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Drought and Precipitation Fluctuations in the Great Plains during the Late Nineteenth Century

Cary J. Mock
University of Oregon, mockcj@sc.edu

DROUGHT AND PRECIPITATION FLUCTUATIONS IN THE GREAT PLAINS DURING THE LATE NINETEENTH CENTURY

Cary J. Mock

Department of Geography, University of Oregon
Eugene OR 97403

Abstract. *Monthly precipitation data in the Great Plains from the late nineteenth century (1851-1890) were compared with modern analogs. Seasonal precipitation changes were identified since 1858-1877, depending on the amount of data available, and additional droughts were inferred back to 1851. Regional droughts did not clearly fit any cycle. Precipitation during fall and winter was less than 1951-1980 averages during most of the late nineteenth century. Wetter than modern average springs and summers occurred in the mid-1870s to the mid-1880s. Relationships of these conditions to changes in mid-tropospheric circulation are suggested. Results from this study can be used for verification of dendroclimatic reconstructions and assessment of climatic impact on settlement.*

Recurring drought has had marked economic and agricultural consequences in the Great Plains region of the United States since Euro-American settlement began in the latter half of the nineteenth century (Hecht 1983; Wilhite 1983). The drought of 1988-1989 in the northern and eastern portions of the Plains ranks in the top five most severe droughts of the twentieth century (Trenberth et al. 1988; National Climate Program Office 1988). Severe droughts similar in magnitude, spatial extent, and duration to those of the late-1980s and the 1930s may occur more frequently in a future of globally-warmer climate and dramatically alter the character of human life in the Plains (Borchert 1971; Bowden 1977).

Substantial research has been conducted on past, present, and future climates of the Great Plains. Scholars have studied the mechanisms of Great Plains climatology (Borchert 1950; Klugman 1978; Barry 1983; McGregor 1985; Rosenberg 1986), attempted to predict future climates (Manabe and Wetherald 1986), and assessed impacts of future droughts on society (Wilks 1988). All of these works focus on and utilize climatic information within the twentieth century, since most continuous meteorological records extend back only to about 1895. These records have limitations in providing information on climatic variability. For example,

some scholars have inferred periodic cycles of severe drought of approximately 16-22 years due to solar activity (Mitchell et al. 1979; Currie and O'Brien 1990). These cycles have been disputed (Karl and Koscielny 1982), in part because the meteorological record is limited. A better understanding of climatic variability and its impact on society can be achieved by reconstructing climatic conditions of the Great Plains in the nineteenth century. An understanding of how climate-society relationships have changed through time may enable assessment on the impact of future severe drought (Warrick and Bowden 1981).

To date, little is known about nineteenth-century Great Plains climate. The Great Plains was perceived as a dry, barren land called the "Great American Desert" prior to 1860 (Allen 1985). The western barrier to the agricultural frontier, separating the humid east from the arid west, was between the 98th and 100th meridians (Smith 1947). Following the Civil War, the livestock industry moved northward from Mexico into the Plains (Allen 1985), and Euro-American settlement expanded westward from the east (Wishart 1987). By the late 1870s and early 1880s, thousands of settlers had traveled beyond the 98th meridian (Baltensperger 1979; Wishart 1987). The Great Plains was then perceived as the Garden of the world (Allen 1985). The Garden Myth was related to the belief that increased irrigation caused permanent increases in Great Plains precipitation (Smith 1947). The advent of new technology such as barbed wire, the steel windmill, and the railroad made settlement in the Great Plains possible, but an abnormally wet climate may have also played a significant role. However, drought may have occurred occasionally and locally. The cattle industry declined during the mid-1880s (Wishart 1987), perhaps related to reduced precipitation during spring and summer that decreased the amount of forage (Albertson et al. 1957). The influx of settlers to the Great Plains was reduced at times because of drought (Baltensperger 1979).

An accurate climate reconstruction is the first step for answering questions about the impact of climate on settlement and environmental perception during the nineteenth century (Lawson 1974; Lawson and Stockton 1981). Climate cannot be inferred from historical non-meteorological sources because the reconstruction would lead to circular reasoning about historical climate impact assessment (Kates 1985).

Much of the climate record for the Great Plains prior to 1895 has been reconstructed from tree rings (Weakly 1943; Harper 1960; Lawson 1974; Lawson et al. 1980; Duvick and Blasing 1981; Stockton and Meko 1983; Blasing and Duvick 1984; Stahle and Herr 1984; Meko et al. 1985; Blasing et al. 1988; Stahle and Cleaveland 1988). Although tree rings are a useful proxy data source, dendroclimatic implications must be cross-checked with other proxy evidence for verification. Furthermore, many

parts of the Great Plains are devoid of trees more than one hundred years old, making dendroclimatic applications impossible.

A network of meteorological stations was established in the Great Plains in the mid-nineteenth century, well before the establishment of the United States Department of Agriculture in 1891 (Darter 1942; Bates and Fuller 1986). Wahl and Lawson (1970) analyzed 20-year anomalies of precipitation and temperature for 1850-1870, but no other studies have utilized these data. Although these instrumental data are not as reliable as modern weather data, they can be used for studying past climatic trends through careful analysis and screening (Roden 1966; Bradley 1976). This study utilizes monthly precipitation records from 1851-1890 to detect drought in the last half of the nineteenth century. The possibility of drought cycles is also discussed. Nineteenth century seasonal climatic data were also compared with modern climatic normals (1951-1980) to detect temporal trends. The period 1951-1980 was chosen as the climatic normal because many modern meteorological stations provide records near nineteenth-century stations and can serve as analogs for comparisons. The time period excludes the droughts of the 1930s and the 1980s, which may present misleading representations of climatic normals.

Study Area And Data

The western Great Plains comprises the portions of Montana, Wyoming, Colorado, and New Mexico east of the Continental Divide, and Texas northward of San Antonio. The Continental Divide is the physiographic boundary between the Great Plains and Rocky Mountains. The eastern Great Plains consist of North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma (Figure 1). The eastern border of the study area corresponds approximately to the 98th meridian.

Detailed descriptions of the history of nineteenth century instrumental data have been provided by Lawson (1855), Darter (1942), Lawson (1974), and Bradley (1976), and only a brief summary is provided here. Many problems in the nineteenth-century data set and its comparison with modern data are evident. Despite these problems, previous investigations show that signs of climate anomaly (Wahl and Lawson 1970; Bradley 1976) and occurrences of extreme weather events such as drought and flood (Lawson 1974) can be inferred accurately. Recognition of problems in the data permits the construction of a methodology to work through them.

