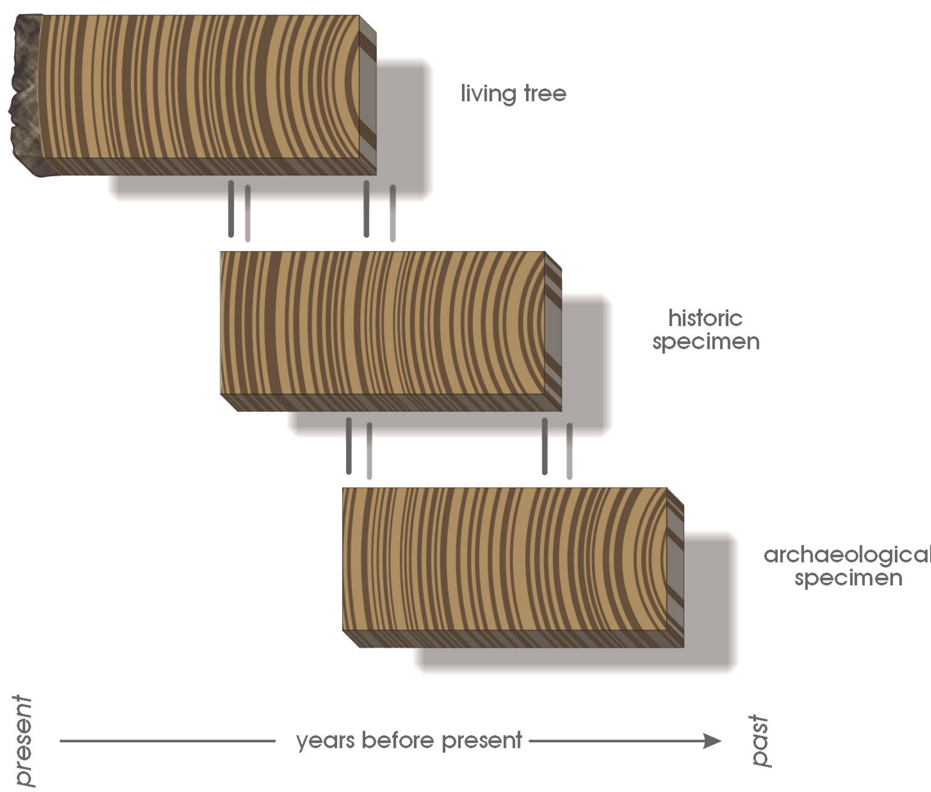
Exploring Drought in the San Antonio Area Between 1700 and 1979



by

Raymond P. Mauldin

Prepared for:
Edwards Aquifer Authority
1615 N. St. Mary's Street
San Antonio, Texas

Prepared by:
Center for Archaeological Research
The University of Texas at San Antonio
Special Report, No. 29

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Abstract:

Relying on tree-ring derived estimates of the summer Palmer Drought Severity Index (PDSI) presented by Cook et al. (1999), this document investigates drought frequency, intensity, and duration in the San Antonio area for a 280-year period between A.D. 1700 and 1979. The PDSI is a widely used index that is based on several variables and is designed to monitor soil moisture conditions. In most circumstances, the PDSI varies between 4.0 and -4.0, with an average year falling between 0.5 and -0.5. Here, I define drought as a value of -1.0 or less on the tree-ring derived PDSI. Using this definition, there were 40 droughts reflected in this 280-year stretch, with the average drought lasting 1.8 years. Long-term droughts, defined as droughts exceeding three years in duration, occurred four times in the available data, with three of these four being in the 1700s, and the fourth occurring in the early 1950s. This 1950s drought, covering a six-year period, was both the longest drought reflected in the available records as well as the most intensive of the four long-term droughts.

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Section 1: Introduction

Attempts to document and understand drought have become increasingly common as the economic and social consequences of this phenomenon are recognized. Obasi (1994) estimates that of the 2.8 billion people who suffered weather-related disasters worldwide in the last quarter of the twentieth century, roughly half (about 1.4 billion) were affected by drought. Unlike more commonly recognized weather-related natural disasters, such as hurricanes or tornados, droughts are widespread, occur frequently, and often last several years. In the United States, the drought of the 1930s devastated the Great Plains. The drought of the 1950s had a similar impact on Texas (Bomar 1995:155–157; Votteler 2000:60–68). However, documentation and investigation of drought are limited, in part, by the relatively short-term climate records available. Instrument records of rainfall and temperature in San Antonio, for example, cover just over 100 years. However, recent work by Cook et al. (1999) presents drought estimates, based on tree rings, for the continental United States that can be used to consider drought in the San Antonio region back to A.D. 1700.

This manuscript, then, provides a longer-term perspective on drought in the San Antonio area. The document has six sections. Beyond this introductory section, sections two and three provide background on tree-ring research and on the Palmer Drought Severity Index (PDSI). These two background sections are followed by an assessment of the tree-ring based PDSI relative to instrument data on temperature and rainfall for the San Antonio area from 1895 through 1979. I demonstrate that the tree-ring derived PDSI values are significantly correlated with both rainfall and temperature data. Also in this assessment section is a comparison of PDSI values relative to annual Edwards Aquifer recharge values between 1934 and 1979. This comparison demonstrates that, with the removal of two outliers, the tree-ring derived PDSI values have a significant linear correlation with aquifer recharge amounts (R=.782, n=44). These comparisons show that the tree-ring derived PDSI values are a useful measure of past water availability for the San Antonio area. The fifth section of this document focuses on 280 years of tree-ring based summer PDSI reflecting a period between A.D. 1700 and 1979 when the sequence ends. Using these data, I assess the frequency, intensity, and duration of drought in the San Antonio area. These data imply that drought, defined as a value of -1.0 or below on the PDSI, occurred 40 times in this 280-year period. Droughts were commonly of short duration, with the average drought lasting less than two years. The most intensive drought year reflected in these data occurred in 1925. Surprisingly, long-term droughts, defined here as droughts exceeding three years in duration, occurred four times in the available data, with three of these four being in the 1700s, and the fourth occurring in the early 1950s. This 1950s drought, covering a six-year period, was both the longest drought reflected in the available records as well as the most intensive of the four long-term droughts. The sixth and final section provides a summary of the research.

Section 2: Tree Rings, Time, and Climate

The drought analysis presented here is heavily dependent on tree-ring research. Cut through temperate forest trees, including most species of pine, fir, and oak, and you will probably see continuous bands of varying thickness circling the tree center. These bands represent seasonal growth rings, with new growth generally added every year as an outermost ring. Figure 1 presents an example of a section of a live oak from Bexar County, Texas, in which these rings are visible. These rings form the basis of dendrochronology, the assignment of time to growth rings in trees, and dendroclimatology, the study of variation in the characteristics of those growth rings as they relate to climate variation. The observation that some species of trees produce annual growth rings has been known for centuries. In the United States, the first suggestion that these annual growth rings would provide a basis for climate reconstruction appears to have been published in 1833 by A. C. Twining. While observing a large number of cut "hemlock timber" logs in New Hampshire in 1827, Twining (1833) noted that the annual rings varied in thickness, with some rings "indicating a growth five or six times as full in some years as in others…" and that "every tree told the same story." He went on to note that a systematic comparison of these patterns of growth might provide weather information back to a period "coeval with the age of the oldest forest trees…" (Twining 1833).

