Published as:
Garbrecht, J. D., and F. E. Rossel. 2002. Decade-Scale Precipitation Increase in Great Plains at End of 20th Century. Journal of Hydrologic Engineering, 7(1):64-75.

Decade-Scale Precipitation Increase in Great Plains at End of 20th Century

By Jurgen D. Garbrecht* and Frederic E. Rossel
U.S. Department of Agriculture, Agricultural Research Service
Grazinglands Research Laboratory,
West Cheyenne Str., El Reno, Oklahoma

Abstract

During the 1980-1999 period, many regions in the Central and Southern Great Plains experienced the longest and strongest increase in average annual precipitation of the century. The size of the increase ranged from 6% to 12% of mean annual precipitation, and from 25% to 60% of inter-annual precipitation variability. Precipitation increased for dry, average and wet years, though not equally for each category. Generally precipitation in very wet years increased less than in average and dry years. The probability of occurrence of dry years was greatly reduced compared to earlier in the century, whereas the probability of average years remained about the same and the probability of wet years increased. The observed decade-scale precipitation increase is attributed to a reduction in the number and severity of dry years, as well as to an increase in the number of wet years, though very wet years did not increase as much. The seasonal distribution of the increase in precipitation showed no statistically significant prevalence during any one particular month, yet qualitative considerations suggest that early summer and autumn months capture more of the annual precipitation increase. In the northern and northwestern Great Plains, a similar precipitation increase, but of smaller proportions, was observed during the 1990-1999 period.

Key words: Climatic Changes; Precipitation; Water Resources; and Water Supply

---

* Corresponding author address: Jurgen GARBRECHT, Grazinglands Research Laboratory, USDA-ARS, 7207 West Cheyenne Str., El Reno, Oklahoma, 73036, USA. Tel: (405) 252-5291, Fax: (405) 262-0133.

Introduction

The Dust Bowl of the 1930's was a decade-scale climate variation that led to destructive dust storms that wrecked the agricultural economy of the Great Plains and resulted in mass migration of thousands of farm families (Worster, 1982). Another example of climate variations is the 1987-1992 droughts in California (Dixon et al., 1996) that slowly depleted state water reserves and ultimately affected irrigated agriculture, urban water supply, and reservoir operations. An oversupply of water can be damaging as well. The 1980's rise of the Great Salt Lake, the 1993 Upper Mississippi River basin flood (Kunkel et al., 1994), and the rise of North Dakota's Devils Lake in the late 20^{th} century (Newsweek, 1999) have all been related to large scale climatic events, have caused substantial flood damage, and have resulted in challenging engineering problems.

The high sensitivity of surface runoff to decade-scale precipitation variation was recently illustrated by Garbrecht et al. (2001) and Garbrecht and Van Liew (2001) for watersheds in the Nebraska-Kansas-Oklahoma region. Annual surface runoff volume was shown to increased on average 40% over a 20 years period as a result of a 10% increase in precipitation over the same period. Sectors of today's economy that are vulnerable to decade-long climate variations include agriculture, urban and industrial water supply, hydro-electric power generation, transportation, and recreation. The broad and far reaching consequences of decade-scale climate variations suggests that such variations be identified early, adaptive and mitigating strategies be developed, opportunities exploited, and policies and investments made to ensure a secure water supply and a responsive and competitive economy.

Climate variations manifest themselves in various forms and at various temporal scales, from seasonal to centennial and longer (NRC, 1998). The seasonal-to-interannual variations are generally related to changes in atmospheric circulation and sea-surface temperatures at seasonal and annual time scales (Trenberth, 1997). Research on seasonal-to-interannual variations has centered around the El Nino-Southern Oscillation (ENSO) phenomenon and its influences on continental and global climate (Changnon, 1999; Pielke and Landsea, 1999; Barnston et al., 1999; Montroy, 1997; Ropelewski, and Halpert, 1996; Kiladis and Diaz, 1989). The impacts of these variations on water resources are seasonal in character and are partially overcome by consideration of seasonal climate forecasts, and can be mitigated by early preparations, relief efforts, tactical reallocation of resources, and adaptive management strategies.

On the other hand, decade-to-century scale variations are driven by slower components of the climatic system such as shifts in deep-ocean circulation, alteration in sea ice, or gradual changes of land cover and use (NRC, 1998) and have been studied by Chu and Clark (1999), Gershunov and Barnett (1998), Hu et al. (1998), NRC (1998) and others. In particular, Karl et al. (1996) found that precipitation in the United States is undergoing a slow trend towards higher annual precipitation values, and Karl and Knight (1998) concluded that weather extremes are occurring at a higher frequency than in the past. Much of this research is aimed at identifying long-term trends in precipitation characteristics and at developing climate indices for monitoring and quantifying global climate change. The impacts of these smaller amplitude but longer duration variations are more subtle, more difficult to detect, and may go unrecognized for some time. However, decade-scale variations have the potential to greatly surpass short-term variations in their societal, economic and political impacts (Mantua et al., 1997; Woodhouse and Overpeck, 1998).

The objectives of this study are to review decade-long variations in precipitation in the Great Plains from 1895 through 1999 and to establish the existence, magnitude and geographic extent of a precipitation increase in the Great Plains during the last two decades of the 20th century. The purpose of presenting these climate variations to the engineering community is to advocate consideration of decade-long precipitation variations in practical applications such as long-term water resources planning, irrigation operations, water conservation strategies, and water storage/supply projections. Traditional considerations with respect to climate in engineering and agricultural applications are often based on long-term average values, short-term seasonal-to-interannual variations, and/or extreme events. Comparatively less attention has been given to multi-year climate cycles or variations, even though it is at the 10 to 15-year time scale that many water resources planning decisions are made. Recognition and consideration of decade-long variations in precipitation is key to the successful development of long-term water resources planning and management strategies. Even though it is difficult at this time to predict future decade-scale variations in precipitation (NRC, 1998; Barnston et al., 1994), the long duration of such variations does provide the opportunity to develop adaptive and mitigating strategies, and exploit favorable conditions during the time of their existence.

The main beneficiaries of this study include water resources planners and managers; agricultural producers; agricultural loan and insurance agents; flood and drought preparedness agencies; reservoir storage and release operators; users of weather-generation models; and, others that rely on, or are involved in, water resources budgeting, planning and systems operations. The framework of this study does not include the identification of, or speculations about, atmospheric forcing mechanisms leading to decade-scale precipitation variations, nor does it intend to establish, or speculate about, any relationship to global climate change. Such identification of cause-effect mechanisms is important for scientific knowledge and development of predictive capabilities; however, for assessment of impacts on and management of water resources systems, the identification of current precipitation departures is often sufficient. The level of statistical procedures and other methods used in this study are tailored to the purpose of this study.

Data and Methodology

The geographic region for this study consists of the Great Plains states between the Rocky Mountains and the Mississippi River. Each state is composed of up to ten climate divisions that have been defined by the U.S. Weather Bureau in the 1940's (Guttman and Quayle, 1996). The average size of a climate division is 23,000 km^2 and ranges from few thousand up to 105,000 km^2. These climate divisions are the spatial units at which the decade-scale precipitation variations are analyzed in this study. The climate divisions in western portions of Montana, Wyoming, Colorado, New Mexico and Texas are excluded because they are within the Rocky Mountains region and do not reflect climatic conditions of the plains. The 108 climate divisions considered in this study are identified in Figure 1 by the shaded area.

The precipitation data for this study consist of the state divisional monthly precipitation data published by the National Climatic Data Center (NCDC, 1994). The historical origin of this data set and the calculation of divisional data values are described Guttman and Quayle (1996).

Fig. 1. Climate divisions used in this study.

The period of available data spans 105 years starting in January 1895 and ending in December 1999. Decade-scale precipitation variations are analyzed using annual precipitation values. Annual Precipitation (*AP*) is obtained by summation of the state divisional monthly precipitation values for each climate division.

Long-term mean annual precipitation values vary substantially across the Great Plains with values ranging from under 380 mm/year in New Mexico to above 1400 mm/year in Louisiana. These spatial gradients make direct comparison of precipitation values between the various climate divisions difficult. Standardized Annual Precipitation (*SAP*) values provide a common reference frame for comparison of patterns in annual precipitation time series.

$$SAP_{(cd,y)} = \frac{(AP_{(cd,y)} - \overline{AP}_{(cd)})}{std(AP_{(cd)})}$$

where *AP* is annual precipitation, *SAP* is Standardized Annual Precipitation (unitless), *cd* is climate division index, *y* is year index, *std*(*AP*) is standard deviation of *AP* over the 1895-1999 period, and the overbar represents the long-term mean over 1895-1999 period.

