A COMPARISON OF DIVISIONAL GROWING SEASON DROUGHT BETWEEN WESTERN AND SOUTHEASTERN SOUTH DAKOTA

Matthew J. Bunkers and James R. Miller, Jr.
Institute of Atmospheric Sciences
Carolyn Hull Sieg
Rocky Mountain Forest and Range Experiment Station
South Dakota School of Mines and Technology
Rapid City, South Dakota 57701-3995
Arthur T. DeGaetano
Northeast Regional Climate Center
Cornell University
Ithaca, New York 14853

ABSTRACT

The recent dry conditions over the northern Great Plains have caused much concern about rapidly changing climatic patterns. Regional climate records are of limited length, generally less than 100 years, and therefore are insufficient to identify periodic fluctuations in climate with confidence. However, these data may be investigated to determine if trends exist in average annual precipitation and temperature records. The purpose of this study was two-fold: first, to identify drought periods based on precipitation records and examine their variability across the state, and second, to identify 10- and 20-year fluctuations in average growing season precipitation and temperature.

The climatic data used in this study encompassed stations in the Northwest, Southeast, and Black Hills Divisions of South Dakota. There were 8 to 14 stations used in each division, with records extending from the early 1900's. Only growing season (April - September) drought conditions were considered. Individual years were compared with the long-term distribution of precipitation for each respective division and drought was defined as a year below the 25th percentile. The Student t-statistic was used to compare means for consecutive epochs (i.e. there are two S-year epochs in a IO-year period) in order to determine if a significant change had occurred between epochs. The 1930's was by far the worst period of drought in the century and exhibited the largest decrease of growing season precipitation in western South Dakota. Significant changes ($P < 0.10$) in the mean temperature and precipitation occur within 10- and

year periods. Spatial gradients were also evidenced across the state of South Dakota. For example, an early-to-mid 1980's wet period was evident over southeastern South Dakota while more average precipitation fell over the western third of South Dakota. Finally, the mean growing season temperature exhibited much more variability at the IO-year time-scale while the mean growing season precipitation fluctuated more at the 20-year time-scale.

INTRODUCTION

Drought has been a major concern over the grain producing areas of the northern Great Plains, especially over the past four to five years. Persistent years of anomalously low rainfall have spurred concern that the climate has been changing towards drier conditions at an accelerated rate. But climate is dynamic, and drought is expected to occur over time.

Drought can have significant impacts upon society and has costs comparable to severe weather episodes such as tornadoes, floods, and hurricanes. The 1988 North American drought had widespread repercussions, including $40 billion in estimated direct. economic losses and costs in the United. States (Orville, 1990). Even the relatively mild 1974-77 North American drought resulted in federal expenditures between $7-8 billion (Wilhite et al., 1986). Drought impacts are often worse in interior portions of the United States since once a serious drought was underway, the probability of recovering or amelioration is usually less than in places farther east or west (Karl et al., 1987). Diaz (1983) and Karl (1983) also found that_ the interior and western portions of the United States experience more periods of anomalously dry and wet 'weather than other parts of the country. Therefore, the Great Plains offers a tremendous opportunity and challenge for meteorologists to attempt climate studies and predictions. However, detecting droughts in advance is nearly impossible at best, due to the many controlling factors that are involved (e.g. the uncertainty of the role of oceanic circulations and the feedback from clouds).

In some instances, knowledge of teleconnections between atmospheric phenomena aids forecasters in predicting drought conditions for certain areas of the country. An example is ENS0 (El Niño Southern Oscillation), which occurs in the Southern Pacific Ocean. This phenomenon is associated with a warming of sea surface temperatures (SST) in the eastern Pacific Ocean in conjunction with changes in the oceanic and atmospheric circulations. During winter months, ENS0 conditions usually favor the development of a stronger than average area of high pressure near the west coast of the United States and anomalously low pressure in the Aleutian Low over the

Gulf of Alaska (Rassmusson and Wallace, 1983). The teleconnections from this global fluctuation are understood quite well, and either drought or deluge can be expected in certain regions of the earth provided that an ENS0 is occurring (Philander, 1990).

A common synoptic feature associated with the 1988 drought in the United States was that the jet stream became displaced northward of its usual position so that the storms tracked further northward (Trenberth et al., 1988). Model results from Trenberth et al. (1988) suggested that persistent global-scale anomalies in the atmospheric circulation set the stage for this drought in the United States, and these were linked with an anomalous distribution of the sea surface temperature (SST) in the Tropical Pacific Ocean that occurred as an aftermath of the 1987 ENSO. The most pronounced effect of ENS0 on South Dakota has been a warmer winter (December - March) during its mature phase (Ropelewski et al., 1986).

It has also been suggested that droughts over the western two-thirds of the United States may be associated with the double sunspot cycle resulting in a tendency for drought recurrence in 20-25 year periods (Namias, 1983). Once again, this has been very difficult to show with confidence and has attained only modest success when climatic records have been extended with climate sensitive tree-ring data. Stockton and Meko (1983) reconstructed drought from tree-rings for Iowa, Oklahoma, eastern Montana and eastern Wyoming for the period of 1700 to 1977. They then used spectral analysis to search for periodicity of drought as related to the 18.6-year lunar nodal cycle and the 22-year Hale double sunspot cycle. Their research revealed that drought averaged over the four separate regions was rhythmic, with an average period near 19 years, but the periodicity was neither characteristic of all regions nor of all segments of the drought record in any region. The reconstructions of Stockton and Meko also indicated that the severe droughts of the 1930’s and 1950’s were at least equaled in magnitude, duration, and regional extent by the following. periods: mid- to-late 1750's, early-to-mid 1820's, mid 1850’s to late 1860's, and 1890’s. This illustrates the fact that the Dust Bowl drought was not unique, and similar occurrences will likely happen again.