Twining's precocious suggestions were developed into what we now know as dendroclimatology in the early and mid 1900s, primarily through the work of Andrew Ellicott Douglass. Douglass, an astronomer at the University of Arizona, was interested in potential relationships between sunspot activity and rainfall. Douglass needed a long record of rainfall in order to search for these relationships, and recognized that tree rings could potentially provide that record (Douglass 1914, 1919). Working with cores from a number of living trees, where the ring chronology of a given core could be established simply by counting the rings back from the bark to the center, Douglass was able to establish a

Figure 1. *Example of tree-ring formation in a cross-section of a live oak, Bexar County, Texas.*

master chronology stretching back several centuries. At the same time, Douglass, along with a variety of other researchers, were recording rings in beams from archaeological sites in the American Southwest (Nash 1999; Robinson 1976). The chronological placement of these samples were essentially "floating" in that while a section was, for example, known to represent 250 years (i.e., it contained 250 rings), a specific calendar year could not be assigned to any of the rings in these archaeological cores. Douglass and his collaborators began to try to identify specimens that would bridge the gap between these floating chronologies and the modern chronologies, thereby allowing individual year assignments to the archaeological specimens, and the extension of the overall chronology back in time (see Figure 2). Eventually, in the 1920s, a number of specimens that bridged the gap were discovered, and a dendrochronology for the American Southwest was established that covered more than 1,000 years (Douglass 1929; Nash 1999). Dendrochronologies currently exist for most temperate regions of the world and, in some places and with some species, cover impressive lengths of time. For example, a bristlecone pine chronology, developed in the western United States, extends back close to 9,000 years (Brown 1996; Feng and Epstein 1994).

With a basic chronology in place for many areas, researchers have increasingly turned to developing an understanding of the climate signals contained in tree rings. A variety of factors influence ring width. The average ring width of a tree is a function of a variety of variables, minimally including species, the age of the tree, overall health of the tree, amount of competition with other trees, the slope of the location, the soil moisture conditions, and the nutrients in the soil. Added to this are a variety of variable climate factors, including the distribution of light, temperature, precipitation, wind speed, and humidity over the course of a year (see Bradley 1985:330–343). The problem of factoring out what, for the dendroclimatologist, is noise and isolating a climatic signal is daunting. Nevertheless, through the detailed analysis of a variety of trees from across the world, researchers have become increasingly successful at isolating climate signals. Much of this success is the result of a series of empirical studies of tree-ring width variation and climate variables using both principal component analysis and stepwise multiple regression techniques (see Fritts 1962, 1991; Fritts et al. 1971). Currently, dendroclimatology is a critical element of climate research, providing fine-grained information on both rainfall and temperature differences from throughout the world (e.g., Blasing and Fritts 1976;

Fritts et al. 1979; Grissino-Mayer 1996; Karl and Koscielny 1982; Stahle et al. 1985).

Section 3: The Palmer Drought Severity Index (PDSI)

What is drought? At a conceptual level, drought is relatively easy to define. Drought is a prolonged period of below normal water availability as a result of below normal rainfall and/or above normal temperatures. Such a conceptual definition, however, is of little use when we are attempting to define drought in an operational sense. That is, how "prolonged" must a below normal period be to qualify as a drought? How far below normal must water availability fall before we are in a drought? When does a drought end? It was with the goal of developing an operational definition of drought that the Palmer Drought Severity Index (PDSI) was initially developed.

W. C. Palmer developed the index in the early 1960s as a way to quantify drought (Palmer 1965). I will use the index in the current study to assess the frequency and intensity of drought in the San Antonio area. The PDSI is a measure of the departure from normal soil moisture conditions. The index is, in effect, a measure of (1) the amount of moisture in a particular soil, plus (2) the amount of moisture absorbed into the soil from rainfall, minus (3) water loss from the soil as a function of evapotranspiration and other soil moisture demands. The calculation of the index is complex, and involves several elements beyond simply tallying precipitation and temperature. These factors include potential evaporation, evapotranspiration, and estimates of surface and subsurface soil moisture content, recharge, and runoff (see Alley 1984; Karl 1986; Palmer 1965; Votteler 2000:253–258).

Usually calculated on a monthly basis, although yearly and weekly calculations are also common, the PDSI generally

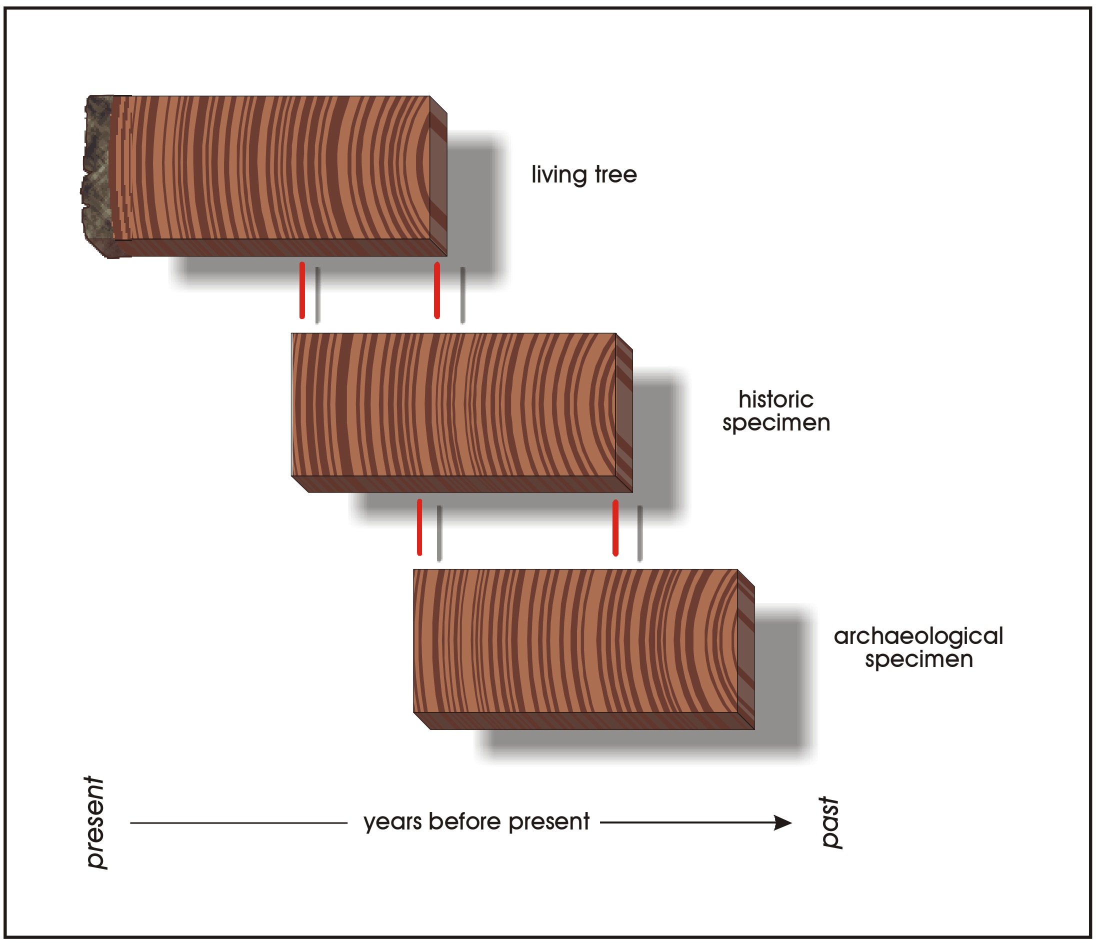

Figure 2. *Comparison of tree-ring segments representing same general time frame.*

ranges between values of -4.0 and 4.0, though both higher and lower values are possible. Figure 3 provides a schematic of the interpretations commonly assigned to the PDSI scores. The interpretations run from "normal" to "extreme" conditions, with normal soil moisture reflected in values ranging from 0.5 to -0.5, and the onset of extreme wet or extreme drought conditions signified by values of greater than 4.0 and less than -4.0, respectively. Palmer (1965) suggested these interpretations based on studies in Iowa and Kansas. The interpretations, as well as the locations of the break points, are somewhat arbitrary in that there is no qualitative difference between a score of -0.49 and -0.51 that necessarily indicates the onset of something called "incipient drought." However, the interpretations do provide some guidance to the meaning of the various PDSI values. Note that the PDSI was designed as a relative index of departure from normal soil moisture conditions at a given location. That is, a PDSI of -2.0 in El Paso should be similar, in terms of soil moisture departures from normal, to a -2.0 at Houston even though annual Houston precipitation is about 54 inches and El Paso receives about nine inches.