A moving average filter is applied to the *SAP* time series to remove high frequency inter-annual variations and to identify temporal variations of 10 or more years in duration (decade-scale). Though not ideal, an 11-point linear moving average filter was selected as opposed to a triangular or cosine filter because it provides filtered data to within five years of the end of the time series. The moving average calculations are also extended to both ends of the time series (1895 and 1999) by omitting values that are beyond the range of available time series data. Thus, moving average values for the first and last 5 years of the time series represent incomplete eleven-year moving average values and some inter-annual variations are not fully filtered for the first and last 5 years of the time series. Despite this shortcoming, extending the time series to the end of the record produces valuable information for practical water resources problems because it reflects current conditions that are needed to resolve present water supply issues. In the remainder of this paper the 11-year moving average of the *SAP* time series is simply referred to as the filtered time series of the *SAP*, or *FSAP* time series.

An example of a *SAP* and *FSAP* time series is shown in Figure 2 for Climate Division 5 in central Oklahoma. The "ups" and "downs" in the pattern of the *FSAP* time series (bold line) represent decade-scale variations in annual precipitation. The low in the *FSAP* (dotted area) around 1915 is the result of the dry years in 1909, 1910, 1911, 1912, 1914 and 1917. The wet period of the last two decades of the 20th century is also clearly visible (hatched area). It is further noted that an up or down in the *FSAP* identifies a general decade-scale variation, and not every single year within a decade-scale variation is necessarily wet or dry. The inter-annual precipitation variability is illustrated in Figure 2 by the *SAP* time series (thin line).

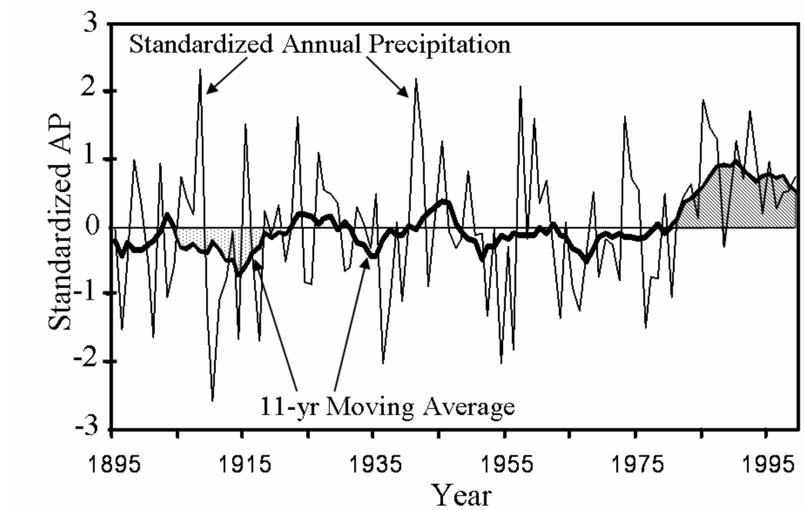

Fig. 2. Standardized *AP* and Filtered-Standardized *AP* time series for climate division 5 in central Oklahoma. The decade-scale dry (1905-1920) and wet (1980-1999) periods are identified by the dotted and hatched areas, respectively.

The *FSAP* time series of adjacent climate divisions often display distinctively similar and concurrent variations in their pattern. In this study, the similarity in *FSAP* pattern between two or more adjacent climate divisions is identified by visual interpretation. Primary criteria for the visual identification were the timing and intensity of prominent features in pattern, such as those during the Dust Bowl years in the 1930s, the wet years of the 1940s, and/or the trend over the 1980-1999 period. Climate divisions that have similar prominent features in the patterns and that are adjacent to one another are grouped into a region. Climate divisions that did not fit the entire pattern of one of several possible adjacent regions were assigned to the most suitable region based on subjective interpretation of distinctive similarities in trends and other features of individual wet or dry time periods. Visual interpretation was selected over clustering or correlation techniques because grouping decisions often required that different sub-portions and prominent features of the record be evaluated separately for their trend/pattern as opposed to the closeness in value of the overall record. The purpose for the grouping of climate divisions into regions is solely for ease of presentation, and the identified regions are not to be viewed as a definition or proposal for time-invariant and homogeneous areas of same atmospheric processes and same climatic behavior for use beyond this study. For actual water resources applications, precipitation data of a single climate division, or better, precipitation data of a single weather station at the location of the project should be used.

Once all climate divisions are assigned to a region, a representative *SAP* is calculated by area-weighted averaging *SAP* time series for the climate divisions within the regions. This resulting time series is called the Representative Standardized Annual Precipitation (*RSAP*) and is given by:

$$RSAP_{(R,y)} = \frac{1}{A_R} \sum_{cd=1}^{ncd} A_{cd} * SAP_{(cd,y)}$$

where A_R is area of region *R*, A_{cd} is area of climate division *cd*, and *ncd* is number of climate divisions in the region.

An 11-year moving average, as described earlier, is then applied to the *RSAP* to produce the Filtered Representative Standardized Annual Precipitation time series, or *FRSAP*. This *FRSAP* is used to identify decade-scale precipitation variations for the region. A precipitation variation is present when the Time-Accumulated Precipitation (*TAP*) in the *FRSAP* exceeds a predetermined threshold value. The *TAP* is the area under a given precipitation variation that is continuously above or below the zero line in the *FRSAP* (similar to the situation of the *FSAP* curve in Figure 2).

$$TAP = \sum_{y=j}^{k} FRSAP_{(R,y)}$$

where *j* and *k* are the beginning and ending years for consecutive years with positive or negative *FRSAP* values, and *y* is the year counter.

The *TAP* approach for identifying precipitation variations has been selected here because it combines duration and intensity of the variation. Thus, based on this definition, a shorter duration but higher intensity, and a longer duration but lower intensity variation equally qualifies as a decade-scale precipitation variation. This *TAP* definition only identifies important *FRSAP* departures from the zero line and does not imply that the impact of a shorter duration and higher intensity variation is similar to the impact of a longer duration and lower intensity variation.

The *TAP* threshold value that defines a precipitation variation must be selected to meet the objectives of an application. Here, for the purpose of this study, the threshold values were selected to identify only the largest and most prominent decade-scale precipitation variations. A positive decade-scale precipitation variation with a *TAP* value above +4.0 is called a wet period (illustrated by hatched area under *FSAP* in Figure 2). Smaller positive variations with *TAP* value between +2.5 and +4.0 are called wet conditions. A negative decade-scale precipitation variation with a *TAP* value below –4.0 is called a dry period (illustrated by dotted area under *FSAP* in Figure 2). Smaller negative variations with *TAP* value between -2.5 and -4.0 are called dry conditions. The duration of a variation is the number of years of the variation, the intensity of a variation is the *TAP* value divided by the duration, and the amplitude of a variation is the departure from the zero line at any time during the variation. The units of intensity and amplitude are standard deviation of annual precipitation. The precipitation variations in the regions (*FRSAP*) are used to identify the geographic extent, duration and intensity of the most recent wet period in the Great Plains.

Finally, basic statistics (mean, standard deviation), probability of wet, average and dry year occurrence, Cumulative Frequency Distributions (*CFD*) comparisons, and tests of significance are used to quantify differences in the magnitude and distribution of *SAP* between the long-term (1895-1999) period and recent decades. The level of these statistical methods is tailored to the intended purpose of the study. The selection of the long-term period (1895-1999) as the reference against which other periods are compared assumes that the *SAP* is stationary in time and all variations are temporary departures from the overall mean. Thus, a long duration continuous trend or climate change is not implied or sought after in this study. Also, a Representative Cumulative Frequency Distribution (*RCFD*) of the *SAP* and for the climate divisions in a region is calculated by area-weighted averaging of the individual cumulative frequency distributions for the climate divisions within the region.

$$RCFD_R^{SAP} = \frac{1}{A_R}\sum_{cd=1}^{ncd} A_{cd} * CFD_{cd}^{SAP}$$

where *RCFD* is representative cumulative frequency distribution, *CFD* is cumulative frequency distribution, and all other terms have been defined previously.

Results and Discussions

Regions with similar decade-scale precipitation variations

The grouping of the 108 climate divisions into regions with similar pattern produced the nine regions shown in Figure 3. Table 1 lists the number of climate divisions in each region, the size of each region, the states in each region, the existence of a wet period in the last decades of the 20th century, and the existence of wet conditions in the last 10 years of the 20th century. The *FSAP* time series of each climate division in a region, and the corresponding *FRSAP* time series, are plotted in Figure 4 for Regions 4, 5, 6 and 7. These regions comprise the majority of the Central and Southern Great Plains. Corresponding time series for Regions 1, 2 and 3 show wet conditions in the last 10 years of the 20th century (Figure 5). These latter regions represent the northern and northwestern Great Plains. Finally, Regions 8 and 9 (southwestern Texas, eastern Arkansas and southeastern Missouri) are the only regions that did not exhibit wet or dry conditions at the end of the 20th century. The reader is reminded that the regions and their boundaries are qualitatively defined solely for the ease of data presentation and are not to be understood as a definition of or proposal for a set of unique boundaries that optimally represent any particular climatic behavior.

