Illinois State Water Survey
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THE EFFECT OF IRRIGATION ON PRECIPITATION IN THE GREAT PLAINS

by

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Final Report on
An Investigation of Potential Alterations
in Summer Rainfall Associated with Widespread
Irrigation in the Great Plains

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INTRODUCTION

Man's inadvertent modification of weather and climate through changes in land use has become the focal point of many worldwide environmental concerns. Major shifts in land use patterns, such as those due to irrigation and cropping practices, suggest alteration in the weather and climate over substantial regions (Changnon, 1973a). Bryson and Gaerris (1967) have suggested that over-grazing in northern India has resulted in enormous additions of dust to the atmosphere which, through sizeable alterations in the radiative budget, have produced the extensive Rajasthan Desert.

Stidd (1967, 1975) and Joos (1969) have suggested that the development of irrigation projects in arid and semi-arid climates has led to increased evaporation which has, in turn, led to more clouds and rainfall. Stidd concluded that a climatic change in the precipitation in the vicinity of the Columbia Basin Project (an irrigation project in the State of Washington) was due to the growth of irrigation. -However, Fowler and Helvey (1974, 1975) also investigated precipitation in the same area and concluded that the irrigation had no effect on precipitation.

Joos (1969) suggested that precipitation increases of 10-40% since 1955 in large areas extending from the Texas and Oklahoma Panhandles northeastward to Nebraska may have been related to irrigation projects within the area. Changnon (1973b) showed a post-1940 increase of 25% in the irrigated area of west Texas and a decrease of 19% in clear sky days. Henderson and Changnon (1972) found a 100% increase in hailfalls in the 1940's in the same region. Beebe (1974) reported a maximum in dew point temperatures and tornado frequencies over this heavily irrigated area of west Texas. Other investigators (Hammer, 1970; Burman et al; 1975; and Marotz, 1976) have found similar trends in cloudiness, rainfall, and other parameters in their studies of other irrigated areas.

The research in this report was directed toward the question of whether the phenomenal growth of irrigation in the Great Plains has had an appreciable effect on the climate of the region. The specific objective of the research was to determine if a rainfall anomaly due to irrigation existed, and if so, to demonstrate the magnitude of the effect. A second objective was to investigate other associated weather variables for supportive relationships which could also be used to help explain the physical causes for any anomalies discovered.

RATIONALE FOR A RAINFALL INCREASE DUE TO IRRIGATION

It would appear that the most likely cause for a rainfall increase due to irrigation would be the increased availability of evaporated moisture. However, whether the increase in moisture, by itself, is enough to bring about climatic change at a detectable level (eg. an observable rainfall anomaly) has been a source of debate for many years. Prior to 1937, it was generally believed that moisture derived locally from evaporation and transpiration of water stored in the soil played an important role in the precipitation process (Stidd, 1967). However, when upper air moisture measurements became available, Holzman (1937) made a study in which he concluded that local moisture was of little importance in the precipitation process. Holzman's conclusion was supported by Benton et al. (1950) who concluded that 10% of the precipitation falling in the Mississippi River watershed came from local evaporation, whereas 90% came from oceanic sources. The apparent unimportance of local evaporation in the precipitation process was further supported by Budyko (1958), who estimated that 91% of the precipitation over a 2 million mi^2-area in Russia was advected into the area from outside sources. In contrast, studies by Libby (1959) indicated that 32% of the annual land precipitation in the Upper Mississippi valley comes from land-evaporated water.

Regardless, it is important to note that these are annual values. Higher percentages of land-evaporated water may be present in land precipitation due to summertime convective storms in the Great Plains. Furthermore, it is assumed that the above percentages are a direct reflection of the relative importance of advected moisture versus local moisture. It is conceivable that a given percentage of moisture from local sources may be more important than an equal percentage of moisture advected in. For example, Stidd (1967) indicates that most of the excess moisture associated with convective storms comes from a layer of air close to the ground. He also reasons that re-evaporated rainfall as well as the triggering effect of a relatively small amount of moisture introduced at ground level must be considered.

McDonald (1960) , in an attempt to demonstrate the fallacy of a rain increase due to additional moisture from local evaporation, also indicated the importance of dynamic processes. He stated: "In the driest period of a severe drought in any part of the world, huge masses of water are still drifting invisibly overhead, the principal cause of the drought almost invariably being lack of dynamic processes capable of producing ascending motions that cause adiabatic cooling and hence cloud-formation as the indispensable first steps in getting any of the water down to the earth's surface." If McDonald's statement is correct, then it is also logical to assume that the interjection of a mechanism capable of producing ascending motions (particularly, if such a mechanism was previously unavailable) could lead to more clouds, and potentially more rainfall.

Stidd (1967) suggested that the mechanism for a precipitation increase is the latent instability (which could cause ascending motions) created by the increase in moisture rather than the addition of moisture itself. Joos (1969) noted three principal irrigation effects at the soil surface. These included: 1) the albedo is lowered from approximately 25-35% to approximately 15-25%, and the increased absorption of radiant energy is used in the evaporation or transpiration of water; 2) the effective surface temperature under sunny skies is lowered by about 12°C which results in decreased lapse rates near the surface, reduced surface wind speed, and reduced wind erosion of soil; and 3) actual evapotranspiration approaches the potential rate of .02-.25 in/day as compared to .02 to .04 in/day on non-irrigated land during rainless periods in mid-summer. The lowered effective temperature tends to decrease the lapse rate, whereas the addition of water vapor tends to increase the lapse rate through the release of latent energy at the lifted condensation level thereby increasing conditional instability. The increase of evapotranspiration would also increase the amount of water vapor for condensation in the air mass passing over the surface.

An increase in atmospheric moisture and instability could be enough to trigger thunderstorm activity on non-thunderstorm days when only a slight increase in potential instability is required. This would in turn create a much larger area of newly moistened surface, which in turn would produce more numerous and widespread showers on the second day if synoptic conditions were similar.. Thus, a "chain reaction" would be set up which might, on the average, increase the rainfall over the non-irrigated land as well as over the irrigated land (Joo's, 1969).

Another mechanism which has the potential for increasing cloud development and thereby increasing rainfall, is suggested in this report. It would appear that the circumstances surrounding the potential cloud development in irrigated areas is similar to those treated by Purdom and Gurka (1974), Weiss and Purdom (1974), and Gatz and Schickedanz (1975). In all of these studies, thunderstorms were observed to occur at the boundary between cloudy and clear areas. Purdom and Gurka state:

> "When the major factor controlling afternoon thunderstorm formation is solar heating, early morning cloud cover plays a dominant role in controlling where afternoon thunderstorms will first form. In the early cloud free areas, the sun's energy will freely heat the ground and air. The early morning cloud covered areas, however, are kept several degrees cooler due to the clouds' higher albedo as well as the evaporation of water droplets as the cloud cover dissipates. The situation which develops due to this differential heating is analogous to the land-sea breeze effect. The air in the early morning cloudy region, being more dense, sinks and spreads out, lifting the warmer and more unstable air at its perimeter. Thus, the first thunderstorms to form are along the early morning cloud cover boundary. In addition, the subsidence and slower heating rate in the early morning cloudy areas help keep that region free from convection for most of the day."

Gatz and Schickedanz (1975) noted a similar condition in relation to the effect of the urban area of St. Louis on precipitation. They found that the first radar echo and the first surface raincell to form developed near the maximum temperature gradient and the confluence line in advance of an approaching squall line. The temperature gradient had formed along the boundary between cloudy and clear areas. It was speculated that the early morning cloudiness was caused by evaporation from recent heavy rainfall as well as from rivers and nearby low-lying areas. In this particular case, the squall line produced its heaviest rain on an axis perpendicular to the squall line and along the maximum temperature gradient. This case provided strong evidence that even small changes in meteorological conditions caused by cities (e.g., enhancement by fog or haze) can provide a "trigger" that eventually leads, perhaps only after a whole chain of subsequent physical processes, to redistribution of precipitation.

In the case of irrigation, the temperature gradient could be caused by the presence of early morning cloudiness, but this is not a necessary condition. As noted by Joos (1969), the effective temperature of the surface under sunny skies is lowered by about 12°C. This would be sufficient to set up the land-sea breeze effect along the boundary between irrigated and non-irrigated areas, which could lead to ascending motions, and eventually to rain at the surface. It further seems likely that the increased precipitation would occur in the temperature gradient on the downwind side of the irrigated area. This assumes that a portion of the moisture-laded air over the irrigated area is advected downwind so that the air being lifted by the land-sea breeze mechanism would be more moist than air on the upwind side.

However, the effect could occur both on the downwind and upwind side. For example, Hammer (1970) conjectured that the development of a cool, moist dome over water or irrigated surfaces might cause an increased convergence along the windward side of the cool dome, resulting in greater low-level cloud development. This causative mechanism appeared to explain a preferred area of cloud development noted on the windward side of irrigation and river flow in the vicinity of Khartoum in the Sudan. It should be noted, however, that the areas over which the rain fell did not appear to adhere to such a relationship.

Thus, there are several mechanisms which could produce greater low level cloudiness and, subsequently, greater rainfall in the vicinity of large irrigated areas. It is the opinion of the author that any increased rainfall does not come directly from the increased moisture alone, but from thermodynamic and physical side effects produced by the presence of a cool, moist dome over the irrigated area. Whether the mechanisms discussed above are sufficiently operative on a temporal and spatial scale to effect climatic change on a detectable level in rainfall is the subject of the remainder of this report.

BASIC DATA AND REDUCTION PROCEDURES

The basic study region included the states of Kansas, Nebraska, and a large portion of the state of Texas. In addition, some data from the states of Colorado, New Mexico, Wyoming, Iowa, Missouri, and South Dakota were used for extra-area control purposes. The basic study area is shown on Figure 1.

Monthly precipitation data for the growing season months of April-September, 1931-1970 and for a total of 1638 reporting stations were obtained on magnetic tape from the National Weather Center, Asheville, North Carolina. Although the major portion of these data was obtained on magnetic tape, some of it was obtained from printed climatic records. These data were computer filed on magnetic disk storage so that all station amounts for a given month of a particular year were grouped together. Using this disk file, the station data were gridded on a 32 km x 32 km grid. The estimation of the data at the 1380 grid points was made in the following manner. For each grid point a computer search was initiated for the nearest three 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.

$$P_1 = \overline{P} + C_1X_1 + C_2Y_1 + C_3X_1Y_1 \qquad \text{Eq. (1)}$$

$$P_2 = \overline{P} + C_1X_2 + C_2Y_2 + C_3X_2Y_2 \qquad \text{Eq. (2)}$$

$$P_3 = \overline{P} + C_1X_3 + C_2Y_3 + C_3X_3Y_3 \qquad \text{Eq. (3)}$$

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 rainfall values respectively at the 1st nearest, 2nd nearest, and 3rd nearest stations,

$\overline{P}$ - is the mean of the three rainfall 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 boundaries, the solution becomes unstable and extremely large or

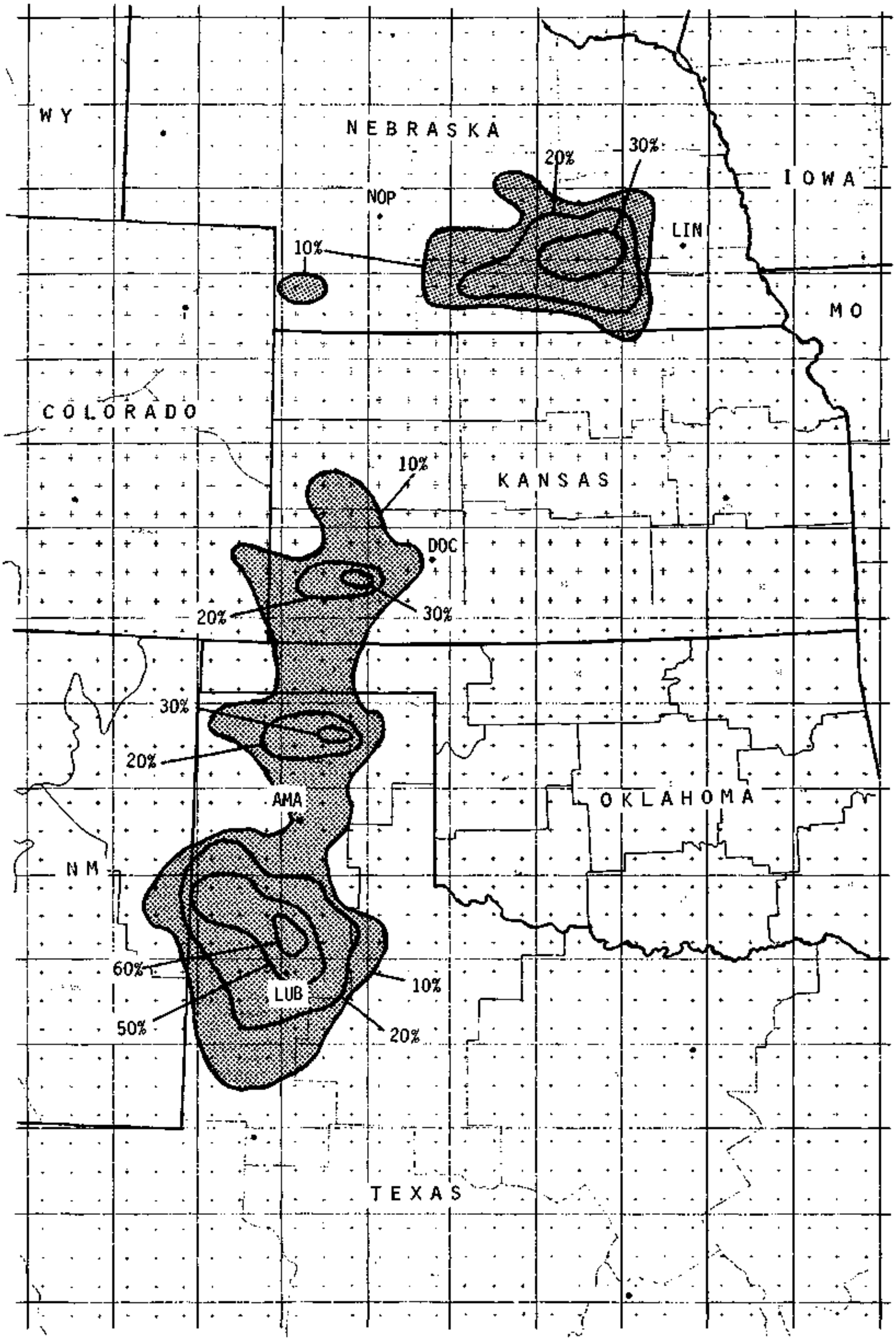

Figure 1. The study area and the irrigated regions of interest.

even negative values will be computed. Thus, whenever the computed value exceeds 2 standard deviations of the three-station mean or is negative, the computed value is set equal to the mean of the rainfall values at the three points.

This data reduction procedure provided a set of 1380 grid point estimates for each of the six months, April-September, and for each year during the period 1931 to 1970. The gridded data were output on punch cards so that a set of cards was obtained for each of the monthly precipitation patterns (240 patterns for the total study area).

It was found that the application of multivariate techniques to 1380 grid points created several difficulties. Of greatest importance were the cost of analyses and the inconvenience of plotting and interpreting results from such a large set of points. Thus, it was found efficient and convenient to form the square sampling areas shown on Figure 1. These sampling squares were 96.6x96.6 km (9,332 km^2) and contained 9 grid points. The rainfall at the 9 grid points within each sampling area was then averaged, and this created basic rain patterns based on 150 sampling squares. Practically all of the subsequent multivariate analyses were performed on this basic data set of 150 sampling squares.

As noted previously, the specific objective of this research is to determine if a rainfall anomaly due to irrigation exists, and if so, to demonstrate the magnitude of the effect. This requires a sophisticated pattern analysis, so the density of rainfall reporting stations becomes a critical factor. Initially, it was intended that only rainfall data during the period 1931-1970 be used in the pattern analysis. However, in the final assessment of the irrigated-related anomalies, it became essential to obtain rainfall data from more non-irrigated years for control purposes. Hence, the rainfall data from the period 1921 to 1930 were used as a supplementary data source in selected analyses involving the 150 sampling squares.

However, the data from 1931-1970 were considered to be the primary (basic) data source. They were recognized to be of higher level quality than the supplementary data, and were used in the vast majority of the analyses. The supplementary data were used in a supportive role to confirm the results obtained from the primary data source. The supplementary data were unavailable from magnetic data and had to be obtained from printed climatic records of the National Climatic Center. These data were then entered on punch cards.

In order to determine the influence of irrigation on hailfall, a limited analysis was made using crop-insurance data from the crop reporting districts of High Plains and Low Rolling Plains in the Texas Panhandle. The data employed consisted of the crop-hail insurance data compiled by Texas insurance companies who are members of the Crop-Hail Insurance Actuarial Association (CHIAA).

The annual loss-cost rations were determined for the period 1941-1970 for 49 countries in these two districts. There were many countries for which the loss-cost ratios were not determined because of a lack of liability during certain years. If the number of years without liability exceeded 10, the entire county was excluded from the analysis. These countries were considered to be "missing" and are so indicated on Figure 28a.

In addition, a limited analysis was made of the hail-day data for Lubbock and Plainview, two stations near the center of the heavily irrigated regions in the Texas Panhandle. These data were obtained from the National Climatic Center.

The monthly temperature patterns during the period 1931-1970 were investigated in the southern half of the study area shown on Figure 1. These data were available on the same magnetic tape that was used for the monthly rainfall data.

In addition, daily rain and temperature data from stations in the Texas Panhandle were used to further confirm results obtained from the monthly analyses. Also, synoptic and sounding data were used to help explain the physical causes of the irrigated-related anomalies. The sources and limitations of these data are discussed by Barnston (1976).

In order to relate the basic precipitation data to the growth of irrigation, it was necessary to carefully delineate the major irrigation regions. Detailed data on the number of hectares irrigated in each county of the study region were found to be available from 5-year inventories (U.S. Bureau of the Census, Census of Agriculture, 1919-1969). These data were extracted and expressed as a percent of the total land area within each county, and the percent values were plotted on maps. The resulting patterns for selected years in the southern part of the study area (Texas, Oklahoma, New Mexico) are depicted on Figure 2a-f.

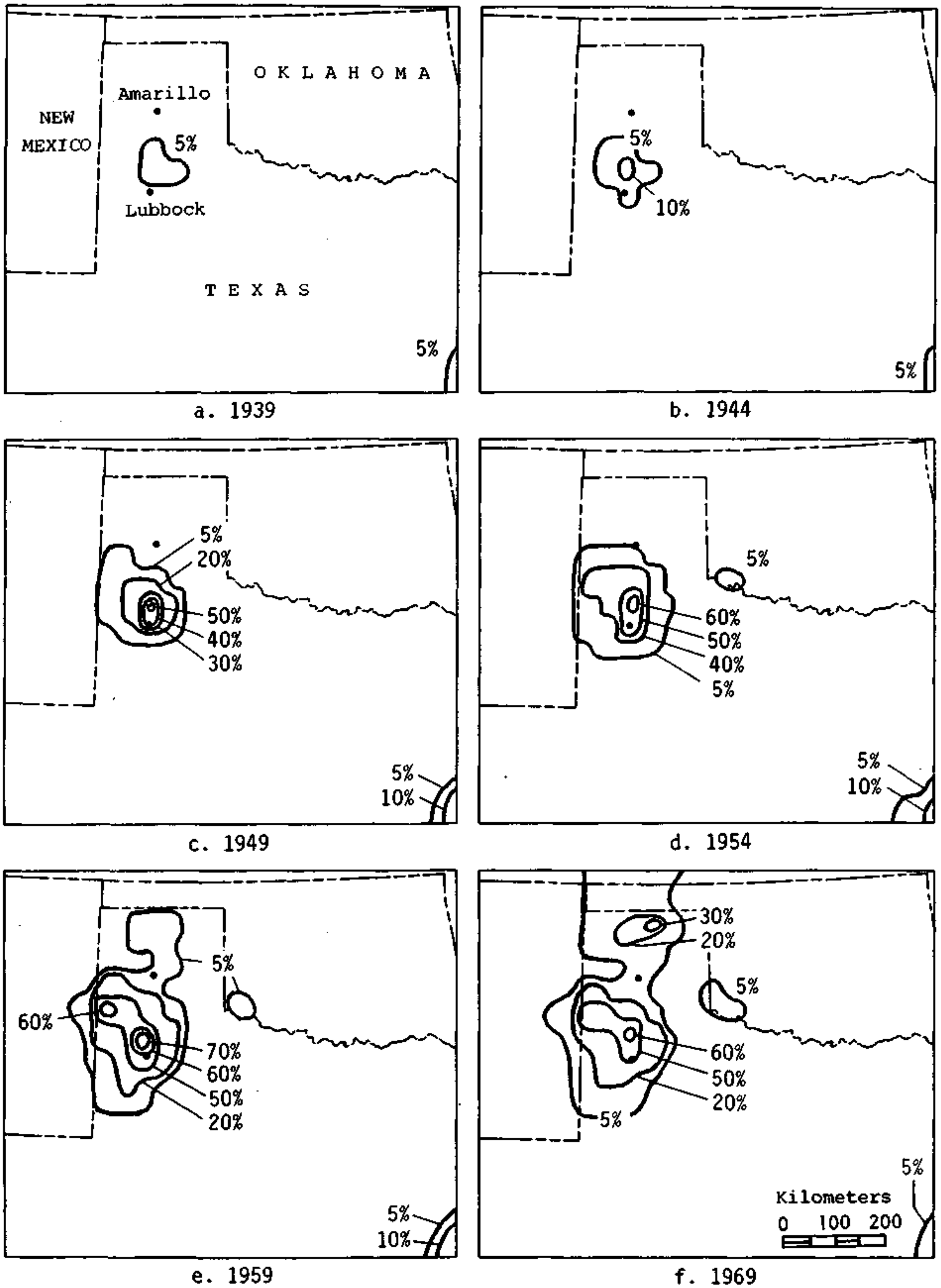

Figure 2. The percent of total land under irrigation for selected years during 1931-1969 in the southern study area.

A phenomenal growth of irrigation occurred in the Lubbock-Amarillo region of the irrigated area during the 5-year period, 1944-1949, with the percent of area irrigated increasing from 10% to 50% in the core of the irrigated region. Another expansion of the total area under irrigation occurred in the late 1950's and irrigation growth persisted throughout the 1960's, reaching northward across the state of Oklahoma. During the 1960's the percent of land under irrigation in the central portion of the irrigated area decreased somewhat due to dwindling usable ground-water supplies and the initiation of water conservation procedures (Texas Water Development Board, 1971). However, by 1969 there was approximately 95,000 km^2 (36,680 mi^2) with 5% of the total land area irrigated, 37,000 km^2 (14,286 mi^2) with 20% irrigated, and 10,000 km^2 (3,861 mi^2) with 50% irrigated. The peak value was 75% which occurred in Hale County during 1959. For Texas, surface water accounted for approximately 25% of the total irrigation water used and ground-water accounted for 75% in 1969. The sprinkler method of application accounted for 19% of all irrigation.

The patterns of irrigation coverage for selected years in the northern part of the study area (Kansas, Nebraska, Colorado, Wyoming, South Dakota, Iowa, Missouri) are shown on Figure 3. The major growth of irrigation occurred in east-central Nebraska and western Kansas. The intensity of irrigation in these two regions never reached the level that was achieved in the southern area. Also, the two major expansions of the latter 1940's and 1950's are not so evident in the northern area as compared to the southern area, and thus, the rate of growth is more gradual and steady in the northern area. However, by 1969 in east-central Nebraska, there was approximately 60,000 km^2 (23,170 mi^2) with 5% of the total land irrigated, 16,000 km^2 (6,180 mi^2) with 20% irrigated and 1,000 km^2 (386 mi^2) with 40% irrigated. The peak value was 40% of the land area irrigated which occurred in Hamilton County, Nebraska, during 1969. At the same time, in western Kansas, there were approximately 35,000 km^2 (13,510 mi^2) with 5% of the total land irrigated, 5,000 km^2 (1930 mi^2) with 20% irrigated, and 1,500 km^2 (580 mi^2) with 30% irrigated. The peak value of 34% occurred in Haskell County during 1969.

The irrigated regions in western Nebraska, Colorado, and Wyoming are relatively constant over the 40-year period, with the exception of an area of small growth along the Kansas-Colorado border in the late 1960's. This is

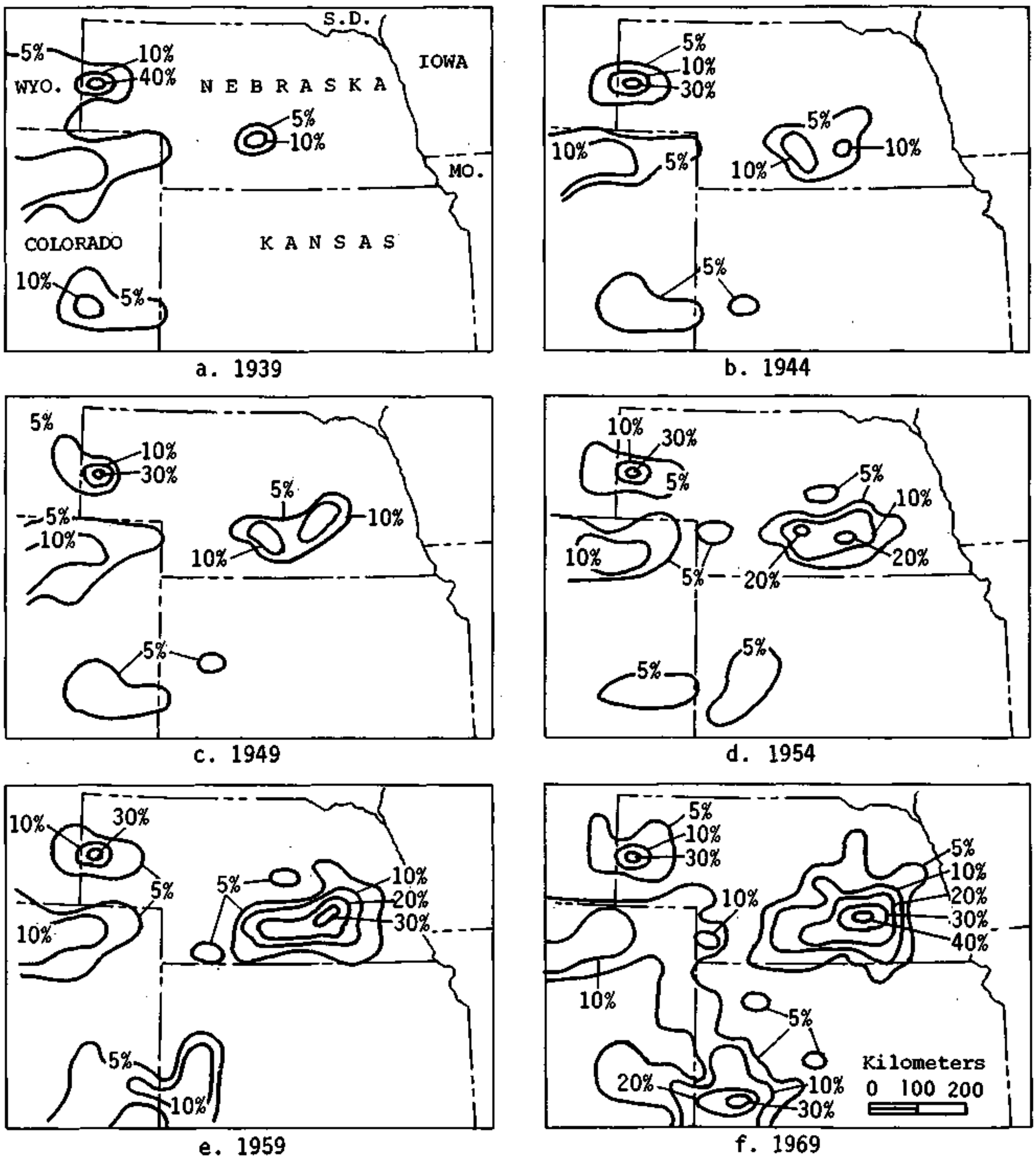

Figure 3. The percent of total land under irrigation for selected years during 1931-1969 for the northern study area.

an important finding because the subsequent analyses relating irrigation to rainfall are based on a joint temporal-spatial change in the patterns of irrigation and rain. Since the growth of irrigation was relatively stationary over the 40-yr period, it was hypothesized that there would not be a rain increase in these areas. Thus, the irrigated regions of Wyoming and western Nebraska are treated as a upwind control area in the subsequent analyses.

Furthermore, an area with 5% of the total land irrigated was considered to be relatively unimportant, and these areas are not depicted on the pattern maps presented in this report. Thus, the irrigated regions depicted on Figure 1 were considered to be the major irrigation-source regions for the analyses presented in this report.

GENERAL CLIMATIC BACKGROUND

In the Great Plains, heavy irrigation occurs during the summer months of June, July, and August. In the Texas Panhandle, there is light irrigation 1) in the February-May period for winter wheat and pre-watering summer crops, and 2) in the September-October period for winter wheat and pre-watering of wheat. The heavy irrigation is for sorghum, soybeans, and cotton and occurs during the period from mid June to the end of August. *

In the Kansas region, there is light irrigation 1) in April-May for winter wheat and pre-watering for sorghum, 2) in June for summer crops and 3) in the August-September period for wheat and pre-watering of wheat. The heavy irrigation is for sorghums, beets, soybeans, and corn and occurs from the first part of July to mid September. **

In the Nebraska region, there is light irrigation in 1) May-June for wheat and beets, and 2) September-October for wheat and pre-watering of wheat. The heavy irrigation is for corn, soybeans, beets, and hay and occurs from early July to early September. *** Thus, the heavy irrigated period

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* Personal communication with Leon New, Texas Agricultural Extension Service of Texas ASM University, Lubbock, Texas

** Personal communication with W.E. Steps, Water Resources Board, State of Kansas, Topeka, Kansas

*** Personal communication with Michael Jess, Department of Water Resources, State of Nebraska, Lincoln, Nebraska begins 2-3 weeks earlier in Texas than in Kansas-Nebraska, and ends 1-2 weeks later in Kansas-Nebraska than in Texas. In general, the irrigation for winter wheat is considered light compared to irrigation for summer crops in all three regions, particularly in Kansas and Nebraska. Consequently, except for the early part of September in the Kansas-Nebraska region, the heavy irrigation is confined to the summer months of June, July, and August with June having lighter irrigation than the other months. Thus, for general comparisons, June, July, and August are considered to be "irrigated months" whereas April, May, and September are considered to be "non-irrigated" months.