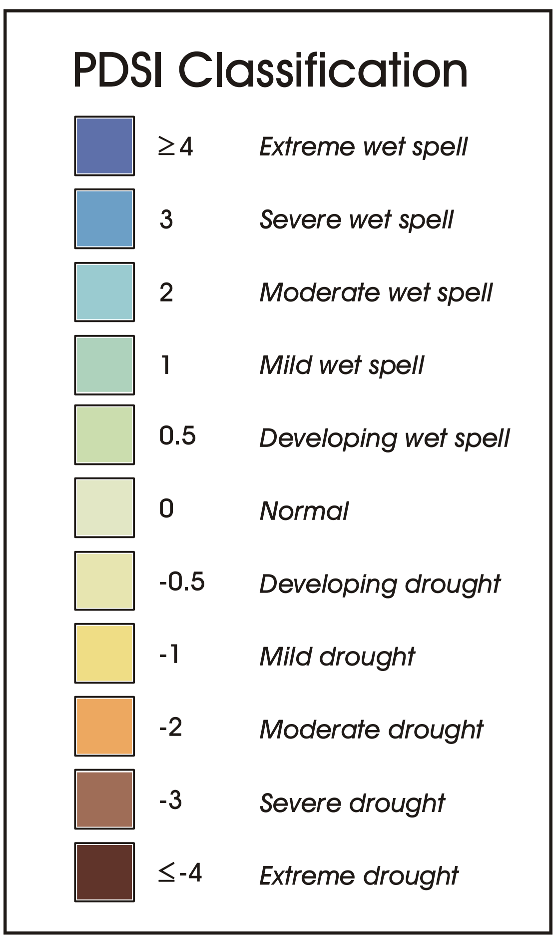

Figure 3. *Commonly used interpretive scheme for PDSI values.*

The PDSI is one of the most widely used measures of meteorological drought in the United States, and several state level agencies, as well as federal organizations, rely on this index as one of the elements in triggering drought relief efforts. Nevertheless, the index does have several limitations, summarized below, in both the way that it is calculated and the way that it is frequently applied (see Alley 1984; Karl 1986). First, the index appears to be sensitive to the average water holding capacity of a particular soil type. The PDSI, then, should not be applied at large special scales, such as at a state level or even at the level of a climate division as these scales crosscut a wide variety of soil types. Second, it appears that the PDSI does not adequately account for lags in precipitation inputs. For example, all precipitation is calculated as rainfall and, therefore, seen as immediately available. Precipitation tied up in snow pack or ice, however, may not be available to the soil until the spring. Runoff may also be under-represented by the PDSI. With the possible exception of the under-representation of runoff, these more common limitations appear to be negligible. The PDSI, then, potentially provides a quantitative measure of soil moisture that can be used to effectively monitor aspects of drought in the San Antonio area.

Section 4: Tree-Ring Derived PDSI and San Antonio Climate

In this section, I introduce a variety of data sets, including the tree-ring derived PDSI values that span the period between A.D. 1700 and 1979, and a variety of instrument data on precipitation, temperature, and the instrument-derived PDSI values for San Antonio. These instrument-derived climate data span the period from 1895 through 1979. In addition, data on levels of Edwards Aquifer recharge from 1934 through 1979 are presented. These data sets are then used to investigate relationships between climate, aquifer levels, and the tree-ring derived PDSI values.

The principal data set used in this document is derived from Cook et al. (1999) who have developed tree-ring based summer PDSI scores from across the continental United States dating back to before A.D. 1700. The tree-ring based PDSI values were developed by use of a point-by-point regression analysis involving principal component analysis (see Cook et al. 1999:1147–1148). Instrument data from 1928 through 1978 were used to calibrate the data sets, and the results were verified with pre-1928 instrument data. The resulting PDSI data were presented as a series of 154 evenly spaced grid points covering the continental United States. The grid PDSI is based on a detailed analysis of 425 individual tree-ring chronologies. Figure 4 presents a blowup of the section of this grid that encompasses Texas and surrounding states. Grid point 85, centered just to the south of San Antonio, was the location used in the current study. This grid point contained PDSI estimates derived from several post-oak based sequences in the general region (see also Stahle and Cleaveland 1988).

The tree-ring based PDSI values used here were calculated for years between 1685 and 1979, though I focus only on the 1700 through 1979 period. All raw tree-ring PDSI data used in this analysis are available at http://wdc.casnw.net/paleo/treenet.html. Note that the values used here are summer PDSI values rather than year-round measurements. This is because climate variables in the summer have the highest correlation with tree-ring growth. It is useful, then, to conduct an assessment of the utility of these summer PDSI scores for reflecting overall water availability at a year-round scale. To do this, I turn to several additional data sets that focus on aspects of San Antonio climate, as well as on the Edwards Aquifer itself.

The instrument-based data sets are for temperature and rainfall for San Antonio. These weather data reflect a period between 1895 and 1979 and come from the National Climate

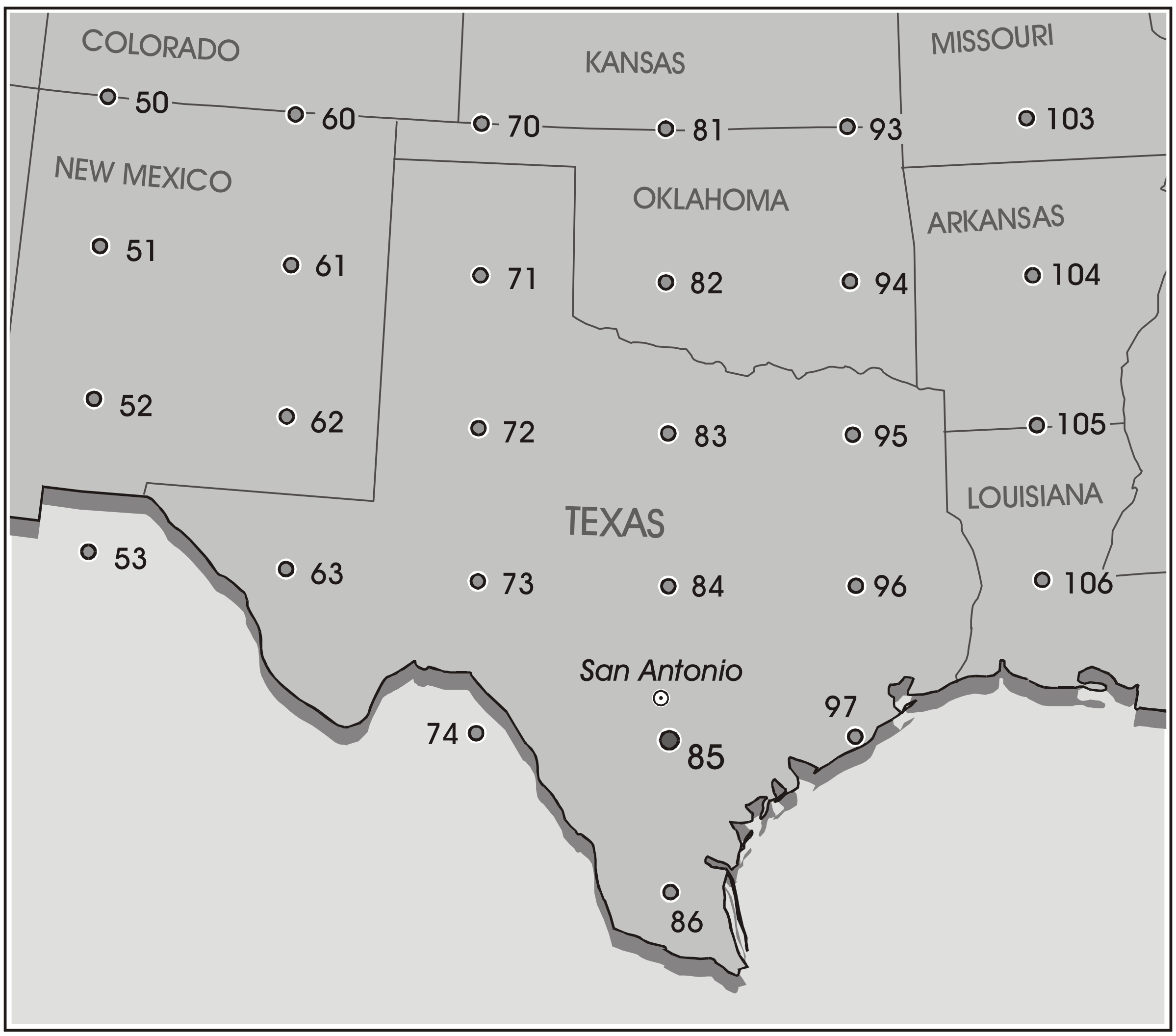

Figure 4. *Example of systematic grid developed for tree-ring based PDSI values.*

Data Center of the National Oceanic and Atmospheric Administration. The data are available at www.ncdc.noaa.gov/oa/climate/research. Finally, the Edwards Aquifer recharge data, from 1934 through 1979, were derived from the USGS Water Resources Division, San Antonio, Texas, and accessed through the Edwards Aquifer Authority Web site at www.edwardsaquifer.org.