Decade-scale precipitation variations

In Figure 4, the precipitation variations for Regions 4 and 5 clearly show the Dustbowl years (dry period) in the mid-1930s. After 1955, a continuous gradual increase in precipitation takes place and results in a wet period towards the end of the 20th century. Region 6 has two moderate dry periods around 1900 and in the 1960s, and one wet period at the end of the 20th century.

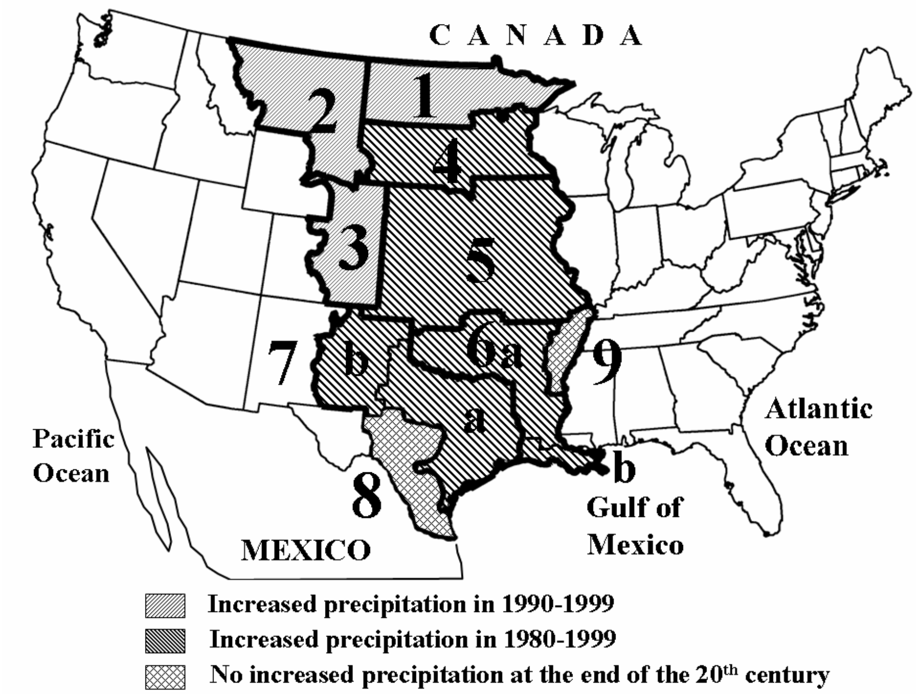

Fig. 3. Definition of regions with similar Filtered Standardized *AP*.

Table 1. General characteristics of Regions 1 through 9.

Region	Number of Climate Divisions	Area Km^2	States	Wet period* 1980-1999	Wet conditions** 1990-1999
1	12	278,040	ND, MN	No	Yes
2	9	339,320	MT, WY	No	Yes
3	5	218,270	CO, NE, WY	No	Yes
4	14	322,270	SD, MN	Yes	Yes
5	32	703,140	NE, IA, KS, MO	Yes	Yes
6	21	339,520	AR, LA, OK	Yes	Yes
7	8	538,220	TX, NM	Yes	Yes
8	3	156,210	TX	No	No
9	4	60,100	AR, MO	No	No

*Wet period: precipitation variation with a TAP value greater than +4.0.
**Wet conditions: precipitation variation with a TAP value between +2.5 and +4.0.

Finally, Region 7 has two decade-scale precipitation variations: a 15-year shortfall in precipitation during the middle of the century and an excess precipitation after about 1980. The duration, intensity and *TAP* values for each wet and dry period are given in Table 2 for comparison purposes. All four regions display a wet period after about 1975 or 1980. Most importantly, for all four regions these wet periods are the longest in duration and highest in intensity over the entire 105-year study period, and the *TAP* value for the wet period for the four regions is larger than +5.9. For Regions 4 through 7, only the 1910-1940 dry period in Region 4 and the 1940-1970 dry period in Region 7 are more severe in magnitude than that of the wet periods at the end of the 20th century.

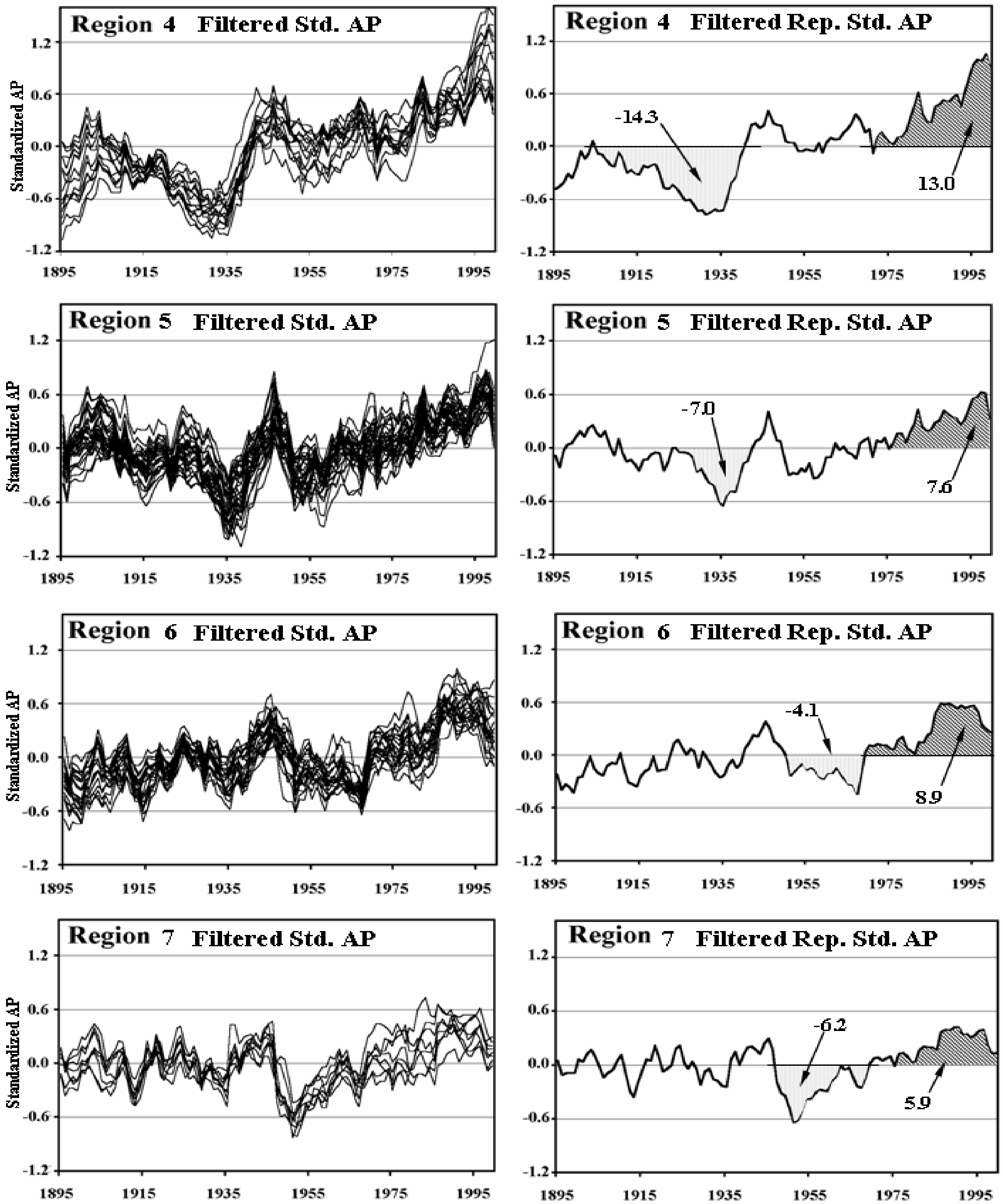

Fig. 4. Filtered Standardized *AP* (left) and Filtered Representative Standardized *AP* (right) time series for Regions 4, 5, 6 and 7. Hatched areas identify wet periods and dotted areas dry periods with *TAP* values indicated for each.