It is recognized that individual years may vary from these general patterns of irrigation application, however, it is extremely informative to compare the climatic backgrounds of the summer months of June, July, and August to the spring and fall months of April, May, and September. For this purpose, the average rainfall patterns for the irrigated months are shown on Figure 4 and the average rainfall patterns for the non-irrigated months are shown on Figure 5.

The main features of interest, insofar as a possible irrigation effect in June, are the westward bulge in the isohyets in the Texas Panhandle and the bulge in the 4.5 isohyet in the Nebraska irrigated region (Figure 4). During July, the dipping of the 2.5 isohyet in the Texas Panhandle and the westward bulge of the 3.0 isohyet in western Kansas are of interest. For August, there is a ridge of relatively high rainfall which extends from the Texas Panhandle into western Kansas (ridge delineated by the 2.5 isohyets). Thus, there is a suggestion of rainfall anomalies in the irrigated areas, but the assessment of these anomalies from the 40-yr monthly patterns is not easily done. There is a stronger suggestion of a rainfall anomaly when all of the summer months are totaled together. The average rainfall pattern for the entire summer is shown on Figure 4. Here, there is a definite suggestion of a rainfall anomaly (note the 7 and 8 inch isohyets) in the irrigated area of Texas and Kansas.

An inspection of the non-irrigated months (Figure 5) reveals less indication of rainfall anomalies in the irrigated regions. The pattern for September has a westward bulge in the southernmost irrigated region of Texas so there is a suggestion of a possible irrigated-related anomaly. There is little suggestion in April and May, and when all three months are totaled (Figure 5), there is practically no suggestion of a rainfall anomaly in the

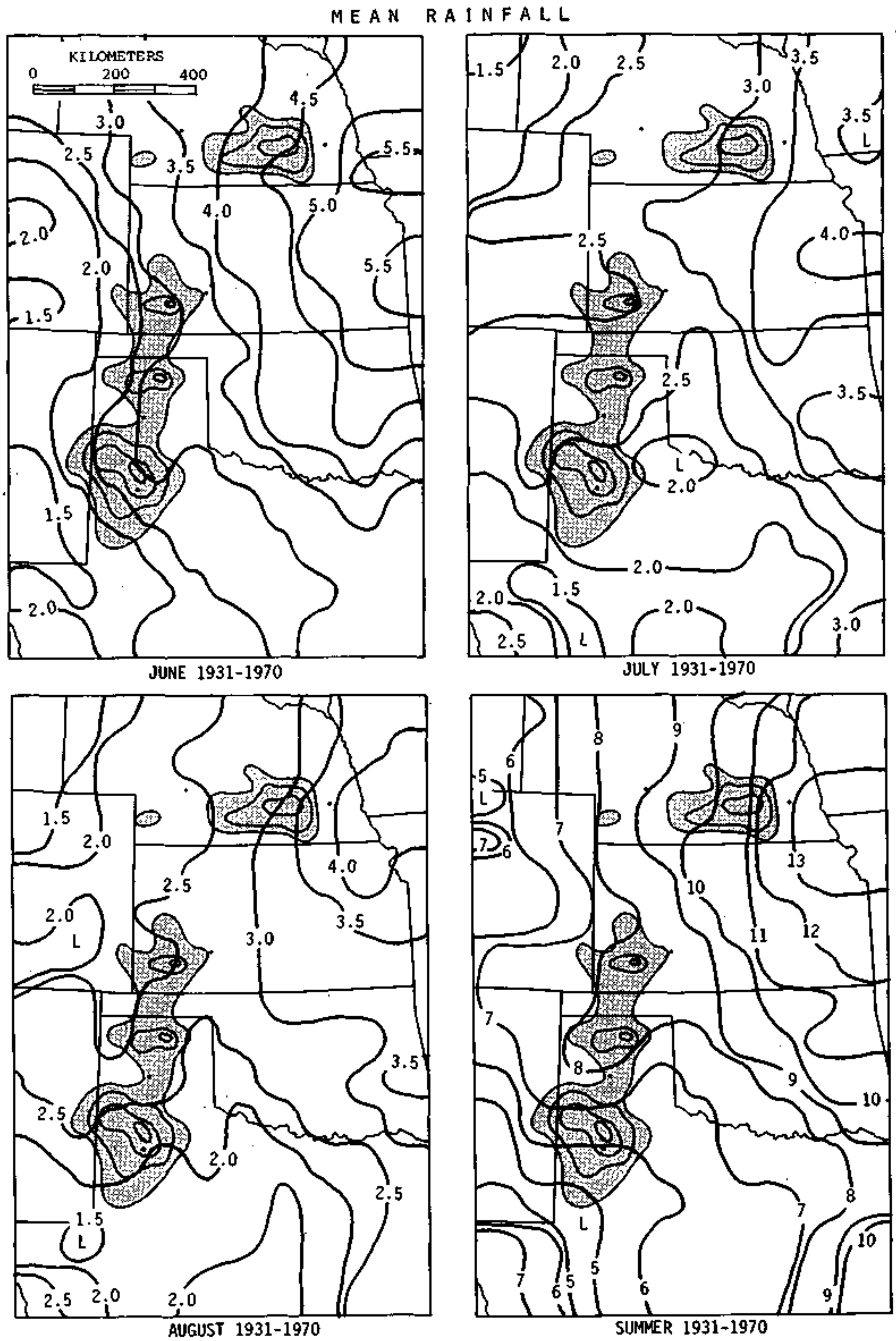

Figure 4. The average rainfall patterns for the irrigated months (rainfall in inches).

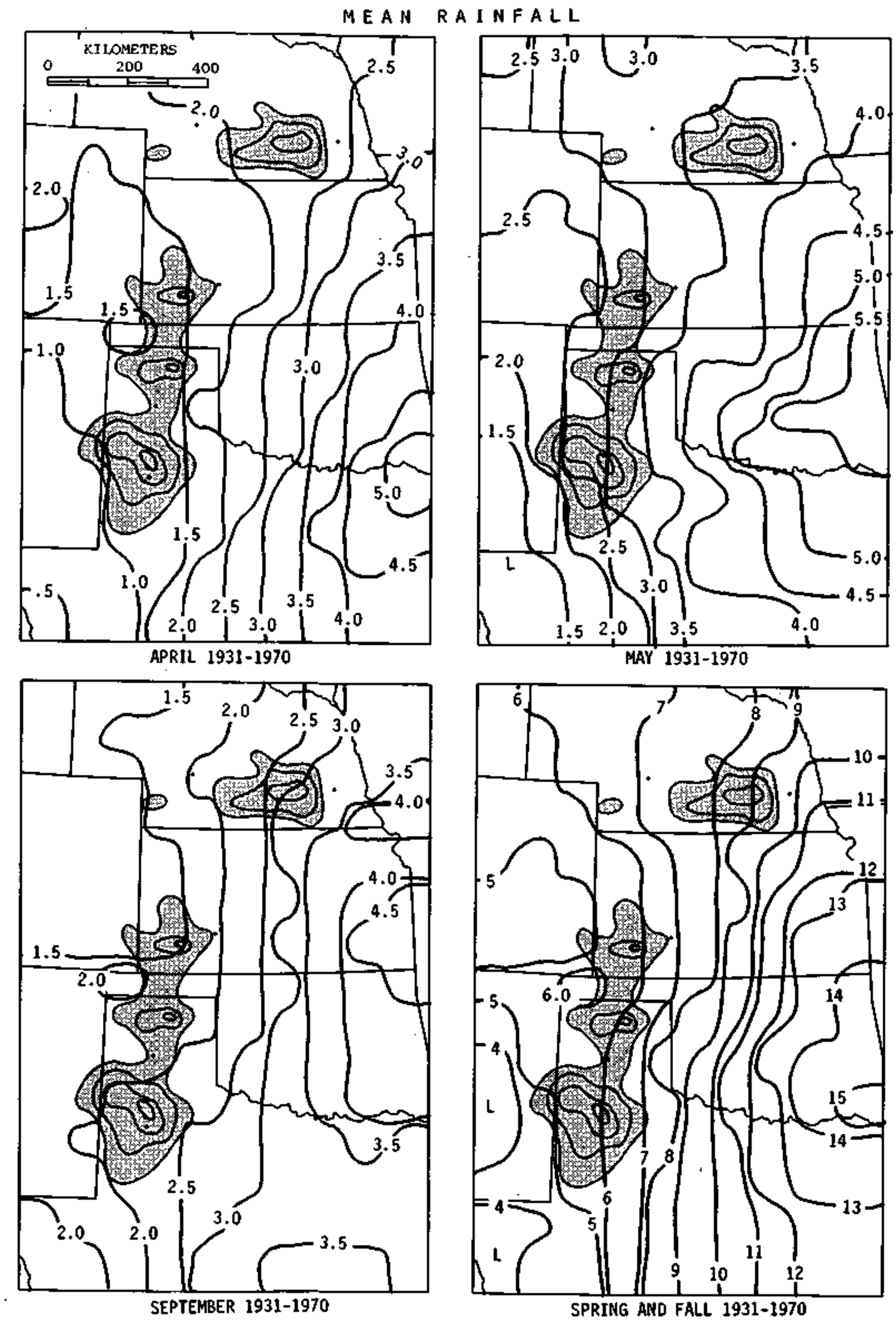

Figure 5. The average rainfall patterns for the non-irrigated months (rainfall in inches).

irrigated areas. Accordingly, with the exception of September, there is only a weak indication of anomalies in the irrigated areas during non-irrigated months.

Another climatic comparison of interest is the general trend in rainfall over the period 1931-1970. In order to determine the overall trend, the simple linear regression coefficient was determined for each of the 150 sampling areas. The coefficient (a measure of trend) was determined from the temporal series (40 values) of each month and the resulting patterns of the coefficient (b) are shown on Figure 6 for the irrigated months and on Figure 7 for the non-irrigated months.

For the month of June (Figure 6), there are upward trends in the irrigated areas of Texas, Kansas, and Nebraska. In July there are upward trends in the irrigated area of Texas-Oklahoma-Kansas, and in August there are upward trends in Oklahoma-Kansas and Nebraska. The overall summer pattern (Figure 6) indicates an upward trend throughout all of the irrigated regions. In contrast, the patterns of trend for the non-irrigated months (Figure 7) indicate that the upward trends are well east of the irrigated areas with either no trends or downward trends in the irrigated areas. Thus, it would appear that there is a upward trend in and surrounding the irrigated area during irrigated months and there is no trend or downward trend in and surrounding the irrigated areas during non-irrigated months.

The general upward trend can also be inspected by investigating the average rainfall by decades during the 1940-1970 period. The average rainfall patterns for 1931-1940, 1941-1950, 1951-1960, and 1961-1970 are shown on Figure 8 for June and on Figure 9 for July. In the Kansas-Oklahoma-Texas irrigated region, there is a gradual increase in the rainfall by decades. This is strongly reflected by the closed isohyets of 3 inches in 1951-1960 and 4 inches in the 1961-1970 periods (June, Figure 8). The rainfall anomalies represented by these isohyets were not present during the earlier periods of 1931-1940 and 1941-1950. Also, a protrusion in the isohyetal pattern in the Nebraska region had become established during the 1961-1970 period (5 inch isohyet). During July, rainfall anomalies developed in the 1941-1950 and 1951-1960 periods. There is also a suggestion of anomalies during the 1961-1970 period (dipping of the 3 in. isohyet) but it is not as strong as in the previous two periods. The rainfall patterns by 10-year periods for August and Summer (not shown) also contain evidence of anomaly development over 10-year periods, but the development is not as evident as in the June and July 10-year patterns.

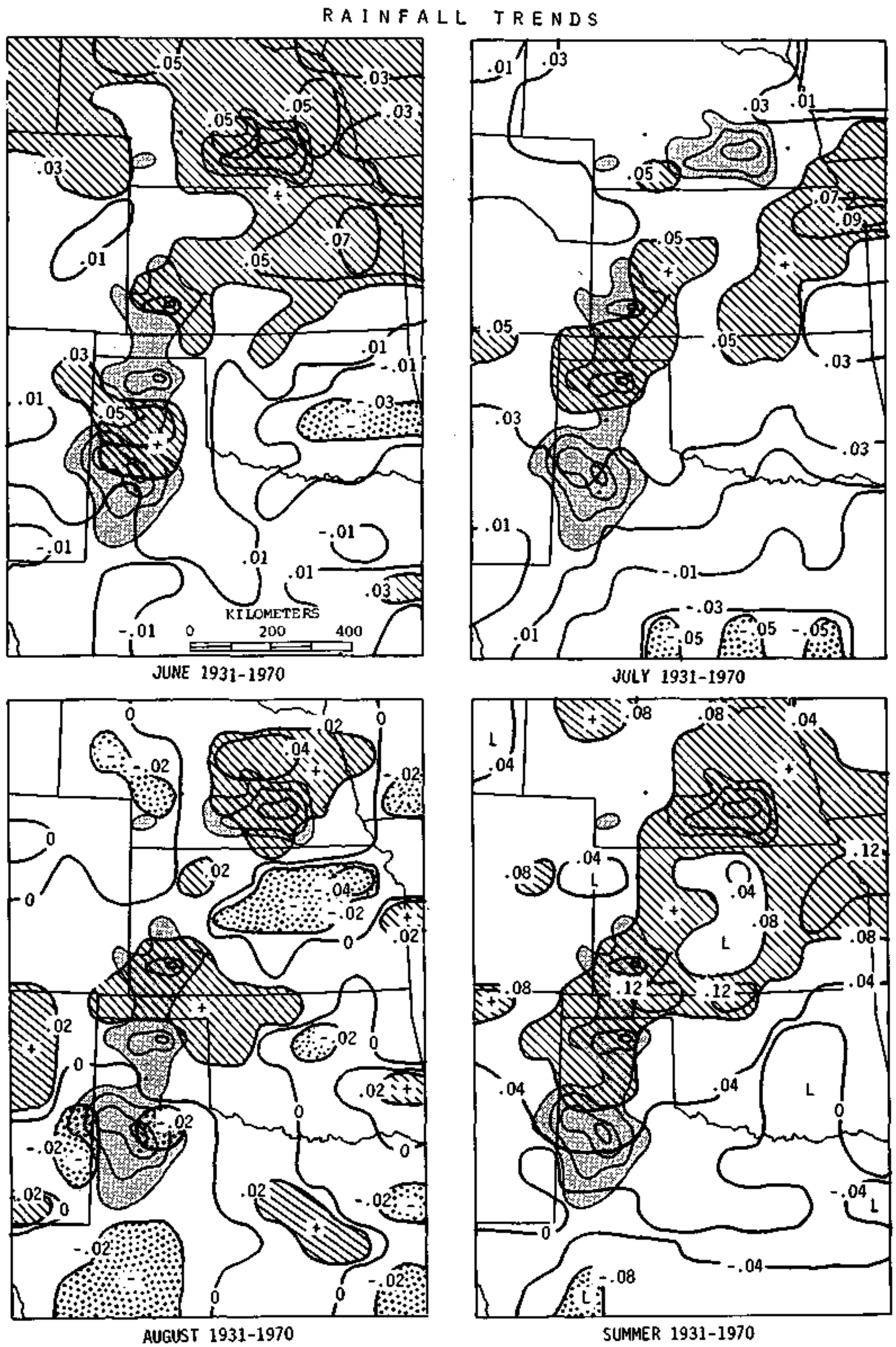

Figure 6. The rainfall trend patterns for the irrigated months (trend in inches/year.).

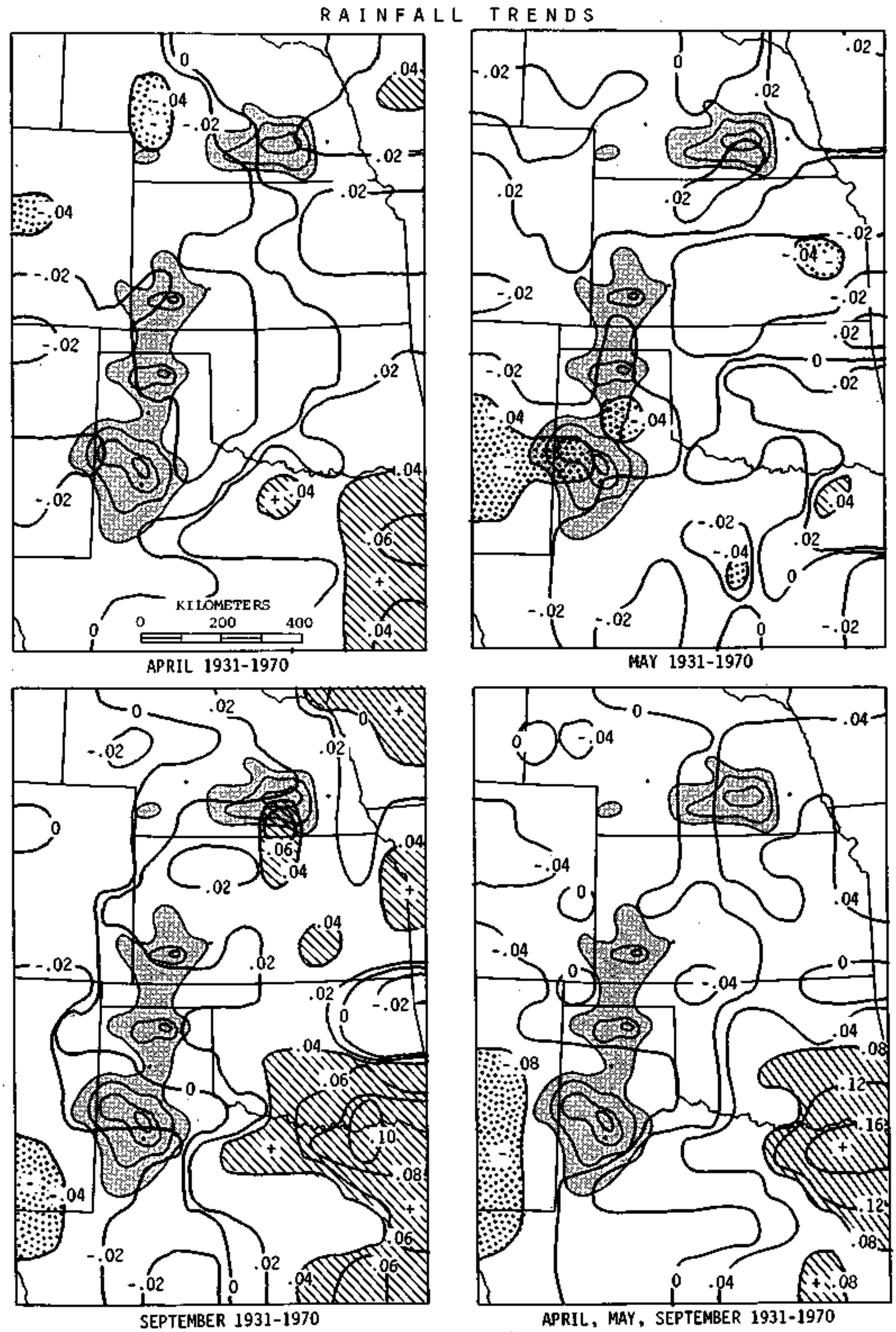

Figure 7. The rainfall trend patterns for the non-irrigated months (trend in inches/year).

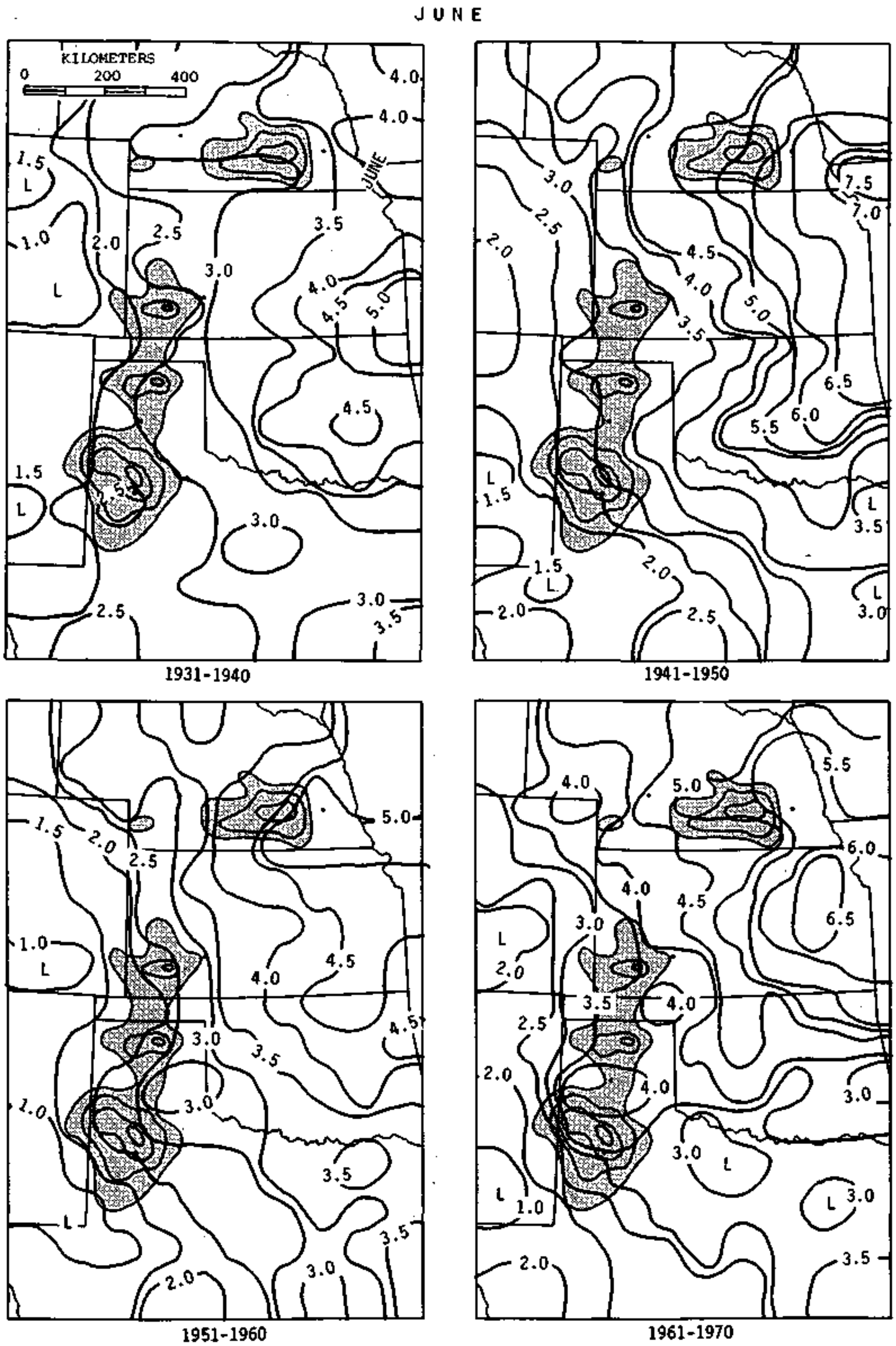

Figure 8. The average rainfall patterns for 10-year periods during June (rainfall in inches).

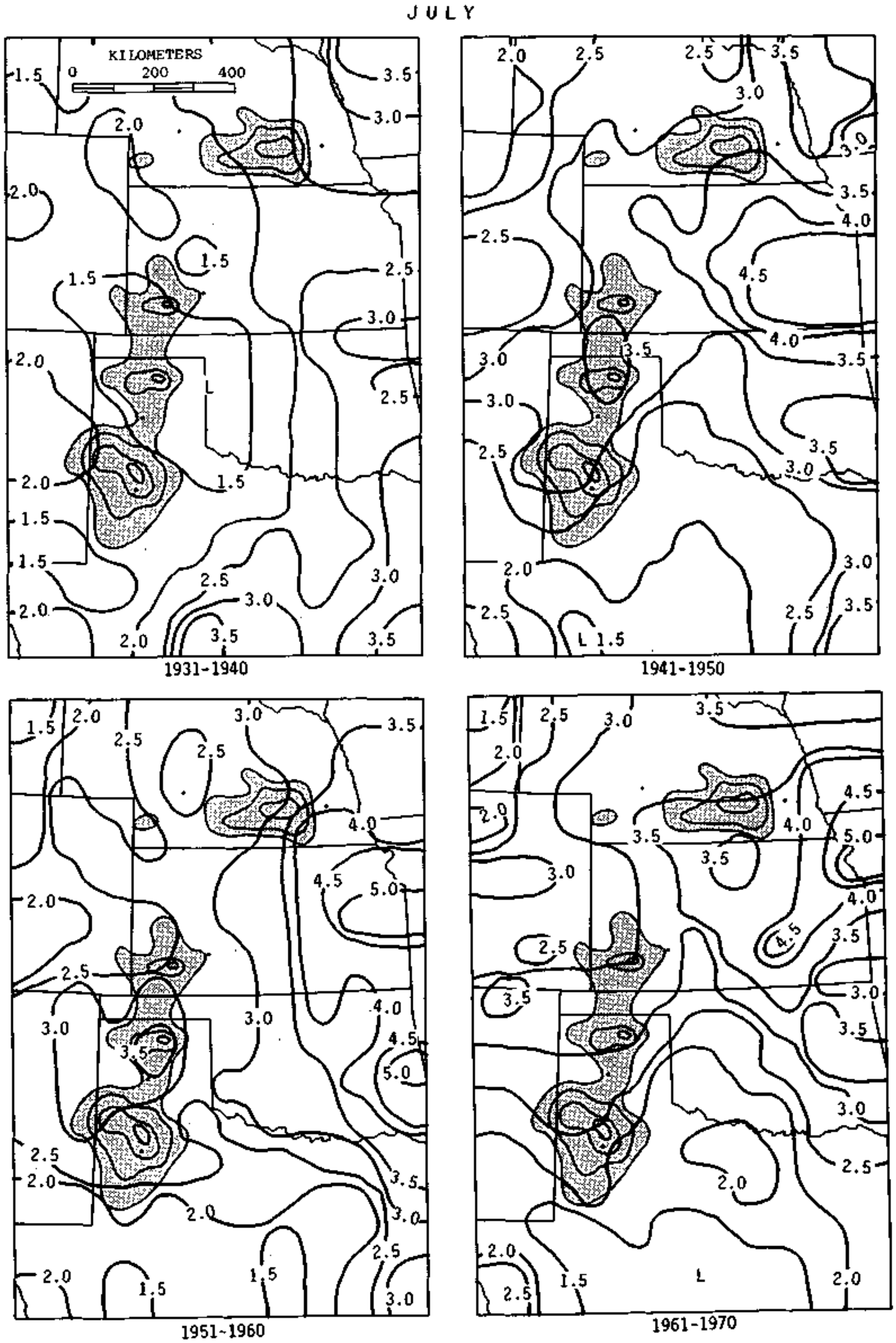

Figure 9. The average rainfall patterns for 10-year periods during July (rainfall in inches).

SEPARATION OF IRRIGATION EFFECTS FROM CLIMATIC VARIABILITY

DELINEATION OF THE RAINFALL ANOMALIES AND THE ASSOCIATED IRRIGATION FACTOR

The Criteria For An Irrigation Effect

In order to separate the effect of irrigation from the climatic variability of rainfall over time and space in the region, a multivariate statistical technique known as factor analysis was used. This approach provided a means of removing spurious relationships in the spatial-temporal data set, and was also a method for evaluating the influence of irrigation on the rainfall patterns. The factor analysis was applied to the mean areal rainfall during a particular month over each of the 60 mi x 60 mi sampling areas (3600 mi^2) shown on Figure 1. First, the mean areal rainfall values from the 150 sampling areas (variables) were determined for each year (observation) of the period 1931-1970 and for each of the months April through September.

The mean areal values from the 150 areas were used to form a m x n (m = 150 areas x n = 40 years) matrix X. The matrix was then subjected to a Q-type factor analysis. This analysis was performed by first standardizing each of the columns (years of the X matrix) by their respective means and variances so that a m x n matrix Z of standardized variates was obtained. The correlation matrix R, which is a matrix of correlation coefficients between the columns (years) of Z, was then determined. Since the correlation matrix is between observations (years) instead of between variables (areas), the application of factor analysis to the R matrix results in a Q-type factor analysis instead of a R-type factor analysis (Kim, 1975). (For a R-type factor analysis, the X matrix would have been transposed and the R matrix would have been between variables (areas)). From the R matrix, a set of new variables is constructed such that the new variables are exact mathematical transformations of the original data. This transformation is accomplished by determining the characteristic scalar roots (eigenvalues) and the non-zero vectors (eigenvectors) of R which simultaneously satisfy the equation:

$$RE = \lambda E \tag{4}$$

where E is the n x n matrix consisting of set of orthonormal eigenvectors of R as the columns and X represents the eigenvalues (characteristic scalar roots) of R. Equation 4 can be rewritten in the form:

$$(R - \lambda I_n)\ E = 0 \tag{5}$$

where I_n is the identity matrix of order n x n. The solution of the scalars λ and the eigenvectors E is the classical Characteristic Value Problem of matrix theory (Hohn, 1960).

