Eighth Conference on Applied Climatology,
17–22 January 1993, Anaheim, California

THE RELATIONSHIP OF DROUGHT FREQUENCY AND DURATION TO TIME SCALES

Thomas B. McKee, Nolan J. Doesken and John Kleist

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

1.0 INTRODUCTION

The definition of drought has continually been a stumbling block for drought monitoring and analysis. Wilhite and Glantz (1985) completed a thorough review of dozens of drought definitions and identified six overall categories: meteorological, climatological, atmospheric, agricultural, hydrologic and water management. Dracup et al. (1980) also reviewed definitions. All points of view seem to agree that drought is a condition of insufficient moisture caused by a deficit in precipitation over some time period. Difficulties are primarily related to the time period over which deficits accumulate and to the connection of the deficit in precipitation to deficits in usable water sources and the impacts that ensue.

Usable water sources include soil moisture, ground water, snowpack, streamflow and reservoir storage. Any impacts of drought associated with water demand exceeding water supply originate with one or more of these five usable supplies. The time period from the arrival of precipitation until water is available in each useable form differs greatly. Water uses also have characteristic time scales. Consequently, the impacts of a water deficit are a complex function of water source and water use. The time scale over which precipitation deficits accumulate becomes extremely important and functionally separates different types of drought. Agricultural (soil moisture) droughts, for example, typically have a much shorter time scale than hydrologic (groundwater, streamflow and reservoir) droughts.

Many examples are available where quantitative links have been established between precipitation deficits and drought impacts in particular water use areas. These use-specific relationships will likely continue to be expanded to assist in crop yield predictions, hydroelectric power projections and in many other drought-sensitive fields. However, the importance of monitoring and assessing water supply from a general climate perspective beginning with precipitation has not diminished.

Five practical issues become important in any analysis of drought. These include: 1) time scale, 2) probability, 3) precipitation deficit, 4) application of the definition to precipitation and to the five water supply variables, and 5) the relationship of the definition to the impacts of drought. Frequency, duration and intensity of drought all become functions that depend on the implicitly or explicitly established time scales. Our experience in providing drought information to a collection of decision makers in Colorado is that they have a need for current conditions expressed in terms of probability, water deficit, and water supply as a percent of average using recent climatic history (the last 30 to 100 years) as the basis for comparison. No single drought definition or analysis method has emerged that addresses all these issues well. Of the variety of definitions and drought monitoring methods used in the past, by far the most widely used in the United States is the Palmer Drought Index (Palmer, 1965), but its weaknesses (Alley, 1984) frequently limit its wise application. For example, time scale is not defined for the Palmer Index but does inherently exist.

The purpose of the following discussion is to propose an indicator and definition of drought which could serve as a versatile tool in drought monitoring and analysis. This indicator requires only one input variable, could be applied in a similar way to precipitation, snowpack, streamflow, reservoir storage, soil moisture, and ground water, recognizes a variety of time scales, and provides information on precipitation deficit, percent of average and probability.

2.0 A FUNCTIONAL DEFINITION OF DROUGHT

The definition of drought proposed here is based on standardized precipitation. Standardized precipitation is simply the difference of precipitation from the mean for a specified time period divided by the standard deviation where the mean and standard deviation are determined from past records. This same method can also be used to evaluate variations in any of the five usable water sources. A disadvantage of this simple method is that precipitation is typically not normally distributed for accumulation periods of 12 months or less, but this can be overcome by applying a transformation to the distribution. The resulting computation of standardized precipitation is linearly proportional to precipitation deficit and allows specification of probability, percent of average, and accumulated precipitation deficit. The basic approach is to use standardized precipitation for a set of time scales which together represent water sources of several types. Soulé (1990) used standardized precipitation in a study of spatial patterns. Bhalme and Mooley (1980) also used the standardized precipitation as a starting point for a drought definition.

