Hydroclimatic Variability on the Great Plains

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Abstract. *This study identifies the spatial variability of the hydroclimatology of the Great Plains. Spatial associations of monthly midtropospheric circulation anomalies, total precipitation, and mean stream discharge are identified using an unrotated principal component analysis. Three hydroclimatic associations, representing synoptic circulation features and associated precipitation and stream discharge patterns, identify specific circulation anomalies and corresponding spatial patterns of surface hydrology in the northern, central, and southern Great Plains. Results indicate that nearly 47% of the hydrologic (precipitation and stream discharge) variability during summer is attributed to synoptic-scale midtropospheric circulation anomalies, with sub-synoptic convectional processes accounting for approximately 42% of the hydrologic variance.*

Understanding the relationship between climatic variability and stream discharge is a challenging problem for climatologists and hydrologists alike. Spatial patterns of precipitation and stream discharge occur in response to the presence and frequency of specific synoptic-scale atmospheric circulation patterns which enhance or suppress precipitation. Persistence of a particular circulation regime may generate anomalous hydrologic conditions. For example, circulation patterns which steer storm systems away from a region for a period of time tend to produce extended periods of drought. Similarly, flooding may result when prevailing circulation patterns that supply abundant quantities of water vapor, increase atmospheric instability, or otherwise enhance the precipitation process.

Hydroclimatic variability is important in the Great Plains because the availability of water resources is a significant factor in this highly productive agricultural region. The response of the hydrologic system in the Great Plains to global warming is very uncertain. In order to postulate the impact of such climatic change on precipitation and stream discharge, the relationship between the circulation and the surface hydrology in the present climate must first be identified. Once these relationships are established, hypotheses may then be offered concerning the effect of

climate change on the water resources in the Great Plains.

This study investigates the hydroclimatic variability in the Great Plains since 1950. The primary objective is to identify the dominant spatial associations of midtropospheric circulation anomalies over North America and precipitation and stream discharge in the Great Plains.

Background

Few studies exist concerning the long-term relationship between atmospheric circulation patterns and surface hydrology. Hayden (1988) produced a global classification of flood climates, identifying 16 flood types based on the type of flood reservoir (atmospheric or accumulated snow and ice cover), the causal mechanisms (barotropic, i.e., air mass, or baroclinic, i.e., frontal precipitation, snowmelt), and the seasonality of the mechanisms. In the Great Plains, the flood reservoirs are predominantly atmospheric moisture, with accumulated snow cover significant during winter and spring in the central and northern Plains; causal mechanisms include localized convection (both organized and unorganized) in summer, and midlatitude storm fronts present in all seasons, but particularly in winter (Hayden 1988:22-25).

Atmospheric circulation anomalies influence monthly precipitation and stream discharge anomalies. Positive stream discharge anomalies are associated with circulation anomalies representing stronger than average airflow from a moisture source region (Bartlein 1978). In the Upper Mississippi River Basin, monthly maximum stream discharges are significantly greater and have a higher probability of occurrence when a negative height anomaly in the 700 mb surface is positioned to the west of the basin. The negative anomaly results in increased water vapor advection from the Gulf of Mexico, thereby enhancing precipitation over the basin. Monthly maximum stream discharge is suppressed by the advection of drier, continental air when positive height anomalies are positioned to the west of the basin (Keables 1988). Knox (1988) tested the significance of the relationship between flood magnitudes and air temperature and precipitation for both annual and seasonal flood series in the Upper Mississippi River Basin. A significant positive relationship exists between annual flood magnitude and seasonal precipitation during the summer months for small basins, and for summer and winter months for large basins. No statistically significant relationships were found between air temperature and annual flood magnitude.

The majority of research dealing with climate-hydrology relationships has primarily dealt with either the hydrometeorologic characteristics of floods or the identification and documentation of climate and stream discharge variability. Few studies (Hirschboeck 1988; Keables 1988;

Bartlein 1978; Knox et al. 1975) are devoted to the specification of large-scale atmospheric circulation patterns and the associated response of the hydrologic system within regions of the United States, and the Great Plains in particular.

