Extended Chronology of Drought in the San Antonio Area

Revised Report March 30, 2006

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Introduction

Drought is a big problem in Texas due to its semiarid and drought-prone climate, particularly in West and Central Texas (Griffiths and Ainsworth 1981). Meteorological observations in Texas date from the late 19th century, but this short record is inadequate to characterize rare events such as prolonged multiyear droughts (Namias 1981). Rodriguez-Iturbe (1969) has also demonstrated that very large numbers of observations may be needed to derive accurate statistical parameters for hydrometeorological phenomena. It is certainly possible that worse droughts than any seen in the instrumental record may have occurred in the past (e.g., Stahle et al. 2000) and drought may have unforeseen consequences (e.g., that affect human health; Acuna-Soto et al. 2002).

One means of overcoming the lack of observed data uses things strongly influenced by climate data as a substitute or "proxy" for instrumental data, e.g., pollen or tree rings (Stahle et al. 1988; Stahle and Cleaveland 1992; Cleaveland 2000; Fye and Cleaveland 2001; Watson and Core Writing Team 2001). One of the best such proxies is tree rings because trees that produce rings annually are widely distributed and readily available, each ring can be dated exactly and the climate information is relatively easy to extract from properly dated samples (Stahle 1996; Fritts 2001).

Previous efforts to analyze the climate of Texas with proxy series include pollen studies (Bryant 1977; Bryant and Holloway 1985) and tree-ring studies by Stahle and Cleaveland (1988; 1995), Dunne et al. (2000), Dunne (2002), Cook et al. (1996) and Mauldin (2003). One failing of the above studies was that they were too short to cover periods known to have had severe droughts, particularly the last half of the 16th century (Stahle et al. 1998; 2000; Cleaveland et al. 2003). Paleoclimatic investigations have helped find links in southwestern climate to large scale circulation features such as the El Niño/ Southern Oscillation (Cleaveland et al. 1992; Stahle and Cleaveland 1993; Stahle et al. 1998; Fye and Cleaveland 2001). Such links to persistent circulation features are one path to a reliable long lead-time climate prediction capability (Barnston et al. 1994).

Observed Climate Records and Available Tree-Ring Chronologies

Precipitation records at the San Antonio International Airport begin in 1893 and continue to the present with few missing observations (National Climatic Data Center, Climate Diagnostic Center, 2006). Precipitation, temperature and Palmer drought index (Palmer 1965) data for the Texas climate divisions (Fig. 1) begin in 1895 (Karl et al. 1983; National Climatic Data Center, Climate Diagnostic Center, 2006). The divisional climatic data often exhibits stability lacking in single stations, probably because the divisional data are averages of all stations within the division (Stahle and Cleaveland 1992).

Homogeneity testing of the climatic data is required to find discontinuities in the instrumental record. The accepted method for doing this is called double mass analysis (Kohler 1949). Cumulative totals of the precipitation record being tested are plotted versus cumulative totals of a record known to be homogeneous. Cleaveland and Stahle (1989) showed that tree-ring chronologies could be used as the homogeneous climate record. Double mass testing of the seasonalized climatic data versus the South Central tree-ring chronology (Therrell 2000) indicates that no serious discontinuities exist in the San Antonio or the division 6 or 7 climatic data (Appendix A). In addition, autoregressive modeling (Box et al. 1994) showed that the seasonal precipitation series had no significant serial correlation, i.e., the amount of rainfall varies randomly from year to year.

Although standard tree-ring chronologies often have strong persistence, statistically characterized by the lag one serial correlation (Fritts 2001), autoregressive modeling can be used to create chronologies without any significant serial correlation (Cook 1985). All the chronologies used for reconstruction had persistence removed so that their autoregressive characteristics matched the rainfall series being reconstructed.

Various investigators have used a variety of data and modeling techniques to reconstruct climate in Texas since the last high point of glaciation (e.g., COHMAP Members 1988 and Bryant and Holloway 1985), but this project concentrates on the nearer term, i.e., the last 1000 years. The proxy used is tree rings from a variety of species. One existing reconstruction of averaged June, July and August (JJA) Palmer Drought Severity Index (PDSI; Palmer 1965) on a 2.5° x 2.5° grid has been produced by Dr. Edward Cook of Lamont-Doherty Earth Observatory (Cook et al. 1996; 1999; 2004). I have created a total of three new reconstructions for this report: (1) San Antonio February – June total precipitation; (2) Texas climate division 7 (South Central) February – June total precipitation; and, (3) Texas climate division 6 (Edwards Plateau) February – May total precipitation.

I averaged six post oak (*Quercus stellata*) tree-ring chronologies, three from living trees and three from timbers of old buildings (Therrell 2000; Table 1) to make one very well replicated composite chronology. The averaged chronology began in 1648 and ended in 1995. I correlated the tree-ring series with the monthly and seasonalized San Antonio and divisional precipitation data. The correlations showed that the San Antonio and division 7 (South Central) February – June precipitation was most strongly related with tree growth, while February – May precipitation was best correlated in the Edwards Plateau climate division.

Because the earliest of the available post oak chronologies in South Central Texas starts in 1648, I also investigated other, more distant chronologies that were longer (Table 1). These included chronologies of different species (i.e., Douglas-fir [*Pseudotsuga menziesii*], ponderosa pine [*Pinus ponderosa*], pinyon pine [*P. edulis*] and baldcypress [*Taxodium distichum*] in Texas, New Mexico and Louisiana. None of these additional chronologies was as well correlated with the observed climatic data as the Texas post oak chronologies used, which is at least partially a function of the considerable distances between the climatic data and the tree-ring sites. Only the post oak chronologies are really close to San Antonio.

The baldcypress chronologies lie well east of San Antonio and the two climate divisions. Correlations with climatic data were weak and a principal components analysis of the additional chronologies showed that the baldcypress chronologies had relatively weak loadings on the first principal component eigenvector compared to the Douglas-fir, ponderosa and pinyon chronologies. For these reasons the baldcypress chronologies were not used. A principal components analysis of eight long chronologies put 55.7% of the variance of the dataset into the first principal component (PC). While the first PC was significantly correlated with Texas division 6 (Edwards Plateau) precipitation, the second PC was not, so only the first PC was used in the reconstruction 1537-1972 (the common period of the eight chronologies).

Calibration and Validation of the Transfer Functions for Reconstruction

I used linear regression (Draper and Smith 1981) to generate the transfer functions for reconstruction. The variance accounted for by regression was markedly different in the different calibrations (Tables 2a-2c). Verification procedures have been formulated to investigate the validity of the reconstructions (Snee 1977) beyond the simple statistic of the amount of variance accounted for by regression. The verification statistics are summarized in Tables 3a-3c.

Examination of the regression statistics shows that although all calibrations were successful, the best calibration by far was with the South Central climate division (Table 2b; Fig. 2). That regression relationship of divisional February – June precipitation with the post oak composite chronology accounted for 56% of the variance in climate, where the same post oak chronology accounted for only 32% of the same seasonalization of San Antonio IAP precipitation (Table 2a). The superior performance of the divisional climate data over the single station data just means that an average of all stations in a climatically homogeneous region gives a better estimate of climate than data taken at a single point, no matter how much care was taken in collecting the single station data. The first principal component of eight tree-ring chronologies of three species only accounted for 21% of the Edwards Plateau divisional February – May precipitation variance (Table 2c). The relatively weak calibration must be attributed to the considerable distance between most of the tree-ring chronologies and the region being reconstructed (Fig. 1).