The magnitude of the eigenvalues represents the variance of the observations in the Z matrix explained by each eigenvector. The eigenvectors are then ordered so that the first diagonal element of λI_n represents the largest eigenvalue, and the second the next largest, etc. The eigenvectors are also scaled by multiplying each orthonormal eigenvector by the square root of its eigenvalue to obtain the "principal components loading matrix":

$$A = ED^{\frac{1}{2}} \tag{6}$$

where $D = \lambda I_n$, the n x n diagonal matrix of the eigenvalues of R. The columns of the A matrix are called factors and are independent of each other. This extraction of factors results in a principal component solution (i.e., an exact mathematical transformation without assumptions), and the factors are designated as defined factors (Kim, 1975). If the diagonal elements of the R matrix are replaced with initial estimates of communalities (i.e., the squared multiple correlation between each variable and all others in the set) prior to factoring, the result is the principal factor solution (Kim, 1975). In this case, the matrix is defined to be the "principal factors loading matrix", and the factors are called inferred factors (i.e., assumptions about the variance in common have been imposed). Whether the factors be defined or inferred, the first factor explains the largest amount of the combined variance of the observations in the Z matrix, the second factor explains the second largest amount of variance, the third factor explains the third largest amount of variance, etc.

The exact configuration of the factor (eigenvector) structure is not unique; one factor solution can be transformed into another without violating the assumptions or mathematical properties of a given solution (Kim, 1975). Since some factor structures are more meaningful than others (i.e., some are more simple, some are more informative, some are more revealing), it is often desirable to rotate the factors to a terminal solution that satisfies both the practical and theoretical needs of the research problem. Occasionally, the initial factor structure satisfies these needs and can be used for the terminal solution.

The factors of the A matrix are temporal functions which are linear combinations of the various years, and each year possesses a certain amount of the variance contained within a particular eigenvector (see Figure 10b). For example, the years 1944, 1950, 1951, 1953, 1960, 1962, 1963, 1966, and 1967 contain a high amount of variance (large positive values of the fourth eigenvector). Thus, it can be stated that "these years are loaded heavily on the fourth eigenvector." Since irrigation has increased and has become more widespread over time, the eigenvector of interest is the one with a significant trend in the factor loadings. There is a significant upward trend in the fourth eigenvector and, therefore, this is a candidate for the "irrigation factor". Since the growth of irrigation and the eigenvector are both time-dependent, the fourth eigenvector can be treated as a "forcing function".

However, in order to be an "irrigation factor", there must also be correspondingly high values on the principal components or principal factors for the areas in and around the heavily irrigated regions shown on Figure 1. The matrix A is a transformation matrix which can be used to transform the matrix into a set of principal components (or principal factors).

$$F = Z\,(A^T)^{-1} \tag{7}$$

where F is the principal components (or principal factors) matrix of order m x n. The scaled eigenvectors (factors) of the A matrix are orthogonal (uncorrelated) functions of time and the principal components of the F matrix are orthogonal (uncorrelated) functions of space. (In a R-type factor analysis the time and space roles would have been reversed.) It is obvious from Equation 7 that the spatial functions (patterns) are dependent on the temporal function of time. *Thus, the criteria chosen for an "irrigation factor" were that the scaled eigenvectors (factors) must have a significant time trend and that the corresponding principal components (or principal factors) must have large values in and around the heavily irrigated areas (Figure 12a) which are, according* *to Equation 7, dependent on the temporal forcing functions.* Using the factor approach, the above criteria were applied to the monthly precipitation data.

Temporal and Spatial Delineation of the Irrigation Effect

In the section on climatic background, it was found that there was 1) little evidence for irrigation-related anomalies in the months of April, May, and September, but 2) strong evidence for irrigated-related anomalies in the months of June, July, and August. This indication was further strengthened when the factor analysis was applied to the monthly rainfall data. For the months of April, May, and September, the criteria for the irrigation factor could not be satisfied. That is, no factor could be found in these months which simultaneously had a significant upward trend in the eigenvector and large values on the principal component in and around the heavily irrigated areas. Accordingly, the months of April, May, and September were treated as control months in the majority of the analyses performed in this report. The various ramifications of the application of the factor analysis to the other months is amplified by the following discussion of the 40-year rainfall patterns, the temporal series of the eigenvectors, and the spatial patterns of the principal components.

The average rainfall for the period June, 1931-1970 is shown on Figure 4. The main feature of interest insofar as a possible irrigation effect is concerned is the westward bulge in the 4.5 inch isohyet in the Nebraska irrigation region. The time series of the Fourth Eigenvector, which was obtained from a varimax rotation using communalities, is shown on Figure 10a. This eigenvector has an upward trend with a slope (b) equal to .0043 and its t-ratio is 1.67. Since the t-ratio exceeds 1.5, this is assumed to be a significant slope.*

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* The word significance in this report is used in a very special way. It does not carry the same connotation as does the oft-cited 'significance level'. The reason is that, throughout this report, we are dealing with population values and not sample values. That is, the irrigated years cannot be treated as a sample from all the weather that has ever occurred Cor even all the weather that has ever occurred in the last century) because there is only a fixed number of available irrigated years. In order

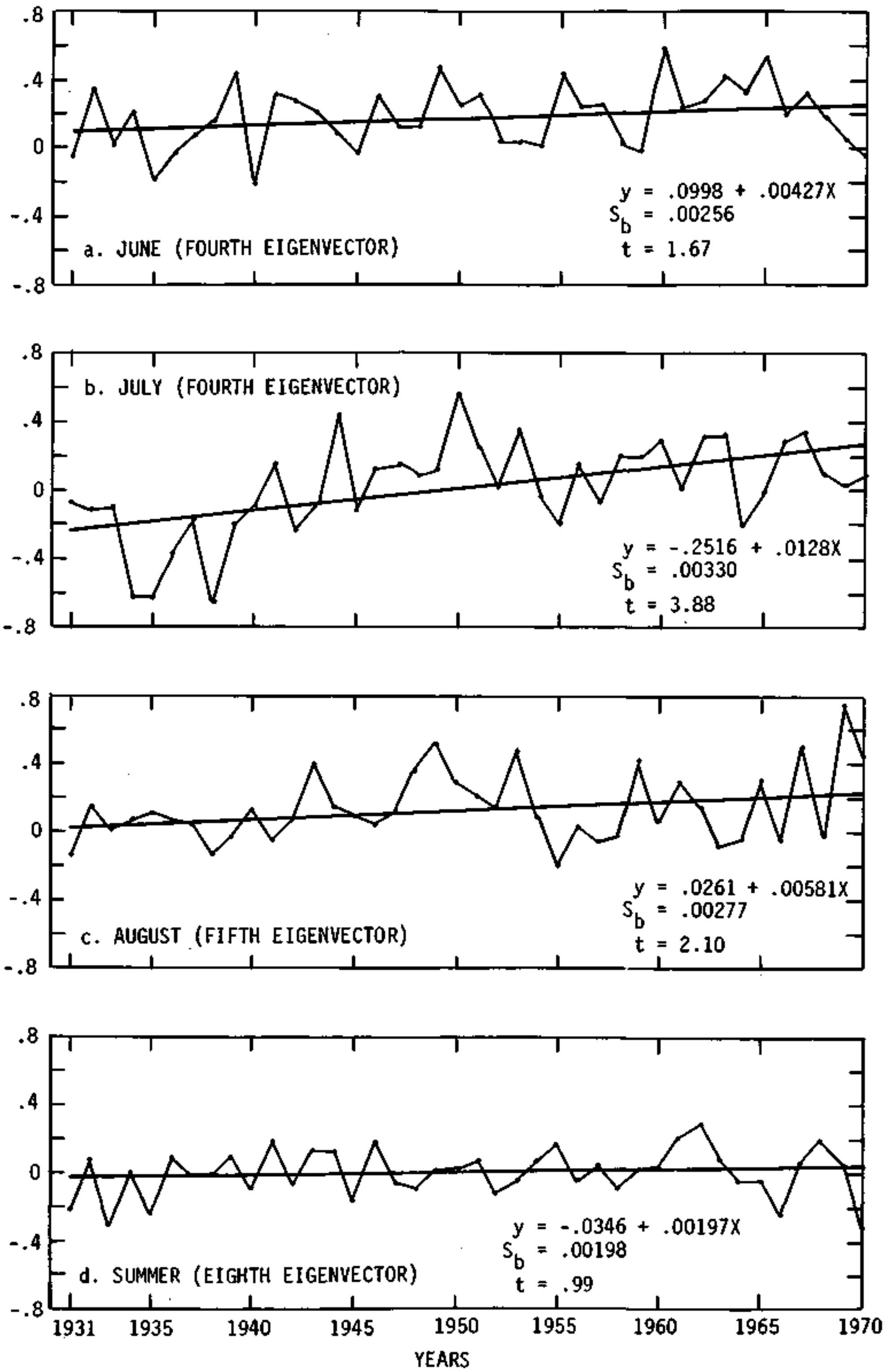

Figure 10. The temporal series of the monthly and summer eigenvectors.

The temporal characterisitics of this time series suggest the possibility of a "forcing function" since irrigation also has an upward trend during the same time period. However, the second condition must also be satisfied: i.e., there must be a spatial conformity of the fourth principal component in and surrounding the irrigated areas. The spatial pattern of the Fourth Principal Factor is shown on Figure 11a.

There are anomalies in the principal factor pattern in the vicinity of the irrigated areas. The areas of positive anomalies are associated with the peaks in the eigenvector curve on Figure 10a. That is, a peak in the temporal curve during a particular year indicates that the rainfall pattern was high in the positive regions of the principal factor pattern (Figure 11a), whereas the rainfall pattern is low in the negative region of the spatial principal factor. Conversely, a trough in the temporal eigenvector represents a year in which the rainfall was high in the negative regions of the principal factor pattern and low in the positive regions. Since the peaks have an upward trend over time, the positive regions of the spatial principal factor pattern have become more intense over time.

The rainfall highs have grown more intense over time in a broad region (.5 inch isoline) extending from the southernmost irrigated region, A, in Texas to the northernmost irrigated region, D, in Nebraska. Within this general area, the highs have grown more intense in three local areas as indicated by the 1.0 isolines. These are 1) an area extending NE from the center of irrigated Region A in Texas to Western Oklahoma, 2) an area encompassing irrigated region C in western Kansas, and 3) an area extending E-S from the irrigated region D in Nebraska. Since both the temporal and spatial conditions of the irrigation criteria are satisfied, it was concluded that factor 4 is the "irrigation factor" for the month of June.

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* to produce a sample, one would need to randomly select samples from the irrigated years and non-irrigated years and then compare the sample means to determine if they gave the same results as the population means (determined from all the irrigated and non-irrigated years). This is clearly inappropriate since one is dealing with a limited number of years to begin with.

Therefore, the usual theory of sampling statistics is inappropriate. However, the t-ratio is used in this report as a measure of the magnitude of the population values in relation to their standard error. Thus, a t-ratio of 1.5 is considered to possess "significance" in that the magnitude of the population value exceeds its standard error by 50%. In this sense, the t-ratio is treated as an informative summary statistic and is to be clearly distinguished from the test statistic t-ratio.

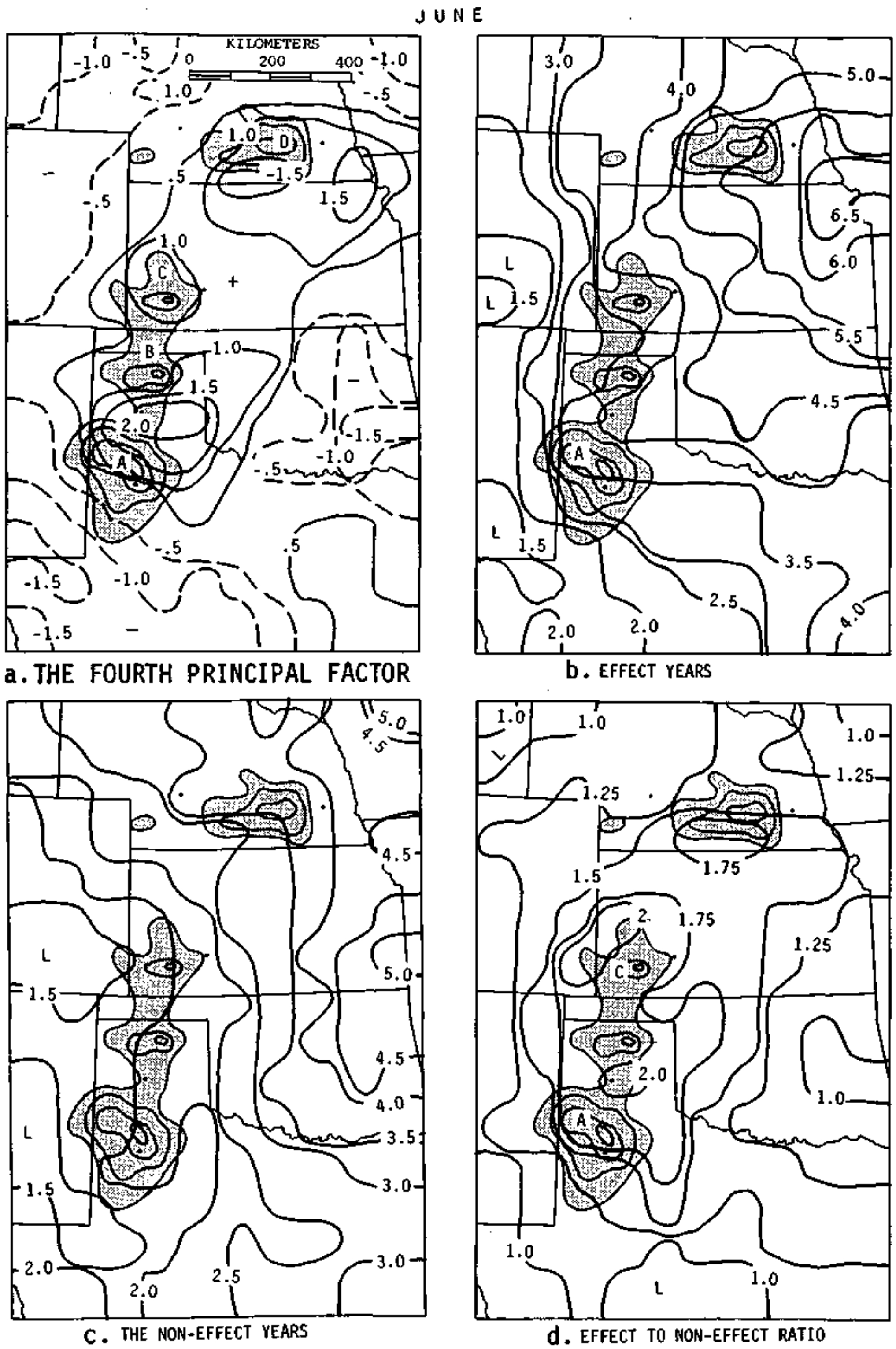

Figure 11. Spatial characteristics of the irrigated-related anomalies during June, 1931-1970 (rainfall patterns for effect and non-effect years in inches).

Since the peaks in the eigenvector curve represent years in which rainfall highs were present in the positive regions of the principal factor pattern on Figure 11a, the eigenvector curve was used to classify the years into "effect" and "non-effect" years. First, the mean (.1874) and standard deviation (.1910) were determined for the eigenvector curves on Figure 10a. The years were then classified as effect years if the eigenvector equaled or exceeded .1874, the mean value, or as non-effect years if the eigenvector was less than .1874.

The average rainfall patterns for the effect and non-effect years were then determined for June and are shown on Figures 11b and 11c, respectively. The average rainfall pattern is of greater magnitude during the effect years than on the non-effect years. This suggests that the irrigation effect occurs on the wetter years as opposed to the drier years. Both patterns include a protrusion of isolines into the vicinity of irrigated area A which suggests that this may be a characteristic of both effect and non-effect years.

In order to more clearly differentiate between effect and non-effect years, the pattern of the ratio of the effect to non-effect years was determined and is shown on Figure 11d. The result is indeed striking, since the high region in the positive ratios occurs in a broad region (1.5 isoline) which generally corresponds to the positive region of the principal factor pattern on Figure 11a. A large inner region (1.75 isoline) encompasses the Texas-Kansas irrigated region, and another smaller region (1.5 isoline) is associated with the Nebraska irrigated region. Smaller inner cores (2.0 isoline) are also associated with the irrigated regions of A and C. It is concluded that the ratio pattern offers strong evidence for an irrigation effect during the month of June.

The average rainfall for the period July, 1931-1970 was shown on Figure 4. With the exception of the dipping of the 2.5 isohyet in the Texas Panhandle and the westward bulge in the 3.0 isohyet in the west-central part of Kansas, there is little evidence of rainfall anomalies due to irrigation. However, the time series of the fourth eigenvector (Figure 10b) has a significant upward trend with a slope value of .0128, a t-ratio of 3.88, and a suggestion of a discontinuity in the early 1940's. (This eigenvector was obtained from a varimax rotation without communalities). The spatial pattern of the Fourth Principal Component (Figure 12a) possesses anomalies in and surrounding the irrigated areas, and it was concluded that factor 4 is the irrigation factor for the month of July.

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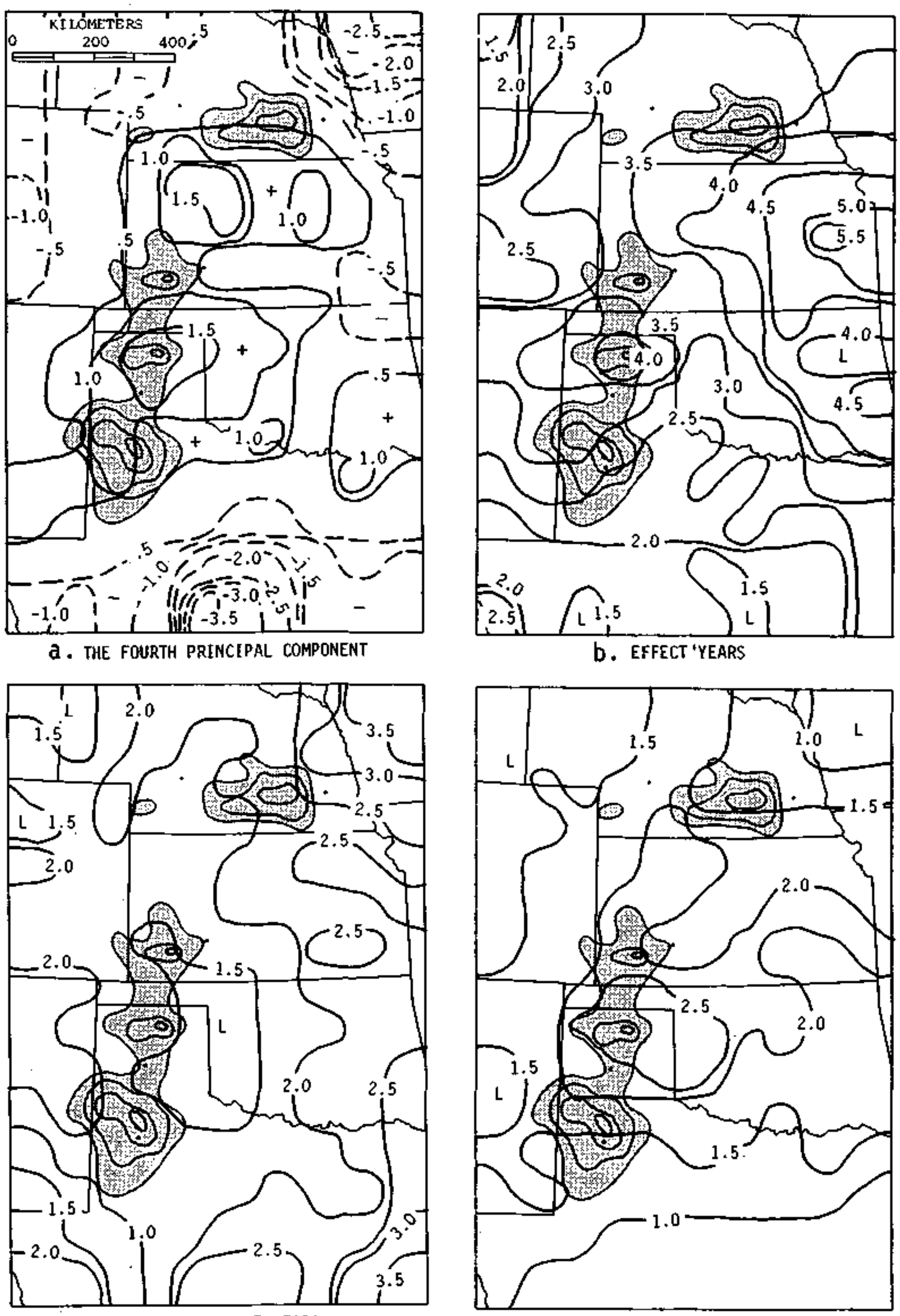


Figure 12. Spatial characteristics of the irrigated-related anomalies during July, 1931-1970 (rainfall patterns for effect and non-effect years in inches).

The rainfall highs have grown more intense over time 1) in a broad region (1.0 isoline) surrounding the irrigated region of Texas and Kansas and extending to the E, 2) in a broad region (1.0 isoline) situated between the Kansas and Nebraska irrigated regions and 3) in a secondary smaller region in eastern Kansas. The inner region as defined by the 1.5 isoline (Figure 12a) in the Texas Panhandle is located slightly further north of the 1.5 inner region during the month of June (Figure 11a). If the inner core of 1.5 in Kansas (Figure 12a) corresponds to the inner core of 1.0 in Kansas for June (Figure 11a), it is also located further north, and the cores in Nebraska which were present during June are non-existent in the July pattern.

The mean (.0115) and standard deviation (.2815) were determined for the eigenvector curve shown on Figure 10b. The years were then classified as effect years if the eigenvector equaled or exceeded .0115, or as non-effect years if the eigenvector was less than .0115.

The average rainfall patterns for the effect and non-effect years were then determined for July and are shown on Figures 12b and 12c, respectively. The average rainfall pattern is of greater magnitude during the effect years than on the non-effect years. This suggests that the irrigation effect occurs on the wetter years as opposed to the drier years. The ratio pattern of the effect to non-effect years (Figure 12d) indicates an irrigation effect in the Texas and Oklahoma Panhandles as well as western Oklahoma (note the 2.5 isoline). There is a suggestion of a weaker effect in the Kansas irrigated region and in the area between the Kansas and Nebraska irrigated regions. It is concluded that the ratio pattern offers strong evidence for an irrigation effect during the month of July, particularly in the Texas-Oklahoma area.

The average rainfall for the period August, 1931-1970 was shown on Figure 4. The only suggestion of a potential irrigation effect for this month is the ridge of relatively high rainfall which extends from the Texas Panhandle into western Kansas (ridge delineated by the 2.5 isohyet). The time series of the Fifth Eigenvector (Figure 10c) has a significant upward trend with a slope value of .00581 and a t-ratio of 2.1 (This eigenvector was obtained from a varimax rotation without communalities). The spatial pattern of the Fifth Principal Component (Figure 13a) possesses anomalies in and surrounding the irrigated area of Kansas and Nebraska, so it was concluded that Factor 5 is the irrigation factor for month of August.

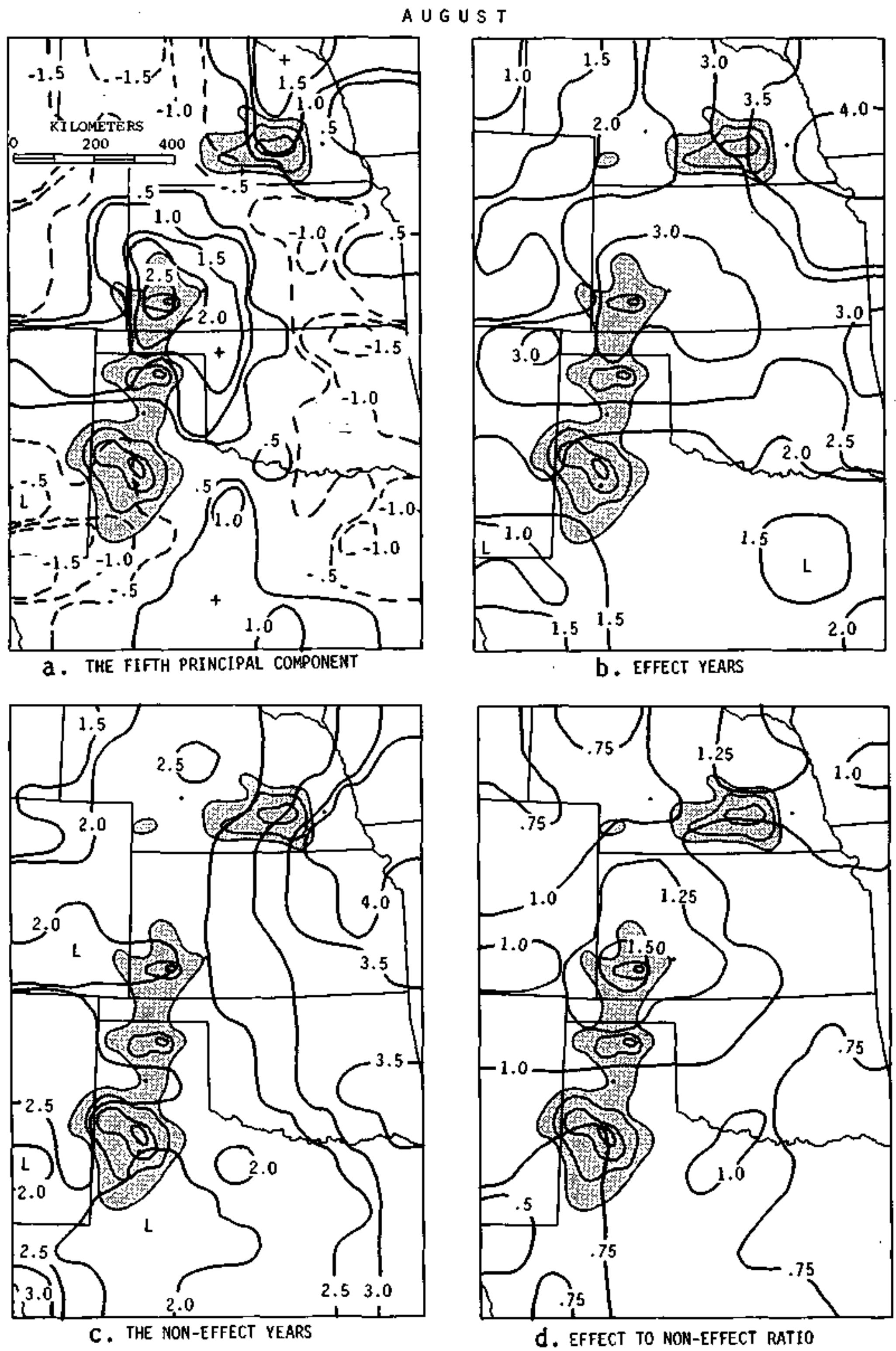


Figure 13. Spatial characteristics of the irrigated-related anomalies during August, 1931-1970 (rainfall patterns for effect and non-effect years in inches).

The rainfall highs have grown more intense over time in 1) an area (1.5 isoline) in and surrounding the Kansas irrigated region and in 2) an area (1.5 isoline) in and north of the Nebraska irrigated region. Thus, in contrast to the June and July patterns, there are no anomalies associated with the Texas irrigated regions.

The mean (.1452) and the standard deviation (.2111) were determined for the eigenvector curve shown on Figure 10c. The years were then classified as effect years if the eigenvector equalled or exceeded .1452, or as non-effect years if the eigenvector was less than .1452.

The average rainfall patterns for the effect and non-effect years were then determined for August and are shown on Figures 13b and 13c, respectively. The average rainfall pattern is of greater magnitude in the Kansas irrigated region on effect years, but not in the Texas or Nebraska irrigated regions. This suggests that the irrigation effect occurs in the wetter years in the Kansas irrigated region, but not necessarily in wetter years in the Nebraska region. The failure of the irrigation effect to occur on the wetter years in the Nebraska region represents the first exception to the effect occurring in the wet years as opposed to the dry years.

The ratio pattern of the effect years to the non-effect years (Figure 13d) indicates an irrigation effect in the Kansas irrigated region and on the north side of the Nebraska irrigated region (note the 1.25 inch isoline). It is concluded that the ratio pattern offers strong evidence for an irrigation effect in the Kansas irrigated region during August and somewhat weaker evidence for an irrigation effect in the Nebraska region. The evidence for the effect is judged to be weaker in the Nebraska region because it does not necessarily occur in the wetter years as was the case with the other potential irrigation effects.

Another classification (Classification 2) was made for each month. In this classification, the individual years were classified as effect years if the eigenvector exceeded or equaled the mean plus one standard deviation, or as non-effect years if the eigenvector was less than the mean minus one standard deviation. Both classifications are listed in Table 1.

It is evident that the effect classifications have increased in the later years as compared to the earlier years. For June, there are 21 years classified as effect with an average of .4 (6 out of 15) effect classifications per year

Table 1. Classification of the various years into Effect (E) and non-effect (NE) months using the factor approach.