Data

Data for the summer months (May-September) for the period 1951-1979 were used in this investigation. Trewartha (1982) identified two precipitation regimes within the study region (bimodal in the southern Plains, unimodal in the north). The addition of the months of May and September to the months of meteorological summer assured that both precipitation regimes were detected in the analysis. These five months represent the time of year when the hydrologic system in the Great Plains is most active. The period 1951-1979 was one in which data collection was continuous for both the precipitation and stream discharge stations. Beginning in 1980, data collection at numerous stream gauging stations in the region was discontinued. Quality upper-air data are not available prior to the late 1940s. Midtropospheric circulation data consisted of mean monthly heights of the 700 millibar surface derived from twice-daily observations for the period 1951-1979. These data are a subset of the National Meteorological Center (NMC) octagonal grid for the Northern Hemisphere and were obtained from the National Center for Atmospheric Research (NCAR). The data were interpolated onto a 5° x 5° latitude-longitude diamond grid covering the North American sector (Fig. 1) and then standardized (zero mean, unit variance) to remove the seasonal cycle. The 700 millibar surface is located at an average altitude of three kilometers above sea level. This surface was used because it has significant impact on surface weather systems (Hawkins 1956) and hydroclimatic associations (Keables 1988), and because of the spatial coherence of the patterns at regional scales.

Monthly total precipitation data were obtained from the National Climatic Data Center (NCDC) for 24 climate stations throughout the Great Plains (Fig. 2). Only stations in continuous operation throughout the study period were used. Most station records were complete; in the few instances in which data were missing, the long-term mean for the station was substituted for the missing record. The data were then transformed to a normal distribution using a cube-root transformation and then standardized.

Monthly mean stream discharge data were obtained from the United States Geological Survey (USGS) for 28 stream gauging stations throughout the Great Plains (Fig. 2). Stations were selected based upon the length

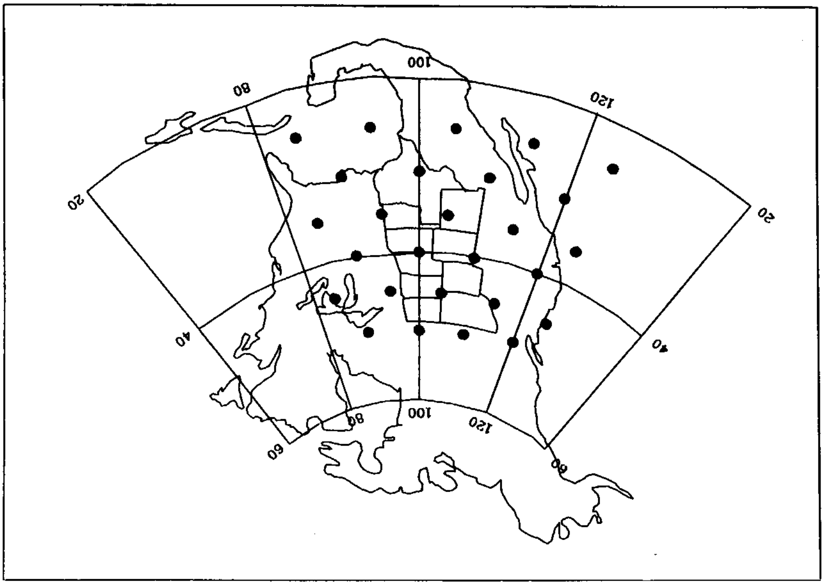

Figure 1. 700 millibar grid points used in the study.

and continuity of record. As flow diversion for agricultural irrigation is common in much of the region, only stations with minimal flow regulation (less than 10% of the total annual flow) were used (Langbein and Slack 1982). As with the precipitation data, most station records were complete. Long-term mean values were substituted for missing data. The data were then transformed to a normal distribution using a logarithmic transformation and then standardization.

Method

A single hydroclimatic data matrix was constructed, consisting of monthly standardized observations of 700 mb heights, total precipitation, and mean stream discharge. Matrix dimensions were 145 temporal observations by 79 spatial variables (27 circulation gridpoints, 24 precipitation stations, 28 stream gauging stations). This combined data matrix was constructed in order to use the joint variability of the climate and hydrology variables as a means of identifying the hydroclimatic associations.