A network of meteorological stations existed west of the Missouri River by 1860, but they were few in number and limited to eastern Nebraska, eastern Kansas, and Texas. Throughout the nineteenth century, many stations operated for less than five years (Table 1). Many stations

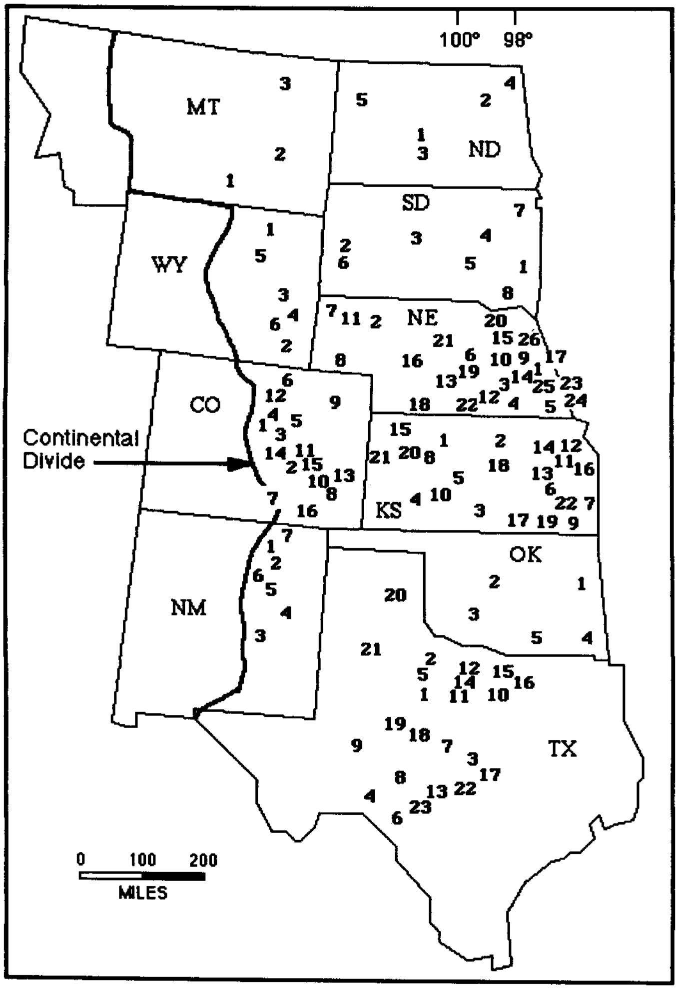

Figure 1. Locations of nineteenth-century meteorological stations in the study area. Station names are given in Table 1.

moved locally, and some moves likely went unrecorded (Bradley 1976). Station histories that have numerous gaps most likely indicate numerous moves. In order to retain a basis for comparison of temporal trends of precipitation, only stations with histories having a minimum of three consecutive years were used. Monthly precipitation data for the nineteenth century were obtained from Lawson (1855), Greely (1891), and Bigelow (1912). Only seven stations with histories of at least three years were in operation by 1851, and the number did not increase sharply until 1870 when 25 stations were in operation. Data remained scarce for the northern Plains throughout virtually the entire nineteenth century. However, even a few stations in an area may allow some inference of climatic change (Lawson 1974). Besides, temporal and spatial coverage in the meteorological record is related to the increasing rate of population and settlement within the Great Plains, satisfying most data needs for any historical climate impact study.

Precipitation and other weather data were collected and recorded by surgeons and by volunteer observers. They were mostly concerned about relationships between weather and health (Thompson 1981). Precipitation observations (to the nearest hundredth of an inch) were made along with observations of temperature, cloudiness, and wind. Daily and monthly totals were calculated from these data. Some precipitation gauges at military forts before 1860 were kept at least eight feet (2.44 m) off the ground (Lawson 1855). This is considerably higher than the modern standard of 0.58 m (Mather 1984, p. 47). The problem is that precipitation gauges at higher exposures are subject to faster wind speeds, which decrease the catch of precipitation (Henderson-Sellers and Robinson 1986, 135). Underestimation of precipitation is much greater for snow than rain due to the smaller fall velocities for snowflakes. Thus temporal comparisons may not be accurate for data prior to 1860. Data from the military forts prior to 1860 were analyzed mostly to detect past drought rather than absolute precipitation amounts. No corrections for underestimation were made because the author assumed that such errors in anomalies were probably negligible when nineteenth-century data were compared with modern data. Few nineteenth-century stations corresponded exactly in location to their nearest modern meteorological station, making corrections difficult. Some nineteenth-century locations are actually at lower elevations than their nearby modern analog placement of precipitation gauges. A few feet higher than the modern would actually have enabled a more accurate comparison. Furthermore, most of the nineteenth-century data came from the period after 1860. After this date, meteorological observers used a new set of instructions issued by the Surgeon General's Office, and the Signal Office. These were more similar to instructions used today (Darter 1942).

TABLE 1.
NINETEENTH-CENTURY METEOROLOGICAL STATIONS.
SEE FIGURE 1 FOR LOCATIONS.

State	Map #	Station	First year within 1851-1890	Record (years)
Colorado	1	Alma	1886	5
	2	Canon City	1888	3
	3	Colorado Springs	1871	17
	4	Como	1886	5
	5	Denver	1872	19
	6	Fort Collins	1872	15
	7	Fort Garland	1858	26
	8	Fort Lyon	1867	22
	9	Fort Morgan	1888	3
	10	Fort Reynolds	1868	5
	11	Husted	1886	5
	12	Idaho Springs	1886	5
	13	Las Animas	1867	24
	14	Pikes Peak	1873	16
	15	Pueblo	1869	17
	16	Trinidad	1877	4
Kansas	1	Alton	1878	13
	2	Concordia	1885	6
	3	Cunningham	1884	7
	4	Dodge City	1866	25
	5	Ellinwood	1875	16
	6	Emporia	1881	10
	7	Fort Scott	1851	12
	8	Hays	1868	23
	9	Independence	1872	19
	10	Larned	1860	20
	11	Lawrence	1868	23
	12	Leavenworth	1851	40
	13	Lebo	1887	4
	14	Manhattan	1858	33
	15	Oberlin	1887	4
	16	Paola	1869	5
	17	Rome	1886	5
	18	Salina	1883	8
	19	Sedan	1885	6
	20	Wakeeney	1883	8
	21	Wallace	1870	21
	22	Yates Center	1879	12

TABLE 1 CONT.

State	Map #	Station	First year within 1851-1890	Record (years)
Montana	1	Crow Agency	1879	12
	2	Miles City	1877	14
	3	Poplar	1882	9
Nebraska	1	Ashland	1883	8
	2	Camp Sheridan	1876	5
	3	Crete	1879	12
	4	Fairbury	1875	16
	5	Falls City	1883	8
	6	Fort Hartsuff	1875	7
	7	Fort Robinson	1883	8
	8	Fort Sidney	1872	13
	9	Fremont	1878	13
	10	Genoa	1876	15
	11	Hay Springs	1886	5
	12	Hebron	1886	5
	13	Kearney	1851	18
	14	Lincoln	1875	16
	15	Norfolk	1873	7
	16	North Platte	1874	17
	17	Omaha	1857	26
	18	Precept	1882	9
	19	Ravenna	1878	13
	20	Santee	1871	5
	21	Sargent	1883	7
	22	Superior	1879	7
	23	Syracuse	1877	10
	24	Tecumseh	1878	13
	25	Weepingwater	1878	13
	26	Westpoint	1884	7
New Mexico	1	Camp Burgwin	1854	6
	2	Fort Union	1851	40
	3	Fort Stanton	1856	20
	4	Fort Sumner	1864	6
	5	Gallinas Springs	1885	6
	6	Las Vegas	1887	3
	7	Springer	1887	4
North Dakota	1	Bismarck	1875	16
	2	Devils Lake	1870	21

TABLE 1 CONT.