	Classification 1 (mean)				Classification 2 (stand, dev.)			
Year	June	July	August	Effect months per year	June	July	August	Effect months per year
1931	NE	NE	NE	0	NE	NE	NE	0
1932	E	NE	E	2	NE	NE	NE	0
1933	NE	NE	NE	0	NE	NE	NE	0
1934	E	NE	NE	1	NE	NE	NE	0
1935	NE	NE	NE	0	NE	NE	NE	0
1936	NE	NE	NE	0	NE	NE	NE	0
1937	NE	NE	NE	0	NE	NE	NE	0
1938	NE	NE	NE	0	NE	NE	NE	0
1939	E	NE	NE	1	E	NE	NE	1
1940	NE	NE	NE	0	NE	NE	NE	0
1941	E	E	NE	2	NE	NE	NE	0
1942	E	NE	NE	1	NE	NE	NE	0
1943	E	NE	E	2	NE	NE	E	1
1944	NE	E	NE	1	NE	E	NE	1
1945	NE	NE	NE	0	NE	NE	NE	0
1946	E	E	NE	2	NE	NE	NE	0
1947	NE	E	NE	1	NE	NE	NE	0
1948	NE	E	E	2	NE	NE	NE	0
1949	E	E	E	3	E	NE	E	2
1950	E	E	E	3	NE	E	NE	1
1951	E	E	E	3	NE	NE	NE	0
1952	NE	NE	E	1	NE	NE	NE	0
1953	NE	E	E	2	NE	E	E	2
1954	NE	NE	NE	0	NE	NE	NE	0
1955	E	NE	NE	1	E	NE	NE	1
1956	E	E	NE	2	NE	NE	NE	0
1957	E	NE	NE	1	NE	NE	NE	0
1958	NE	E	NE	1	NE	NE	NE	0
1959	NE	E	E	2	NE	NE	E	1
1960	E	E	NE	2	E	E	NE	2
1961	E	NE	E	2	NE	NE	NE	0
1962	E	E	E	3	NE	E	NE	1
1963	E	E	NE	2	E	E	NE	2
1964	E	NE	NE	1	NE	NE	NE	0
1965	E	NE	E	2	E	NE	NE	1
1966	E	E	NE	2	NE	NE	NE	0
1967	E	E	E	3	NE	E	E	2
1968	NE	E	NE	1	NE	NE	NE	0
1969	NE	E	E	2	NE	NE	E	1
1970	NE	E	E	2	NE	NE	E	1
Effect years	21	20	15	31 (years)	6	7	7	15 (years}

prior to 1946, and .6 (15 out of 25) per year after 1945. The averages are .13 (2 out of 15) before 1946 and .72 (18 out of 25) after 1945 for July, and .13 (2 out of 15) and .52 (13 out of 25) for August. Because of the various combinations of effect months possible during the summer, 1954 is the only summer after 1945 that does not show some evidence for an effect.

Some of the years that are classified as effect have only weak evidence for effect, and some of these may not be effect years. For example, a high can be located in the vicinity of the irrigation region by random chance. If this is a "weak" high, and if it occurred in the early years, and if there are stronger highs in the later years, the earlier weak high would be loaded on the eigenvector as part of the overall trend.

Thus, the second classification provides a measure of the years with strong evidence for effect since a higher criteria level was used to classify the effect years. This classification indicates that there is only one major effect year prior to 1946 in each of the individual months. Consequently, the first classification is useful in studying all potential effect years, whereas the second classification is useful for studying only those years with strong potential for effects.

The average rainfall for the period of Summer, 1931-1970 was shown on Figure 4. There is a ridge of high rainfall extending into the Kansas and Texas irrigated regions as indicated by the protrusion of the 7.0 and 8.0 isohyets into these regions. However, an irrigation factor could not be found for the Summer period. That is, no factor could be found for the Summer period which simultaneously had a significant upward trend in the eigenvector and large values on the principal component in and around the irrigated areas. In fact, there were only two factors that had good spatial conformity in and surrounding the irrigated areas. One was factor 8, and it was obtained from a unrotated solution; and the other was also Factor 8, but it was obtained from a varimax solution without communalities. The corresponding temporal eigenvector of the unrotated solution is shown on Figure 10d. This eigenvector has a slope value of .00197 and a t-ratio of .99 which is clearly insignificant. The temporal eigenvector of the rotated solution (not shown) has a slope value of .00215 and a t-ratio of .96 which is also insignificant. Thus, the temporal portion of the irrigation criteria is not satisfied by the factor solution.

There are positive anomalies in both the unrotated and rotated principal component patterns shown on Figures 14a and 14b which generally correspond to the highs in the isohyetal summer pattern of Figure 4. This correspondence is shown more clearly by Figures 14c and 14d on which selected isohyets have been superimposed on the positive anomalies of the principal component patterns. Obviously, some features of the isohyetal pattern have been more clearly described by the unrotated solution, whereas other features have been more clearly described by the rotated solution. Certainly, neither factor can be considered to be superior to the other, and neither has a significant upward trend in their eigenvectors. Consequently, another method must be used to delineate the apparent irrigation-related ridge of high rainfall indicated in the summer rainfall pattern on Figure 4.

An important question which must be addressed is: What is the reason for the lack of temporal trend and the failure to obtain a decisive areal component in the summer data? The importance of this question is made even more evident by the fact that there are apparent irrigation effects in the individual months of June, July, and August. It is now hypothesized that the lack of trend in the summer eigenvectors is due to the tendency for the irrigation effect to occur in the wetter months as opposed to the drier months. It is very rare for all of the summer months to be wet in the same year. The more typical chain of events is for a mixture of wet, dry, and moderate months during the summer. Thus, if June is wet and an irrigation effect occurs, but this is followed by a dry period extending through July and August when no irrigation effect occurs, the June irrigation effect may be masked or distorted in the overall summer pattern. It is duly noted that such a masking or distortion could occur whether or not the irrigation effect occurs predominantly in the wetter months. That is, any combination of effect and non-effect months during the summer can contribute to this masking or distortion of the overall trend. For example, there is only one summer after 1945 (Table 1) that does not have some evidence of an effect; that is, each year there is at least one month with an effect classification. Therefore, the temporal trend in the summer data is not as strong as in individual months where more years are being classified as effect years as time progresses. However, because of the scarcity of effect summers prior to 1940, there will be some trend, and this is indeed the case as is illustrated in Figure 10d.

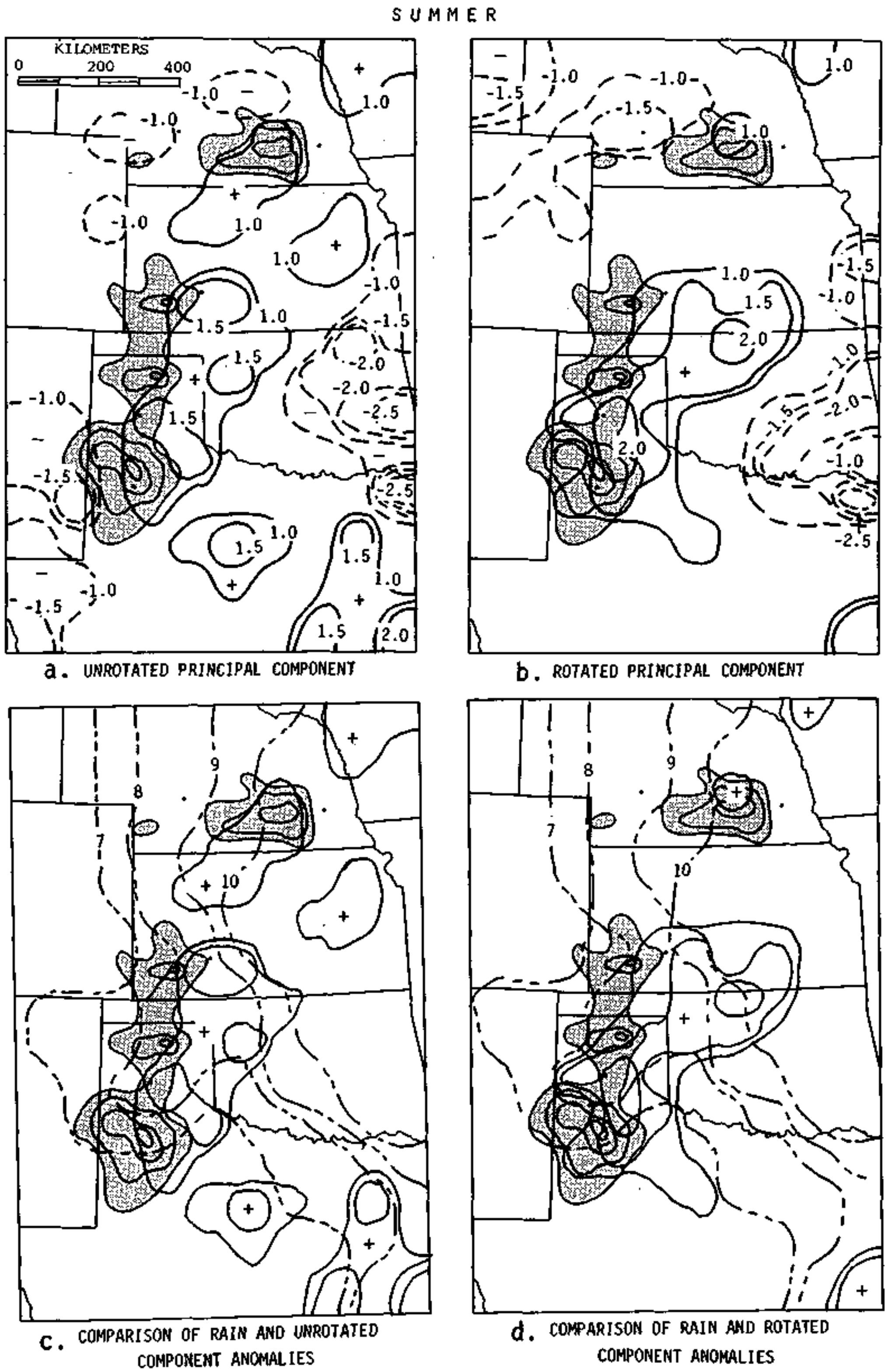


Figure 14. Spatial characteristics of the irrigated-related anomalies during summer, 1931-1970 (dashed lines on lower figures represent rain in inches).

However, the trend is much less than in the individual months, whose trends are shown on Figures 10a-c.

The failure to obtain a decisive areal component can be attributed to the fact that the location of the irrigated-related anomalies varies from month to month during the summer. Thus, the unrotated principal component (Figure 14a) appears to reflect most of the June component and the Kansas portion of the July component (Figures 11a and 12a), whereas the rotated component (Figure 14b) appears to reflect more of the July component on Figure 12a (particularly, the southern part and the part along the Kansas-Oklahoma border). Both the rotated and unrotated factors (Figures 14a and 14b) reflect parts of the August component (Figure 13a). Clearly, the variation of the location of the effect areas from month to month during the summer could lead to difficulty in obtaining a decisive areal component from the summer factor analysis.

Consequently, the viewpoint is adopted that the classification of effect and non-effect years for the summer data by the factor approach is inadequate. Rather, the classification of effect and non-effect summers should be made according to whether the individual months are classified as effect. Thus, those summers with no irrigation effect are classified as non-effect summers, whereas those summers with at least one effect month are classified as effect summers. Moreover, those summers with two effect months should have a stronger overall summer effect that those with one effect month, and those summers with three effects months should have the strongest overall summer effect.

To test the above concept, the average summer rainfall patterns were determined for those years in which there were zero effect months, one effect month, two effect months, and three effect months. These patterns are shown on Figures 15a-d.

The results are indeed striking. There is absolutely no indication of an irrigation-related anomaly in the average summer rainfall pattern of those years without effect months. On the other hand, there is a clear-cut indication of greater development and intensification in the summer patterns with a great number of effect months.

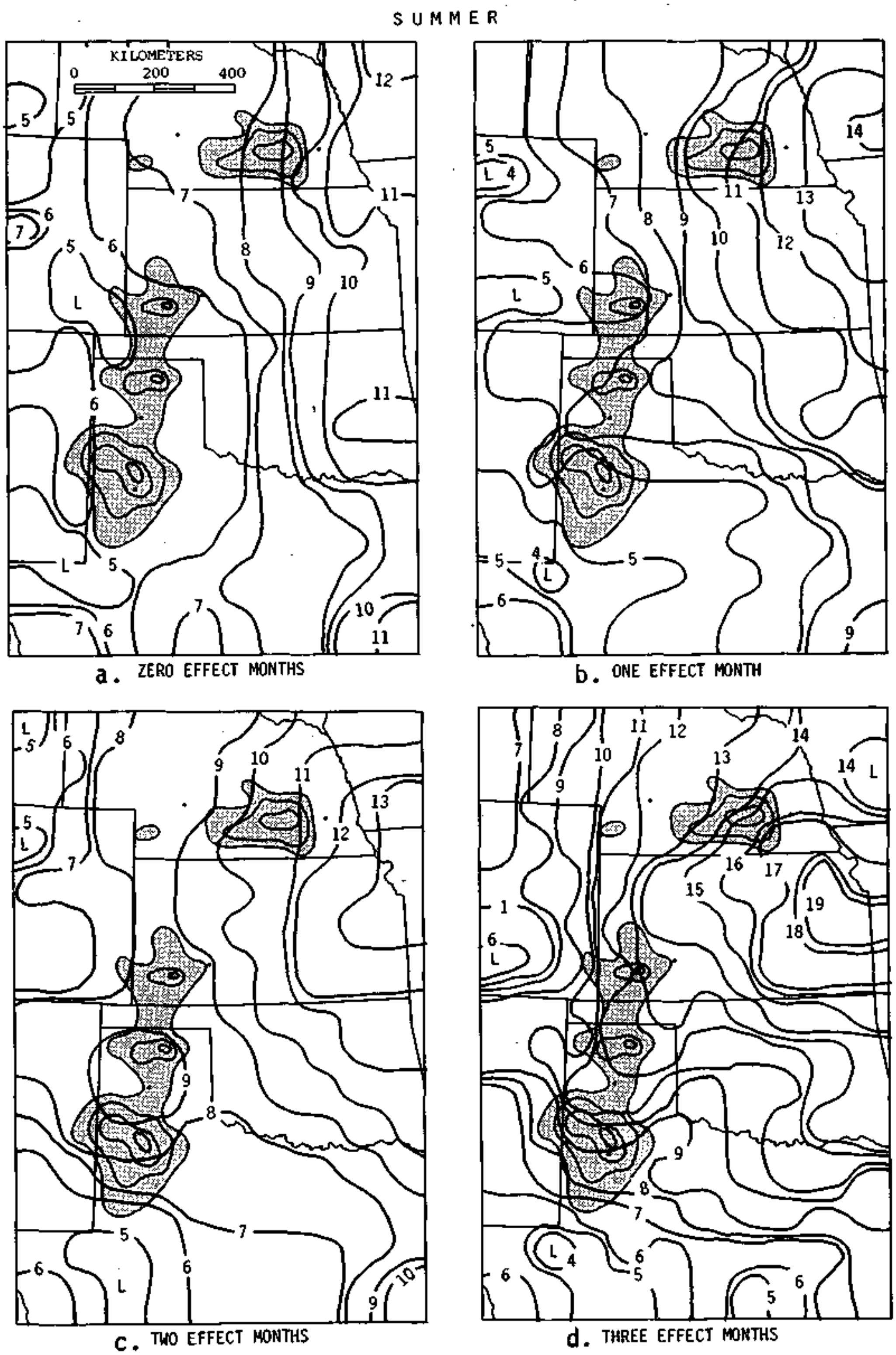


Figure 15. The average rainfall patterns for summers, 1931-1970 with varying numbers of effect months (rainfall in inches).

DELINEATION OF THE AREA-EFFECT ZONES OF INFLUENCE: TARGET AND CONTROL AREAS AND THEIR ANALYSES

Delineation of The Target and Control Areas

In order to properly analyze the various aspects of the potential irrigation effect, it was necessary to establish target and control areas (areal control concept) as well as effect and non-effect periods (temporal control concept). Since physical understanding of the irrigation effect is not in itself adequate to pinpoint the zone of influence of the irrigation effect, the principal components patterns obtained from the factor analysis were used to delineate the potential target and control areas (see Figure 16). Specifically, the various isolines of the component patterns were used to define different sizes of the target area, where it was assumed that the effect should be the strongest in the areas encompassed by the higher-valued isolines. For June, the area with .5 isoline (Figure 11a) was subdivided into various sub-areas (Figure 16a) of EN1, an area associated with the Nebraska irrigated region; EK1, an area associated with the Kansas irrigated region; ET1, an area associated with the Texas irrigated region, and ESl, an area associated with positive anomaly in the SE corner of the principal component map (Figure 11a). E1 was then formed as the combination of EN1, EK1, and ET1. These areas were designated as the first level-effect areas. The regions enclosed in the -.5 isolines (Figure 11a) were used to define the control areas of C1, C2, C3, C4 shown on Figure 16a. In most of the subsequent analyses the four control areas were combined to form a total control area CT.

The 1.0 isoline was used to form the target areas of EN2, EK2, and ET2 on Figure 16b and EN3 and ET3 on Figure 16c. The target areas on Figure 16b were designated as the second level-effect areas and those on Figure 16c were designated as the third level-effect areas. E2 and E3 were formed as the combination of the second and third level effect areas, respectively.

For July, the area with the .5 isoline (Figure 12a) was subdivided into various sub-areas (Figure 17a) of EK1, an area associated with the Kansas irrigated region; ET1, an area associated with the Texas irrigated region; and ES1, an area associated with the positive component anomaly in eastern Oklahoma. Since EN in northern Nebraska was such a small area, it was not used in any of

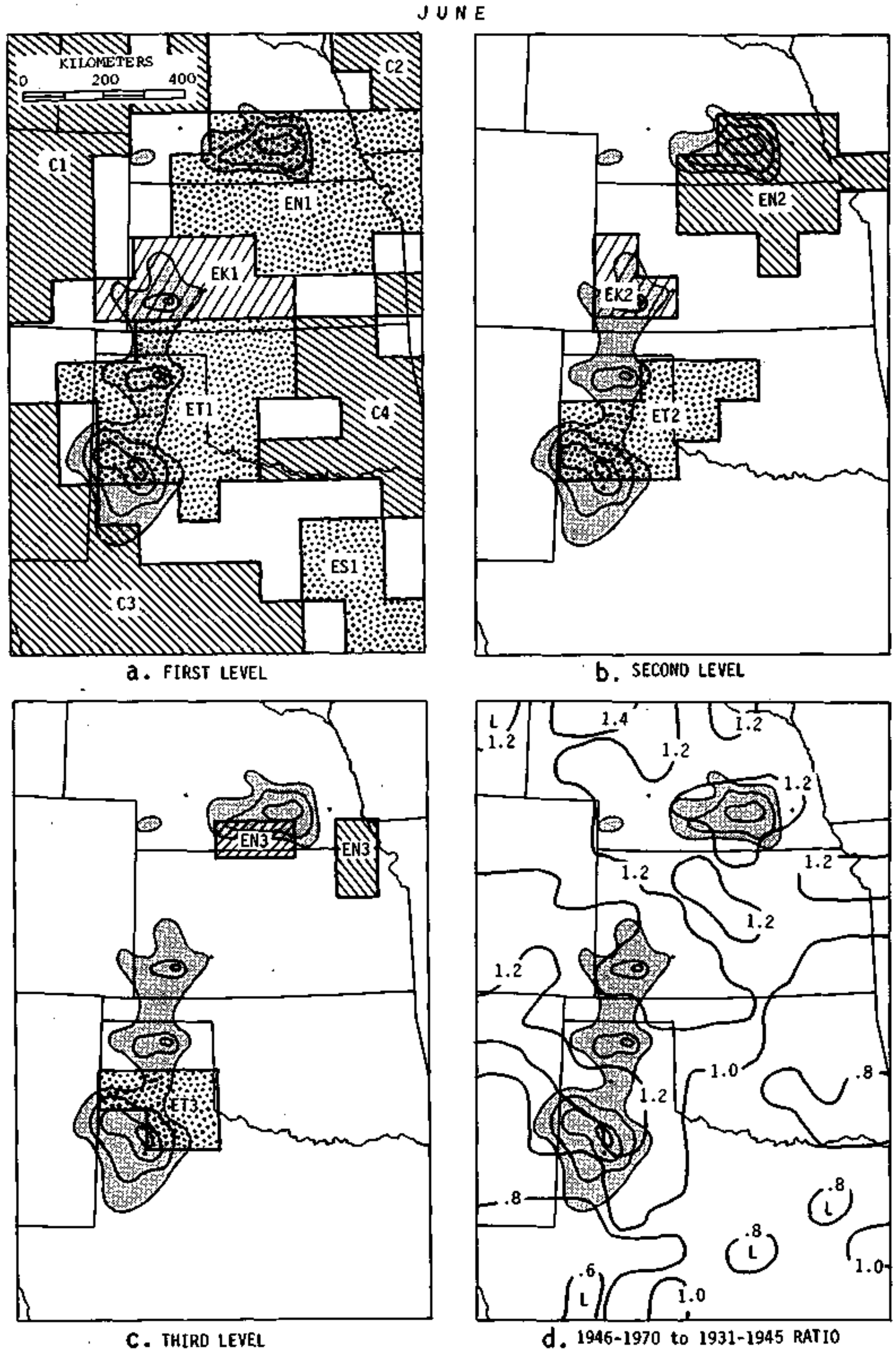


Figure 16. Target and control areas during June and the ratio pattern of irrigated (1946-1970) to non-irrigated (1931-1945) years.

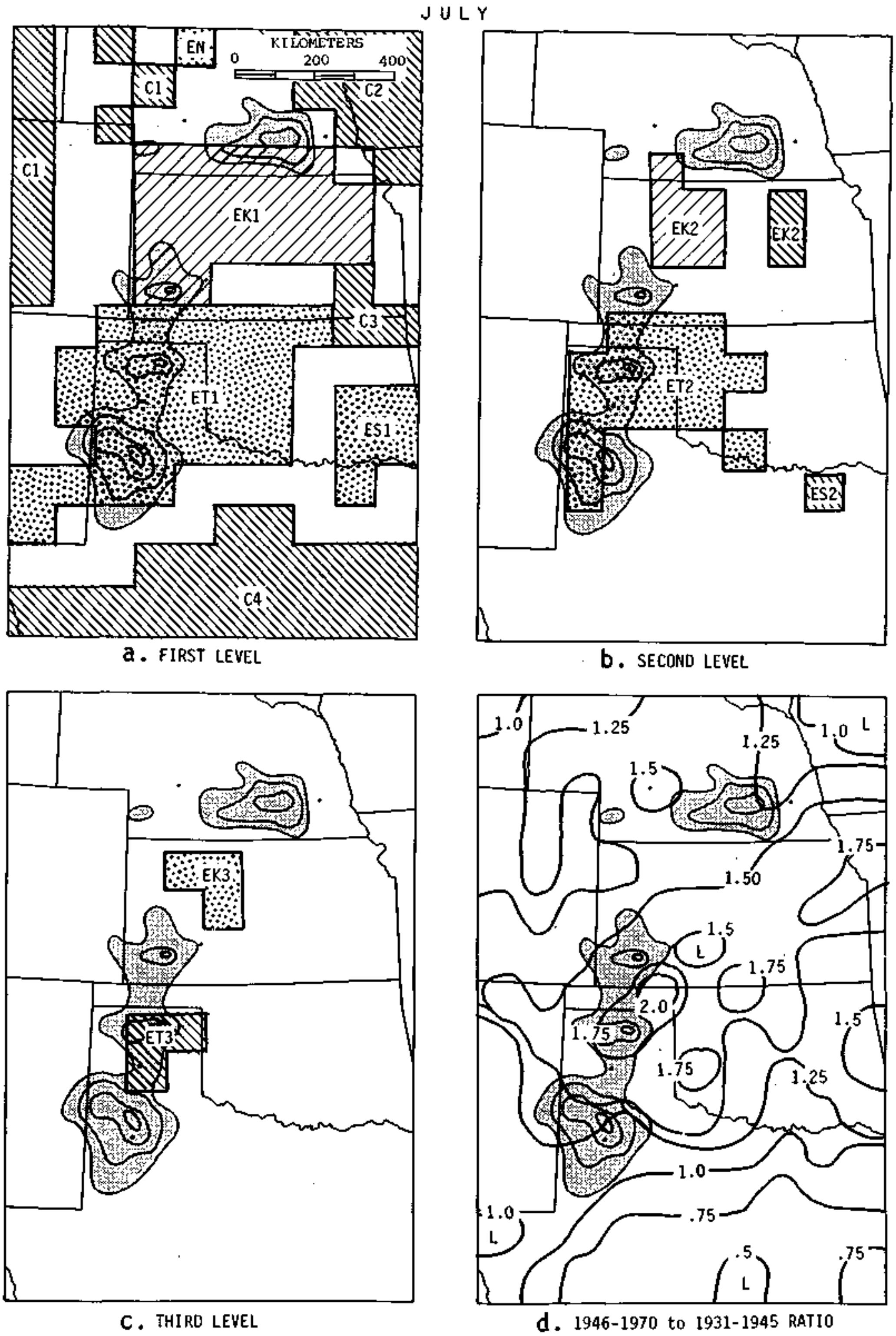


Figure 17. Target and control areas during July and the ratio pattern of irrigated (1946-1970) to non-irrigated (1931-1945) years.

the subsequent analyses. These target areas were designated as the first level-effect areas and E1 was designated as the combination of these areas. The regions enclosed in the -.5 isolines (Figure 12a) were used to define the control areas of C1, C2, C3, and C4 shown on Figure 17a. These areas were combined to form a total control area, CT, in most of the subsequent analyses.

The 1.0 isoline was used to form the target areas EK2, ET2, and ES2 on Figure 17b, and EK3 and ET3 were formed on Figure 17c. The target areas on Figure 17b were designated as the second level-effect areas and those on Figure 17c were designated as the third level-effect areas. The area ES2 was comparatively small, so it was not used in the subsequent analyses. E2 and E3 were formed as the combination of the second and third level effect areas, respectively.

For August, the area within the .5 isoline (Figure 13a) was subdivided into various sub-areas (Figure 18a) of EN1, an area associated with the Nebraska irrigated region; EK1, an area associated with the Kansas irrigated region; ES1, an area associated with the positive component anomaly in central Texas; and EE1, a small area in eastern Kansas. Since EE1 was such a small area, it was not used in any of the subsequent analyses. The target areas on Figure 18a were designated as the first level-effect areas and E1 was designated to be the combination of these areas. The regions enclosed in the -.5 isolines were used to define the control areas of C1, C2, C3, and C4. These areas were combined to form a total control area, CT, for subsequent analyses.

The 1.0 isoline was used to form the target areas EN2, EK2, and ES2 on Figure 18b and EN3 and EK3 on Figure 18c. The target areas on Figure 18b were designated as the second level-effect areas and those on Figure 17c were designated as the third level-effect areas. E2 and E3 were formed as the combination of these areas.

It was noted in the previous section that a decisive areal component could not be obtained from the factor analysis of summer data. This was attributed to the variation of the location of the effect area from month to month during the summer. Thus, the principal component patterns of Figures 14a and 14b cannot be used to delineate the target and control areas in the case of the summer data. Thus, another approach had to be used based on the effect areas for each month.

It was decided to use those target areas on the individual months which were previously defined by the 1.0 isoline. These monthly target areas were

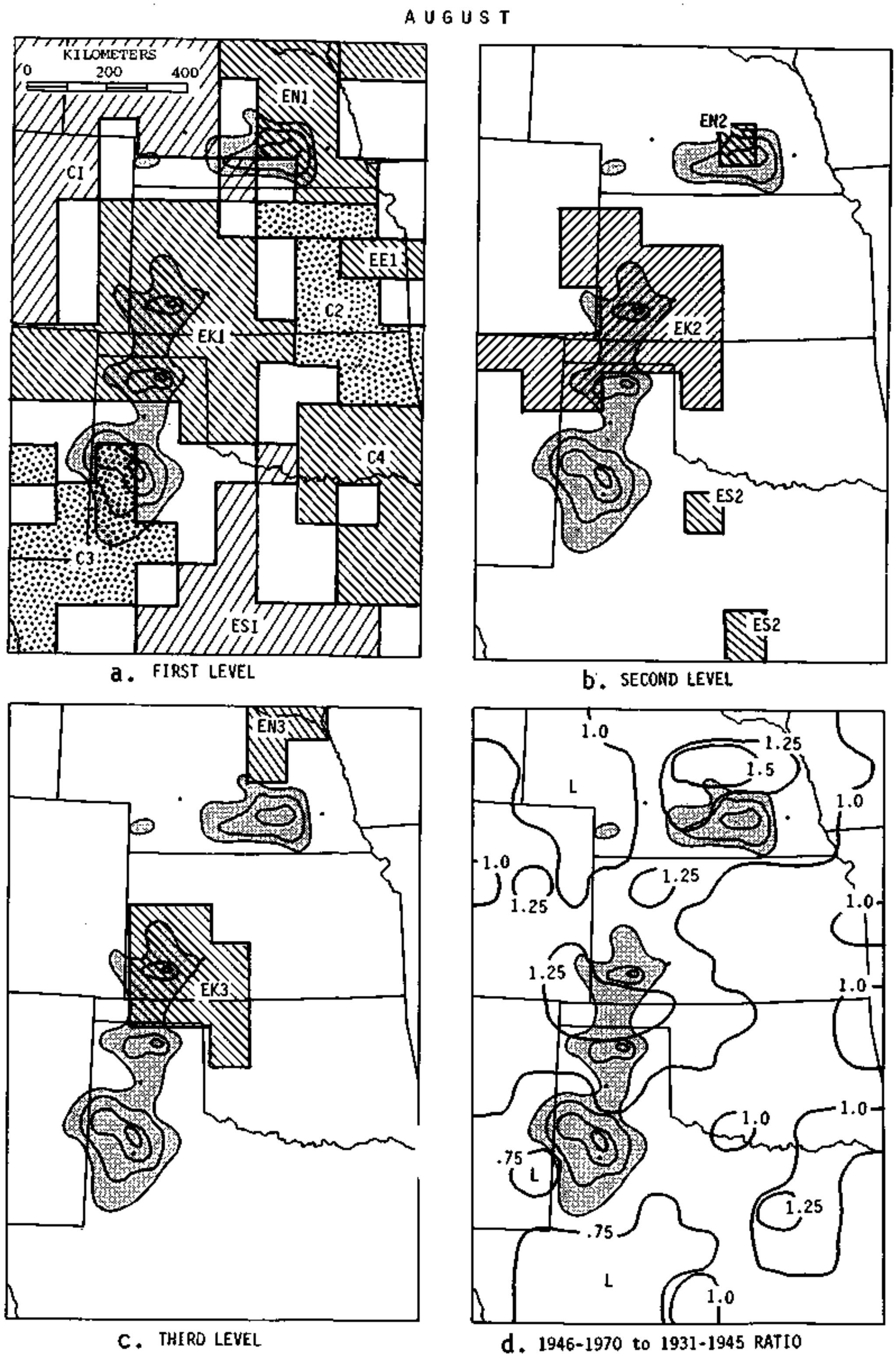


Figure 18. Target and control areas during August and the ratio pattern of irrigated (1946-1970) to non-irrigated (1931-1945) years.