Meko et al. (1985) investigated the Corn Belt region of Iowa and Illinois to search for periodicity of drought. A time series of precipitation for 1680 to 1980 was reconstructed from tree-ring data at 15 sites. Periodicity near the 18.6-year lunar nodal and 22-year Hale double sunspot cycles was analyzed, and the results were similar to Stockton and Meko (1983). Although a significant period of drought was found in the western part of the Corn Belt, the component of drought near 20 years was too weak and irregular to be of use in drought forecasting in the Corn Belt. With the short length (≈ 100 years) of observational records confined to this study, a spectral analysis was not considered. Rather, a time series approach was taken to compare the means of precipitation and temperature for consecutive epochs.

Karl and Riebsame (1984) set out to determine if the 1931-82 United States climate record exhibited fluctuations of sufficient scope and magnitude to be useful in empirical studies of climate impacts. The climatological record was searched for the largest differences in the means between consecutive, non-overlapping time intervals ranging from one to two decades by using the Student t-statistic. This "consecutive epoch" approach was applied to the 344 state climatic divisions of the United States for the greatest spatial and temporal differences of temperature and precipitation. Karl and Riebsame (1984) found the period of study to exhibit many 20- to 40-year climate fluctuations of significant magnitude over the period of study. Results indicated that for temperature, the most significant and widespread climatic variations occurred in the summer. They also noted that climate fluctuations of 20 to 40 years duration for temperature, with no significant fluctuations for precipitation, and vice versa, have occurred. Variations of this study were adapted to data from the three climatic divisions of South Dakota in the present study.

In this article, the Southeast, Northwest, and Black Hills Climate Divisions of South Dakota were explored to identify periods of drought and to determine how the means of precipitation and temperature have changed over time. The data were also analyzed spatially to determine if fluctuations have occurred in one division while not being noted in another. DeGaetano and Miller (1990) reconstructed precipitation with tree-ring data from Slim Butte and Custer, South Dakota, from the mid-1600's to present for Custer and the Northwest Climatic Division (NWD). They found with time series analysis and running mean plots that periods of drought and wetness at Custer coincide with similar periods in the NWD. However, during periods of drought and wetness, anomalies tended to be much greater for the NWD than Custer. An attempt was therefore made to compare the divisions to search for spatial gradients across the state of South Dakota.

THE DATA SET

The data for this study consisted of average monthly temperature and total monthly precipitation and were provided by Dr. Al Bender, the state climatologist. These variables were selected since, of all elements relating to drought, temperature and precipitation are the most widely observed and accessible climatic data and contain the longest period of record. It was desirable to have as many stations as possible within each division in order to reduce the bias introduced by dissimilar periods of record and other inhomogeneities such as station relocations and observation time changes. A total of 30 stations confined to three divisions were used in this study (Table 1). Note that the selection of stations per division is more dense than the Historical Climatology Network (HCN), which only has one to five stations in a given division across South Dakota (Karl et al., 1990). It was hoped that the inclusion of additional stations would enhance the climate homogeneity of the divisions and thus reduce the short term variability (i.e., local variation due to storms) forcing the decadal variability to be more pronounced.

Table 1. Stations and divisions included in the study and the beginning years of record for precipitation and temperature (1 - Southeast, 2 - Northwest, 3 - Black Hills). The stations separated by a hyphen have been obtained by taking averages of the two.

Station	Beginning		Station	Beginning	
	Precip.	Temp.		Precip.	Temp.
1) Alexandria	1898	1898	2) Lemmon	1911	1911
1) Armour	1896	1896	- Bison		
1) Bonesteel	1902	1902	2) Ludlow	1924	1924
1) Canton	1896	1896	2) Newell	1908	1908
1) Centerville	1897	1905	2) Redig	1914	1915
1) Marion	1901	1901	3) Custer	1911	1942
1) Menno	1898	1898	3) Deerfield	1909	1950
1) Mitchell	1896	1896	- Rochford		
1) Sioux Falls	1896	1896	3) Dumont	1909	---
1) Tyndall	1900	1900	- Buskala Ranch		
1) Vermillion	1899	1900	3) Lead	1909	1909
1) Wagner	1916	1916	- Deadwood		
1) White Lake	1909	1920	3) Hermosa	1906	1906
1) Yankton	1881	1881	3) Hot Springs	1908	1908
2) Belle Fourche	1906	1906	3) Rapid City	1888	1888
2) Camp Crook	1896	1896	(town)		
2) Dupree	1922	1922	3) Spearfish	1898	1898
2) Faith	1926	1926	- Orman Dam		

Fourteen stations were included in the Southeast Division, while the Black Hills and Northwest Divisions both encompassed eight stations. Record lengths varied considerably among the stations ranging from 110 years at Yankton to 65 years at Faith (Table 1).

Although data at some stations did not begin until after 1900 (e.g. Wagner), the completeness of the remaining years prompted these stations to be included in the calculations. The stations separated by a hyphen in Table 1 were obtained by taking averages of the two during the period of overlap. Averaging was done because one or both of the stations were missing some data and were in close proximity to each other, both geographically and climatologically. Once the entire data set had been collected, quality control was conducted by calculating monthly means for the data and then comparing them with the published annual means contained in the South Dakota Annual Summaries of Climatological Data. The divisional averages were then computed by averaging the divisions' respective stations together for the period April - September in order to represent the growing season precipitation. If more than one month was missing for a given period, that specific year was not included in the averages so sporadic fluctuations of the means would be reduced.