The verification statistics tell a story similar to the calibration statistics. The division 7 and San Antonio IAP reconstructions pass all verification tests (Tables 3a and

3b). The division 6 reconstruction passes most of the tests (with generally poorer statistics), but fails a few (Table 3c).

Analysis of the process by which Dr. Edward Cook does his gridpoint reconstructions is beyond the scope of this study, but basically, he does many reconstructions that take advantage of the different number of chronologies available in successively earlier time slices, then combines the reconstructions into a single time series (Cook et al. 2004). The quality of the reconstructions will almost certainly decline as you go back in time because fewer and fewer chronologies are available for the reconstruction.

Analyses of the Climatic Data and Reconstructions

The worst drought in the observed climatic data appears to be what is referred to as the 1950s drought. The observed data shows that the 1950s drought actually seems to have begun in 1948 because 1948 and 1949 are both below average in the divisional and Airport data. Precipitation in 1950 is well above average at the Airport, but closer to average in the division 7 data (Fig. 2). A very wet 1957 breaks the drought in both series.

The first proxy dataset used to expand the study of South Central Texas drought beyond information available from instrumental datasets is a reconstruction of climate at points on a 2.5^{o} latitude by 2.5^{o} longitude grid from more than 500 tree-ring chronologies (Cook et al. 2004). Because the grid is continental in scale, from Canada to Mexico, Cook et al. (1996; 1999) chose to reconstruct an average of June, July and August Palmer Drought Severity Index (PDSI; Palmer 1965) as a way of coping with the great phenological differences in tree response to climate that occur at different latitudes. Phenological differences over relatively short latitudinal ranges can make a big difference in climatological response of trees (e.g., Stahle 1990; Stahle and Cleaveland 1992). Figure 3 presents the reconstruction for gridpoint 166 west of San Antonio (Fig. 1). The two gridpoints, 166 and 181, are correlated 0.92 over their full length, 996 – 1990. An examination of the plot seems to show many droughts that were as bad or worse than the 1950s drought, but they occur early in the record, in the 1100s and 1200s. This would place them in the middle of the Medieval Warm Period (Hughes and Diaz 1994) so what we know about paleoclimate may make such extended droughts plausible. On the other hand, the late 16th century drought appears less serious than it is in many other places (Stahle et al. 2000). Since the world appears to be heading into a period of elevated temperatures that may be similar to the Medieval Warm Period (Watson and Core Writing Team 2001), the possibility of experiencing drought similar to the 1100s and 1200s cannot be dismissed lightly.

The reconstruction of the South Central climatic division is shown in Figure 4 and the Edwards Plateau reconstruction in Figure 5. I have examined the two divisional reconstructions for the worst single year droughts, worst two consecutive years of drought, worst three years, worst four years, worst five years and worst 10 years. The results for the divisional reconstructions are presented in Tables 4 and 5.

The reconstruction of the South Central division precipitation appears to have a flaw because the variance in the early part of the reconstruction exceeds the variance in the latest period by a statistically significant amount. This flaw is, of course, shared by the San Antonio Airport reconstruction because they both use the same composite tree-ring chronology. Part of the chronology compilation process is devoted to removing variance trend, which is usually a product of declining sample size on the inside. Plots of the six post oak chronologies show, and statistical tests confirm, that four of the six chronologies retain variance trend in spite of extensive efforts to remove it. I have devoted a considerable amount of time to this problem, but have not found a solution. The reconstruction of the Edwards Plateau division (Fig. 5) does not have variance trend, which may be a reason for regarding it as reliable, despite the low calibration R^2.

Conclusions

In Table 4, the analysis of drought in the South Central division, no year of the late 1940s or the 1950s is found in the worst 20 years reconstructed since 1648. Yet in the decadal droughts some combination of years that includes the late 1940s and/or the 1950s occurs seven times out of 20. Clearly, the 1950s drought ranks high in the reconstruction. Other periods appear to rival it, however. For example, combinations of years in the late 1600s and early 1700s appear six times in the decadal droughts (including the three worst), indicating that the turn of the 18th century must have been plagued by moisture deficits.

In the reconstruction of February – May precipitation in the Edwards Plateau climate division (Table 5, Fig. 5), 1950 appears as the 14th worst drought in the 436 year reconstruction. Looking at the decadal droughts, some combination of years that includes all or part of the 1950s drought occurs five times. Some combination of years in the last half of the 16th century appears eight times, however. This is the period of "megadrought" that appears to have spanned the continent at times (Stahle et al. 2000), so the droughts of the last half of the 16th century certainly exceeded the 1950s drought in duration and probably would have a greater impact on Texas if it happened again.

To summarize, the reconstructions of San Antonio Airport, South Central and Edwards Plateau climate were successful, although there is a problem with variance trend in the Airport and South Central reconstructions (Fig. 4). The reconstructions confirm that the 1950s drought was very bad, even when viewed in a long-term context. The reconstructions also indicate that there may have been periods when drought was more protracted and the impact might have been considerably worse. It would appear unwise for civil authorities to assume that the 1950s drought represents the worst case scenario to be used for planning purposes in water resources management in the South Central and Edwards Plateau climate divisions of Texas.

Table 1. Chronologies available for reconstruction of South Central Texas climate. Species codes: QUST=post oak, PSME=Douglas-fir, TADI=baldcypress, PIPO= ponderosa pine, PIED=pinyon pine.

Site Name/State/Code	Species	Latitude	Longitude	Dates/Comments
*Yegua Creek/ TX/ YEG	QUST	30°19′	96°38′	1658-1995
*Lavaca River/ TX/ HAL	QUST	29°18′	96°58′	1668-1995
Coleto Creek/ TX/ COL	QUST	28°46′	96°43′	1682-1995
*Gonzales County Pioneer Village/TX/GPV	QUST	29°30′	97°27′	1649-1995
*McBryde Log House/ TX/ YOK	QUST	29°15′	97°05′	1668-1847
*West-Adkisson Cabin/ TX/ WAD	QUST	30°30′	97°46′	1648-1853
**Big Bend National Park/ TX/ BSC	PSME	29°15′N	103°18′W	1473 – 1992
**Guadalupe National Park/ TX/ GUA	PSME	30°26′N	104°51′W	1537 – 1992
Peachtree Bottoms/ TX/ PTB	TADI	31°54′N	94°05′W	1255 – 1993
Big Cypress State Park/ LA/ BIG	TADI	32°15′N	92°58′W	997 – 1988
**El Malpais National Monument/ NM/ MLC	PSME	34°58′N	108°06′W	-136 – 1992
**Echo Amphitheater/ NM /171	PSME	36°21′N	106°31′W	1362 – 1989
Satan Pass/ NM	PSME	35°36′N	108°08′W	1312 – 1990
Fort Burgwin/ NM	PIPO	36°15′N	105°31′W	1482 – 1989
**Elephant Rock/ NM (ERE)	PIPO	36°42′N	105°29′W	1391 – 1987
**Agua Fria/ NM/ AFN	PIED	34°14′N	108°37′W	1403 – 1987
**Ft. Wingate/ NM/ 283	PIED	35o26′	108o32′	1478 – 1972
**Turkey Springs/ NM/ 273	PIED	35o24′	108o31′	1411 – 1972
El Morro/ NM/	PIPO	35°02′	108°21′	1536 – 1972
Fenton Lake/ NM/	PIPO	35°53′	106°40′	1532 – 1986
Gila Cliff Dwellings/ NM/	PIPO	33°13′	108°16′	1530 – 1987

* Used in reconstruction of San Antonio IAP and climate division 7 (S. Central)

** Used in the reconstruction of climate division 6 (Edwards Plateau)

Table 2a. Calibration for the reconstruction of San Antonio, Texas February – June total precipitation from the average of the six South Central post oak residual chronologies.