EN2, EK2, and ET2 for June (Figure 16b), EK2 and ET2 for July (Figure 17b), and EK2 and EN2 for August (Figure 18b). The first level target areas for summer were determined to be those areas which were included in these monthly target areas (defined by the 1.0 principal component isolines) during at least one month during the summer. The partitioning of these areas according to major irrigation regions resulted in three first level target areas which are shown on Figure 19a. The second level target areas for summer were determined to be those areas which were included in the monthly target areas at least for two months during the summer. The partitioning of these areas according to major irrigation regions resulted in two second-level target areas (see Figure 19b). The third level target areas were defined to be those areas which were included in the monthly target areas in all three months during the summer. There was only one third level target area which was associated with the Texas irrigated region and this is shown on Figure 19c. The areas E1, E2, and E3 were formed as the combinations of the first, second, and third level targets, respectively.

The control areas were defined to be those areas separated from the first level target areas by at least 90 miles. The resulting areas were designated as CT2 and are shown on Figure 19a. In most of the subsequent analyses, the two control areas were combined to form a total control area, CT.

The determination of the summer target areas in this way ensures a method of evaluating the summer irrigation effect according to the number of times the effect occurred during the individual months. The elimination of the target areas as defined by the .5 isoline sharpens the summer analysis by limiting these analyses to those areas with stronger monthly effects. It also removes from consideration the weaker monthly effects which would be difficult to detect in the overall summer pattern due to the variation of effect area location from month to month.

In order to adequately analyze the target and control area rainfall, it is also necessary to define treated (irrigated) and non-treated (non-irrigated) years. It was noted earlier that those areas associated with the ten-percent irrigated regions on Figure 1 were the areas in which the use of irrigation increased over the period 1931-1970. This was determined from an inspection of Figures 2 and 3, which indicated that the other irrigated regions were relatively constant in the use of irrigation during the 40-year period.

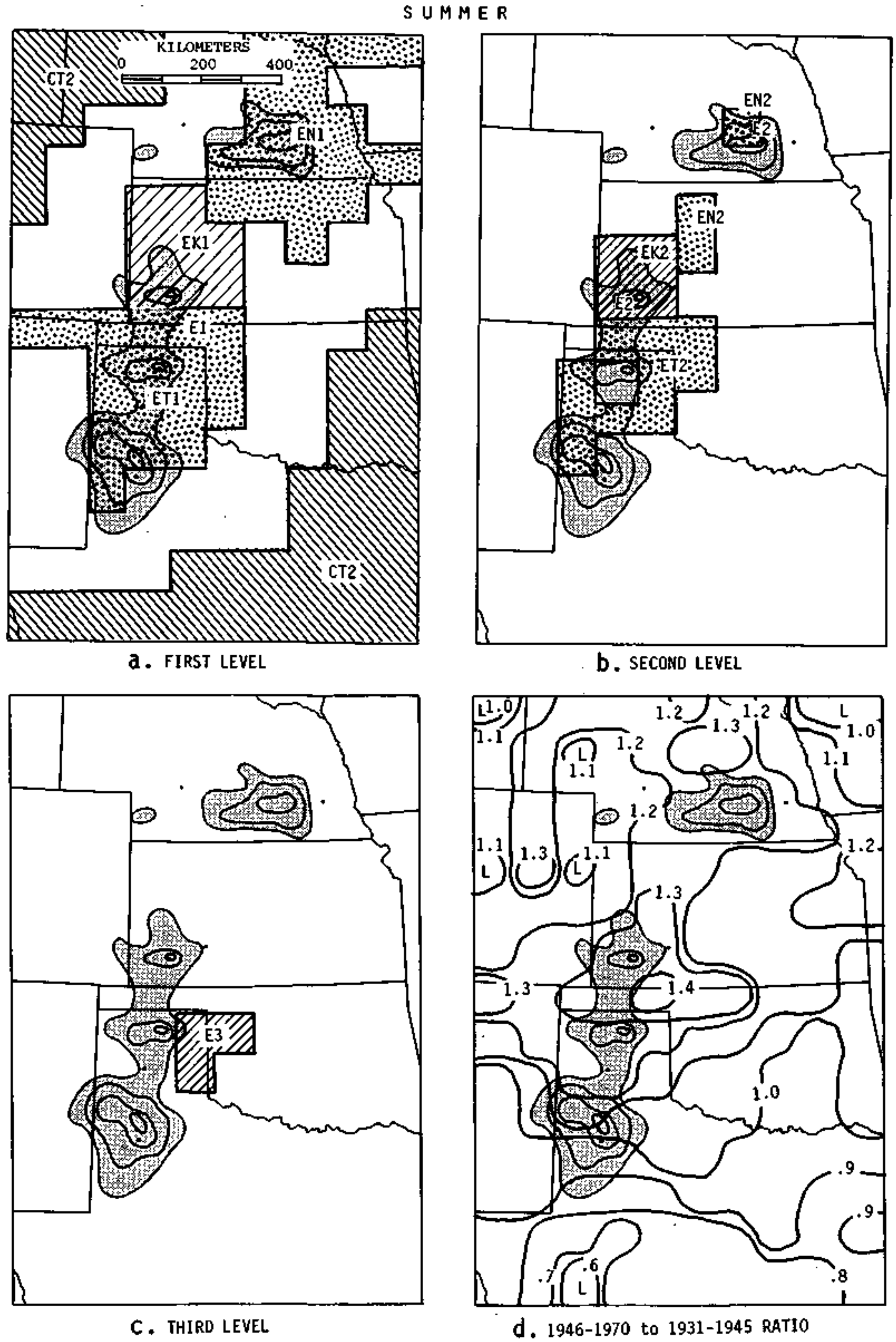


Figure 19. Target and control areas during summer and the ratio pattern of irrigated (1946-1970) to non-irrigated (1931-1945) years.

A further inspection of Figures 2 and 3 indicated that the best division point of treated and non-treated years would be prior to 1939 since there is some irrigation present in the variable irrigation usage regions shown on Figure 1 during this period. However, the data available for pattern analysis was limited due to the lower station density in the years prior to 1931, so the major portion of the pattern analysis had to be limited to the 1931-1970 period. As a result, 1939 could not be used as a division point between treated (T) and non-treated (NT) years because of the small number of year prior to 1939.

In fact, the major growths in irrigation occurred after 1945; hence, the major irrigation effects should also occur after 1945. Accordingly, the year 1945 was used as a division point to separate the T and NT years. This was done with full recognition of the fact that some of the NT years will be subjected to influences from irrigation. Assuredly, any determination of major irrigation influences using this division point for T and NT years would be of major significance, since some influences would be expected in the non-treated years. The analyses based on the 1945 division point are considered to be the primary analyses and are presented in the following section.

Later, in an attempt to substantiate the results of this section, data from the period 1921-1930 were used in order to obtain a larger number of non-treated years. Because there were fewer weather stations in operation during this period, the available data are not on a quality level with that of more recent years, but they can be used to either strengthen or weaken the results of this section. By including the 1921-1930 data in the analysis, it was possible to use 1940 as the division point between treated and non-treated years, and the results of these secondary analyses are presented in a later section.

Analysis of the Target and Control Rainfall

The average areal rainfall for each of the first, second, and third level target areas were determined for each year of the summer months and for each year of the summer season. In addition, the areal averages for the control areas were determined for each year for 1) the summer months and 2) the summer season. These areal averages formed the primary data series used in determining the magnitude and significance of the irrigation effect on rainfall.

The mean rainfalls for the non-treated (NT) period 1931-1945 and the treated (T) period 1946-1970 were determined for each of the target and control areas. These means, along with selected ratio comparisons, are listed in Table 2.

It is noted that in each target area every treated mean (irrigated period mean) is greater than the corresponding non-treated mean (non-irrigated period mean) with the exception of the ES1 target area. Conversely, in the control area (bottom of table) the treated mean is less than the non-treated mean. Furthermore, the target-to-control ratio during the treated period is greater than 1.0, and it is greater than the target-to- control ratio during the non-treated period, with the exception of the ES1 and CT comparison. Moreover, over half of the target-to-control ratios during the non-treated period were less than 1.0, indicating that in over 50% of the cases the target rainfall was less than the control rainfall. *The numbers in Table 2 clearly reflect the fact that target rainfall was greater than control rainfall during the irrigated period, and the rainfall during the treated period was greater than rainfall during the non-treated period in the target area.* The only exception to this statement concerns the rainfall associated with the ES1 target area.

Clearly, the differences between treated and non-treated rainfall are the greatest during the month of July. These differences are reflected in the summer differences, which are greater than those in June and August (June and August have nearly the same differences). The greater differences in July as compared to the differences in June and August are also indicated by the trends shown on Figures 10a-c. Clearly, the slope of the eigenvector trend is greater in July (.0128) than in June (.0043) and August (.0058). Also, the slope during July is more significant (t=3.88) than during June (t=1.67) and August (t=2.10). Both table and figures are indicative of greater increases in rainfall in and surrounding the target areas during July than during the other summer months.

It is not adequate to merely investigate the various comparisons listed in Table 2. Trends, cycles, abnormally wet years, and abnormally dry years are in the data of both the target and control areas and must be taken into account. If these items are not allowed for, the greater rainfall during the irrigated period (in July, for example) could be due entirely to the fact that the irrigated years are naturally wetter than the non-irrigated years. Thus, an

Table 2. The mean average rainfall of treated (1946-1970) and non-treated (1931-1945) periods for the target and control areas including selected ratio comparisons.

Comparison	Target means T_	Target means NT	Target ratio T/NT	T target/ control ratio	NT target/ control ratio
			June		
E1 vs CT	4.04	3.47	1.16	1.43	1.19
E2 vs CT	4.23	3.64	1.16	1.50	1.25
E3 vs CT	4.14	3.48	1.19	1.47	1.19
ET1 vs CT	3.23	2.89	1.12	1.15	.99
ET2 vs CT	3.34	3.04	1.10	1.19	1.04
ET3 vs CT	3.27	2.77	1.18	1.16	.95
EK1 vs CT	3.48	2.91	1.20	1.23	1.00
EK2 vs CT	3.14	2.62	1.20	1.11	.90
EN1 vs CT	5.04	4.25	1.19	1.79	1.46
EN2 vs CT	5.16	4.33	1.19	1.83	1.48
EN3 vs CT	5.23	4.38	1.19	1.85	1.50
ES1 vs CT	3.15	3.46	.91	1.12	1.18
			July		
E1 vs CT	3.09	2.07	1.49	1.26	.81
E2 vs CT	3.11	1.99	1.56	1.27	.77
E3 vs CT	3.32	2.07	1.60	"1.35	.80
ET1 vs CT	2.78	1.86	1.49	1.13	.72
ET2 vs CT	2.86	1.80	1.59	1.17	.70
ET3 vs CT	3.15	1.79	1.76	1.29	.70
EK1 vs CT	3.55	2.38	1.49	1.45	.93
EK2 vs CT	3.64	2.42	1.50	1.49	.94
EK3 vs CT	3.48	2.36	1.47	1.42	.92
ES1 vs CT	3.74	2.82	1.33	1.53	1.10
			August		
E1 vs CT	2.88	2.57	1.12	1.26	1.04
E2 vs CT	2.85	2.54	1.12	1.25	1.03
E3 vs CT	2.83	2.42	1.17	1.24	.98
EK1 vs CT	2.63	2.37	1.11	1.15	.96
EK2 vs CT	2.67	2.39	1.12	1.17	.97
EK3 vs CT	2.73	2.36	1.16	1.20	.96

Table 2 (Cont.)

Comparison	Target means T	Target means NT	Target ratio T/NT	T target/ control ratio	NT target/ control ratio
			August (cont.)		
EN1 vs CT	3.47	3.06	1.13	1.52	1.24
EN2 vs CT	3.32	2.93	1.13	1.46	1.19
EN3 vs CT	3.15	2.60	1.21	1.38	1.06
ES1 vs CT	1.86	2.22	.84	.82	.90
			Summer		
E1 vs CT	10.09	8.47	1.19	1.35	1.07
E2 vs CT	9.11	7.27	1.25	1.22	.92
E3 vs CT	8.50	7.15	1.19	1.13	.90
ET1 vs CT	8.32	6.85	1.21	1.11	.86
ET2 vs CT	8.69	6.91	1.26	1.16	.87
ET3 vs CT	8.50	7.15	1.19	1.13	.90
EK1 vs CT	9.27	7.54	1.23	1.24	.95
EK2 vs CT	8.89	6.94	1.28	1.19	.87
EN1 vs CT	12.11	10.40	1.16	1.62	1.31
EN2 vs CT	10.79	8.90	1.21	1.44	1.12

Control

	June	July	August	Summer
T mean	2.82	2.45	2.28	7.49
NT mean	2.92	2.57	2.46	7.94
T/NT ratio	.96	.95	.93	.94

adjustment of treated and non-treated means is needed to allow for natural differences in the region. The analysis of covariance provides a means for making such an adjustment through the use of control areas (covariates).

In this research, the analysis of covariance is used to adjust treated and non-treated means of the target areas for differences in the control areas; that is, it is used to adjust the treated and non-treated means in the target areas to be estimates of what they would be if the treated and non-treated period means were the same in the control area. For the case of one target area and one control area, we define the variate Y to be the target (dependent) variable and the variate X to be the control (independent) variable. The 2 x 2 covariance matrix, C_t , and the 2 x 2 covariance matrix C_{nt} , are computed where the subscripts t and nt denote the treated (irrigated period) and non-treated (non-irrigated period) groups, respectively. The within-groups sum of squares 2 x 2 matrix, W, is then computed by:

$$W = (n_t-1)\, C_t + (n_{nt}-1)\, C_{nt} \tag{8}$$

where n_t denotes the number of treated years and n_{nt} denotes the number of non-treated years.

The observations from the treated and non-treated years are combined to form an overall group of observations for the target and control variables. The 2 x 2 covariance matrix, C, is then computed for the overall group. The total-group sum of squares matrix, T, is then computed by:

$$T = (n-1)\, C \tag{9}$$

where $n=n_t + n_{nt}$. The between-group sum of squares is computed directly by:

$$B = T - W \tag{10}$$

It is noted that the degrees of freedom (df) is n-1 for T, n-g for W, and g-1 for B where g is the number of groups (2 in this case).

The total-groups correlation, r_T , is given by:

$$r_T = t_{xy} / (t_{xx}^{\frac{1}{2}} t_{yy}^{\frac{1}{2}}) \tag{11}$$

where t_{xx} is the x sum of squares in the T matrix, t_{yy} is the y sum of squares in the T matrix, and t_{xy} is the xy sum of products in the T matrix. Similarly, the within-groups correlation coefficient, r_W, is given by:

$$r_W = w_{xy} / (w_{xx}^{\frac{1}{2}} w_{yy}^{\frac{1}{2}}) \tag{12}$$

where w_{xx} is the x sum of squares in the W matrix, w_{yy} is the y sum of squares in the W matrix, and w_{xy} is the xy sum of products in the W matrix. It is noted that the df for r_T is n-2 and the df for r_W is n-g-1.

The total-groups regression coefficient, b_T, is then computed and given by:

$$b_T = t_{xy} / t_{xx} \tag{13}$$

and the within-groups regression coefficient, b_W , is given by:

$$b_W = w_{xy} / w_{xx} \tag{14}$$

It is now desired to adjust t_{yy} and w_{yy} so that the variation due to regression has been removed. The variance remaining after such an adjustment is nothing more than the residual variance, or square of the standard error of estimate, S_e^2, which is always given by:

$$S_e^2 = S_y^2 - r^2 S_y^2 \tag{15}$$

where S_y^2 is the variance in the dependent variable, and r is the correlation coefficient between the independent and dependent variables. We can now express the residual variance in terms of sums by substituting for S_y^2 and r in the following manner:

$$S_e^2 = \Sigma y^2 / (n-1) - [(\Sigma xy)^2 / (\Sigma x^2) (\Sigma y^2)] \cdot \Sigma y^2 / (n-1) \tag{16}$$

and Equation 16 can be reduced to the adjusted sum of squares (or residual sum of squares):

$$\text{Adj. SS} = (n-1)\, S_e^{\,2} = \Sigma y^2 - (\Sigma xy)^2 \,/\, \Sigma x^2 \tag{17}$$

With the use of Equation 17 we can now express the adjusted y sum of squares, ta_{yy}, for the T matrix by:

$$ta_{yy} = t_{yy} - t_{xy}^{\,2} \,/\, t_{xx} \tag{18}$$

and the adjusted y sum of squares for the W matrix, wa_{yy} , by:

$$wa_{yy} = w_{yy} - w_{xy}^{\,2} \,/\, w_{xx} \tag{19}$$

The adjusted y sum of squares for the B matrix, ba_{yy}, is given by the subtraction of wa_{yy} from ta_{yy}:

$$ba_{yy} = t_{yy} - (t_{xy}^{\,2} \,/\, t_{xx}) - w_{yy} - (w_{xy}^{\,2} \,/\, w_{xx}) \tag{20}$$

where the df is n-2 for ta_{yy}, n-g-1 for wa_{yy}, and g-1 for ba_{yy}.

The treated and non-treated means ($\overline{Y}_t$, $\overline{Y}_{nt}$) in the target areas can be adjusted to reflect the control conditions by:

$$\overline{Ya}_t = \overline{Y}_t - b_W\,(\overline{X}_t - \overline{X}) \tag{21}$$

$$\overline{Ya}_{nt} = \overline{Y}_{nt} - b_W\,(\overline{X}_{nt} - \overline{X}) \tag{22}$$

where $\overline{X}_t$ is the control mean during the treated period, $\overline{X}_{nt}$ is the control mean during the non-treated period, and $\overline{X}$ the control mean during the overall period, 1931-1970.

Since the adjusted means are more valid than the unadjusted means for comparison purposes, it is also desired to provide a method of assessing the significance of the differences between adjusted treated and non-treated means. Since we are not dealing with means from random samples, but rather means from total populations, the usual F test is not appropriate. However, as indicated earlier, the test statistics can be used as indicators of the important differences in the population means. In this case, we first consider the following F-ratio:

$$F = [ba_{yy}/(g-1)]/[wa_{yy}/(n-g-1)] \qquad (23)$$

Since only two groups are involved, the t-ratio can be obtained by taking the square root of the F-ratio, yielding:

$$t = F^{\frac{1}{2}} = ([ba_{yy}/(g-1)]/[wa_{yy}/(n-g-1)])^{\frac{1}{2}} \qquad (24)$$

Thus, even though the t-ratio does not carry the same connotation as it does in the usual sampling sense, it can be used to judge the relative importance of the differences of the adjusted means. As noted previously, t-ratios of 1.5 are considered to represent important differences between the population parameters.

Of course, the violation of the assumptions involved in the analysis of covariance will reduce the suitability of the adjustment procedure. There are two assumptions that are of particular interest when the adjustment procedure is used:

1) equality of slopes (regression coefficients) in the two groups, and 2) the fact that the independent (control) variable is not affected by the treatment (irrigation) in the target area. In regard to the first assumption, McNemar (1969) indicates that even though it may fail to hold, it may or may not be crucial in the analysis, and that minor violations are certainly tolerable. In regard to the second assumption, Steele and Torrie (1960) indicated that violations of it need not mean that the analysis of covariance should not be used, but that care must be exercised in the interpretation of the data.

Consequently, in this research, the adjustment procedure was used for all target means, regardless of whether the assumptions were violated. However, such violations are noted, and appropriate caution is exercised.

The adjustment procedure was applied to the data in Table 2 and the resulting adjusted data and t-ratios are listed in Table 3. Primary attention should be directed toward the adjusted target ratios T/NT. It is noted that

Table 3. The adjusted means, ratios, and percent effects as determined from the analysis of covariance for the period 1931-1970.

Comparison	Adjusted means T	Adjusted means NT	Adjusted target ratio T/NT	t ratio	Equality of slopes	Percent effect
			June			
E1 vs CT	4.09	3.39	1.21	2.10	yes	21
E2 vs CT	4.27	3.55	1.20	1.94	yes	20
E3 vs CT	4.18	3.41	1.23	1.88	yes	23
ET1 vs CT	3.27	2.83	1.16	1.15	yes	16
ET2 vs CT	3.38	2.97	1.14	.92	yes	14
ET3 vs CT	3.30	2.72	1.21	1.16	yes	21
EK1 vs CT	3.54	2.82	1.26	1.71	no	26
EK2 vs CT	3.19	2.53	1.26	1.46	no	26
EN1 vs CT	5.10	4.15	1.23	1.99	yes	23
EN2 vs CT	5.22	4.23	1.23	1.87	yes	23
EN3 vs CT	5.29	4.27	1.24	1.76	yes	24
ES1 vs CT	3.19	3.40	.94	-.34	no	-6
			July			
E1 vs CT	3.15	1.98	1.59	4.12	no	59
E2 vs CT	3.16	1.90	1.66	3.77	no	66
E3 vs CT	3.38	1.97	1.72	3.47	no	72
ET1 vs CT	2.83	1.77	1.60	3.36	no	60
ET2 vs CT	2.91	1.70	1.71	3.36	no	71
ET3 vs CT	3.21	1.68	1.91	3.34	no	91
EK1 vs CT	3.61	2.38	1.58	3.47	no	58
EK2 vs CT	3.70	2.31	1.60	3.05	no	60
EK3 vs CT	3.54	2.26	1.57	2.63	yes	57
ES1 vs CT	3.83	2.69	1.42	1.82	no	42
			August			
E1 vs CT	2.92	2.51	1.16	2.07	yes	16
E2 vs CT	2.88	2.49	1.16	1.85	yes	16
E3 vs CT	2.87	2.36	1.22	1.99	yes	22
EK1 vs CT	2.67	2.30	1.16	1.57	no	16
EK2 vs CT	2.70	2.34	1.15	1.41	no	15
EK3 vs CT	2.77	2.30	1.20	1.48	yes	20

Table 3 (Cont.)

Comparison	Adjusted means T	Adjusted means NT	Adjusted target ratio T/NT	t ratio	Equality of slopes	Percent effect
			August (cont.)			
EN1 vs CT	3.50	2.99	1.17	1.32	yes	17
EN2 vs CT	3.35	2.89	1.16	1.18	yes	16
EN3 vs CT	3.19	2.53	1.26	1.62	yes	26
ES1 vs CT	1.91	2.13	.90	-.70	yes	-10
			Summer			
E1 vs CT	10.21	8.28	1.23	3.13	yes	23
E2 vs CT	9.25	7.04	1.31	3.33	yes	31
E3 vs CT	8.67	6.86	1.26	2.42	no	26
ET1 vs CT	8.46	6.62	1.28	3.12	no	28
ET2 vs CT	8.83	6.67	1.32	3.22	no	32
ET3 vs CT	8.67	6.86	1.26	2.42	no	26
EK1 vs CT	9.42	7.29	1.29	2.64	yes	29
EK2 vs CT	9.04	6.69	1.35	2.81	yes	35
EN1 vs CT	12.19	10.27	1.19	2.28	yes	19
EN2 vs CT	10.91	8.71	1.25	2.70	yes	25

these ratios are somewhat larger than the corresponding unadjusted ratios (Table 2) in all cases. The greater ratios result from the fact that the rainfall in the control area was less during the treated period than during the non-treated period, which caused a positive adjustment on the treatment means. *Clearly, both the adjusted and unadjusted ratios indicate greater rainfall in and surrounding the irrigated regions during the treated (irrigated) period than during the non-treated (non-irrigated period)*.

In general, there is a tendency for the effect to be greater in the higher level target areas. This tendency is the strongest in June and July, particularly in the Texas target areas (ET1, ET2, ET3) and overall target areas (E1, E2, and E3). The obvious conclusion to be drawn from this table is that the irrigation effect is the strongest in the month of July. This effect is most apparent in the irrigated regions of the Texas Panhandle. This corresponds well to the fact that the irrigation usage is also the strongest in the Texas irrigated region (See Figure 1).

The magnitude of the irrigation effect varies from 14 to 26% in June, 57 to 91% in July, 15 to 26% in August, and 19 to 35% during the summer depending on location of the effect and the intensity level of irrigation within the target areas. The t-ratios indicated that the differences between treated and non-treated means are insignificant in the Texas irrigated region in June, in the lower level targets in Nebraska during August, and in the ES1 regions during June and August. The Kansas irrigation region is on the borderline of significance during August. All other comparisons appear to be significant.

The ES1 areas are of interest. For each month these areas are separated from the major target areas by some distance (Note Figures 16a, 17a, and 18a). However, July is the only month when the ES1 area is located downwind from the major effect areas (Figure 17a), and July is the only month when the ES1 region has a significant difference between the treated and non-treated years. Whether this is a spurious result or actually represents evidence for a far downwind effect will be investigated more fully in a later section.

Gradations In The Precipitation Regime and Their Influence On The Rainfall Anomalies

It has been demonstrated that there has been an increase in the rainfall in and surrounding the irrigated regions during the same period that the growth of irrigation has occurred. It has also been demonstrated that the increase has occurred in all summers since 1945 with the exception of 1954 (See Table 1). However, this increase has not occurred in every year in each of the three individual months. As noted previously, for the month of June 15 of 25 years after 1945 had potential increases (ie., effect classifications; see Table 1) while for July and August, the number of years with potential increases were 18 and 13, respectively. Thus, even though the average number of months with effect classification per year has increased over the 40-year period, the effect has only occurred in selected months per year.

The important question that now must be addressed is: Why does the rainfall increase occur only in selected months? In the section on rationale for an irrigation effect, several potential mechanisms were presented. However, the issue of why these mechanisms should only be operative during selected months was not considered. We now turn our attention to this important issue.

It has been alluded to frequently that the effect appears to occur more often in wet years rather than in dry years. Since this tendency may help to explain the reason why the effect occurs in certain years, the average rainfall patterns for dry, moderate, and wet years were determined for individual months and for the summer. The dry, moderate and wet years were selected by first obtaining the areal mean over the entirety of the study area (all 150 sampling squares) for each year during June, July, August, and Summer. The 25 and 50-percentiles were determined for the monthly and seasonal distributions of areal means. The years were classified as wet if the areal means exceeded the 75-percentile and dry if the area means were less than or equal to the 25-percentile, while the remaining years were classified as moderate.

In the next section, the supplementary rainfall data from the period 1921-1930 are used to confirm the results obtained from the primary data source (1931-1970). In particular, this supplementary data source is used to further verify that the increase in rainfall after 1945 was not simply due to the abnormally dry thirties. Rather than use two classifications of dry, wet, and moderate (one based on 1931-1970 and one based on 1921-1970), it was decided to use the same classification in both sections and throughout the remainder of the report. Consequently, the 50-yr sample was used to obtain the various distributions from which the 25 and 50-percentiles were determined.

The percent frequencies of effect and non-effect years according to dry, moderate, and wet years after 1940 and after 1945 were determined using Classification 1 of effect and non-effect years from Table 1. The percent frequencies after 1940 were also presented since some growth of irrigation occurred during the period 1941-1945 (see Figure 2a). The interest here is now directed toward the role of precipitation gradations in all irrigated years.

The percent frequencies during the period after 1940 are essentially the same as those after 1945, indicating that the role of precipitation gradations on the rainfall anomalies are similar in both periods. Therefore, attention is focused on the period after 1940, which contains more of the irrigated years. For June and July, the frequency of effect and non-effect years are the same in dry years, but the frequency of effect is clearly greater than non-effect in wet years. Also, the frequency of effect is greater than non-effect in the moderate years during July. Thus, there is a greater tendency for the irrigation effect to occur in ,the wetter years than in the drier years. However, this is not true for August. During this month, the frequency of effect is much less than non-effect in the wet years. When all months are combined, there is still a greater tendency for effect rather than non-effect during moderate and wet years, whereas the frequencies of effect and non-effect are nearly the same in dry years (see Table 4).

The fact that the irrigation effect does not occur in the wetter years during August was also noted in the discussion of Figures 11, 12, and 13. An inspection of Figure 13 and Table 3 shows that the irrigation effect only occurred in the Kansas and Nebraska area, and that the strongest effect was located in the Kansas area. It is noted that although the rainfall is greater on the effect years than on non-effect years in the vicinity of the Kansas irrigated region, the overall rainfall pattern of the effect years does not appear to be wetter than the pattern on the non-effect years. Indeed, a

Table 4. The percent frequencies of effect and non-effect years according to gradations in the precipitation regime.

	After 1940			After 1945		
	dry	moderate	wet	dry	moderate	wet
			June			
E	50	44	100	50	46	100
NE	50	56	0	50	54	0
			July			
E	50	67	78	60	67	87
NE	50	33	22	40	33	13
			August			
E	57	56	14	50	60	25
NE	43	44	86	50	40	75
			All Months (Summer)			
E	53	55	67	53	58	78
NE	47	45	33	47	42	22

computation of the areal mean rainfall for both patterns shows that the areal mean during the non-effect years was 2.36 inches while the areal mean during the effect years was 2.58 inches. Thus, the tendency for the frequency of the effect to be less than that of non-effect during wet years can be partially explained by the fact that the rainfall in the general vicinity of the Kansas irrigated region was heavier in the effect years than in the non-effect years, even though this was not true for the overall areal means.

The influence of gradations in the precipitation regime on the magnitude of precipitation was investigated by determining the average precipitation patterns during dry, moderate dry, moderate wet, and wet years after 1940 for each of the months and for Summer. (The 'moderate dry' and 'moderate wet' years were determined by dividing the moderate years at the 50-percentile). The patterns for June are shown on Figure 20.

