ILLINOIS STATE WATER SURVEY
ATMOSPHERIC SCIENCES SECTION

CLIMATIC STUDIES OF EXTRA-AREA
EFFECTS FROM SEEDING

by

P. T. Schickedanz

TECHNICAL REPORT NO. 5
ILLINOIS PRECIPITATION ENHANCEMENT PROGRAM
PHASE I

June 30, 1973

To

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of Interior

Contract 14-06-D-7197
September 1, 1971
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The application of trend surface analysis in the delineation of precipitation highs from a complex rainfall pattern (June 1955-59).</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Significant precipitation highs (5% and 10% residuals) as determined by trend surface analysis for the 1950-59 summer pattern.</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Significant precipitation highs (5% and 10% residuals) as determined by the trend surface analysis for the 1950-59 June pattern.</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>The number of times that each sampling point was included in a high (5% residual) on 1-yr summer patterns during 1950-69.</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>The number of times that each sampling point was included in a high (5% residual) on 1-yr June patterns during 1950-69.</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>The number of times that each sampling point was included in a high (5% residual) on 1-yr December patterns during 1950-69.</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>Persistence of summer rainfall 1950-69 as determined by the lag 1 correlation coefficient.</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>The correlation of summer rainfall at Salem with all other points in the PEP study area during the period 1950-69.</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>Areal residual means for various sampling areas downwind of St. Louis for the summer period 1950-69.</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>Areal residual means for various sampling areas downwind of Kansas City for the summer period 1950-69.</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>Significant precipitation highs (5% and 10% residuals) as determined by trend surface analysis for the 1950-69 summer patterns in and surrounding the test cities</td>
<td>32</td>
</tr>
<tr>
<td>12</td>
<td>The number of times that each sampling point in the vicinity of test cities was included in a high (5% residual) on 1-yr summer patterns during 1950-69.</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>Significant Rainfall Excess (SRE) in the vicinity of test cities during 1950-69 (10% level).</td>
<td>34</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>14</td>
<td>The number of times that each sampling point in the areas defined as adjacent and downwind of test cities was included in a high (5% residual) on 1-yr summer patterns during 1950-69.</td>
<td>36</td>
</tr>
<tr>
<td>15</td>
<td>Significant Rainfall Excess (SRE) in the vicinity of test cities during 1950-69 (10% level).</td>
<td>38</td>
</tr>
<tr>
<td>16</td>
<td>Areal means of significant rainfall excess and deficit values (10% level) for varying distances from effect cities.</td>
<td>42</td>
</tr>
<tr>
<td>17</td>
<td>Areal means of significant rainfall excess and deficit values (10% level) for varying distances from non-effect cities.</td>
<td>43</td>
</tr>
<tr>
<td>18</td>
<td>The significant rainfall excess (10% level) in the immediate vicinity of St. Louis during summer 1972 based on storm rainfall patterns (10% level).</td>
<td>45</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>A comparison of highs (5% residuals) from 20-yr seasonal patterns (1950-69) according to varying areal sizes.</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>The spacing of highs (5% residuals) in summer rainfall patterns as determined by the distance to the nearest high.</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>The spacing of lows (5% residuals) in summer rainfall patterns as determined by the distance to the nearest low.</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>The spacing of highs (5% residuals) in summer rainfall patterns as determined by the distance to the nearest downwind high.</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>The spacing of downwind highs (5% residuals) in 5-yr monthly rainfall patterns as determined by the distance to the nearest high.</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>The variability between 5-yr periods of the average spacing and size of highs on 5-yr patterns.</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>Comparison of the city population and the presence of highs within 50 miles of the city as determined by 20-yr residuals, the number of highs, and the Significant Rainfall Excess (SRE).</td>
<td>35</td>
</tr>
<tr>
<td>8</td>
<td>Comparison of the joint occurrence of extra-area highs with the city high (5% residuals).</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>Comparison of the joint occurrence of extra-area lows with the city high (5% residuals).</td>
<td>41</td>
</tr>
<tr>
<td>10</td>
<td>Areal means of Significant Rainfall Excess (10% level) from storm rainfall patterns during Summer, 1972 according to hypothesized effect and non-effect areas. (Zero points excluded).</td>
<td>47</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

This research was performed under the general direction of Stanley A. Changnon, Jr., Head of the Atmospheric Sciences Section of the Illinois State Water Survey and principal investigator of this contract, and Floyd A. Huff who supervised this study area. The drafting of all figures was supervised by John W. Brothers, Jr.

Appreciation is expressed to Marion Busch who performed most of the computer analyses, assisted in the development of computer programs, and supervised various other critical analyses. Student employees who assisted were Marilyn Dille, Steve Hathaway, and Barbara Ackermann.

ABSTRACT

Two climatic investigations concerning detection of alterations of precipitation beyond a target area were pursued. In the first investigation, monthly and seasonal precipitation data were used to study the natural distribution of highs and lows in precipitation patterns over a 325,000 mi$^2$ area centered in southern Illinois during the period 1950-69. The highs were studied in regard to their location, spacing, frequency, and persistence. Overall, the most frequent distance between highs is in the range 40-60 miles. However, on 1-yr and 5-yr patterns the mean distance is in the range 75-95 miles and when the mean distance is determined in a directional sense (downwind) the mean distance is 100-117 miles. The mean distance between persistence areas and preferred locations of highs is approximately 60 miles. The implication of the natural distribution study is two-fold: 1) the mean and median distances between natural occurring precipitation highs in the Midwest are in the range of downwind highs reported caused by seeding; 2) the broadness of the correlation pattern between points in a pattern indicates that one must be very cautious when postulating extra-area effects out to distances as great as 300 miles from the target in weather modification experiments.

The second investigation concerned the monthly and seasonal precipitation patterns (1950-69) in and downwind of large cities having urban-induced increases in precipitation. Overall the results indicated that the urban effect is limited to 50 miles of the city, and that no downwind effect occurs beyond 50 miles. There was also some indication that rainfall deficits tend to occur in the neighborhood of excesses. In addition, the individual storm patterns in and downwind of St. Louis were investigated in most detail using 1972 METROMEX data. The analysis indicated that the major effect occurs within 0-25 miles with a smaller increase in the area 25-50 miles of the city. However, the storm analysis was based on a 1-yr sample only, and additional data and analyses are required to confirm the storm results.
INTRODUCTION

A major problem for rain enhancement projects, both in scientific interpretation of effects and in public relations, concerns whether an enhancement in one area is causing a depletion or enhancement of rainfall in the off-target area. It has been postulated by some investigators that an enhancement of rainfall in the target area would likely cause a depletion of rainfall in the off-target area. This is a logical assumption based largely on the concept of "robbing Peter" to "pay Paul".

One example of the confusion in evaluating downwind results is Project Whitetop in Missouri. Lovasich, et al. (1971) implied that the loss of rainfall was 21% in an area up to 180 miles from the target center and in all directions. Schickedanz and Huff (1970) report that the evidence for a downwind decrease in rainfall in the Whitetop experiment is very weak. Flueck (1971) also reported that there is little evidence to support an overall seeding effect in the control areas outside of the Whitetop Research Area. From an analysis of an Arizona experiment, Neyman et al. (1973) reported apparent decreases of 45% and 31% in downwind localities 90-180 miles away from the target.

In contrast, Adderely (1968) indicated increases up to 200 miles from the target area in Australia. Brown and Elliot (1968) indicate increases at 100 miles and up to 250 miles downwind of a target in the western United States. Grant (1971) reported evidence of increases 90-120 miles downwind in Colorado. Mielke (1971) indicated increases downwind of the Park Range project in Colorado. In some cases, it has been indicated that the increases of precipitation in the downwind areas are often greater than those in the target area. Thus, evidence exists for both an enhancement of rainfall and depletion in the downwind areas.

The conflicting results point to the difficulty of evaluating extra-area effects. Statistical analyses of the subject are difficult because of 1) the difficulty and yet necessity of defining the extended area, 2) the posterior nature of the analysis, 3) the extended area being outside the area in which the experiment was designed, 4) the natural variability of precipitation, and 5) the possibility of a "good" or "bad" draw caused by the failure of randomization to balance out the uncontrolled background factors.

Because of the conflicting results and the difficulty of evaluating extra-area seeding effects, three climatic investigations were planned as part of the PEP program. Results from two of these are included in this report. Phase 1 was a study of the natural distribution of bands and centers of relatively high and low precipitation in a 325,000 mi² area. This area includes the states of Illinois, and Indiana, as well as parts of Iowa, Missouri, Arkansas, Tennessee, Kentucky, Ohio, Michigan, and Wisconsin. Phase 2 was an Investigation of the persistence and spatial distribution of high and low centers of precipitation downwind from where rainfall has been inadvertently modified by major urban-industrial centers. Phase 3, which was canceled because of the termination of most of the PEP program on June 30, 1973, would have involved evaluation of inadvertent modification downwind from irrigation areas in the Great Plains.
DATA AND ANALYSIS PLAN

The choice of data to be used in the study was based on several requirements placed on the analysis. These requirements included 1) a data sample from a reasonably long period of records (20 year), 2) the existence of "treated" targets, 3) a data sample from a large geographic area so that the natural distribution of highs and lows could be defined, and 4) location of the study area in and surrounding the proposed PEP experimental seeding site (Changnon, 1972). Requirements 1 and 3 eliminated the consideration of daily, storm or hourly data except on a limited scale because the cost of obtaining and analyzing the required amount of data was prohibitive in relation to the funds available for the project. Thus, the primary source of data was monthly data for the summer months of June, July, and August, and the winter months of December, January, and February of 1950-1969. These data came from 1171 cooperative reporting stations of the National Weather Service located within the area shown on Fig. 1e. In addition, storm rainfall data for the summer of 1972 from the extended METROMEX network (Changnon, 1973) was used.

The analysis plan was to 1) study the natural distribution of highs and lows in monthly and seasonal patterns in regard to space and time, 2) investigate the monthly and seasonal patterns in and downwind of cities with urban-induced increases in precipitation (treated), 3) study the monthly and seasonal patterns in and downwind of control cities (non-treated), and 4) investigate storm rainfall patterns in and downwind of St. Louis. Project Whitetop was not considered as a potential study area because of the large amount of research already performed and the conflicting results in regard to downwind effects (Lovasich, 1971; Schickedanz and Huff, 1970; and Flueck, 1971).