State	Map #	Station	First year within 1851-1890	Record (years)
North Dakota (cont.)	3	Fort Yates	1882	9
	4	Pembina	1872	19
	5	Williston	1879	12
Oklahoma	1	Fort Gibson	1851	7
	2	Fort Reno	1883	8
	3	Fort Sill	1870	21
	4	Fort Towson	1851	4
	5	Fort Washita	1851	9
South Dakota	1	Alexandria	1882	5
	2	Fort Meade	1879	12
	3	Fort Sully	1869	22
	4	Huron	1881	10
	5	Kimball	1886	5
	6	Rapid City	1888	3
	7	Sisseton Agency	1866	22
	8	Yankton	1873	18
Texas	1	Abiline	1885	5
	2	Albany	1869	13
	3	Austin	1856	35
	4	Comstock	1858	3
	5	Decatur	1877	9
	6	Eagle Pass	1871	15
	7	Fairland	1851	7
	8	Fort Clark	1871	16
	9	Fort Lancaster	1856	5
	10	Fort Worth	1851	5
	11	Graham	1852	15
	12	Henrietta	1878	5
	13	Hondo City	1877	5
	14	Jacksboro	1868	14
	15	Keene	1881	8
	16	Kopperl	1851	3
	17	Luling	1882	9
	18	Mason	1852	11
	19	Menardville	1852	21
	20	Mobeetie	1879	11
Texas	21	Mt. Blanco	1886	5

TABLE 1 CONT.

State	Map #	Station	First year within 1851-1890	Record (years)
Texas	22	San Antonio	1871	19
(cont.)	23	Uvalde	1851	15
Wyoming	1	Buffalo	1886	5
	2	Cheyenne	1871	20
	3	Fort Fetterman	1869	12
	4	Fort Laramie	1860	17
	5	Fort Washakie	1880	9
	6	Laramie	1869	10

Methodology

Nineteenth-century seasonal data were expressed as percentages of 1951-1980 normals at nearby analog stations. For example, a value of 150% for summer 1887 indicates that precipitation during that summer was 50% greater than the 1951-1980 average. Seasons were defined as natural subdivisions of annual fluctuations (Wahl and Lawson 1970) as follows: winter, January through March; spring, April through June; summer, July and August, early fall; September through November; and late fall, November and December. In some cases, nineteenth-century stations have the same locations as their twentieth-century equivalents, according to published station histories. However, locations of nineteenth-century stations were often only approximated by observers. Short distances of a few miles between nineteenth-century stations and modern analogs may be responsible for inaccuracy in the calculated anomalies. Diverse topography creates a variety of small-scale climatic conditions, especially for precipitation (Bradley 1976). Twentieth-century urbanization around some modern stations may also distort comparisons (Changnon 1981). Some nineteenth-century stations have no modern analog. Tests for homogeneity could not be applied directly to the nineteenth-century data because many nineteenth-century stations had records of less than ten years, gaps appeared in many records, and some stations changed their locations. Continuous records, as well as many reference sites around the meteorological station being tested, are needed for conducting homogeneity tests (Alexandersson 1986). Unless any modern analog stations suggest that their respective nineteenth-century stations may not be homogeneous, the nineteenth-century meteorological data are assumed to be homogeneous in relation to their respective climatic regions.

The Great Plains are not expected to behave as a single unit with respect to annual or seasonal climatic fluctuations because many climatic mechanisms are involved (Rosenberg 1986). A cluster analysis of modern analog stations depicted climatic regions that behave homogeneously on an annual basis. For the analysis, a matrix consists of twelve months as the variables and the analog stations as the cases. Cases were grouped according to their Euclidean distances, with similar stations being grouped first and dissimilar ones grouped last. Stations dissimilar to adjacent stations were regarded as not homogeneous. They, along with their nineteenth-century equivalents, were eliminated from the data set.

Nineteenth-century stations were assigned to the regions identified by the cluster analysis. I assumed that little spatial climatic variation occurred within each region, and that all stations in a region responded similarly to the same mechanisms. On rare occasions, a few stations reported much higher precipitation than nearby stations. These data may distort anomaly signs for an entire climatic region. Conservatively, I eliminated any seasonal precipitation percentages from stations that were 200% higher than any other stations in the same climatic region. Clearly, these data are not homogeneous, although errors in measurement and recording are also possible (Bradley and Barry 1973). This filter was applied only to climatic regions and periods that had at least four stations in operation.

The next part of the analysis involved detection of past drought for each climate region. Unfortunately, no uniform definition of drought exists (Dracup et al. 1980). Hydrologists are mostly concerned with streamflow anomalies, meteorologists with precipitation deficits, and economists with the impact of drought on society. Lawson et al. (1971) discussed several different definitions of drought that have been applied to the Great Plains. Dracup et al. (1980) suggested that definitions of drought should consider the kind of drought of interest to the researcher (e.g., hydrological drought), the fundamental averaging period of time being studied, how drought events are distinguished from other events, and how the regional aspects of drought are considered. In this study, the types of drought of interest are those that may have affected the cattle industry and agricultural systems during settlement. Seasonal droughts are considered here, based on precipitation: spring/summer drought, fall/winter drought, and annual drought. Each of these three types may have affected different societies living in the Great Plains.

Spring and summer precipitation are important to many agricultural crops in the Plains. Potential evapotranspiration is highest during summer, and more precipitation than in winter is needed to meet water demand. Summer precipitation equal or less than 80% of normal occur in the Great Plains during severe drought (Borchert 1950, 1971). Borchert (1950) also showed that low spring precipitation percentages also characterize drought,

although not as clearly as summer percentages. Many portions of the Plains receive their annual maximum of precipitation during the spring. Bamforth (1988) suggested that spring precipitation plays an important role in affecting grassland productivity. This study used Borchert's definition, as compared to 1951-1980 normals, and required a spring deficit during the same year. A year was defined as a typical calendar year from January to December. To be conservative, the definition of a spring/summer drought also required that only one of the seasons of early fall, late fall, and winter for a drought year can have a precipitation percentage above normal (100%), and it cannot exceed 150%. This step was applied in order to eliminate years when short, extremely wet periods of a month or two supply abundant water to the soil. Water from wet periods recharge moisture during the following dry months. One season was allowed to exceed 100% of normal because positive precipitation anomalies are not uncommon for a few months during a drought year. For example, above-normal June precipitation occurred in Kansas between the dry winter and summer of 1932 (Bonnifield 1979).

Fall/winter droughts have not been defined in any previous studies for the Great Plains. Although spring/summer droughts may have greater impact on society, fall/winter droughts should not be ignored. Fall precipitation and winter snowfall most likely played an important role in maintaining lake and river levels during the nineteenth century. Wheat and some garden crops commenced growth in the fall and winter in some areas of the Great Plains and the growing season might have extended to as long as eleven months in some areas of the southern Great Plains (Rosenberg 1986). The definition of a fall/winter drought also used the criteria of 80% or less precipitation compared to 1951-1980 normals in order to be consistent. All three seasons of early fall, late fall, and winter had to meet this criteria to classify a fall/winter drought. In addition, only spring or summer could have a precipitation percentage greater than 100%, and it also must not exceed 150% of normal. Annual droughts were defined as years that have both spring/summer and fall/winter droughts.