A one-tailed Student-t test at a 0.1 significance level was performed to determine if the 1980-1999 mean annual precipitation was significantly higher than that of the 1895-1979 period. In Region 4, the mean precipitation of all climate divisions (100%) was found to be significantly higher during the 1980-1999 period. In Region 5, mean precipitation of 28 out of 32 climate divisions (87%) was higher. In Region 6, mean precipitation of 17 out of 21 climate divisions (81%) was significantly higher. And, in Region 7, mean precipitation of 5 out of 8 climate divisions (62%) was significantly higher. The percentage of climate divisions with significant increase in precipitation decreases gradually from north (Region 4) to south (Region 7). This confirms the visual perception in Figure 4 (right) that the prominence of the 1980-1999 wet period decreases from Region 4 to Region 7. In summary, the above considerations demonstrate that a wet period of unprecedented duration, intensity and amplitude has prevailed over large portions of the Central and Southern Great Plains for the last two decades of the 20th century. From the *FRSAP* it also appears that the amplitude of the 1980-1999 wet period for all four regions began to decline starting in about 1997.

Table 2. Characteristics of the decade-scale precipitation variations for Regions 1 through 9.

Region	Duration [years]	Intensity [Std. of AP]	Time Accumulated Precipitation	Wet/Dry
1	1895-1911 [17]	.295	5.01	wet
	1912-1941 [30]	-.316	-9.47	dry
2	1901-1920 [20]	.369	7.38	wet
	1929-1940 [12]	-.422	-5.06	dry
	1947-1965 [19]	-.324	-6.15	dry
3	1895-1928 [34]	-.304	-10.33	dry
	1929-1941 [13]	-.369	-4.80	dry
	1948-1981 [36]	-.306	-11.01	dry
4	1905-1940 [36]	-.396	-14.26	dry
	1972-1999 [28]	.465	13.02	wet
5	1925-1942 [18]	-.388	-6.99	dry
	1976-1999 [24]	.315	7.55	wet
6	1950-1968 [19]	-.214	-4.06	dry
	1969-1999 [31]	.285	8.85	wet
7	1947-1968 [22]	-.282	-6.20	dry
	1976-1999 [24]	.244	5.86	wet
8	1946-1961 [16]	-.499	-7.99	dry

Precipitation variations for Regions 1, 2, 3, 8 and 9 are shown in Figure 5. All regions except Region 9 show decade-scale wet and dry periods. Examples of dry periods include the drought conditions during the Dustbowl years (1930s) for Regions 1, 2, and 3, and drought conditions during the 1950s for Regions 2, 3 and 8. Examples of wet periods are seen at the beginning of the 20th century for Regions 1, 2 and 3. For Region 1, 2 and 3, wet conditions prevailed during the 1990s. Even though the size of this increase was below the *TAP* threshold value of +4.0 of a wet period, it is important to recognize that it does show an increase in precipitation over the last 10 years of the 20th century. These wet conditions could lead to a wet period if the observed wet conditions persist in coming year. For Regions 8 and 9, no change or trend in precipitation is observed over the last 10 to 20 years. A Student-t test was conducted to establish if the 1990-1999 mean annual precipitation was significantly higher than the 1895-1989 period. In Region 1, the mean precipitation in 6 out of 12 climate divisions (50%) was significantly higher. In Region 2, mean precipitation in only 2 out of 9 climate divisions (22%) was higher. In Region 3, mean precipitation in 4 out of 5 climate divisions (80%) was higher. And, in Region 8 and 9 no significant increase was found. Thus, the north and northwestern

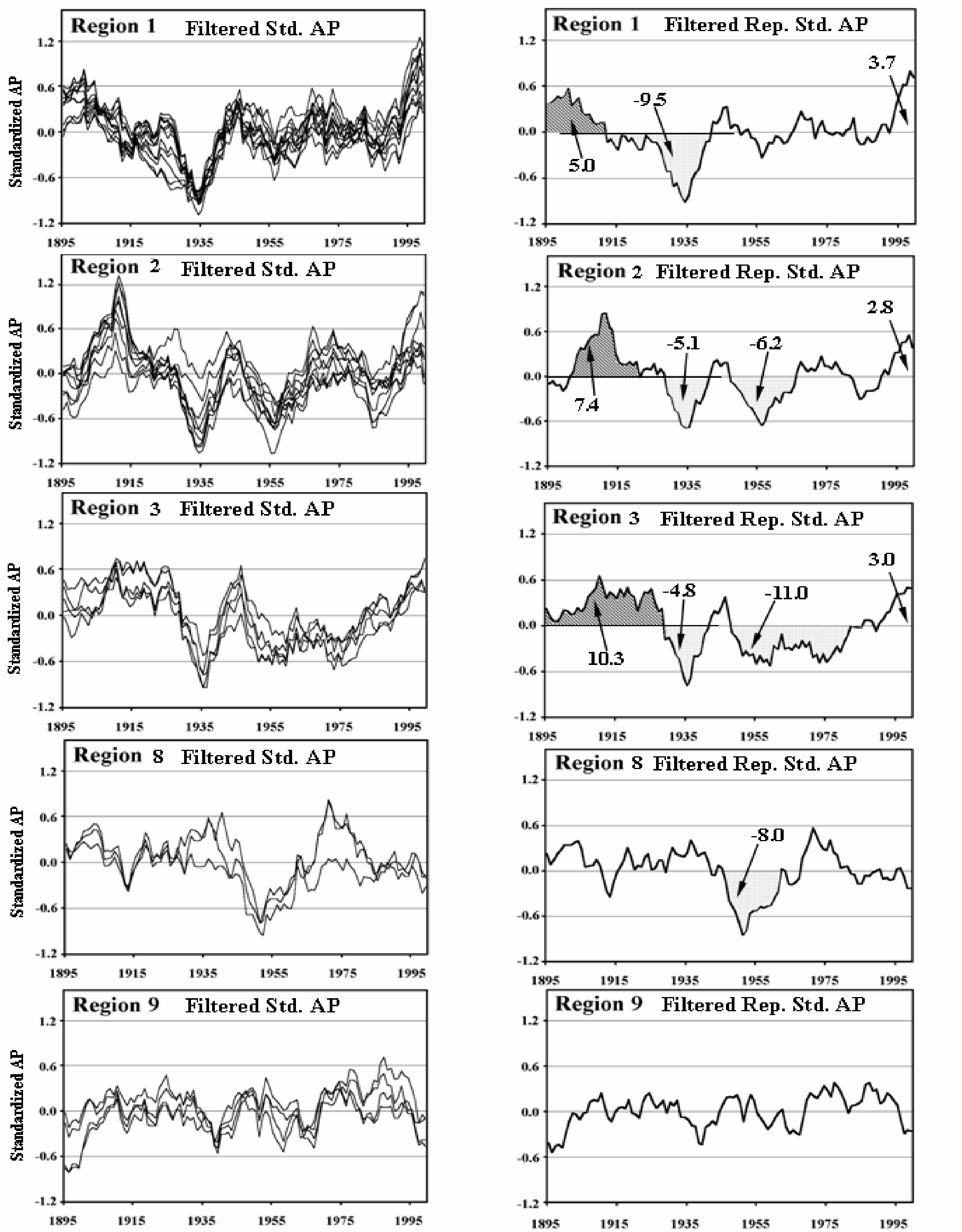

Fig. 5. Filtered Standardized *AP* (left) and Filtered Representative Standardized *AP* time series for Regions 1, 2, 3, 8 and 9. Hatched areas identify wet periods and dotted areas dry periods with *TAP* values indicted for wet and dry periods and conditions.

portions of the Great Plains have experienced a moderate increase in precipitation over the last decade of the 20th century, whereas in southwestern Texas and eastern Arkansas average precipitation conditions have prevailed over the last 20 years.

Characteristics of the wet periods at the end of the 20th century

Table 3 shows the increase in precipitation between the 1895-1999 and 1980-1999 periods for Regions 4, 5, 6 and 7, and between the 1895-1999 and 1990-1999 periods for Regions 1, 2 and 3. The increase in mean precipitation is expressed in percent of long-term mean and inter-annual variability. Expressing the precipitation increase in terms of percentages overcomes the need for reporting spatially variable due to the west-to-east precipitation gradient. Inter-annual variability is given as the standard deviation of annual precipitation over the 1895-1999 period, and the long-term mean is for the same period. On average Regions 1 through 7 have experienced an increase in precipitation of 7 to 8% of the long-term mean and of 35 to 40% of the inter-annual variability. The maximum increase is observed in Region 4 (South Dakota and southern Minnesota) with sustained differences over the 1980-1999 period reaching 12% of the long-term mean and 60% of the inter-annual variability. These increases in precipitation are substantial not only in terms of inter-annual variability, but also in term of the mean because they are sustained over such a long period of time.