ANALYTICAL TECHNIQUES USED IN DESCRIBING THE NATURAL PATTERNS

In order to provide versatility and flexibility in the various analyses, all station data were gridded on a 20 mi × 20 mi grid and the data from each grid intersection entered on punch cards. Thus, each month had a set of punch cards which contained the gridded monthly patterns. This procedure permitted certain computer analyses of the data that would not otherwise have been possible. For the summer months, the data were plotted on base maps and the data were gridded by visual interpolation. For the winter months, the data were gridded directly with the computer. The gridded data were then subjected to trend surface analysis which was the basic statistical tool used throughout the study. Near-neighbor analysis (Schickedanz, 1973) was used to indicate the spacing between highs and lows and whether the highs and lows in a particular pattern were aggregate, random, or systematic. Lag correlation analyses over time at each grid point were used to describe the persistence of the pattern from year to year and the inter-correlation analysis between grid points was used to describe the persistence of the pattern in space.

Grid Interpolation Technique

The computer estimation of data at the grid points was made in the following manner. For each grid point a computer search was initiated for the nearest three
Figure 1. The application of trend surface analysis in the delineation of precipitation highs from a complex rainfall pattern (June, 1955-59).
stations with non-missing data. A quadratic surface was then fitted by solving
the following equations simultaneously for the coefficients \( C_1, C_2, \) and \( C_3 \).

\[
P_1 = \overline{P} + C_1 X_1 + C_2 Y_1 + C_3 X_1 Y_1 \tag{1}
\]
\[
P_2 = \overline{P} + C_1 X_2 + C_2 Y_2 + C_3 X_2 Y_2 \tag{2}
\]
\[
P_3 = \overline{P} + C_1 X_3 + C_2 Y_3 + C_3 X_3 Y_3 \tag{3}
\]

Where: \( X_1, Y_1 \) are the coordinates of the 1st nearest station with
a non-missing rainfall value

\( X_2, Y_2 \) are the coordinates of the 2nd nearest station with
a non-missing rainfall value

\( X_3, Y_3 \) are the coordinates of the 3rd nearest station with
a non-missing rainfall value

\( P_1, P_2, P_3 \) are the values respectively at the 1st nearest, 2nd
nearest, and 3rd nearest stations

\( \overline{P} \) is the mean of the three values at the nearest three
stations

Once the coefficients are determined, the value of the grid point is estimated
by substituting the values of its coordinates into Equation 1 in place of \( X_1, Y_1 \),
and then solving for \( P_1 \). Under certain conditions, especially along the boun-
daries, the solution becomes unstable and extremely large or even negative values
will be computed. Thus, whenever the computed value exceeds 2 standard deviations
of the three-station mean, the computed value is set equal to the mean of the
rainfall values at the three points.

Trend Surface Analysis

Maps which portray the spatial pattern of a given rainfall variable are
widely used in meteorology and climatology as a general research device. How-
ever, there are two chief disadvantages associated with the use of rainfall pattern
maps. These are: 1) the construction and analysis of isohyetal maps can be
difficult, tedious, and time consuming; and 2) the map as it is often employed
by the meteorologist is a graphic device, and a visual examination of the map does
not provide the critical values that are required for statistical hypotheses
testing of pattern features. Trend surface analysis utilizing the residuals from
2-dimensional regression surface can overcome these limitations.

\[
\hat{R}_{ij} = A + B_1 \cdot I + B_2 \cdot J \tag{4}
\]

Where: \( I \) is the north-south coordinate axis increasing to the
south with the origin at northern map edge

\( J \) is the east-west axis increasing to the east with
origin at the western edge of the map
\( \hat{R}_{ij} \) is the estimate of the mapped rainfall variable at the ith and jth location

A - is the intercept

B_1, B_2 - are the slope parameters of the linear plane

Thus, \( \hat{R}_{ij} \) represents the estimated value of the precipitation variable at the ith and jth location determined from its position in the map coordinate system.

The estimated values of \( R_{ij} \) from Equation 4 describe the first order trend of the precipitation over the area. By adding higher terms and cross-product terms to Equation 4, trend surfaces of successively higher order could be generated. If the resulting equation consisted of n terms, the computed surface would pass through all the n data points on the map. The standard output from regression analysis, such as multiple correlation, standard error of estimate, and standard error of the slope parameters would yield a measure of the amount of variance explained and how well the surface actually described the trend. However, in the analysis of highs and lows in a rainfall pattern, it is the unexplained portion, the residuals from regression, that is of interest. These residuals represent highs and lows in the overall rainfall pattern, and for this representation the linear trend surface is often quite adequate.

The basic residual, \( R_b \), is defined as \( R_b = R_{ij} - \hat{R}_{ij} \) where \( R_{ij} \) is the actual precipitation at the ith and jth location. These basic residuals take on both positive and negative values (i.e., precipitation highs and lows). However, a disadvantage of these absolute residuals is that they are not relative to other residuals on the map or to residuals from other maps. Thus, the basic residual, \( R_b \), is often standardized by dividing \( R_b \) by \( S_e \), the standard error of estimate of the 2-dimensional regression surface. Not only does this procedure standardize the residuals, but it also provides significant factors for the resulting highs and lows. Values of this residual assumes a range from -3.00 to 3.00 regardless of the average magnitude and range characteristics of the data. Since the long-term frequency of these values is known, hypothesis testing can be applied directly to the standardized map of residuals (Thomas, 1968). Thus, the location of statistically rare highs and lows can be determined. For additional details and examples concerning trend surface analysis of precipitation patterns, the reader is referred to Schickedanz (1973).

An example of the application of trend surface analysis in the delineation of precipitation highs from a complex precipitation pattern is shown on Fig. 1. The basic residuals greater than specified values are portrayed in sequence to demonstrate the type of pattern clarification that can be obtained. For most analysis, the residuals would be standardized and only those greater than 1.64 (10% significance level) or those greater than 1.96 (5% significance level) would be retained on the map. These would be considered to be the significant highs and lows of the pattern. For example, the standard error of estimate is .845 for the data in Fig. 1 so that basic residuals greater than 2.00 in (Fig. 1d) would have standardized values greater than 2.47 and would be significant at the 5% level of significance.
Near-Neighbor Analysis

Once the highs and lows have been delineated, it is difficult to describe the nature of them in precise and meaningful terms. In order to describe their nature, an objective method is needed which will produce universal generalizations which are comparable from map to map. One method for doing this is the use of near-neighbor analysis.

Near-neighbor analysis has often been used by plant ecologists to describe the distribution patterns of plant species over the earth's surface (Clark and Evans, 1954) and has also been used by geographers to describe the distribution patterns of urban settlements over the United States (King, 1968). Near-neighbor analysis provides a measure of whether the spatial distribution of highs (or lows) is aggregate, random, or systematic. This measure is determined by indicating the degree to which any observed distribution of points deviates from what might be expected if the points were distributed in a random manner within the same area. For these purposes, a random distribution of points is a set of points on a given area 1) for which any point has had the same chance of occurring on any sub-area as any other point, 2) for which any sub-area of specified size has had the same chance of receiving a point as any other sub-area of that size, and 3) for which the placement of each point has not been influenced by that of any other point (Clark and Evans, 1954). Thus, randomness as here employed is a spatial concept, dependent upon the boundaries of space chosen by the investigator. A set of points may be random with respect to a specified area but decidedly non-random with respect to a larger space which includes the specified area (Clark and Evans, 1954). In applying this concept to highs and lows in a pattern, it must be realized that the theory applies to points, whereas the highs have definite areas. Thus, near-neighbor analysis is only applicable to the centers of individual highs.

Near-neighbor analysis is applied by measuring the distance between the center of each high (or low) and the high nearest to it in space. The mean of these distances, \( \overline{D}_a \), is computed as well as the expected distance, \( \overline{D}_e \), in a random distribution from Equation 5:

\[
\overline{D}_e = \frac{1}{(2\pi)^{3/2}}
\]

Eq. (5)

where \( p \) is the density of the highs expressed as the number of highs per unit area. The near-neighbor statistic, \( D \), is then defined as:

\[
D = \frac{\overline{D}_a}{\overline{D}_e}
\]

Eq. (6)

and this statistic has a range from 0 to 2.15. Under condition of maximum aggregation, \( D = 0 \); under condition of maximum spacing (systematic), \( D = 2.15 \); and in a random distribution \( D = 1.0 \). A test of significance is made from the standard deviate of the normal curve by:

\[
C = \frac{\overline{D}_a - \overline{D}_e}{\sigma_{\overline{D}_e}}
\]

Eq. (7)
where \( \sigma \) is given by \( 0.26136/(N\rho)^{\frac{1}{2}} \) and \( N \) is the number of near-neighbor distances measured. A negative \( C \) indicates a tendency towards an aggregate condition and a positive \( C \) indicates a tendency towards a systematic condition.

The probability distribution of the near-neighbor distances is useful in that statements concerning the probability of a high being within a specified number of miles can be made. It has been suggested that the distribution of near-neighbor distances conform closely to that of a gamma distribution (Dacey, 1968). It has been shown by Schickedanz (1973) that the near-neighbor distances of precipitation highs can indeed be described by the gamma distribution.

**Natural distribution of precipitation highs and lows**

The distribution of highs and lows can be expressed in several ways depending on the definition used for defining highs and lows. After investigating several methods of defining highs including 1) subjective definition of highs (isolated highs and lows), 2) relative residuals*, and 3) standardized residuals, it was found that 5 and 10% standardized residuals provided the best measure available. In this section, the distribution of both positive and negative residuals (highs and lows) are described according to summer and monthly patterns. Near-neighbor analysis is used to describe the spacing of highs and lows as well as other characteristics of the patterns. The highs and lows are then studied in regard to their frequency, persistence, and location.

**Distribution of highs and lows on summer rainfall patterns**

The significance of highs (5- and 10-percent residuals)**, as determined from trend surface analysis of the 1950-69 summer rainfall (June, July, and August) patterns are shown on Figure 2. The most prominent highs are those in the Kansas City area and those in the southeastern part of the map. Smaller, more isolated highs are present at other locations on the map which include the high in the vicinity of LaPorte, Indiana (Changnon, 1968). The highs in the southeastern portion of the map are in the vicinity of the Blue Ridge and Appalachian Mountains and may be the result of an orographic influence. Similarly, the isolated high in Arkansas is near some of the highest elevations in the Ozark Mountains. Other highs in the map are not located in areas of large scale topographic features.

A prominent feature of the map is the absence of highs throughout the central portion of the map. This occurs because any test of significance on the pattern will be based on the boundaries of space chosen and the variability inherent in the data over the area of interest. Thus, in general, trend surface analysis on a smaller sub-sample of the area will produce significant highs which were not present in the analysis of the larger area. For example, the high at St. Louis

Relative residuals are obtained by dividing the basic residual by the actual rainfall at the same location.

