MULTI-CENTURY TRENDS IN PAST CLIMATE FOR THE MIDDLE RIO GRANDE BASIN, AD 622 TO 1992

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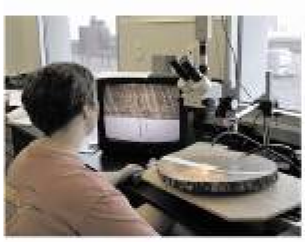

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Project Summary

Ecosystem processes and changes in the physical environmental are intimately tied to the health and well-being of human, faunal, and floral populations. In the Middle Rio Grande Basin of central New Mexico, human influences on the environment have exacerbated conditions caused by natural perturbations, resulting in significant strains on local resources and for agencies charged with managing this areas. To better understand present and future conditions in the region, a historical perspective on the past environment is necessary. In this study, we reconstructed drought for the Middle Rio Grande Basin from a tree-ring chronology based on long-lived conifers found at three peripheral sites: the Sandia Mountains, the Magdalena Mountains, and El Malpais National Monument. The chronology was based on 239 measurement series averaging over 450 years in length. We found a statistically significant relationship with the Palmer Drought Severity Index for June ($r = 0.73$, $p < 0.0001$) and reconstructed this climate variable back to AD 622. The reconstruction had several noteworthy features:

1. The reconstruction revealed over 60 multi-year periods (each > 5 years in length) of either severe drought or extreme wetness. Notable among these were the five driest periods between 1571–1593, 1272–1297, 1945–1963, 701–712, and 1131–1151. The five wettest periods occurred between 1553–1557, 1627–1653, 1978–1992, 724–733, and 1377–1396. These shorter periods were superimposed on ten longer-term, sub-century scale alternations between wet and dry conditions.

2. The reconstruction clearly revealed a major change in climate *ca*. AD 960 contemporary with changes in climate variance and a dramatic change to below-average rainfall. Prior to 960, climate variance was highly variable and marked by periods lasting decades. After 960, climate was marked by rapid alternations between short-term periods of high and low variability.

3. A unique situation occurred between AD 1100–1150. Following a long-term period of below-average rainfall between 940–1040, a period of above-average rainfall followed between 1040–1100 may have contributed to population increases and changes in settlement patterns among both the Anasazi and Mimbres peoples. This period of above-average rainfall culminated with one of the wettest multi-year periods in the entire reconstruction between 1100–1125. However, an extended 25-year period of unprecedented below-average rainfall occurred between 1125–1150. By 1150, the Chacoan and Mimbres cultures had both collapsed.

4. Recovery soon followed between AD 1150–1200. The 13th century, however, is reconstructed as the driest century in the last 1,371 years, marked by three severe multi-year droughts: 1213–1221, 1246–1258, and 1272–1297. Climate between 1272–1297 was very unfavorable, ushering

in the "Great Drought" period that likely caused major relocations of native populations that lived in northern and central New Mexico.

5. The latter half of the 16th century witnessed what has been called the "megadrought." The intensity, duration, and even the spatial extent of this drought across North America can not be over-emphasized. This drought lasted between 1571–1593, although drought years occurred in years prior to and after this period. The duration (23 years) and average June PDSI for each year (–1.99) make this drought the most severe multi-year drought during the last 1,371 years in the Middle Rio Grande Basin. Interestingly, a drought of similar length (17 years, from 1571–1587) and magnitude (average annual rainfall = 7.60 inches) occurred in the Southern Rio Grande Basin.

6. Climate alternated between long-term periods of above-average and below-average conditions between 1600 and 1900. The 1600s claim the greatest number (four) of extreme wet periods: 1608–1613, 1618–1622, 1627–1653, and 1688–1693. In contrast, the 1700s were considerably dry, marked by three severe drought periods: 1727–1740, 1748–1757, and 1772–1782. Finally, the 1800s were considerably wet, especially between 1830–1841, 1845–1858, 1866–1869, and 1881–1885. Another remarkable feature of the 1800s was the lowest values for variability observed since the early 1300s.

