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Spatial and Temporal Correlation of Precipitation in Illinois

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ABSTRACT

Analyses were made of the correlation patterns of annual, seasonal, monthly, storm, and partial storm precipitation in Illinois, with major emphasis on the warm season months of May-September when convective rainfall dominates and spatial variability maximizes. Data were from the climatic network of the National Weather Service in the annual analyses, and that from dense raingage networks of the State Water Survey in the seasonal, monthly, and storm analyses. Results provide knowledge and basic information concerning the spatial and temporal distribution characteristics of precipitation. This is needed in various endeavors, such as hydrologic studies, weather modification experiments, and agricultural research in which precipitation sampling to meet certain standards of accuracy is pertinent to the success of the project.

INTRODUCTION

The problem of accurately representing the spatial and temporal distribution of precipitation frequently arises in hydrologic investigations, weather modification experiments, and agricultural research. Primarily, the problem is one of determining the measurement requirements (number of raingages) to maintain the sampling error of point and/or areal mean rainfall within acceptable limits for a particular research or operational project. The sampling requirements depend upon the precipitation event that is to be measured. Depending upon the application, this could be annual, seasonal, monthly, storm, or partial storm precipitation amounts.

One method of evaluating raingage sampling requirements is through determination of spatial correlation patterns of the natural distribution of precipitation for various time increments of interest. As part of the precipitation research program of the Illinois State Water Survey, correlation analyses of Illinois precipitation have been determined for time periods ranging from one-minute intervals within storms to total annual precipitation. This report describes and summarizes the findings from the various correlation studies carried out over the past 25 years. In pursuing these studies, we have utilized data from the climatic network of the National Weather Service and from several dense raingage networks operated by the Water Survey in conjunction with various meteorological research projects.

Acknowledgments

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ANNUAL PRECIPITATION

Data from 36 weather stations in and adjacent to Illinois were used in the study of the correlation patterns for annual precipitation. These consisted of 6 first-order and 30 cooperative stations of the National Weather Service. Station locations are shown in figure 1. The correlation patterns were based upon records for the 50 years, 1906-1955.

Spatial correlation patterns are shown in figures 2 and 3 for 8 selected stations that are typical of the distributions obtained throughout the state. In most cases, the annual correlation patterns reflect the prevailing storm movements. Thus, at Chicago the correlation decay with distance is least in an approximate SW-NE direction; that is, the strongest correlation of annual precipitation extends SW and NE of Chicago. This orientation of the major axis of the correlation pattern relates well to storm movements which are most frequently out of the SW to WSW in the Chicago area (Huff and Vogel, 1976).

The same prevailing storm movements are reflected in the correlation patterns for Peoria and Quincy in figure 2b and c and for Urbana, Springfield, and St. Louis in figure 3b, c, and d. The Cairo pattern in figure 2d appears to have more of a SSW-NNE orientation, but this may be because there is no pattern information south of the station. Also, the pattern for Rockford in figure 3a, is not well-defined as a result of insufficient data to the north and east.

The patterns of figures 2 and 3 show distinctly that the correlation between points, and, therefore, between raingages, decreases faster in some directions than in others. As indicated above, this variation is related to prevailing storm movements, but it also is affected by topography and other factors. In general, optimum raingage spacing for the measurement of annual precipitation in Illinois would require a greater density of raingages in north and south directions than in west and east directions to maintain an equivalent degree of measurement accuracy in all directions.

Table 1 shows median correlation coefficients in each of 8 directions for all stations combined over distances of 25 to 150 miles. The largest correlation coefficients at all four distances occurred with NE, E, SW, and W directions, which is in agreement with expectancies from the standpoint of prevailing storm movement. However, differences among directions are not exceptionally large. For example, the highest correlation at 50 miles was 0.76 and the lowest was 0.68. These account for 58% and 46%, respectively, of the variance between point precipitation measurements separated by this distance. For all directions combined, the coefficients of 0.90, 0.72, 0.58, and 0.45 at distances of 25, 50, 100, and 150 miles account for 81%, 52%, 46%, and 20% of the variance. Thus, the correlation decay with distance, and, therefore, the representativeness of point precipitation measurements, decreases quite rapidly.

Figure 1. Precipitation stations used in annual correlations

Table 1. Correlation Decay of Annual Precipitation with Distance and Direction

	Median coefficient at given distance (miles)			
Direction	*25*	*50*	*100*	*150*
NE	0.93	0.76	0.63	0.52
E	0.92	0.75	0.60	0.55
SE	0.89	0.71	0.57	0.38
S	0.88	0.69	0.53	0.38
SW	0.90	0.73	0.62	0.53
W	0.90	0.73	0.60	0.50
NW	0.85	0.68	0.51	0.33
N	0.89	0.72	0.55	0.38
All directions combined	0.90	0.72	0.58	0.45

