Irrigation-Induced Rainfall and the Great Plains

NATHAN MOORE AND STUART ROJSTACZER

Center for Hydrologic Science, Division of Earth and Ocean Sciences, Duke University, Durham, North Carolina

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ABSTRACT

The post–World War II increase in irrigation in the Great Plains represents the largest human-induced hydrologic impact in North America. Drawn primarily from the High Plains aquifer, water applied as irrigation in the region amounts to billions of cubic meters (2×10^{10} m^3 in 1990) annually and is applied to more than 60 000 km^2 of farmland. Following studies by Schickedanz and by Barnston and Schickedanz, empirical orthogonal functions and precipitation magnitude comparisons were employed to examine trends in precipitation over the region and to determine if this enormous addition of irrigation water to the surface has had a measurable influence on precipitation during the summer months of June, July, and August.

The Barnston and Schickedanz study observed a transition from unirrigated to heavily irrigated conditions; in contrast, this examination focused on a more recent period during which irrigation took place throughout the time of interest. Loading patterns and temporal precipitation trends for 1950–97 show, at best, slight evidence that irrigation induces rainfall. The most prominent evidence of an irrigation effect is found in the Texas Panhandle for 1950–82. If irrigation-induced rainfall exists, its impact is only minor relative to the natural determining factors of plains climate. It also is possible that the chief influence of irrigation on rainfall may take place at some threshold magnitude of irrigation (not explored in this study) that already had been exceeded by 1950.

1. Introduction

The influence of human activities on climate and weather has aroused abundant discussion and research within the global change community. From studies of the effects of deforestation and burning on the climate in Amazonia (e.g., Jonquieres and Marenco 1998) to the desertification of the Sahel due to overgrazing (Charney 1975) and the ''heat island effect'' of cities, researchers have looked at land use change in areas ranging from urban locations to the most remote edges of agricultural activity. Previous theoretical and observational studies have explored various local climate impacts due to land use alteration by agricultural activities. Yan and Anthes (1988), Mahfouf et al. (1987), Ookouchi et al. (1984), and Segal et al. (1988) studied sharp contrasts in surface vegetation characteristics, including effects from large irrigated areas in semiarid regions. These contrasts in land cover induce strong horizontal gradients in surface heat fluxes, which trigger mesoscale circulation and provoke convective precipitation. Large hydrologic perturbations, such as water mining in the Aral Sea for irrigation, were studied by Small et al. (1999), and Rabin et al. (1990) have analyzed cloud formation–landscape interactions in the plains of Oklahoma. All these diverse efforts have sought to determine both past human influences on climate and future consequences of land modification.

Climate change also raises concerns about its potential effects on agriculture, a subject that becomes more pressing as the world population swells to more than six billion. Agriculture in the Great Plains supplies the United States with more than \$16 billion of crops annually (National Agricultural Statistics Service 1998), making this breadbasket crucially important to the nation and the world.

Much of the Great Plains under cultivation is irrigated, primarily drawing on the High Plains (Ogallala) aquifer (Fig. 1). Since World War II, irrigation has transformed the region and has given rise to the largest human-induced hydrologic disturbance in North America. During the 1940s, approximately 7500 km^2 of land were irrigated with water from the High Plains aquifer. By 1980, this had expanded to more than 60 000 km^2. This alteration of the hydrologic cycle in the region has added approximately 2×10^{10} m^3 of groundwater annually to the surface and has approximately doubled the amount of water available for evapotranspiration.

Barnston and Schickedanz (1984) made a statistical analysis of warm-season precipitation and irrigation data in the Texas Panhandle region of the Great Plains and found a roughly 25% increase in precipitation associated with irrigation over and near the irrigated areas over the time period of 1931–70. They also observed

Corresponding author address: Nathan Moore, Center for Hydrologic Science, 103 Old Chemistry Bldg., Duke University, Durham, NC 27708.
E-mail: njm@duke.edu

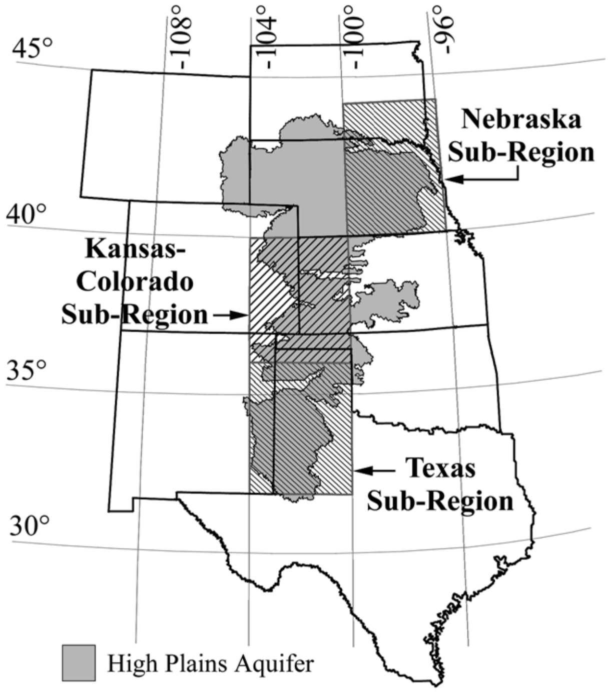

FIG. 1. Map of the study area showing the location of the High Plains aquifer and regions undergoing irrigation that are examined.

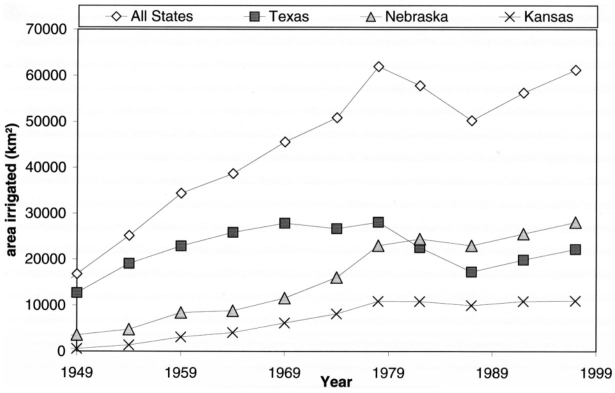

FIG. 2. Irrigated land in Texas, Kansas, and Nebraska, 1949–97.

that surface temperatures may have been lowered by as much as ~2°C by irrigation. The fundamental mechanism driving this change is offered in a study in the Sudan by Hammer (1970), who theorized that a "dome" of cool, moist air would develop over a heavily irrigated area; this dome would cause convergence at the windward boundary, lifting air and assisting cloud formation. With an increase in cloud formation, precipitation events could be triggered more often and for a longer duration.

The Barnston and Schickedanz study surveyed precipitation changes from a period of virtually no irrigation to a period of historically very intense irrigation (1931–70). The change owes its origins to the development of the submersible pump and the availability of inexpensive energy, which allowed full access to the High Plains aquifer by farmers throughout the Great Plains. By examining this hydrologic change, Barnston and Schickedanz were able to observe climate changes in the region as it was transformed from dry land to irrigated agricultural land.