7. The 20th century was nothing short of "volatile" climatically. First, the variability of climate was the highest noted during the last 1,371 years. Second, three major extended periods of dry and wet conditions occurred that appear to have been modulated by the Pacific Decadal Oscillation. The warm phase PDO event between 1923 and 1948, when we would expect enhanced rainfall in the Southwest, was contemporary with the above-average rainfall conditions (inferred from PDSI) that occurred between 1930–1944. The cold phase PDO event between 1949–1976, when we would expect lowered rainfall amounts, was contemporary with the 1950s drought between 1945–1963. The warm phase PDO event between 1977 and 1998 was contemporary with a period of enhanced rainfall between 1978–1992. This modulation has important implications for future climate because researchers believe the PDO has recently (*ca*. 1998) switched to a cold phase, suggesting drought conditions may once again be returning to New Mexico.

Introduction

The Middle Rio Grande Basin was identified by the USDA Forest Service and other land management agencies as a core research area where baseline information was needed to better understand the impacts of natural and human perturbations on the sustainability of resources within the region (Finch and Tainter 1995). Extending from the Cochiti Dam near Peña Blanca to Elephant Butte Reservoir, just north of Truth or Consequences, New Mexico, the area has been strongly influenced by natural disturbance factors (*e.g.*, climatic fluctuations, wildfires, and floods) that operated for millennia to create, shape, and eventually maintain the local ecosystems. The area has also been subject to extensive human influences, especially during the Spanish-Mexican era from the mid-16th to mid-19th centuries (Scurlock 1995, 1998; Baisan and Swetnam 1997). Beginning with Euro-American settlement in the mid- to late 1800s, widespread livestock grazing, population expansion, recreational use, and the introduction of exotic plant species occurred with increasing magnitude and frequency (Finch *et al*. 1995; Loftin *et al*. 1995), straining local resources and creating complex problems for agencies charged with managing this highly diverse area (Scurlock 1995, 1998).

To ensure the sustainability of ecosystems within and bordering the Rio Grande, management agencies begin by characterizing the present state of conditions using biological surveys and inventories, soil surveys, and surface and groundwater studies (see especially Sharkey 2001), coupled with available technologies such as geographic information systems and remote sensing (see Carroll and Morain 1992; Allen 1994). Understanding *past* dynamics of the Middle Rio Grande ecosystem, however, is essential to determine how the current environment evolved and which factors were most responsible for these present-day conditions (Finch and Tainter 1995, Kaufman *et* al. 1995). In this sense, the present characteristics of landscape-scale processes must be tempered with a historical perspective. Only by knowing both the present and the past can we learn to prepare and manage for the future (Swetnam *et al*. 1999).

The purpose of our study is the reconstruction of past climate for the Middle Rio Grande Basin using tree-ring data collected from sites surrounding the core study area (Figure 1). This reconstruction will enhance our understanding of probable environmental mechanisms that impacted the dynamics of the floral, faunal, and human populations over the past 1000 years (or longer). This reconstruction will further provide a historical context for analyzing expected changes in landscape-scale processes of the Middle Rio Grande Basin, such as water availability, cultural fluctuations, and disturbance processes, given the pervasive (but controversial) influence of humans on global climate (Jacoby and D'Arrigo 1997; Houghton 2001). We will base our reconstruction on long-lived conifer species growing at high elevation sites that have been proven to provide a superior climate signal in the tree-ring record. We will explore several new locations in the Middle Rio Grande area that have previously demonstrated significant potential for preserving remnant samples of conifer wood lying on the forest floor. Furthermore, we will examine past climate for the study area using a network of tree-ring sites rather than relying on information from one site only. By analyzing the composite information from three sites, a more accurate picture of the palaeoclimate for the study area should be possible.

Our reconstruction of climate will help address several of the research objectives for the overall project concerning the Middle Rio Grande Basin (see Finch and Tainter 1995). We will specifically note long-term century-scale trends in past climate (*e.g.,* the Medieval Warm Period from 950–1400) that may have impacted, to some degree, the natural and/or human history of the Basin. Shorter-term (< 50 years) decadal periods of above average or below average precipitation may help identify shifts in climate patterns that necessitated shifts in faunal and floral populations and alterations of disturbance processes. Because of the length of the climate reconstruction (> 1000 years), fluctuations in past climate will be identified that should help elucidate the mechanisms behind certain observed natural and human features of the Rio Grande landscape (*e.g.,* arroyo cutting and floodplain aggradation), especially when coupled with results from other ongoing projects. It is reasonable to assume that certain components of regional climate (*e.g.,* the El Niño-Southern Oscillation and the Southwestern summer monsoon) have been temporally unstable in the past (Grissino-Mayer 1995; Swetnam and Betancourt, 1998). This instability may have greatly affected ecosystem processes (such as water availability and the seasonal distribution of precipitation) that, in turn, affected human processes (such as floodplain farming).