Time series of annual precipitation from nineteenth-century stations with no modern analog were analyzed qualitatively to confirm implications of regional spring/summer, fall/winter, and annual droughts. Low annual precipitation should correspond with any of the three types of drought in this study because negative anomalies are required for at least four seasons of the year. Each time series should show distinct minima during years when drought occurred. For example, the time series for Wallace, KS suggests that 1873 is a drought year (Fig. 2). Any disagreements between qualitative and quantitative approaches do not indicate that drought did not occur. However, the qualitative results indicate that such a drought may have been moderate instead of severe or extreme. Any moderate

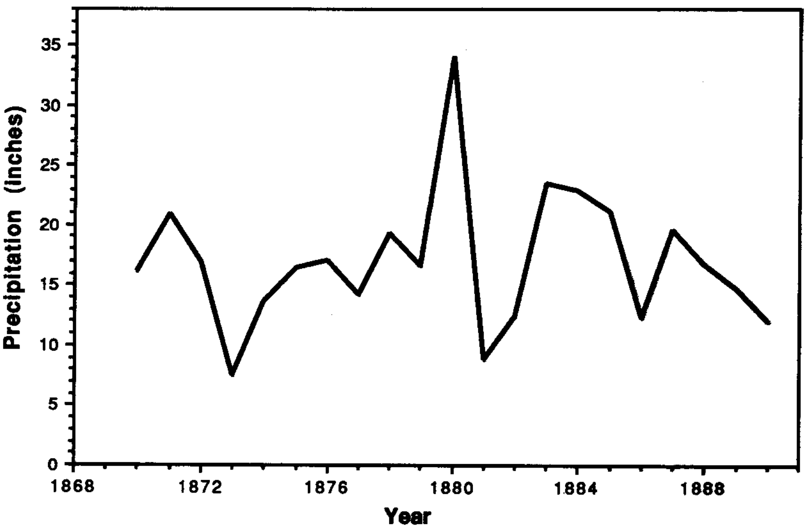

Figure 2. Annual precipitation at Wallace, Kansas.

droughts were noted in the results.

Analyses of seasonal changes of precipitation for each climatic region involved constructing histograms indicating seasonal precipitation percentages compared to 1951-1980 normals for each year. These analyses used the same seasons of winter, spring, summer, early fall, and late fall defined earlier. They were performed only on continuous data within each climatic region that had at least two stations in operation. Precipitation percentages were preferred over actual amounts of precipitation because a few stations within climatic regions may have precipitation amounts several inches different than the regional average. Since the number of stations changed many times during the nineteenth century for each climatic region, reconstructed regional precipitation amounts through time are not comparable to each other. However, all of the stations within a climatic region are expected to behave similarly to climatic change, and precipitation percentages with respect to modern normals would reflect these changes. This procedure of using precipitation percentages has been applied to early meteorological data in other parts of the world (Craddock 1976).

Results

Climatic Regions

The cluster analysis of modern data yielded nine climatic regions (Fig. 3). A gradient was aligned from eastern Montana and the Dakotas southeastward to the southern Plains. Climagraphs for eastern Montana and the Dakotas show a distinct peak of June precipitation. Most of this precipitation comes from storms that originate from cyclogenesis in Alberta (Whittaker and Horn 1984). The June peak is less evident in the central Plains, central Nebraska/Kansas, eastern Nebraska, and eastern Kansas. The sharp gradients in central Nebraska/Kansas, eastern Nebraska, and eastern Kansas may be partially due to the large number of stations, but they also reflect high thunderstorm frequency during June and July (Changnon 1988). Stations in eastern Nebraska, eastern Kansas, and the southern Plains have bimodal precipitation distributions, with secondary peaks in August for eastern Nebraska, and in September for eastern Kansas and the southern Plains. Secondary precipitation peaks for eastern Nebraska, eastern Kansas, and the southern Plains are caused by the subtropical jet. It brings moisture from southwest of Texas (Bomar 1983). Occasionally, remnants of tropical storms and hurricanes from the eastern Pacific and the western Atlantic also dump precipitation in these regions during the fall.

An east-west precipitation gradient is also evident in the study area. Although June is the wettest month for the central Plains, central Nebraska/Kansas, eastern Nebraska, and eastern Kansas, May is a close second. May is the wettest month of the year for eastern Wyoming and northeastern Colorado, and the southern Plains. May precipitation is also higher in eastern Montana and western North Dakota than in the North and South Dakota region. The climagraph for southeastern Colorado and eastern New Mexico shows a secondary precipitation peak for May. Increases of spring precipitation, which are best reflected in May, originate from cyclogenesis on the leeward side of the Rocky Mountains (Whittaker and Horn 1984). Precipitation is lower during summer than during spring and fall in the southern Plains because hot, dry air masses enter the region from northern Mexico. Southeastern Colorado and eastern New Mexico have a precipitation peak in July. This peak shows the influence of the summer monsoon when moisture from the Gulf of Mexico is transported along the eastern edge of the southern Continental Divide (Tang and Reiter 1984).

Winter precipitation is low in all of the climatic regions. No distinct gradients of winter precipitation were detected except perhaps for the

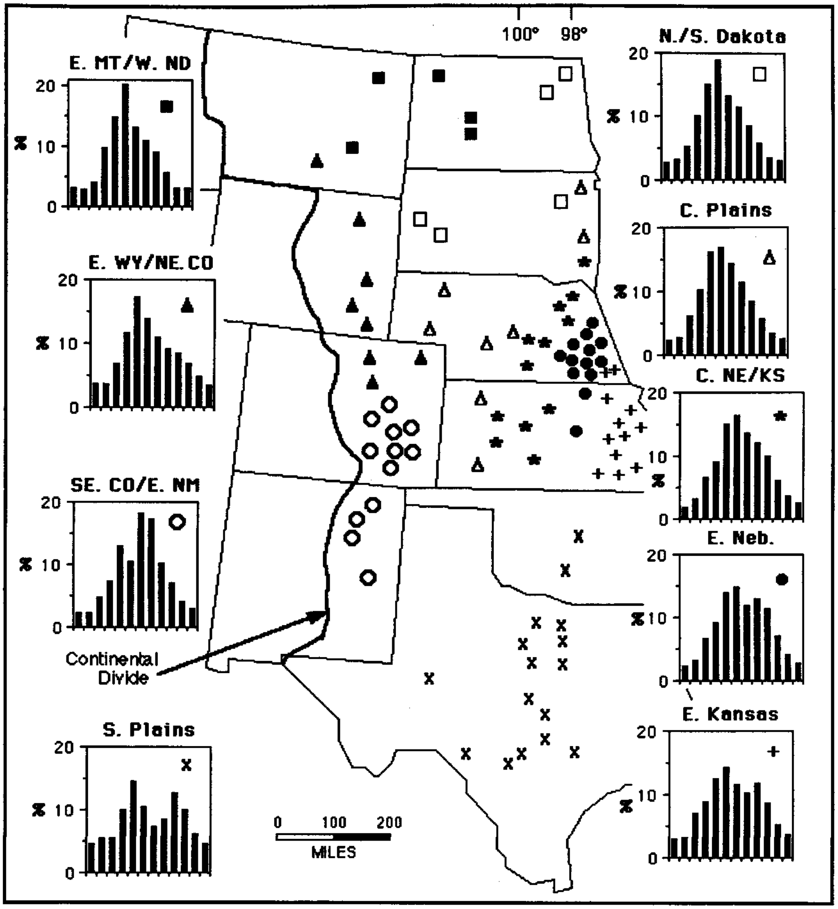

Figure 3. Climatic regions according to a cluster analysis of modern analog stations. Climagraphs refer to monthly percentages of annual precipitation from January (left) to December (right).

southern Plains. More moisture from the Gulf of Mexico and warmer temperatures may intensify cyclonic storms originating in eastern Colorado and New Mexico. Low winter precipitation percentages suggest that precipitation departures from other seasons during the course of a year may exhibit higher variability.