By 1970, innovations in water conservation were being applied, first with sprinkler systems and later with subirrigation and low-energy precision application systems. Improved irrigation methods became widespread by 1990, reducing the amount of water applied to the surface. These changes to irrigation water use were accompanied in the 1980s by a shift to monoculture of cotton, a crop that demands less water (~100 mm less) than corn and has a different schedule of water demands. Some land was also converted to rangeland during the decade. Together, these factors led to a decrease both in water use and in irrigated acreage. Here, we examine whether changes in land use and irrigation over the time period of 1950–97 have altered precipitation patterns in the Great Plains region.

2. Available data and methods

a. Crop, irrigation, and precipitation data

Although irrigation water is not applied in a regular, periodic pattern, application is scheduled to avoid water stress on the crops during critical points in growth (i.e., boot, heading, and flowering). In the High Plains region of north Texas, these critical growth points for the most common crops (corn, cotton, and sorghum) fall in the months of June through August. The optimum seasonal water use for corn falls between 710 and 810 mm and for cotton is approximately 685 mm (Sweeten and Jordan 1987).

Corn is the predominant crop in eastern Nebraska; most irrigation water for corn in this region is applied from July to late August. Cotton, the major irrigated crop in north Texas, usually receives most of its irrigation water in early to midbloom (June–early July) and

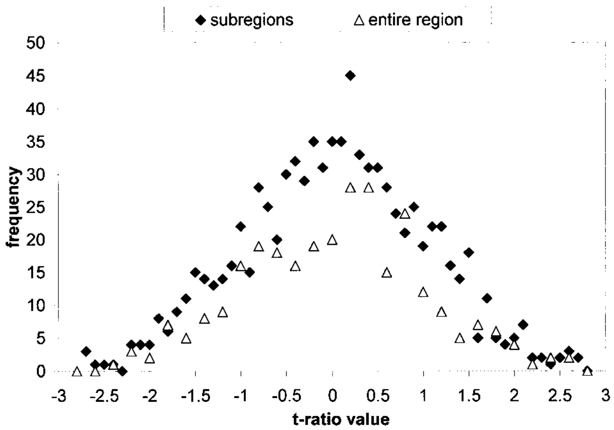

FIG. 3. Histogram of t ratios for all eigenvectors, with values for the entire region and for the subregions shown separately. A value of 1.5 was used as the criterion for significance.

again from peak to late bloom (mid August). The fastest increase in irrigation usually occurs during June. Some light irrigation is applied for preplanting in April–May and for winter wheat in September–October; harvesting falls in October and November.

In western Kansas and eastern Colorado, the predominant irrigated crop is corn. Planting usually begins in early May, and irrigation water is applied most intensively from late June to August.

Given the irrigation schedules for the crops noted above, June, July, and August are treated as ''irrigated months,'' and April, May, and September are treated here as ''nonirrigated months.'' Records of acres irrigated by county were obtained from the U.S. Census of Agriculture for individual states over the time period of interest. These agricultural surveys have been conducted roughly every 5 years (Fig. 2). As a result, only long-term changes in irrigation patterns and their influences can be examined.

Most precipitation in the Great Plains occurs during the warm season months of April–September. In general, rainfall patterns in the region show a decrease of precipitation from east to west and from the Gulf of Mexico to the north. Mean annual precipitation in the Texas High Plains is approximately 500 mm. Monthly rainfall data by county for 1950–97 were obtained from the National Climatic Data Center in Asheville, North Carolina (http://www.ncdc.noaa.gov/ol/climate/climatedata.html), for 6632 gauging stations in the region. Inverse distance–weighted linear interpolation was used to create a uniformly spaced dataset for each year. This method was used instead of kriging (which is also a weighted interpolation) to preserve local contrasts in precipitation better; kriging minimizes error variance, but it also tends to obscure smaller, confined areas of higher precipitation and make detection of the effect more difficult.

b. Empirical orthogonal functions (EOFs) and principal components analysis

In this study, we use EOFs to identify statistical precipitation patterns during the 1950–97 period, which are used for comparison with irrigation patterns. EOFs are representations of data (associated with principal components analysis and eigentechniques) that are used for examining trends in statistical patterns (see appendix). Here, we obtained the temporal principal components (eigenvectors) by performing a varimax rotation without commonalities.

Following the approach used in the Barnston and Schickedanz (1984) and Schickedanz (1976) studies, a distance-weighted linear interpolation (higher weights for closer points) was made using rainfall records for stations throughout the Great Plains. From these data, $m \times n$ matrices of standardized variates were constructed ($m = 4636$ points $\times$ $n = 48$ yr). These matrices were used to calculate the principal components and eigenvalues. Principal components (eigenvectors) for each month (May–September) were calculated first for the entire Great Plains region and subsequently for three smaller, heavily irrigated subregions: the Texas Panhandle, eastern Nebraska, and western Kansas/eastern Colorado. Components that had eigenvalues less than unity were discarded; the remaining components were used to produce spatial loading patterns of rainfall. We also plotted the time series of these components (eigenvectors) and fitted a regression line to them to determine if changes in rainfall had occurred over the period of interest for each particular month.

The criteria for selecting the irrigation-induced principal component for a given month were 1) the presence of a significant positive temporal trend and 2) a loading pattern that showed large precipitation anomalies over and around the heavily irrigated areas (spatial congruity). Significant temporal trends were determined from the principal component loadings based on the value of the standard error and a summary t-ratio statistic defined by

$$t = \frac{r}{S_r} = r\left(\frac{n - 2}{1 - r^2}\right)^{1/2}, \qquad (1)$$

where S_r is the standard error in the regression line, r is the regression coefficient, and n is number of years. Although the years are not randomly selected, this statistic can still be used as an arbiter of distinction between significant and insignificant trends. This sampling statistic can be applied to the data because they can be viewed as either a single stochastic result of many possible rainfall patterns or as a set of spatially resampled values.

Following the method of Schickedanz (1976), we treated populations with t ratios above 1.5 as significant, selecting loadings that exceed the standard error by at least 50%. The spatial congruence criterion was met if some part of the precipitation loading pattern with a loading greater than 1 covered 4000 km^2 and was at least partly overlapping a region with at least 20% of its area irrigated.

In addition to the period of 1949–97, we also examined the 33-yr period of 1949–82 for the Texas Panhandle. This region experienced a tremendous increase in irrigation until the early 1980s, after which irrigated acreage declined to some extent because of a switch to monoculture cultivation of cotton.

c. Comparison of precipitation magnitudes in irrigated and nonirrigated regions

In addition to the principal components analysis, we also looked directly at changes in the magnitude of precipitation over the study area and the study period. To do this, we calculated the mean precipitation values for the irrigated months in areas defined by the fourth loading pattern for June and the fifth loading pattern for July and August. Only loading patterns for the entire plains region were examined. These particular loading patterns tended to exhibit spatial congruity and thus indicated where we would expect to see a stronger irrigation effect if it exists.