Insofar as the average patterns are concerned, there appears to be some evidence of rainfall anomalies and protrusions in all four strata of years. Spatially, the anomalies appear to be more clearly defined in the drier years than in the wetter years. Thus, although the frequency of effect is greater in the wetter years, the magnitude of the effect is at least as great, and perhaps even greater in the drier years.

An inspection of the July patterns (Figure 21) indicates that, although there is weak evidence of anomalies in the drier years, the strongest evidence for anomalies occurs in the wetter years. Relationships in the August patterns (not shown) are generally less defined because of the tendency for the rainfall in the vicinity of the Kansas irrigated region to differ from the overall areal mean rainfall. However, the pattern results were consistent with the frequency results in that, as the frequency of effect was greater than the frequency of non-effect in the drier years, the rainfall anomalies in the Kansas region also appeared in the drier years.

It was noted previously that the effect occurred in all summers after 1945 except for the Summer of 1954 (an extremely dry summer throughout the plains). It was also noted that there was lack of trend in the summer eigenvectors, and it was hypothesized that this was due to the tendency for the irrigation effect to occur in wet months as opposed to dry months. Since most summers are a mixture of dry, moderate, and wet months, there should be some effect in all

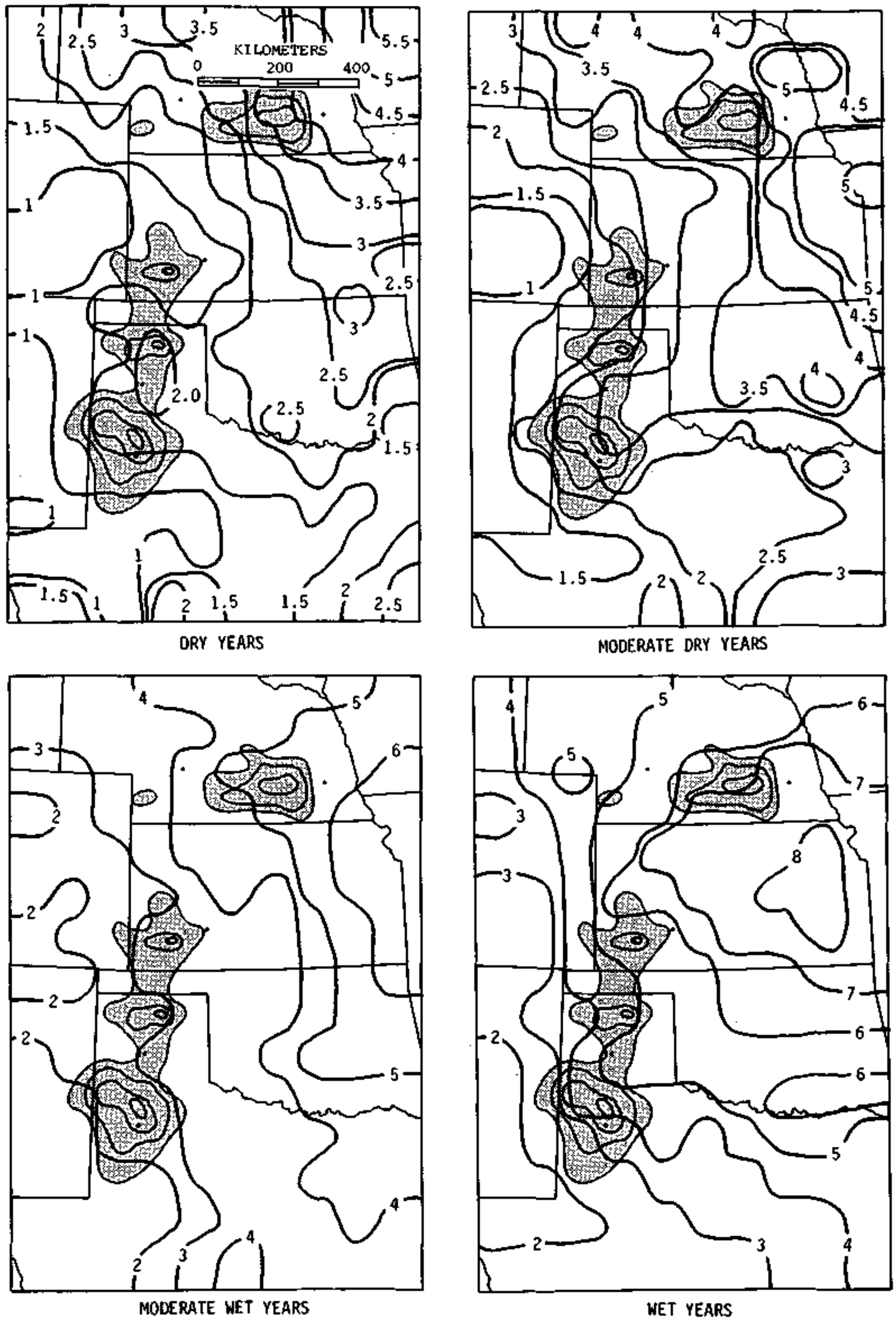


Figure 20. The average rainfall patterns for dry, moderate dry, moderate wet, and wet years during June after 1940 (rainfall in inches).

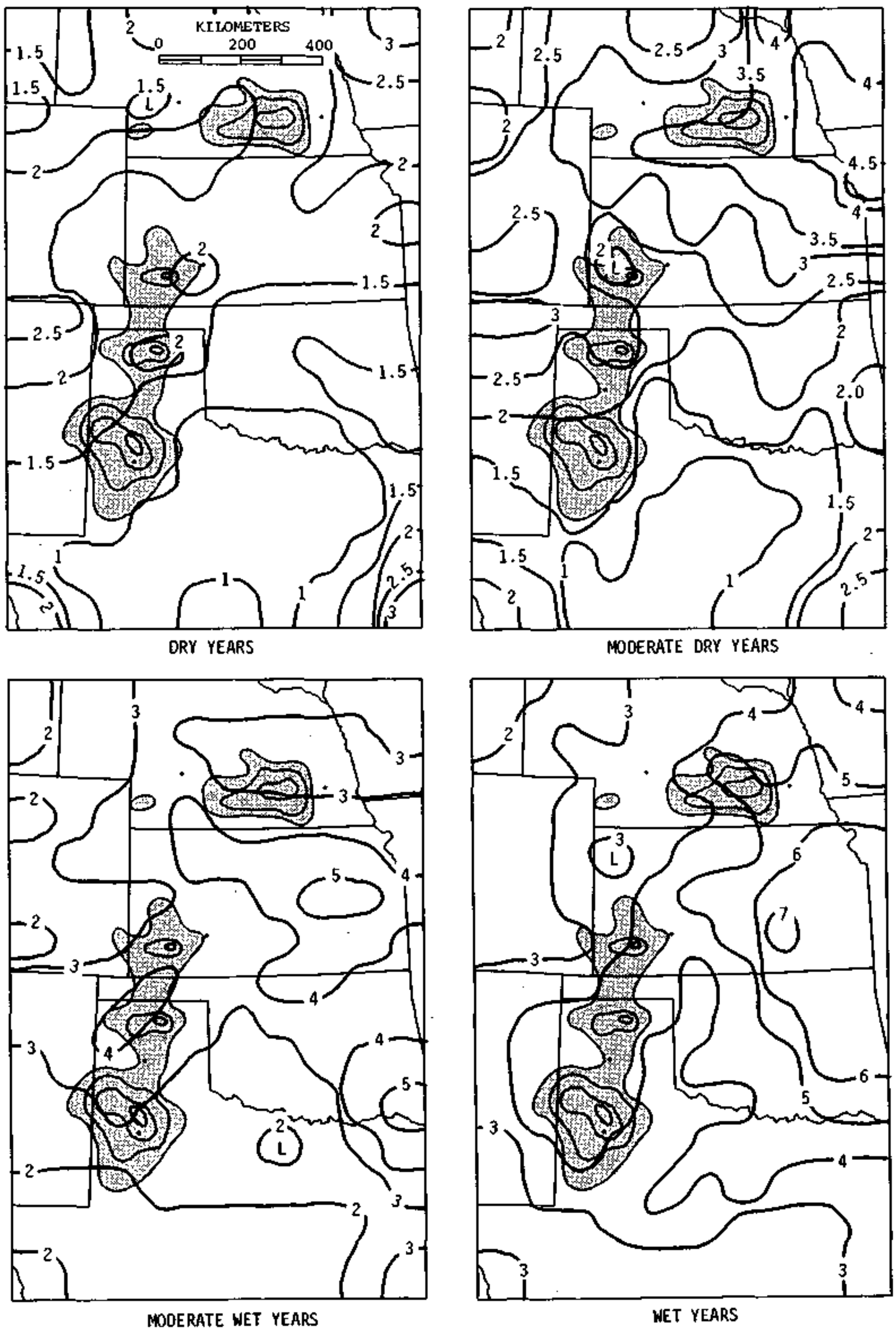


Figure 21. The average rainfall patterns for dry, moderate dry, moderate wet, and wet years during July after 1940 (rainfall in inches).

summers. The average rainfall patterns for summer (Figure 22) confirm this suspicion, since irrigation-related anomalies or protrusions are present in all four strata of years.

From the above analysis it is concluded that there is some tendency for the irrigation effect to either 1) occur in the wetter months as opposed to the drier months over the study area, or 2) occur when the rainfall in the general vicinity of the target area is somewhat heavy. With this tendency in mind, attention is again directed to the Kansas and Texas irrigated regions on Figures 11b, 12b, and 13b. In June, the irrigation effect is present in all irrigated regions. In July, the irrigation effect shifts slightly northward, and in August, the irrigation effect has disappeared in the Texas irrigated area and has intensified in the Kansas irrigated region.

It is noted that, in July, the general rainfall pattern during effect years was much drier than in June in the region south of a E-W line roughly parallel to the southern border of Oklahoma. *It is now hypothesized that the generally drier climate in this region has caused the irrigation effect area to shift northward.* This hypothesis is supported by the August effect pattern (Figure 13b) in that the extent of generally dry conditions has shifted northward to a E-W line approximately parallel to the middle of the state of Oklahoma. Correspondingly, the effect- area has disappeared from the Texas irrigated region. It is further noted that the effect area is present only when the general rainfall in the region is in the neighborhood of 2.5 inches or more. That is, the first curvature of the isolines in the irrigated areas occurs at a magnitude of 2.5 to 3.0 inches.

It would appear that for the irrigation effect to be present, a general level of synoptic activity must first be present. *The irrigation effect would then shift northward during the summer in the same manner that the synoptic activity shifts northward as the summer progresses.* This premise is strongly supported by Barnston (1976), who studied the synoptic conditions associated with the irrigation-related anomalies in the Texas and Oklahoma irrigated regions.

Barnston (1976) found that any synoptic condition providing low-level convergence and uplift was fundamental in allowing irrigated-produced low-level moisture to increase cloud development and rainfall. Convergence and uplifting

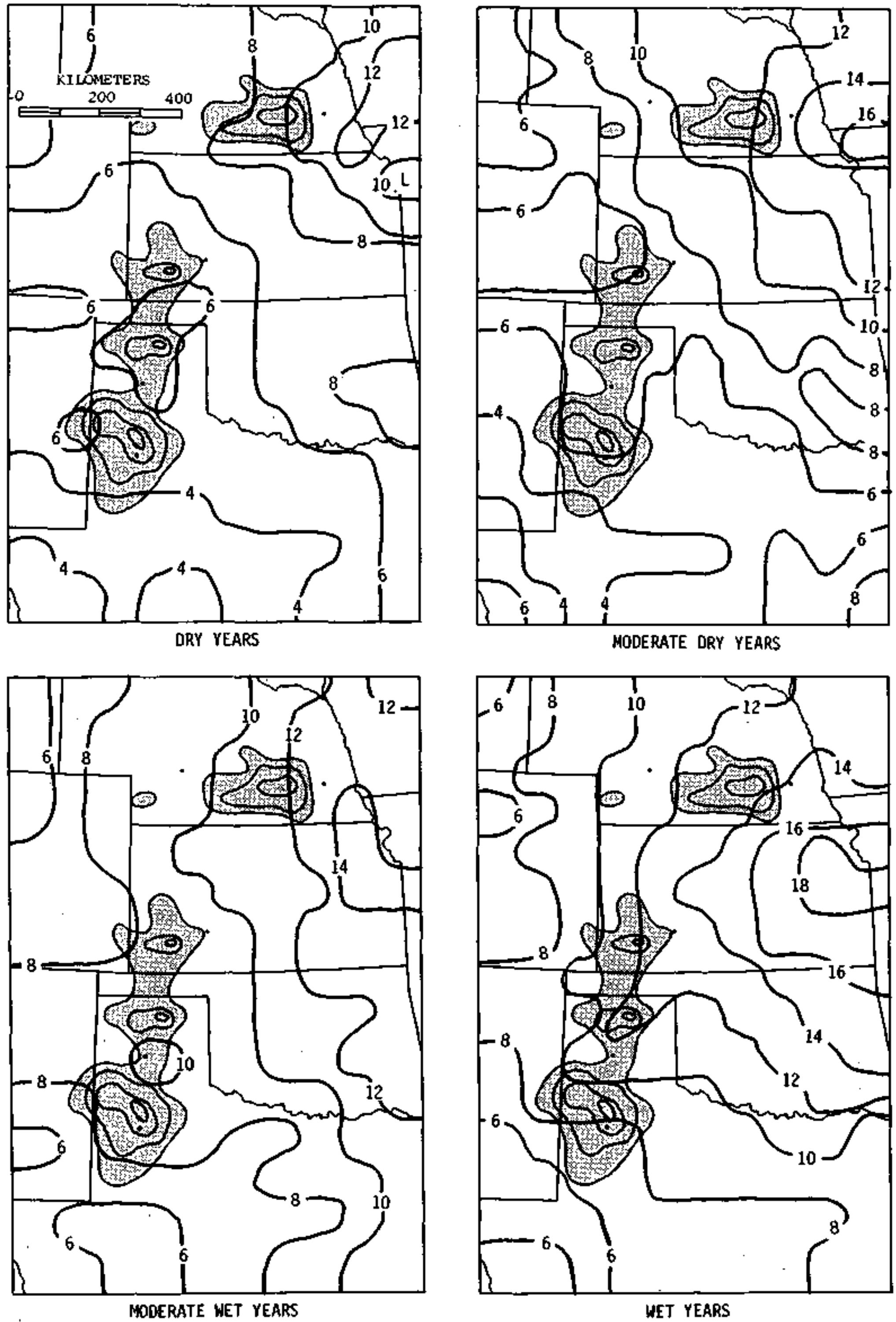


Figure 22. The average rainfall patterns for dry, moderate dry, moderate wet, and wet years during Summer after 1940 (rainfall in inches).

are underlying processes associated with most frontal passages, and these processes are particularly important when associated with stationary fronts, which can persist over a single area for an extremely long period of time. In his analysis, Barnston noted that stationary fronts appeared to be particularly crucial in producing irrigated-related rainfall. He found that only one or two persistent stationary fronts during the month of June were sufficient to yield an irrigation-related rainfall excess of a noteworthy magnitude.

Cold fronts were also important, but the magnitude of irrigated-related rainfall was not as great in this case as with stationary fronts. Presumably, cold fronts allow for covergence of surface moisture for only a brief period of time over a given area, and therefore the total contribution from irrigation over a given area cannot be large. However, slower moving cold fronts could produce a larger contribution.

The fact that uplifting caused by a stationary front can ingest a significantly greater amount of moisture from land irrigation than can a moving storm or frontal system can be demonstrated from Sellers' assessment (1965) of lake and class A pan evaporation rates in various locations. Sellers indicates that nearly one cm of water per day evaporates from a class A pan in summer for regions with ambient conditions similar to those of the Texas Panhandle, Barnston concludes that if one cm per day (or, for moist, cold days, about half this amount) can be ingested into the atmosphere over an area the size of the irrigation region in the Texas Panhandle, a storm system hovering over the area for 12 hours rather than two hours would tend to add substantial irrigation-related rainfall potential to the vicinity.

Thus, we would expect the effect of irrigation to be more evident during generally rainy periods, because these are the periods in which there are likely to be a lot of surface disturbances involving low-level convergence. Furthermore, Barnston showed that the general storm track shifted northward out of the Texas Panhandle as the summer progresses, so we conclude that the irrigated-related anomalies should also shift northward.

The issue of why the irrigated mechanism should only be operative during selected months is to a large degree determined by the general synoptic conditions. The sub-synoptics of the irrigation effect which appears to be generally associated with instability generated by the temperature and moisture conditions in the vicinity of the irrigated regions, is discussed in a later section. However, one other question should be discussed before leaving this section.

It is noted from Table 4 that the irrigation effect is present in 50% of the dry Junes and Julys. Why would this happen if the effect is generally associated with wetter conditions? The answer appears to lie in the fact that the dry years in which the irrigation effect was absent were particularly "bone dry" as opposed to the dry years in which the irrigation effect was present. The average effect and non-effect patterns for the dry Junes are shown on Figure 23.

Note the existence of extremely dry conditions in the areas to the west and south of the Texas irrigated region in the non-effect years. In contrast, these areas are not as dry in the effect years. It was noted previously that one or two persistent stationary fronts are sufficient to yield an irrigation-related rainfall excess. If there was only one stationary front and this was the only rain producing storm during the month, an irrigation effect could be present in what generally would be considered to be a 'dry' month.

Attention should be directed toward the protrusion of the 1.0 isoline into the irrigated region during the non-effect years (Figure 23). It would appear that this rainfall isoline is part of the irrigation effect, but the region of rainfall within the 1.0 isoline did not increase over time. This fact is demonstrated in the next section with data from 1921-1930. (It is shown that this ridge of rainfall is present in the 1921-1940 period). This finding further proves the extreme usefulness of the factor approach, for it was able to discern this distinction using only the data from 1931-1970.

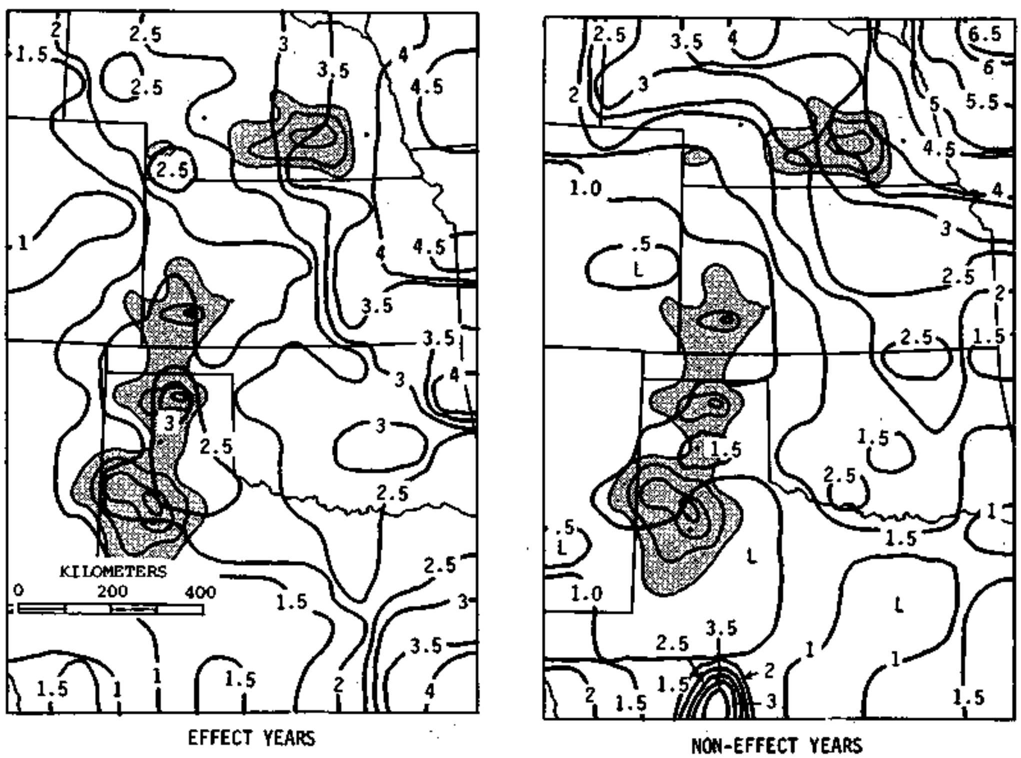


Figure 23. The average rainfall patterns during effect and non-effect dry Junes, 1931-1970 (rainfall in inches).

SEPARATION AND EXPLANATION OF IRRIGATION EFFECTS USING SUPPLEMENTARY DATA AND ANALYSES

DELINEATION AND ANALYSES OF IRRIGATION EFFECT USING SUPPLEMENTARY RAINFALL DATA

Analysis of the Target and Control Rainfall

As noted previously, the data from the period 1921-1930 were not on a quality level with that of more recent years, because there were fewer reporting stations in the 1920's. Initially, these years were not intended to be used in the pattern analysis because of density limitations. However, the need for more years prior to the onset of irrigation to substantiate the results obtained from the primary data source of 1931-1970 dictated that these years be used.

These earlier years were particularly useful in verifying that the increase in rainfall after 1945 was not simply due to the abnormally dry 1930's. This verification was accomplished by availability of additional pre-irrigated years, which permitted a division point between irrigated (treated) and non-irrigated (non-treated) years of 1940. This was particularly useful in that the division point of 1945 caused some of the irrigated years to be placed in the non-treated category (See Figures 2a, 2b, 3a, and 3b which indicate that some irrigation did occur in the major irrigation-source regions during the period 1941-1945).

Due to the lower quality level of the 1921-1930 data, it was decided that it was not appropriate to apply the factor analysis in the manner that was done with the 1931-1970 data. *Thus, the purpose of the additional 10 years of rain data is to demonstrate that the irrigation effect is still present after including the generally wet 1920 's in the analysis.*

The average areal rainfall in the target and control areas used in the 1931-1970 analyses was determined for each year of the summer months and each year of the summer season during 1921-1930. The mean rainfalls for the non-treated (NT) period 1921-1940 and the treated (T) period 1941-1970 were determined for each of the target and control areas. These means, along with selected ratio comparisons, are presented in Table 5.

Table 5. The mean average rainfall of treated (1941-1970) and non-treated (1921-1940) periods for the target and control areas including selected ratio comparisons.

Comparison	Target means T	NT	Target ratio T/NT	T target/ control ratio	NT target/ control ratio
		June			
E1 vs CT	4.12	3.39	1.22	1.40	1.21
E2 vs CT	4.33	3.46	1.25	1.48	1.24
E3 vs CT	4.26	3.28	1.30	1.45	1.18
ET1 vs CT	3.26	2.98	1.09	1.11	1.07
ET2 vs CT	3.40	3.05	1.11	1.16	1.09
ET3 vs CT	3.29	2.80	1.18	1.12	1.00
EK1 vs CT	3.48	2.95	1.18	1.19	1.06
EK2 vs CT	3.15	2.62	1.20	1.08	.94
EN1 vs CT	5.19	3.94	1.32	1.77	1.41
EN2 vs CT	5.33	3.94	1.35	1.82	1.41
EN3 vs CT	5.46	3.81	1.43	1.86	1.37
ES1 vs CT	3.35	3.29	1.02	1.14	1.18
		July			
E1 vs CT	3.05	2.27	1.34	1.23	.90
E2 vs CT	3.08	2.18	1.41	1.24	.87
E3 vs CT	3.30	2.19	1.51	1.33	.87
ET1 vs CT	2.75	2.02	1.36	1.11	.80
ET2 vs CT	2.84	1.95	1.46	1.15	.77
ET3 vs CT	3.13	1.83	1.71	1.26	.73
EK1 vs CT	3.50	2.62	1.34	1.41	1.04
EK2 vs CT	3.62	2.66	1.36	1.46	1.06
EK3 vs CT	3.47	2.55	1.36	1.40	1.01
ES1 vs CT	3.59	3.26	1.10	1.45	1.29
		August			
E1 vs CT	2.88	2.64	1.09	1.23	1.12
E2 vs CT	2.85	2.63	1.08	1.22	1.12
E3 vs CT	2.82	2.46	1.15	1.21	1.05
EK1 vs CT	2.66	2.37	1.12	1.14	1.01
EK2 vs CT	2.70	2.41	1.12	1.15	1.03
EK3 vs CT	2.73	2.30	1.19	1.17	.98

Table 5 (Cont.)

Comparison	Target means T	NT	Target ratio T/NT	T target/ control ratio	NT target/ control ratio
		August (cont.)			
EN1 vs CT	3.41	3.28	1.04	1.46	1.40
EN2 vs CT	3.26	3.21	1.02	1.39	1.36
EN3 vs CT	3.10	2.95	1.05	1.32	1.26
ES1 vs CT	2.04	1.66	1.23	.87	.71
		Summer			
E1 vs CT	10.16	8.54	1.19	1.31	1.15
E2 vs CT	9.11	7.61	1.20	1.17	1.02
E3 vs CT	8.54	7.47	1.14	1.10	1.00
ET1 vs CT	8.36	7.07	1.18	1.07	.95
ET2 vs CT	8.68	7.31	1.19	1.12	.98
ET3 vs. CT	8.54	7.47	1.14	1.10	1.00
EK1 vs CT	9.33	7.68	1.21	1.20	1.03
EK2 vs CT	8.89	7.19	1.24	1.14	.97
EN1 vs CT	12.21	10.27	1.19	1.57	1.38
EN2 vs CT	10.81	9.12	1.18	1.39	1.23

Control

	June	July	August	Summer
T mean	2.93	2.48	2.34	7.77
NT mean	2.79	2.52	2.35	7.43
T/NT ratio	1.05	.98	1.00	1.04

The T/NT ratios for June are somewhat higher in the E and EN target areas, and are nearly the same in the ET and EK target areas as they were for the 40-yr analysis (Table 2). For July, the ratios are generally lower than they were for the 40-year analysis, and for August, they are nearly the same except for the EN target area, which has slightly lower ratios. For Summer, the ratios are nearly the same in both the 40-year analysis (Table 2) and the 50-year analysis (Table 5). In any event, the treated mean (irrigated period) is greater than the corresponding non-treated (non-irrigated) mean.

The target-to-control ratios during the treated period are nearly the same as they were in the 40-year analysis, and all are greater than 1.0 with the exception of the ES1 target area in August. With the exception of EN in June, the target-to-control ratios are slightly higher in the non-treated years than they were in the 40-year analysis (Table 2). However, it is still true that the target rainfall is greater than the control rainfall during the irrigated period, and the rainfall during the treated period was greater than rainfall during the non-treated period in the target area. The fact that the relationship holds with the addition of the 1921-1930 data is indeed an important finding.

Again, the analysis of covariance was used to adjust the target means for climatic fluctuations in the control areas. The adjusted data obtained from the 1921-1970 analysis are listed in Table 6. In regard to t-ratios, the EK areas in Kansas during June and the ES1 area during July are no longer significant. In August, all areas are insignificant with the exception of the E3 and EK3 areas in Kansas.

In summary, the t-ratios are only significant in the EN and E areas during June, in the E, ET, and EK areas during July, and in the E3 and EK3 areas during August. This indicates that the addition of the generally wet 1920's led to a diminishment of the effect in Kansas during June and in Nebraska during August. However, the addition of these years to the analyses supports the indication of effects found in Nebraska during June, in the Texas and Kansas areas during July, and in Kansas during August.

During summer, third level target areas in E and ET3 are also insignificant. In this regard, it is noted that the ET3 and E areas are in fact the same and are also small (See Figure 19). Also, the extent of these target areas

Table 6. The adjusted means, ratios, and percent effects as determined from the analysis of covariance for the period 1921-1970.

Comparison	Adjusted means T	NT	Adjusted target ratio T/NT	t ratio	Equality of slopes	Percent effect
			June			
E1 vs CT	4.05	3.49	1.16	2.01	no	16
E2 vs CT	4.27	3.55	1.20	2.34	yes	20
E3 vs CT	4.20	3.36	1.25	2.53	yes	25
ET1 vs CT	3.20	3.06	1.05	.39	yes	5
ET2 vs CT	3.34	3.14	1.06	.53	yes	6
ET3 vs CT	3.25	2.87	1.13	.87	yes	13
EK1 vs CT	3.40	3.07	1.11	.90	no	11
EK2 vs CT	3.08	2.73	1.13	.94	yes	13
EN1 vs CT	5.12	4.04	1.27	2.63	no	27
EN2 vs CT	5.26	4.04	1.30	2.71	no	30
EN3 vs CT	5.40	3.91	1.38	3.08	no	38
ES1 vs CT	3.27	3.40	.96	-.24	no	-4
			July			
E1 vs CT	3.07	2.24	1.37	3.28	no	37
E2 vs CT	3.10	2.15	1.44	3.23	no	44
E3 vs CT	3.32	2.16	1.54	3.29	no	54
ET1 vs CT	2.77	2.00	1.39	2.71	no	39
ET2 vs CT	2.85	1.92	1.48	2.96	no	48
ET3 vs CT	3.15	1.80	1.75	3.40	no	75
EK1 vs CT	3.52	2.59	1.36	2.82	yes	36
EK2 vs CT	3.64	2.63	1.38	2.54	yes	38
EK3 vs CT	3.49	2.52	1.38	2.27	yes	38
ES1 vs CT	3.62	3.21	1.13	.70	yes	13
			August			
E1 vs CT	2.88	2.64	1.09	1.39	no	9
E2 vs CT	2.86	2.63	1.09	1.19	no	9
E3 vs CT	2.82	2.46	1.15	1.63	no	15
EK1 vs CT	2.66	2.36	1.13	1.46	no	13
EK2 vs CT	2.70	2.41	1.12	1.29	no	12
EK3 vs CT	2.73	2.30	1.19	1.63	no	19

Table 6 (Cont.)