Throughout the remainder of the report, the terms standardized residuals and relative residuals refer to the collection of the point residuals in space to form pattern highs and lows.
Figure 2. Significant precipitation highs (5% and 10% residuals) as determined by trend surface analysis for the 1950-59 summer pattern.
which has been documented in other studies, (Huff and Changnon, 1972) is not present. However, a smaller sub-area analysis centered only on Missouri and Illinois will show the high to be significant in this area. Thus, highs in the pattern can only be judged significant in relation to pattern features within their local sphere of interest. Even though a high is not significant in relation to some larger area, it can be very significant in the immediate area of interest. Thus, the highs shown on Figure 2 are significant with regard to the rainfall variability inherent over the entirety of the area (325,000 mi$^2$). The application of near-neighbor analysis to the 5% residuals on the 20-yr pattern indicated that a distribution was random.

A study was made of the effect of reducing the size of sampling area on various characteristics of the highs, and the results are presented in Table 1.

Table 1. A Comparison of Highs (5% residuals) from 20-yr Summer Patterns (1950-69) According to Varying Areal Sizes

<table>
<thead>
<tr>
<th>Areal sizes (mi$^2$)</th>
<th>Density (highs/100,000 mi$^2$)</th>
<th>Near-Neigh. Dist.</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean Random Ave. Near Norm. Nature of Pattern</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean Nbr. Size Dev. Size Stat. Stats of Pattern</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>exp. size stat. dev.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>325,000</td>
<td>2.8</td>
<td>86 95 1378 .9 -.6 random</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90,000</td>
<td>5.6</td>
<td>75 67 560 1.1 .5 random</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40,000</td>
<td>7.5</td>
<td>87 58 533 1.5 1.7 approach system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

First, note the increase in the density of highs as the size of the area is decreased. The listed sub-areas are centered on St. Louis. The density of highs increases from 2.8 to 7.5 per 100,000 mi$^2$. The mean near-neighbor distances do not indicate a trend with area and have an overall average of 83 miles separation. The distance expected under random conditions and the areal size decrease as the sampling areas decrease. The behavior of the near-neighbor statistic itself indicates that whereas the distribution of highs over the large area was decidedly random, the distribution of highs over the smaller sub-sample of 40,000 mi$^2$ approached a systematic condition. Although significance would be obtained when the normal deviate approached 1.96, which corresponds to a spacing of 92 miles, a spacing of 124.7 miles would represent a completely systematic condition for the 40,000 mi$^2$ area.

The empirical distribution of the near-neighbor distances from the 20-yr summer patterns was determined by plotting cumulative ogives. In addition, the near-neighbor distances of 5% residuals from each of 5-yr pattern maps, 1950-54, 1955-59, 1960-64, and 1965-69 were determined and grouped together to obtain a frequency distribution of the distances from the 5-yr patterns. Also, the
distances from each of the 1-yr patterns maps 1950–69 were grouped together to obtain a frequency distribution of distances from 1-yr maps. Cumulative ogives were also determined for the 5-yr and 1-yr patterns and the results are listed in Table 2.

Table 2. The Spacing of Highs (5% Residuals) in Summer Rainfall Patterns as Determined by the Distance to the Nearest High

<table>
<thead>
<tr>
<th>Pattern</th>
<th>1st Frequent Class Interval (mi)</th>
<th>2nd Frequent Class Interval (mi)</th>
<th>3rd Frequent Class Interval (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-yr</td>
<td>41-50(16)*</td>
<td>71-80(16)</td>
<td>51-60(14)</td>
</tr>
<tr>
<td>5-yr</td>
<td>51-60(24)</td>
<td>41-5.0(18)</td>
<td>31-40(13)</td>
</tr>
<tr>
<td>20-yr</td>
<td>31-40(22)</td>
<td>41-50(22)</td>
<td>71-80(22)</td>
</tr>
</tbody>
</table>

*Value in parenthesis is the percent probability of a value– occurring within the indicated class interval.

The values in the table indicate that there is extreme variability between the patterns, but there are consistent features also. The 1-yr pattern has bi-model values at 41-50 miles and at 71-80 miles (i.e., the probability of a given distance occurring within the indicated class interval is the same for both). However, the probability of a value being in the 51-60 interval is 14% and thus the probability is about the same for all three intervals. For the 5-yr pattern the model value occurs, at 51-60 miles with 42% of the values occurring within 40-60 miles. For the 20-yr pattern, there is no difference between the intervals 31-40, 41-50, and 71-80 with 66% of the values occurring in these three intervals. The mean values are 75, 94, and 86 miles respectively for the 1-yr, 5-yr, and 20-yr patterns. Since the means are greater than their respective medians, the distributions are positively skewed. The median ranges from 60 to 72 miles over the three patterns and the 80 percentile ranges from 90 to 124 miles.

The frequency distributions of the near-neighbor distances associated with lows were also determined and the results are listed in Table 3. The mean distance for lows in the 5-yr pattern is 140 miles compared to a mean of 94 miles for the highs (Table 2). Similarly, the mean distance for the lows in the 20-yr pattern in 104 miles compared to a mean of 86 for the highs in the 20-yr pattern. Thus, the spacing of lows is greater than the spacing of highs in the same pattern. This occurs because rainfall data are skewed and also bounded by zero. Thus the magnitude of the low is bounded, but the magnitude of the high is not bounded and can take on large positive values. Because of the larger values, more highs than lows will be judged significant in relation to the mean or a trend surface.
Table 3. The Spacing of Lows (5% Residuals) in Summer Rainfall Patterns as Determined by the Distance to the Nearest Low

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Distance (mi) Associated With the Given Percentile</th>
<th>1st Frequent Class Interval (mi)</th>
<th>2nd Frequent Class Interval (mi)</th>
<th>3rd Frequent Class Interval (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>.20</td>
<td>.50</td>
<td>.80</td>
<td>Mean (mi)</td>
</tr>
<tr>
<td>5-yr</td>
<td>72</td>
<td>130</td>
<td>172</td>
<td>140</td>
</tr>
<tr>
<td>20-yr</td>
<td>44</td>
<td>84</td>
<td>144</td>
<td>101</td>
</tr>
</tbody>
</table>

*Value in parenthesis is the percent probability of a value occurring within the indicated class interval.

**The 2nd and 3rd most frequent intervals cannot be determined since there are several other intervals which have the same probability of .11 which is also the 2nd largest value.

Even though the mean and median distances of lows are greater than the highs, there is still some tendency for some smaller distances to occur. Thus, even though the model value occurs in the 130-140 interval, the intervals 31-40, 71-80, and 81-90 have equal probabilities of .11 and all represent the 2nd most frequent class interval.

Distribution of Downwind Highs and Lows on Summer Rainfall Patterns

In the previous analysis of highs, the nearest high was chosen without regard to direction. Thus, the nearest high may be the nearest high upwind, instead of downwind. Also, the distances obtained will be smaller than the distances to a downwind high, since the nearest high has the opportunity to be chosen from a larger region. Since much of the interest is in downwind highs, an analysis was made in which the nearest neighbor is chosen from only the downwind area. For this analysis, the downwind area was defined as the region anywhere from 0 degrees (north) east through 90 degrees and on to 180 degrees (south). Thus, a downwind location from a given area or point would be those areas to the NE, E, and SE where most precipitation systems moving over the point would pass. Upwind would be anywhere else. The frequency distributions of the distances to the nearest downwind highs were obtained and the results are listed in Table 4. For a 1-yr pattern, the mean distance from a high to the next downwind high is 100 miles and the median distance is 80 miles. Eighty percent of the highs occur within 136 miles of a given high. For a 5-yr pattern, the mean distance to the downwind high is 117 miles with a median distance of 84 miles. The means and medians for the downwind highs are approximately 20 miles greater than the corresponding means and medians for distances obtained irrespective of direction (Table 2). The most frequent class interval is 71-80 miles for the 1-yr pattern and 51-60 for the 5-yr pattern.
Table 4. The Spacing of Highs (5% Residuals) in Summer Rainfall Patterns as Determined by the Distance to the Nearest Downwind High

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Distance (mi) With the Given Percentile</th>
<th>Mean (mi)</th>
<th>1st Frequent Class Interval (mi)</th>
<th>2nd Frequent Class Interval (mi)</th>
<th>3rd Frequent Class Interval (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-yr</td>
<td>.20 52 .50 80 .80 136</td>
<td>71-80(16)*</td>
<td>51-60(10)</td>
<td>41-50(10)</td>
<td></td>
</tr>
<tr>
<td>5-yr</td>
<td>.20 48 .50 84 .80 180</td>
<td>51-60(17)</td>
<td>41-50(12)</td>
<td>31-40(10)</td>
<td></td>
</tr>
</tbody>
</table>

* Value in parenthesis is the percent probability of a given distance occurring within the indicated class interval.

The mean and median distances are of particular interest, for they are in the range of downwind highs reportedly due to seeding. For example, Brown and Elliot (1968) have reported downwind highs at approximately 100 miles and at 250 miles; Brown (1971) has reported highs in the range 70-100 miles downwind; and Grant (1971) has indicated highs in the range 90-120 miles downwind. Grant (1971) has also found little evidence of highs beyond 150-200 miles downwind. Thus, the mean and median distances of downwind highs (natural spacing) correspond closely to the distances associated with highs downwind of seeding experiments. Since the experiments of Grant (1971) and of Brown (1971) were randomized experiments, the above results do not disapprove the presence of downwind seeding-induced highs. However, it does indicate that the reported seeding-induced downwind highs fall in a region where highs occur naturally. The results of Table 4 show that 80% of the nearest downwind highs-in 5-yr periods are within 180 miles. This result corresponds with Grant's finding that there is little evidence of highs beyond 150-200 miles.

The frequency distribution of downwind lows was obtained and the results for 5-yr patterns indicate that the mean distance is 165 miles and the median distance is 136 miles. Bi-model values occur in the 131-140 interval and in the 151-160 mile interval with 40% of the values occurring in the two intervals. Thus, there is an indication that the spacing between downwind lows is greater than the spacing between downwind highs with the mean distance of lows being about 40% larger than the mean distance between highs. This occurs because rainfall data are skewed and also bounded by zero. Thus, the magnitude of the low is bounded, but the magnitude of the high is not bounded and can take on large positive values.

It is of interest to compare the natural spacing of downwind lows with lows which have occurred downwind of seeding experiments. In this regard, Brown and Elliot (1968) indicate that in their compositive analysis of several western seeding projects, a systematic decrease did not occur in the downwind area. Since there is a natural tendency for rainfall lows to be less prominent and further apart than highs, it is quite possible that the lack of a systematic decrease is the result of natural patterns.
Distribution of Downwind Highs on Monthly Rainfall Patterns

The distribution of highs during the month of June for the period 1950-59 is presented on Figure 3. During June, the highs at LaPorte, Kansas City, and St. Louis are prominent enough to be significant in relation to the data over the entire 325,000 mi$^2$ area. The spacing of the highs on 5-yr June patterns as well as the spacing of highs in 5-yr July, August, and December patterns are presented in Table 5.