The regions with loadings greater than 1 were classified as ''target'' areas, and regions with loadings between -0.5 and $+0.5$ were classified as ''control'' areas. Mean precipitation in the control and target areas was then calculated for a low-irrigation period (1951–60) and for a high-irrigation period (1981–90). These various means were compared to detect any significant changes in precipitation magnitude coinciding with the irrigation-affected areas. Because irrigated acreage approximately doubled from 1954 to 1984, an increase in precipitation magnitude would be expected.

To remove bias resulting from one decade being generally wetter (or drier) than another, the mean precipitation in a target area is normalized by the mean precipitation in the control area. We call this normalized parameter the target:control ratio. To account for the general east–west and Gulf–inland precipitation gradients present, the mean precipitation during the 1980s is divided by the mean precipitation during the 1950s for each target area and for the control area. We term this parameter the heavily irrigated years:lightly irrigated years (HIY:LIY) ratio.

3. Temporal trends and spatial comparisons

a. Analysis of the entire plains

Our approach to identifying irrigation-induced precipitation is admittedly only weakly rigorous. A given month would have 8 or 9 principal components (out of 48) that were associated with eigenvalues greater than unity. Of the eight or nine principal components for each month, we sorted out those that had positive time trends as determined by *t* ratios; a histogram of *t* ratios in Fig. 3 shows their distribution. A *t* ratio of 1.5 was used as the criterion for determining the significance of the loading pattern. Of course, factors other than irrigation could cause these changes in precipitation. We also note that the presence of spatial congruity between the loading patterns for the principal components identified is not sufficient to prove the existence of an irrigation effect. This work simply tries to identify where irrigation potentially influences local precipitation.

In general, the first and second principal components for each month exhibit the two strongest spatial precipitation trends (loading patterns) in the Great Plains: the ''wet east–dry west'' pattern and the ''wet Gulf of Mexico–dry interior'' patterns. Because of the strength of these orographic effects, first and second principal components were generally ruled out as irrigation-effect candidates even if they demonstrated significant *t* ratios. These orographic effects were also present in the subregional loading patterns.

Table 1 lists the principal components (eigenvectors), *t* ratios, and spatial agreements of the best candidates for an irrigation effect. Positive *t* ratios represent an increase in precipitation over time, and negative *t* ratios represent a decrease over time. In contrast to the findings of Barnston and Schickedanz (1984), we find few instances of temporal increase in precipitation for our time period of interest (Fig. 4). Several significant precipitation trends are negative and, in some cases, correspond to a pattern of anomalously low precipitation.

Spatial loading patterns of the best candidates for an irrigation effect are given in Fig. 5. Irrigated land for 1978, the most intensely irrigated year on record, is also displayed for comparison. For the entire region, we observed that only the fifth principal component of August satisfied all the criteria for an irrigation effect and has only modest spatial similarities with irrigation patterns. No other significant positive trends were detected during the irrigated months that also had spatial congruence. Note that the fourth principal component for September (a nonirrigated month) satisfied the temporal test and had some spatial correspondence to the irrigation pattern. Several significant negative trends in precipitation were located in and around the irrigated areas (an ''inverse'' pattern) for other vectors, notably July, implying a suppressive effect rather than an enhancing one. Entekhabi et al. (1992) and Brubaker and Entekhabi (1996) have inferred a suppressive effect via a wet mode–dry mode climate fluctuation due to land–atmosphere feedbacks and water recycling.

Although every qualifying loading pattern was located ''over and around'' an irrigated region to some degree, the alignment was often vague. Precipitation component analysis for the Great Plains as a whole indicates that, for the period of interest, evidence for significant irrigation-induced rainfall is lacking except perhaps for August. In addition, patterns with spatial congruity (with the exception of August and September) have insignificant positive temporal trends or even negative temporal trends. A simple comparison of selected precipitation patterns and irrigated areas of the Great Plains from 1949–97 could be viewed, at the time of writing, on the Internet (http://www.eos.duke.edu/grad/jv_ss.html).

b. Analysis of subregions of the Great Plains

Irrigation schedules differ from region to region and most notably from crop to crop. It is expected that an irrigation-induced rainfall response, if it exists, will also vary in accordance with these differences; consequently, evidence for such a response should be more apparent in a smaller region where crop types and irrigation schedules are more consistent from year to year and throughout the area. Barnston and Schickedanz (1976) confined their study to the southern Great Plains and focused on the intensely irrigated Texas Panhandle. To get a more refined picture, we applied the EOF analysis to this area as well as to western Kansas/eastern Col-

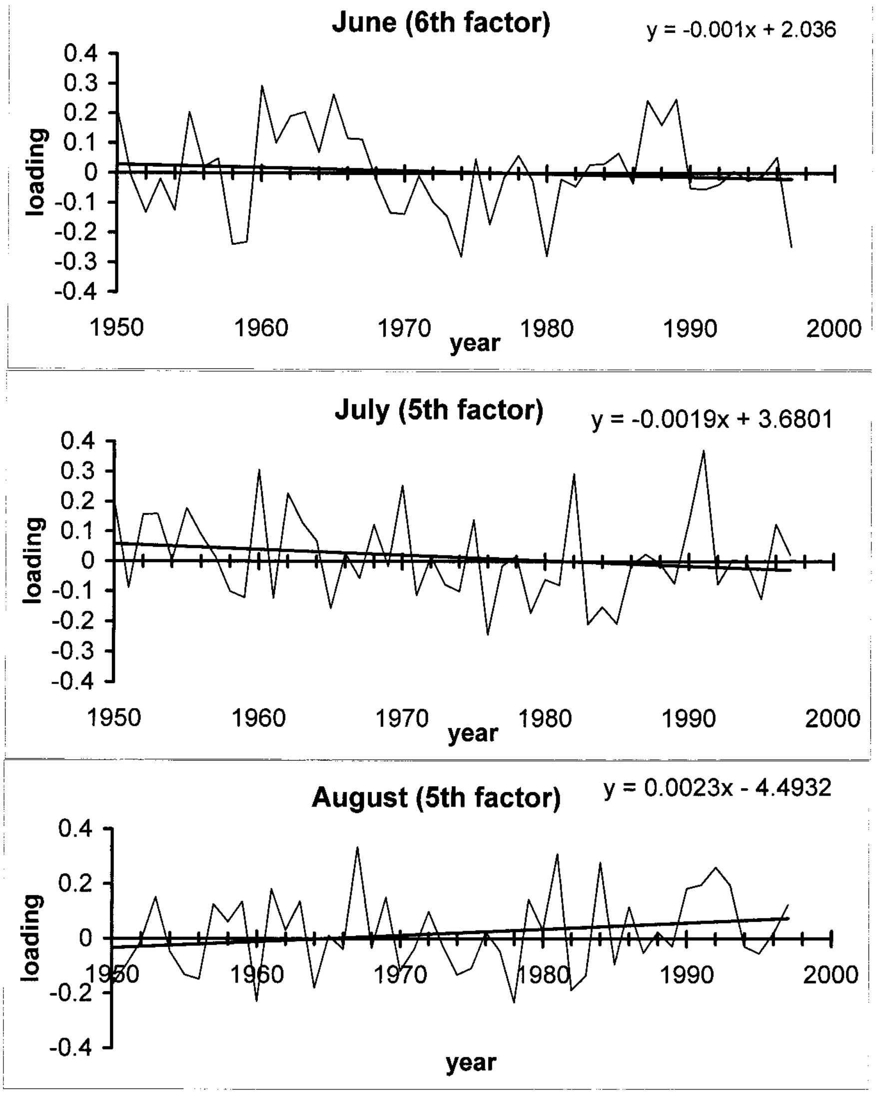

FIG. 4. Examples of precipitation loadings and trends for the entire plains region, 1950–97.

orado and eastern Nebraska/South Dakota. These areas are delineated in Fig. 1.