Because "environmental problems are essentially human problems" (Finch and Tainter 1995), future changes in climate may necessitate changes in human behavior and characteristics (*e.g.*, population aggregation or separation, reliance on surface or subsurface water sources). For the Southwest, temperatures are predicted to increase by as much as 10%, while summer precipitation is expected to decrease by as much as 15% under a CO_2-doubled atmosphere by the year 2030 (IPCC 1990). These expected changes will have significant repercussions for Southwestern environments, as some plant and animal species may not be able to adapt rapidly enough to withstand such changes (IPCC 1990). A tree-ring based climate reconstruction for the Middle Rio Grande Basin should prove valuable as it provides the template by which future anticipated changes can be gauged. If analogs of these anticipated changes occurred in the paleorecord as reconstructed from tree-ring data, then management agencies of the Middle Rio Grande Basin will have baseline data that could place these future changes in historical context.

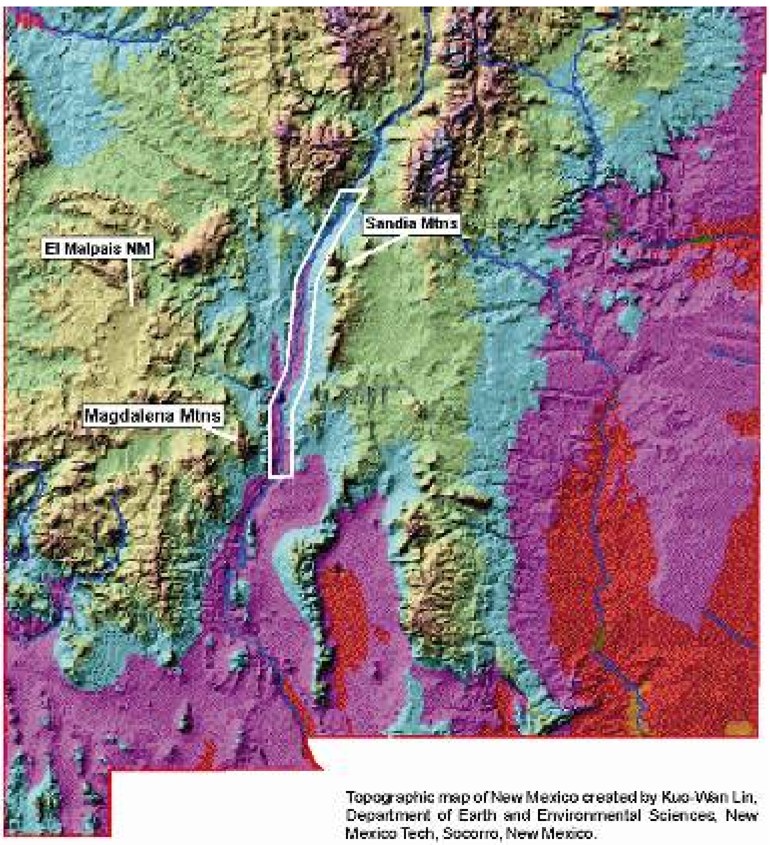

Figure 1. Shaded-relief topographic map of New Mexico, showing the three study sites: (1) the Sandia Mountains, (2) the Magdalena Mountains, and (3) El Malpais National Monument. The middle reaches of the Rio Grande relevant to this study are also depicted.

Study Sites

Three sites were selected for intensive collection that provided a logical geographic boundary around the core study area of the Middle Rio Grande Basin. These sites included (1) the Sandia Mountains, just east of Albuquerque, (2) the Magdalena Mountains, along the southern periphery of the core study area, and (3) El Malpais National Monument, located to the east of the Rio Grande Basin (Figure 1).

The Sandia Mountains

Our sites were located adjacent to and within the *Abies lasiocarpa*/*Erigeron eximius* (subalpine fir/forest fleabane) habitat type (Alexander *et* al. 1987), common throughout the spruce-fir forests of northern New Mexico and southern Colorado. Forest fleabane is a ubiquitous ground forb. Other forbs include western red columbine (*Aquilegia elegantula* Greene), Arizona peavine (*Lathyrus arizonicus* Britt.), and mountain parsley (*Pseudocymopterus montanus* (Gray) Coult. & Rose). Less common shrub associates include mountain snowberry (*Symphoricarpos* *oreophilus* Gray) and creeping mahonia (*Berberis repens* Lindl.). Graminoids commonly found in the Sandia Crest area include fringed brome (*Bromus ciliatus* (L.) Holub) and dryspike sedge (*Carex foenea* Willd.).