METHODS

Defining Drought

The term “drought” has many different meanings. Members of the agricultural community often refer to it as deficient precipitation amounts during the growing season. However, drought conditions also occur during the winter season and may result in a reduction in runoff that is crucial to replenishing aquifers and reservoirs and initiating spring plant growth. The American Meteorological Society (AMS) states that three months of deficient precipitation is usually the minimum specification for a drought, with typical time scales of a season to a few years (Orville, 1990). Of course, severe droughts can last for many years or even decades, such as the Dust Bowl drought of the 1930's. Oftentimes drought in one region is associated with heavy rain elsewhere. This can be seen even on a small scale such as across the state of South Dakota.

The growing season (April - September) rainfall ranges from 66 - 82% of the annual average over the state of South Dakota. This is crucial to the development of crops which subsequently constitute the livelihood of many Americans in the Great Plains. In this study, drought has been defined as deficient rainfall below the 25th percentile for the April September period of a given year. This definition was intended to reflect the significant impact of drought on Great Plains agriculture, which is dependent upon ample spring and summer rainfall. The 25th percentile rather than a method based on mean precipitation was used to define drought since precipitation tends to deviate from the normal distribution. Also, the median is more robust than the mean. Although the occurrence of drought is based only on the lack of rainfall, exceedingly warm temperatures enhance drought conditions by increasing evapotranspirative water loss. Time series of mean growing season temperatures were therefore examined. Drought years (precipitation below the 25th percentile) in which the growing season temperature exceeded the 75th percentile were classified as severe drought periods.

Time Series Analysis

A procedure (similar to that used by Karl and Riebsame (1984) to analyze the 1931-82 record of divisional data across the United States) was used to detect changes in the precipitation and temperature time series for consecutive 5- and IO-year time periods. Karl and Riebsame (1984) compared the means for consecutive 10- to 20-year periods by using the Student t-statistic and identified three types of climate fluctuations: 1) the largest changes of precipitation or temperature that occurred independently of each other; 2) the largest simultaneous changes of precipitation and temperature; and 3) sharp spatial gradients of climatic conditions. In the present study, the same three types of climate variations were identified using a variation of Karl and Riebsame's methodology. The present study differed from Karl and Riebsame (1984) in that it was limited to consecutive epochs with lengths of either 5 or 10 years, and omitted epochs of intermediate lengths (Karl and Riebsame looked at epochs with lengths of 10 to 20 years; note that two lo-year epochs are equivalent to one 20-year interval). Despite this limitation, the variability in the means should be well represented.

To compare the means of two consecutive epochs, the t-statistic given by Karl and Riebsame (1984) as

$$t_{2,1} = (X_2 - X_1)\, n^{1/2}\, (S_2^2 + S_1^2)^{-1/2}$$

was used under the null hypothesis $H_o: u_1 \approx u_2$. The subscripts indicate the relative epochs. The means and variances are given by X and S^2 respectively and the sample size is denoted by *n*. Diaz and Quayle (1980) used a two-tailed t-test to calculate changes in the means of temperature and precipitation independent of each other for three periods of climatic record. They used the F-ratio test to determine if the variances were equal or not, since the sample sizes were different. This t-statistic is the same for both equal and unequal variances when the sample size *n* is the same for both samples. Therefore, use of the pooled variance or the F-ratio test was not necessary because the sample sizes were equivalent. Table 2 provides an example calculation of the t-statistic. A positive (negative) t-value reveals an (a) increase (decrease) in the mean of precipitation or temperature.

Table 2. Example of T-statistic calculations for two consecutive 5-year epochs of mean precipitation. Epoch 1 and 2 both consist of 5 years, and the 10-year interval of interest is 1930-39.

-Epoch 1	**1930**	**1931**	**1932**	**1933**	**1934**
Epoch 2	**1935**	**1936**	**1937**	**1938**	**1939**
X_1 = 18.6		S_1^2 = 8.0		n = 5	
X_2 = 16.3		S_2^2 = 6.7		t = -1.34	

Assuming two samples are independent and normally distributed, it can be shown that the t-statistic follows a t-distribution (Milton and Arnold, 1990). Klugman (1983) compared two methods for determining climate change. in United States precipitation data and found that such data were autocorrelated (i.e., one observation was dependent upon the previous). Since this violated the assumption of independence, the significance of the t-statistic could not be determined by using the t-distribution table. Therefore, Monte Carlo simulations were used to construct a theoretical distribution of t by which the statistical significance of the t-statistics could be assessed. To find a P-value, each precipitation and temperature time series was randomized 10,000 times allowing the original t-statistic to be compared to the theoretical distribution of those from the randomized series.

Climate fluctuations were identified by the t-statistic associated with difference in the means of consecutive epochs. Positive t-values indicated an inter-epoch increase in precipitation or temperature, while negative values showed a shift toward less precipitation or lower temperature. Since the largest t-statistics were selected from several hundred calculations of the statistic, they should be judged in a purely qualitative manner rather than in a strict statistical sense. The following equation was used to derive a fluctuation index, I, which was used to choose cases in which temperature and/or precipitation exhibited a substantial degree of inter-epoch change

$$I_{jd}=\Sigma(|t_{jd}+\Delta M_{jd}|) + w_{jd},$$

where j and d are the interval and division respectively, t is the statistic, and Ah4 is the inter-epoch difference of the means. w was given a value of 3 for $P < 0.01$; 2 for $0.01 \leq P \leq 0.05$; and 1 for $0.05 \leq P \leq 0.10$. Epochs with indices of four or less were rejected. Also, if three consecutive epochs (e.g. 1910-19, 1911-20, 1912-21) each had an index 4 the epoch with the largest index was selected as being an experimental case. The intent of such a selection procedure was to look for and examine periods with large temperature and precipitation fluctuations rather than to identify every change that occurred. The second set of climate fluctuations were determined by identifying periods in which I_{jd} exceeded four for both precipitation and temperature for a division. Finally, spatial gradients for either precipitation or temperature were assessed by identifying periods where significant I-values in one division were associated with significant I-values of opposite sign in another division.