1) TEXAS PANHANDLE SUBREGION

When the Texas Panhandle time series is examined as a whole, irrigation effects are not significant. Time series for this subregion yield only slight indications of an irrigation effect. The seventh principal component for May (a nonirrigated month) met the temporal and spatial qualifications, but none of the irrigated-month loading patterns met both criteria. The third principal component for June, shown in Fig. 6, shows close spatial congruity but fails to exhibit a statistically significant *t* ratio for the 1950–97 period. These findings are notably different from those of the Barnston and Schickedanz study, which found a very clear and significant result for the period of 1931–70 in the southern plains area. No components with a positive *t* ratio showed a suppressive effect in the same manner as the July tenth principal component for the entire region.

Again, as with the entire Great Plains, each of the three irrigated months displayed a loading pattern that met the spatial congruity criterion, but each failed to have a significant temporal trend. The absence of a pronounced trend, particularly for June (the month of maximum cotton irrigation), may have resulted from changes in irrigation water use and the types of crops grown in the Texas High Plains in the past 30 yr. This raises the possibility of precipitation decreases due to a decline in irrigation water use. Have more efficient water application methods and decreased irrigated acreage curtailed the irrigation-induced precipitation identified by Barnston and Schickedanz?

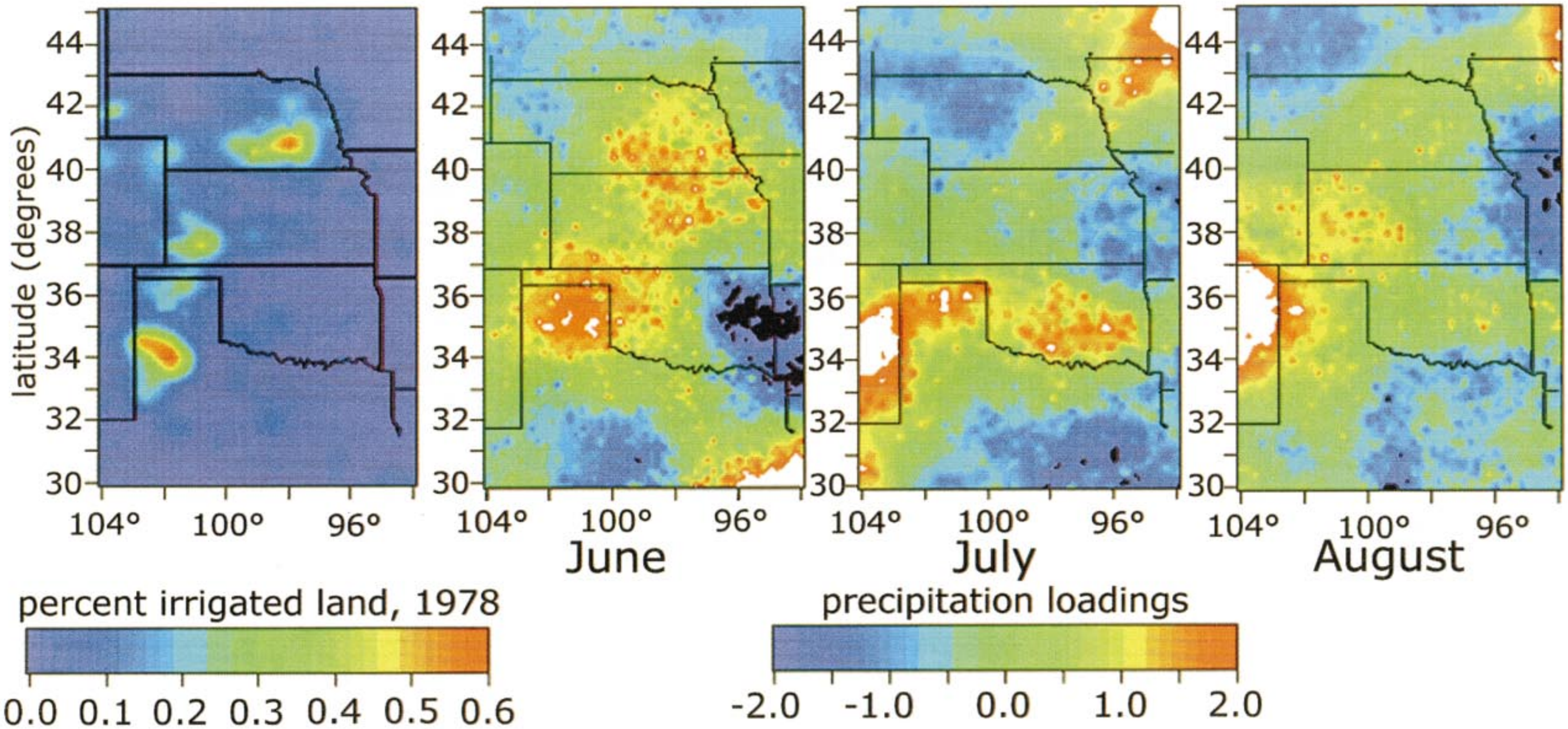

FIG. 5. Irrigated land and principal component loading patterns for irrigation effect candidates for the entire plains region. White areas signify precipitation loadings greater than 2. The three factors shown are the sixth, fifth, and fifth loading patterns for Jun, Jul, and Aug, respectively. The factors shown for Jun and Aug do not exhibit a significant *t* ratio but do meet the spatial criterion. These three loading patterns are used to define target and control areas in section 3c.

TABLE 1. Principal components with relatively significant t ratios and their relationship to irrigation. Components in parentheses failed the t-ratio test but show spatial agreement with the irrigation patterns for irrigated months.

Month	Loading pattern	t ratio	Overlay
Entire region			
Apr	1	1.67	No
May	7	1.13	Yes
(Jun)*	6	−0.67	(Yes)
Jul	10	−1.98	Inverse
(Jul)*	5	−0.17	(Yes)
Aug	5	1.54	Yes
Sep	4	2.15	Yes
Eastern Nebraska			
Apr	6	2.2	No
May	5	1.01	Yes
Jun	5	−1.95	Inverse
(Jun)	4	−0.1	(Yes)
Jul	5	1.27	Yes
Aug	7	2.05	No
Sep	4	1.84	No
Western Kansas			
Apr	7	1.86	No
May	3	0.93	Yes
Jun	3	1.64	Yes
Jul	4	−1.72	Inverse
Aug	10	1.86	No
Sep	6	2.55	No
Texas Panhandle			
Apr	4	−1.04	Yes
May	7	1.8	Yes
(Jun)	3	−0.73	(Yes)
Jul	3	1.66	No
Aug	4	2.34	No
Sep	8	2.55	No
Texas Panhandle (1949–82 only)			
Apr	5	−1.2	Yes
May	6	1.37	No
Jun	3	1.51	Yes
(Jul)	2	−1.21	(Yes)
(Aug)	5	−0.95	(Yes)
Sep	5	1.2	No

* Components used in magnitude comparison.

