Examination of Figure 8 shows small differences, in general, except for regions where major centers have been displaced between Figures 1 and 7. Figures 7 and 8 indicate that the summer hail distribution pattern in Illinois can be satisfactorily explained by relating it to the multiple effects of other climatic events, whose distribution is dictated by atmospheric conditions related to hail development. The lower multiple correlation coefficients obtained in the North

Central and South Central Sections compared to the other two sections, based on the hail pattern of Figure 1, may have been largely due to displacement of the frontal centers from the hail centers and improper location of the low and high centers due to sampling inadequacies. Although the hail and frontal high centers do not coincide in the North Central and South Central Sections (Fig. 7), the displacement is logical and may have led to a fallaciously low correlation when it was not taken into account in the analysis.

SUMMARY AND CONCLUSIONS

Correlation analyses were employed to investigate the relationship between the summer hail pattern in Illinois and the climatological distribution of other meteorological elements, after dividing the state into sections with similar climatological characteristics. Thunderstorm, maximum temperature, dew point temperature, rainfall, and frontal distributions were correlated with the hail distribution. Simple correlation of the hail distribution with each of the meteorological elements produced poor correlation coefficients, in general, and these coefficients exhibited an erratic pattern between sections. However, great improvement was obtained when multiple correlation analysis was performed to determine the relation between the hail distribution and the combination of all five meteorological elements. In the northwestern and extreme southern sections of the state the correlation coefficients exceeded 0.90. Over the rest of the state, however, the coefficient lowered to 0.75.

Regression equations were determined for each of the four sections by relating the hail distribution to the five meteorological elements listed above, and a computed hail pattern for the state was constructed from these equations. The computed hail pattern compared closely with the observed hail pattern, except for minor displacement of high and low centers. The displacements on the computed map appear logical, particularly when frontal distribution patterns and topographic factors are taken into consideration. Analysis indicated that logical displacement of maximum and minimum centers of frontal activity from corresponding centers of hail occurrence may have led to fallaciously low correlation coefficients in the North Central and South Central Sections of the state, since displacement effects were not considered in the correlation analysis.

Although this study has not provided the complete answer to the cause of the summer hail distribution in Illinois, it is believed that the results do appreciably advance our knowledge on this subject. Indications are that in a region of minor topographic influences, such as Illinois, the hail distribution can be explained largely by relating it to the multiple effects of other climatic events, whose distribution is determined by atmospheric conditions which are related to hail development. Frequently, the distribution patterns of these climatic events are better defined than the hail distribution, and refinement of the hail distribution may be feasible through consideration of their relationship to hail. The Illinois study suggests that the frontal distribution pattern strongly influences the location of centers of maximum hail frequency, especially when the frontal pattern tends to maximize in regions of relatively strong topographic gradient with respect to the surrounding area.

Further attempts could be made to improve the relationship between the summer hail distribution and the distribution of associated meteorological elements. Correlation of data for individual months rather than for 3-month periods would be desirable since certain relations may have been masked to some extent by the seasonal grouping. Also, the displacement factor could be integrated into the correlation analysis, particularly in the case of frontal distributions. Possibly, the hail climatological pattern in Illinois is dependent in some regions upon storm developments to the southwest, west, and northwest in bordering states, and a study of this possible relationship would be desirable. Time and personnel limitations have not permitted further investigations, such as suggested above.

REFERENCES

1. Huff, P. A. and S. A. Ghangnon, Jr., *Hall Climatology in Illinois*, Report of Investigation 38, Illinois State Water Survey, Urbana, 111., 1959.

2. Chiang, I-min, *A Study of Synoptic Climatology in Illinois*, Master's Thesis, Southern Illinois University, Carbondale, 111., 1961, unpublished.

3. Huff, P. A., *Relations Between Summer Hailstorms in Illinois and Associates Synoptic Weather*, Research Report No. 5, prepared for Crop-Hail Insurance Actuarial Association, Chicago, Ill., by Illinois State Water Survey, Dec. 1960.

4. Anon., *Summer Weather Data*, the Marley Company, Kansas City, Kansas, 1944.

5. Huff, P. A. and J. C. Neill, *Frequency Relations for Storm Rainfall in Illinois*, Bulletin 46, Illinois State Water Survey, Urbana, Ill., 1959.