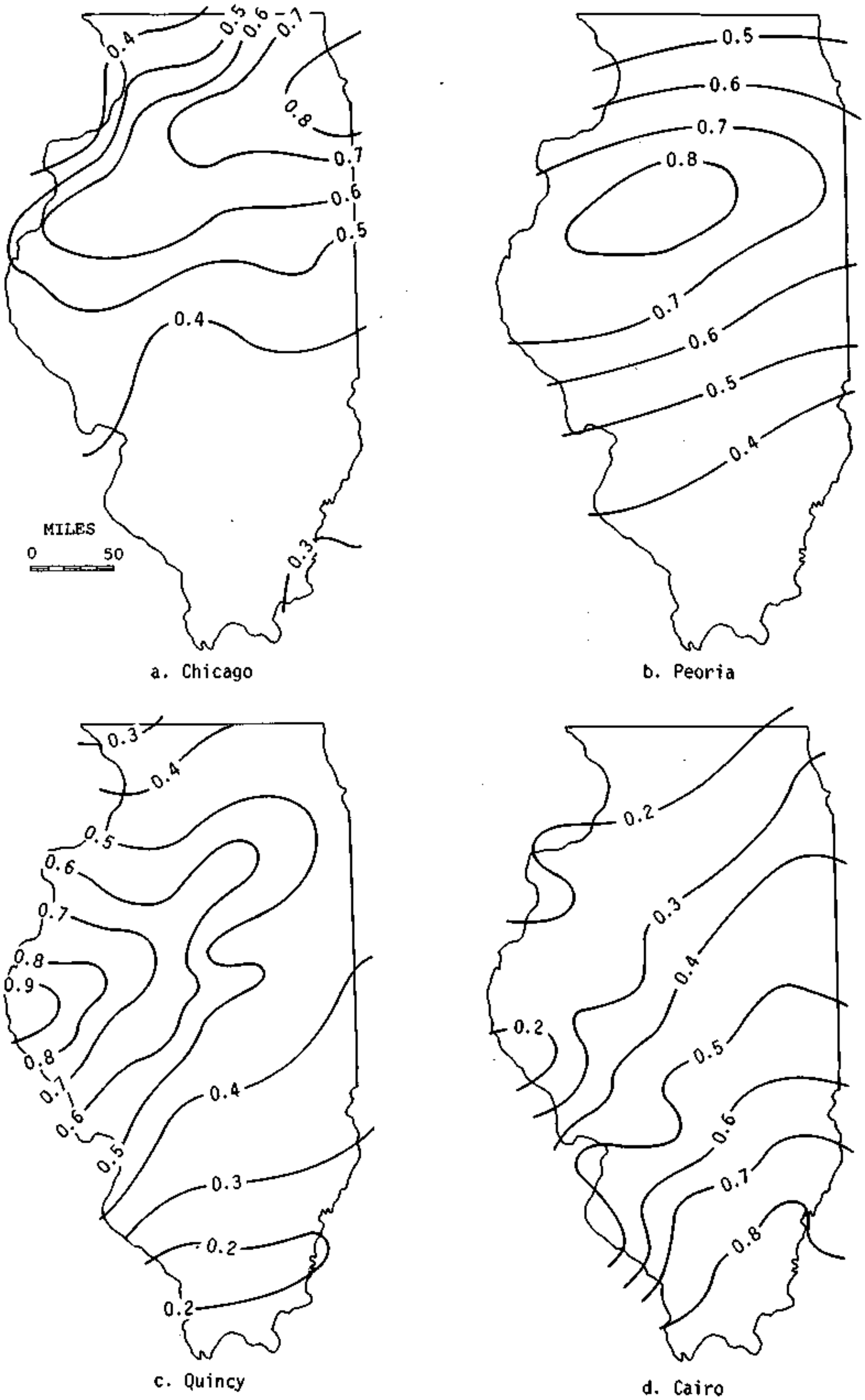

Figure 2. Examples of annual precipitation correlation patterns

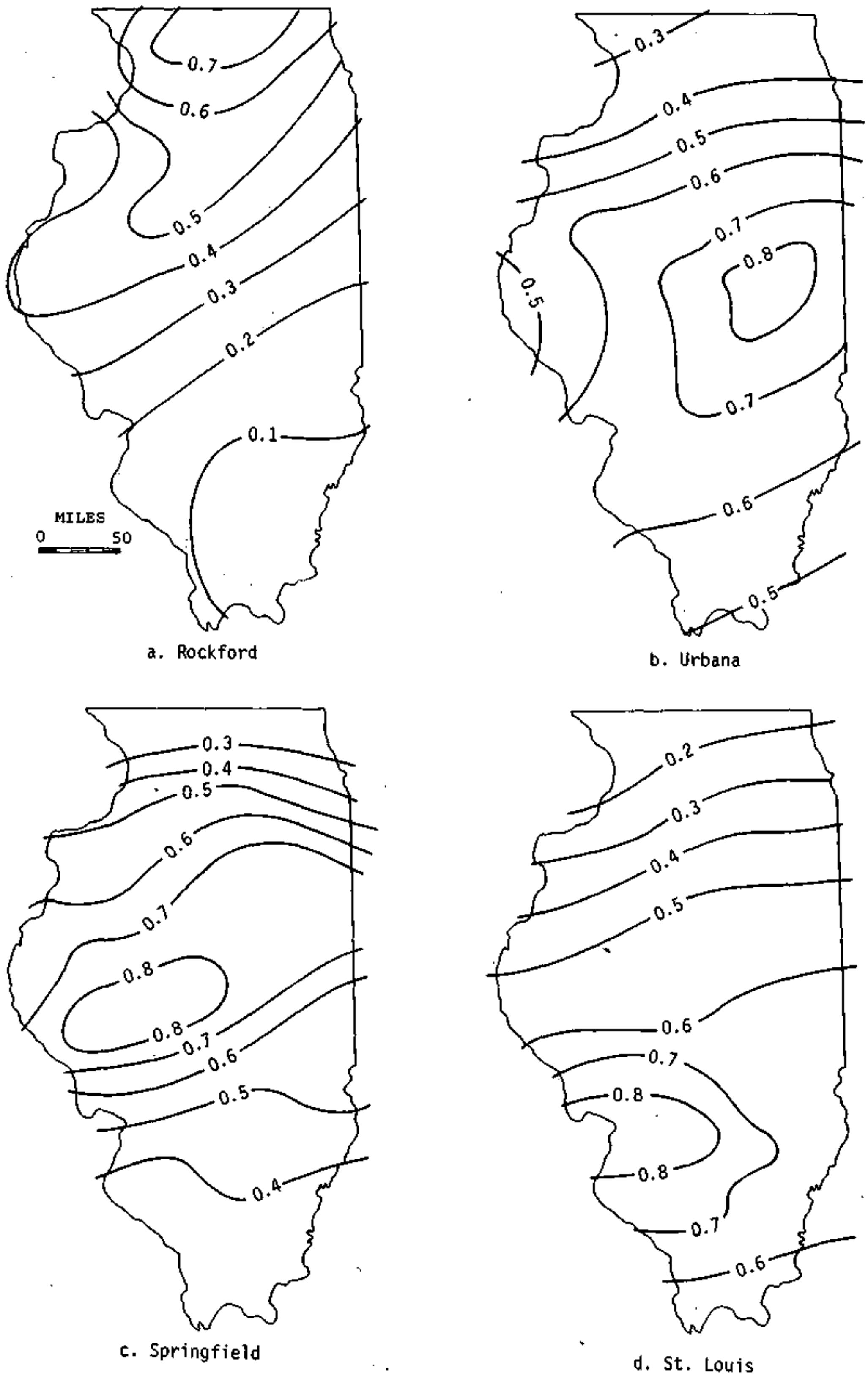

Figure 3. Examples of annual precipitation correlation patterns

MONTHLY AND SEASONAL PRECIPITATION

For some purposes, knowledge of the spacing requirements for the measurement of monthly and seasonal precipitation is of primary interest. Certain types of agricultural research and long-term weather modification operations are two examples of such application. Data from two dense networks in east central and southern Illinois (figure 4) were used to investigate monthly and seasonal correlation patterns. Analyses were restricted to the May-September period which encompasses the growing season. Also, convective precipitation dominates in this period, so that sampling requirements are greatest because of the great spatial variability in the rainfall (Huff, 1966).

Altogether, 13 and 10 seasons, respectively, were available from the east central and southern networks for the analyses (Huff and Schickedanz, 1970). Correlation coefficients were calculated for distances of 2 to 20 miles. Distance was limited by the size of the networks. The East Central Illinois Network (ECIN) encompassed 400 square miles, and the Little Egypt Network (LEN) in southern Illinois enveloped 550 square miles. Results of the monthly and seasonal analyses combining data from both networks are summarized in table 2. Only small differences occurred between monthly and seasonal correlation relations so that a total storm sampling network would satisfy sampling for both periods. There would be little economic benefit in differentiating between raingage spacing requirements, especially if a relatively high degree of accuracy is desired in all measurements.

STORM PRECIPITATION

In analyses of the spatial correlation relationships in storms, data from three dense raingage networks were used to provide a range of measurements that included 1-minute and 10-minute average rainfall rates in addition to total storm rainfall. Analyses were also made of the effects of season, synoptic weather type, precipitation type, storm intensity and duration, storm movement, wind flow, and other factors affecting the spatial distribution of storm precipitation.

Data for the 5-year period, 1960-1964, from the East Central Illinois Network (ECIN) and the Little Egypt Network (LEN) in southern Illinois (figure 4) were used in the total storm analysis. A storm was defined as a precipitation period separated from preceding and succeeding precipitation by 6 hours or more.