Figure 5 presents the tree-ring derived summer PDSI values between 1895 and 1979 (Y-axis) and contrasts it with average summer temperatures (X-axis). Note that while there is considerable scatter in the plot, it is generally the case that tree-ring derived PDSI values are inversely correlated with temperature. That is, high temperatures tend to be associated with low PDSI values, and low temperatures tend to be associated with higher PDSI scores. Overall, the Pearson's correlation coefficient for these 85 cases is -.434. This correlation is statistically significant ($p = 0.01$).

Figure 6 presents a similar plot for annual rainfall totals (Y-axis) and summer PDSI values (X-axis). Here, a positive correlation is reflected, with low rainfall totals associated with low PDSI values, and high rainfall totals associated with high PDSI values. The Pearson's correlation coefficient for these 85 cases is .452. As with the summer temperature values in Figure 5, the correlation is statistically significant ($p = 0.01$). Note that in Figure 6, I have identified in brown those years that fall below a PDSI score of -1.0, a value identified as indicating "mild drought," along with those that reflect more normal years (PDSI < 1.0 and > -1.0, green) and wet years (PDSI > 1.0, blue). The average rainfall for the 17 drought years identified by the PDSI is 21.8 inches (median = 18.8 inches). For the more normal years, the average is 28.05 inches (median = 27.65 inches). For the 31 wet years, the average is 30.38 inches (median = 29.64 inches).

The patterns seen in Figures 5 and 6, along with the summary rainfall statistics noted previously, clearly suggest that at least for the 85 years with comparable data, summer PDSI scores derived from tree rings provide a good reflection of several critical climate variables for San Antonio, including annual rainfall. The effectiveness of the tree-ring PDSI values is also apparent in Figure 7. Here, I plot the summer tree-ring derived PDSI values (Y-axis) against the instrument-based PDSI values (X-axis) for grid point 85 using the 85 years of instrument data. Overall the correlation coefficient is .726, a statistically significant result, suggesting

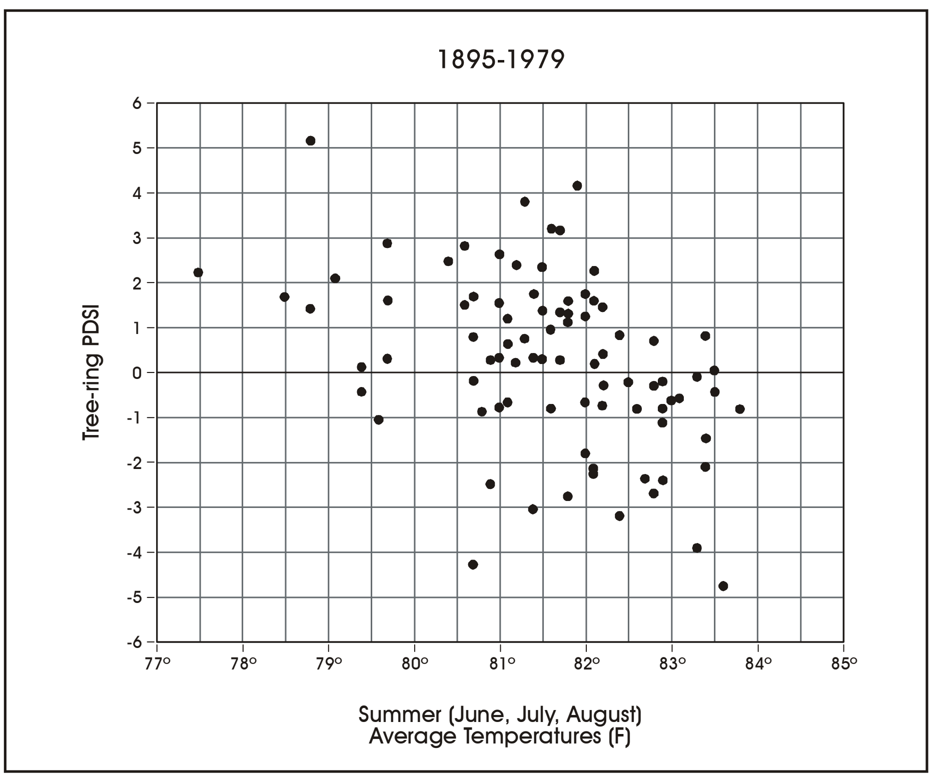

Figure 5. *Bivariate plot of tree-ring PDSI values and average summer temperatures for San Antonio (1895–1979).*

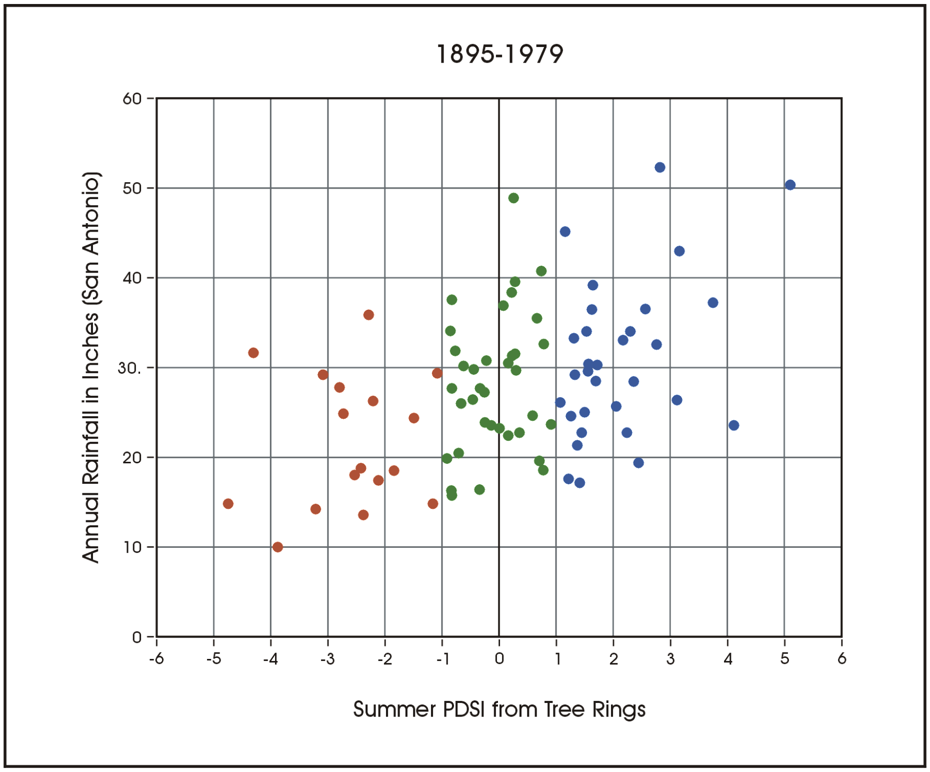

Figure 6. *Bivariate plot of tree-ring PDSI values and annual rainfall for San Antonio (1895–1979).*

that the tree-ring derived PDSI is a good indicator of the instrument PDSI.