		Coefficient (mm)		Standard Error(mm)		t-Statistic (H_0: $\beta=0$)		Regression[b] Residual
Period	R^2_{Adj}[a]	β_0	β_1	β_0	β_1	β_0	β_1	Autocorr.
1893-1995	0.32	-2.82	16.11	2.37	2.32	-1.2NS	6.9***	0.12NS
1893-1943	0.41	-2.93	15.29	2.65	2.54	-1.1NS	6.0***	0.12NS
1944-1995	0.26	-4.13	18.36	4.18	4.18	-1.0NS	4.4***	0.05NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).

[b] Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table 2b. Calibration for reconstruction of Texas climate division 7 (S. Central) February – June total precipitation from the average of the six South Central post oak residual chronologies.

Period	R^2_{Adj}[a]	Coefficient (mm) β_0	Coefficient (mm) β_1	Standard Error(mm) β_0	Standard Error(mm) β_1	t-Statistic (H_0: $\beta=0$) β_0	t-Statistic (H_0: $\beta=0$) β_1	Regression[b] Residual Autocorr.
1895-1995	0.56	-2.39	17.69	1.61	1.57	-1.5NS	11.2***	0.16NS?
1895-1943	0.59	-1.39	16.62	2.09	2.00	-0.7NS	8.3***	0.25*
1944-1995	0.53	-4.10	19.50	2.60	2.59	-1.6NS	7.5***	0.06NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

NS? Not significant, but the Durbin-Watson statistic fell within the zone of uncertainty (Draper and Smith 1981).

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).

[b] Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table 2c. Calibration for reconstruction of Texas climate division 6 (Edwards Plateau) February – May total precipitation from the first principal component of eight Douglas-fir, pinyon and ponderosa residual chronologies.

		Coefficient (mm)		Standard Error(mm)		t-Statistic (H_0: $\beta=0$)		Regression[b] Residual
Period	R^2_{Adj}[a]	β_0	β_1	β_0	β_1	β_0	β_1	Autocorr.
1895-1972	0.21	8.99	0.66	0.34	0.14	26.6***	4.6***	0.05NS
1895-1933	0.14	9.38	0.51	0.50	0.19	18.8***	2.7***	0.02NS
1934-1972	0.24	8.74	0.84	0.47	0.23	18.4***	3.6***	0.02NS

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] R^2 adjusted downward for loss of degrees of freedom (Draper and Smith 1981).

[b] Autocorrelation of the residuals from regression, tested with the Durbin-Watson statistic (Draper and Smith 1981). Failure to reject the null hypothesis indicates that the residuals occur randomly, an indication that the regression model is valid.

Table 3a. Verification statistics for the reconstruction of San Antonio, Texas February – June total precipitation from the average of the six South Central post oak residual chronologies. The verification procedure uses the climate estimates derived in the calibration period, e.g., verification against observed data 1893-1943 uses climate estimated by regression 1944-1995.

Verification Period	Pearson Corr.	1st Dif.[a] Corr.	Paired t-Test[b] of Mean	Sign Test[c] (Hit/Miss)	Cross-Products[d] t-Test	Reduction of[e] Error Statistic
1893-1943	0.53***	0.50***	1.27NS	34/17*	-3.20**	0.29
1944-1995	0.65***	0.74***	-1.52NS	35/15**	-4.21***	0.40

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] Observed and reconstructed data first differenced ($t - t_{-1}$). The transformation removes trends that may affect the Pearson correlation coefficient (Fritts 2001).

[b] Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.

[c] Signs of departures from the mean of each series (Fritts 2001). Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit". If either observed or reconstructed data lie near the mean, the year is omitted from the test.

[d] Comparison of the relative magnitude of hits/misses in the sign test above.

[e] There is no formal test of significance for this statistic, but any positive result indicates that the reconstruction contributes unique paleoclimatic information (Fritts 2001)

Table 3b. Verification statistics for the reconstruction of Texas climate division 7 (S. Central) February – June total precipitation from the average of the six South Central post oak residual chronologies. The verification procedure uses the climate estimates derived in the calibration period, e.g., verification against observed data 1895-1943 uses climate estimated by regression 1944-1995.

Verification Period	Pearson Corr.	1st Dif.[a] Corr.	Paired t-Test[b] of Mean	Sign Test[c] (Hit/Miss)	Cross-Products[d] t-Test	Reduction of[e] Error Statistic
1895-1943	0.73***	0.74***	0.17NS	40/12***	-4.51***	0.53
1944-1995	0.77***	0.84***	-0.24NS	39/11***	-4.92***	0.60

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] Observed and reconstructed data first differenced ($t - t_{-1}$). The transformation removes trends that may affect the Pearson correlation coefficient (Fritts 2001).

[b] Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.

[c] Signs of departures from the mean of each series (Fritts 2001). Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit". If either observed or reconstructed data lie near the mean, the year is omitted from the test.

[d] Comparison of the relative magnitude of hits/misses in the sign test above.

[e] There is no formal test of significance for this statistic, but any positive result indicates that the reconstruction contributes unique paleoclimatic information (Fritts 2001)

Table 3c. Verification statistics for the reconstruction of Texas climate division 6 (Edwards Plateau) February – May total precipitation from the first principal component of eight Douglas-fir, pinyon and ponderosa residual chronologies. The verification procedure uses the climate estimates derived in the calibration period, e.g., verification against observed data 1895-1943 uses climate estimated by regression 1944-1995.

Verification Period	Pearson Corr.	1st Dif.[a] Corr.	Paired t-Test[b] of Mean	Sign Test[c] (Hit/Miss)	Cross-Products[d] t-Test	Reduction of[e] Error Statistic
1895-1943	0.51***	0.52***	-1.62NS	27/11**	-2.25**	0.17
1944-1995	0.41**	0.53***	0.96NS	24/15NS	-1.76NS	0.18

NS Not significant, i.e., there is greater than a 5% probability that the result occurred by chance.

* Significant, $p < 0.05$.

** Significant, $p < 0.01$.

*** Significant, $p < 0.001$.

[a] Observed and reconstructed data first differenced $(t - t_{-1})$. The transformation removes trends that may affect the Pearson correlation coefficient (Fritts 2001).

[b] Paired comparison of observed and reconstructed data means (Steel and Torrie 1980). Note that no difference is the desired result.

[c] Signs of departures from the mean of each series (Fritts 2001). Means are subtracted from each series and the residuals are multiplied. A positive product is a "hit". If either observed or reconstructed data lie near the mean, the year is omitted from the test.