For monthly and seasonal analyses, data from the entire 13-year period of record, 1955-1967, on ECIN, and the complete 10-year record, 1958-1967, on LEN were used to obtain the maximum possible sample size for analysis. In addition, 3142 minutes of data from 29 storms during 1952-1953 on the Goose Creek Network (GCN) of 100 square miles in central Illinois were used to obtain correlation patterns for 1-minute rainfall amounts, the best available estimate of instantaneous rainfall rates, and for investigating average 10-minute rates. This special network, installed for radar-rainfall research in a part of the same area as ECIN, contained 50 recording gages with 12.6-inch orifices and 6-hour gears which permitted reading of 1-minute amounts (Huff and.Neill, 1956).

Total storm data were divided into the usual two seasonal groups, May-September and October-April. Next, within these two seasonal groups, the data were

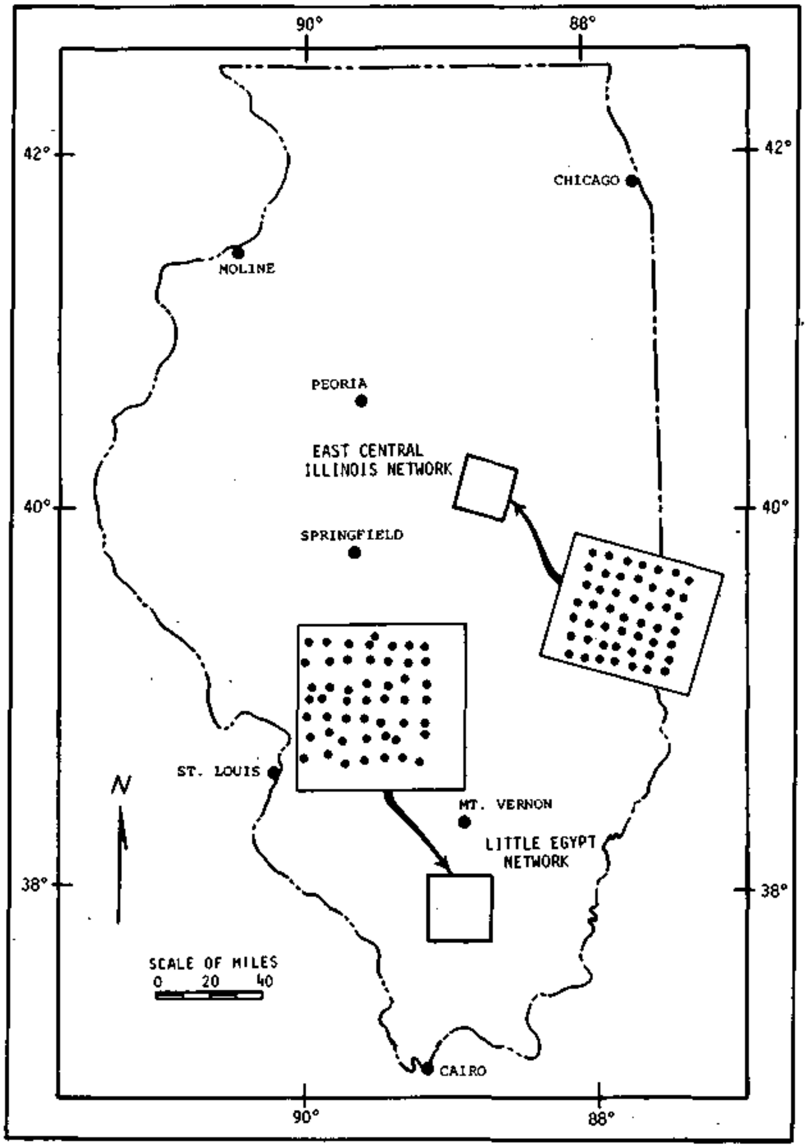

Figure 4. Location of East Central Illinois and Little Egypt raingage networks

Table 2. Average Monthly and Seasonal Correlations for May-September

	Average correlation coefficient at given distance (miles)							
Period	*2*	*4*	*6*	*8*	*10*	*12*	*15*	*20*
Monthly	0.95	0.91	0.89	0.86	0.84	0.83	0.81	0.78
Seasonal	0.95	0.91	0.89	0.87	0.86	0.85	0.84	0.81

separated into three basic synoptic storm types through use of published synoptic weather maps of the National Weather Service. Types included frontal storms, low center passages, and air mass storms. Analyses did not show substantial differences in the patterns associated with the various frontal types and squall lines, so all were combined in the frontal storm group (Huff and Shipp, 1969).

Synoptic Storm Pattern

Figure 5 shows correlation patterns about the central gage on ECIN in May-September storms associated with air mass instability, low center passages, and fronts. These patterns were derived from 195 frontal storms, 73 air mass storms, and 28 low center passages. The differences in correlation are striking, especially between air mass storms and low centers. With low centers, the correlation coefficient exceeds 0.90 over the entire 400 square miles, whereas in air mass storms it decreases to less than 0.60 at the southern edge of the network, 9 to 10 miles from the central gage. The correlation patterns indicate a general SW-NE orientation, although this tendency is less pronounced with air mass storms. Storms move most frequently across the network from SW or WSW (Huff, 1967), and the correlation patterns are, of course, responsive to this climatological characteristic.