Patterns of Nineteenth-Century Drought

Drought did not occur synchronously throughout the Great Plains during the latter half of the nineteenth century (Table 2). If a 16-22 year cycle exists, widespread drought would have occurred in the early 1870s as inferred from the occurrences of widespread droughts in the 1890s, 1910s, 1930s, 1950s, and 1970s. Drought did occur in the central Plains, central Nebraska and Kansas, eastern Kansas, eastern Nebraska, and eastern Wyoming/northeastern Colorado during the early 1870s (Table 2). It was most widespread in 1872 and 1873, but limited to three climatic regions. Although all of the severe droughts of the twentieth century occurred in at least four states, they were not equally widespread spatially nor were they of equal magnitude (Borchert 1971; McGregor 1985; Oladipo 1986). Numerous occurrences of drought during the 1850s, 1860s, and 1880s suggest that inferred cycles of widespread drought are tenuous at best. Most of the seasonal precipitation percentages for climatic regions during drought years prior to 1861 are less than 70%.

Since drought appears to follow no simple pattern in time or space, probabilities on the occurrences of drought for each climatic region were calculated. Probabilities for each climatic region are represented by the number of droughts divided by the length in years of the instrumental record. A drawback to this analysis is that lengths of instrumental records for most climatic regions differ. Probabilities would not be comparable between different climatic regions if drought occurrences exhibited distinct interdecadal climatic variability. However, occurrences of drought strongly suggest temporal trends within shorter time scales of a few years (Table 2). Therefore, differences in the lengths of instrumental records between the climatic regions should not distort comparisons of drought probabilities.

Diaz's (1983) analysis implies that the central portion of the Great Plains often experiences more frequent and longer drought than areas to the north and south. McGregor (1985) and Thompson (1990) derived similar results, with central Nebraska and Kansas having the highest probabilities for drought. This spatial pattern appears to have been true during the latter half of the nineteenth century as well. Probabilities are highest in the central portion of the study area, comprising the climatic regions of eastern Wyoming/northeastern Colorado, the central Plains, central Nebraska/Kansas, eastern Nebraska, and eastern Kansas (Table 3). Probabilities decrease from the center of the Plains to the south and east. Probabilities for southeastern Colorado/eastern New Mexico and the southern Plains are lower while probabilities for eastern Montana and the Dakotas are zero. However, instrumental records for the northern regions are limited, extending back only to the early 1870s.

A spatial pattern of drought types appears to exist from west to east.

TABLE 2

*DROUGHTS DURING THE LATE NINETEENTH CENTURY**

				CLIMATIC REGION					
Year (1800s)	E. MT/ W. ND	ND/ SD	E. WY/ NE. CO	C. Plains	C. NE/ KS	E. NE	E. KS	SE.CO/ E. NM	S. Plains
51	--	--	--	--		--			
52	--	--	--	--		--			
53	--	--	--	--		--			
54	--	--	--	--		--	FW		
55	--	--	--	--		--			
56	--	--	--	--		--			
57	--	--	--	--		--			
58	--	--	--	--					
59	--	--	--	--	SS				SS
60	--	--	--	--	A	--	SS		
61	--	--	--	--	SS	--			
62	--	--	--	--		--			FW
63	--	--	--	--		--		SS	
64	--	--	--	--	--	--	SS		
65	--	--	--	--		--			
66	--	--	--	--	--	--	SS	--	
67	--	--	--		FW	--		FW	
68	--	--	--	SS		--			
69	--	--		SS					
70	--		FW			SS			
71	--			SS				SS	
72	--			FW	A		FW		
73	--		FW		*FW	FW			
74							SS		
75						FW			
76				*SS					
77									
78									
79			FW					*FW	FW
80							FW		

TABLE 2 (CONT.)

Year (1800s)	E. MT/ W. ND	ND/ SD	E. WY/ NE. CO	C. Plains	C. NE/ KS	E. NE	E. KS	SE.CO/ E. NM	S. Plains
81									
82			FW						
83									
84									
85									
86				SS					
87							SS		
88									
89									
90			*FW	A	A	FW		*FW	

*SS = Spring/Summer drought, FW = Fall/Winter drought, A = Annual drought, "- -" indicates that little or no data were available. Asterisks indicate that a drought may have been moderate instead of severe according to station records with no modern analog.

TABLE 3

DROUGHT PROBABILITIES FOR EACH CLIMATIC REGION DURING THE LATE NINETEENTH CENTURY

Region	#	Yrs	Prob
E. MT & W. ND	0	17	0.00
ND & SD	0	21	0.00
E. WY & NE. CO	5	22	0.23
CENTRAL PLAINS	7	24	0.29
CENTRAL NE & KS	7	38	0.18
E. NE	4	24	0.17
E. KS	8	40	0.20
SE. CO & E. NM	5	39	0.13
SOUTH PLAINS	3	40	0.08

All of the droughts in eastern Wyoming/northeastern Colorado are fall/winter droughts (Table 2). Annual droughts occurred only in the central Nebraska/Kansas and the central Plains. Spring/summer drought was more frequent in this area, particularly for the central Plains. Southeastern Colorado/eastern New Mexico, the southern Plains, and eastern Kansas also had mixed occurrences in spring/summer and fall/winter drought. Out of the eight droughts detected for eastern Kansas, five were spring/summer droughts. During drought years, negative precipitation anomalies were more predominant during fall and winter in the western central climatic regions than in the central, southern, and eastern climatic regions. Spring/summer droughts occurred more frequently towards the south and east. To date, no studies have been done to determine whether similar spatial patterns on drought types occurred during the twentieth century. Such information from both nineteenth-century and modern climate data may provide insight on seasonal, synoptic mechanisms that cause severe drought in particular climatic regions.

Comparisons with Dendroclimatic Studies

Most dendroclimatic studies within and nearby the study area have focused on annual precipitation fluctuations, defined different climatic regions, and defined a year in other than a calendar basis (e.g., Blasing and Duvick 1984). Comparisons of dendroclimatic reconstructions with the seasonal precipitation trends identified in this study were therefore difficult. However, dendroclimatic comparisons with drought occurrences discussed above is possible, particularly for spring/summer drought since all of the climatic regions receive much of the annual precipitation percentage during these seasons. Dendroclimatic comparisons with fall/winter droughts may not be as clear, but the requirement of a minimum of four negative seasonal precipitation anomalies during a drought year will often correspond with low annual precipitation.

Dendroclimatic reconstructions for eastern Montana and the western Dakotas show no evidence of severe drought (Lawson 1974; Stockton and Meko 1983). Reconstructions from sites in eastern Wyoming illustrate that several drought years occurred during the late 1860s and early 1870s (Stockton and Meko 1983). These interpretations are consistent with results from the nineteenth-century data, but the eastern Wyoming tree rings do not indicate severe drought in 1879 and 1881. Also, tree-rings within the southeastern Colorado/eastern New Mexico region show no signs of any severe drought during the late nineteenth century (Lawson 1974).