The Standardized Precipitation Index (SPI) is calculated in the following sequence. A monthly precipitation data set is prepared for a period of m months, ideally a continuous period of at least 30 years. A set of averaging periods are selected to determine a set of time scales of period i months where i is 3, 6, 12, 24, or 48 months. These represent arbitrary but typical time scales for precipitation deficits to affect the five types of usable water sources. The data set is moving in the sense that each month a new value is determined from the previous i months. Each of the data sets are fitted to the Gamma function to define the relationship of probability to precipitation. Once the relationship of probability to precipitation is established from the historic records, the probability of any observed precipitation data point is calculated and used along with an estimate of the inverse normal to calculate the precipitation deviation for a normally distributed probability density with a mean of zero and standard deviation of unity. This value is the SPI for the particular precipitation data point.

The SPI calculated in this way has the following desirable traits:

The SPI is uniquely related to probability.

The precipitation used in SPI can be used to calculate the precipitation deficit for the current period.

The precipitation used in SPI can be used to calculate the current percent of average precipitation for time period of i months.

The SPI is normally distributed so it can be used to monitor wet as well as dry periods.

SPI can be calculated for the other water variables of snowpack, reservoir, streamflow, soil moisture, and ground water.

The SPI is normalized so that wetter and drier climates will be represented in a similar way.

An example of the SPI for Fort Collins, CO, is shown in Figure 1 for i = 3, 6, 12, 24, and 48 months for the period 1889-1991. When the time periods are small (3 or 6 months), the SPI moves frequently above and below zero. As the time period is lengthened to 12, 24, and 48 months, the SPI responds more slowly to changes in precipitation. Periods with the SPI negative and positive become fewer in number but longer in duration.

Using the SPI as the indicator, a functional and quantitative definition of drought can be established for each time scale. A drought event for time scale i is defined here as a period in which the SPI is continuously negative and the SPI reaches a value of -1.0 or less. The drought begins when the SPI first falls below zero and ends with the positive value of SPI following a value of -1.0 or less. Drought intensity is arbitrarily defined for values of the SPI with the following categories:

SPI Values	Drought Category	Time in Category
0 to -0.99	mild drought	~24%
-1.00 to -1.49	moderate drought	9.2%
1.50 to -1.99	severe drought	4.4%
≤ -2.00	extreme drought	2.3%
		~40%

In a long-term climate record each category ≤ -1.00 will be represented a known amount of time which is indicated above.

The definition of drought thus far has included a beginning date, ending date, and a current drought intensity. Duration of drought can be either a current duration since the beginning or the duration of a historic drought event from beginning to ending. Peak intensity can easily be determined from the SPI. A measure of the accumulated magnitude of the drought can be included. Drought Magnitude (DM) is defined as:

$$DM = -\left(\sum_{j=1}^{x} SPI_{ij} \right) \qquad (1)$$

where j starts with the first month of a drought and continues to increase until the end of the drought (x) for any of the i time scales. The DM has units of months and would be numerically equivalent to drought duration if each month of the drought has SPI = -1.0. In fact, many droughts will have a DM very similar to the duration in months since most of the SPI values are between 0 and -2.0.