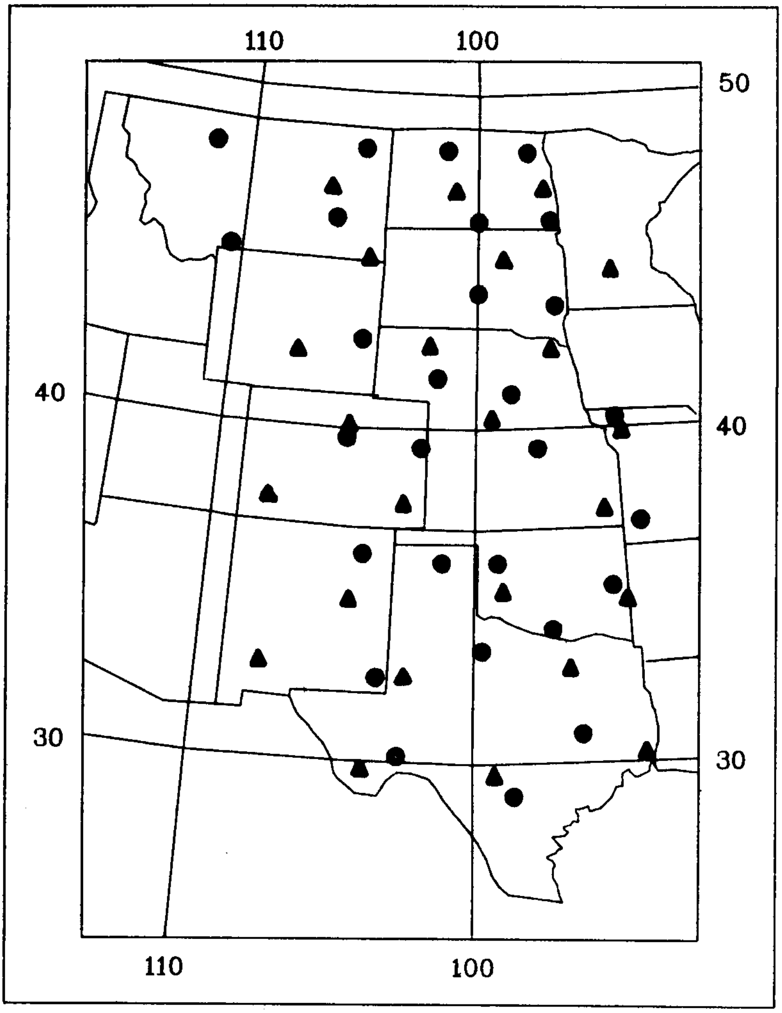

Figure 2. Precipitation (triangles) and stream gauging (dots) stations used in the study.

The dominant hydroclimatic associations were identified by subjecting the hydroclimatic matrix to an unrotated principal component analysis. Separate multiple regression analyses were less successful in identifying the

hydroclimatic associations. Principal component analysis describes the variance-covariance structure of a data set through a small number of linear combinations of the original variables; details are provided in multivariate statistical texts such as Johnson and Wichern (1982). Principal component analysis has been widely used in both climatic and hydrologic applications (Keables 1988; Lins 1985; Beaudoin and Rousselle 1982; Bartlein 1982; Diaz and Fulbright 1981).

Considerable discussion exists in the literature concerning the benefits of computing orthogonal or oblique rotations in the calculation of the principal components (Richman and Lamb 1985: Walsh et al. 1982; Richman 1981). Rotated components are useful to identify spatial clusters within the data, while unrotated solutions maximize the variance over the region. Rotated analyses are useful if regionalization is the sole purpose of the study. When a combined hydroclimatic matrix is used, as in this study, orthogonal rotation identifies for a particular component a specific region in one observed field (e.g., circulation) at the expense of the remaining variables (precipitation and stream discharge). The result is a number of regional clusters of circulation, precipitation, and stream discharge that are independent of one another. However, if the purpose of the research is to emphasize interactions among variables throughout a specific region, unrotated solutions are appropriate. As the purpose of this study is to elucidate associations among numerous hydroclimatic variables within the Great Plains, an unrotated analysis was performed.