Table 5. The Spacing of Downwind Highs (5% Residuals) in 5-yr Monthly Rainfall Patterns as Determined by the Distance to the Nearest High

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Distance (mi) Associated With the Given Percentile</th>
<th>Mean (mi)</th>
<th>1st Frequent Class Interval (mi)</th>
<th>2nd Frequent Class Interval (mi)</th>
<th>3rd Frequent Class Interval (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>.20  60  .50  84  .80  136</td>
<td>105</td>
<td>51-60(21)*</td>
<td>71-80(12)</td>
<td>81-90(12)</td>
</tr>
<tr>
<td>July</td>
<td>.20  56  .50  76  .80  140</td>
<td>100</td>
<td>51-60(20)</td>
<td>71-80(18)</td>
<td>81-90(11)</td>
</tr>
<tr>
<td>August</td>
<td>.20  52  .50  100  .80  148</td>
<td>116</td>
<td>41-50(16)</td>
<td>91-100(14)</td>
<td>**</td>
</tr>
<tr>
<td>December</td>
<td>.20  68  .50  100  .80  160</td>
<td>135</td>
<td>61-70(22)</td>
<td>91-100(15)</td>
<td>141-150(11)</td>
</tr>
</tbody>
</table>

* Value in parenthesis is the probability of a given distance occurring within the indicated class interval.

** This interval is indeterminable because more than one interval have the same probability and this is the 3rd largest probability.

For the summer months, the mean distance to the nearest downwind high varies from 105 to 116 miles, while the median varies from 76 to 100 miles. The most frequent interval lies within the range 70-100 miles.

The month of December has a greater spacing in the downwind highs than the summer months. December has a mean of 135 miles compared to the summer month means which range from 105 to 116 miles and a modal class interval of 61-70 miles compared to the range of 41-60 for the summer months. This greater spacing of December highs would be expected since the winter pattern is more uniform than the summer pattern and thus the highs would be less prominent in winter.

A comparison of the monthly distribution of highs with the seasonal distributions (Table 4) reveals that there is little difference between the spacing of highs on the individual summer months and in the spacing on the summer seasonal maps.
Figure 3. Significant precipitation highs (5% and 10% residuals) as determined by the trend surface analysis for the 1950-59 June pattern.
Distribution of the Preferred Areas of Highs and Lows

The number of times that each sampling point was included in a high (5\% residual) on 1-yr summer patterns during the 1950-69 period is shown on Figure 4. The most frequent occurrence of highs is at Kansas City (seven counts) indicating that this is a preferred area for rainfall highs. There are also preferred locations of highs at St. Louis and LaPorte. Some of the preferred areas appear to occur along lines with some degree of uniformity. Possible combinations along preferred storm system motions (WSW-ENE) are shown as dotted lines on Figure 4. In order to determine the nature of the pattern and the distribution of these areas, the following procedure was used to isolate the cores of the preferred areas. Whenever the area of an enclosed isoline was less than or equal to 1/3 of the underlying isoline, the area was considered to be the core of a preferred high area. If the underlying isoline was not present, the delineation of the core was uniquely defined by the separation between the presence of counts and no counts. Some of the cores are connected by the dotted lines shown on Figure 4.

The near-neighbor statistic was applied and the distribution of cores was found to be systematic. The mean near-neighbor distance and the median were determined to be 52 miles with a modal class interval value of 51-60 miles. Thus, the spacing of the cores is close to the modal values of the distances on 5-yr patterns instead of the mean distances (Table 2).

The counts of highs at the various sampling points represent only the significant highs. It is of interest to compare these counts to the counts obtained by summing all residuals above the trend surface (basic residuals) over the 20-yr period. This summation produced counts of 16 at Kansas City, 14 at LaPorte, and 10 at St. Louis, and 18 in the southeastern part of the map. However, a comparison of the number of counts in these areas with the number of counts in their immediate vicinity revealed differences on the order of 1-4 counts. This implies that the net difference between counts in a preferred location of highs and its surrounding is small and on the order of the numbers shown on Figure 4. Hence, the numbers of Figure 4 represent realistic and meaningful values.

The number of times that each sampling point was included in a high (5\% residual) on 1-yr June patterns during the period 1950-69 is shown on Figure 5. Kansas City, St. Louis, and LaPorte are again preferred locations for the occurrence of highs. There is also a tendency for the preferred areas to occur along lines with some degree of uniformity. In order to study the distributions further, the cores of the preferred areas were delineated with the procedure applied to the season data on Figure 4.

The near-neighbor statistic was applied and the distribution of cores was found to be systematic. The mean near-neighbor distance was found to be 61 miles with a median value of 50 miles. The modal class interval was 31-40 miles and the 2nd most frequent class interval was 41-50 miles. Thus, for June the mean was slightly larger than the mean for the summer data, and the mode was smaller than the mode for seasonal data. This implies that the distribution of distances between cores has a greater degree of skew than the corresponding seasonal distribution of distances.
Figure 4. The number of times that each sampling point was included in a high (8% residual) on 1-yr summer patterns during 1950-80.
Figure 5. The number of times that each sampling point was included in a high (5% residual) on 1-yr June patterns during 1950-69.
It is of interest to *speculate* on physical reasons for the spacing of highs observed in the rainfall patterns. Elliot (1971) has suggested artifical cirrus seeding and precipitation pulsation as two possible mechanisms to explain some 'observe highs downwind of seeding sites in the west. Braham (1965) has suggested a dynamic wave mechanism to account for the spacing of radar echoes observed in Project Whitetop.

The first hypothesized mechanism (artifical cirrus seeding) states that updrafts are enhanced in the seeded area and more ice particles are thrown out the top of convection. These crystals create artifical cirrus clouds which drift downwind and eventually descend to lower levels, where they seed cumulus in the downwind area. Calculations by Elliot show that a 60-100 mile drift during descent is reasonable.

The second hypothesized mechanism (precipitation pulsation) is based on the enhancement of precipitation due to increased cloud top heights in individual rainstorms in a squall line. Sub-cloud evaporation occurs and cloud downdrafts develop which spread forward as a pseudo clod front in low levels. This outflow induces an updraft along the leading edge which causes new cumulus to develop. If the pulsation is roughly 3 hours (Newton and Newton, 1959) and if one assumes a translational velocity of 10-20 miles per hour, the spacing of precipitation maxima would have a spacing of 60-90 miles along the movement of the squall line.

The third hypothesized mechanism (dynamic wave) is based on increased cloud growth in the seeded area. It is suggested that this increased growth may set up a stationary wave-like perturbation which spreads outward and down­stream with some sort of damped harmonic motion with a wave length of 30-50 miles.

All of these mechanisms could be present in natural storm data and possibly lead to spacing of precipitation maxima similar to that observed in the natural distribution study. However, development of storms would need to occur repeatedly in approximately the same location if such regularly spaced maxima are to manifest theirselves in monthly and seasonal rainfall patterns. In seeded data, the target area provides the genesis source for the consistent creation of the first maxima and feeder storm. However, in natural data, a triggering mechanism such as pronounced topographical features, large bodies of water, or the chance creation of alternating wet and dry regions, would be required to provide favorable genesis areas for day to day. It is extremely doubtful whether moisture source regions created by chance heavy rainfalls would persist beyond a single season, certainly, not for 5- and 20-yr periods.

There are topographical features present in the PEP study area (Ozarks and Appalachian Mountains) which help to expaln some of the spacing along lines such as depicted in Figures 4 and 5. However, other lines of highs occur apart from topographical features and have no apparent explanation. Therefore, it must be assumed that the observed spacing of many highs in the natural patterns is due to mesoscale or macroscale features of the atmospheric circulation which are either not understood or not detectable in the existing meteorological observational systems.
In June there is a broad band of frequent occurrence of stationary fronts extending from Kansas City to St. Louis to Indianapolis and a band along the Missouri-Arkansas border*. The preferred frontal locations correspond closely to some of the lines of preferred areas of highs shown on Figures 4 and 5. Thus, they help explain the existence of these particular lines but not the observed spacing between the highs within these lines or other lines not subjected to significant topographical features.

The number of times that each sampling point was included in a high (5% residual) on 1-yr December patterns during the period 1950-69 is shown on Figure 6. Note the lack of highs in the Kansas City, St. Louis, and LaPorte areas as opposed to the prominence of highs in these areas during the summer. This tendency for the urban highs to be present in summer and not in winter agree with the earlier findings of Huff and Changnon (1972).

A prominent feature of the map is the presence of the lake effect along the eastern shore of Lake Michigan. The excellent positioning of the lake effect straddling the shore where lake snowstorms occur (Changnon, 1968) illustrates the sensitivity of the techniques involved. In particular, it would appear that the computer gridding of the station data, and the sub-sequent use of these data present no special problems. The large area of highs in the southern part of the map reflect to a large degree the frequent position of fronts during the month of December".

There is again an indication that the preferred areas of highs occur along lines with some degree of uniformity. The cores were delineated as was done with the seasonal and June data, and the near-neighbor statistic indicated that the distribution of cores is systematic. The mean near-neighbor distance was found to be 76 miles with a median value of 64 miles. The modal class interval was 51-60 miles. Thus, the spacing of the cores of preferred areas in December is considerably greater than the spacing in the summer season and in the month of June.

Calculations similar to the above were performed for the preferred area of lows. It was found that the preferred areas for lows were further apart than those for highs. The mean near-neighbor distance was 120 miles with a median value of 88 miles.

Distribution of Time Persistence in Rainfall

In order to measure the persistence of rainfall during the 20-yr period, the lag 1 correlation coefficient ($r_1$) was computed for each sampling point in the study area and the isoline pattern for all coefficients ≥.3 (.05 significance level is .31) is shown on Figure 7. There is a broad area of persistence ($r_1$ ≥ .4) in the southwest portion of the map. A major portion of this persistence area is located in the Ozark Mountains. However, there is not a corresponding area of persistence in the region of the Appalachian Mountains in the south-eastern portion of the map.