Dendroclimatic evidence from the central portion of the study area generally agree with indications of drought in the nineteenth-century data,

but some disagreements exist. Duvick and Blasing implied that Western Iowa experienced drought during the late 1850s (Duvick and Blasing 1981; Blasing and Duvick 1984). Narrow tree rings in eastern Nebraska throughout most of the 1850s and to the mid-1860s, might indicate low summer precipitation and severe drought (Lawson et al. 1980). This dendroclimatic evidence is consistent with this study's implication of severe drought in the late 1850s and 1860 in central Nebraska/Kansas and eastern Kansas. Western Nebraska experienced severe drought in 1861-1863, with 1862 being an extremely dry year (Weakly 1943). The central Plains climatic region may have experienced later drought than nearby regions, or Weakly's chronology may be inaccurate. However, Weakly's implications of severe drought in 1871, the early and mid-1870s, 1879, and 1886 agree with nineteenth-century data from the central Plains and adjacent regions.

The instrumental record for the southern Plains shows that drought occurred in 1859, 1862, and 1879. Dendroclimatic reconstructions for Texas and Oklahoma show low annual precipitation during the 1850s to early 1860s (Stockton and Meko 1983; Stahle and Hehr 1984; Blasing et al. 1988). However, a minor dry period occurred in the late 1880s (Stahle and Herr 1984; Blasing et al. 1988). Other dendroclimatic studies suggested severe droughts in 1855, 1859, 1879, and 1886 in central Oklahoma (Harper 1960), and in 1855, 1857, 1859, 1862, and 1887 in northern Texas (Stahle and Cleaveland 1988). Dendroclimatic and instrumental data agree on the droughts of 1859 and 1862. The drought of 1879 may have been restricted northward since it also occurred in eastern Wyoming/northeastern Colorado, and southeastern Colorado/eastern New Mexico (Table 2). However, the droughts of 1855, 1886, and possible minor drought in the 1880s were not detected by the nineteenth-century data.

The foregoing discussion indicates that dendroclimatic and instrumental data do not always agree on drought occurrence. However, they agree enough to suggest that premodern instrumental records can provide valuable information on past drought, and confirm that simple drought cycles across the region are not evident. Stockton and Meko (1983) inferred 58-year drought cycles for southeastern Montana and eastern Wyoming, a 22-year cycle for Iowa, and a 17-year cycle for Oklahoma. However, they also noted that periodicities of drought exhibited variability through time. Meko et al. (1985) suggested an 18-year cycle for the western corn belt. Currie and O'Brien (1990) differ slightly by suggesting an 18.6-year drought cycle for the corn belt. Blasing et al. (1988) detected an 18-19 year drought periodicity in the southern Plains, but they noted that it was rather unstable through time. The nineteenth-century instrumental record roughly support the notion of drought cycles for the northern Plains, for the central Plains only after the late 1860s, and not for Oklahoma (perhaps due to the lack of instrumental data from Oklahoma).

Seasonal Precipitation Fluctuations in the Late Nineteenth Century

All of the seasonal trends of precipitation percentages compared to modern values show variability at short time scales of a few years (Figs. 4-8). Precipitation for each region fluctuates around a central tendency, which in turn fluctuates within decadal time scales. The purpose of this section is to discuss decadal trends in anomaly patterns and determine the climate patterns that may have been responsible.

Winter precipitation percentages for all climatic regions south of eastern Montana and the Dakotas generally indicate dry conditions (Fig. 4). The record for eastern Kansas shows dry conditions during the 1860s, opposite to Wahl and Lawson's (1970) interpretation that almost all of the Great Plains, including eastern Kansas, was "decisively wetter." Wahl and

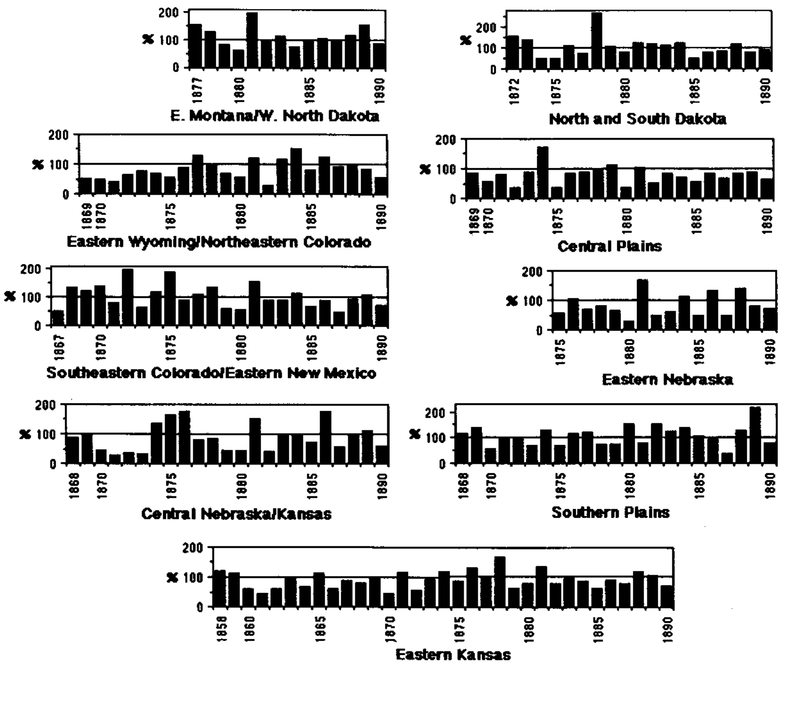

Figure 4. Winter precipitation percentages compared to modern normals (1951-1980) for climatic regions in the late nineteenth century.

Lawson used 1931-1960 normals which included several severe drought years for the Great Plains, but even so such large differences between their results and those of this study should not be apparent. Most likely, parts of the Great Plains were wet, but climatic regions such as eastern Kansas had different anomaly signs than others at the same time. The most distinct periods of wet winters were 1868-1870 for southeastern Colorado/eastern New Mexico and 1870-1874 for central Nebraska/Kansas. Other wet winters were usually preceded or followed by a dry winter. A slight increase of winter precipitation occurred during the 1880s, but temporal characteristics are not consistent. Precipitation was close to normal in eastern Montana/western North Dakota, and North and South Dakota during the early 1880s, in eastern Wyoming/northeastern Colorado during the mid and late 1880s, in central Nebraska/Kansas during the mid-1880s,

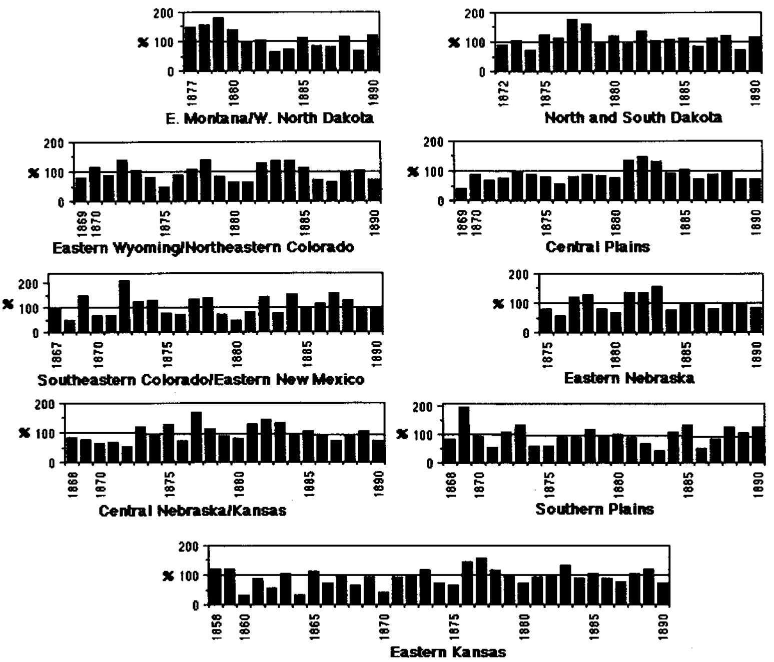

Figure 5. Spring precipitation percentages compared to modern normals (1951-1980) for climatic regions in the late nineteenth century.

and in the southern Plains during the early and late 1880s.