Representative Cumulative Frequency Distributions of the *SAP* (*RCFD*) are used to quantify the change in frequency of annual precipitation between the two periods. On the left side of Figure 6 the *RCFD* for Regions 4, 5, 6 and 7 are displayed for the periods 1895-1999 and 1980-1999. A marked shift to higher values is observed for most precipitation frequencies.

Table 3. Relative precipitation increase and changes in probabilities of wet, average or dry years for all regions.

		Precip. Increase in % of		Probability of being		
Region	Time period	long term mean	Inter-annual variability	dry [%]	average [%]	Wet [%]
1	90-99	8	47	20	31	49
2	90-99	4	20	28	34	38
3	90-99	8	44	18	33	49
4	80-99	12	60	18	29	53
5	80-99	6	35	18	33	49
6	80-99	7	37	19	33	48
7	80-99	6	25	21	37	42

For the 1980-1999 time period, the increase at the median (50 percentile) is about .55, .34, .36 and .21 standard deviations, respectively. Since the precipitation values have been standardized, the amounts correspond roughly to 55%, 34%, 36% and 21% of the inter-annual variability, similar to the values reported in Table 3. The difference in *RCFD* (Figure 6 right) shows that the increase in *SAP* for the 1980-1999 period is approximately the same size in the 10 to 90 percentile range.

This means that most precipitation frequencies experienced a similar shift towards higher precipitation values. However, towards the upper tail end of the cumulative frequency

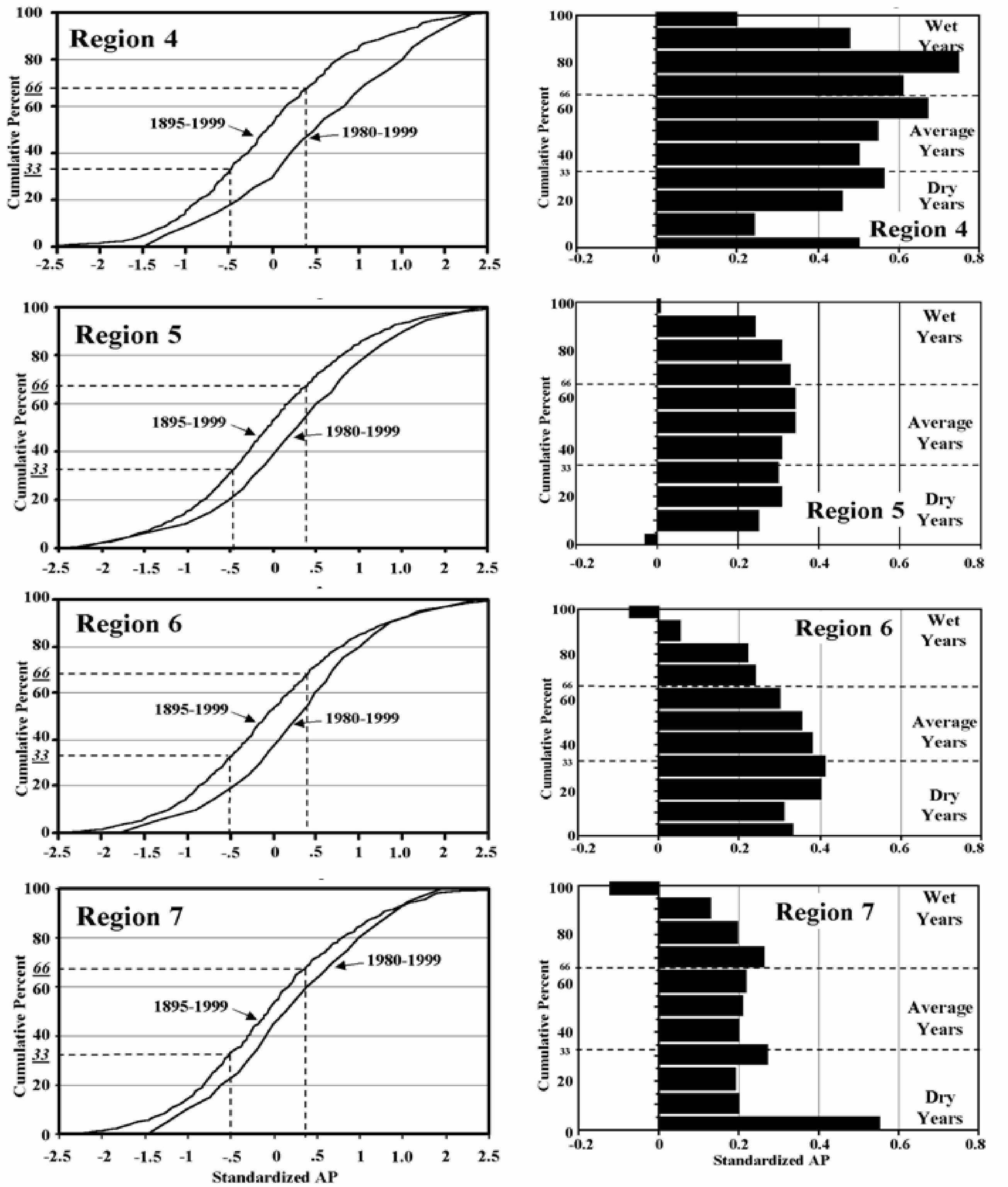

Fig. 6. Representative cumulative frequency distributions of Standardized *AP* (left side) and differences in the distributions (right side) for periods 1895-1999 and 1980-1999 and for Regions 4, 5, 6 and 7.

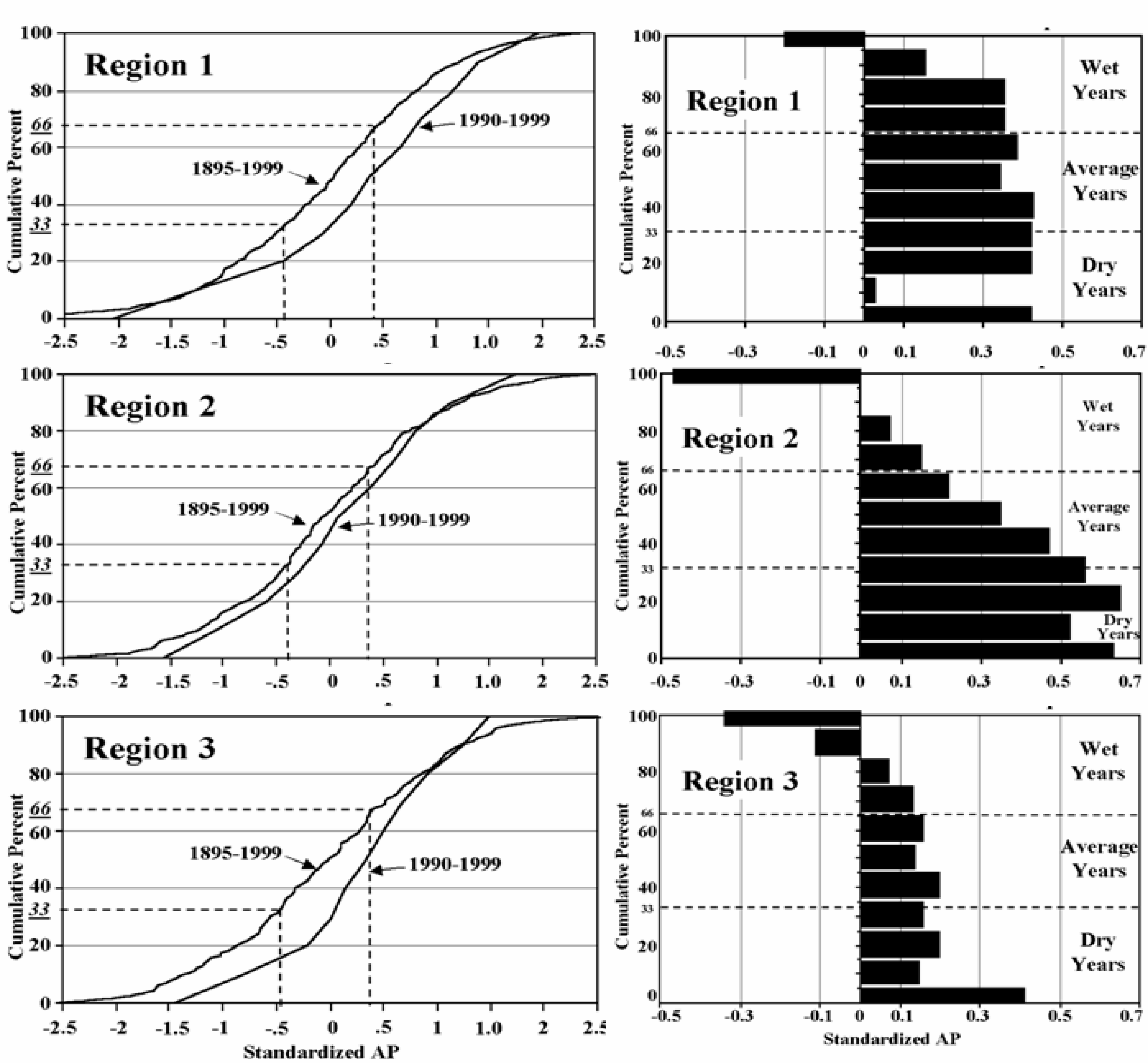

Fig. 7. Representative cumulative frequency distributions of *SAP* (left side) and differences in the distributions (right side) for periods 1895-1999 and 1990-1999 and for Regions 1, 2 and 3.

distribution (at the 95% level), the change is near zero or negative. Thus, wet years in the upper 95% range for the 1980-1999 period are not appreciably wetter than corresponding wet years during the entire century. For Region 4, 6 and 7 the driest years of the 1980-1999 period (at the 5% level) are not quite as dry as the corresponding precipitation frequencies during the entire century.