Rain Type and Rainfall Rate Patterns

The difference in correlation patterns between rainfall types is illustrated in figure 6 which shows isocorrelation maps about the central gage for May-September storms in which thunderstorms, rainshowers, or steady rain produced the surface precipitation. The two maps are quite comparable to those for fronts and low centers in figure 5.

Figure 6 also shows the average correlation pattern of 1-minute rainfall rates about the most central gage on GCN. Most of these storms consisted of thunderstorms and rainshowers, and occurred during the warm season. Although not a completely representative climatological sample, these storms do provide a first approximation of the correlation decay with distance in the spatial distribution of instantaneous rainfall rates.

The general effects of various meteorological factors on the correlation decay with distance in storms are illustrated in table 3 through the use of May-September data from ECIN. In this table, correlation coefficients are shown about the network's central gage. At the bottom of table 3, relations are shown for the ungrouped storm data, and for 1-minute and 10-minute rainfall rates from the GCN data for comparison with grouped storm relations.

Storm Duration Effects

The storm duration relations in table 3 are interesting. Correlation decay decreases with increasing duration with storms lasting up to 12 hours, then the trend reverses. Since this same behavior was observed in the ECIN October-April storms and on LEN, the reversal appears to be real rather than a sampling vagary present in this particular sample of storms. A possible explanation is that the long-duration storms are

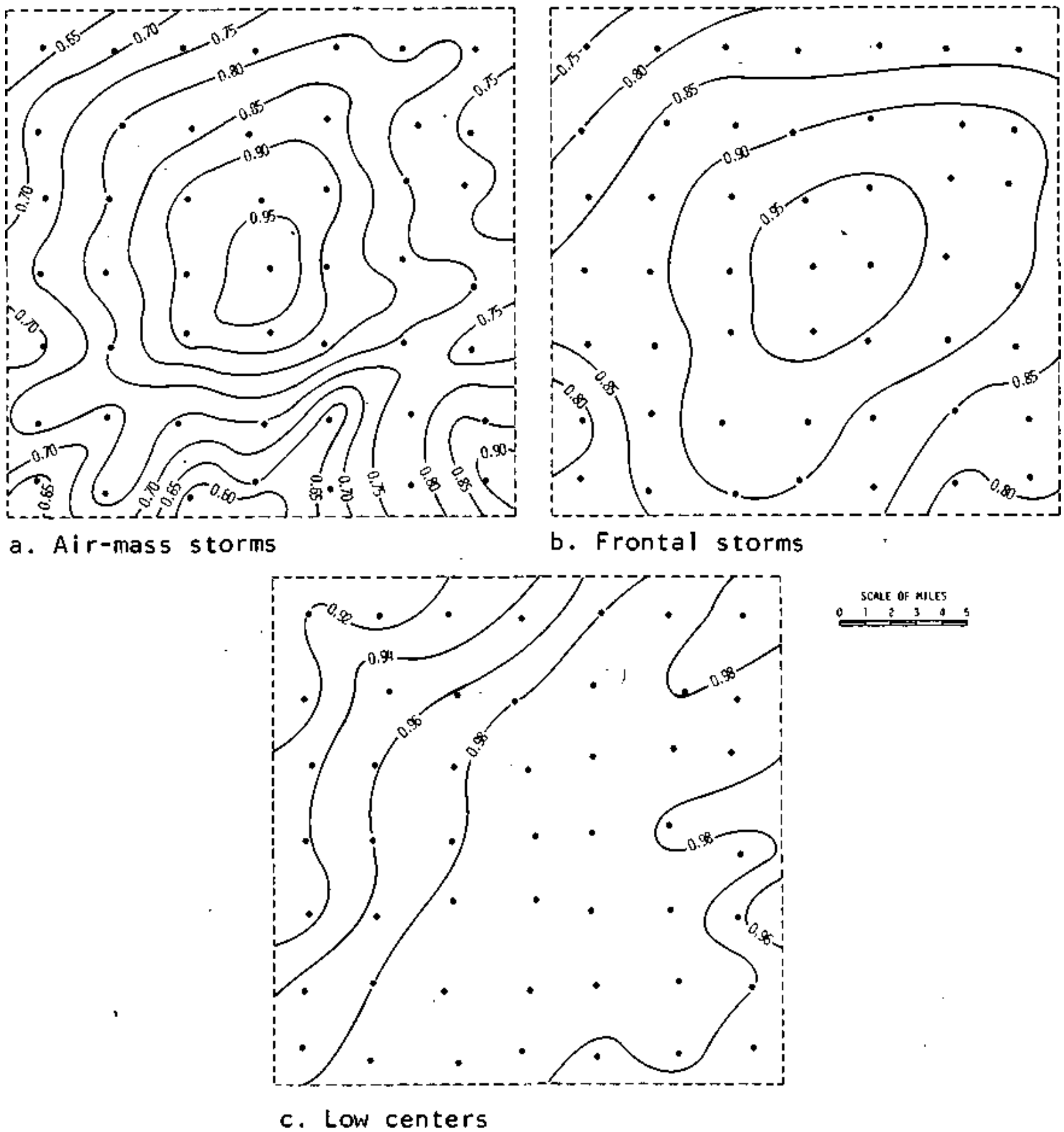

Figure 5. Average correlation patterns associated with three synoptic storm types

usually associated with extensive synoptic storm systems, and storm movements across the network are more likely to shift during these lengthy storm periods as the weather system approaches and passes.