[d] Comparison of the relative magnitude of hits/misses in the sign test above.

[e] There is no formal test of significance for this statistic, but any positive result indicates that the reconstruction contributes unique paleoclimatic information (Fritts 2001)

Table 4. Twenty droughts of 1-5 and 10-year lengths in order of severity in the reconstruction of climatic division 7 (S. Central) Feb. – June total precipitation (inches), 1648-1995. The average Feb. – June precipitation over the 348-year reconstruction is 15.39 inches.

Case	Single Yr/ Precip.(in)	2 Yr/ Avg Precip. (in)	3 Yr/ Avg Precip. (in)	4 Yr/ Avg Precip. (in)	5 Yr/ Avg Precip. (in)	10 Yr/ Avg Precip. (in)
1 (Worst)	1925/ 4.63	1789-1790/ 7.85	1714-1716/ 9.88	1714-1717/ 10.00	1713-1717/ 10.84	1708-1717/ 12.28
2	1661/ 4.77	1656-1657/ 8.00	1703-1705/ 9.92	1713-1716/ 10.96	1712-1716/ 11.06	1707-1716/ 12.60
3	1656/ 6.01	1714-1715/ 9.18	1915-1917/ 10.09	1712-1715/ 11.01	1711-1715/ 11.68	1696-1705/ 12.91
4	1789/ 6.19	1916-1917/ 9.41	1789-1791/ 10.20	1702-1705/ 11.08	1750-1754/ 11.72	1885-1894/ 13.13
5	1971/ 6.26	1703-1704/ 9.63	1750-1752/ 10.27	1654-1657/ 11.25	1751-1755/ 12.00	1947-1956/ 13.25
6	1714/ 6.63	1886-1887/ 9.80	1712-1714/ 10.77	1728-1731/ 11.57	1727-1731/ 12.22	1949-1958/ 13.38
7	1659/ 7.18	1785-1786/ 10.01	1713-1715/ 10.86	1711-1714/ 11.67	1951-1956/ 12.33	1950-1959/ 13.40
8	1785/ 8.03	1915-1916/ 10.27	1655-1657/ 11.11	1749-1752/ 11.86	1913-1917/ 12.40	1709-1718/ 13.40
9	1857/ 8.36	1754-1755/ 10.34	1715-1717/ 11.12	1696-1699/ 12.04	1950-1954/ 12.54	1948-1957/ 13.44
10	1675/ 8.38	1704-1705/ 10.38	1736-1738/ 11.21	1752-1755/ 12.05	1951-1955/ 12.64	1886-1895/ 13.41
11	1738/ 8.38	1750-1751/ 10.39	1702-1704/ 11.27	1953-1956/ 12.05	1696-1700/ 12.69	1703-1712/ 13.51
12	1967/ 8.38	1713-1714/ 10.42	1728-1730/ 11.40	1750-1753/ 12.07	1886-1890/ 12.90	1951-1960/ 13.60
13	1805/ 8.59	1901-1902/ 10.48	1885-1887/ 11.42	1915-1918/ 12.07	1785-1789/ 12.90	1839-1848/ 13.60
14	1736/ 8.72	1730-1731/ 10.64	1729-1731/ 11.46	1727-1730/ 12.26	1710-1714/ 12.92	1705-1714/ 13.67
15	1750/ 8.96	1805-1806/ 10.78	1741-1743/ 11.48	1937-1940/ 12.31	1885-1889/ 12.93	1749-1758/ 13.67
16	1703/ 9.00	1716-1717/ 10.82	1654-1656/ 11.68	1914-1917/ 12.31	1748-1752/ 12.97	1952-1961/ 13.71
17	1916/ 9.09	1751-1752/ 10.93	1661-1663/ 11.83	1751-1754/ 12.41	1749-1753/ 12.98	1750-1759/ 13.73
18	1652/ 9.12	17291730/ 11.16	1954-1956/ 11.85	1741-1744/ 12.50	1967-1971/ 13.01	1748-1757/ 13.76
19	1730/ 9.21	1819-1820/ 11.18	1892-1894/ 11.94	1886-1889/ 12.50	1936-1940/ 13.10	1883-1892/ 13.77
20	1696/ 9.28	1684-1685/ 11.21	1937-1939/ 11.98	1775-1778/ 12.51	1701-1705/ 13.02	1954-1963/ 13.77

Table 5. Twenty droughts of 1-5 and 10-year lengths in order of severity in the reconstruction of climatic division 6 (Edwards Plateau) Feb. – May total precipitation (inches), 1537-1972. The average Feb. – May precipitation over the 436-year reconstruction is 8.99 inches.

Case	Single Yr/ Precip.(in)	2 Yr/ Avg Precip. (in)	3 Yr/ Avg Precip. (in)	4 Yr/ Avg Precip. (in)	5 Yr/ Avg Precip. (in)	10 Yr/ Avg Precip. (in)
1 (Worst)	1748/ 4.88	1818-1819/ 5.93	1818-1820/ 6.56	1817-1820/ 7.26	1818-1822/ 7.24	1571-1580/ 7.84
2	1847/ 5.39	1950-1951/ 6.38	1817-1819/ 7.08	1899-1902/ 7.39	1950-1954/ 7.57	1950-1959/ 7.84
3	1904/ 5.45	1684-1685/ 6.38	1583-1585/ 7.18	1950-1953/ 7.45	1666-1670/ 7.60	1576-1585/ 7.84
4	1818/ 5.75	1899-1900/ 6.46	1878-1880/ 7.28	1818-1821/ 7.48	1664-1668/ 7.71	1573-1582/ 7.91
5	1685/ 5.83	1728-1729/ 6.66	1666-1668/ 7.31	1666-1669/ 7.51	1819-1823/ 7.74	1572-1581/ 7.94
6	1899/ 5.85	1805-1806/ 6.73	1728-1730/ 7.33	1953-1956/ 7.52	1951-1955/ 7.76	1773-1782/ 7.99
7	1861/ 5.90	1879-1880/ 6.87	1879-1881/ 7.39	1573-1576/ 7.54	1622-1626/ 7.76	1575-1584/ 8.00
8	1925/ 5.90	1573-1574/ 6.94	1578-1580/ 7.40	1582-1585/ 7.56	1576-1580/ 7.79	1574-1583/ 8.05
9	1773/ 6.04	1819-1820/ 6.96	1573-1575/ 7.41	1878-1881/ 7.57	1573-1577/ 7.79	1949-1958/ 8.07
10	1971/ 6.08	1584-1585/ 7.02	1727-1729/ 7.42	1667-1670/ 7.58	1953-1957/ 7.81	1570-1579/ 8.08
11	1573/ 6.09	1579-1580/ 7.06	1667-1669/ 7.46	1819-1822/ 7.62	1572-1576/ 7.82	1577-1586/ 8.11
12	1819/ 6.12	1667-1668/ 7.14	1859-1861/ 7.47	1623-1626/ 7.64	1900-1904/ 7.85	1948-1957/ 8.12
13	1806/ 6.25	1592-1593/ 7.19	1623-1625/ 7.48	1777-1780/ 7.65	1817-1821/ 7.86	1871-1880/ 8.13
14	1950/ 6.27	1773-1774/ 7.24	1899-1901/ 7.49	1622-1625/ 7.67	1898-1902/ 7.86	1817-1826/ 8.14
15	1822/ 6.30	1559-1560/ 7.27	1953-1955/ 7.49	1559-1562/ 7.71	1558-1562/ 7.87	1946-1955/ 8.16
16	1729/ 6.33	1822-1823/ 7.27	1949-1952/ 7.50	1727-1730/ 7.73	1773-1777/ 7.88	1818-1827/ 8.16
17	1951/ 6.49	1870-1871/ 7.32	1950-1952/ 7.52	1870-1873/ 7.74	1571-1575/ 7.89	1775-1781/ 8.16
18	1880/ 6.59	1623-1624/ 7.34	1902-1904/ 7.54	1577-1580/ 7.75	1776-1780/ 7.89	1663-1672/ 8.18
19	1851/ 6.68	1846-1847/ 7.37	1683-1685/ 7.55	1571-1574/ 7.78	1581-1585/ 7.90	1664-1673/ 8.19
20	1542/ 6.68	1583-1584/ 7.38	1898-1900/ 7.55	1572-1575/ 8.78	1949-1953/ 7.90	1947-1956/ 8.19