Spring precipitation percentages show that the climatic regions in the central portion of the study area experienced more dry years during the late nineteenth century (Fig. 5). Eastern Kansas experienced more wet springs during the early and mid-1870s to the mid-1880s. Eastern Montana/western North Dakota and North and South Dakota experienced wet springs in the late 1870s. Wet springs did not occur in the central Plains until the early 1880s. Eastern Nebraska and central Nebraska/Kansas experienced some wet springs from 1875-1883. Records for eastern Wyoming/northeastern Colorado, southeastern Colorado/eastern New Mexico, and the southern Plains show considerable variability, but no distinct trends.

Dry summers in the Great Plains were not as numerous compared to

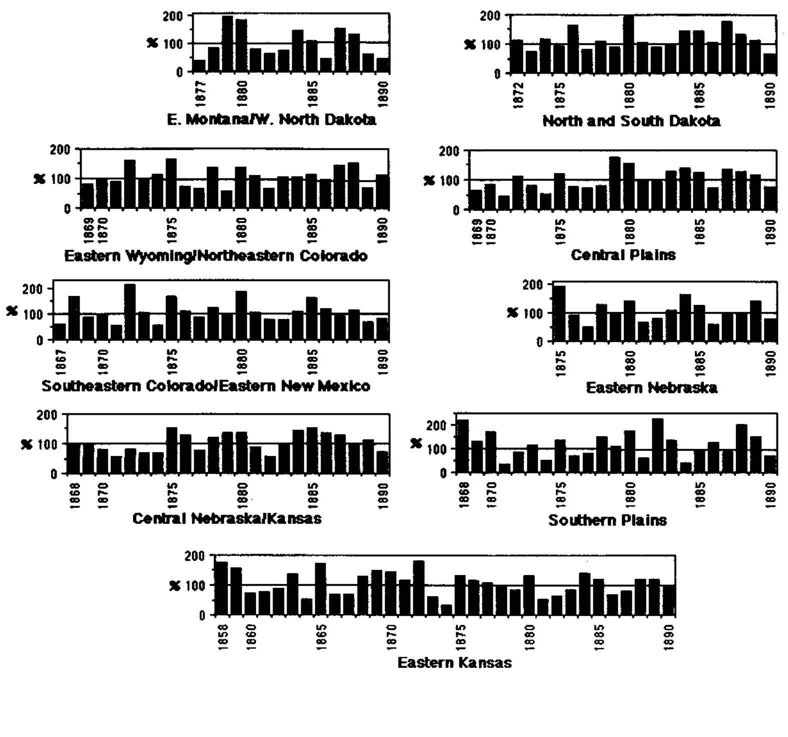

Figure 6. Summer precipitation percentages compared to modern normals (1951-1980) for climatic regions in the late nineteenth century.

the other seasons (Fig. 6). Precipitation trends for the central Plains and central Nebraska/Kansas show that wet summers were more frequent during the mid-1870s and 1880s. Precipitation from the North and South Dakota region may have followed a similar trend, but the record is too short to provide conclusive evidence. Records from the other climatic regions indicate alternating periods of wet and dry summers of a few years with no distinct trends.

Early fall precipitation percentages indicate mostly dry conditions for the Great Plains (Fig. 7). No distinct trends were detected. Only the central Plains, central Nebraska/Kansas, and perhaps southeastern Colorado/eastern New Mexico show that average early fall precipitation may have been close to modern values during the late nineteenth century.

Precipitation was most variable during late fall than in the other

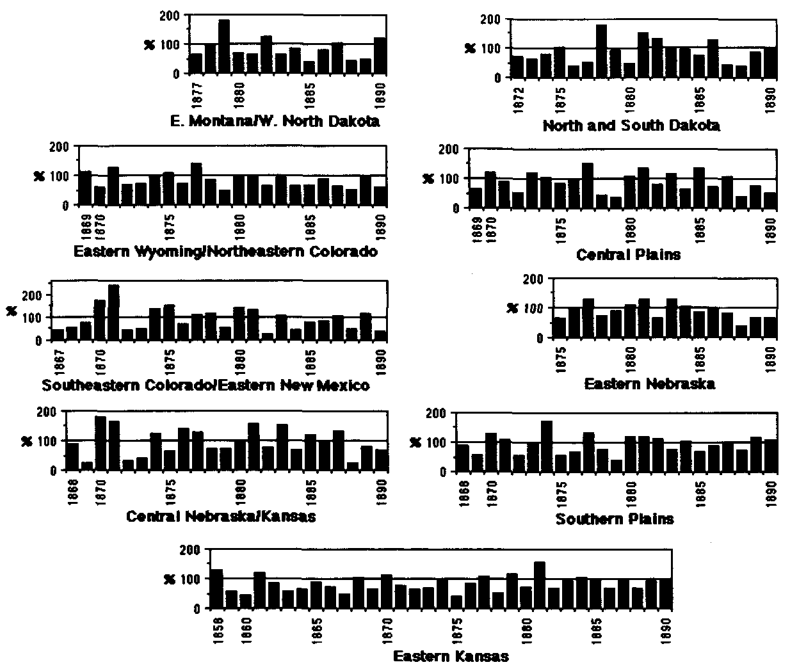

Figure 7. Early fall precipitation percentages compared to modern normals (1951-1980) for climatic regions in the late nineteenth century.

seasons (Fig. 8). In some cases, late fall precipitation exceeded 200% of modern amounts. For example, highly anomalous precipitation occurred during the late fall of 1871 in eastern Wyoming/northeastern Colorado, southeastern Colorado/eastern New Mexico, and central Nebraska/Kansas. However, generally, dry late falls were more numerous than wet ones. The North and South Dakota region has the most late falls that were wetter than normal. Records from eastern Wyoming/northeastern Colorado, southeastern Colorado/New Mexico, central Nebraska/Kansas, and the central Plains indicate very dry conditions in the early 1870s and the late 1880s.