To explore this possibility, data for the Texas Panhandle were subjected to another EOF analysis for the years of 1949 (first postwar irrigation records) to 1982 (the ''high-water mark'' of intense irrigation in Texas High Plains). This analysis removes the effects of declining water use and decreased irrigated acreage that took place in the 1980s. The results of this short-period EOF analysis mimicked the results of the Barnston and Schickedanz study more closely. The third principal component for June is compared with the longer period principal components in Fig. 6. Barnston and Schickedanz found an irrigation effect for Texas manifest in June and July but not in August. Our short-period analysis found that although the fifth principal component for August and the second principal component for July had t ratios less than 1.5, both were at least greater than 0.9. Though insufficient to meet the criterion of 1.5, these lesser t ratios represent a modest positive temporal trend. Moreover, all three irrigated months satisfied the spatial condition. June's third principal component demonstrated particularly close spatial congruence and was the strongest irrigation-effect component overall. All three months had components for the period of 1949–97 that showed spatial correspondence but failed to show a persistent temporal increase (they had lower t ratios). Principal components analysis was not carried out for the years of 1983–97 because the time period encompassed a decline in irrigated acreage of only about 20% and covered too short a duration to have meaningful significance.

2) WESTERN KANSAS SUBREGION

Farms in western Kansas/eastern Colorado irrigate the least amount of acreage among the three subdivisions that this study examined. No significant principal components were found for July and August, but the third principal component for June satisfied the selection criteria (Fig. 7). Once again, the only significant July component with a positive t ratio (the fourth) exhibited an inverse spatial correspondence to (or suppressive effect on) the irrigated area. The third principal component for May overlays the irrigation area well but fails the temporal trend condition. Preplanting irrigation for corn would typically occur during early May, but this lower level of application (combined with lower irrigated acreage density) is apparently not influential enough to induce a convincing trend. Evidence for an irrigation-induced rainfall effect is limited to the June data.

This subregion was the only one failing to show spatial agreement in at least one loading pattern for each month, regardless of t ratio values. Because this subregion has comparatively lower levels of irrigation, it may fail to exhibit any irrigation-induced precipitation effect. The Barnston and Schickedanz study noted the distinctly lower irrigation densities here and did not address possible effects; however, Schickedanz (1976) identified a small effect in July and a minimal effect (on the order of 10%) for June and August.

3) NEBRASKA SUBREGION

More aggressively irrigated than the western Kansas subregion, eastern Nebraska shows stronger evidence for an irrigation effect in July and August (Fig. 8). Schickedanz (1976) found the primary irrigation effect to be in June for Nebraska with virtually no effect in August and none in July, but our EOF analysis for the period produced contrary results: no significant trends for June and only a weak temporal trend ($t = 1.27$) for the fifth principal component for July. The seventh principal component for August demonstrated the strongest temporal trend and was the only component to satisfy both criteria despite poor spatial agreement. As with the

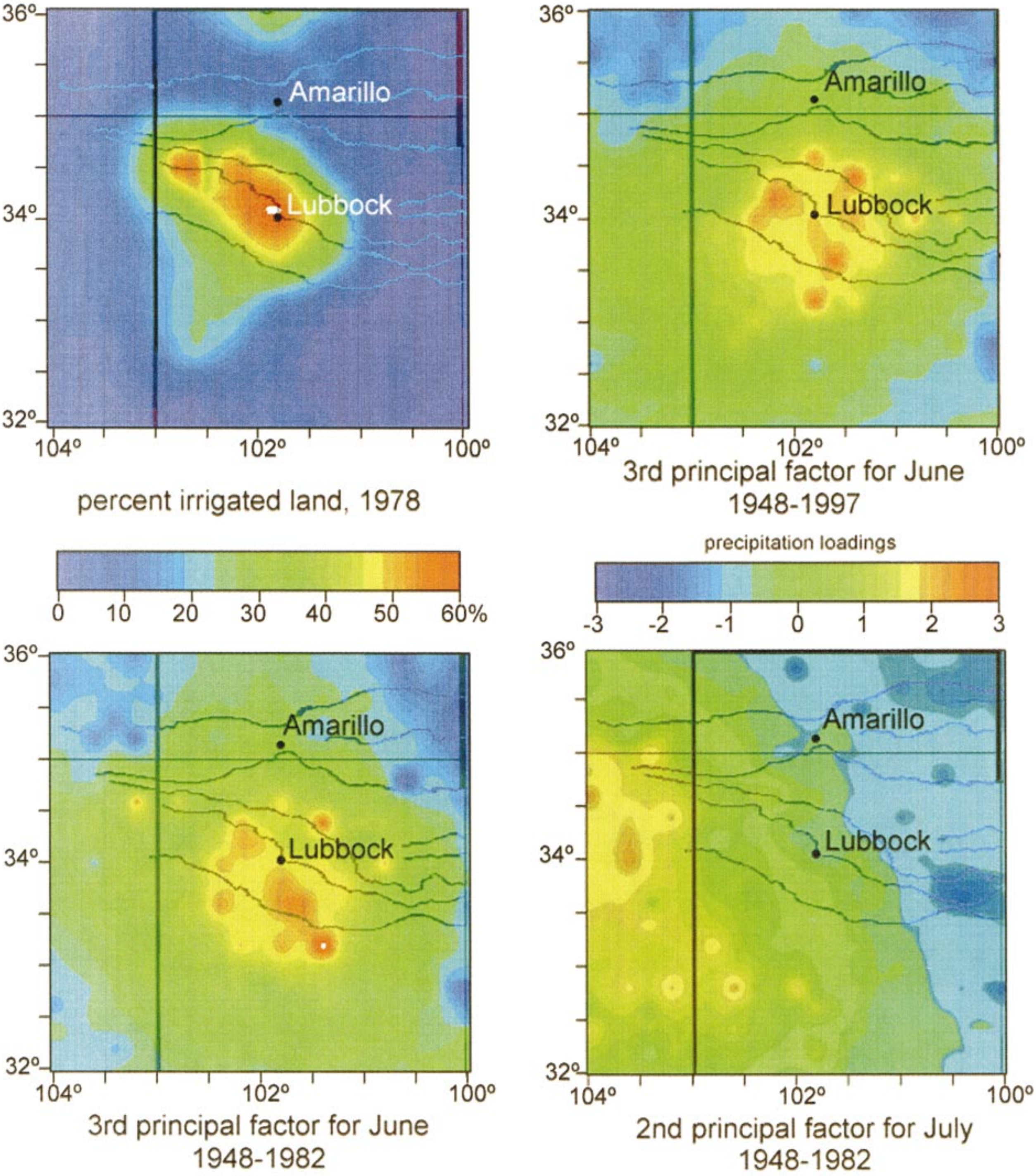

FIG. 6. Irrigation and precipitation patterns for the Texas Panhandle subregion, 1950–97.