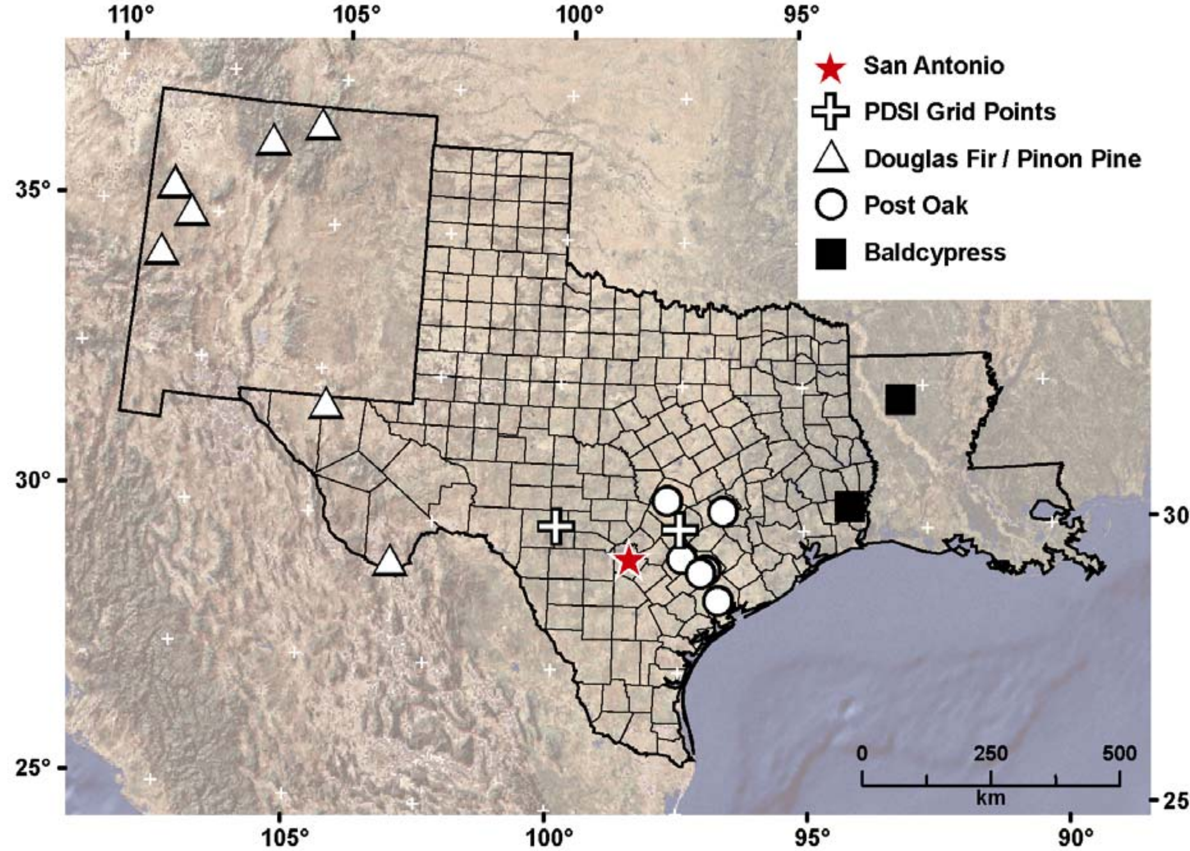

Figure 1. Map of area of reconstructions. Heavy black lines within the boundaries of Texas outline climate division 7 (S. Central) mainly to the east of San Antonio and climate division 6 (Edwards Plateau) mainly to the west of San Antonio. San Antonio lies within division 7 near its western border.

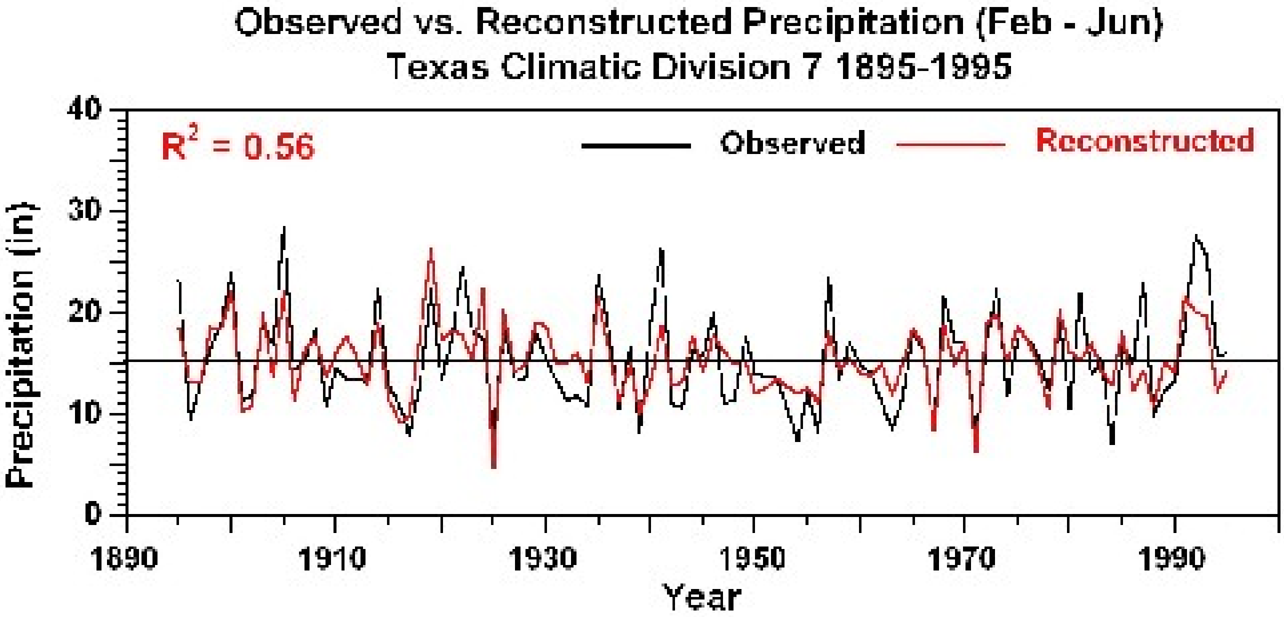

Figure 2. Calibration of Texas climate division South Central with a composite post oak chronology.