RESULTS

For the three divisions, the 1930's stood out as the most severe period of drought in the 20th century (Figure 1, Tables 3 and 4). When the effects of deficient precipitation and extremely warm temperatures were both taken into consideration, 1931, 1934, 1936, and 1939 were common to all three divisions (Table 4). This suggested the wide aerial extent of the Dust Bowl drought. There were no other years common among the three divisions for the severe drought episodes. When the Southeast and the Northwest Divisions were compared, the only other corresponding year of severe drought was 1980 (Table 4). This was another widespread Great Plains drought. During the height of the 1980 summer heat wave, temperatures averaged as much as 8.1°F above average and precipitation was 25% of average over the Central and Southern plains (Namias, 1983). The only other common year of severe drought among the divisions was 1988 in which drought affected both the Black Hills and the Northwest Climate Divisions (Table 4) The Black Hills Division appeared to behave very independently from the other two divisions. Only in the extreme case of the 1930's did broad similarities exist among them. DeGaetano et al. (1990) found similar results for the extreme events. It is likely that the Black Hills topography induces rainfall that would otherwise not occur over the plains. The other years of general drought that were in common for the three divisions were 1924, 1930, and 1980 (note the bold years in Table 3).

There was no consistent pattern for drought in a single division or among the divisions. The Southeast Division experienced prolonged drought during the 1920's, 1030's 1950's and 1970's (Figure la). The Black Hills Division differed in that prolonged drought conditions existed in the 1930's and the 1980's (Figure lb). The Northwest Division was different than the other two and exhibited patterns with prolonged drought conditions in the 1910's, 1930's, and 1980's (Figure lc). The data (Figure 1, Table 3) illustrate that the climate is notably different between the west and the southeast, possibly owing to large-scale atmospheric circulations. The variability among the Black Hills Division and the other two may be due to the orographic effects of the division. Among possible explanations for the variability between the west and the southeast may be the influence of ENS0 on the large scale atmospheric circulation patterns, which ultimately affect the storm tracks (mesoscale convective complexes (MCCs) are another possible explanation).

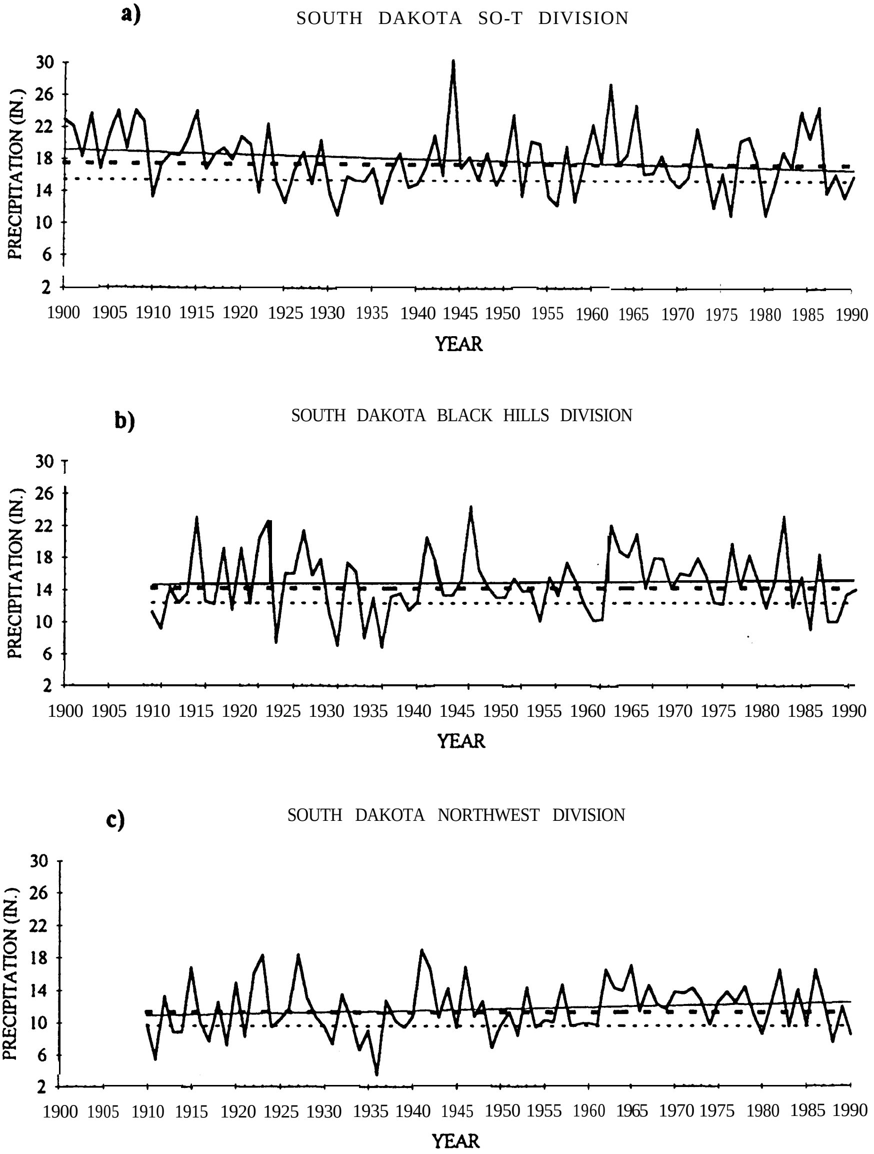

Figure 1. Growing season (April September) precipitation versus time for the three divisions. The time series plot of rainfall versus time is indicated by the dark solid line. The thin shaded line is the least squares fit for rainfall versus time. The bold dashed line is the median rainfall and the thin dotted line is located at the 25th percentile.

Table 3. brought years based on the 25th percentile. Dates are arranged from the driest year to the least dry. Dates in bold-faced type are those years that coincide with the other two divisions.