The most noticeable trend is the change from dry to wet during the mid-1870s and 1880s. This trend is most clearly illustrated by summer precipitation data from the central Plains and central Nebraska/Kansas, but

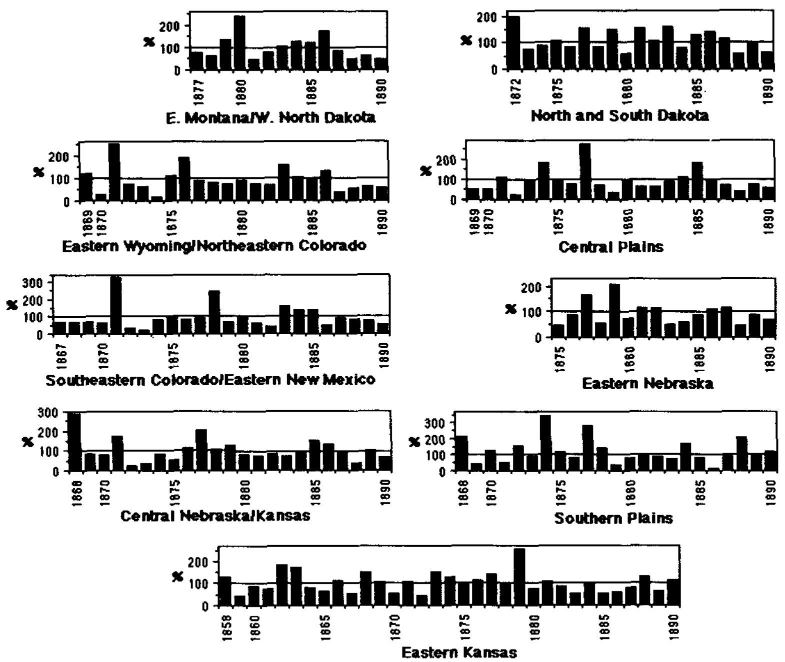

Figure 8. Late fall precipitation percentages compared to modern normals (1951-1980) for climatic regions in the late nineteenth century.

it was also detected in spring data, and to a lesser extent, in winter and late fall data. Increases in precipitation may relate with changes in mid-tropospheric atmospheric circulation. The western Atlantic trough moved steadily eastward from the early 1800s until the period 1845-1884 (Lamb and Johnson 1959). The position of the western Atlantic trough at 45°N was as far west as 56°W during the early 1800s. Wahl (1968) and Wahl and Lawson (1970) showed that cold air invaded the eastern United States during the early and mid-1800s. They suggested that northwest flow at the back side of the trough was responsible. Wahl and Lawson (1970) implied that this climatic pattern persisted until at least 1869. Subsidence and a ridge would be expected west of the back side of the trough, implying dry conditions for the Great Plains. This pattern would be consistent with the results of this study.

Bradley's (1976) analysis of premodern instrumental records for the western United States shows precipitation changes beginning around 1870, but they are restricted to summer. Summer weather in the western United States changed from wet to dry. Most of the precipitation in the United States west of the Continental Divide (excluding the Pacific Northwest) comes from warm, moist air masses in the Gulf of California (Hales 1974). Summer precipitation is low when northwesterly winds from the Pacific intensify and enter the southwestern United States. Increased northwesterly winds would cause shearing, preventing the formation of heat lows (Tang and Reiter 1984). These conditions may have been more frequent after 1870. Furthermore, the simultaneous eastward movement of the western Atlantic trough may have led to a buildup of a ridge along the eastern United States. Both changes may result in a zone of upper-level divergence centered in the middle of the Great Plains, leading to increased precipitation. The same changes may have occurred during winter and spring as well. However, further studies are needed on premodern temperature, wind, and pressure data in the United States to verify these implications.

Conclusions

This study analyzed premodern precipitation records from the Great Plains region of the United States in order to detect past drought and seasonal trends. Drought and precipitation fluctuations showed both regional and temporal variability. Drought occurred in isolated regions, suggesting that no drought since 1868 was as severe as the Dust Bowl in the 1930s. The drought of 1860 may have been severe according to dendroclimatic evidence (Blasing et al. 1988), but the lack of stations in this study cannot verify widespread drought.

Information from this study could be used to analyze climatic impact

on settlement in the Great Plains. Greater summer precipitation relative to the modern norm in the center portion of the Great Plains may have played a big role in the westward expansion of settlement into marginal lands. The Garden Myth may have been popularized by an increase in precipitation around the 1870s. Occurrences of localized drought may have led to the perception that a widespread drought in the Great Plains was not possible. Some farmers may not have planned on the possibility of severe drought, and may have planted corn that was more prone to the 1890s drought hazard than wheat and dairying (McQuillan 1982). Yet, occurrences of severe drought may have affected the cattle industry and agriculture in some areas of the Great Plains before the 1890s. Wilhite (1983) noted that drought relief efforts began as early as 1860. Although this study defined annual, spring/summer, and fall/winter droughts, settlers may have been susceptible to even shorter droughts because of the variety of possible climate impacts. For example, the 1874 grasshopper invasion and drought in the Republican Valley of southern Nebraska and northern Kansas appear in numerous literary accounts (Baltensperger 1979). Data in this study did not detect a drought for this region. However, precipitation percentages for the central Plains in the summer of 1874 illustrate dry conditions (Fig. 6). An extremely dry summer alone may have hampered settlers' attempts at practicing agriculture and reshaped the imagery of the Plains.

To date, no comprehensive synoptic climatological studies on the Great Plains has been done. Questions still remain on synoptic controls of Great Plains drought, particularly for summer. Lawson et al. (1978) and Namias (1955, 1983) suggested that drought in the Great Plains is associated with a 700 mb anticyclone centered in the southeastern United States. Namias (1983) further suggested that effects from the anticyclone depend on a teleconnection between pressure centers in the east central Pacific and the east central Atlantic. If these pressure centers are strong, then intensification of the 700 mb anticyclone in the southeastern United States would occur. A strong 700 mb anticyclone centered north of the western Gulf of Mexico would create a dry, southerly flow to the Great Plains, causing above-normal temperatures. Such a pattern is plausible since summer temperature and precipitation are inversely related (Madden and Williams 1978). However, a shift of the 700 mb anticyclone a few hundred miles eastward would create a flow of warm, moist air from the Gulf of Mexico into the Great Plains.

Other scholars suggested that sea surface temperatures from the tropical Pacific are linked with severe drought (Trenberth et al. 1988; Palmer and Brankovic 1989) and interannual precipitation variability in the Great Plains (Kiladis and Diaz 1989). Results from this study show that precipitation in the Great Plains fluctuates within interannual and decadal

time scales. Borchert (1950) suggested that strong, zonal westerlies are the major cause of severe drought. Most likely, several possible mechanisms are responsible for Great Plains drought due to the extreme variability of precipitation (Barry 1983; McGregor 1985). An understanding of modern relationships between pressure, temperature, and precipitation patterns as well as their magnitudes during drought must be achieved to assess the causes of modern and past drought.

Furthermore, more dendroclimatic studies are needed to fill temporal and spatial gaps. Dendroclimatic studies are lacking in most of the Great Plains interior. Within some of the climatic regions derived from the cluster analysis in this study, no chronologies yet exist. Documentary climatic reconstructions are possible for many regions of the Great Plains where dendroclimatic reconstructions are impossible. However, one must use documentary reconstructions only for answering questions on climate variability, not on historical climate impact assessment. Instrumental observers based at stations used for this study also recorded temperature, wind, relative humidity, occasional pressure, and descriptive data in addition to precipitation. These data have yet to be analyzed within short time scales. Extraction of climatic information from all proxy and historical sources are far from being accomplished, and these eventually will give researchers a full understanding of drought and climate in the Great Plains prior to the twentieth century.

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