Figure 2. The Sandia Crest, composed largely of limestone caprock overlying the granite escarpment. Limber pine trees exhibit the characteristic flagged form caused by high, persistent winds.

We collected samples from five areas along the edge of the granite escarpment below the limestone cap exposed at the summit, within the Sandia Peak Wilderness area (Figure 2). The southernmost of these is 0.5 km to the north-northwest of the terminus of a commercial aerial tram service, and 0.5 km to the southwest of Kiwanis Meadows. The northernmost area is approximately 1.6 km north of the antenna farm located on the crest, about 0.5 km to the southeast of Sandia Peak itself. The other three sites lie at approximate evenly-spaced distances between these two locations. The stands sampled are open forest stands typically found scattered along precipitous cliffs and crags. Soils along the granite/limestone cliff margins are shallow or absent, sandy and well-drained, with very xeric environmental conditions, despite the higher elevations. Trees growing in such areas exhibit a high degree of sensitivity to annual fluctuations in climate (Baisan and Swetnam 1997). Furthermore, the cliff margins are protected from both natural disturbances (*e.g.*, wildfires and herbivory) and human activities (*e.g.*, logging and fuelwood gathering), causing trees to reach extreme ages.

The Magdalena Mountains

This mountain range is located approximately 29 kilometers west of Socorro, New Mexico (Figure 1), and is administered by the Magdalena District, Cibola National Forest, USDA Forest Service. The Magdalena Mountains rise to 3290 meters at South Baldy, and have similar vegetational zonations as theSandias. However, the Magdalenas strongly exhibit features characteristic of ecosystems near altitudinal treeline. For example, the mountains are topped by alpine meadows, interspersed with isolated forests of Douglas-fir and southwestern white pine (*Pinus strobiformis* Engelm.) trees growing in several growth forms: the characteristic erect form (but of short stature), the windswept (or “flagged”) form, and the krummholz form (short, scrubby, mat-like growth). The latter growth form is unusual in that Douglas-fir trees rarely exhibit the krummholz form. Even more surprising were the numerous krummholz mats of Colorado pinyon (*Pinus edulis* Engelm.). We found many pinyons growing at elevations above 3000 meters, a rare habitat for this species (Kearney and Peebles 1960). The presence of krummholz suggests elevations in the Magdalenas approach the alpine tundra zone, generally regarding as found above 3500 meters (Moir 1993).

We sampled near the summit of the Magdalena Mountains near South Baldy. The habitat type is classified as *Abies lasiocarpa*/*Vaccinium myrtillus* (subalpine fir/Rocky Mountain whortleberry) (Fitzhugh *et al*. 1987), with both subalpine fir and Engelmann spruce dominant in closed canopy stands. On drier ridges and talus slopes commonly found in the central Mogollon Mountains, occasional but infrequent Douglas-fir trees are found that exhibit characteristic physical features of being long-lived (Schulman 1937; LaMarche 1982). In addition to Rocky Mountain whortleberry, other common shrubs in the closed canopy stands include twinberry (*Lonicera involucrata* Banks ex. Spreng), Utah honeysuckle (*Lonicera utahensis* S. Wats.), and Wolf's currant (*Ribes wolfii* Rothrock). Common herbs found include fringed brome, forest fleabane, fireweed (*Epilobium angustifolium* L.), and Rocky Mountain strawberry (*Fragaria ovalis* (Lehm.) Rydb.).

Figure 3. Douglas-fir trees growing in talus near South Baldy in the Magdalena Mountains. The trees are often short and contorted, reflecting the poor soil conditions and limited nutrient availability.