* Unpublished data compiled by Griffith M. Morgan, Jr., of the Water Survey Staff.
Figure 6. The number of times that each sampling point was included in a high (5% residual) on 1-yr December patterns during 1950-69.
Figure 7. Persistence of summer rainfall 1950-69 as determined by the lag 1 correlation coefficient.
Cores (or peaks) in the persistence pattern were delineated by the method used for delineating the cores of the preferred high areas. Some of the cores are connected by the dotted lines depicted on Figure 7. There is again some tendency for these cores to occur along east-west lines with some degree of uniformity. The near-neighbor statistic indicates that the persistent cores have a systematic areal distribution. The mean nearest-neighbor distance was 61 miles with a modal class interval value of 41-50 miles. Thus, the mean distance of the persistent cores in summer is approximately the same as the mean distance of preferred high areas. Also, the mean distance of persistent cores is approximately the same as the modal values of the distances between highs in the 1-yr and 5-yr patterns.

Correlation of Rainfall Between Points in the Pattern

The correlation coefficients of summer rainfall with the rainfall at all other points in the study area were computed. Those correlation coefficients ≥ .5 are shown on Figure 8, based on correlation with Salem, Illinois. Note the tendency for the rainfall to be correlated up to large distances from Salem and with isolated cores of correlation as far away as 250 miles to the northwest. The broadness of the correlation patterns indicates that one must be very cautious when posulating extra-area effects out to distances of 200 miles from the target. Certainly, the existence of correlation at these distances would give the appearance of downwind effects of upwind effects (when in fact there was none) unless the effect was so great as to alter the relationship between the two areas.

Correlation cores were delineated in the manner used for the delineation of the cores of the preferred high areas. It is apparent that there is a tendency for the cores to occur along southwest-northeast lines with some degree of uniformity. The near-neighbor statistic indicated a systematic arrangement of the cores. The mean near-neighbor distance was 71 miles with a median value of 72 miles.

The average distances between cores along the lines depicted on Figure 8 were determined. The average distances along the various lines were 86, 80, 82, and 92 miles with an overall average of 85 miles.

Variability in the Spacing of Highs Between 5-Yr Periods

To obtain a measure of the variability between 5-yr periods of the spacing and sizes of highs, the average spacing and size of highs on each 5-yr period were compared. The ranges of the average near-neighbor distances and the average sizes between 5-yr periods are listed in Table 6.

The average distance between highs during any 5-yr period ranges from 67-136 miles for the summer patterns. For the summer months, the range over time is somewhat less with the maximum range being 63-124 miles for the month of July. In December, the range of mean distances over time is considerably greater with the upper limit of the range being 230 miles. This wider range occurs because of the tendency for winter patterns to be very flat, without
Figure 8. The correlation of summer rainfall at Salem with all other points in the PEP study area during the period 1950-69.
any discernable local features. However, in some years, the winter pattern does not begin in December, and the results will be a closer spacing of the highs during some years.

Table 6. The variability between 5-yr periods of the average spacing and size of highs on 5-yr patterns.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Near-neighbor distances (mi²)</th>
<th>Size (mi²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>67-136</td>
<td>518-1371</td>
</tr>
<tr>
<td>June</td>
<td>77-98</td>
<td>640-1520</td>
</tr>
<tr>
<td>July</td>
<td>63-124</td>
<td>578-1333</td>
</tr>
<tr>
<td>August</td>
<td>72-93</td>
<td>575-1055</td>
</tr>
<tr>
<td>December</td>
<td>80-230</td>
<td>640-2960</td>
</tr>
</tbody>
</table>

The flat nature of winter patterns as opposed to summer is also reflected in the areal size of the highs. The size of highs in winter have a much broader range with the maximum size being almost twice as large as the maximum size in summer.

Thus, there is considerable variability in size and spacing from one 5-yr period to the next. However, the distances between highs in summer seasons fall in the range of 67-136 miles with 100 miles being the mid-point of the range.

ANALYTICAL TECHNIQUES USED IN THE STUDY OF RAINFALL PATTERNS IN AND DOWNWIND OF CITIES

Trend surface analysis was again used, but in a different manner than with the analysis of natural patterns. Instead of performing the trend surface analysis over the entirety of the area, it was performed individually for each city and its corresponding downwind region (see Figure 14). In this manner, the importance of a high is judged in relation to the variability over the local sphere of interest. Such a comparison was necessary because some highs are significant in relation to a relatively small area, but are not significant in regard to a very large multi-state area.

To test for the areal spread of the urban effect, the downwind areas at St. Louis and Kansas City were divided into downwind sampling areas (see Figure 9). The areal means were determined within each sampling area for individual months and seasons and then determined for 5- and 20-yr periods.

From the trend surface analyses of individual seasons, the Significant Rainfall Excess (SRE) and the Significant Rainfall Deficit (SRD) were computed. The SRE is defined as the net difference between the rainfall contained within
a significant positive rainfall residual and the amount of rainfall necessary for the residual to be significant. The SRE is computed with the use of Equation 8:

\[ \text{SRE} = R^+_S - (\alpha \cdot S_e) \]  
\[ \text{Eq. (8)} \]

Where:

- \( R^+_S \) = significant positive rainfall residual
- \( \alpha \) = the desired significance level
- \( S_e \) = is the standard error of estimate of the underlying trend surface

The SRD is defined as the difference between the amount of rainfall contained within the significant negative rainfall residual and the amount of rainfall necessary for the residual to be significant. The SRD is computed with the use of Equation 9.

\[ \text{SRD} = R^-_S - (\alpha \cdot S_e) \]  
\[ \text{Eq. (9)} \]

Where:

- \( R^-_S \) = significant negative rainfall residual
- \( \alpha \) = the desired significance level
- \( S_e \) = is the standard error of estimate of the underlying trend surface

The excess and deficit calculations were made for each individual season and are then summed over 5- and 20-yr periods to obtain the rainfall excesses and deficits. These calculations are useful in that they represent only the rainfall that is significantly different from its surroundings. The total excess over time contains the total contribution of the significant portion of rainfall from each year and is a very meaningful value.

After the SRE and SRD regions were established, the highs and lows within downwind regions of SRD and SRE were compared to the highs and lows in the city regions of SRE and SRD. These comparisons were made for cities with urban effects and cities without urban effects. Then, the spacing of the SRE and SRD regions was compared to the natural spacing of highs and lows. Also, the average excess and deficits for 20 mile intervals upwind and downwind of the effect cities were compared to similar averages for the non-effect cities.

An analysis was made as to whether extra-area highs and lows are occurring during the same year as the city highs occur. If the joint yearly occurrence of the extra-area highs with the city high is low, and/or if the joint occurrence of the extra-area lows with the city highs is low, than it is extremely doubtful that the city is the causative factor.
Using the 1972 METROMEX data (Changnon, 1973), the storm patterns in and downwind of St. Louis were investigated. Trend surface analyses were performed for each storm during the summer of 1972. The SRE values were computed for each storm during the summer of 1972 and the values were summed over the entire summer. The resulting downwind excess areas were compared to the urban-induced areas.

INVESTIGATION OF RAINFALL PATTERNS IN AND DOWNWIND OF CITIES

Investigation of the Downwind Highs Using Areal Means

The sampling areas in and downwind of St. Louis and Kansas City are shown on Figures 9a and 10a. Outer (eastern boundaries) of sampling cells are 50, 100, 150, and 200 miles downwind of each city. The angle defining the complete set of sampling cells is 100 degrees wide centered on east with 4 subdivisions of 25 degrees each. Downwind is used in a climatic sense and encompasses the region most frequently downwind of the urban area.

Areal residual means were computed for each of the sampling areas and are shown on Figures 10 and 11. These means were obtained in the following manner: The points within a positive residual within a given sampling area on a particular month were averaged. The means thus obtained for the three summer months of a particular year were then averaged to obtain a weighted summer mean for each sampling area (the weights were given according to the number of points within each residual). The seasonal means were then averaged to obtain a weighted 20-yr mean. Since these weighted means are not masked by the zero sampling points, they should be more reflective of the urban effect than unweighted means.

On Figures 9a and 10a the highest areal average occurs within the 50-mile radius. Figures 9b and 10b illustrate that the average of the inner sector (extent 100 miles) is larger than the average of the two outer sectors (extent 100-200 miles). However, the difference between the inner and outer sectors for St. Louis is very small.

On Figure 9d the inner ring (extent of 50 miles) has a larger areal mean than the other rings. For Kansas City (Figure 10d) the first two rings (extent of 100 miles) have the same means and are greater than the averages of the other two rings. The results from these two figures suggest that the urban effect is contained within 50 miles at St. Louis and within 100 miles at Kansas City. Certainly, there is little suggestion of the effect extending beyond these distances.

Areal means based on all points within each sampling area were also obtained for each season and month and unweighted averages of these means over the 20-yr period were computed. The results for St. Louis again showed that the highest average occurred within the 50 mile radius with little evidence of an urban effect beyond 50 miles. The results for Kansas City also showed that the largest areal mean occurred within the 50 mile radius with little
Figure 9. Areal residual means for various sampling areas downwind of St. Louis for the summer period 1950-69.
Figure 10. Areal residual means for various sampling areas downwind of Kansas City for the summer period 1950-69.
evidence of an effect beyond 50 miles. This differed from the weighted means in that they showed some evidence up to 100 miles of Kansas City.

Unweighted areal means in the various sampling areas were also obtained over the 20-yr period for the months of June, July, August, and December. For June, the results were identical to the results obtained with the summer data in that the largest mean occurred within 50 miles for both Kansas City and St. Louis. For the month of July, the urban effect did not appear to be present since the largest areal mean occurred in the area of 150-200 miles. In addition, the results indicated that the urban effect was not present in August data. However, for Kansas City the urban effect was present in all three months with the largest areal means occurring within the 50 mile radius. For the month of December, the urban effect was non-existent in winter and the largest areal mean occurred in the 150-200 mile ring.

Thus, the net result of the analysis of the downwind sampling areas is that 1) the largest areal means occur within the first 50 miles of the city, and the urban effect apparently does not exist beyond 50 miles, 2) the urban effect is non-existent in winter, 3) the urban effect is stronger at Kansas City than at St. Louis, and 4) the urban effect is present in all three summer months at Kansas City, but only during June at St. Louis.

Delineation of Effect and Non-Effect "Target" Cities

The analysis of areal means in the fixed downwind sampling areas provides useful information, but there are some disadvantages associated with this type of analysis. First, the necessity of delineating boundaries for the areas creates the possibility of a rainfall high being divided into two parts, with the parts being assigned to two different sampling areas. This has the consequence of masking the presence of the high. Also, the nature of an areal mean tends to mask small localized features in the pattern, and these localized features may be the only reflection of the modification effect.

In addition, it was difficult to obtain non-effect cities for comparisons with effect cities because of the size of the total sampling area (Figure 9). Practically any positioning of the sampling area would require a sampling region which contained more than 1 city over 300,000 population or which would overlap the sampling areas of Kansas City and St. Louis.