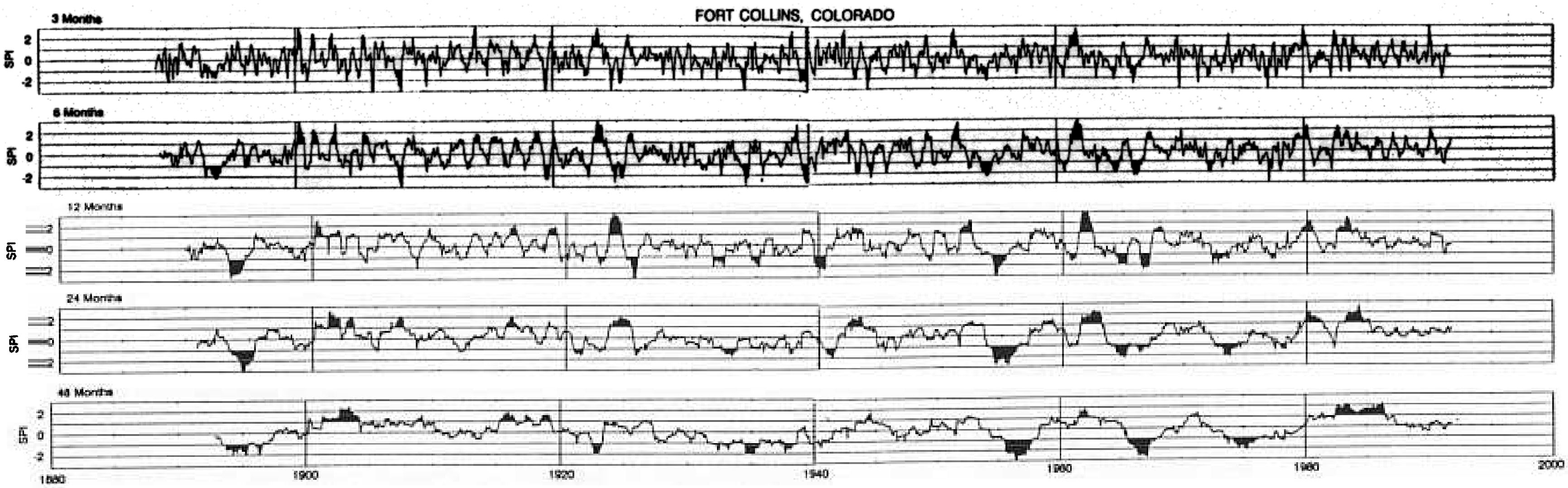

Figure 1. Standardized Precipitation Index time series calculated for Fort Collins, Colorado, 1889-1991 using time scales of 3, 6, 12, 24 and 48 months.

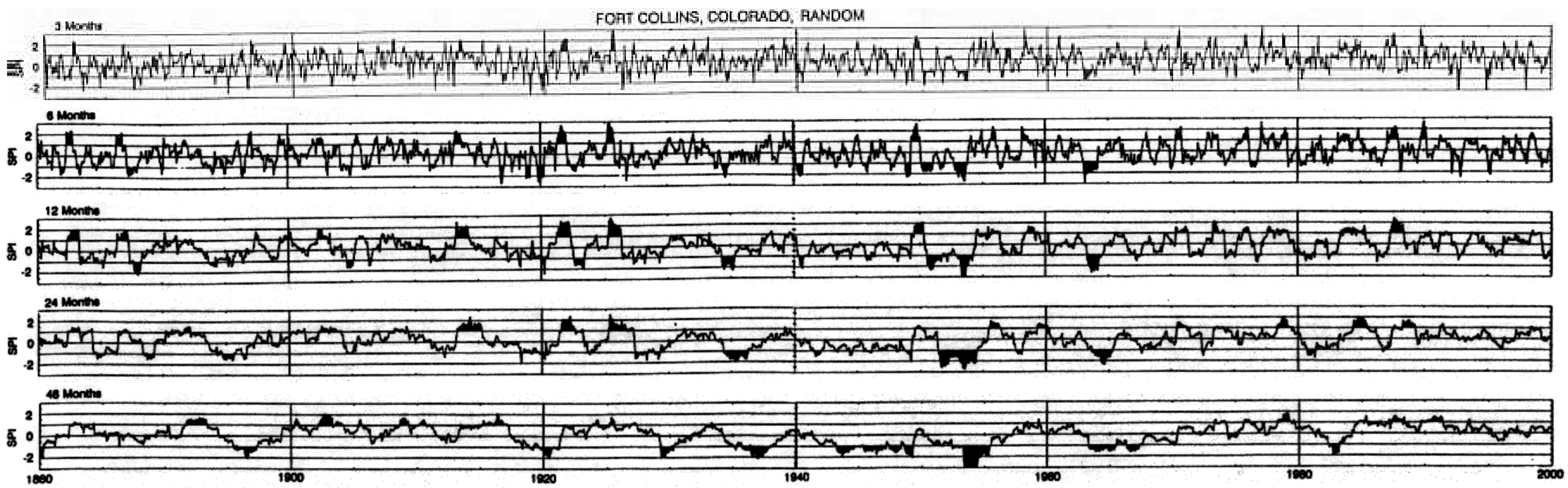

Figure 2. SPI for 120-year time series of random precipitation values but with monthly mean values and variability equivalent to Fort Collins, CO.