Southeast	Black Hills	Northwest
1931, 1976		
1980, 1974	1936, 1931	1936, 1911
1956, 1936	**1924,** 1934	1934, 1949
1925, 1958	1985, 1911	1919, 1931
1910, 1989	1987, 1988	1988, 1917
1952, 1955	1954, 1960	1921, 1952
1922, 1987	1961, **1930**	**1990, 1980**
1930,1939	1910, 1939	1913, 1914
1970, 1949	1919, **1980**	1935, 1945
1981, 1928	1983, 1975	**1924,** 1954
1940, **1924**	1959, 1917	1939, 1930
1934, 1947	1921, 1913	1983, 1958

Table 4. Years with deficient rainfall and warm temperatures (severe). Dates are arranged chronologically from earliest to most recent. Dates in bold-faced are those that coincide with the other two divisions.

Southeast	Black Hills	Northwest
1922		
1925		
1930		
1931	1910	1914
1934	1911	**1931**
1936	1913	**1934**
1939	1919	**1936**
1949	1921	**1939**
1955	**1931**	1949
1970	**1934**	1952
1976	**1936**	1980
1980	**1939**	1988
1987	1988	1990

No significant trend was evident in the precipitation or temperature time series for the length of observational record (Figure 1). The correlation coefficients for precipitation versus time ranged from -0.179 for the Southeast Division to a +0.149 for the Northwest Division. Similarly, the correlation coefficients for temperature versus time (least squares regression not shown) ranged from a +0.228 for the Southeast Division to a -0.398 for the Black Hills Division. However, precipitation and temperature were better correlated. A correlation analysis was run between temperature and precipitation for the April - September period for each of the three divisions. These correlation coefficients ranged from a -0.36 to a -0.43 for the three divisions. This was in agreement with Namias (1983), who found that the negative correlations between temperature and precipitation have exceeded -0.60 and even -0.80 in records over the 26 summers extending from 1947 to 1972. These findings suggest that summer droughts over the Great Plains are usually associated with high temperatures, but the correlation coefficients are too low to offer any forecasting capability.

A large number of epochs showed significant changes in the means of precipitation and temperature when considered independently (Table 5). Three to-eight epochs were contained in each category with fluctuations spanning the period of record. In the Southeast division (Table 5, Figure 2a), the 5-year epoch 1905-09 received 4.59 inches less of growing season rainfall on the average than the 5-year epoch 1910-14 (P < 0.01). Thus a significant change in rainfall occurred in the 10-year interval extending from 1905- 14.

Table 5. Epochs of significant change for the means of precipitation and temperature for 10- and 20-year climate fluctuations (epoch lengths of 5 and 10 years, respectively) according to the Student t-statistic for the three South Dakota divisions. The 5-year fluctuations for precipitation and temperature are listed first for each division. The 10-year fluctuations are listed immediately afterward. The interval of significant change in the means is listed in the second column with the t-statistic, P-value, difference in the means, and the variable of consideration following.

SOUTHEAST DIVISION					
Epoch	**Interval**	**f-statistic**	**P-value**	**Diff. in Means**	Variable
5-year	**1905-09 vs. 1910-14**	**-2982**	**0.01**	**-4.59 inches**	P
	1917-21 vs. 1922-26	**-1.854**	**0.04**	**-3.31 inches**	P
	1937-41 vs. 1942-46	**+1.541**	**0.05**	**+4.18 inches**	P
	1950-54 vs. 1955-59	**-1.640**	**0.04**	**-3.71 inches**	P
	1955-59 vs. 196064	**+2.280**	**0.01**	**+5.51 inches**	P
	1961-65 vs. 1966-70	**-2245**	**0.03**	**-4.88 inches**	P
	1977-81 vs. 1982-86	**+1.775**	**0.06**	**+4.13 inches**	P
5-year	**1903-07 vs. 1908-12**	**+1.996**	**0.02**	**+1.56 F**	T
	1910-14 vs. 1915-19	**-1.887**	**0.04**	**-1.52 F**	T
	1914-18 vs. 1919-23	**+2.059**	**0.03**	**+2.02 F**	T
	1925-29 vs. 1930-34	**+3.187**	**0.01**	**+2.80 F**	T
	1937-41 vs. 1942-46	**-4.312**	**0.01**	**-3.05 F**	T
	1950-54 vs. 1955-59	**+1.925**	**0.01**	**+2.58 F**	T
	1977-81 vs. 1982-86	**-2.105**	**0.01**	**-1.44 F**	T
	1981-85 vs. 1986-90	**+ 2.336**	**0.05**	**+1.75 F**	T
10-year	**1900-09 vs. 1910-19**	**-2455**	**0.04**	**-295 inches**	P
	1906-15 vs. 1916-25	**-1.659**	**0.08**	**-2.51 inches**	P
	1914-23 vs. 1924-33	**-3.150**	**0.01**	**-3.98 inches**	P
	1920-29 vs. 1930-39	**-1.913**	**0.03**	**-2.46 inches**	P
	1932-41 vs. 1942-51	**-2161**	**0.03**	**+3.45 inches**	P
	1949-58 vs. 1959-68	**+1.701**	**0.05**	**+2.96 inches**	P
	1957-66 vs. 1967-76	**-2.086**	**0.01**	**-3.49 inches**	P
	1967-76 vs. 1977-86	**+ 1.913**	**0.04**	**+ 3.09 inches**	P
10-year	**1915-24 vs. 1925-34**	**+2.583**	**0.01**	**+224F**	T
	1920-29 vs. 1930-39	**+ 3.721**	**0.01**	**-2.72 F**	T
	1932-41 vs. 1942-51	**-4.134**	**0.01**	**-3.18 F**	T