Mean Rainfall Relations

The mean rainfall groupings in table 3 indicate that average precipitation within a sampling area has very little effect upon point-to-point correlations. The trend of correlation is very erratic with increasing mean rainfall, and is relatively low in three of the five data groups. Erratic trends and relatively low correlation coefficients were also found during the October-April period and on LEN for both seasons.

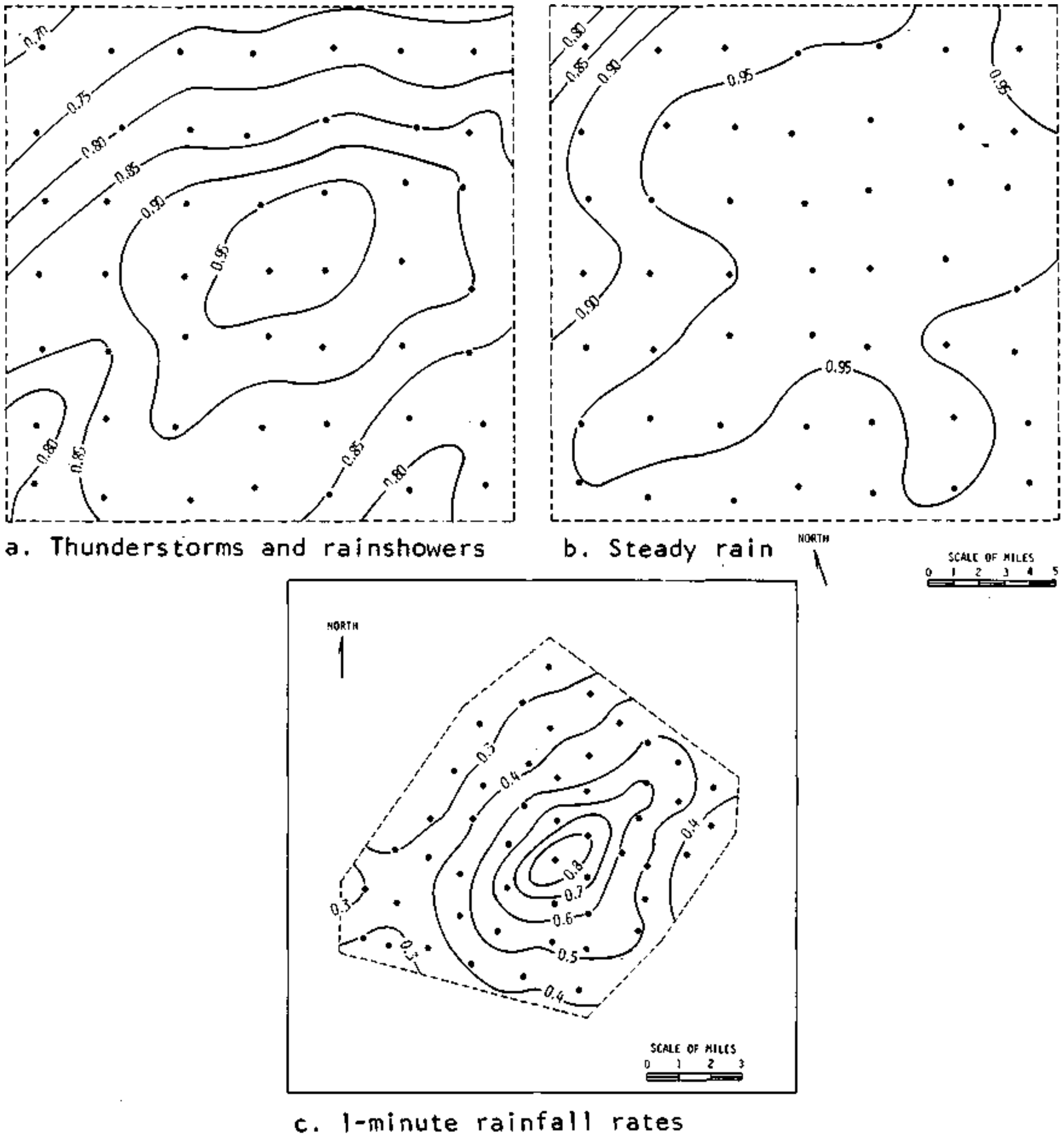

Figure 6. Average correlation patterns associated with selected types of rainfall

Directional Effects

The directional effect on storm rainfall correlations is illustrated in table 4 through use of May-September data from ECIN. In this table, average correlation coefficients are shown for distances up to 20 miles when the correlations are calculated in each of four directions. With increasing distance W-E correlations are consistently higher than the N-S values, and explain 10 to 12% more of the variance at distances of 10 to 15 miles. The SW-NE correlations are very close to the W-E values and the NW-SE correlations are similar to the N-S group. The slightly better correlations with the W-E and SW-NE groups reflect the more frequent movement of storms from these directions compared with the other two directional groups. Similar May-September relations were found on LEN.