3.0. DROUGHT CHARACTERISTICS

The specification of a time scale in the definition of drought leads to several basic characteristics of drought. Two of the most important characteristics are frequency and duration. Figure 2 illustrates series of SPIs for each time scale based on 120 years of random monthly precipitation based on the annual cycle and expected variability of precipitation at Fort Collins, CO, which has a spring maximum in precipitation. The most obvious characteristics of the drought events in Figure 2 is that drought changes as the time scale changes. At longer time scales drought becomes less frequent and of longer duration very similar to what was noted in Figure 1. A summary of these traits is given in Figure 3 for twenty separate runs of random monthly precipitation and for actual observed data for Fort Collins, CO. The dashed line is added to illustrate the simple relationship between the number of droughts per one hundred years (N) and the time scale i of

$$N = \frac{c}{i} \qquad (2)$$

where c is a constant which in this example is a product of the time scale 3 and 96 or 288. Similarly,

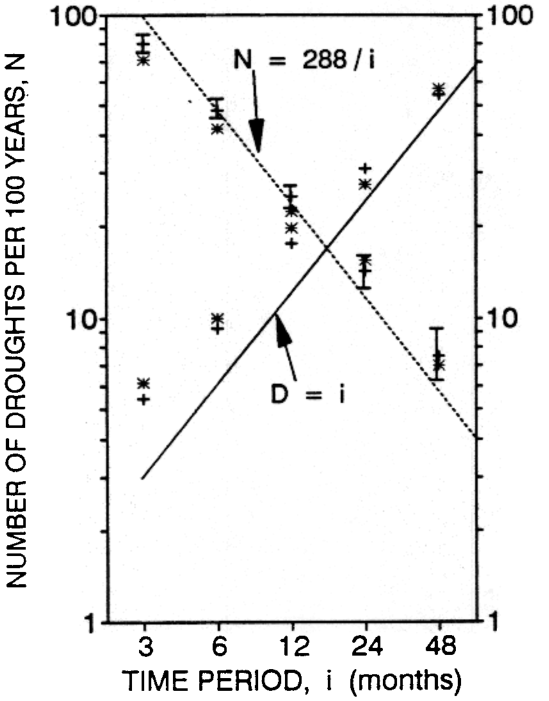

Figure 3. Frequency (N) and duration (D) of drought as functions of time period, i, for Fort Collins, CO, observed precipitation (*) and random precipitation (+). Line segment (I) represents ± one standard deviation determined from 20 time series of random precipitation.

the solid line represents a relationship of drought duration (D) and time scale as

$$D = i \qquad (3)$$

The general behavior of the number of droughts and the duration for a random climate is quite similar to these simple curves. For small time scales of 3 months, each new month has a large impact on the period sum of precipitation, so it is relatively easy to have the SPI respond quickly and move from dry to wet values. As i becomes larger each new month has less impact on the total (almost linear with time scale) and the index responds more slowly which leads to fewer droughts of longer duration. The total duration of drought for all time scales is approximately 40% of the time. This number is included in the table above.

Examples of questions often asked about drought include the following. How many droughts have occurred in the past 100 years? How long did they last? Which was the worst? How do dry conditions now compare with the past? The answers necessarily depend on definition. Drought has no simple or unique functional definition. However, a definition based on the SPI is obviously useful because is can provide answers to these questions and many others. One interesting test is the comparison of the present definition to the Palmer Drought Index (PDI). A comparison for Fort Collins, CO, is given in Figure 4. The correlation between the two has a maximum near a time scale of 12 months with a correlation coefficient of 0.85 suggesting that the PDI does indeed have an inherent time scale even though it is not explicitly defined.