A closer examination of Figure 7, however, will show that in the drought area of the plot, the tree-ring based PDSI appears to be more positive than the instrument PDSI, and in the wetter areas of the plot, the tree-ring PDSI appears to be more negative than the instrument data. For the San Antonio based data, the tree-ring PDSI underestimates the frequency of drought, and underestimates the frequency of wet spells, relative to the instrument records. The instrument records are more variable, an observation supported by both the higher standard deviation on these records (s.d.= 2.58) relative to the tree-ring data (s.d.= 1.91) as well as the greater overall range of the instrument data (-5.19 to 5.33) relative to the tree-ring PDSI (-4.76 to 5.12). These data suggest that a strict interpretation of the onset of drought using the tree-ring derived PDSI values may under-represent drought relative to the instrument-based PDSI.

Figure 8 shows two examples of the systematic under-representation of wet and dry extremes in the tree-ring data. Here, I compare the PDSI values derived from tree rings (right) and instrument data (left) for a wet year (1941, top) and a dry year (1956, bottom) across the continental United States. Data used in these plots are available at http://wdc.casnw.net/paleo/pdsiyear.html. Note that, as suggested in the bivariate plot of the San Antonio data in Figure 7, the wet year appears less wet in the tree-ring PDSI plots, and the dry year appears less dry in the tree-ring derived plots. As my focus in subsequent sections will be on identifying drought using the tree-ring PDSI, the observation that the actual frequency of drought may be under-represented by the tree-ring data is of considerable interest. In light of this observation, I chose to define all droughts as indicative of a tree-ring PDSI value of -1.0 or less, a level that Palmer (1965) suggested was indicative of the onset of "mild" drought. In spite of this somewhat conservative designation, note that it may still be the case that the tree-ring values somewhat underestimate the actual frequency and intensity of drought. However, even if this is true, the tree-ring PDSI values provide a consistent scale for roughly three centuries, allowing us to compare the intensity, frequency, and duration of drought from A.D. 1700 into the modern era.

The tree-ring PDSI values are correlated with climate elements such as rainfall and temperature, as well as the instrument-derived PDSI. Figure 9 provides an additional

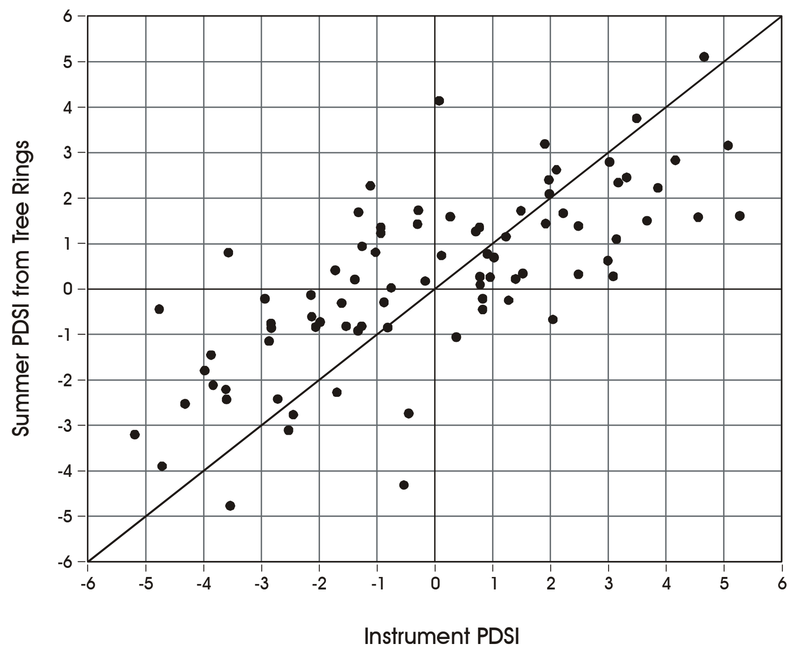

Figure 7. *Comparison of PDSI values derived from instrument and tree-rings for San Antonio data.*

comparison. Here, I plot tree-ring PDSI values (X-axis) against Edwards Aquifer recharge estimates (Y-axis) for 46 years, between 1934 and 1979, when data are available. Consideration of the figure will show that there is a strong, positive correlation between these two data sets with high PDSI years correlated with high recharge, and low PDSI years associated with low recharge. Using all 46 years, the Pearson's correlation coefficient is .603. This value is statistically significant. Note, however, that two years, identified by triangles on the figure (1958 and 1971), do not seem to follow the overall trend. Removing these two outliers, the correlation coefficient rises to .782 (n=44). As with the previous correlation, the value is statistically significant.

Finally, Figure 10 presents the same data sets used in Figure 9 in a slightly different way. Here, both the summer PDSI (red line) and the Edwards Aquifer recharge levels (blue line) have been standardized for the 1934 through 1979 period. Note that standardization, which produced a mean of 0 and a standard deviation of 1, allows us to plot these two data sets on the same scale. With the exception of the two outliers (1958 and 1971), there is a remarkably similar pattern between the two data sets. The patterns in Figures 9 and 10, when combined with the earlier correlations with climate data, demonstrate that the tree-ring derived PDSI values have considerable utility in assessing drought in the San Antonio area.

Section 5: Drought in the San Antonio Region from 1700 to 1979

The tree-ring derived PDSI values have considerable utility in monitoring both certain variables of climate as well as probable recharge into the Edwards Aquifer. I now turn to monitoring drought frequencies in the San Antonio area over the 280 years with available data.

San Antonio is located at between 29 and 30 degrees latitude, a location that, because of global circulation patterns, frequently is associated with persistent high-pressure systems. These systems tend to block or deflect incoming storms. In fact, this latitude is often associated with deserts in both the northern and southern hemispheres as a function of that global circulation pattern (see Bradley 1985; Wallen