Table 3. Variation of Correlation Coefficient with Distance about Central Gage in East Central Illinois and Goose Creek Networks during May-September Storms

		Average correlation coefficient for given distance (miles)					
Group	*N*	*1*	*2*	*4*	*6*	*8*	*10*
TRW-RW	249	0.98	0.96	0.92	0.88	0.85	0.82
R	33	0.99	0.98	0.96	0.94	0.93	0.92
Fronts	195	0.98	0.96	0.94	0.91	0.88	0.86
Low centers	28	1.00−	0.99+	0.99	0.98	0.97	0.96
Air mass storms	73	0.97	0.94	0.87	0.79	0.76	0.74
≤ 3 hour	184	0.96	0.91	0.82	0.75	0.70	0.65
3.1-6.0 hour	61	0.97	0.95	0.90	0.86	0.81	0.76
6.1-12.0 hour	29	0.98	0.96	0.93	0.91	0.89	0.87
12.1-24.0 hour	19	0.97	0.95	0.82	0.72	0.69	0.66
0.01-0.10 inch	111	0.96	0.93	0.90	0.88	0.87	0.82
0.11-0.25 inch	53	0.46	0.22	0.05	−0.02	−0.06	−0.10
0.26-0.50 inch	33	0.86	0.69	0.32	0.11	0.06	0.03
0.51-1.00 inch	36	0.84	0.68	0.38	0.22	0.12	0.06
>1.00 inch	19	0.96	0.93	0.88	0.82	0.77	0.71
All storms	296	0.98	0.96	0.93	0.89	0.86	0.84
1-minute rain rate (Goose Creek)	3142	0.77	0.60	0.40	0.31		
10-minute rain rate	2829	0.76	0.61	0.44	0.38		

In the October-April period, the directional differences were even smaller than in the May-September period on both networks. Overall, this phase of the analyses indicates a slightly greater sampling density is required in the N-S and NW-SE directions to maintain an equivalent measurement error in the isohyetal patterns of total storm rainfall throughout a given sampling area.

The lower part of table 4 shows the average spacing of raingages required in W-E and N-S directions to maintain selected levels of variance explained. These statistics were calculated from the relations shown in the upper part of the table. They may be used as a guide if one wishes to maintain equivalent measurement accuracy in various directions within a sampling area.

Raingage Spacing Requirements

Table 5 provides a general summary of raingage spacing required on a grid pattern to achieve various degrees of average correlation (r) and, in turn, percentages of explained variance (r^2) under various conditions. The relations are based upon weighted averages of the correlation coefficient obtained in the directional analysis. The 1-minute rainfall rate values are based upon interpolation of the correlation decay curve, since the average network spacing was 1 gage per 1.4 mile and the average correlation coefficient had decreased to approximately 0.7 at this distance from correlated points. Also, curve interpolation was involved in obtaining the values for some of the higher correlations in the other groupings because of the limiting gage spacing on the networks. A maximum distance of 20 miles has been used in the calculation because of the network sizes.

Table 4. Direction Effect on Correlation Decay with Distance in May-September Storms

Direction	Average correlation coefficient for given distance (miles) 2	4	6	8	10	12	15	20
W-E	0.96	0.93	0.90	0.88	0.86	0.84	0.81	0.77
N-S	0.96	0.91	0.87	0.83	0.79	0.76	0.74	0.72
NW-SE	0.96	0.92	0.88	0.84	0.80	0.77	0.75	0.71
SW-NE	0.94	0.91	0.89	0.87	0.85	0.83	0.79	0.73

Variance explained (%)	Spacing for given direction (miles) W-E	N-S
90	2.7	2.2
80	6.0	4.5
70	12.4	7.8
60	19.6	11.3
50	20	20

Table 5. Average Storm Relation between Raingage Spacing and Correlation Coefficients

Spacing for given correlation (miles)

r	r^2 (%)	All storms	TRW, RW*	R + RW*	R*	Lows	Fronts	Air mass	1-minute rates
May-September storms									
0.95	90	2	2	3	10	10	2	1	0.2
0.90	81	5	4	7	>20	>20	5	3	0.4
0.85	72	8	7	15			9	5	0.6
0.80	64	12	10	>20			13	7	0.8
0.75	57	17	14				18	9	1.0
0.70	49	>20	>20				>20	13	1.2
Number of storms		629	544	33	50	62	410	157	29

r	r^2 (%)	All storms	TRW, RW*	R R + RW*	Lows	Fronts	S*	R + S*
October-April storms								
0.95	90	6	5	13	8	4	1	2
0.90	81	18	10	>20	>20	13	2	8
0.85	72	>20	15			>20	4	13
0.80	64		20			.	6	>20
0.75	57						11	
0.70	49						20	
Number of storms		654	267	188	310	305	90	28