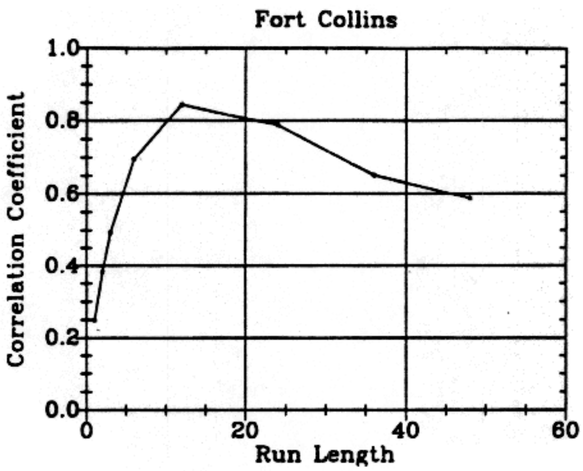

Figure 4. Correlation of SPI and Palmer Drought Index computed for Fort Collins, CO, 1889-1991.

4.0 DROUGHT ASSESSMENT AND MONITORING

Any specific evaluation of drought and its impacts requires a specification of time scale since drought initiation, intensity, duration, magnitude and ending are all dependent on time scale. A time scale of 3 months has more than 70 droughts per century using the thresholds suggested here. A time scale of 24 months is needed to get the total number of droughts down to the range of 10-15 per century. An illustration of the use of the present definition is given in Figure 5 again using Fort Collins data. Time scales of 12 and 24 months are included along with the precipitation deficit accumulated during each drought. The ordinate of the SPI graph has solid lines drawn to SPI = -2, -1, 0, 1, 2. Each of these values of SPI has a unique value of the probability that the SPI will be equal to or less than the stated value. These values of 0.02, 0.16, 0.50, 0.84, and 0.92 are included. In addition, each value of SPI has a constant value of precipitation as a percent of average which will vary with time scale, geographic location, and period of record of the observations. The index value, probability, and percent of average are all useful measures of dry or wet conditions for each time scale. The accumulated precipitation deficit for each drought event is the sum of the monthly departures of precipitation from the mean during the drought event. Under each of the larger droughts the DM value for the entire drought is included in parentheses.

The series for 12 months shows the worst single drought to be in the 1950s with other major droughts in the 1890s, 1960s and 1970s. It also shows that the 1930s had 4 smaller droughts which, if combined, would be more serious than any one of the others. The 24-month time scale illustrates that often more than one smaller drought is combined to form a single large drought as in the 1930s and 1960s. Even at 24 months the 1930s are not caught as a single drought event. The depiction of water deficits also reveals how in the 1930s and 1960s a deficit rapidly accumulated followed by a lull and then a second drought phase before any real recovery was achieved. Accumulated water deficit is another candidate to use in defining the magnitude of drought if the initiation is identified. The choice here to use DM as a measure is based on the logic that the longer the drought persists without a water recharge the worse is the magnitude as evaporation continues to occur.

Another aspect of the application of the SPI is related to estimates of recovery from drought. Probability of future precipitation based on the past can be calculated for all time scales such that estimates can be provided of the probabilities to emerge from drought. Such estimates are particularly useful when they indicate that drought is not likely to end soon and the impacts must be minimized.

5.0 SUMMARY

A new definition of drought has been proposed which explicitly specifies time scales and utilizes a standardized precipitation index. Drought frequency decreases inversely and duration increases linearly with time scale. Frequency and duration of random climate and actual climate are very similar. The new definition allows a consistent set of information to be calculated including drought beginning, ending, intensity, and magnitude. It also produces monitoring information of index values, probability, percent of average, and precipitation deficit during drought.

Beginning in the fall of 1992, the SPI will be used as an experimental drought monitoring tool in Colorado. Operational evaluations will then be performed as experience is gained relating SPI values to actual impacts.

ACKNOWLEDGMENTS

This research was supported by the Colorado Water Resources Research Institute and the Colorado Agricultural Experiment Station.