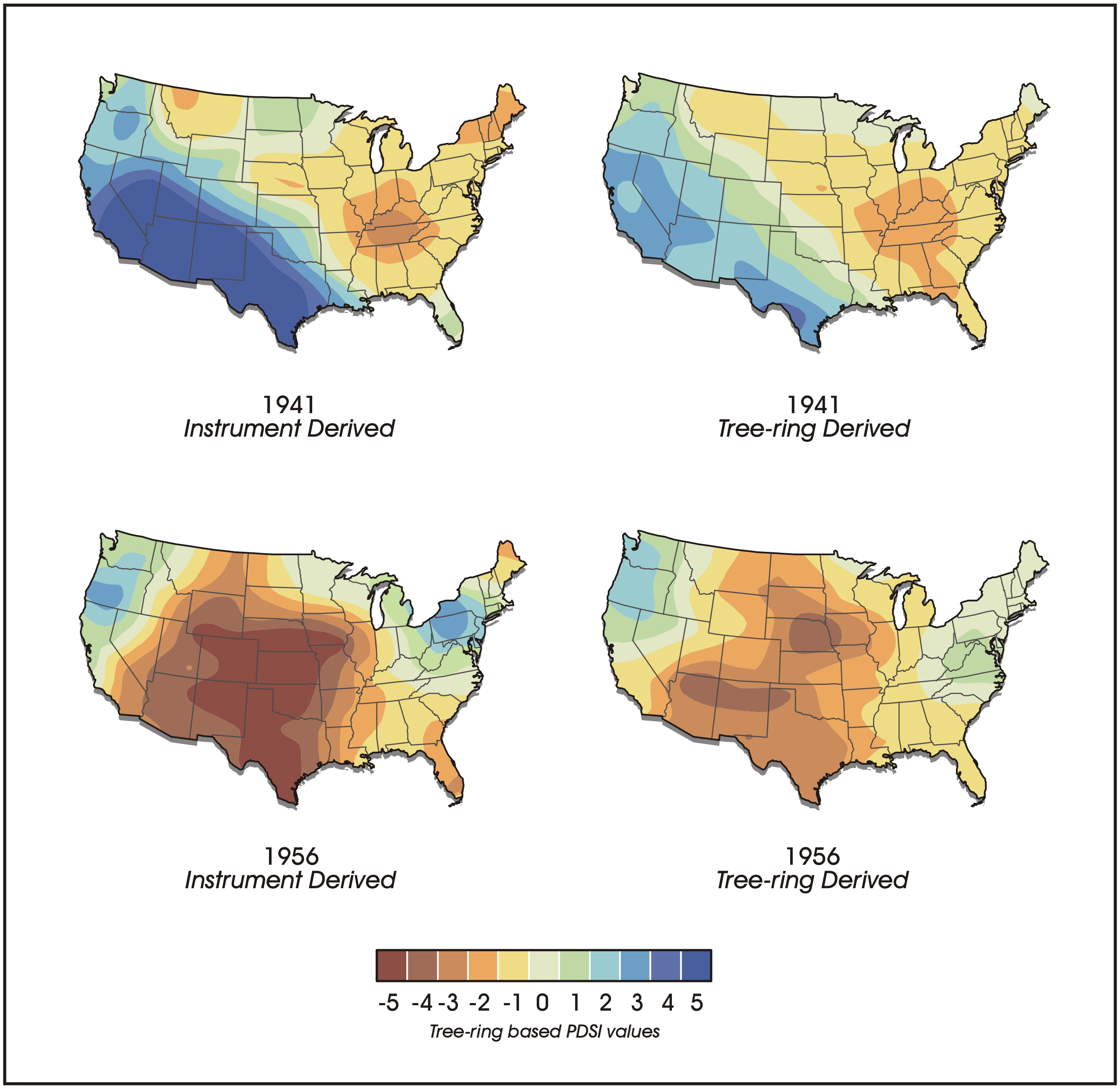

Figure 8. *Comparisons of instrument and tree-ring derived PDSI for the Continental United States, 1941 and 1956.*

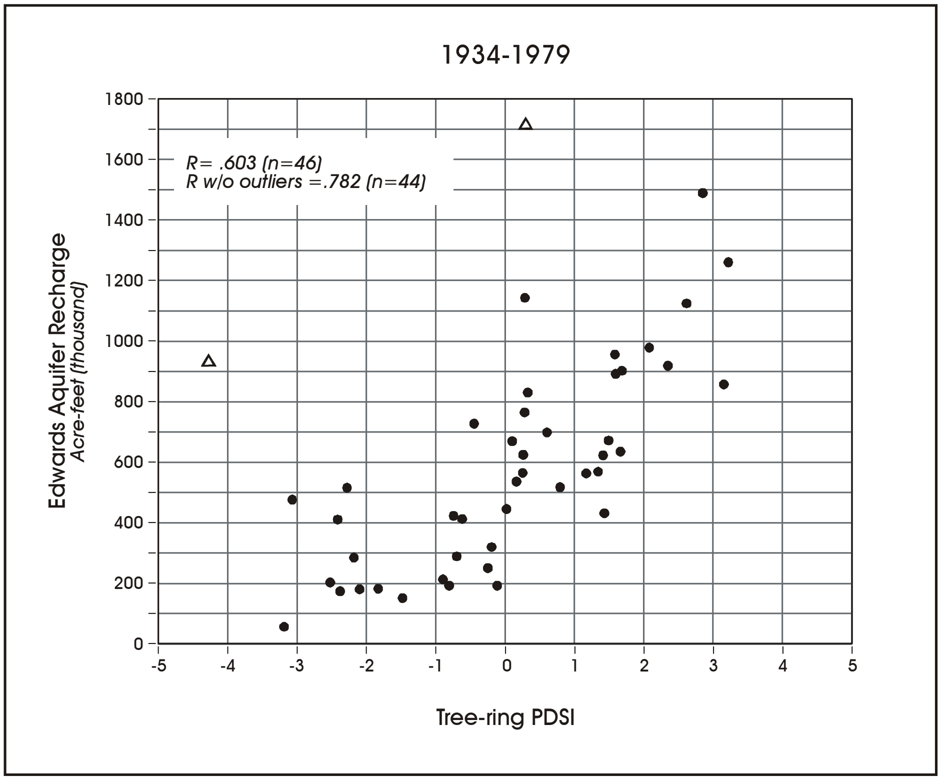

Figure 9. *Plot of tree-ring PDSI and Edwards Aquifer recharge amounts for period between 1934 and 1979.*

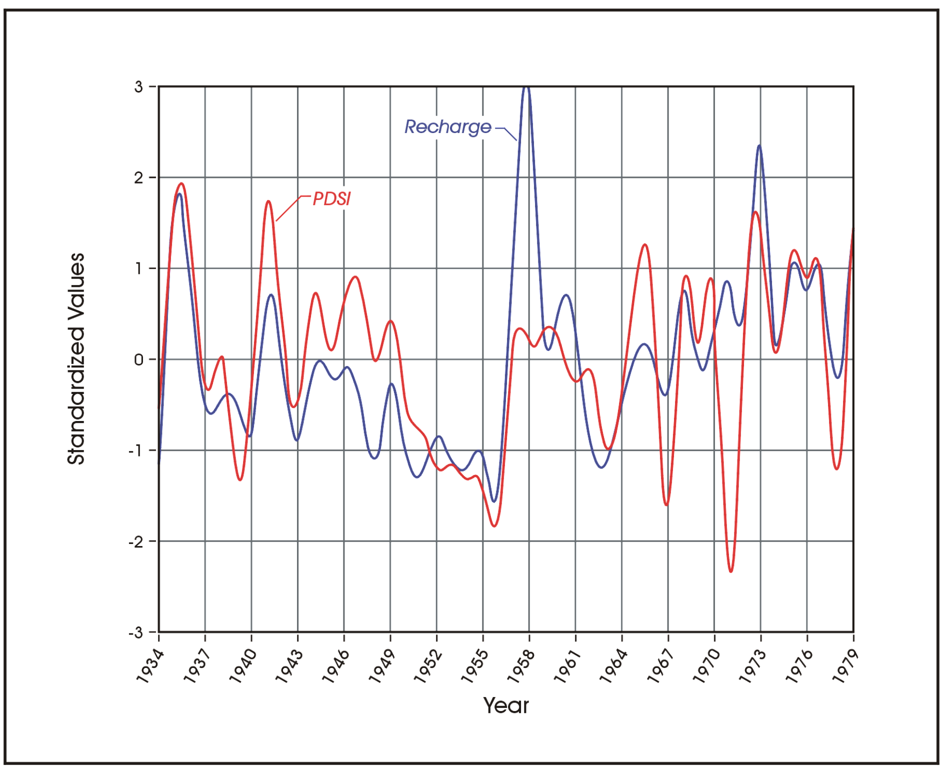

Figure 10. *Standardized Edwards Aquifer recharge and PDSI values (1934–1979).*

1966). It is not unreasonable, then, to expect a highly variable climate, with frequent, prolonged periods of little or no rain, in the San Antonio region. However, this does not seem to be the case for most of the instrument sequence. Using 92 years of available data, San Antonio has an average annual rainfall of 28.3 inches. The wettest year had over 52 inches of precipitation while the driest year had only 13.7 inches. Using 960 individual months between 1900 and 1979, the average monthly rainfall was 2.34 inches, and there were only eight months (0.83%) with no rainfall recorded. The wettest month during this 960-month span had 15.78 inches of rainfall recorded, and 70% of the 960 months had at least 1.0 inches of rainfall recorded. Nevertheless, there have been persistent periods of low rainfall, such as between 1951 and 1956. In this 72-month span, rainfall averaged only 1.59 inches per month, no precipitation was recorded for 2.8% of the months, and 1.0 inches or more precipitation was recorded in only 57% of the months. Coupled with higher temperatures, these persistent low rainfall totals produced the 1950s drought.

The severity of the 1950s drought is clearly shown in Figure 11. This figure presents the tree-ring PDSI scores from 1900 through 1979 for San Antonio (grid point 85). Using the value of -1.0 as an indicator of drought, examination of the figure will demonstrate that during this 80-year period, 17 years (21.3%) can be classified as drought years. Eleven different droughts are present. While the average drought during this period lasted 1.54 years, only twice, during 1916 and 1917, and again between 1951 and 1956, were multiple-year droughts reflected in the tree-ring PDSI. The overall range of values for this 80-year period was from a low of -4.76 to a high of 5.12, and the average PDSI value was slightly positive, with a score of 0.22. Note also that PDSI values for the post-1979 period have not been developed. As such, the drought in the early 1990s in the region is not reflected in these data.