BLACK HILLS DIVISION					
Epoch	Interval	f-statistic	P-value	Diff. in Means	Variable
5-year	1910-14 vs. 1915-19	+1.461	0.07	+3.59 inches	P
	1925-29 vs. 1930-34	-2.317	0.05	-5.41 inches	P
	1936-40 vs. 1941-45	+2.439	0.01	+4.46 inches	P
	1957-61 vs. 1962-66	+ 2.946	0.02	+5.75 inches	P
	1980-84 vs. 1985-89	-1.229	0.10	-3.28 inches	P
5-year	1925-29 vs. 1930-34	+3.310	0.01	+3.04 F	T
	1937-41 vs. 194246	-5.352	0.01	-4.08 F	T
	1952-56 vs. 1957-61	-2.287	0.04	-1.75 F	T
	1959-63 vs. 1964-68	-1.967	0.03	-1.82 F	T
	1964-68 vs. 1969-73	+2.695	0.02	+1.91 F	T
	1971-75 vs. 1967-80	+ 2.787	0.03	+1.80 F	T
	1977-81 vs. 1982-86	-4.205	0.01	-2.92 F	T
	1981-85 vs. 1986-90	+2.100	0.05	+2.10 F	T
10-year	1910-19 v.s 1920-29	+ 1.551	0.05	+3.00 inches	P
	1920-29 vs. 1930-39	-2.774	0.01	-5.06 inches	P
	193140 vs. 1941-50	+ 2.523	0.01	+4.16 inches	P
	1942-51 vs. 1952-61	-1.856	0.04	-2.47 inches	P
	1952-61 vs. 1962-71	+ 3.836	0.01	+4.38 inches	P
	1962-71 vs. 1972-81	-1.923	0.05	-2.31 inches	P
10-year	r1915-24 vs. 1925-34	+2.096	0.01	+1.87 F	T
	1920-29 vs. 1930-39	+4.229	0.01	+3.05 F	T
	1932-41 vs. 1942-51	-5.144	0.01	-4.44 F	T
	1959-68 vs. 1969-78	+2.000	0.02	+1.33 F	T

NORTHWEST DIVISION					
Epoch	Interval	t-statistic	P-value	Diff. in Means	Variable
5-year	1925-29 vs. 1930-34	-1.777	0.05	-3.35 inches	P
	1935-39 vs. 1940-44	+ 2.376	0.03	+5.25 inches	P
	1942-46 vs. 1947-51	-1.832	0.02	-3.31 inches	P
	1957-61 vs. 1962-66	+2.710	0.02	+3.84 inches	P
5-year	1910-14 vs. 1915-19	-2.152	0.03	-2.24 F	T
	1925-29 vs. 1930-34	+ 4.270	0.01	+3.13 F	T
	193741 vs. 194246	-3.930	0.01	-2.58 F	T
	1959-63 vs. 1964-68	-2.314	0.04	-1.62 F	T
	1964-68 vs. 1969-73	+2.456	0.01	+1.62 F	T
	1971-75 vs. 1976-80	+2.773	0.01	+1.87 F	T
	1977-81 vs. 1982-86	-2.655	0.01	-1.80 F	T
	1981-85 vs. 1986-90	+1.787	0.05	+1.64 F	T
10-year	1910-19 vs. 1920-29	+1.981	0.03	+3.09 inches	P
	1920-29 vs. 1930-39	-2.627	0.01	-3.86 inches	P
	1929-38 vs. 1939-48	+2.53	0.01	+ 3.63 inches	P
	1937-46 vs. 1947-56	-2.036	0.03	-2.61 inches	P
	1947-56 vs. 1957-66	+2.018	0.02	+2.30 inches	P
	195261 vs. 1962-71	+ 3.63	0.01	+3.25 inches	P
	1962-71 vs. 1972-81	-1.991	0.02	-1.69 inches	P
10-year	1915-24 vs. 1925-34	+2.040	0.01	+1.76 F	T
	1920-29 vs. 1930-39	+ 4.87	0.01	+3.17 F	T
	1932-41 vs. 1942-51	-3.716	0.01	-2.70 F	T