The spatial associations existing within the hydroclimatic data matrix were identified by mapping the component loadings (the correlation coefficients between the variables and the particular principal component) for each significant principal component. Because each component has both a positive and negative score, the pattern portrayed by the loadings actually represents two specific associations (the pattern as depicted and its opposite).

Results

The principal component analysis produced 79 components completely reproducing the variance in the correlation matrix of the 79 hydroclimatic variables. The eigenvalues were tested for significance using the Rule-N Monte Carlo technique (Overland and Preisendorfer 1982; Preisendorfer and Barnett 1977). This technique compares the eigenvalues obtained from the observed data with eigenvalues obtained from 100 randomly generated data matrices with identical dimensions. Eigenvalues of the observed data are significant if the magnitude of the eigenvalue exceeds that of the corresponding randomly generated eigenvalue at the

TABLE 1

VARIANCE EXPLAINED BY PRINCIPAL COMPONENTS

Component	Eigenvalue	Variance Explained (%)	Cumulative Variance Explained (%)
1	10.984	13.90	13.90
2	8.591	10.88	24.78
3	5.993	7.59	32.37
4	4.076	5.96	38.33
5	4.118	5.21	43.54
6	3.751	4.75	48.29
7	3.390	4.29	52.58
8	2.592	3.28	55.86
9	2.236	2.83	58.69
10	1.891	2.39	61.09
11	1.826	2.31	63.40
12	1.667	2.11	65.51
13	1.599	2.02	67.54

95th percentile. In this study, the first 13 eigenvalues are significant, accounting for nearly 68% of the total hydroclimatic variance (Table 1).

When a combined data matrix is used, certain principal components may produce spatial clusters that emphasize one variable (e.g., circulation), two variables (e.g., precipitation and stream discharge), or all three variables. In order to interpret how each component is depicting the three variables, the percentage of the variance explained by the circulation, precipitation, and stream discharge variables for each principal component was calculated. The variance explained by a component is defined as the total sum of squares of the component loadings. For each significant component, the sum of squares of the loadings for each set of variables was calculated and expressed as a percentage of the component explained variance to aid in the interpretation of each of the principal components (Table 2).

Three of the significant components (the second, fourth, and sixth) identify six associations between synoptic-scale circulation features, precipitation, and stream discharge. These associations are described by the spatial patterns that result when the component loadings of circulation, precipitation, and stream discharge are mapped. Since the data comprising the original correlation matrix consist of standardized departures, the spatial patterns on the maps are interpreted as departures from the

average of the particular observation field. Each of the circulation loading maps represents departures from the mean summer 700 mb surface for the study period (Fig. 3), which is characterized by a west to east air flow as indicated by the orientation of the height contours.

Principal component 2 (PC2) identifies the two most prominent associations between synoptic circulation features, precipitation, and stream discharge (Fig. 4). The circulation anomaly field consists of anomaly centers located over the Pacific Northwest and the southcentral United States, with a pronounced north-south gradient positioned over the majority of the study area. Precipitation and stream discharge associated with this circulation pattern are most responsive in the southern Great Plains, with the largest loadings located in Kansas, Oklahoma, and Texas. With a positive component score, the circulation anomaly field identifies a significant increase in northerly flow over much of the Great Plains, transporting dry continental air into the northern and central part of the study area. This dry air is not conducive to precipitation as it lacks the necessary humidity to generate precipitation. Over the southern Plains,

TABLE 2

PERCENTAGE OF VARIANCE EXPLAINED BY CIRCULATION, PRECIPITATION, AND STREAM DISCHARGE VARIABLES IN EACH COMPONENT

	Percent of Component Variance Explained By		
Component	Circulation	Precipitation	Discharge
1	78.85	16.96	4.19
2	40.85	24.47	34.68
3	74.53	12.76	12.71
4	30.40	28.16	41.44
5	30.32	14.43	55.25
6	35.61	20.25	44.13
7	33.27	30.02	36.72
8	3.90	24.85	71.25
9	18.94	46.97	34.09
10	17.89	51.89	30.22
11	21.71	26.34	51.95
12	18.41	55.21	26.37
13	16.36	38.69	44.95

however, the large negative anomaly identifies the presence of a trough of low pressure which is often associated with increased atmospheric instability. Months characterized by unstable atmospheric conditions over the southern Plains will therefore experience increased precipitation and stream discharge.