The PDSI values for the period between 1800 and 1899 are shown in Figure 12. Using the value of -1.0 as a drought indicator, during this 100-year period, 25 years (25.0%) can be classified as drought years. Sixteen separate droughts are present, with the average drought lasting 1.56 years. There are eight multiple-year droughts, with seven of these lasting two years and one, between 1862 and 1864, lasting three years. The average PDSI for this 100-year period was 0.157, and the scores ranged from a low of -3.60 to a high of 4.15.

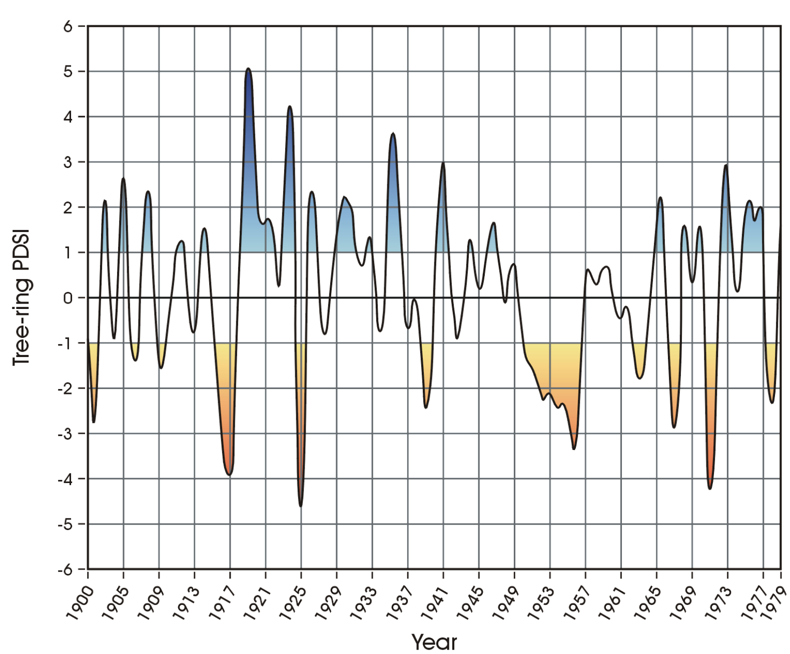

Figure 11. *PDSI values, 1900–1979.*

Finally, the PDSI values for the period between 1700 and 1799 are shown in Figure 13. Thirty percent of these years fall within the drought range, and 13 different droughts are present. The average drought was 2.31 years. Multiple droughts were common during this period, with nine cases present. Droughts covering two years in duration were present four times, and there were two three-year droughts and three four-year droughts. The average PDSI for this period was 0.177, and values ranged from -3.83 to 5.46.

For the entire sequence, then, there were 40 droughts reflected in this 280-year stretch. Overall, 72 of the 280 years (25.7%) were within the drought designation, with the average drought lasting 1.8 years. Droughts lasting only a year were most common, with 21 such cases reflected in the graphs. Droughts of two years in length occurred 12 times, and only three droughts were three years in length. Long-term droughts, defined as droughts exceeding three years in duration, occurred only four times in the available data, with three of these four being in the 1700s, and the fourth occurring in the early 1950s. As can be seen in Figure 11, the well-documented 1950s drought covered a six-year stretch, between 1951 and 1956. This was the longest continuous drought reflected in the record, and it was also the most intensive of the four long-term droughts with an average PDSI of -2.32.

Strictly defined at the -1.0 PDSI value, then, long-term droughts are certainly not common in these records, and a drought as severe as the well-documented 1950s drought was not reflected in the records of any earlier periods. However, there have been several substantial dry periods that, while not consistently within the arbitrarily defined drought range (-1.0 or less), were nevertheless quite dry. Seven such periods are reflected in the 280 years of data. Examinations of the graphs will suggest that there were four such periods in the 1700s, with the most protracted occurring for 22 years between 1770 and 1791. During this 22-year period, the average tree-ring PDSI was -0.70. Similarly, in the 1800s two such periods were present, with the longest reflecting 13 years between 1852 and 1864 when the PDSI averaged -0.867. A single such period is evident in the 1900s, and centered on the 1950s drought. For 17 years between 1948 and 1964, the PDSI averaged -0.95.