Comparison	Adjusted means T	NT	Adjusted target ratio T/NT	t ratio	Equality of slopes	Percent effect
			August (cont.)			
EN1 vs CT	3.41	3.28	1.04	.40	yes	4
EN2 vs CT	3.26	3.20	1.02	.17	yes	2
EN3 vs CT	3.10	2.95	1.05	.38	yes	5
ES1 vs CT	2.04	1.66	1.23	1.47	yes	23
			Summer			
E1 vs CT	10.08	8.65	1.16	2.68	yes	16
E2 vs CT	9.02	7.75	1.16	2.09	yes	16
E3 vs CT	8.41	7.67	1.10	1.06	yes	10
ET1 vs CT	8.26	7.20	1.15	1.98	yes	15
ET2 vs CT	8.59	7.46	1.15	1.84	yes	15
ET3 vs CT	8.41	7.67	1.10	1.06	yes	10
EK1 vs CT	9.23	7.83	1.18	1.99	yes	18
EK2 vs CT	8.79	7.35	1.19	1.98	yes	19
EN1 vs CT	12.17	10.32	1.18	2.68	yes	18
EN2 vs CT	10.74	9.23	1.16	2.09	yes	16

for Summer had to be delineated according to superimposition of the monthly target areas with variable locations due to the lack of a summer eigenvector with significant trend. Thus, this small higher-level target area is delineated with a great degree of potential error, and this most likely accounts for the lack of significance.

The failure of the ES1 areas to achieve significance with the addition of the wetter years leads to the conclusion that the earlier indication of significance in the ES1 area during July was a spurious result. That is, there is little evidence to support the concept of a far-downwind effect.

The analysis of covariance of the 1921-1970 data strongly supports the indication of effects obtained from the factor analysis and rainfall trend patterns in Nebraska during June, Texas and Kansas during July, and in Kansas during August. It does not support the indication of effects obtained for the other analyses in Kansas and Texas during June, and in Nebraska during August.

Pattern Analysis According to Pre-Irrigated and Irrigated Periods

In the earlier analyses, it was difficult to directly compare patterns during periods prior to irrigation with those during the irrigated period. This difficulty was created by the lack of enough years of rainfall patterns prior to the more desirable division point of 1940 for the separation of effect and non-effect years (See Figures 2a, 2b, 3a, and 3c). However, with the availability of the patterns for 1921-1930, direct comparisons of the irrigated and non-irrigated patterns became possible.

In this section, ratio comparisons of patterns for non-irrigated periods are presented based on division points of 1940 and 1945. It is the opinion of the author that the ratio comparisons based on the division point of 1940 are superior to those based on a division point of 1945. However, there is merit in basing the comparisons on a equal number of years (25) in each period, and this was done to further verify the patterns associated with the 1940 division point. The 1940 division point produces 20 years in the non-irrigated period and 30 years in the irrigated period.

The average rainfall patterns for the 1921-1940 and the 1941-1970 periods for June and July are presented on Figure 24. Attention is directed toward the protrusions of the 3.0 isoline into the Texas irrigated region during June in both periods (Figures 24a and 24b). It is difficult to decide from the general appearance of the protrusions whether an irrigation effect is present or not since the protrusion is present in both periods. However, the factor analysis and the rainfall trend patterns indicate an irrigation effect in this irrigation region, whereas the analysis of covariance for 1921-1970 did not indicate such an effect.

The ratio comparison map shown on Figure 25a clearly reveals anomalies in the Texas irrigated region (note the 1.1 and 1.2 isolines) and in the Kansas irrigated regions (1.2 isoline). Thus, the results of both the factor analysis and the rainfall trend patterns are confirmed. An anomaly is clearly present in the Nebraska irrigated regions. It is believed that the ratio map, along with the analyses that have been previously presented, provides strong evidence for an irrigation effect in the Nebraska irrigated region during the month of June. There is also considerable evidence for an effect in the Texas and Kansas regions, but the effect is not confirmed by the analysis of covariance.

The average rainfall patterns for the 1921-1940 and 1941-1970 periods for July are shown on Figures 24c and 24d. There is considerably heavier rainfall throughout the Texas irrigated region in the latter period , and the difference between the two periods is strikingly evident in the ratio maps shown on Figure 25c.

There is a clearly defined ratio anamaly of considerable magnitude in the Texas and Oklahoma Panhandles. Thus, the results of Table 6 are strongly supported by the ratio comparison maps based on the 1945 division point (Figures 25b and 25d). However, more emphasis is placed on the results from Figure 25a and 25c since irrigation effects in the ratio maps of Figure 25b and 25d are somewhat masked. This masking occurs because the 1945 division point causes some irrigated years to be placed in the control period.

Ratio comparison maps for August and Summer are shown on Figure 26, Again, the ratio maps are quite supportive of the results of Table 6. Note that the irrigation effect is the weakest during August as indicated in Table 6, and that the effect is spread rather uniformly over the three primary irrigation regions during Summer, which is also indicated in Table 6.

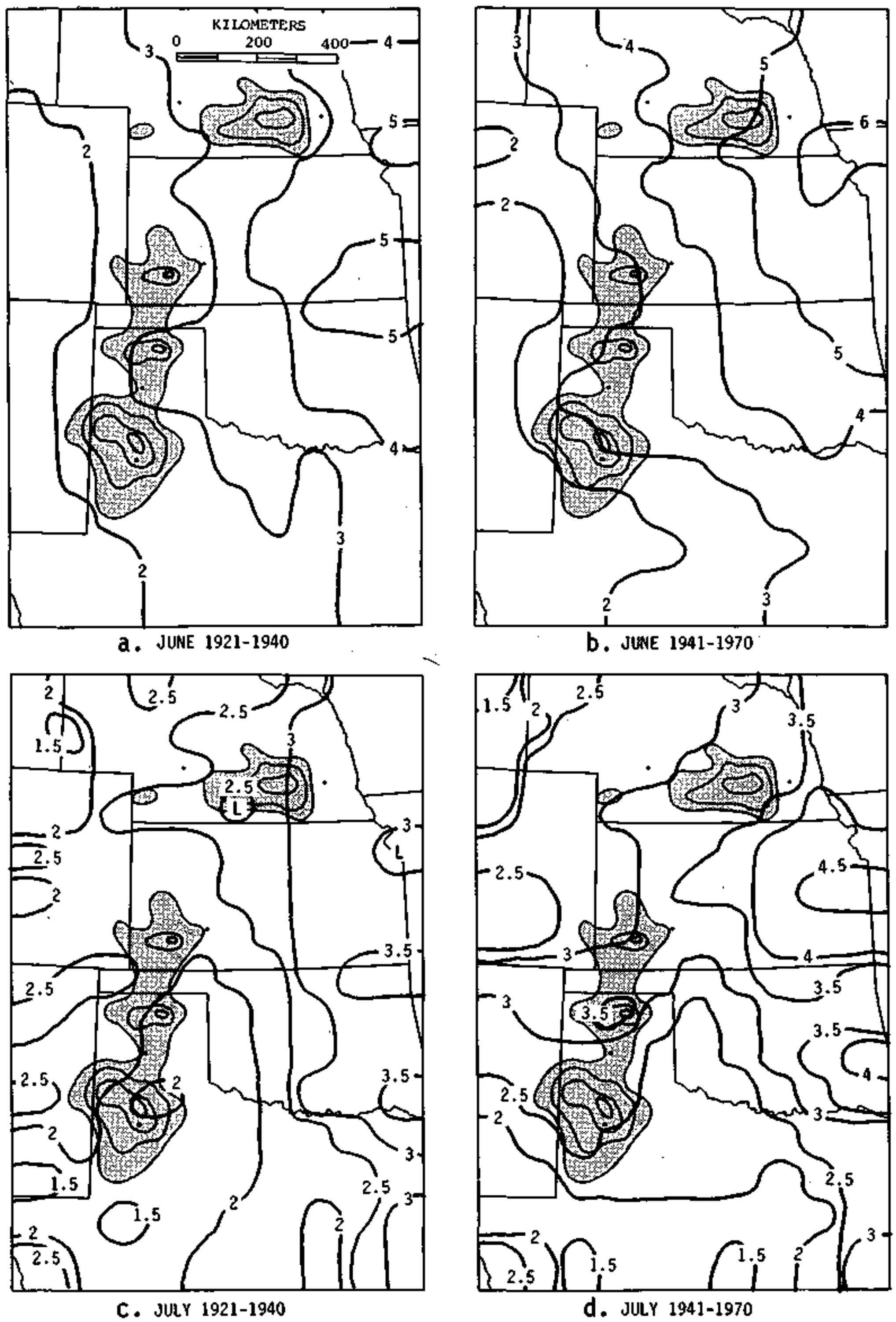


Figure 24. The average rainfall patterns before irrigation (1921-1940) and during irrigation (1941-1970) for June and July (rainfall in inches).

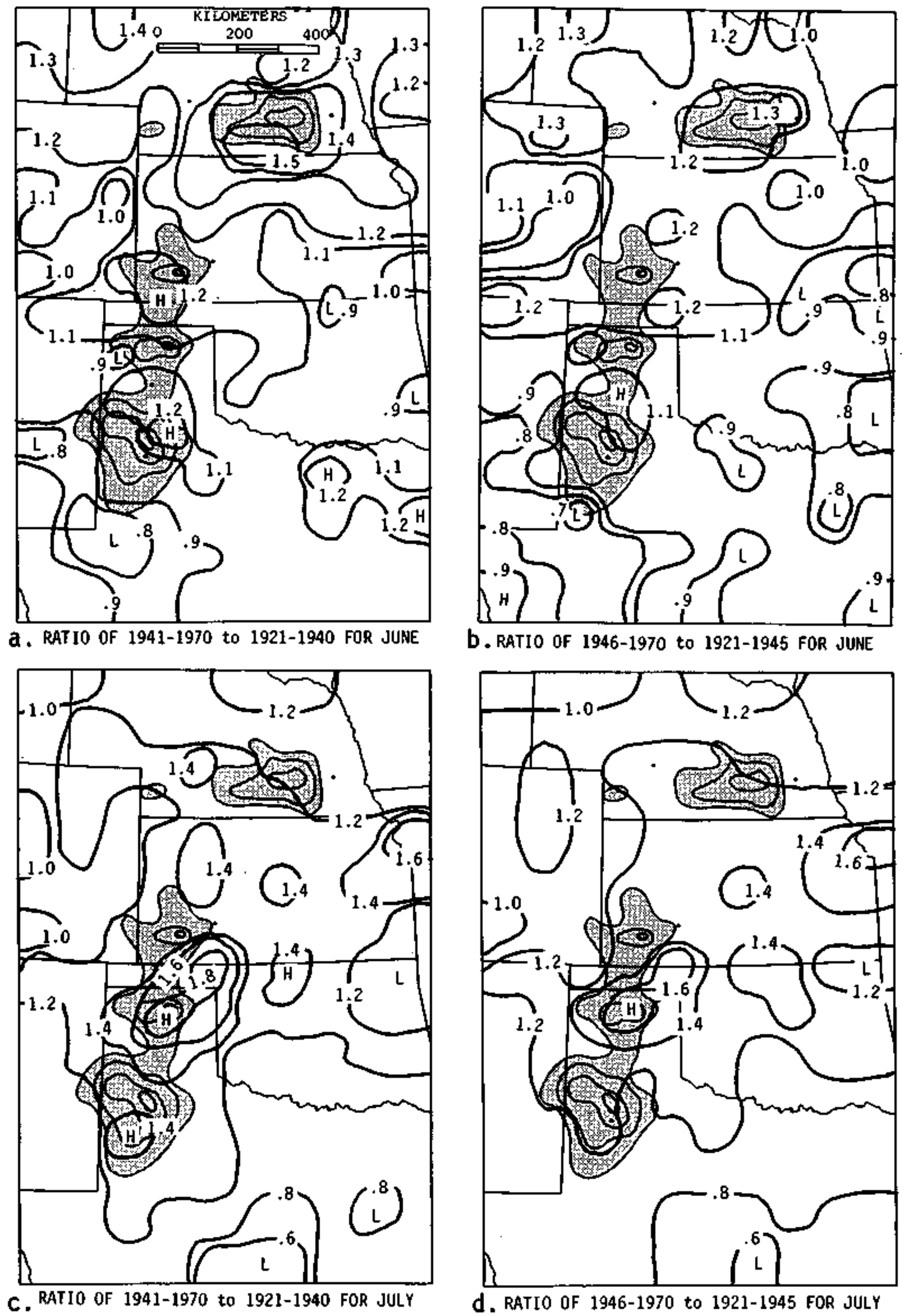


Figure 25. The ratio comparison patterns for June and July (irrigated months) based on division points of 1940 and 1945.

It was shown on Figure 6 that there were positive rainfall trends in the vicinity of the irrigated areas in all three months and during the summer season. This was in direct contrast to the spring and fall months in which the positive rainfall trends were clearly absent from the irrigated regions (Figure 7). Since the irrigation is slight during these months as compared to the summer months, these findings are strongly supportive of an irrigation effect during the summer months. Since consistency of results in the various analyses is crucial for the verification of the irrigation effect, strong evidence would be forthcoming if the ratio anomalies on Figures 25 and 26 were absent from the spring and fall patterns. Consequently, the ratio comparison maps for these months were determined based on the 1940 division point and are presented on Figure 27. There is a clear-cut absence of anomalies in the irrigated regions during the spring and fall months. This finding illustrates considerable consistency between the various analyses which have been presented and adds greatly to the substantiation of the irrigation effect.

The joint use of Table 6 and Figures 25 and 26 provides a method of assessing and describing the magnitude and extent of the irrigation effect. Figures 25a, 25c, 26a, and 26c show that the percent effect is the strongest in Texas and Oklahoma during July, strongest in Kansas during August, and strongest in Nebraska during June. Clearly,the magnitudes and locations of these effects in the individual months are averaged in the overall summer pattern. That is, the individual monthly patterns contain anomalies which are higher in magnitude and more isolated in location than those of the summer pattern, This is illustrated by the broad general high which extends from the southern portion of the Texas irrigated region to the northern portion of the Nebraska irrigated region.

The broadness of the summer effect area throughout the general irrigated region is also reflected on the 40-year trend patterns of Figure 6 and on the 40-year summer rainfall pattern of Figure 4. This feature is further reflected in Table 6 where the percent effect is distributed rather uniformly over the various target areas and varies from 16 to 19 percent in those areas which have significant t-ratios. (The areas of ET3 and E3 are not significant in the summer pattern because of the error involved in delineating the small variable areas during the individual months, and the subsequent masking of the effects in the overall summer patterns.)

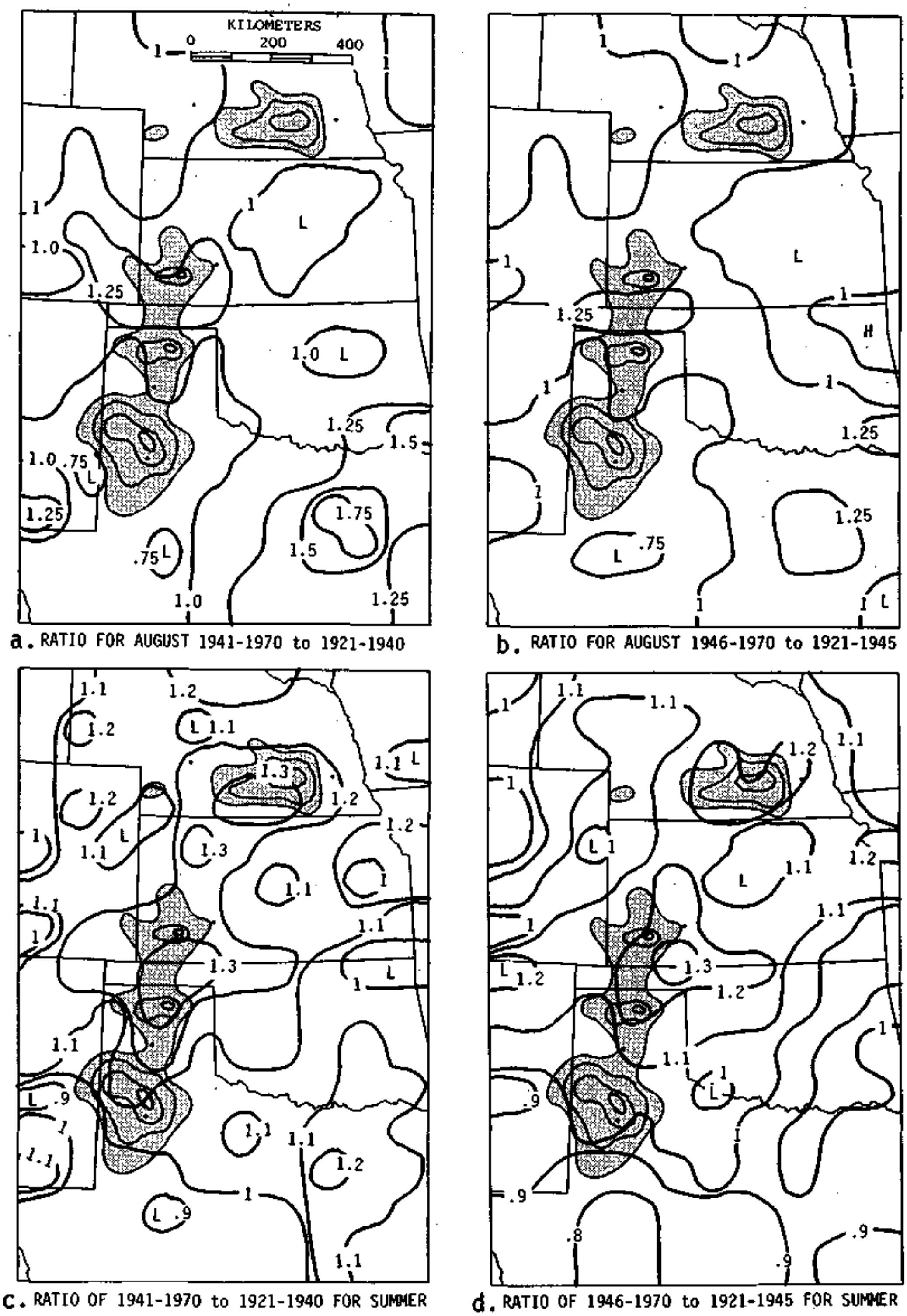


Figure 26. The ratio comparison patterns for August and Summer (irrigated months) based on division points of 1940 and 1945.

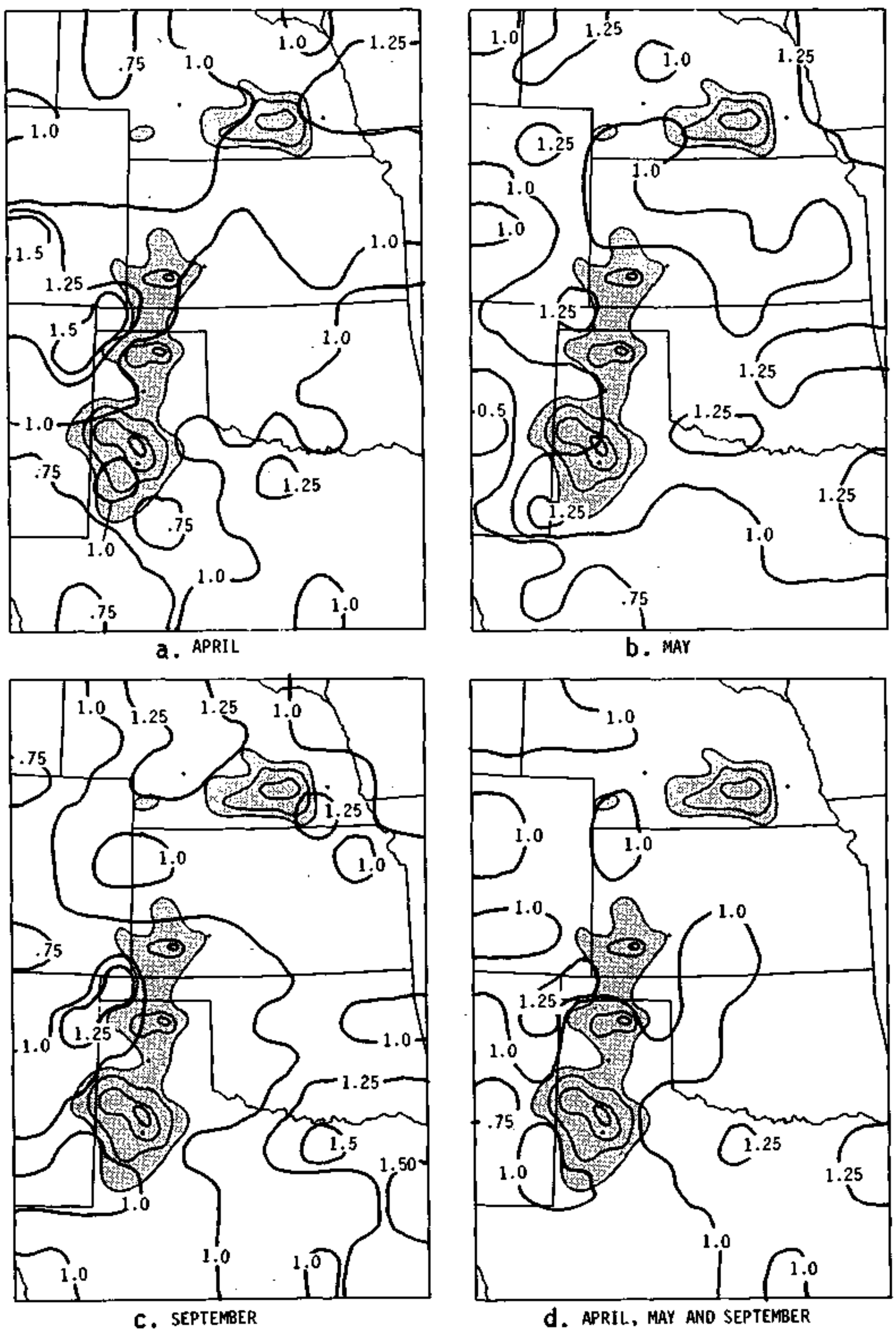


Figure 27. The average ratio comparison patterns for non-irrigated months based on the division point of 1940.

For Texas (ET areas) the percent effect varies from 5 to 13% during June, and 39 to 75% during July according to the target level being considered (Table 6), and there is no effect during August. For Kansas (EK areas) the effect varies from 11 to 13% in June, 36 to 38% in July, and 12 to 19% in August. For Nebraska (EN areas), the effect varies from 27 to 38% in June, 2 to 5% in August and none in July. (These percentages agree generally with Joos (1969) who found 10-40% increases throughout the overall irrigated area.) Thus, the effect appears to be the largest in Texas and Kansas during July, and the largest in Nebraska during June.

However, the magnitude of the effect can not be assessed from percent figures alone. Since the areal extent of the effect varies from region to region, the areal extent must also be taken into consideration. The final assessment of the rain increase using the areal extent, percent increase, and total rain volume is the subject of the next section.

Assessment of the Magnitude and Areal Extent of the Rain Increase

The areal extent was determined for each target area and the resulting values, along with the corresponding percent increase values, are tabulated in Table 7. Considering the first level target area, the areal extent is the greatest in Texas during July (101,000 mi^2), in Kansas during August (94,000 mi^2), and in Nebraska during June (72,000 mi^2). For the overall irrigated region, the areal extent is the greatest in June (169,000 mi^2) and July (169,000 mi^2). In regard to states, the areal extent of the effect is greatest in Texas (101,000 mi^2) and Kansas (94,000 mi^2).

For comparison purposes, the areal extent of the 10-, 20-, and 30- percent irrigated areas are listed in the last column on Table 7. During individual months, the first-level target areas are at least two times and are occasionally as much as 10 times as large as the 10-percent irrigated regions. In contrast, the first-level target areas during summer are never larger than four times the 10-percent irrigated region.

Since the largest percent increase does not necessarily occur in the largest effect area, it is necessary to make another assessment based on the rain volume. Thus, the average volume in acre-ft was computed for each target

Table 7. Assessment of the magnitude and areal extent of the effect.

Target level	Areal extent of effect (10^3 mi^2) June	July	August	Summer	Areal extent of irrigated region (10^3 mi^2)
			Texas		
First	68(5)*	101(39)	none	65(15)	28(10)**
Second	36(6)	54(48)	none	36(15)	14(20)
Third	18(13)	11(75)	none	11(10)	8(30)
			Kansas		
First	29(11)	68(36)	94(13)	29(18)	9(10)
Second	11(13)	25(38)	65(12)	14(19)	9(20)
Third	none	11(38)	32(19)	none	1(30)
			Nebraska		
First	72(27)	none	40(4)	68(18)	11(10)
Second	47(30)	none	25(2)	11(16)	6(20)
Third	14(38)	none	11(5)	none	2(30)
			Total		
First	169(16)	169(37)	134(9)	162(16)	48(10)
Second	94(20)	79(44)	90(9)	61(16)	22(20)
Third	32(25)	22(54)	43(15)	11(10)	11(30)

* percent effect

** percent of land area irrigated

area (see Table 8). In all cases, the rain volume decreases as the target level increases. This occurs because higher-level target areas are smaller than the lower-level target areas. (See Figures 16-19). Even so, there is still more than 1.0 million acre-ft of effect in the third-level target areas over the total irrigated region during June.

It was mentioned previously that the method used to obtain the summer target areas differed from the method used to obtain the monthly target areas. This was attributed to the variation in the location of the effect from month to month and the mixture of dry, moderate, and wet conditions during the summer. As a result of these factors, the summer target areas had to be delineated using only the second and third level target areas from the individual months. This caused some of the effect to be excluded from the summer target areas. Therefore, the percent comparisons in Table 6 for Summer do not include all of the effect.

Nevertheless, the t-ratios were large, which indicates that the summer comparisons are significant even when part of the effect is excluded. However, the total effect on rain volume can be obtained more conveniently by simply adding up the rain volumes from the individual months. The estimates of rain volume presented in Table 8 were obtained in this manner, rather than from the summer target areas. In this way, all of the summer effect could be obtained.

If one considers the first-level target areas, the effect on total rain volume is the greatest in Texas during July (4.2 million acre-feet), in Kansas during July (3.4 million acre-feet), and in Nebraska during June (4.1 million acre-feet). In the overall region, the greatest effect occurs in July, a lesser effect occurs in June and the smallest effect is noted in August. *These results are strongly supported by the ratio comparison patterns of Figures 25 and 26.* Hence, the validity and usefulness of the analysis of covariance to estimate the magnitude of the effect is also verified.

In contrast, there is no effect in Texas during August or in Nebraska during July. The effect is weak in Texas during June, in Kansas during June and in Nebraska during August. The weakness of the effect in these states and months is generally supported by the analysis of covariance of the 1921-1970 data (note the asterisks in table 8). Also, these results are also strongly supported by the ratio comparison patterns of Figures 25 and 26.

Table 8. Assessment of the average rain volume associated with the effect.

Target level	June	Rain volume (10^6 acre-ft.) July	August	Summer
		Texas		
First level	.5	4.2*	none	4.7*
Second level	.4	2.7*	none	3.1*
Third level	.4	.8*	none	1.2*
		Kansas		
First level	.5	3.4*	1.5	5.4*
Second level	.2	1.3*	1.0	2.5*
Third level	none	.6*	.7*	1.3
		Nebraska		
First level	4.1*	none	.3	4.4*
Second level	3.0*	none	.1	3.1*
Third level	1.1*	none	.1	1.2
		Total		
First level	5.1*	7.6*	1.8	14.5*
Second level	3.6*	4.0*	1.1	8.7*
Third level	1.5*	1.4*	.8*	3.7

* The analysis of covariance for the 1921-1970 data indicated that the percent effects in these areas were significant.

With regard to the overall summer pattern, the effect is nearly the same in all three states, with average volumes ranging from 4.4 to 5,4 million acre-ft. The total effect over the entire region during summer is 14,5 million acre-feet.

It is of interest to compare the amount of effect to the amount of water applied by irrigation. The Texas Water Development Board (1971) has published detailed information on the amount of water applied per county in Texas during the years 1958, 1964, and 1969. Using these data, the total water applied within the 10% irrigated area in Texas (Figure 1) was determined to be 4.9 million acre-feet in 1958, 7.3 million acre-feet in 1964, and 6.0 million acre-feet in 1969. The average amount applied per year was 6.1 million acre-feet.

The average effect is 4.7 million acre-ft per year in the Texas area, or about 77% of the amount of water applied. This result is clearly supportive of the author's earlier assertion that any increased rainfall does not come directly from the increased moisture alone, but from thermodynamic and physical side-effects produced by the cool, moist dome over the irrigated area. This result is also in agreement with McDonald (1960) and Stidd (1967), who stress the importance of dynamic processes in addition to the increased supply of evaporable water. The possible role of dynamic and physical processes is expounded upon in the next section.

One final point should be made before leaving this section. There has been considerable analysis and discussion concerning the potential increase in rainfall due to irrigation. Is there any evidence that this potential rain increase caused a decrease in the regions surrounding the irrigation effect areas? This is an extremely difficult question since the concept of target and control areas is based on the assumption that the rainfall in the control areas is unaffected by the effects of irrigation in the target areas.

However, the control means listed in Table 2 and 5 provide considerable insight into the answer for this difficult question. It is noted that the differences between irrigated and non-irrigated period means range from -7% to 5% (i.e. ratios range from .93 to 1.05). Furthermore, differences for the analysis based on the division point of 1940 (Table 5) range from -2% to 5% (ratios range from .98 to 1.05). These differences are quite small, and hence there is little evidence for a decrease in the control area due to increased rainfall in the target areas.