A negative component score identifies an association in which precipitation and stream discharge are suppressed in the southern plains in response to the location of a large midtropospheric ridge of high pressure positioned over the southern Plains and extending eastward into the Mississippi River Valley. This circulation feature is generally associated with stable atmospheric conditions which tend to inhibit the dynamics necessary to generate precipitation over the southern Great Plains.

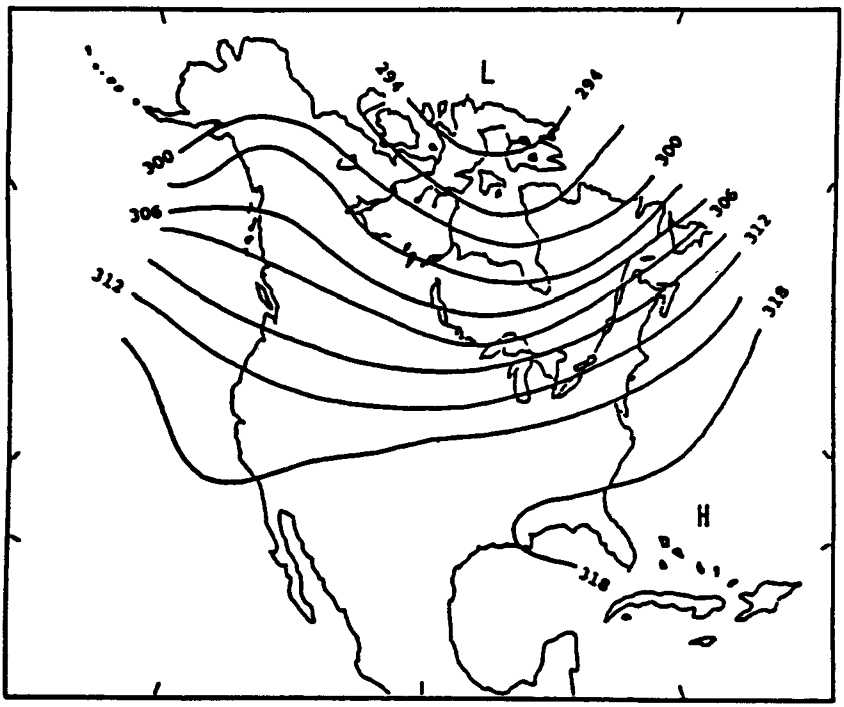

Figure 3. Mean summer 700 mb surface, 1951-1979. Heights are in dekameters.