It is noted that the change at the tails of the frequency distribution is based on a very few data points, and, therefore, the values and resulting inferences should be considered with caution. Yet, the change in the tails of the frequency distributions (Fig. 4 left) are, in many regions, a consistent extension of a trend already established over a broader range of the frequency spectrum. Also, the trend is similar for many regions, adding further to the credibility of the values at the tails. In summary, the above analysis shows that dry years have been less severe and less frequent in 1980-1999, and wet years have become more frequent, but not more severe.
In Figure 7, the *RCFD* and the differences in distributions are displayed for Regions 1, 2 and 3 and for the periods 1895-1999 and 1990-1999. Regions 8 and 9 have been omitted in Figure 7 because these regions did not experience an increase in precipitation (see Figure 5). For Region

1, 2 and 3, the increase in precipitation at the median (Figure 7 left) correspond roughly to 34%, 35% and 14% of the inter-annual variability, and the differences in *RCFD* (Figure 7 right) is approximately the same size over the 10% to 70% range of cumulative frequency distribution values. Here too, the cumulative frequency distribution at the 95% level shows a decrease, and at the 5% level show an increase. Thus in 1990-1999, very wet years are dryer and very dry years are wetter than corresponding values for the entire century. Similar caution regarding the tails of the frequency distribution, as discussed in the previous paragraph, applies here.

The difference between the 1980-1999 and 1895-1999 period are also examined in terms of probabilities of being wet, average or dry. The delimiters that identify wet, average and dry categories are taken from the 33% and 67% cumulative distribution for the 1895-1999 period (Figure 6 and 7). Thus, for this 1895-1999 period one third of the years would be wet, one third average, and one third dry. Using the same category delimiters for wet, average and dry, the probabilities of being wet, average or dry during the 1980-1999 period are calculated as the number of year in each category divided by 20, the total number of years in the 1980-1999 period. In general, these calculated probabilities (Table 3) shows a much higher probability of being wet, about the same for being average and a much lower probability for being dry. For example, for Region 3 and for the 1980-1999 period, 49% of the years are wet, 33% are average and 18% are dry. Thus, the wet and dry year probabilities show a sizable departure from the expected 33%. These frequency distribution and dry/wet year probabilities are very important for water resources planning because projected water supply and confidence in the projections depend on the size and duration of the recent trend, as well as on the sensitivity of the water supply to the trend.

Seasonal Distribution of Precipitation

Seasonal distribution of precipitation for each climate division and differences between the 1895-1999 and the 1980-1999 period are illustrated in Figure 8. Precipitation values are expressed in percent of annual precipitation. A closer examination of the climate division data (Figure 8, left) shows that the curves with the higher summer-time values belong to the western portion of the regions and those with lower summer-time values to the eastern portion. Despite this range of values the general shape of the seasonal precipitation distribution is consistent within each regions with two exceptions. First, in Region 6 the three Louisiana climate divisions adjacent to the Gulf of Mexico (Region 6b, Fig. 3) have a distinctly different seasonal precipitation distribution than all other climate divisions in the region (Region 6a, Fig. 3). And, second, in Region 7 the climate divisions in eastern New Mexico and western portion of Texas (Region 7b, Fig. 3) are different, most likely due to the moonsonal activity that is observed in the southwestern United States during the summer. These climate divisions are removed from the respective regions and treated separately, but only for this seasonal distribution analysis.

Analysis of changes in the seasonal distribution of precipitation between the long-term average distribution and the distribution over the last decades (Fig. 8, right) show that the general seasonal precipitation pattern did not change during the 1980-1999 period. This was confirmed by a test of significance for each climate division and for each month: less than one third of the months in the climate divisions showed a significant change. This lack of significance is in part due to the large year-to-year precipitation variability at the monthly time scale. However, if one looks at annual distribution of the average monthly values (Fig. 8, right), one can recognize that

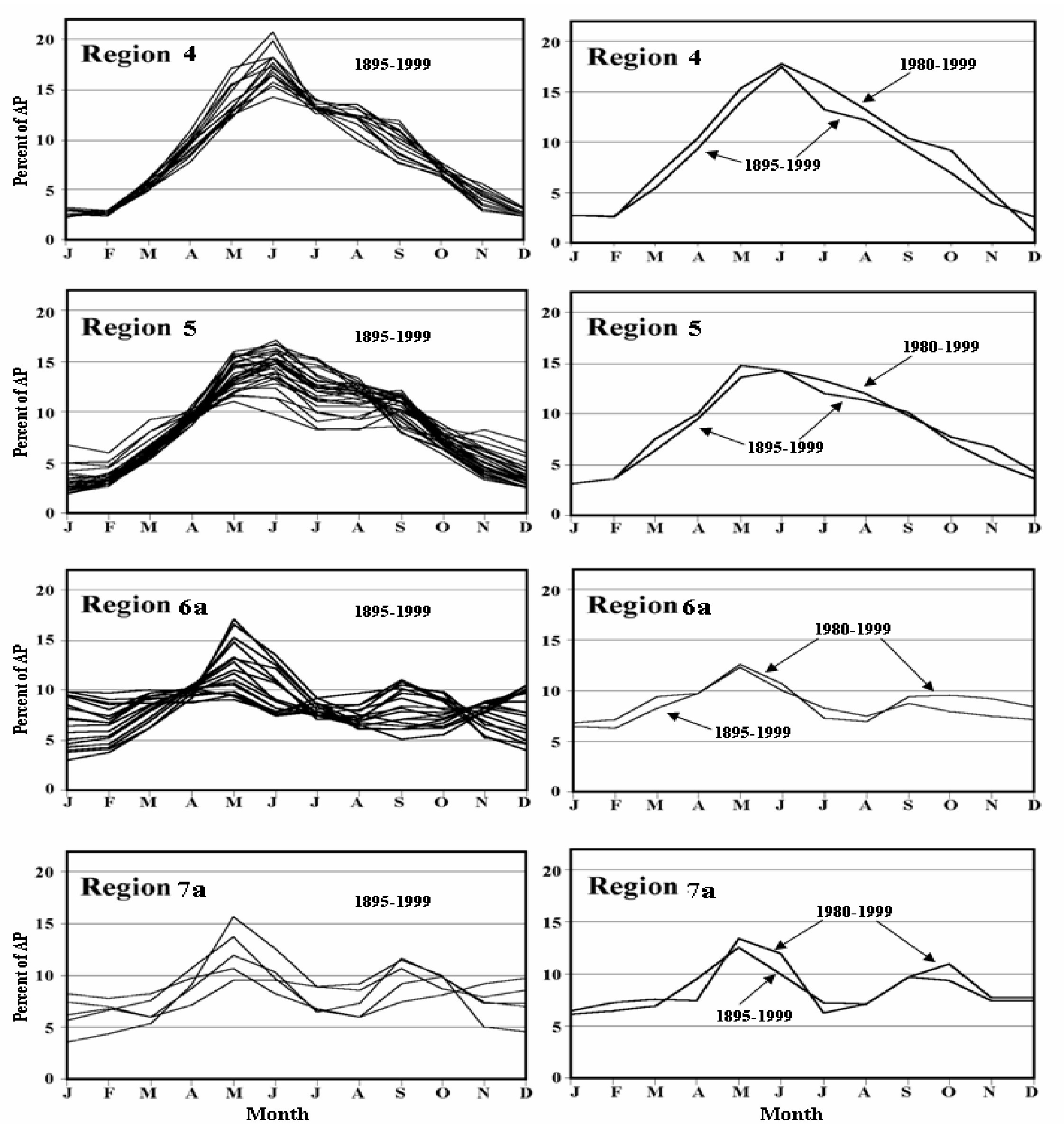

Fig. 8. Seasonal distribution of precipitation for individual climate divisions and 1895-1999 period (left), and average seasonal distribution for the regions for the 1895-1999 and 1980-1999 periods (right) for Regions 4, 5, 6 and 7.