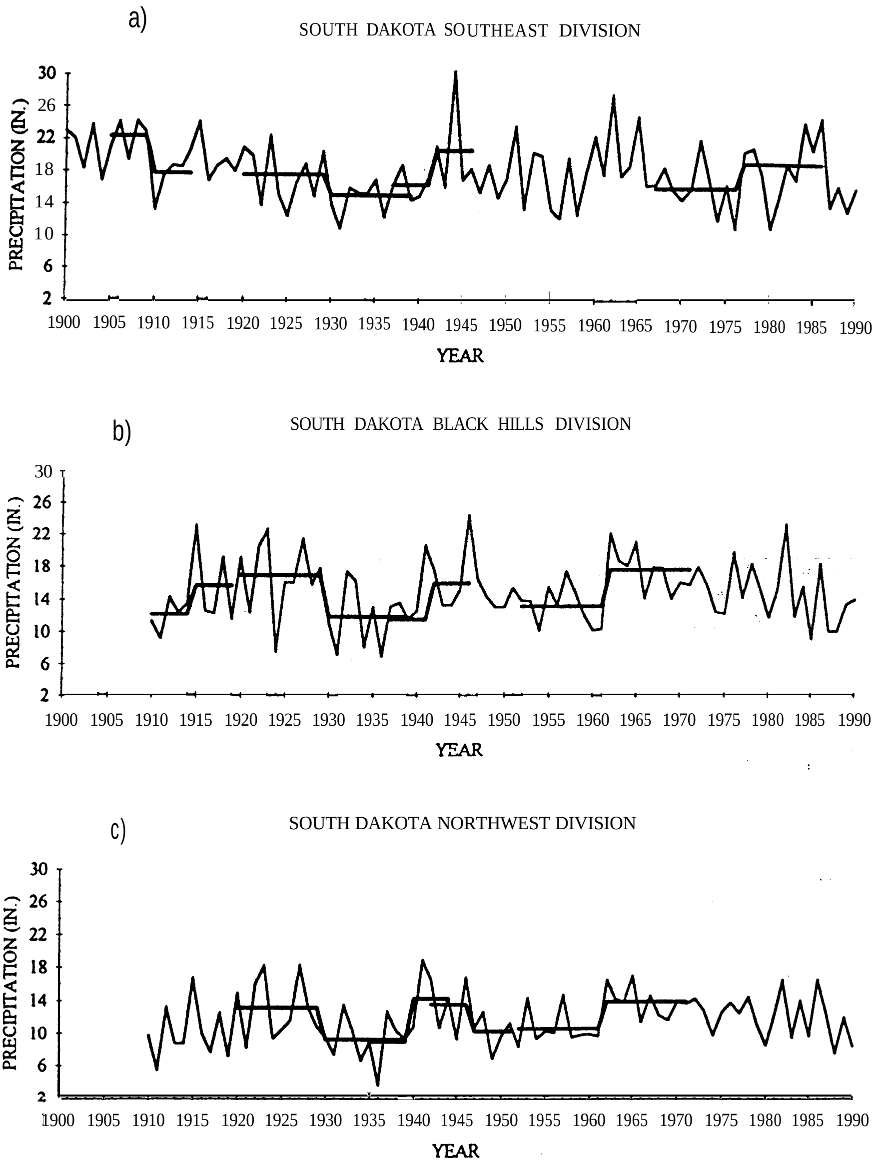

Figure 2. Examples of time series plots depicting climate fluctuations of increasing and decreasing growing season precipitation for both and 10-year epochs for the three divisions. The straight solid lines indicate the average precipitation for the representative interval.

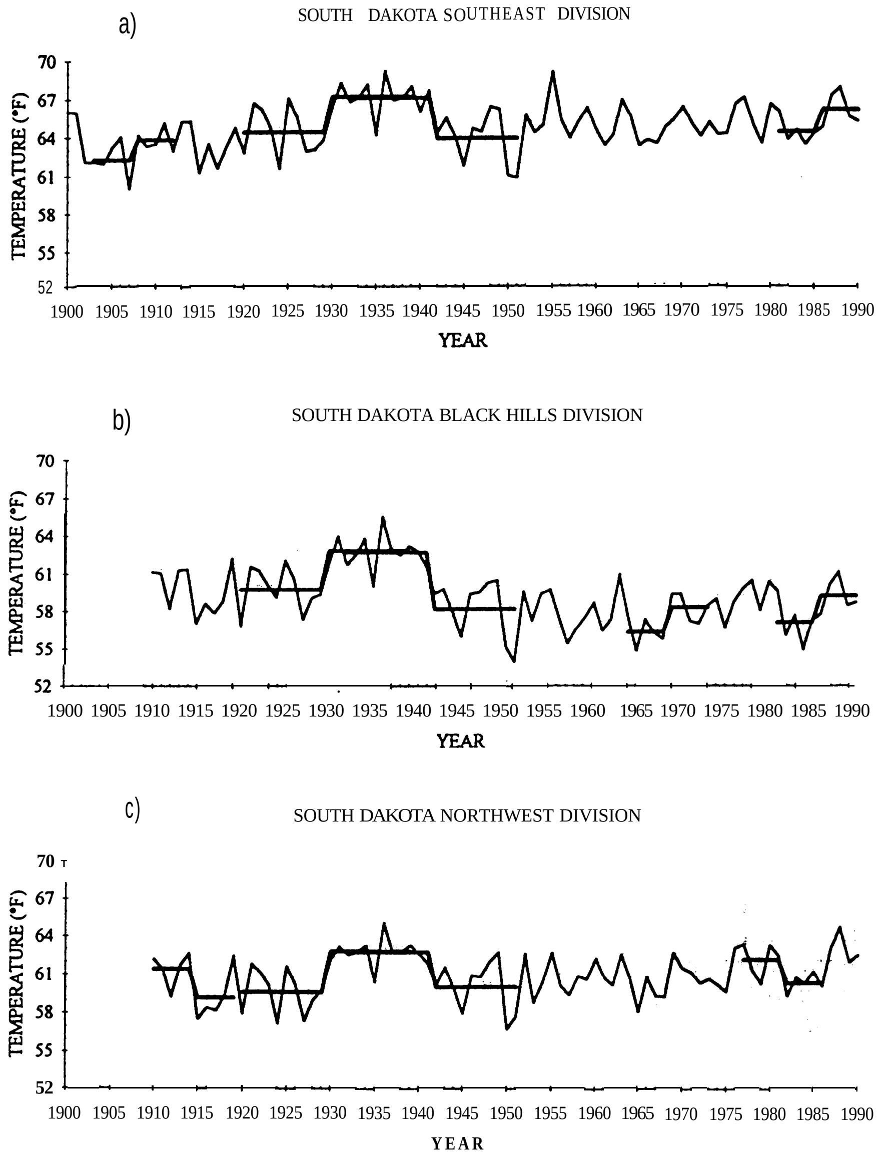

Figure 3. Examples of time series plots depicting climate fluctuations of increasing and decreasing growing season average temperature for both 5- and 10-year epochs for the three divisions. The straight solid lines indicate the average temperature for the representative interval.

Periods where both the temperature and precipitation means changed were evident (Table 5, Figures 2 and 3). Twenty-year fluctuations for the period 1920-29 versus 1930-39 were prevalent for all three divisions for both precipitation and temperature. The average growing season precipitation decreased 2.46 to 5.06 inches across the state between these decades ($0.01 < P < 0.03$). The largest decrease occurred in the western divisions and the average growing season rainfall was considerably less than the Southeast Division. The average growing season temperature increased 2.72 to 3.17°F during the 1930's ($P < 0.01$), and the greatest increase again occurred in the western part of South Dakota.