Texas Panhandle and the region as a whole, at least one loading pattern met the spatial test, and, once again, a significant inverse loading pattern was discovered (the fifth principal component for June).

Intense irrigation in Nebraska has grown relatively smoothly and fairly consistently over the period of interest, starting later than irrigation in the Texas Panhandle and having a less fitful history of use. Center-pivot irrigation after the 1960s along with the abundant Ogallala groundwater supply spurred major irrigation development in Nebraska (Kuzelka 1993). In addition, the panhandle area has been subjected to more varied

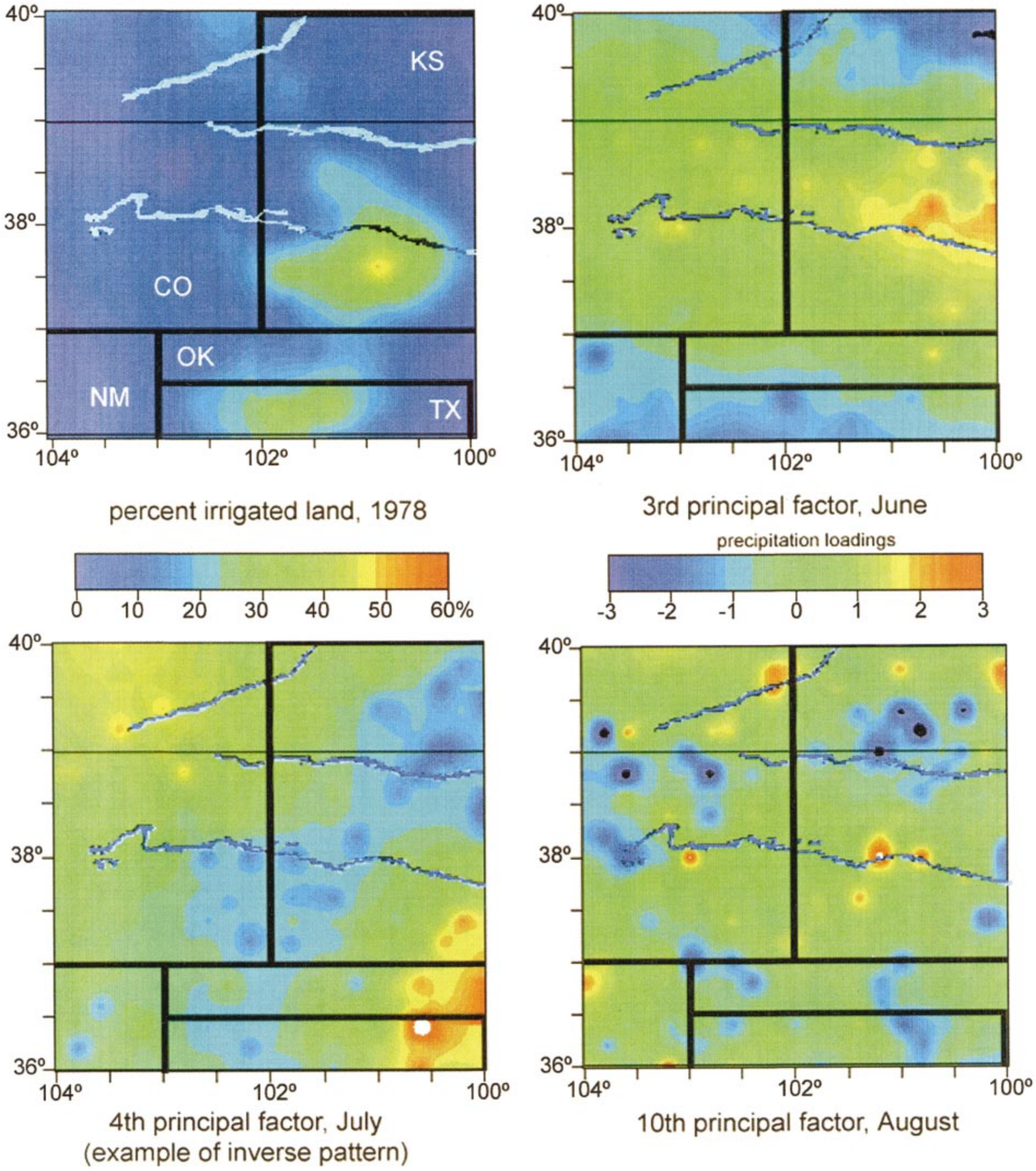

FIG. 7. Irrigation and precipitation patterns for the western Kansas/eastern Colorado subregion, 1950–97.

crop cultivation over the last 50 years (from sorghum, cotton, corn, and others to mostly monoculture cotton) than has the eastern Nebraska subregion.

Contrasting the histories of Nebraska and Texas may yield clues to discrepancies between the Schickedanz study and our analyses. For example, current irrigation water use in eastern Nebraska sees its peak in July and August, with relatively less during June for which Schickedanz found the strongest irrigation effect. Because irrigation in Nebraska did not experience rapid development until the 1970s and 1980s, the Schickedanz study would have missed this growth as well as any irrigation effect it induced. Eastern Nebraska is also not as intensely irrigated as the Texas Panhandle, and evidence is weaker for an irrigation effect in this subregion, as is indicated by low t ratios and poorer spatial matching of irrigated areas and loading patterns.

c. *Precipitation magnitude comparison of target and control areas*

An investigation of precipitation magnitude change was conducted with those irrigation-month principal components that best satisfied the spatial criteria but not necessarily the time criteria; in other words, the negative temporal trends of June (sixth principal component) and July (fifth principal component) for the entire region were ignored. Only the loading patterns for the entire plains region were examined; the smaller subregions were not treated in this investigation. Figure 9 depicts the target and control regions of each component that were compared. Target areas for each month (e.g., ''Texas'' and ''SE corner'') are outlined; black areas correspond to high precipitation (greater than 1) in the loading patterns from Fig. 5 for the month indicated. The black regions in the control areas indicate ordinary precipitation (between −0.5 and +0.5) in the loading patterns from Fig. 5.

Table 2 shows values of mean precipitation for target and control areas as well as comparison ratios of target to control values and of heavily irrigated to lightly irrigated years. For June, the Texas area and the SE-corner area both exhibited a positive increase over time. Texas precipitation fell below the control precipitation during the 1950s and just equaled it during the 1980s, but the SE-corner area (where no intense irrigation has occurred) produced a strong rise in precipitation in comparison with the control area. These target:control ratios were expected to some degree because of the nature of the humid Gulf Coast climate and the arid panhandle. The Nebraska/Kansas region shows no significant trends for June.

TABLE 2. Mean precipitation intensities and comparisons.