the additional annual precipitation is not distributed uniformly throughout the year. In most regions, a few months capture more of the precipitation increase, though not significantly more. For all regions, individual months in early summer and autumn receive a larger amount of the annual precipitation increase. In Region 6a and 7a, somewhat drier summer conditions appear to prevail for July and August. The same can be said for the three Louisiana climate division adjacent the Gulf of Mexico (Region 6b in Figure 9). On the other hand, the climate divisions in eastern New Mexico and western Texas have substantially drier summer months and wetterwinter and spring months (Region 7b in Figure 9). Finally, in Regions 1, 2 and 3 the increase in annual precipitation is preferentially distributed in summer with some in early autumn (Figure 10), but again the increases are not statistically significant. Given the variability

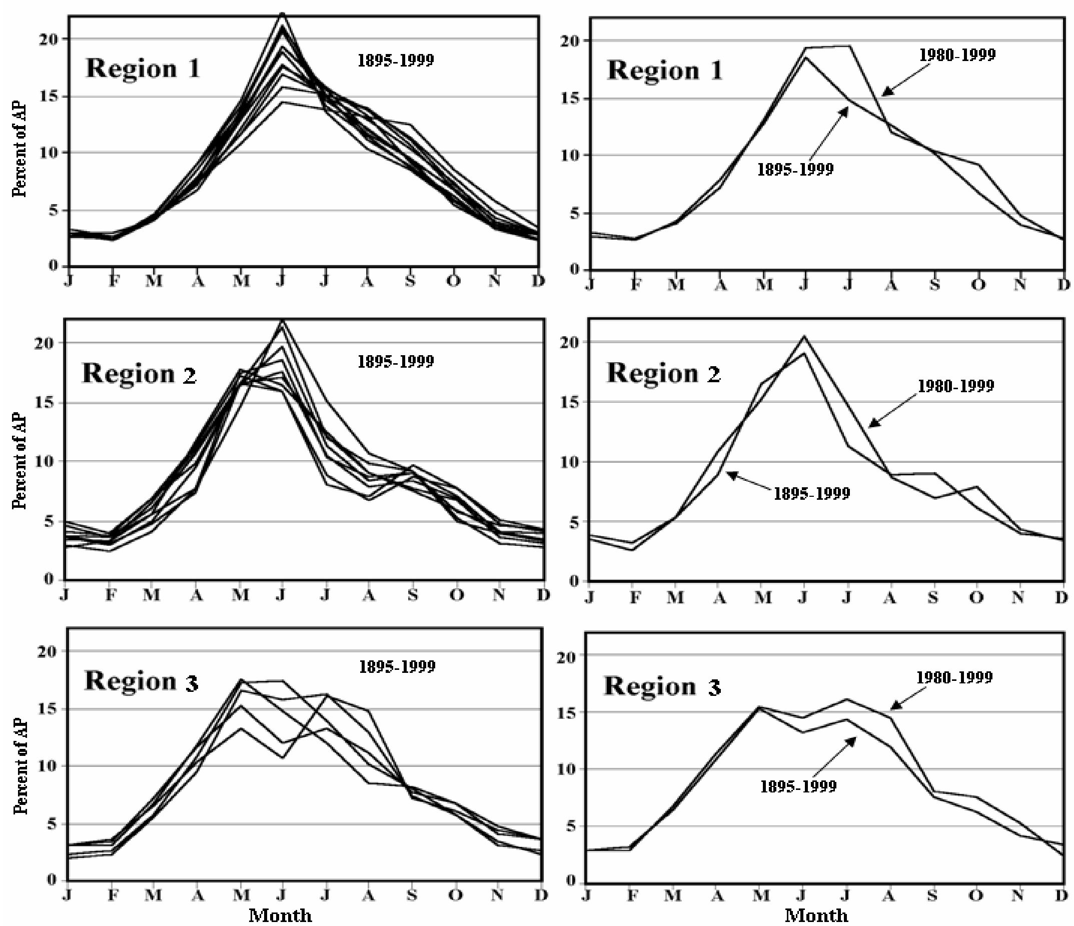

Fig. 9. Average seasonal distribution for Sub-Regions 6b and 7b for the 1895-1999 and 1980-1999 periods.

of the seasonal pattern between climate divisions within a region, it is important for practical applications to verify these general trends for the particular climate division under consideration.

Conclusions

The object of this study was to quantify the magnitude and geographic extent of variations in precipitation within the Great Plains with the purpose to expose subtle changes in precipitation characteristics that are important for practical water resources and agricultural applications. To this end decade-scale variations in annual precipitation have been analyzed for the Great Plains between the Rocky Mountains and the Mississippi River and for the 1895-1999 period.
The study revealed that most regions in the Central and Southern Great Plains were subjected to above average precipitation conditions over the last two decades of the 20th century (1980-1999). This decade-scale wet period was found to be the longest and most intense during the entire 1895-1999 period of analysis. The decade-scale precipitation increase was primarily the result of a reduction in the number of dry years and an increase in the number of wet years. However, the number of very wet years did not increase as much and even showed a decrease for many regions. With respect to the seasonal distribution of the increase in precipitation, a few late spring, early summer and autumn months captured a larger portion of the annual precipitation increase, though the changes were not statistically significant. For some regions a slight decrease in precipitation during summer months was also observed.

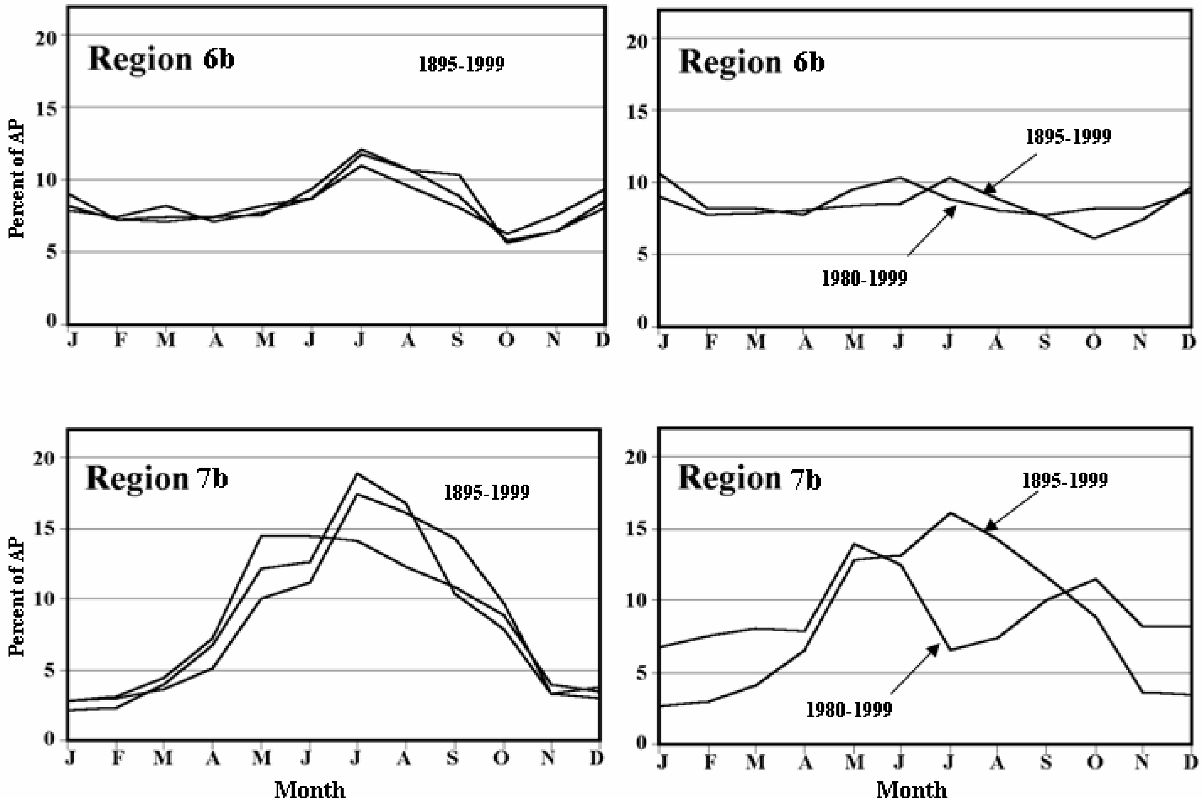

Fig. 10. Seasonal distribution of precipitation for individual climate divisions and 1895-1999 period (left), and average seasonal distribution for the regions for the 1895-1999 and 1990-1999 periods (right) for Regions 1, 2 and 3.