Thus, to eliminate these problems as much as possible and to get a better measure of small localized effects, another sampling area was also used. This sampling region was not partitioned into smaller sub-areas and was used on a study by Huff and Changnon (1972). In their study of the precipitation at St. Louis, Huff and Changnon concluded that there was strong circumstantial evidence for the presence of an urban effect on summer precipitation. A sampling area of approximately 120 miles from west to east and 90 miles from north to south was used. This area was large enough to include upwind control, major effect, minor effect, and downwind control areas. These areas were based on earlier studies of cell movement, duration, and speed. Since the size of the overall sampling area provided meaningful analysis of the urban
high, a similar area was chosen for use in delineating effect and non-effect cities in the present study. Trend surface analysis was applied to the 120 x 90 mile areas, and the resulting highs and lows (residuals) could be evaluated in relation to the variability of data over these sampling areas.

These sampling areas were used with each city in the multi-state study area with a population equal to or greater than 300,000. Sampling areas for the various cities are shown on Figure 11. The cities of Dayton, Peoria, and Cincinnati were also used, but were not depicted on Figure 11 because their sampling domains overlap those of other cities on the map.

The significant highs (5% and 10% residuals) determined by the trend surface analysis from the 1950-69 summer pattern of each boxed area are shown on Figure 11. Significant highs exist at or near LaPorte (downwind of Chicago-Gary), St. Louis, Kansas City, Indianapolis, and immediately south of Memphis. In addition, Dayton and Cincinnati (not shown) had significant highs.

The number of times that each sampling point was included in a significant high (5% residual) on summer patterns during the period 1950-69 is shown on Figure 12. LaPorte, St. Louis, and Kansas City are preferred locations for highs. Cincinnati and Dayton (not shown) are also preferred locations for highs. It is noted that the preferred area of highs is 25 miles southeast of Indianapolis, while the 20-yr high was located 10 miles east (Figure 11). For Memphis, the preferred area of highs is located 15 miles east, whereas the significant high from the 20-yr pattern was located 20 miles south of the city. The failure for the location of the preferred area of highs and the 20-yr high to confirm each other, indicate that if the urban effect is present, it is weaker in Memphis and Indianapolis than at LaPorte, St. Louis, and Kansas City. Also, the high southeast of Indianapolis is located in a range of hills that extends from southwest-south of Indianapolis east-northeast to Richmond, Indiana.

The Significant Rainfall Excess (based on 10% residuals) for the various cities is shown on Figure 13. For the cities of LaPorte, Kansas City, and St. Louis, excesses are heavy and are located in the same position as the preferred areas of highs and the 20-yr high. The excess at Memphis is light and the excess at Indianapolis is located 40 mile southeast of the city. Cincinnati (not shown) also has an excess, but it is not as heavy as the excesses at LaPorte, Kansas City, and St. Louis.

In order to make the final determination of the effect and non-effect cities, the information from Figures 11, 12, and 13 were compared in relation to each city and in relation to the population of each city. This comparison is shown in Table 7.

The most consistent presence and location of highs occur at LaPorte, St. Louis, Kansas City, and the Quad Cities. However, in regard to the Quad Cities, there are other highs of the same size and magnitude within its sampling domain (see Figures 12 and 13). For the other cities, the high is not present on all 3 maps or the location is not consistent. Thus, LaPorte, St. Louis, and Kansas City were chosen as the effect cities.
Figure 11. Significant precipitation highs (5% and 10% residuals) as determined by trend surface analysis for the 1950-69 summer patterns in and surrounding the test cities.
Figure 12. The number of times that each sampling point in the vicinity of test cities was included in a high (5% residual) on 1-yr summer patterns during 1950-69.
Figure 13. Significant Rainfall Excess (SHE) in the vicinity of test cities during 1950-69 (10% level).
Table 7. Comparison of the city population and the presence of highs within 50 miles of the city as determined by 20-yr residuals, the number of highs, and the Significant Rainfall Excess (SRE).

<table>
<thead>
<tr>
<th>City</th>
<th>Population</th>
<th>20-yr residual</th>
<th>Number of highs</th>
<th>SRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago- Gary-Hamond</td>
<td>7,423,000</td>
<td>LaPorte</td>
<td>LaPorte</td>
<td>LaPorte</td>
</tr>
<tr>
<td>St. Louis</td>
<td>2,423,000</td>
<td>St. Louis</td>
<td>St. Louis</td>
<td>St. Louis</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>1,237,000</td>
<td>None</td>
<td>Cincinnati</td>
<td>20mi S</td>
</tr>
<tr>
<td>Kansas City</td>
<td>1,231,000</td>
<td>Kansas City</td>
<td>Kansas City</td>
<td>Kansas City</td>
</tr>
<tr>
<td>Indianapolis</td>
<td>1,062,000</td>
<td>10mi E</td>
<td>25mi SE</td>
<td>40mi SE</td>
</tr>
<tr>
<td>Dayton</td>
<td>836,000</td>
<td>15mi NE</td>
<td>Dayton</td>
<td>None</td>
</tr>
<tr>
<td>Louisville</td>
<td>802,000</td>
<td>None</td>
<td>35mi S</td>
<td>35mi S</td>
</tr>
<tr>
<td>Memphis</td>
<td>770,000</td>
<td>20mi S</td>
<td>15mi E</td>
<td>15mi E</td>
</tr>
<tr>
<td>Nashville</td>
<td>536,000</td>
<td>None</td>
<td>None</td>
<td>40mi E</td>
</tr>
<tr>
<td>Quad Cities</td>
<td>366,000</td>
<td>25mi NE</td>
<td>25mi NE</td>
<td>25mi NE</td>
</tr>
<tr>
<td>Peoria</td>
<td>336,000</td>
<td>None</td>
<td>None</td>
<td>Peoria</td>
</tr>
<tr>
<td>Des Moines</td>
<td>300,000</td>
<td>None</td>
<td>None</td>
<td>20mi N</td>
</tr>
</tbody>
</table>

For the cities of Peoria, Des Moines, and Nashville, highs are only present in regard to SRE. Since the Peoria area overlaps that of the Quad Cities, Des Moines and Nashville were chosen as the non-effect cities. Thus, the effect cities were chosen on the basis of consistent appearance of highs and the non-effect cities were chosen on the lack of consistent appearance of highs.

For an additional control, non-city sampling point was chosen to represent a hypothetical city. This point did not have a city with population > 300,000 within its sampling domain. This point was designated as the "fake" city and its location is shown on Figure 14.

Investigation of Highs and Lows Downwind from the Target Cities

For the downwind study of cities trend surface analyses were performed on sampling areas (120 miles x 90 miles) immediately downwind of the three effect and three non-effect sampling areas defined in the previous section. The totality of these two sampling areas for each city permitted the investigation
Figure 14. The number of times that each sampling point in areas defined as adjacent and downwind of test cities was included in a high (5% residuals) on 1-yr summer patterns during 1950-69.
of downwind highs and lows out to distances of 200 miles. The use of two sampling areas of the same size instead of one sampling area of the size 90 x 240 miles, enables one to judge the highs and lows in the extended downwind area on the same basis that was used to determine the effect and non-effect cities. These sampling areas are shown on Figure 14 along with a dashed line separating the 2 sub-sampling areas, "adjacent" and "downwind".

Evaluation of the Magnitude and Spacing of Highs and Lows. The number of times that each sampling point was included in a high (5% residual) on summer patterns during the 1950-69 period is shown on Figure 14. For the Chicago-Gary area, the preferred area of highs at LaPorte has a larger count than any of the preferred areas in the downwind region. It has a count of 5 compared to a maximum of 2 counts in the preferred areas of highs in the downwind areas of highs. Kansas City has a preferred area with 4 counts, but downwind preferred areas are also evident with counts of 3 and 4 in addition to other areas with counts of 2. The Fake domain has a count of 6 in the preferred area 20 mi west of the Fake city, but there are also downwind preferred areas with counts of 5 and 3. It should be noted that for the Fake domain the high counts are in regions of high elevations and may be related to orographic effects. Thus, for Kansas City and Fake there are preferred areas of highs downwind which are as large as the preferred areas of highs at the city.

Values of Significant Rainfall Excess (SRE) are shown on Figure 15. For the Chicago-Gary region, the largest high is at LaPorte with an excess value of 12 inches at the center of the high. This completely dwarfs any other highs in the sampling region. The excess values in the downwind highs do not exceed 2 inches, although there are some excess highs upwind with values of 3 and 4 inches.

For the St. Louis sampling domain, the high at St. Louis is larger than anything in its surroundings and in the area which extends downwind to 180 miles. The excess at the center of the St. Louis high is 10 inches. The 10-inch value represents an average excess of 0.5"/hr. Since the value of the trend surface at this point is 11.1 inches, this represents a 4.5% excess/yr over the climatic gradient in the area. For the 20-yr period 1949-69, Huff and Changnon (1972) estimated an urban induced difference of 0.31"/yr with an estimated climatic mean of 10.7"/yr. (that is a 2.9% excess/yr over the climatic gradient). This represents excellent agreement of the estimates in view of the fact that the estimates were derived using different techniques and different data.

For the Kansas City region, there is a high with an excess of 6 inches at Kansas City. However, there is another dominant high 120 mi NE of Kansas City with an excess of 8 inches.

For Nashville and Des Moines, the highs of SRE are, in general, smaller than the highs of the effect city regions, and the magnitude of the highs range from 2 to 6 inches for Des Moines and 4 to 6 inches for Nashville. For the Fake region, there is a high with an excess value of 12 inches 20 miles west of the Fake City, and a high with a 10-inch excess 180 miles downwind. There are also other highs with values of 4 inches.
Figure 15. Significant Rainfall Excess (SRE) in the vicinity of test cities during 1950-69 (10% level).
To help determine if the downwind highs can be attributed to the effect cities, the spacing of the highs in the six sampling areas was investigated. Using near-neighbor distances, the average distance between highs was determined to be 56.9 miles for the three effect city domains and 50.5 miles for the three non-effect city domains. Another measure of spacing was obtained by averaging the distance between highs on W-E lines. The average distance between highs on these lines was determined to be 60.7 miles for the effect city domains and 60.2 miles for the non-effect city domains. These calculations indicate that the spacing of highs is the same in the effect and non-effect cities regions.

Although highs in SRE for natural patterns were not determined, it is of interest to compare these results to those obtained with the natural spacing of preferred areas of highs. Thus, the mean distances obtained here compare well with the modal class value of 51-60 miles and the mean of 50 miles. Thus, the spacing of the excess highs in the effect and non-effect city domains is the same and compares closely to the natural spacing of areas of preferred highs.