REFERENCES

Alley, W.M., 1984: The Palmer drought severity index: Limitation and Assumptions. *J. Climate Appl. Meteor.*, **23**, 1100-1109.

Bhalme, H.N., and D.A. Mooley, 1980: Large-scale drought/floods and monsoon circulation. *Mon. Wea. Rev.*, **108**, 1197.

Dracup, J.A., K.S. Lee, and E.G. Paulson, Jr., 1980: On the definition of droughts. *Water Res. Res.*, **16**, 297.

Palmer, W.C., 1965: Meteorological drought. *U.S. Weather Bureau Res. Paper No. 45*, 58.

Soulé, P.T., 1990: Spatial patterns of multiple drought types in the contiguous United States: a seasonal comparison. *Clim. Res.*, **1**, 13-21.

Wilhite, D.A., and M.H. Glantz, 1985: Understanding the drought phenomenon: The role of definitions. *Water International*, **10**, 111-120.

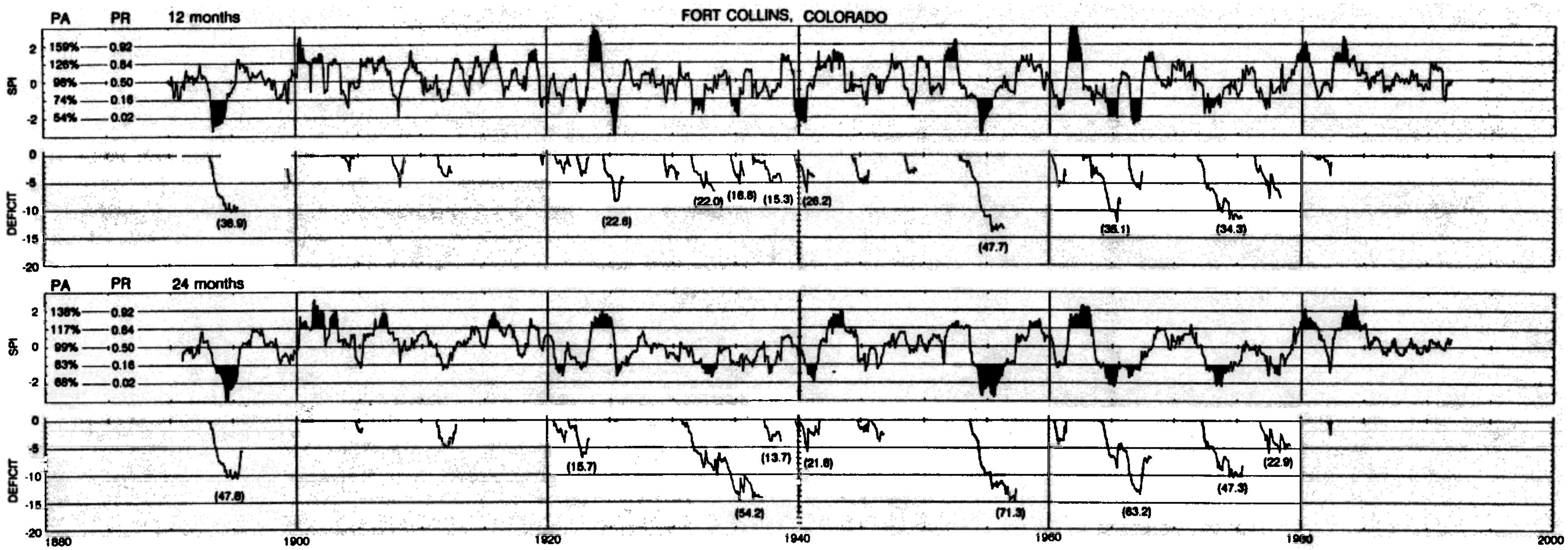

Figure 5. SPI for 12 and 24 months and associated accumulated precipitation deficits (inches) for Fort Collins, CO. Y-axis for SPI as non-dimensional index, percent of average (PA), and probability (PR). Numbers in parentheses are the DM values for the indicated drought period.