	Mean precipitation (cm)		HIY : LIY Ratio	Target : control ratio	
	LIY* (1950s)	HIY** (1980s)		LIY (1950s)	HIY (1980s)
Jun					
Texas	6.13	8.80	1.43	0.84	1.01
Nebraska/Kansas	9.62	9.49	0.99	1.31	1.09
SE corner	8.48	13.29	1.57	1.16	1.53
Control area	7.32	8.69	1.19	—	—
Jul					
Texas/New Mexico	7.33	5.64	0.77	0.94	0.81
Iowa	9.33	9.50	1.02	1.19	1.36
Oklahoma	9.48	5.93	0.63	1.21	0.85
Control area	7.82	6.99	1.12	—	—
Aug					
Texas/New Mexico	5.90	7.77	1.32	0.95	1.02
Iowa	9.72	10.76	1.11	1.56	1.41
Kansas	6.36	8.42	1.32	1.02	1.10
Control area	6.22	7.65	0.81	—	—

* LIY = Lightly irrigated years (1951–60).
** HIY = Heavily irrigated years (1981–90).

Rainfall for July declined in the Texas/New Mexico area and in the pattern over Oklahoma, but no significant rise in rainfall was evident in the Iowa area. Precipitation changes in the Iowa target area may not be at all related to irrigation. If irrigation does influence precipitation in this region, however, the most likely source of influence would be Nebraska (on the basis of proximity). Its target-to-control ratio showed a small boost in the lightly irrigated period and a greater boost in the heavily irrigated period, a result coinciding with the rapid expansion of irrigation in the intervening years. The August comparisons provided support for increased precipitation magnitude over the Iowa pattern, particularly in that the target:control ratios were roughly 50% greater than control. Both the Kansas and Texas precipitation comparisons yielded a rise over the intervening years but no significant change versus control precipitation. Because both ratios should be taken into account jointly to detect a trend, we conclude that the Texas and the SE-corner areas both show increased rainfall intensity in June, the Iowa area alone shows an increase for July, and all three areas in August demonstrate at best very mild increases in magnitude. However, no target areas showed a consistent and strong rise in precipitation for more than one summer month. As a consequence of low HIY:LIY ratios and a lack of consistency in temporal trends, evidence for an irrigation effect is equivocal from these data.

4. Conclusions

There is at best minor evidence for irrigation-induced rainfall in the Great Plains in our data. The most convincing, albeit still weak, evidence comes from the Texas Panhandle subregion over the shortened time period of 1950–82. In comparison with previous studies of the area, our EOF analysis of the entire Great Plains region as well as three smaller subregions shows only slight positive precipitation anomalies in and around irrigated areas with lower t-ratio values. Months showing an irrigation effect in this study were different than the months determined by Schickedanz (1976) in almost every case.

Several target areas did not exhibit excessive precipitation in comparison with control areas, and others did not show significant changes in precipitation from lightly irrigated to heavily irrigated times. Magnitude analysis suggests that additional precipitation fell in the Texas Panhandle and in the Nebraska/Iowa area. However, anomalous increases in an unirrigated region (the SE corner) indicate that influences other than irrigation could have caused this effect.

Because the Barnston and Schickedanz study compared a period of no irrigation and severe drought (the

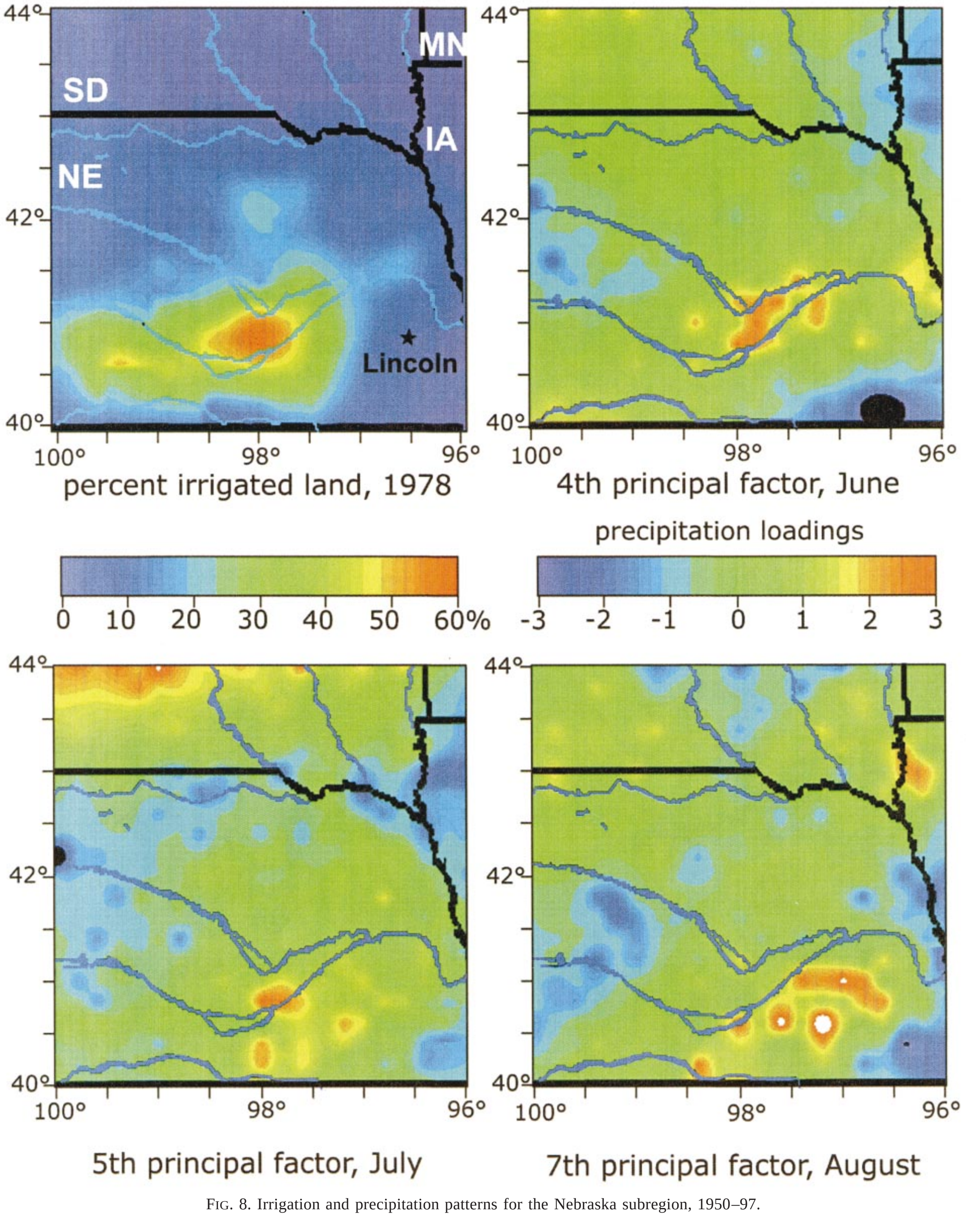

FIG. 8. Irrigation and precipitation patterns for the Nebraska subregion, 1950–97.