We collected samples at three sites in the highest elevations of the Magdalena Mountains. The first is a ridge that extends two km northwest from the peak of South Baldy along a maintained trail. The elevation at this site was 3130 m. The ridge is steep-sided on its northern face, and contained numerous, though scattered individual Douglas-fir trees growing in rocky scree slopes. The second site is located at 3050 m elevation 1.2 km east of South Baldy. This easily accessible site lies only 50 m west of the main road leading into the Magdalena Mountains. The site is characterized by a rocky substrate with little soil except on the eastern face. We found exceptional Douglas-fir trees no more than 5–6 meters in height growing on the western flank of a small knob (Figure 3). Finally, we collected samples at Timber Peak located three km southeast of South Baldy along a maintained trail. Most samples were collected from southwest-facing, drier talus slopes above the trail, although a small group of samples was collected on the northeast-facing talus slope. At all three sites, increment cores were extracted from living trees and cross sections were collected using a chain saw.

El Malpais National Monument

El Malpais National Monument is located approximately 112 km west of Albuquerque, just south of Grants, New Mexico, along Interstate 40 (Figure 1). The monument is a unique environment that features numerous geologically recent lava flows ranging in age from 3000 years (McCartys Flow) to 115000 years (El Calderon Flow). Classic examples of cinder cones, spatter cones, shield volcanoes, kipukas, and other volcanic features are found within the monument (Laughlin *et al.* 1993). The different ages of the lava flows create a highly diverse landscape that allows grasslands, woodlands, and forests to exist in various stages of development. Furthermore, the lava is porous, allowing water to infiltrate and collect within the lava, acting much like an elevated subaquifer (Grissino-Mayer 1995). Extensive open stands of mixed conifer forests containing Douglas-fir, ponderosa pine, Colorado pinyon, and Rocky Mountain juniper trees exist within the lava flows, despite the near absence of soil (Figure 4). These interior areas of the lava flows, however, are protected from both natural and human disturbances, thus allowing trees to reach great ages (Grissino-Mayer 1995, 1996; Grissino-Mayer *et al*. 1997a).

The most comprehensive classification of vegetation types for the malpais area is based on "biophysical land units" (BLUs), relatively homogeneous areas defined by lithology, surface drainage, soil types, vegetation cover, and land use (Carroll and Morain 1992). Based on 12 distinct BLUs identified for the national monument, eight vegetation cover types have been delineated, although only one, mixed conifer, is relevant to this study. Mixed conifer is the dominant cover type (BLUs G and H), occupying large areas of the Bandera Lava Flow, Hoya de Cibola Lava Flow, and western portions of the McCartys Lava Flow. The longest lived trees were found in these mixed conifer forests, although the “pygmy forests” of the eastern portion of the monument could potentially contain old trees as well. Other tree species found include alligator juniper (*Juniperus deppeana* Steud.), quaking aspen (*Populus tremuloides* Michx.), and Gambel oak (*Quercus gambelii* Nutt.). Typical shrubs include alderleaf mountain-mahogany (*Cercocarpus montanus* Raf. var. *montanus*), Apache plume (*Fallugia paradoxa* (D. Don) Endl.), and skunkbush sumac (*Rhus trilobata* (Nutt.) A. Gray var. *trilobata*) (Lindsey 1951; Bleakly 1994), while prevalent grasses are blue grama (*Bouteloua gracilis* (Willd. ex H.B.K.) Lag. ex Steud.) and mountain muhly (*Muhlenbergia montana* (Nutt.) A.S. Hitch.) (Bleakly 1994).

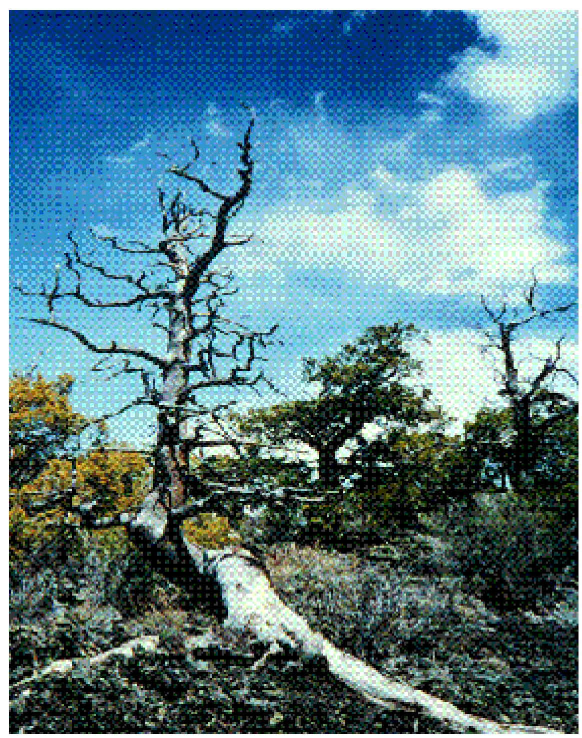

Figure 4. A Douglas-fir snag, having grown on lava substrate with no soil. Trees here are short and twisted, often with a near-horizontal spiral grain, and dead spike top.