Spatial differences were common between the Southeast and the western divisions. Significant changes in mean precipitation occurred in the Southeast Division for periods 1917-26, 1961-70, and 1977-86 with little change noted in the other two divisions. For example, a IO-year fluctuation in mean growing season rainfall was noted for 1977-81 versus 1982-86 in the Southeast Division (Table 5) where the precipitation increased 4.13 inches ($P < 0.06$) with no significant changes noted in the other two divisions. Another IO-year fluctuation occurred in the Black Hills and Northwest Divisions for 1925-29 versus 1930-34 (Table 5) which was not apparent in the Southeast Division. The precipitation dropped 5.41 inches ($P < 0.06$) in the Black 'Hills Division, and the precipitation decreased 3.35 inches ($P < 0.06$) in the Northwest Division. These examples illustrate some of the variability that exists between western and southeastern South Dakota. A possible explanation for this spatial gradient is the occurrence of ENSO. The 1982-83 and 1986-87 ENS0 episodes may have altered the storm track in favor of eastern South Dakota. Earlier ENS0 events must be explored to determine the influence of ENS0 on the potential spatial gradient that has been identified.

The recent 1980's warming across the state of South Dakota appeared to be real (Table 5, Figure 3). The average growing season temperature has warmed anywhere from +1.64°F in the Northwest Division to +2.10°F in the Black Hills Division ($0.05 < P < 0.06$) for the period 198 1-85 versus 1986-90. This warming should not be attributed to the greenhouse effect because this change was in the scope of natural variability. In add tion, the 1992 summer was one of the coldest periods on record, possibly owing to the eruption of Mt. Pinatubo (Le Comte, 1993).

Given a large inter-epoch temperature change, large fluctuations in average precipitation were always of opposite sign. There was no single occurrence with the means of both precipitation and temperature increasing or decreasing simultaneously. This was in agreement with some previous studies (e.g. Namias, 1983; Chang and Lau, 1990) where precipitation and temperature were negatively correlated across the Great Plains during the summer season. An increase in the mean for temperature was not expected if the mean for precipitation had increased. This is because more rainfall typically is indicative of more cloud cover and more surface moisture, which leads to more reflected sunlight and increased energy required for evaporation and evapotranspiration. Karl and Riebsame (1984) did find changes of the same sign, but these occurred in the winter (December - February) season and away from the Great Plains. The results of the two studies therefore agreed in the Great Plains region. Also, warmer temperatures in the winter allow the atmosphere to hold more moisture, which may increase the total snowfall.

An interesting finding of the analyses was that temperature fluctuations were more prominent on the shorter time-scale while the precipitation fluctuations dominated the longer time-scale. Based on the t-statistic and the indexing methods, there were only three to four epochs that exhibited a 20-year temperature fluctuation for the three divisions while 8 epochs exhibited a IO-year fluctuation (Table 5). Alternatively, there were two more 20-year precipitation fluctuations than IO-year fluctuations for all but the Southeast division. The cause of these apparent out-of-phase cycles is unclear. Perhaps the reason for the fluctuations in precipitation was that once a drought begins, the deficient precipitation tends to exacerbate itself. The validity of these results needs to be tested further by expanding the scope of the study area and observing if similar results are found throughout the entire region.

CONCLUSIONS

Droughts in South Dakota have been a recurrent event throughout the period of instrumental record. Time series plots and drought defined by growing season (April - September) precipitation below the 25th percentile indicate that dry conditions have occurred in every decade in three of the divisions of South Dakota (Table 3, Figure 1). When exceedingly warm growing season temperatures are taken into consideration with the deficient precipitation, the number of drought years decreased by $\approx 50\%$ (Table 4). This “severe” drought (deficient precipitation combined with very warm temperatures) occurred in the Southeast, Black Hills, and Northwest Divisions of South Dakota for the years of 1931, 1934, 1936, and 1939. There was no other drought as severe and widespread during the current century in South Dakota.

The 1980 drought was noted in all three divisions but was severe only in the Southeast and the Northwest Divisions. The 1988 drought over the Central United States was severe in the Black Hills and Northwest Divisions but failed to meet the definition of drought in the Southeast Division based on just precipitation alone. However, the 1988 temperature was above the 75th percentile for the Southeast Division, which indicated that some effects of drought were felt in that division. The negative correlations between growing season precipitation and temperature indicated that rainfall tends to be less when the temperature had increased. It would therefore be beneficial in future studies to incorporate both precipitation and temperature into the basic definition of drought, due to the increased evaporation and depletion of soil moisture during periods of exceedingly warm temperatures.

The divisional climate record for South Dakota contained numerous 10- and 20-year climate fluctuations, although no significant trend in precipitation or temperature for the time series of the three divisions was identified. The 1920-39 period exhibited fluctuations in the means of precipitation and temperature for all three of the divisions. There was no coherency between the three divisions except for the 1930's. A spatial gradient may exist between southeastern and western South Dakota, but it was not always apparent (e.g. the late 1980's warming, see Figure 3). ENSO may play a very important role in determining the climate of the state, but the secular variability of ENSO may cause the spatial gradient to be fuzzy. This area offers opportunity for further research activities.

Finally, when both the means of precipitation and temperature fluctuated for a given epoch, their change was of opposite sign. In other words, as the average growing season precipitation increased for a given epoch, the average growing season temperature would usually decrease, and vice versa. The negative correlation coefficients for precipitation versus temperature point to this but offer no forecasting capability. Also, the f-tests used in this study pointed to the scenario of more variable temperatures on shorter time-scales and more variable precipitation on longer time-scales. More research needs to be done to validate this hypothesis.

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