The significant rainfall deficit was also computed for the various downwind areas, and the distance between lows was determined. The near-neighbor mean distance was determined to be 107 miles for the effect cities and 94 miles for the non-effect cities. These values correspond to a median value of 88 miles and a mean of 120 miles for the natural spacing of preferred areas of lows in summer patterns. Thus, the spacing of lows for the effect and non-effect city domains was nearly the same and similar to the spacing in the natural spacing of lows.

Evaluation of the Joint Occurrence of Extra-Area Highs and Lows with City Highs. If extra-area highs and lows are being produced by a city, the highs and lows should occur during the same year as the city high occurs. If the joint yearly occurrence of the extra-area highs with the city highs is low, and/or if the joint occurrence of the extra-area lows with the city highs is low, then it is extremely doubtful that the city is the causative factor.

The effect cities were chosen on the basis of the consistent appearance of highs as judged by 20-yr residuals, the number of highs, and the SRE. The same criterion was used to choose the areal extent of the regions which have consistent appearance of extra-area highs and lows in the sampling areas shown in Figure 14. Two comparisons of joint frequency were made.

In the first comparison, the number of times that an extra-area high (5% residual) occurred in a consistent high region during the same year as a high occurred in the city region during the period 1950-69 was determined. The joint frequency of occurrence was determined for each consistent high region and expressed as a percentage of the frequency of highs in the corresponding city region. For non-effect cities, the highs in the nearest consistent high region were treated as control highs. The frequency of these highs was then compared to the frequency of highs in the other consistent high regions within the sampling areas shown on Figure 14. The joint frequency of occurrence for the non-effect cities provided control data for further comparisons.
In the second comparison, the number of times that an extra-area low (5% residual) occurred in a consistent low region during the same year as a high occurred in the city region over the period, 1950-69, was determined. The joint frequency of occurrence was determined for each consistent low region and expressed as a percentage of the frequency of highs in the corresponding city region. For non-effect cities, the highs in the nearest consistent region of the city were again treated as control highs. The frequency of these highs was then compared to the frequency of lows in the consistent low regions to provide control data for further comparisons.

The results for the joint frequency of highs with city highs are listed in Table 8.

Table 8. Comparison of joint occurrence of extra-area high with city highs* (5% residuals).

Percentage of time that the given high occurs simultaneously with the city high

<table>
<thead>
<tr>
<th>Downwind Highs</th>
<th>First nearest high</th>
<th>Second nearest high</th>
<th>Third nearest high</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>Upwind high</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LaPorte</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>No high</td>
</tr>
<tr>
<td>St. Louis</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Kansas City</td>
<td>No high</td>
<td>0</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Des Moines</td>
<td>No high</td>
<td>0</td>
<td>50</td>
<td>No high</td>
</tr>
<tr>
<td>Nashville</td>
<td>No high</td>
<td>20</td>
<td>No high</td>
<td>No high</td>
</tr>
<tr>
<td>Fake</td>
<td>No high</td>
<td>36</td>
<td>14</td>
<td>7</td>
</tr>
</tbody>
</table>

For non-effect cities, the high in the nearest consistent high region of the city is treated as the control high.

The ranges in joint frequency for LaPorte, St. Louis, and Kansas City are 0-10, 0-20, and 0-17 percent, respectively, with an overall average range of 0-16 percent. Such a low frequency of joint occurrence certainly does not warrant a conclusion that these highs are produced by the effect cities. Inspection of the non-effect cities further supports the lack of a city effect in extra-area highs. The range in joint frequency for the non-effect cities has a greater magnitude than the range for the effect cities. The overall average range is 9-35 percent compared to 0-16 percent for the effect cities.

The results for the joint frequency of lows with city highs are listed in Table 9.
Table 9. Comparison of the joint occurrence of extra-area lows with the city high* (5% residuals)

<table>
<thead>
<tr>
<th>City</th>
<th>Upwind low</th>
<th>First nearest low</th>
<th>Second nearest low</th>
<th>Third nearest low</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaPorte</td>
<td>20</td>
<td>0</td>
<td>No low</td>
<td>No low</td>
<td>0-20</td>
</tr>
<tr>
<td>St. Louis</td>
<td>0</td>
<td>20</td>
<td>No low</td>
<td>No low</td>
<td>0-20</td>
</tr>
<tr>
<td>Kansas City</td>
<td>0</td>
<td>0</td>
<td>No low</td>
<td>No low</td>
<td>0-0</td>
</tr>
<tr>
<td>Des Moines</td>
<td>0</td>
<td>0</td>
<td>No low</td>
<td>No low</td>
<td>0-0</td>
</tr>
<tr>
<td>Nashville</td>
<td>0</td>
<td>0</td>
<td>No low</td>
<td>No low</td>
<td>0-0</td>
</tr>
<tr>
<td>Fake</td>
<td>0</td>
<td>7</td>
<td>14</td>
<td>7</td>
<td>7-14</td>
</tr>
</tbody>
</table>

* For non-effect cities, the high in the nearest consistent high region of the city is treated as the control high.

The range in joint frequency is 0-20 for LaPorte and St. Louis. For Kansas City, the extra-area lows never occur at the same time as the city high. The range in joint frequency for the non-effect city of Fake is 7-14 percent. For the non-effect cities of Des Moines and Nashville, the extra-area lows never occur at the same time as the city highs. The overall range for the effect cities is 0-13 percent as compared to an average range of 2-5 percent for the non-effect cities. The low values of the joint frequency of occurrence and the similar size of the values in the effect and non-effect cities do not warrant a conclusion that the extra-area lows are produced by the effect cities.

Evaluation of Areal Averages of SRE and SRD. The areal averages of the SRE and SRD values over the 20-yr period were determined to further investigate the downwind highs. The values were averaged over areas of 20 mi width upwind and downwind of each city. These areas extended in length from the northern boundary to the southern boundary of each effect and non-effect sampling region. The averages for the non-zero points are shown on the left hand column of Figures 16 and 17 and the averages for all points are shown on the graphs in the right column of the figures.

For St. Louis the largest average occurs in the area extending from 10 miles upwind to 10 miles downwind. This average substantiates the large excess high at St. Louis shown on Figure 15. There is no suggestion of a downwind peak in the averages which supports the conclusion of no downwind highs within 50 miles of St. Louis.
Figure 16. Areal means of significant rainfall excess and deficit values (10% level) for varying distances from effect cities.
Figure 17. Areal means of significant rainfall excess and deficit values (107% level) for varying distances from non-effect cities.
For Gary, the largest average occurs in the area extending from 30 to 50 miles downwind. This area corresponds to the LaPorte area and substantiates the excess high shown on Figure 15. There is no evidence of a downwind or upwind peak in the averages, and this supports conclusion of no downwind high beyond 50 miles of the target.

For Kansas City, the averages show peaks at the city, 50-70 miles downwind and 110-130 miles downwind. However, the peak 50-70 miles downwind of the city is dominated by the first downwind high listed in Table 8. This high occurred at the same time as the Kansas City high. Also, there is a similar peak in the averages 50 to 70 miles downwind of the high 20 miles west of the Fake City (control, Figure 17). The peak at 110-130 miles downwind of Kansas City is dominated by the second downwind high listed in Table 8. This high only occurs simultaneously with the Kansas City high 17 percent of the time. Thus, it is doubtful whether either peak is related to the urban area of Kansas City.

It was determined in the section on natural distribution that lows occur less frequently than highs in a pattern because of the skewness of rainfall data and the lower bound of zero. Thus, the average deficits on Figure 16 and 17 are less than the average excesses. An inspection of the deficits reveal little relationship in regard to space except for one feature. There is a slight tendency for the deficits to occur in the neighborhood of excesses. For example, at St. Louis the major deficit area is within 40 miles upwind of the major excess region. At Kansas City the excess occurs in the general region as the deficit and there is a distinct lack of deficit in the areas of low excesses. The tendency is not as distinct at Gary except for the neutral area 0-20 miles west of the large excess at LaPorte. The tendency for deficits to occur in the proximity of the excesses is also present in the overall averages.

The tendency for a excess-deficit relationship is not a strong one, but it is interesting that it seems to exist in climatological data. A firm conclusion is impossible from these data, and this is a subject of future investigation which will require detailed analysis of rain entities such as individual raincells. This investigation is beyond the scope of the present study.

INVESTIGATION OF STORM RAINFALL PATTERNS
IN AND DOWNWIND OF ST. LOUIS

During the first year of METROMEX (1971), a dense network of recording raingages was operated in a research circle of 26 miles radius shown on Figure 18. However, during the summer of 1972 additional gages were installed in an area downwind of the circle in recognition of the need for additional data downwind (Changnon, 1973). These downwind gages were installed at a coarser density (81 mi²/gage) than the density (9.2 mi²/gage) of the gages within the research circle in order to provide a larger area of coverage. It is from these 1972 data that the storm rainfall totals were derived for the present study.
Figure 18. The significant rainfall excess (10% level) in the immediate vicinity of St. Louis during summer 19.2 based on storm rainfall patterns (10% level).
The definition of the storm used for this study is as follows: A storm is a complex of rain entities which occur within 20 miles of each other within a period of 1 hour. In order to handle the analysis effectively, the following corollary is also needed: A merger occurs when 2 or more storms combine to form a composite storm. In order to qualify as a storm merger, the composite storm must contain one rain entity from each storm.

Using these definitions, storm totals were obtained for each gage in the network. This provided a total of 69 storms. Trend surface analysis was then performed on each storm to obtain the significant highs (5 and 10% residuals) in the storm rainfall pattern. For the 10% residuals, the Significant Rainfall Excess (SRE) was computed for each storm and the excesses were summed over the summer to obtain the total significant excess for the 1972 summer storms. The contour pattern of Significant Rainfall Excess values ≥ 1.0 inches is depicted on Figure 18.

Prominent areas of rainfall excess are present within St. Louis, at Edwardsville, east of Alton, south of Collinsville, and 25-30 miles east-southeast of the St. Louis urban center. In addition there is a large 1-in excess area outside the research circle with its center located approximately 40-50 miles NE of the urban center. There are also small 1-in excess areas along the southern edge of the circle. The Edwardsville maximum is located approximately 8 miles east of the large industrial area at the southern edge of Wood River. The maximum in St. Louis is located in the vicinity of a heavy industrial area along the Mississippi River.

An interesting feature is the tendency for the highs to be small in areal extent and to occur relatively close to the urban and industrial areas. The one exception to this is the larger high 40-45 miles NE of the St. Louis urban center. However, a denser network in this vicinity might also shown small highs of larger magnitude.