TRW = thunderstorms; RW = rainshowers; R = steady rains; S = snow

As expected, table 5 shows that a substantially greater density of raingages is needed in the warm season (May-September) than in the colder months of the year (October-April) to maintain a given level of explained variance. For example, assume one wishes to install a network with a raingage spacing that will explain 90% of the storm variance, on the average, combining all types of storms. Then, reference to the 'all storms' columns shows that a gage spacing of 2 miles is needed in May-September compared with 6 miles during October-April. If the user is concerned with a similar accuracy in the measurement of air mass storms, the spacing would be 1 mile. However, if a project is concerned only with measurements during the passage of low centers, a spacing of 8 to 10 miles would be adequate to achieve an explained variance of 90% in Illinois storms.

As part of the correlation studies, average wind flow in the lower 500 mb (approximately 20,000 ft) of the atmosphere was determined for 1960-1964 summer storms in LEN. This was done to determine whether correlation decay is influenced significantly by wind movement which exerts a relatively strong control on storm motion. Also, correlation decay was analyzed according to orientation of the surface rainfall pattern. Knowledge of the wind and orientation effects should be useful in the planning and statistical evaluation of weather modification experiments.

Results of this study are summarized in table 6, and show lesser correlation decay with distance along the major axis of the surface rainfall pattern than along the axis of mean wind flow in the lower 500 mb of the atmosphere. Correlation coefficients for storm orientation are nearly the same as those for the various direction groups in table 4, but the wind movement correlations are less than those in table 4. Similarly, the storm orientation correlations are equivalent to those for the non-directional synoptic and precipitation types in table 3. Thus, the best correlations (least decay with distance) are obtained when storms are grouped by synoptic type, precipitation type, and storm orientation.

SUMMARY AND CONCLUSIONS

Analyses of the correlation change with distance in annual precipitation showed that it tends to minimize along SW-NE and/or WSW-ENE lines from the sampling point (precipitation station). These favored directions of least decay correspond with the most frequent movement of storms through Illinois. In general, correlation decay was quite rapid with increasing distance from the annual precipitation measurement point, but proceeded at a lesser rate than in monthly, seasonal, or storm precipitation. Thus, at 25 miles, the average correlation coefficient for annual precipitation was 0.90 which explains 81% of the variance between points at this distance. In monthly and seasonal precipitation, the correlation coefficient decreased to less than 0.80 (64% of the variance explained) at 25 miles during the convective rainfall season (May-September). Combining all storms, the correlation coefficient reached an average value of 0.70 at 20 miles in the May-September period.

Major emphasis was placed upon storm studies, since the measurement problem is the most acute in these events, and most users are concerned with storm or partial storm measurements rather than monthly, seasonal, or annual amounts. Correlation decay with distance, used to indicate sampling requirements for establishing rainfall patterns, was greatest in storms associated with thunderstorms, rainshowers, and air mass storms. Conversely, minimum decay occurred with steady rain and the passage of low pressure centers. Seasonally, the correlation decay with distance in storms was much greater in the growing season, May-September, than during the October-April period when water supply replenishment normally maximizes. For 90% explained vari-

Table 6. Comparison between W-E Wind-Oriented and W-E Rainfall-Oriented Correlation Patterns

	Number of storms	Distance from sampling point (miles) 1	2	4	6	8	10	12	15	20
Correlation coefficient										
Wind	44	0.97	0.93	0.87	0.81	0.76	0.73	0.70	0.67	0.65
Rainfall	49	0.98	0.96	0.93	0.90	0.87	0.85	0.83	0.81	0.78
Variance explained (%)										
Wind	44	94	86	76	66	58	53	49	45	42
Rainfall	49	96	92	87	81	76	72	69	66	61

ance, on the average, in all storms combined, a gage spacing of 2 miles is needed in the warm season compared with 6 miles in the cold season. However, if similar accuracy is required in air mass storms, the gage spacing must be decreased to 1 mile. If measurements are to be made only in low center passages, a spacing of 8 to 10 miles is adequate for the above accuracy level.

Spatial correlation increased, on the average, with increasing duration in storms lasting up to approximately 12 hours, after which a reversal in this trend occurred. Erratic trends were found when the storms were grouped according to network mean precipitation. General improvement in correlation occurred when the storms were grouped by wind direction and storm movement.

Directionally, slightly higher correlations were obtained in W-E and SW-NE directions compared with those in N-S and NW-SE directions across the networks. Large differences were not found between total storm, monthly, and seasonal correlation relations, so that a total storm sampling network should satisfy sampling needs for all of these periods. However, sampling requirements are much greater when measurements of rainfall rate are needed. For example, with a minimum acceptance of 75% explained variance between sampling points, a gage spacing of 0.3 mile is needed for 1-minute average rates compared with 7.5 miles for total storm rainfall in warm season storms.

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