We sampled at two sites, the first located near the southern periphery of Bandera Crater in the northern section of the monument near a well-known commercial ice cave. The second site is located east-northeast of Cerro Rendija in the northwestern portion of the monument. Both sites are located within the pahoehoe lava that surrounds the lava tube system that emanates from the southern side of Bandera Crater. A forest edge of mixed conifers clearly demarcates both the eastern and western periphery of the collection areas, perhaps also demarcating the limits of water storage within the porous pahoehoe lava. At both sites, conifers exhibit unusual growth forms. Trees are often short (less than seven meters), have a very wide base (often greater than one meter in diameter), gradually taper to a dead spike-top, and exhibit a very pronounced spiral grain that is often near horizontal. These features are characteristic of long-lived conifers (Schulman 1937). Furthermore, we found abundant samples of remnant, subfossil wood from both Douglas-fir and ponderosa pine trees lying on the lava surface throughout both sites. These remnants were critical for extending the chronology back in time with high sample depths.

Methods

Field Methods

At all three locations, we extracted at least two sound increment cores from opposite sides of selected living Rocky Mountain Douglas-fir, ponderosa pine, limber pine, and southwestern white pine trees that displayed physical characteristics indicative of exceptional longevity (LaMarche 1982). The cores were placed in paper straws and labeled. We cut cross-sections from remnant samples of subfossil wood with a chain saw, and all relevant information for all samples (location, dbh, crown condition, lean degree, lean direction, etc.) was recorded on standard site and specimen forms. In the Sandia Mountains, we used a hand saw to obtain cross sections because chain saw use is prohibited in wilderness areas. The collection of cross-sections was necessary because remnant wood is too fragile for successful extraction of sound cores using an increment borer. Cross-sections were wrapped with strapping tape and appropriately marked and labeled to facilitate reassembly in the laboratory.

We refined our sampling techniques to greatly increase the likelihood of successfully finding older samples from both living trees and remnant wood found lying on the surface. Guidelines for selecting samples were based on (1) specific growth forms and characteristics for living trees (*e.g.*, spiral grain, dead spiked tops, heavy lower limbs), (2) specific physical features for remnant wood (*e.g.*, gray color and deeply eroded surfaces on Douglas-fir logs), (3) specific and targeted locations within each site (*e.g.*, ridge tops, limestone crests, talus slopes, and lava tube systems), and (4) high wood density (indicating a compact ring structure) judged by weight in the field. Finally, the use of a chain saw was time and cost efficient, and allowed us to collect several samples from individual specimens, further ensuring that we obtained cross sections that would yield at least two radii for analyses.

Sample Preparation

Preparation of samples followed established dendrochronological techniques (Stokes and Smiley 1968). All air-dried core samples were glued to grooved core mounts and labeled, while cross-sections were reassembled and, if necessary, mounted on plyboard to stabilize the more fragile sections. Cores were sanded using a progression of rough (ANSI 150 grit, 74–105 Fm) to fine (ANSI 320 grit, 32.5–36.0 Fm) sandpaper. Cross-sections were sanded beginning with a coarse grit size (ANSI 36 grit, 500–595 Fm) to remove chain saw cuts, then sanded using progressively finer sandpaper until eventually using a 320 grit. This process ensured that the cellular structure of details in the wood (*e.g.*, the earlywood/latewood boundary) were sharply defined under standard 7X–35X magnification (Stokes and Smiley 1968; Swetnam *et al*. 1985).

Crossdating

Crossdating was aided by keying on certain obvious tree-ring sequences or signature patterns, such as the unique pattern of rings during 1273–1296 (*i.e.*, the “Great Drought”), the 1570–1600 group of extremely narrow rings, and the very wide rings for 1794 and 1816. When possible, we used reference chronologies developed in previous studies for nearby sites, such as Canyon de Chelly, Arizona; Cebolleta Mesa, New Mexico; Cibola, New Mexico; and, Durango, Colorado (Dean and Robinson 1978). We created skeleton plots for particularly difficult samples and matched these against cores and cross sections that contained minimal ring anomalies (called “type series”). If graphical crossdating was not successful, we measured the rings, then entered the series into COFECHA (see description below) as an undated series (Holmes 1983). If COFECHA suggested a temporal placement for the undated sequence based on systematic date adjustments (Grissino-Mayer 2001), we confirmed this placement graphically before the series was placed within the final group of dated samples. Series that could not be absolutely crossdated with 100% confidence were not considered for further analyses.