In regard to the high outside the research circle, it does not appear to be merely a sampling vagary. This is evidenced by comparing the 20-yr excess values on Figure 15 to the storm values. On Figure 15, the excess is also shown to extend 40-45 miles northeast of the urban center, whereas east of the city, the high only extends to approximately 20 miles.

With the exception of the high outside of the research circle, all excesses ≥ 1.0 inch fall within the major and minor effect areas hypothesized by Huff and Changnon (1970) and shown on Figure 18. Since these areas were determined prior to the collection and evaluation of the METROMEX data, comparison between these areas can be quite meaningful. Thus, all excess values within the hypothesized areas shown on Figure 18 were averaged over points with excess only (that is, zero points were excluded). These areal means are shown in Table 10.

The major effect area has the largest mean excess, and the downwind area has the second largest areal mean. The mean of the downwind area is greater than the means of upwind controls and the means of the minor effect area. Based on these values and the information presented on Figures 15 and 18, it
would appear that there is some downwind effect in the area from 25-50 miles, but the magnitude of the effect is smaller than the effect in the 0-25 mile zone.

Table 10. Areal means of Significant Rainfall Excess (10% level) from storm rainfall patterns during Summer, 1972 according to hypothesized effect and non-effect areas. (Zero points excluded).

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean of points with excess (in)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upwind Control</td>
<td>.240</td>
<td>38</td>
</tr>
<tr>
<td>Major Effect</td>
<td>.887</td>
<td>87</td>
</tr>
<tr>
<td>Minor Effect N</td>
<td>.350</td>
<td>24</td>
</tr>
<tr>
<td>Minor Effect S</td>
<td>.474</td>
<td>22</td>
</tr>
<tr>
<td>Downwind Control</td>
<td>.679</td>
<td>17</td>
</tr>
</tbody>
</table>

A firm conclusion can not be drawn on the basis on this 1-yr sample of storms. Furthermore, additional studies in regard to deficits and the movement and direction of each storm contributing to the various excess areas are needed. These studies hopefully will be the subject of future investigations.

SUMMARY AND CONCLUSIONS

Natural Distribution of Precipitation Highs and Lows

Monthly and seasonal data were used to study the natural distribution of highs and lows over a 325,000 mi area of the Midwest. The basic analysis technique was that of trend surface analysis which was used to delineate significant areas of high and low precipitation. Near-neighbor analysis was used to describe the spacing of the highs and lows as well as other characteristics of the patterns. The highs and lows were studied in regard to their frequency, persistence, location and spacing. Such analyses provide useful background information for the studies of extra-area effects from seeding. The primary conclusions derived from the extensive pattern analyses are listed below:

1) The significance of highs and lows in a rainfall pattern is determined by the boundaries of space chosen by the investigator. That is, a high may be judged insignificant with regard to the general pattern over a multi-state area, but may be judged quite significant in regard to a smaller sub-area. Thus, it is critical to determine potential areas of influence based on a knowledge of average cell and storm system duration, speed and movement. Such determination is essential for meaningful studies of cause and effect relationships such as those involving highs or lows downwind of urban areas or areas of cloud seeding operations.
2) The determination of the natural spacing of highs and lows in patterns is highly dependent upon the definition of a high and low. The use of significant residuals from trend surfaces provides an objective method of defining highs and lows.

3) For 1-yr summer patterns, the highs have an average spacing of 75 miles, and for 5-yr patterns the average spacing is 94 miles. For the 5-yr patterns the most frequent distance between highs is in the 51-60 mile interval. These values are based on the distance to the nearest high. When the selection of the nearest high is limited to the downwind area only, the average spacing is somewhat greater. For 1-yr patterns, the mean distance is 100 miles and for 5-yr patterns the mean distance is 117 miles. The most frequent distance occurs in the 50-60 mile interval.

4) The frequency of lows is less than the frequency of highs and the spacing of lows is greater than the spacing of highs. This occurs because rainfall data are skewed and also bounded by zero. The magnitude of lows is bounded by zero, but the magnitude of highs is not bounded and takes on larger values. The mean distance between lows on 5-yr patterns is 140 miles and the median distance is 130 miles.

5) There is little difference in the spacing of highs according to summer months. However, the month of December has a greater spacing of highs than the summer months. For summer months, the mean distance to the nearest downwind high is from 105 to 116 miles. The most frequent distances lie within the range 40-60 miles. For December, the mean is 135 miles and the most frequent distance is in the 61-70 mile interval.

6) Although the spacing of highs and lows in patterns (1-yr, 5-yr, and 20-yr) tends to be largely random over a large multi-state area, the preferred location of highs over a 20-yr period (in respect of the frequency of occurrence over time) tends to be systematic. Also, there is a tendency for these preferred areas of highs to occur along lines with some degree of uniformity. The near-neighbor distance was 52 miles during summer and the most frequent occurrence was in the 51-60 mile interval. During the month of December, the mean near-neighbor distance was 76 miles for preferred areas of highs and the most frequent distance occurred in the 51-60 mile interval. In summer, the preferred areas of lows are further apart than the preferred area of highs with a mean distance of 120 miles and a median value of 80 miles.

7) Persistence from season to season is low in rainfall patterns. The lag 1 correlation coefficient had a maximum value of 0.5 for a given sampling point which only explains 25% of the variance in the 20-yr time series. The majority of sampling points had lag 1 correlations coefficients less than 0.3 which are insignificant. However, persistence centers were found to have a systematic areal spacing with a mean near-neighbor distance of 61 miles and a modal value of 41-50 miles.
8) Correlation coefficients of the rainfall at Salem with all other points in the study area revealed a tendency for the rainfall to be correlated up to 250 miles away. There was also a tendency for correlation cores to occur along southwest-northeast lines with some degree of uniformity. The mean near-neighbor distance was 71 miles and the average distance along lines of correlation cores was 85 miles.

9) There is a considerably amount of variability of the mean distance between highs from one 5-yr period to the next. For summer patterns the mean distance ranges from 67-136 miles and the mid-point of this range is approximately 100 miles.

Overall, the most frequent distance between highs is in the range 40-60 miles. However, on 1-yr and 5-yr patterns the mean distance between highs is 75-94 miles and when the mean distance is determined in a direction sense (downwind) the mean distance is 100-117 miles. The mean distance of persistence areas and preferred locations of highs is approximately 60 miles.

The implications of the natural distribution study is two-fold: 1) the mean and median distances between natural occurring highs are in the range of reported downwind highs due to seeding, and 2) the broadness of the correlation pattern between points in a pattern indicate that one must be very cautious with posulating extra-area effects out to distances of 300 miles from the target.

Rainfall Patterns In and Downwind of Cities

An investigation was made of the monthly and seasonal precipitation patterns in and downwind of cities with urban-induced increases in precipitation. Trend surface analysis was performed individually for each city and its corresponding downwind region so that the importance of a high could be judged in relation to the variability over the local sphere of interest. The trend surface analysis was also performed in and downwind of cities without urban-induced highs for the purpose of control data.

To test for the areal spread of the urban effect, the downwind areas of St. Louis and Kansas City were divided into downwind sampling areas. The areal means were then determined within each sampling area for individual months and seasons, and for 5- and 20-yr periods.

From the trend surface analysis of individual seasons, the Significant Rainfall Excess (SRE) values and the Significant Rainfall Deficit (SRD) values were computed. The excess and deficit values were then summed over 5- and 20-yr periods to obtain the total rainfall excesses and deficits. These calculations are useful in that they represent only the rainfall that is significantly different from its surroundings. The highs and lows within the downwind regions of SRD and SRE were compared to the highs and lows in the city regions of SRD and SRE. These comparisons were made for cities with urban effects and cities without urban effects. Also, the average excess and
deficits for 20 mile intervals upwind and downwind of the effect cities were compared to similar averages for the non-effect cities. Finally, the frequency of joint occurrence of the downwind highs and lows with the city highs were determined and compared for effect and non-effect cities.

Using 1972 METROMEX data, the storm patterns in and downwind of St. Louis were investigated. Trend surface analysis was performed for each storm during the summer of 1972. The SRE values were computed for each storm during the summer of 1971 and the values were summed over the entire summer. The resulting downwind excess areas were compared to urban-induced excess areas.

The primary conclusions derived from the study of rainfall patterns in and downwind of cities are listed below:

1) The areal means in the downwind sampling areas of St. Louis and Kansas City indicated that a) for summer, the largest areal mean occurs within 50 miles of the city, and the urban effect does not exist beyond 50 miles, b) the urban effect is non-existent in winter, c) the urban effect was stronger at Kansas City than at St. Louis, and d) the urban effect is present in all 3 months (areal means) at Kansas City, but only during June at St. Louis.

2) The spacing of excess highs downwind of the effect cities was nearly the same as the spacing downwind of the non-effect cities. The average distance between highs was determined to be 56.9 miles for the effect cities and 50.5 miles for the non-effect cities. Along W-E lines the average distance between excess highs was 60.7 miles for the effect cities and 60.2 miles for non-effect cities. The mean distances correspond closely to the modal and mean values of the natural distances between locations of preferred highs.

3) The results of the trend surface, excess, deficit, and joint frequency analyses indicated that downwind highs and lows beyond 50 miles of St. Louis, Chicago-Gary, and Kansas City were not urban induced.

4) There is a tendency for rainfall deficits to occur in the neighborhood of excesses. The tendency is not a strong one, but it is interesting that it seems to exist in climatological data. A firm conclusion is impossible for these data and this is a subject of future investigation which will require detailed analyses of rain entities such as rain cells.

5) The results of the downwind study using storm data indicated that the major part of the downwind effect from cities occurs within 0-25 miles of the city, with a smaller effect in the area 25-50 miles of the city.
Overall, the results of the climatological studies indicated that the urban effect is limited to 50 miles of the city, and that no downwind effect occurs beyond 50 miles. The results are similar to those obtained by Schickedanz and Huff (1970) and Braham and Flueck (1971) in regard to Project Whitetop, a randomized seeding project in the Midwest. Schickedanz and Huff concluded that the evidence of downwind effects from the Whitetop experiment is very weak. Braham and Flueck concluded that there is little evidence to support an overall seeding effect on precipitation outside of the Whitetop Research area (the radius of the Whitetop Research Circle was 60 miles). Furthermore, the analysis of storm rainfall patterns downwind of St. Louis indicated that the major effect occurs within 0-25 miles, with a smaller effect in the area 25-50 miles of the city.

REFERENCES


Grant, L. O., 1971: Some preliminary analyses to explore the possibility of extended area effects from the Climax seeding experiment. Transactions of Seminar on Extended Area Effects of Cloud Seeding. Santa Barbara, California, 166 pp.