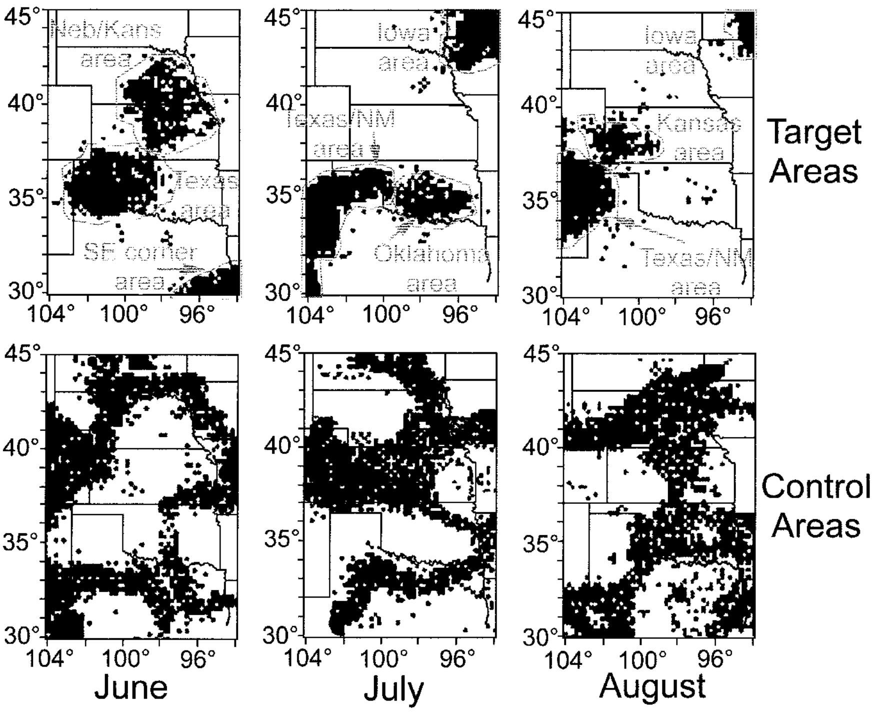

FIG. 9. Target and control areas for precipitation magnitude comparison.

1930s) with a period of relatively high precipitation, it is possible that the strong temporal trends in their examination were strongly influenced by climatic differences, not merely by an irrigation effect. During the past 50 years there has been a general increase in precipitation, a change that further obscures any signal for irrigation-induced precipitation. The results of our study indicate that the influence of irrigation on precipitation, if it exists, affects synoptic conditions only as a second-order effect.

All of the regions studied had some slight increases during May, although they did not show a strong statistical time trend. This finding could be a result of preplanting irrigation common to the study area and generally cooler temperatures, but evidence is insufficient to verify this as a cause. Because preplanting irrigation is not as intense as growing-season irrigation, perhaps a weaker signal for an effect in this month would be expected.

Temporal trends were vague for the entire region, and comparison with unirrigated areas provided only slight evidence of an increase in precipitation magnitudes in and around most of the areas during the irrigated months. The SE-corner area showed the strongest increase in precipitation magnitude yet did not lie near an irrigated area but rather near the Gulf Coast. Spatial precipitation loading patterns with some similarity to the irrigated areas were identified in all three months for the entire plains region and for the subregions (except August), with varying degrees of congruity and, in some cases, with inverse overlays.

If the irrigation effect inferred by Barnston and Schickedanz is real, then our analyses suggest that there is a nonlinear response for the onset of irrigation-induced rainfall. Irrigated acreage has exploded from the end of World War II to the 1980s without a coinciding increase in induced rainfall, which implies that, beyond some threshold irrigation level, additional increase in irrigation water use do not induce a proportionate increase in precipitation. Rather, the irrigation may behave like an "on–off" switch or induce drought-mode and wet-mode oscillations, as suggested by Entekhabi et al. (1992) for arid environments. In our case, relatively significant irrigation influences apparently began before World War II. Subsequent to World War II, irrigation-induced precipitation is difficult to identify unambiguously.

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APPENDIX

The Method of EOFs and Principal Components Analysis

The Great Plains and the subregions were divided into 4636 (61 × 76) grid points, with a point every 0.2° from

30° to 45°N latitude and from 93° to 105°W longitude. The period of interest (1950–97) contained 48 yr of precipitation data, which were used as the variables for intercorrelation. An $m \times n$ matrix $\mathbf{X}$ ($m = 4636$ points $\times$ $n = 48$ yr) was subjected to principal components analysis, a method that assumes that all elements are 1 on the main diagonal of the correlation matrix. A matrix $\mathbf{Z}$ of standardized variates was constructed from matrix $\mathbf{X}$ using $z_{ij} = (x_{ij} - \mu_j)/\sigma_j$ for calculating each element of $\mathbf{Z}$. The mean μ_j and standard deviation σ_j were specific to each year (each column) and made correlations between different years possible. The correlation matrix $\mathbf{R}$ was determined from correlating the columns (years) of $\mathbf{Z}$ against one another. The transformation into an independent set of eigenvectors is made by solving the characteristic value problem $\mathbf{RE} = \lambda\mathbf{E}$, more commonly written as

$$(\mathbf{R} - \lambda\mathbf{I}_n)\mathbf{E} = 0, \tag{A1}$$

where $\mathbf{E}$ is the $n \times n$ matrix composed of the eigenvectors of matrix $\mathbf{R}$ and $\mathbf{I}_n$ is the $n \times n$ identity matrix. The first column of matrix $\mathbf{E}$ represents the eigenvector associated with the largest eigenvalue; this largest eigenvalue represents the largest amount of variance in the precipitation matrix. From this, the principal components loading matrix $\mathbf{A}$ was calculated:

$$\mathbf{A} = \mathbf{ED}^{1/2}, \tag{A2}$$

with $\mathbf{D} = \lambda\mathbf{I}_n$, a matrix composed of the eigenvalues of $\mathbf{R}$ along the diagonal. The term $\mathbf{A}$ is not the principal components matrix but rather is a loading matrix for which each column is a linear combination of the years in the study. From the principal components loading matrix $\mathbf{A}$ we can calculate the $m \times n$ principal components matrix $\mathbf{F}$ by the equation

$$\mathbf{F} = \mathbf{Z}(\mathbf{A}^{\mathrm{T}})^{-1}, \tag{A3}$$

and from the $\mathbf{F}$ matrix, we can extract spatial variation on normalized precipitation from it. Each column in the $\mathbf{F}$ matrix is a spatial ''loading pattern'' that is identified with a corresponding eigenvalue. Columns (loading patterns) linked to large eigenvalues (variances) can be plotted to discern the larger spatial trends in the dataset. Thus, if an eigenvector with a large eigenvalue shows a time trend and its corresponding loading pattern shows a spatial similarity to an irrigated region, this eigenvector was considered to be a candidate for an irrigation effect. This process is also useful for determining temporal fluctuations, which can be achieved by switching the time and space data (each column having the data for a point instead of a year) and executing the EOF analysis.

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