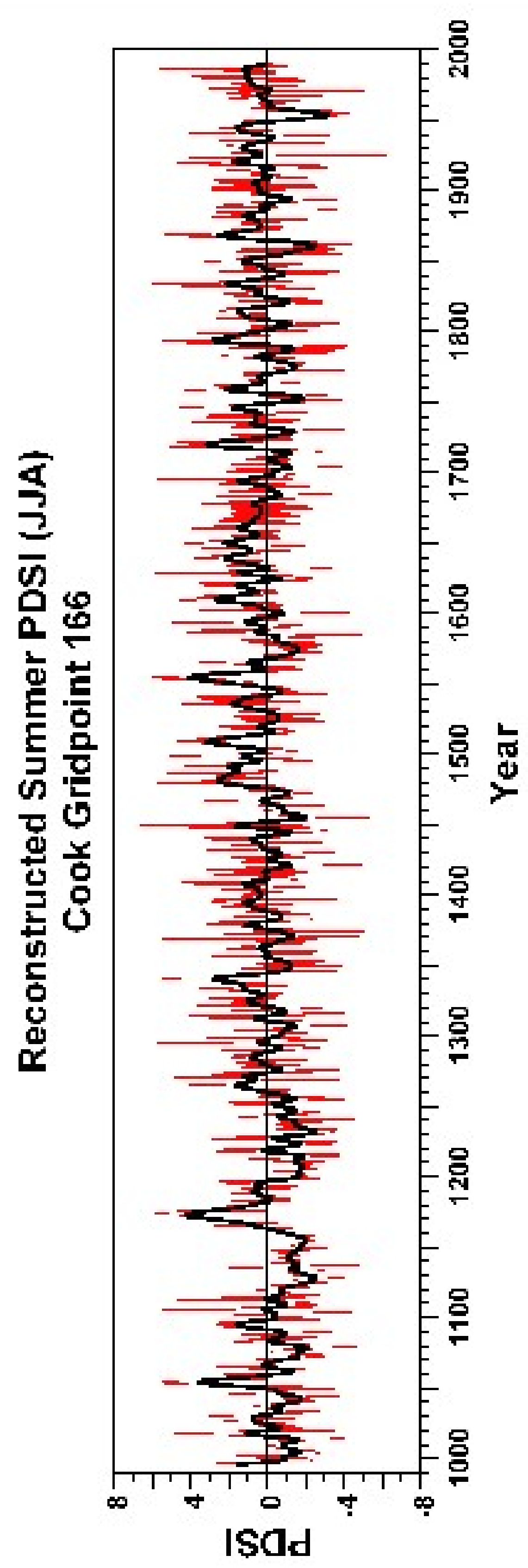

Figure 3. Cook's gridpoint 166 (Cook et al. 2004).

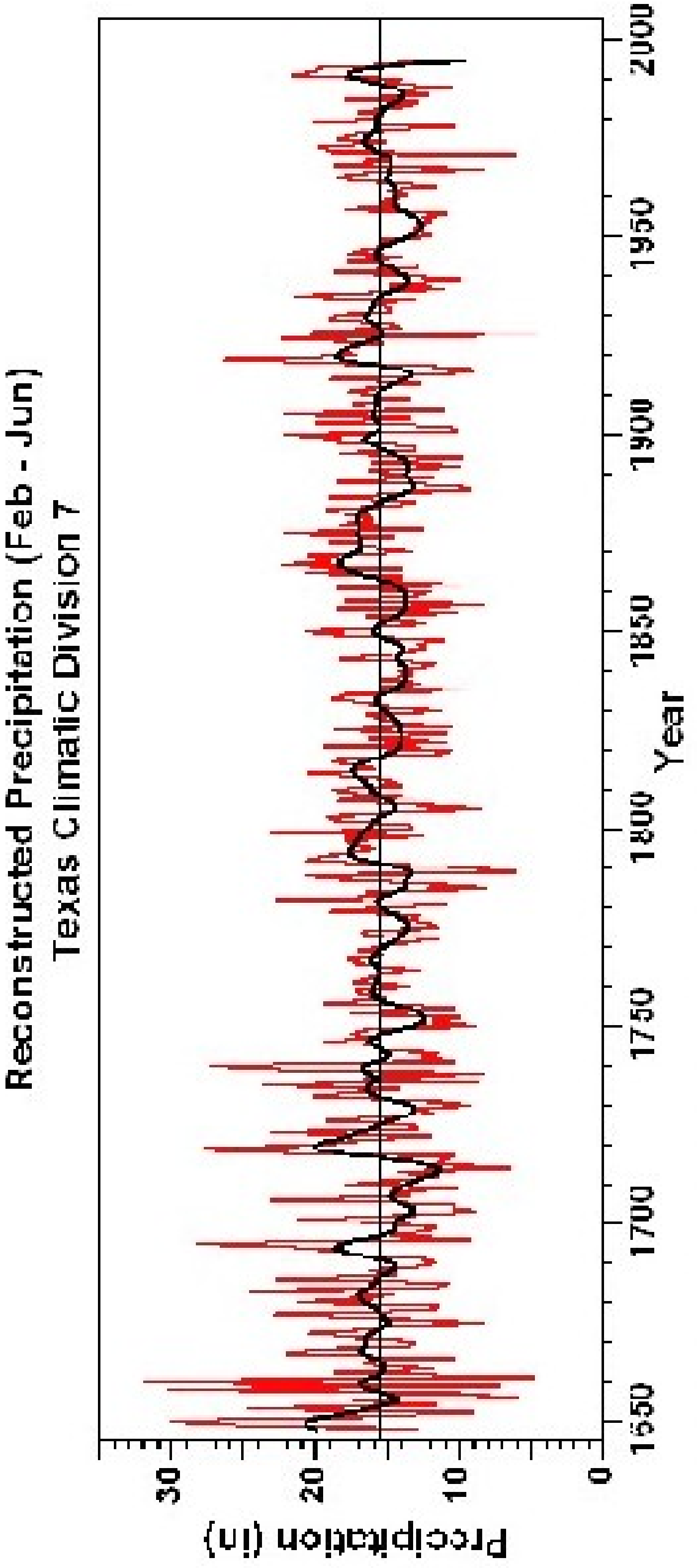

Figure 4. Reconstructed S. Central climatic division Feb. – June precipitation.