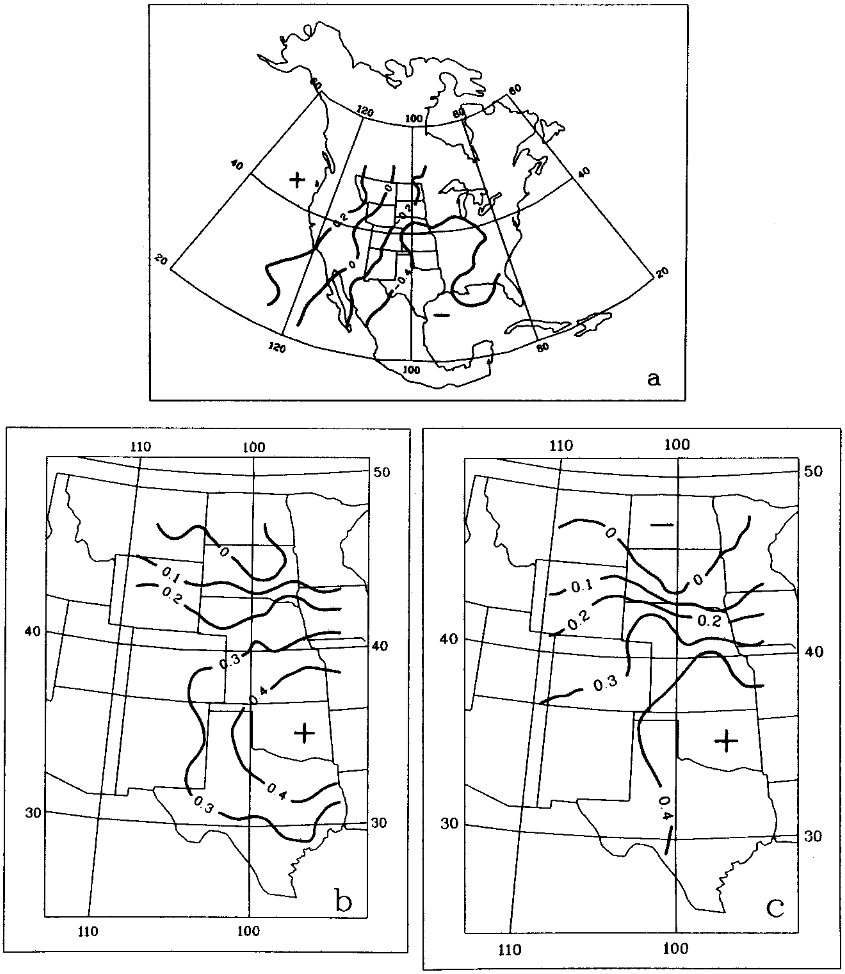

Figure 4. Spatial distribution of the loadings of the second principal component. (a) 700 mb height anomalies, (b) precipitation, (c) stream discharge.

The fourth principal component (PC4) identifies a second hydro-climatic association in the Great Plains (Fig. 5). It is characterized by circulation component loadings of the same sign over the majority of North America, with two anomalies centered over western Montana and southern Texas. Precipitation and stream discharge loadings identify anomalies centered over the northern Plains. The positive circulation anomaly located over southern Texas provides an anomalous southwesterly component of flow into the central Plains, thereby increasing the humidities as a result of the increased transport of water vapor. The high humidity and associated high surface temperatures combine to enhance precipitation and stream discharge over the northern Great Plains.

A negative component score identifies a hydroclimatic association in which below average precipitation and stream discharge occur in the northern Plains in response to a circulation pattern which includes negative anomalies located over southern Texas and western Montana. The anomalous westerly flow associated with the anomaly over western Montana produces an increase in the advection of drier air, producing months with decreased precipitation and stream discharge.

The sixth principal component (PC6) identifies the third association between synoptic-scale circulation features and precipitation and stream discharge (Fig. 6). The map pattern of the circulation loadings identify anomalies of opposite sign centered over North Dakota and east of the study area. Precipitation and stream discharge loadings show two anomalies of opposite sign positioned over the central and southern Great Plains. The effect of this particular circulation pattern (positive score) is to produce an anomalous westerly component of flow over much of the northern and central Great Plains, and an increased southerly component of flow over the southern portion of the study area. Increased westerly flow during summer tends to inhibit the precipitation process as the air flow into the region is generally lacking in humidity. In addition, the dynamics necessary to initiate and sustain the precipitation process are less frequent during months characterized by a strong zonal (west-east) flow. In the southern Great Plains, however, the anomalous southerly component of flow indicates an increase in the transport of water vapor by maritime air masses into the southern Plains, increasing precipitation and stream discharge.

With a negative component score, the precipitation and stream discharge fields are reversed, identifying a condition in which the central Plains experience increased precipitation and stream discharge with below average conditions in the southern Plains. The associated circulation pattern consists of a positive anomaly positioned over the northern portion of the study area and a negative anomaly located to the east, resulting in anomalous easterly flow over the central Plains and northerly flow over the