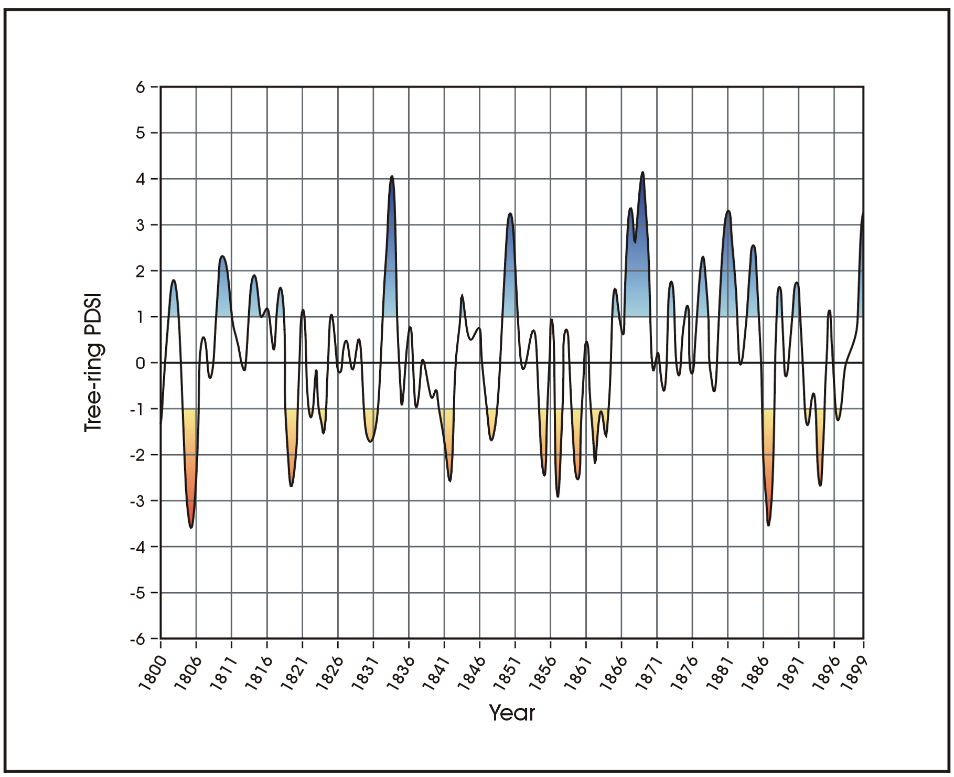

Figure 12. *PDSI values, 1800–1899.*

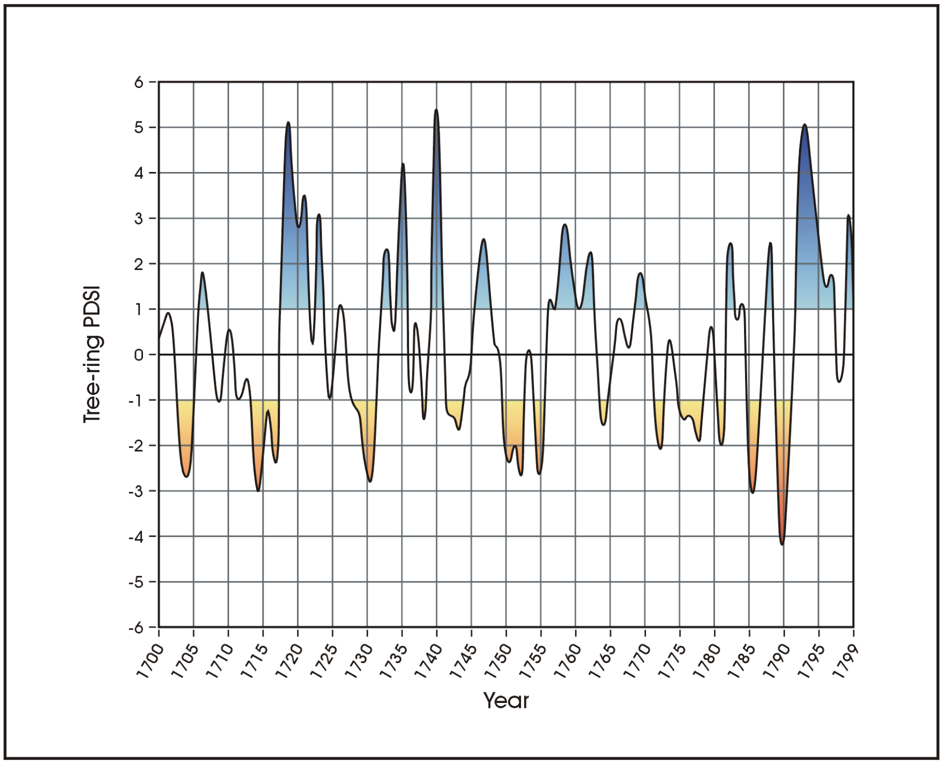

Figure 13. *PDSI values, 1700–1799.*

Section 6: Summary

Any long-term analysis of drought in the San Antonio area is hampered by a lack of long-term instrument records. This analysis has attempted to extend the available records through a reliance on tree rings. Specifically, I have used extant estimates of the summer Palmer Drought Severity Index, derived from tree-rings, to explore frequencies of drought in the San Antonio area back to A.D. 1700. Tree-ring PDSI values are significantly related to several San Antonio climate variables between 1895 and 1979, and PDSI scores are correlated with recharge values observed for the Edwards Aquifer between 1934 and 1979. This analysis suggests that tree-ring based PDSI can provide a good measure of drought prior to 1895, when climate records are unavailable.

Using a strict -1.0 PDSI determination for when drought conditions are present, 72 of the 280 years between 1700 and 1979 are drought years. Multiple years of drought are not common in this data set, with only 12 two-year droughts (24 total drought years), three three-year droughts (9 drought years), and four droughts in excess of three years (18 drought years) noted. However, while not technically classified as droughts in all years, I have identified seven long-term dry periods in the record. These seven periods average 12 years in length. Roughly 30% (n=84 years) of the 280 years reflected in the record occur within one of these dry spells.

The 1950s drought, which is reflected in the PDSI levels between 1951 and 1956, was the most intensive of the four longer-term droughts as well as the longest drought reflected in the 280 years of data. The 1950s drought was, at this time scale, a unique occurrence. Unfortunately, even this three-century time scale is not an adequate window on climate if we are interested in rare events. This can be seen in Figure 14, a plot of tree-ring PDSI values for the Southwest. The line represents a three-year running mean, and data are available back to A.D. 1200. The plot is based on 14 tree-ring chronologies from northern Mexico as well as from Arizona, Utah, and New Mexico (see Cook 2000). Using a PDSI of -1.0 as an indicator of drought, 261 of the 775 years (about 33.5%) reflected in the figure are drought years and numerous droughts, several of which lasted multiple years, are visible. These multiple-year droughts include the early 1950s drought so well documented in

Texas. Between 1953 and 1957, five straight years of drought are reflected in this Southwest data. The average PDSI value during this period was -2.214, a value comparable to the -2.31 PDSI for the San Antonio data during this same drought. Examination of the 1700 to 1975 portion of the figure will suggest that few long-term (four or more years) droughts are present, a pattern that continues into the 1600s. However, long-term droughts, at least in the Southwest, are more frequent, longer in duration, and more severe in the pre-1600 data than in the more recent data. These pre-1600 droughts include what were probably devastating instances, certainly surpassing the 1950s drought in intensity and duration, in both the late 1570s and the late 1270s (Figure 14). These multiple-year droughts, along with the 1950s drought, are highlighted in red in the figure for comparison.

Were droughts similar to those reflected in the 1570s and late 1270s in this Southwest data present in San Antonio? I do not know. At present we lack a detailed understanding of what factors have caused long-term drought to occur. While we can state that droughts such as that seen in the 1950s were not common in the last three centuries in San Antonio, we cannot, with any known degree of confidence, state that long-term droughts were not common prior to 1700, or will not be common in the future.

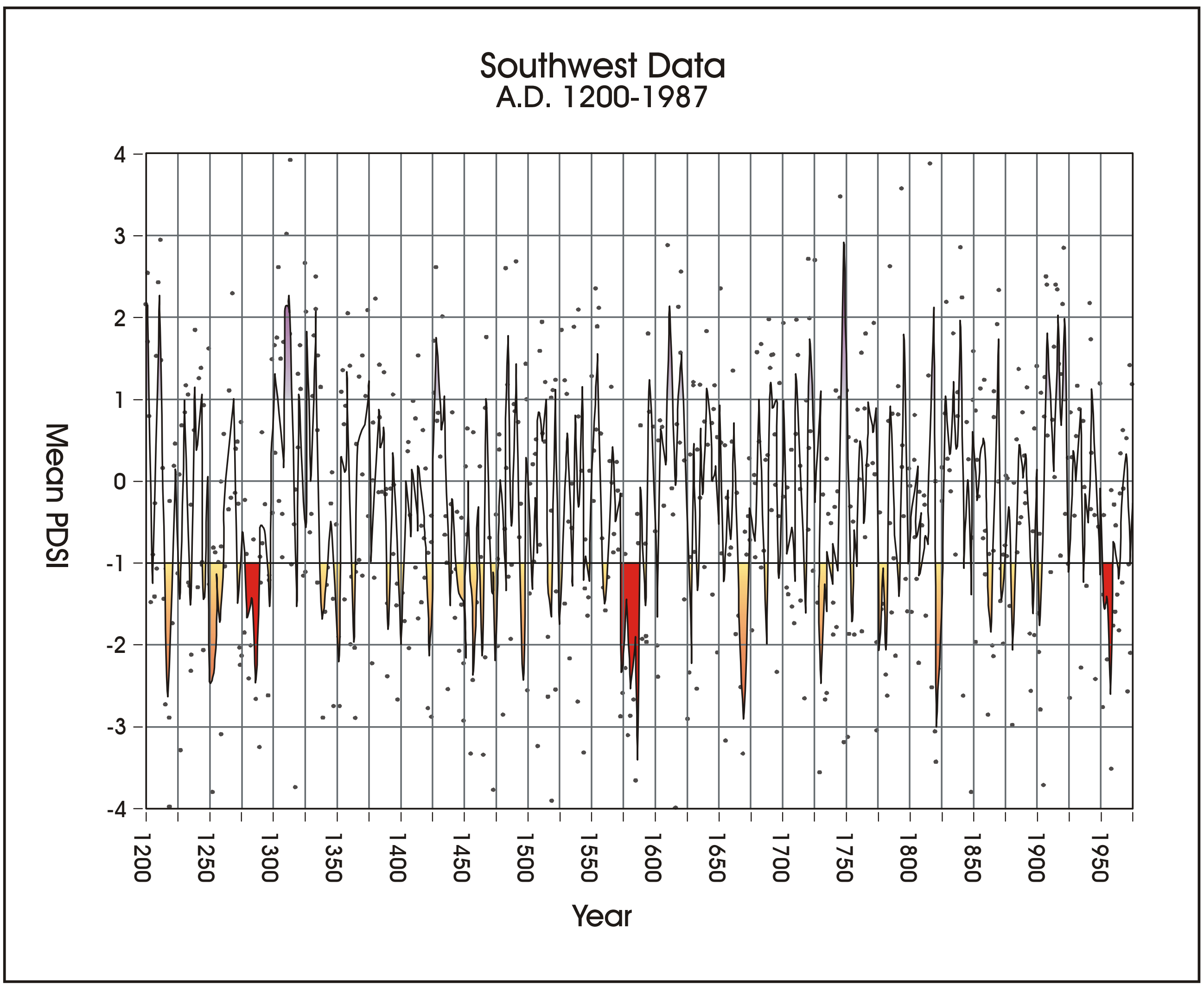

Figure 14. *PDSI values from 1200 to 1987 for a series of sequences in the Southwestern U.S. and northern Mexico.*

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