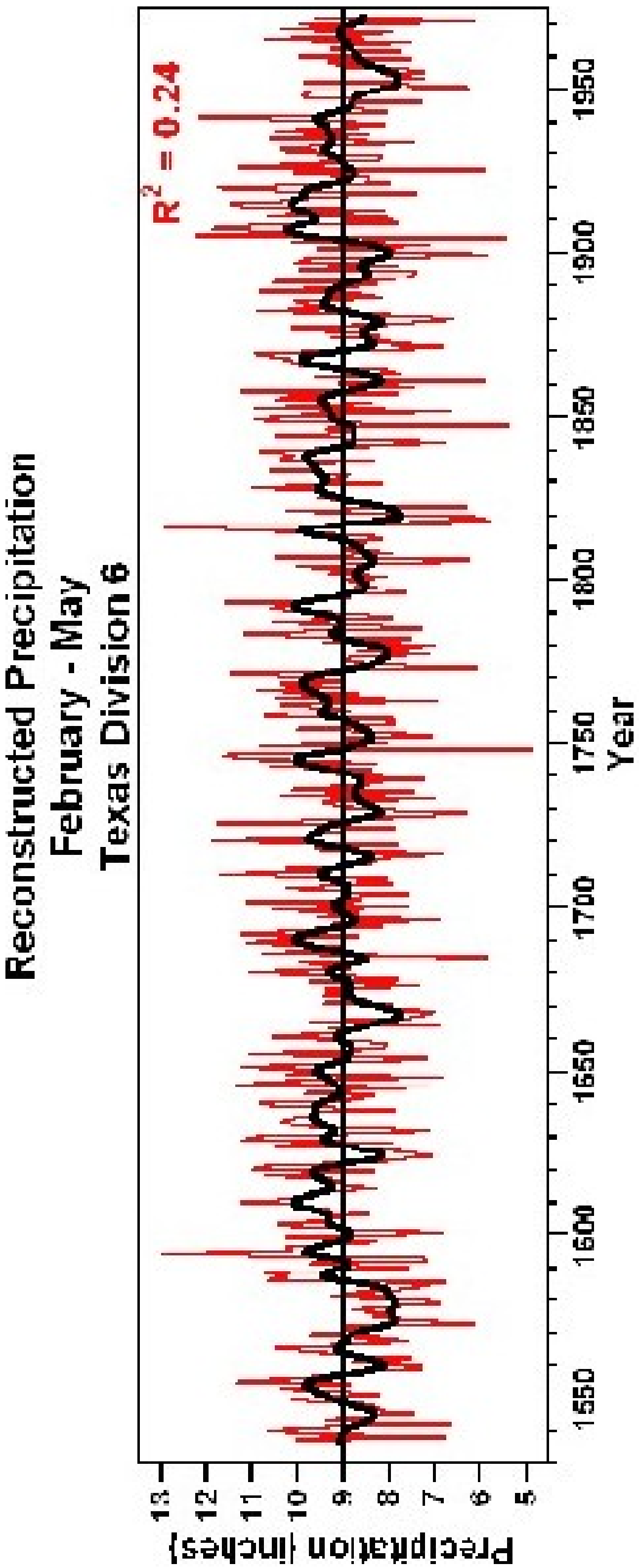

Fig. 5. Reconstructed Edwards Plateau climatic division February – May precipitation.

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Appendix A

Testing Seasonalized Precipitation Series with Double Mass Analysis (Kohler 1949).

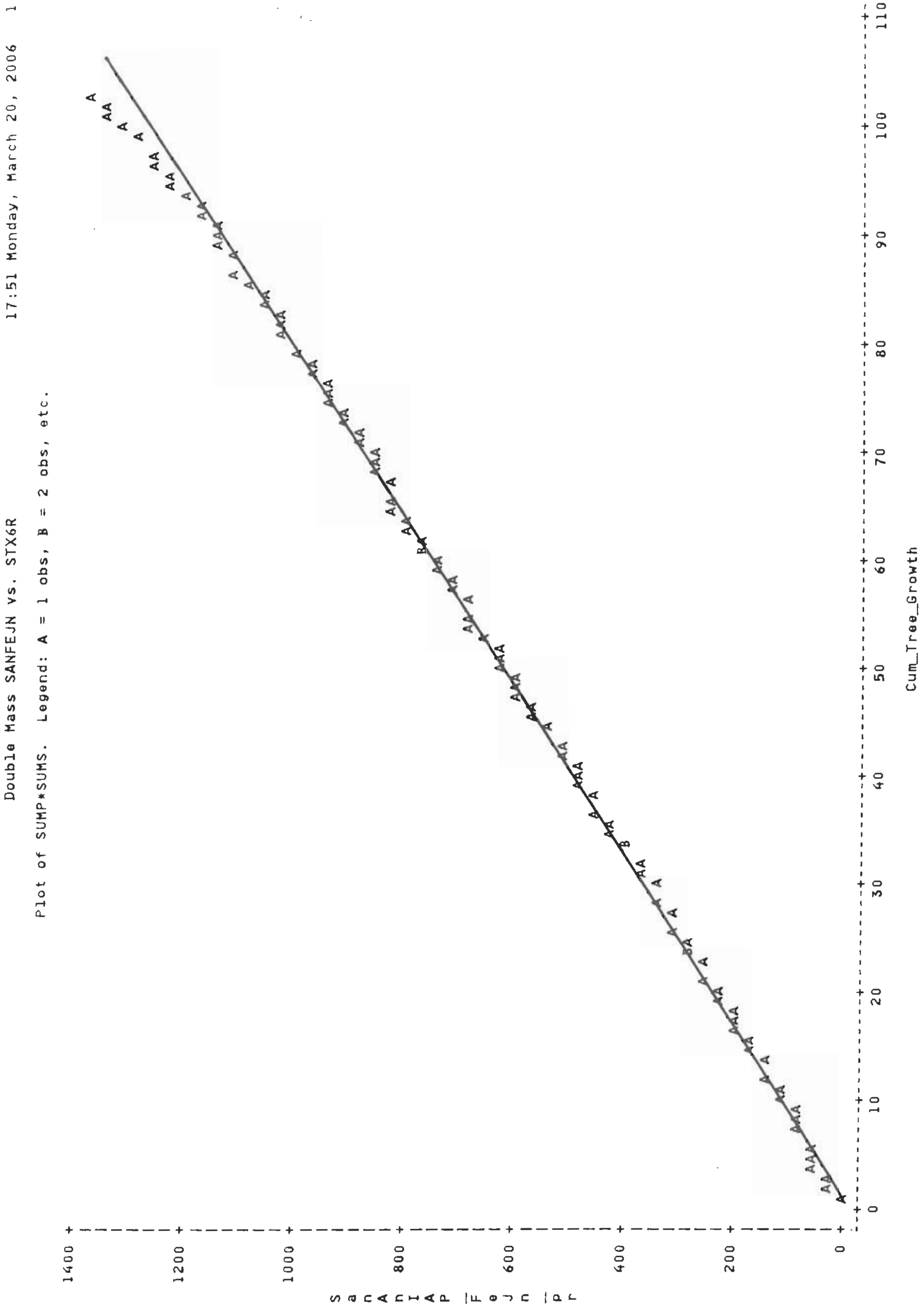

Figure A-1. Double mass analysis of San Antonio IAP Feb-Jun precip.