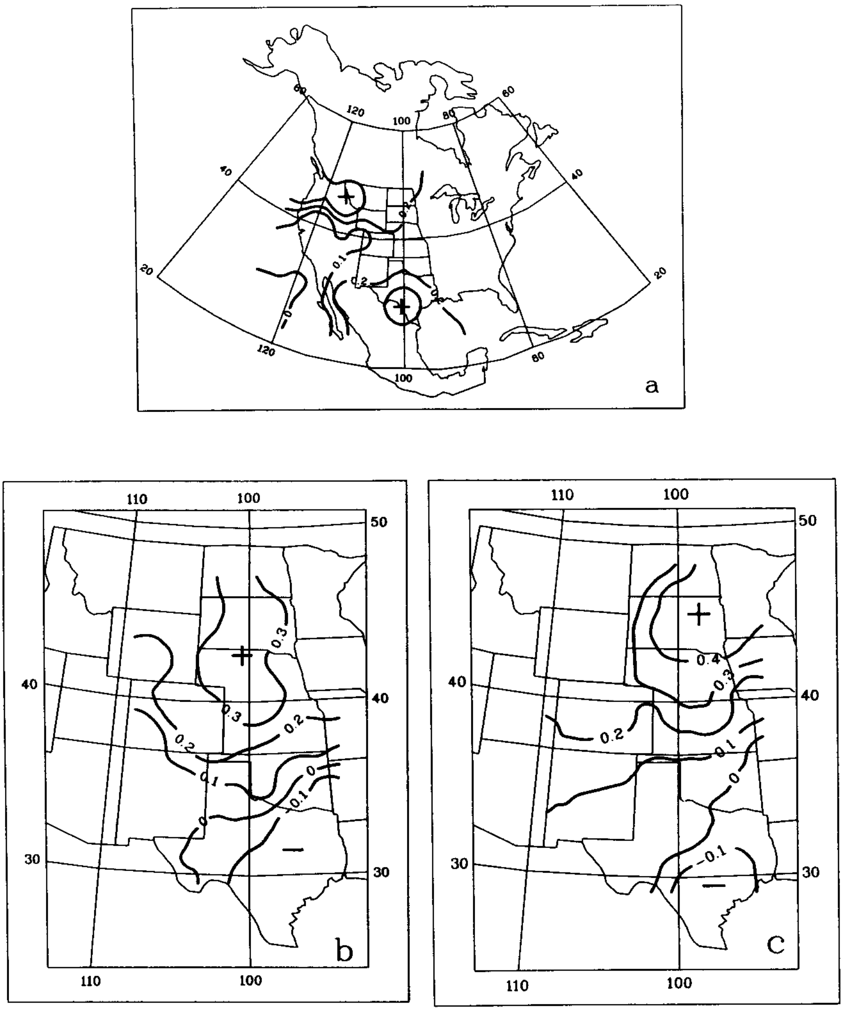

Figure 5. Spatial distribution of the loadings of the fourth principal component. (a) 700 mb height anomalies, (b) precipitation, (c) stream discharge.