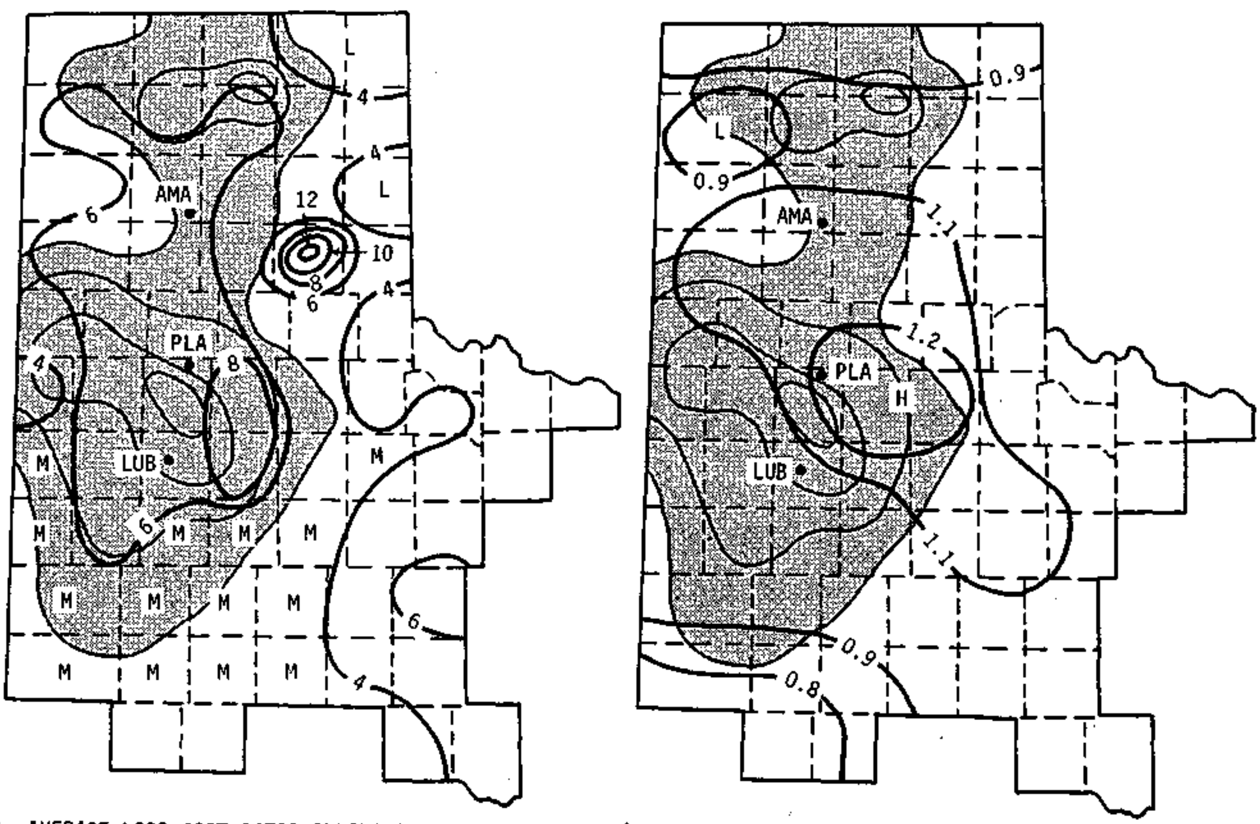
DELINEATION AND EXPLANATION OF THE IRRIGATION EFFECT USING OTHER FORMS OF WEATHER DATA

It is useful to investigate other forms of weather data for the purposes of 1) verifying whether the irrigation effect is also present in these data, and 2) explaining the mechanisms operative in producing the rain increase. Temperature data are useful for these purposes since the density of temperature reporting stations is still approximately one-half that of rainfall reporting stations. Crop-insurance loss data are useful because of their areal coverage, but are limited in that the amount of liability is often low in the area of interest. Unfortunately, other forms of weather data are severely limited in their usefulness due to the limited density of their reporting stations. The stations that are available are often located outside the monthly target areas. This is particulary true of the hail-day, thunderstorm-day, cloud, dewpoint, wind, and sounding data. Therefore, it is difficult to assess the influence of irrigation on these forms of data. However, a limited investigation was made of these data to determine whether they are generally supportive of the irrigation effect and to help explain the cause of the rain increase.

The crop-insurance data for the crop reporting districts of the High Plains and Low Rolling Plains in the Texas Panhandle were used to obtain the average loss-cost (LC) ratio during the period 1941-1973. (The data from the years prior to 1941 were not used because of generally lower liability during these years). The average LC pattern is shown on Figure 28a. (Those counties with limited liability or none at all have been designated with a M).

There is a general high (6 isoline) throughout the irrigated area with an inner maximum (8 isoline) immediately east of Plainview (PLA) and Lubbock (LUB). This maximum is very close to the core of the heavily irrigated region. There is also an intense maximum outside the general high and NE of the core of the heavily irrigated region.

Since June is the only irrigated month during the hail season of April-June, it is of interest to compare the hail loss pattern to the June rainfall pattern. The pattern of the June rainfall ratio of 1941-1970 to 1921-1940 is shown on Figure 28b for comparison purposes.



a. AVERAGE LOSS COST RATIO DURING 1941-1973

b. JUNE RAINFALL RATIO OF 1941-1970 TO 1921-1940

Figure 28. A comparison of hail damage with the ratio comparison patterns of rain in the Texas Panhandle during June.

The hail maximum in the Lubbock-Plainview area coincides with the maximum in the ratio rainfall pattern. The intense hail maximum is located NE of the inner maximum in the rainfall pattern, but it is within the overall rainfall maximum. Thus, there are indications that the irrigation effect is also present in the crop-insurance data. However, the results must be treated with extreme caution due to the lack of liability over much of the area and the general high in the insurance data on the eastern portion of the map.

As a further test of the hail data, the hail-day data from Lubbock and Plainview, two stations near the inner maximum of the LC pattern, were investigated. The average number of hail-days for the periods 1921-1940 and 1941-1969 were determined for the non-irrigated months of April and May and for the irrigated month of June. The monthly averages and the ratio of the latter period to the earlier period for each month are tabulated in Table 9.

Table 9. The average number of hail-days before and during irrigation and the ratios of during-to-before averages.

Period	April	May	June
		Plainview	
1919-1940	.59	1.05	.73
1941-1969	.48	1.45	1.48
ratio of during to before	.81	1.35	2.03
		Lubbock	
1919-1940	.50	1.32	.41
1941-1969	.48	1.38	1.03
ratio of during to before	.96	1.05	2.51

The average number of hail-days during the irrigated period is much greater than the average number during the non-irrigated period for the month of June. For Plainview the average number of hail-days is also greater during the irrigated period than during the non-irrigated period, but the ratios of during-to-before are much less than they are for June. Thus, the number of hail-days is much greater during irrigation than before irrigation in June, an irrigated month. Very little could be deduced from these data alone, but when used in conjunction with the crop loss and rainfall data, they are generally supportive on an overall irrigation effect.

These results are also supported by Henderson and Changnon (1972), who found a 100% increase in hailfalls in the 1940's in the west Texas region. Also, the results of Beebe (1974),who reported a maximum in dew point temperatures and tornado frequencies over the same heavily irrigated region of Texas, are further supportive of the concept that the irrigation effect occurs in the presence of major synoptic activity.

Much has been said in this report about the role of major synoptic activity in producing the irrigation effect. However, convergence and the subsequent lifting of the surface air that occur at surface low pressure centers and at frontal interfaces are not the only processes by which surface air can be transported upward. Local phenomena can achieve the same result, and can determine whether or not the synoptic mechanisms are able to be effective in producing irrigation-related rainfall.

It has been mentioned previously that an unstable temperature lapse rate could be expected to be a contributing factor in getting surface air to rise to a height at which condensation could occur. Does irrigation enhance the development of an unstable lapse rate? The answer to this and other important questions of the microdynamics can be partially approached by considering the anomalous conditions in the irrigated area during the dry period before a thunderstorm day. Thus, an initial hypothesis to be tested is: There is a lowered maximum daily temperature in the irrigated region due to the expenditure of evaporative latent heat.

However, it was considered important to first investigate whether an anomaly of colder temperatures existed over the irrigated region under average monthly conditions. Consequently, the ayerage monthly temperature patterns for July 1931-1945 and 1946-1970 were determined for the Texas-Oklahoma- New Mexico region and are shown on Figures 29a and 29b.

A comparison of the average pattern for the two periods clearly shows that a temperature anomaly developed during the 1946-1970 (irrigated) period. This anomaly should be most prominent in the non-effect rainfall years since those years were generally drier throughout the irrigated region, and more evaporative cooling would be realized under these conditions. The ratio pattern of the non-effect years during 1946-1970 to all years during 1931-1945 is shown on Figure 29c.

During rainfall effect years, there is more rainfall through the general vicinity of the irrigated area, so the anomaly might not be as prominent. Also, during a rainfall effect year, additional rainfall is deposited in the effect areas. This additional rainfall might bring about cooler temperatures in these areas. The ratio pattern of the effect years during 1946-1970 to all years during 1931-1945 is shown on Figure 29d.

As suspected, the temperature anomaly is more clearly delineated in the non-effect ratio pattern than in the effect ratio pattern. Although there is still an anomaly in the irrigated region, the lowest part of the anomaly has shifted NE to the vicinity of the July rain effect area (See Figure 25c). Therefore, even under average monthly conditions, there is a suggestion that the temperature anomaly will be more prevalent during hotter and drier periods. This is due to the fact that the evaporation rate will maximize during these periods.

Verification of the daytime surface cooling effect was further accomplished by Barnston (1976) using daily temperature data from the Texas irrigated region. Barnston selected periods of prolonged hot, rainless conditions and then averaged the maximum temperatures within each period for all available stations in the area shown on Figure 28. Five periods of dry, hot days were used in June and July. These periods had a typical duration of six days, although a somewhat cooler day would occasionally interrupt some of the periods. The results of associated pattern analyses clearly showed a maximum temperature deficit of 3 to 5 degress F over the irrigated region.

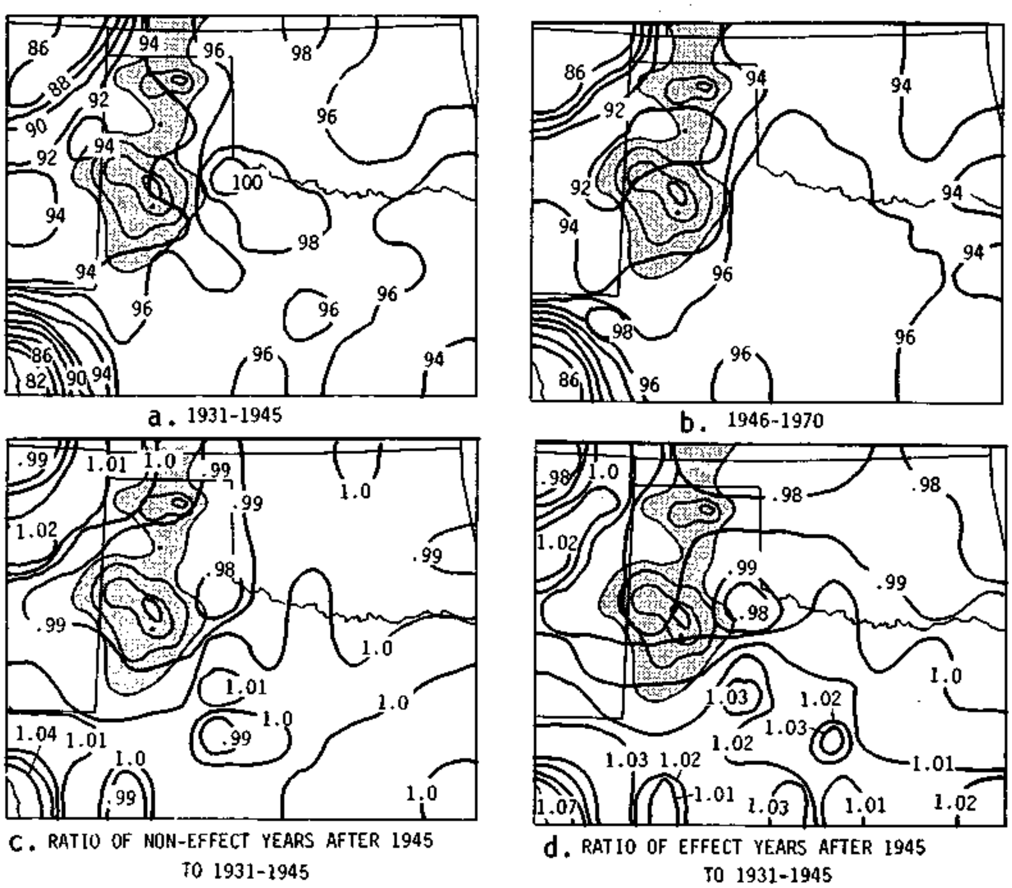


Figure 29. Average temperature patterns for irrigated (1946-1970) and non-irrigated (1931-1945) years and selected ratio comparison patterns during July (temperature in F on a and b).

Correspondingly, it might be expected that there would be a buildup of low-level moisture resulting from the evaporation of irrigation water during these periods. To determine if this excess moisture is particularly conducive to rainfall patterns in the irrigated region, Barnston analyzed the rainfall from storms immediately following each rainless period. The rainfall from these storms was quite light and did not appear to be related to the irrigation. Since most of the effect years during each month are generally wetter than the non-effect years in the irrigated regions and their environs, they do not generally contain prolonged periods of rain-free weather. Consequently, these results are consistent with the conclusion that irrigation's influence should be the greatest during the wetter years of each month,

Since the irrigation effect occurs during generally wetter conditions, it also occurs during times of minimal temperature anomaly. The expected magnitude of the temperature anomaly during days that were cooler and more moist than the ones used in the hot, dry periods was approximated by Barnston using relationships between evaporation rate, kind of water surface, the surface-to-air vapor pressure gradient, and the average wind speed over the surface. Using values typical of cooler, more moist days in the Texas Panhandle, Barnston found that the temperature anomaly would be expected to be approximately 2°F on these days as compared to 3 to 5 degrees F on the hotter, drier days. Consequently, the temperature anomalies would be expected to be about 2^{o} F during effect conditions.

This raises the important question: "What sub-synoptic mechanism can account for increased precipitation over irrigated land when relatively little excess moisture per unit time is ingested into the atmosphere?" The answer appears to involve stability. When the lapse rate is stable, the excess moisture generally rises no more than several tens of feet above the surface. Barnston points out that this is a known fact for lake-induced moisture, and would pertain to moistened earth as well as to water surfaces. During periods of hot, dry days, none of the evaporated moisture has the chance to rise to the. . cloud condensation level. It then follows that an increased amount of moisture would often fail to affect weather other than at the immediate surface. When an unstable lapse rate exists, any upward-moving parcel would continue to rise until the lapse rate stabilizes sufficiently. During such circumstances, any additional moisture at low levels has the potential to produce greater cloud water (ie. greater cloud development) and, hence, a greater amount of precipitation.

Barnston analyzed several unstable soundings during two June effect years, 1962 and 1963. Expected dry-weather anomalies of dew point and temperature were modeled by linearly tapering them vertically so that they reduced to zero at the destination height of a dry rising air parcel. The dewpoint at the surface was assumed to be 6 degrees F higher than it would be without irrigation (Beebe, 1974) and the temperature was assumed to be 3 degrees lower than it would be without irrigation. Hypothesized soundings were then calculated for the non-irrigated condition, given the unstable soundings of the effect years. The lifted index was then calculated for the "irrigated" and "non-irrigated" soundings.

The lifted index was found to be 1 degree C lower for the irrigated condition than for the non-irrigated condition. The temperature anomaly accounted for a 0.4°C change in the lifted index (higher stability for irrigated condition) and the dewpoint anomaly accounted for a 1.4°C oppositely-signed lifted index change (lower stability for irrigated condition). The net change of 1°C on the lifted index is indicative of a slight alteration in stability. The fact that the actual temperature and dewpoint anomalies during storm conditions are likely to be considerably less than the dry weather values used above makes the stability change one half as large. Barnston concluded that the expectation from a slightly reduced index is that, once in a while, a noticeably greater amount of rain would occur, or some rain would occur which otherwise would not. These analyses apply to the cases when the ground-to-cloud base lapse rate is unstable for a sufficient time duration for the surface air to mix upward to the cloud base, and also when the additional moisture bears directly on the nucleation and drop growth processes.

Other aspects of the dynamic situation which might be affected by the presence of irrigation could certainly enhance the possibility of rain over the sounding alone. However, dynamic aspects such as reduced wind speed (Burman et al, 1975) due to a dome of cooler air over the irrigated region, or convergence on the windward side of the dome are difficult to verify due to the sparsity of available data. Also, the land-sea breeze effect due to temperature gradients on the periphery of the irrigated area (Gatz and Schickedanz, 1975) is difficult to verify. Any of these aspects could lead to subsequent vertical motion resulting in additional vertical motions in convective clouds.

Nevertheless, available cloud, dewpoint, relative humidity, wind, and thunderstorm-day data were compared during and before irrigation to ascertain whether the dynamic changes suggested above could be shown in these data. June and July data from Amarillo, Abilene, and Lubbock, Texas, and Roswell, New Mexico were used in the analyses.

In general, the results did not show increases at Amarillo and Lubbock relative to the control stations of Roswell and Abilene. The exceptions to this statement were increases in relative humidity at Lubbock and Amarillo during July, and an increase in thunderstorm-days at Lubbock. There was also an increase in cloudy days at Lubbock and Amarillo relative to Abilene during the irrigated period, but there was also an increase in cloudy days at Roswell. Clearly, a more dense network of reporting stations is required to verify the suggested dynamic influences on irrigation.

Initially, it was planned to apply spectral methods to the long-term records of several meteorological variables from the four stations. The spectral methods of Schickedanz and Bowen (1975, 1976) were applied to a limited number of variables. However, the results were once again inconclusive because of the sparsity of reporting stations. Thus, any further analyses of long-term stations in Kansas and Nebraska were not pursued.

SUMMARY AND CONCLUSIONS

The research reported on in this report was directed toward the question of whether the extensive irrigation in the Great Plains has had an appreciable effect on the climate of the region. The primary specific objective of the research was to examine for a rainfall anomaly due to irrigation and, if so, to measure the magnitude of the effect. A second objective was to investigate other associated weather variables for supportive relationships which could also be used to help explain the physical causes.

The basic study region included the states of Kansas, Nebraska, and a large portion of the state of Texas. In addition, some data from the states of Colorado, New Mexico, Wyoming, Iowa, Missouri, and South Dakota were used for extra-area control purposes. A climatic investigation of monthly rainfall patterns during the period 1931-1970 indicated rainfall anomalies in the vicinity of the irrigated regions during the irrigated months of June, July, and August. Major rainfall anomalies were also present in the overall Summer (June-August) rainfall pattern. On the other hand, there was little evidence of rainfall anomalies in the non-irrigated months of April, May, and September.

An investigation of the rainfall trend patterns during the same period indicated upward trends in the vicinity of the irrigated regions during June, July, August, and Summer. In contrast, the trend patterns for the non-irrigated months indicated either no trend or downward trends in the vicinity of the irrigated regions.

The multivariate statistical technique known as factor analysis was used to separate the effect of irrigation from the climatic variability of rainfall over time and space. This was accomplished by selecting criteria for the existence of the irrigation effect and then implementing the factor approach to determine the "irrigation factor." The criteria selected for the "irrigation factor" were that the scaled eigenvectors (factors) must have a significant time trend and that the corresponding principal components (or principal factors) must have large values in and around the heavily irrigated areas, which are dependent on the temporal forcing functions.

It was discovered that the criteria for the irrigation factor could not be satisfied during the months of April, May, and September. However, the criteria could be satisfied for the summer months. This resulted in the delineation of an irrigation factor for June, one for July, and one for August. These results provided strong evidence for irrigated-related anomalies during the irrigated months, but provided no evidence for irrigated-related anomalies during the non-irrigated months.

The application of the temporal eigenvectors indicated that the irrigation effect has occurred in all summers since 1945 with the exception of 1954, an extremely dry summer. However, associated rainfall increases did not occur in every year in the individual months. For the month of June, 15 of 25 years after 1945 had potential increases, while for July and August, the number of years with potential increases were 18 and 13, respectively. There was a tendency for the irrigation effect to either 1) occur in the wetter months as opposed to the drier months over the general study area, or to 2) occur when the rainfall conditions were somewhat wet in the general vicinity of the target area.

The spatial patterns of the principal components (or principal factors) were used to delineate target and control areas associated with the irrigated . regions in Texas, Oklahoma, Kansas, and Nebraska. The target and control areas were delineated for each of the summer months and for the summer season. The average areal rainfall for each of the target and control areas was determined for each year of the summer months and for each year of the summer season during 1931-1970. In order to obtain a greater number of non-irrigated years, the areal averages were also determined for the years 1921-1930, These areal averages formed the primary data series used in determining the magnitude and significance of the irrigation effect on rainfall.

The temporal mean rainfalls for the periods before and during irrigation were then determined for each of the target and control areas. The analysis of coyariance was then used to adjust the irrigated and non-irrigated period means in the target areas for differences in the control means; that is, it was used to adjust the irrigated and non-irrigated period means in the target areas to be estimates of what they would be if the irrigated and non-irrigated period means in the control were the same. Thus, the adjustment is made to allow for natural climatic differences in the study region.

The analysis of covariance was used to search for differences between the period means of 1931-1945 and 1946-1970. The analysis showed that the target rainfall was greater than control rainfall during the irrigated period (.19.46-1970),. and that the rainfall during the irrigated period was greater than the rainfall during the non-irrigated period (1931-1945) in the target area. The percent rain increase associated with the irrigation effect varies from 14 to 26% in June, 57 to 91% in July, 15 to 26% in August, and 19 to 35% during Summer, depending on the location of the effect and the size of the target area.

Since some irrigation did occur during the 1941-1945 period, the use of 1945 as the division point to separate irrigated and non-irrigated years caused some irrigated years to be placed in the non-irrigated years category. The data from 1921-1930 were not used in the factor analysis, the delineation of target and control areas, and the initial comparisons. These data were not on a quality level with that of the period 1931-1970 because there were fewer reporting stations in the 1920's.

However, the need for rainfall data during more non-irrigated years to compare to that of the irrigated years outweighed this disadvantage, and rainfall data for 1921-1930 were used in the final assessment of the magnitude and areal extent of the effect. These earlier years were particularly needed to verify than the rainfall increase after 1945 was not simply due to the abnormally dry 1930's.

The addition of these years to the analysis led to a diminishment of the effect, in some areas and months, but in general, the addition was generally supportive of a rain increase due to irrigation. For Texas the percent effect varies from 5 to 13 percent during June, and 39 to 75% during July according to the location of the effect and the size of the target area. There was no effect during August. For Kansas, the effect varies from 11 to 13% in June, 36 to 38% in July, and 12 to 19% in August. For Nebraska, the effect varies from 27 to 38% in June, and from 2 to 5% in August. There was no effect in July. (These percentages generally agree with those of Joos (1969), who found 10 to 40% increases throughout the overall irrigated area). Thus, the percent effect appears to be the largest in Texas and Kansas during July, and the largest in Nebraska during June.

The areal extent of the effect was the greatest in Texas during July (101,000 mi^2), in Kansas during August (94,000 mi^2), and in Nebraska during June (72,000 mi^2). For the overall irrigated region, the areal extent was the greatest in June (169,000 mi^2) and July (169,000 mi^2). In regard to states, the areal extent of the effect is the greatest in Texas (101,000 mi^2) and Kansas (94,000 mi^2).

Since the largest percent increase does not necessarily occur in the largest effect area, it was necessary to also make an assessment based on rain volume. The effect on average rain volume per year was the greatest in Texas during July (4.2 million acre-ft), in Kansas during July (3.4 million acre-ft.), and in Nebraska during June (4.1 million acre-ft). In contrast, there is no effect in Texas during August or in Nebraska during July, The effect was weak in Texas and Kansas during June and in Nebraska during August.

With regard to the overall Summer rainfall pattern, the effect was nearly the same in all three states, with average volumes ranging from 4.4 to 5.4 million acre-ft. The total effect over the entire region during summer was 14.5 million acre-ft.

Using crop insurance loss-cost data for Texas, a hail maximum was found near the core of the heavily irrigated region (Lubbock-Plainview area) which coincides with an irrigated-related maximum in the rainfall pattern. The average number of hail-days in the same area was much greater in June, an irrigated month. Because of the lack of liability in some areas, and the sparseness of the hail-day reporting stations, it was difficult to draw a conclusion from the hail data by itself. However, when used in conjunction with the rainfall data, they were generally supportive of an overall irrigation effect.

Average monthly temperature patterns for July 1931-1945 and 1946-1970 showed that a temperature anomaly developed over the Texas irrigated areas during the 1946-1970 (irrigated) period. This temperature anomaly appeared to be more prevalent during hotter and drier periods.

In conclusion, the analysis of rainfall trend maps, the factor analysis, the analysis of covariance, and the ratio comparison patterns produce strong evidence for irrigation effects in Nebraska during June, in Texas and Kansas during July, in Kansas during August, and in all three states during Summer.

The evidence is much weaker in Kansas and Texas during June, and in Nebraska during August. The evidence is weaker because the t-ratios associated with the analysis of covariance are insignificant. Nevertheless, the presence of these weaker effects are supported by the other analyses. Finally, there is no indication for irrigation effects in Texas during August, nor in Nebraska during July.

DISCUSSION

There are several mechanisms which could produce greater low-level cloud activity and, subsequently, greater rainfall in the vicinity of irrigated areas. It would appear that the most likely candidate is the "land-sea breeze effect", which may occur along the temperature gradient between irrigated and non-irrigated areas. The temperature gradient could be caused by the presence of early-morning cloudiness, but this is not a necessary condition. As noted in this report, the temperature in the irrigated regions can be lowered as much as 5°F. This would be sufficient to set up the land-sea breeze circulation along the boundary between irrigated and non-irrigated areas. This could lead to ascending motions and, eventually, to cumuliform clouds and more rain at the surface. It further seems likely that the increased precipitation would occur in the temperature gradient on the downwind side of the irrigated area. This assumes that a portion of the moisture-laden air over the irrigated area is advected downwind so that the air lifted by the land-sea breeze mechanism would be more moist than air on the upwind side.

Thus, it is hypothesized that any increased rainfall does not come directly from the increased atmospheric moisture alone, but by thermodynamic and physical side effects produced by the presence of a cool, moist dome over the irrigated area. This is in agreement with McDonald (1960) and Stidd (1967), who stress the importance of dynamic processes in addition to the increased supply of evaporated moisture.

The presence of a temperature anomaly over the irrigated area was verified by both monthly and daily temperature data. The monthly data indicated that the anomaly was more prevalent during hotter and drier periods due to the fact that the evaporation rate is at a maximum level during these periods. The daily data indicated that the temperature anomaly was on the order of 3 to 5°F during dry, hot, rainless days, and about 2 to 3°F during cooler and more moist days.

Certainly, other mechanisms are possible. One such mechanism could be a reduction in wind speed resulting from a dome of cooler air over the irrigated region. Convergence on the windward side of the dome, as well as the general increase in water vapor, may play some role in the increase in rainfall over this area. In regard to the latter, expected anomalies of dewpoint and temperature were modeled and were used to determine the effect on unstable soundings during the irrigated years.

Results showed the lifted index to be 1°C lower for unstable soundings based on the temperature and dewpoint anomalies (irrigated condition),as compared to unstable soundings in the absence of the anomalies (non-irrigated condition). The fact that the actual temperature and dewpoint conditions during storm conditions are likely to be considerably less than those used in the modeling makes the probable stability change about half as large. The expectation from a slightly reduced lifted index is that, once in a while, a noticeably greater amount of rain would occur, or some rain would occur which otherwise would not.

It has been demonstrated that there has been an increase in the rainfall in and surrounding the irrigated regions during the same period that the growth of irrigation has occurred. It has also been demonstrated that this increase has occurred, in all summers since 1945 with the exception of 1954. Certainly, any of the above mechanisms could contribute to the rain increase. However, this increase has not occurred in every year in the individual months. The issue of why these mechanisms should only be operative during selected months, and consequently only produce rain increases during selected months, is clearly a question that should be addressed. We now turn our attention to this important question.

In the summary it was noted that there was some tendency for the irrigation effect to either 1) occur in the wetter months as opposed to the drier months over the study area, or to 2) occur when the rainfall in the general vicinity of the target area is generally heavy. Thus, it would appear that for the irrigation effect to be present, a general level of synoptic activity must be present. This premise is strongly supported by studies of synoptic conditions associated with the irrigation-related anomalies.

These studies indicated that synoptic conditions which provide low-level convergence and uplift were fundamental in allowing irrigated-produced low-level moisture to increase cloud development and rainfall. Stationary fronts were found to be particularly crucial in producing irrigated-related rainfall. Cold fronts were also important, but the magnitude of irrigated-related rainfall was not as great in this case as it was with stationary fronts.

Consequently, it would appear that the reason for the irrigated mechanism to only be operative during selected months is dictated to a large degree by the general synoptic conditions. Unstable synoptic conditions seem to produce the "trigger" whereby small changes in meteorological conditions in the vicinity of irrigated regions can lead, perhaps only after a whole chain of subsequent physical processes, to redistribution or enhancement of precipitation.

STUDENT PERSONNEL, SCIENTIFIC PAPERS, AND ORAL PRESENTATIONS

Two undergraduate students from the University of Illinois were employed during the course of this investigation. The students were Madeleine D. Korfmacher and Joanne M. Corbett. In addition, Anthony G. Barnston was employed as a graduate research assistant during most of the research period. His efforts on the project resulted in a Master's Thesis which was submitted in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Science at the University of Illinois. This thesis is entitled <u>The Influence of Irrigation on Warm Season Precipitation in the Southern Great Plains,</u> and a copy is being submitted to RANN along with this final report.

A paper summarizing preliminary results from the irrigation project was presented at the Symposium on Arid Lands Irrigation in Developing Countries at Alexandria, Egypt, in February, 1976. This paper was entitled "Influence of Irrigation on Precipitation in Semi-Arid Climates" and was published in the Proceedings of the Symposium. In addition, an oral presentation of the preliminary results was made at the First Annual Meeting of the Midwestern Region of American Geophysical Union, Madison, Wisconsin, in September, 1975. Moreover, a seminar was presented at the Atmospheric Sciences Department, University of Missouri, Columbia, Missouri in December 1975.

At least one paper summarizing the final results from this project will be submitted to the Journal of Applied Meteorology for publication.

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