The northern and northwestern Great Plains also experienced a precipitation increase, albeit only over the last decade of the 20th century (1990-1999). Again, fewer dry years over the last 10 years, as opposed to an increase in very wet years, was the leading cause of the observed wet conditions. The seasonal distribution of the precipitation increase appeared also more concentrated during a few months in early summer and in autumn, but again this was not statistically significant.

The findings that the majority of the Great Plains has experienced a precipitation increase over the last one or two decades of the 20th century, have immediate implications for practical applications. From the water resources planning and management point of view, the simple recognition of sustained increases in annual precipitation provides opportunities to exploit favorable conditions while the wet period lasts. For agriculture in the southern Great Plains of the U.S. that relies mainly on dry-land farming to support a forage, grain and livestock industry, above average precipitation provides higher odds for successful diversification and increased sustainability of more aggressive farming systems. Farther north, in temperate climates, persistent above average precipitation can lead to excessive moisture that can be detrimental to agriculture. For either water resources or agricultural applications, the decade-scale precipitation increase does not imply that every year will be wet. Only the odds of wet year versus average or dry year are higher. These shifts in probabilities are suited for strategic decision making (long-term), whereas seasonal climate forecasts provide more reliable probabilities for tactical decision making (short-term).

On the other hand, should the wet period of the last two decades come to an end, adaptive measures and water conservation strategies will be needed to deal with the potential water shortfall that could affect a society and economy that has come to rely on an ample water supply provided by the recent wet period. This study provides an order of magnitude and a geographic extent for changes that could be expected if annual precipitation characteristics return to normal conditions. For actual engineering and agricultural planning and design applications, the climate data from the location of interest must be used to obtain quantitative estimates of decade-scale precipitation changes. The value of considering decade-scale precipitation variations in practical applications will further increase as current research on the atmospheric forcing mechanism for, and the predictability of, decade-scale climate variations bear fruit (Higgins et al., 1999; Mantua et al., 1997; Latif and Barnett, 1996).

Notation

AP = Annual precipitation
cd = climate division
CFD = Cumulative frequency distribution
FRSAP = Filtered representative standardize annual precipitation
FSAP = Filtered standardized annual precipitation
k = counter limit
j = summation counter
ncd = number of climate divisions in a region
R = Region
RCFD = Representative cumulative frequency distribution
RSAP = Representative standardized annual precipitation
TAP = Time-accumulated precipitation
SAP = Standardized annual precipitation
std = standard deviation
y = Year

References

Barnston, A. G., A. Leetmaa, V. E. Kousky, R. E. Livezey, E. A O'Lenic, H. Van den Dool, A. J. Wagner, and D. A Unger. 1999. NCEP Forecasts of the El Nino of 1997-98 and its US Impacts. Bulletin of the American Meteorological Society, 80(9):1829-1852.

Barnston, A. G., H. M. Van den Dool, S. E. Zebiak, TY. P. Barnett, M., Ji, D. R. Rodenhuis, M. A. Cane, A. Leetmaa, N. E. Graham, C. R. Ropelewski, V. E. Kousky, E. A. O'Lenic, and R. E. Livezey. 1994. Long-Lead Seasonal Forecasts- Where do we Stand? Bulletin of the American Meteorologic Society, 75(11):2097-2114.

Changnon, S. A. 1999. Impacts of 1997-98 El Nino-Generated Weather in the United States. Bulletin of the American Meteorological Society, 80(9):1819-1827.

Chu, P. S., and J. D. Clark. 1999, Decadal Variation of Tropical Cyclone Activity over the Central North Pacific. Bulletin of the American Meteorological Society, 80(9):1875-1881.

Dixon, L. S., N. Y. Moore, and E. M. Pint. 1996. Drought Management Policies and Economic Effects in Urban Areas of California, 1987-1992, RAND, MR-813-CUWA/CDWR/NSF.

DWR. 1978. The 1976-1977 California Drought: A Review. California Department of Water Resources, May 1978, p. 228.

Garbrecht, J., F. E. Rossel, and J. M. Schneider. 2001. Decade-Scale Precipitation and Streamflow Variation in the Kansas-Nebraska Region. In: Proceedings 12th Symposium on Global Change and Climate Variations, 81st American Meteorological Society Annual Meeting, pp. 319-321, January 14-19, 2001, Albuquerque, New Mexico.

Garbrecht, J., and M. Van Liew. 2001. Streamflow Response of a Southern Plains Watershed to Decade-Scale Precipitation Variations. In CD-ROM Proceedings of World Water and Environmental Resources Congress, Orlando, Eds. D. Phelps and G. Sehlke, Florida, May 20-24, 2001, published by Environmental and Water Resources Institute of the American Society of Civil Engineers. (Proceedings)

Gershunov, A., and T. P. Barnett. Interdecadal Modulation of ENSO Teleconnections. Bulletin of the American Meteorological Society, 79(12):27152725.

Guttman, N. B., and R. G. Quayle. 1996. A Historical Perspective of U.S. Climate Divisions. Bulletin of the American Meteorological Society, 77(2):293-303.

Higgins, W., A. Leetmaa, Y. Xue, and A. Barnston. 1999. Dominant Factors Influencing the Seasonal Predictability of United States Precipitation and Surface Air Temperature. Proceedings of the Twenty-fourth Annual Climate Diagnostics and Prediction Workshop, Tucson, AZ, U.S. Dept. of Commerce, 226-229.

Hu, Q., C. M. Woodruff, and S. E. Mudrick. 1998. Interdecadal Variations of Annual Precipitation in the Central Unites States. Bulletin of the American Meteorological Society, 79(2):221-229.

Karl, T. R., and R. W. Knight. 1998. Secular Trends of Precipitation Amount, Frequency, and Intensity in the Unites States. Bulletin of the American Meteorological Society, 79(2):231-241.

Karl, T. R., R. W. Knight, D. R. Easterling, and R. G. Quayle. 1996. Indices of Climate Change for the United States. Bulletin of the American Meteorological Society, 77(2):279-292.

Kiladis, G. N., and H. F. Diaz. 1989. Global Climatic Anomalies Associated with Extremes in the Southern Oscillation. Journal of Climate, 2:1069-1090.

Kunkel, K. E., S. A Changnon, and J. R. Angel. 1994. Climatic Aspects of the 1993 Upper Mississippi River Basin Flood. Bulletin of the American Meteorological Society, 75(5):811-822.

Latif, M. and T. P. Barnett. 1996. Decadal Climate Variability over the North Pacific and North Amerika: Dynamics and Predictability. Journal of Climate, 9:2407-2423.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. Bulletin of the American Meteorological Society, 78(6):1070-1079.

Montroy, D. L. 1997. Linear Relation of Central and Eastern North American Precipitation to Tropical Pacific Sea Surface Temperature Anomalies. Journal of Climate, 10:541-558

Newsweek. 1999. Devils Lake Gets its Dues: Rising Water Wreaks Havoc in North Dakota. Newsweek, June 7, 1999.

NCDC. 1994. Time Bias Corrected Divisional Temperature-Precipitation-Drought Index. Documentation for Data Set TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Avenue, Asheville, NC 28801-2733. 12 pp.

NRC. 1998. Decade-to-Century-Scale Climate Variability and Change, A Science Strategy. Panel on Climate Variability on Decade-to-Century Time Scales; Board on Atmospheric Sciences and Climate; Commission on Geosciences, Environment, and Resources; National Research Council, pp.141.

Pielke Jr., R. A. and C. N. Landsea. 1999. La Nina, El Nino, and Atlantic Hurricane Damages in the United States. Bulletin of the American Meteorological Society, 80(10):2027-2033.

Ropelewski, C. F. and M. S. Halpert. 1996. Quantifying Southern Oscillation-Precipiation Relationships. Journal of Climate, 9:1043-1059.

Rossel, F. and J. Garbrecht. 1999. Climate Division Index and Observed Monthly Precipitation. In Proceedings of the 19th Annual American Geophysical Union, Hydrology Days, Fort Collins, Colorado, August 16-20 1999, Hydrology Days Publication, p. 357-367.

Trenberth, K. E. 1997. Short-Term Climate Variations: Recent Accomplishements and Issues for Future Progress. Bulletin of the American Meteorological Society, 78(6):1081-1096.

Woodhouse, C. A. and J. T. Overpeck. 1998. 2000 Years of Drought Variability in the Central United States. Bulletin of the American Meteorological Society, 79(12):2693-2714.

Worster, Donald E. 1982. Dust Bowl: The Southern Plains in the 1930s. Oxford, 1982. First published in 1979.