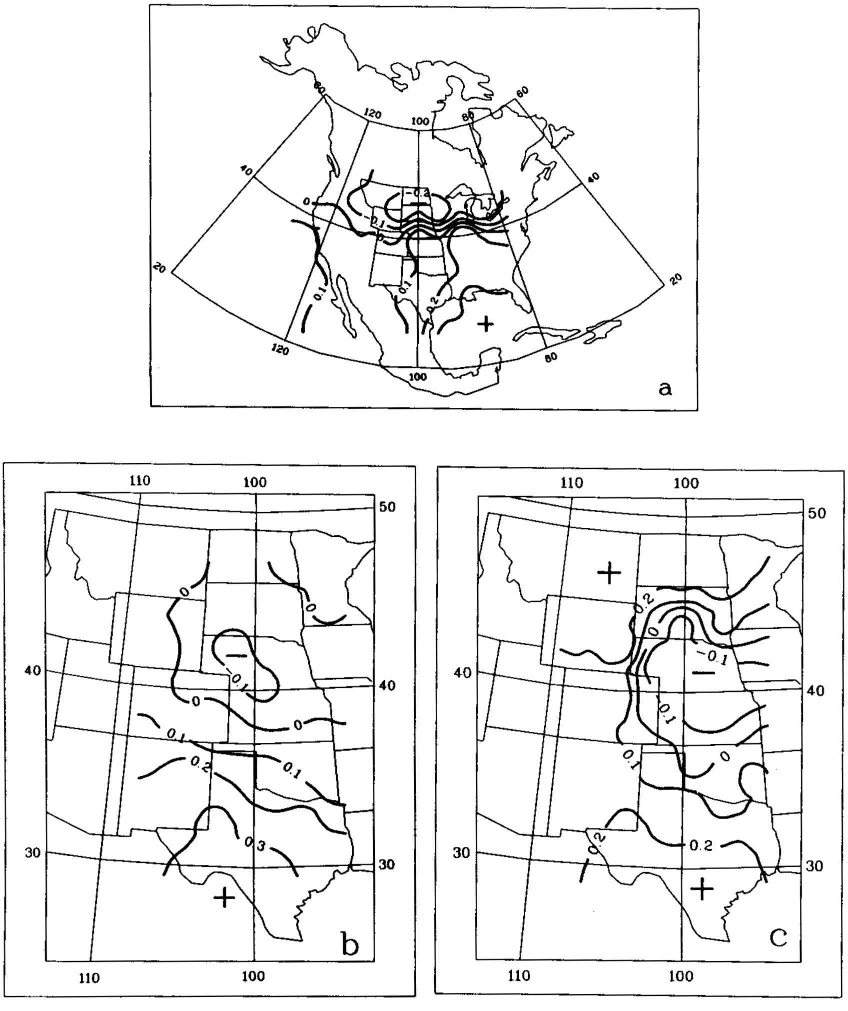

Figure 6. Spatial distribution of the loadings of the sixth principal component. (a) 700 mb height anomalies, (b) precipitation, (c) stream discharge.

southern Plains. In the central Plains, anomalous easterly flow indicates a reduction in the strength of the prevailing westerly winds in favor of conditions more suited to the formation of organized convectional processes and increased precipitation and stream discharge. The anomalous northerly flow over the southern Plains indicates increased dry air advection, lower humidities, and less precipitation and resultant stream discharges.

The components described above (PC2, PC4, PC6) identify six hydro-climatic associations involving synoptic-scale circulation features. Additional components, however, elucidate the portion of the hydroclimatic variance that result from sub-synoptic scale interactions. In particular, PC7-PC13 each identify associations that are highly localized in terms of the circulation, precipitation, and stream discharge patterns. Due to the highly localized nature of these components, the map patterns of the component loadings are not presented. These components are interpreted to be representative of particularly large, localized convectional events. Investigation of the corresponding component scores supports this interpretation.

Conclusions

The purpose of this study was to identify the dominant hydroclimatic associations that exist in the Great Plains. Using a single matrix of circulation, precipitation, and stream discharge data, a principal component analysis identified 13 significant associations explaining nearly 67% of the total variance.

The 13 significant principal components can be categorized into three basic groups in terms of their ability to reproduce the hydroclimatic variance of the circulation-precipitation-stream discharge matrix: components explaining synoptic-scale circulation features and their relation to surface hydrology patterns; components identifying smaller-scale convectional storms and their contribution to the spatial variability of precipitation and stream discharge, and components explaining some of the variance that is not directly related to hydroclimatic variability (Table 3). Components PC2, PC4, and PC6 identify synoptic circulation features and together account for nearly 47% of the hydrology (precipitation and stream discharge) variance. Convectional precipitation and related stream discharge are identified by components PC7-PC13, which account for nearly 42% of the hydrology variance. The remaining components identify either circulation (PC1, PC3) or stream discharge (PC5) variability alone.

This study provides an initial investigation into the hydroclimatology of the Great Plains. Additional research is needed to incorporate these

TABLE 3

PERCENTAGE OF TOTAL VARIANCE AND HYDROLOGIC (PRECIPITATION AND STREAM DISCHARGE) VARIANCE EXPLAINED BY COMPONENT TYPE

Component Type	Total Variance Explained (%)	Hydrology Variance Explained (%)
Synoptic anomalies	31.9	46.9
Convection	28.5	41.8
Circulation only	31.8	0.0
Other	7.8	11.3

hydroclimatic associations into empirical models in order to identify specific cause and effect relationships. Once these relationships are determined, comparison with hydrologic simulations using general circulation models will provide an indication to the suitability of using such hydrologic simulations to predict the effect of climate change on the water resources of the Great Plains.

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