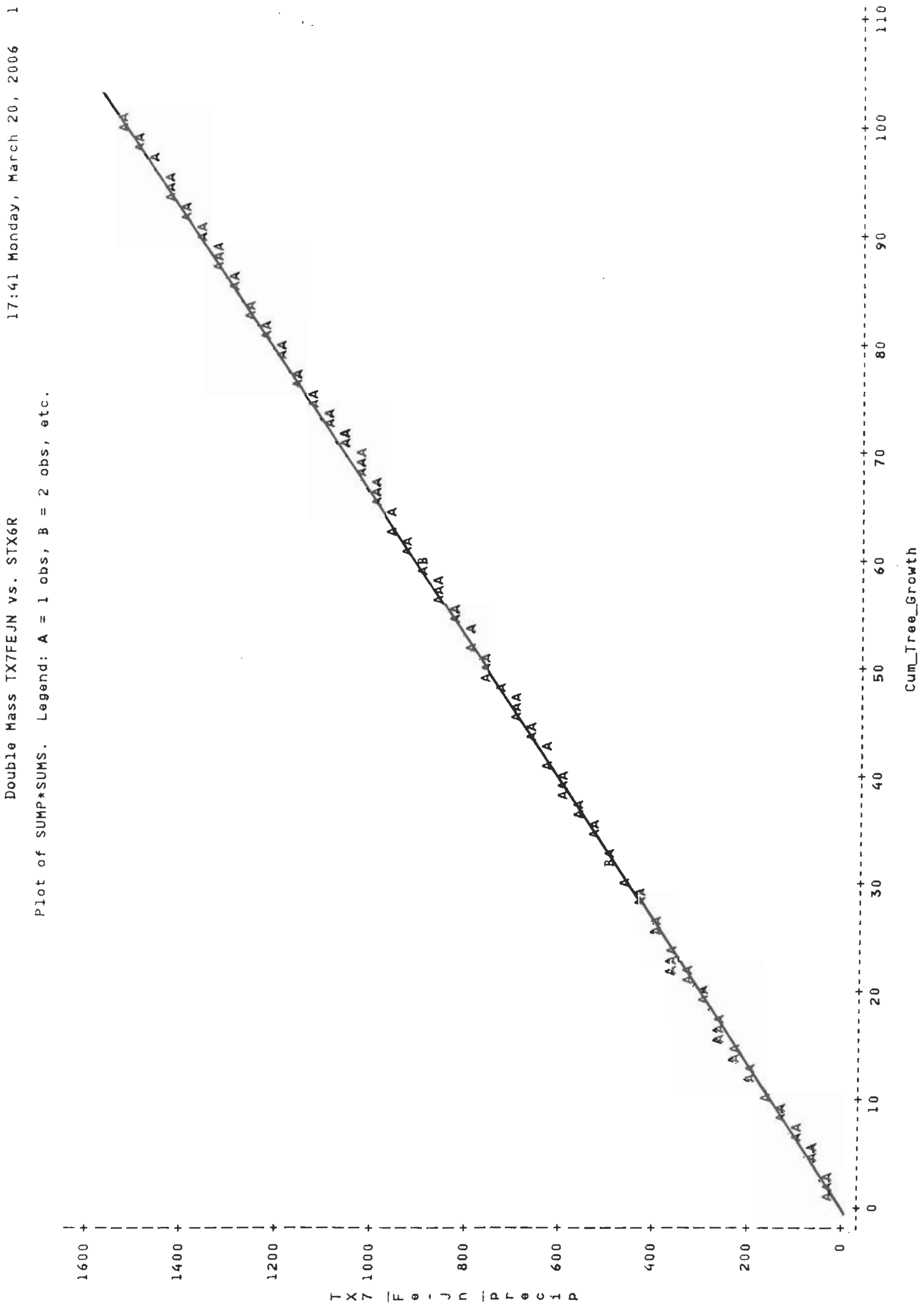

Figure A-2. Double mass analysis of TX div 7(S. Central) Feb-Jun precip.

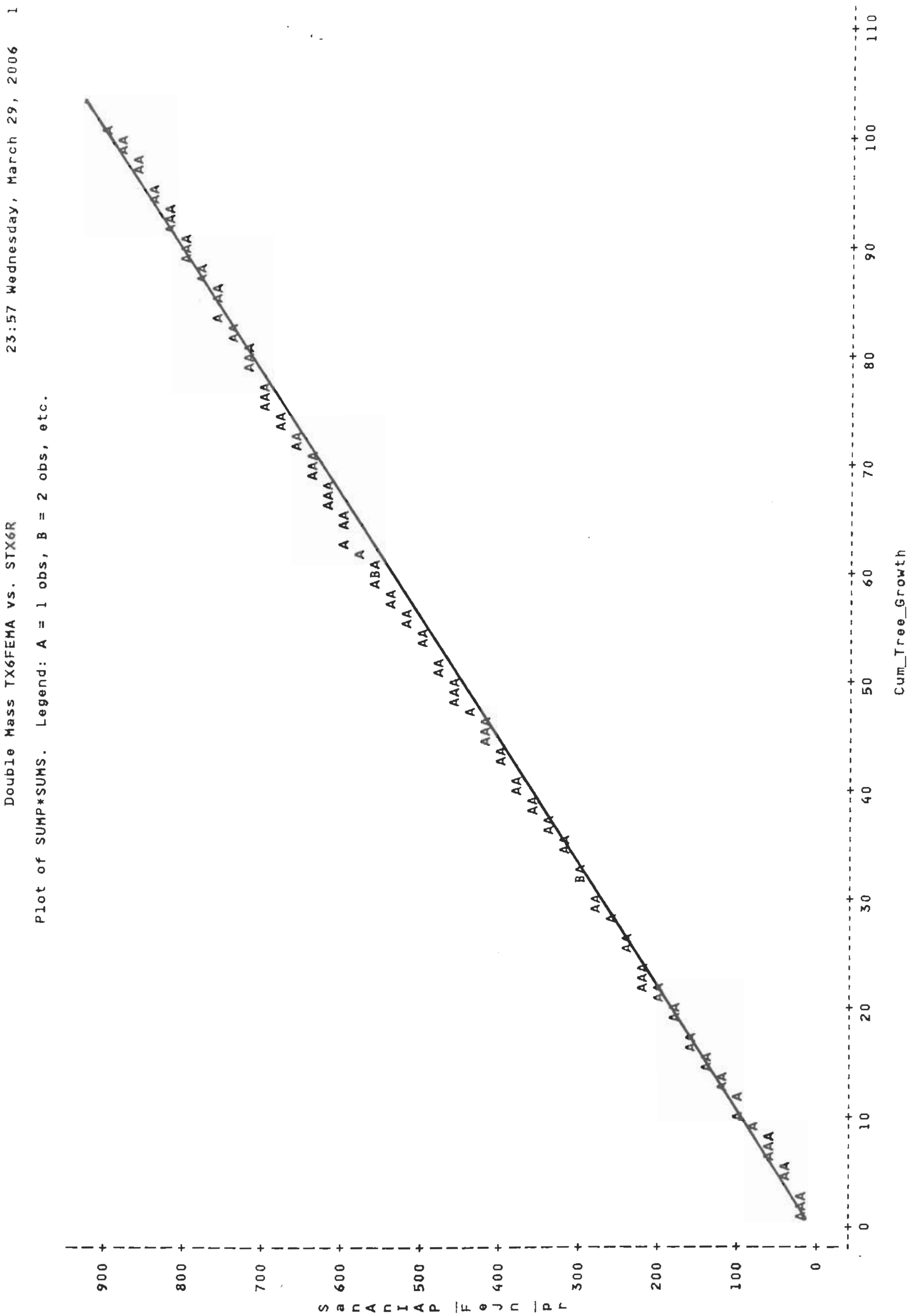

Figure A-3. Double mass analysis of TX div 6(Edwards Plateau) Feb-May precip.