Chronology Development

We measured all rings from all dated series to the nearest 0.01 mm using an incremental measuring stage interfaced to a digital display and personal computer (Robinson and Evans 1980). High standards of quality in ring measurement and crossdating accuracy were maintained using a two-step process. First, we used program VERIFY5 (Grissino-Mayer 1997) throughout the measurement process to perform interactive measurement checks to ensure consistent measurement precision. Second, we used COFECHA (Holmes 1983; Grissino-Mayer 2001) to check crossdating accuracy by taking overlapping and successive 50-year segments of a particular measurement series, and correlated these segments with a master chronology developed from the remaining series. COFECHA flagged segments that correlated low with the master, and these were re-evaluated to determine whether crossdating was inaccurate or if the rings were aberrant due to a local disturbance. COFECHA also flagged individual ring measurements that were statistical outliers (exceedingly wide or very narrow) when compared to the distribution of all ring measurements from all measured series for the same year. All flagged measurements were checked to ensure these were accurately measured.

Because we wished to focus our reconstruction on low-frequency trends in past climate, we felt it essential to filter the tree-ring series to remove those that would compromise preservation of long-term trends. At the same time, we wished to retain those series that would contribute to a minimum sample depth of at least 25 series in the majority of years. We used program SAMDEP (written by Richard L. Holmes, Laboratory of Tree-Ring Research) to filter all series to satisfy the following criteria: (1) retain the series if it contributes to the minimum sample depth of 25 series; (2) retain the best series based on their correlations with all other series; and (3) exclude the series if it spanned less than 200 years. These criteria emphasize the importance of an adequate sample depth while retaining those series in which long-term trends would be preserved, and which reflect a superior environmental signal.

To remove undesirable trends in ring widths associated with physiological processes related to age and size, we standardized all tree-ring measurements for each site by first fitting a trend line to the measurement series using ordinary least squares techniques (Fritts 1976). Indices of tree growth for each year for all series were then obtained by dividing the actual ring width by that predicted from the regression. If actual growth met or exceeded the predicted value, an index equal to or greater than one was generated. In contrast, a ring width that fell below the predicted values resulted in an index below 1.0. In this study, we specifically chose conservative standardization models to ensure that the longer-term, low-frequency trends that may be due to long-term climate change were preserved. We used program ARSTAN (Cook 1985) to standardize the measurement series using either negative exponential or linear growth expressions (Fritts 1976). All negative exponential models were scaled to ensure the trend curve was asymptotic to the mean of the series rather than to zero to prevent spurious increases in growth rates in the outer portions of the detrended series (Fritts *et al*. 1969). Three types of chronologies are developed in this program, each designed for specific objectives. For our study, we chose to use the STANDARD chronology type for all analyses because this type retains the low-frequency variation desirable for analyses of long-term trends in past climate. The RESIDUAL chronology type, developed using autoregressive (AR) modeling (Cook 1985), represents a white noise series with all low-frequency variation removed, and would not have proved useful for analyzing long-term (>100 years) trends in past climate (Grissino-Mayer 1995; Briffa *et al*. 1996).

Once individual series had been standardized and combined using a mean-value function to form a standard tree-ring chronology for each of the three sites, we generated the final tree-ring data set by combining the three tree-ring chronologies into one in such a manner that would retain the variance associated with both short-term and long-term trends. We tested two procedures. First, we took the simple average for each year from the three chronologies. Second, we used principal components analysis to concentrate the common variance from the three chronologies into the first principal component (PC). The scores of this component (mean = 0.0, standard deviation = 1.0) represented a transformed chronology used in subsequent analyses. We decided *a priori* to choose that chronology (either simple average or first PC) which has the higher, more significant correlations with climate.

The Climate-Tree Growth Relationship

To reconstruct climate, we first investigated the climate-tree growth relationship using correlation analyses to isolate those months in which climate had significant effects upon tree growth (Fritts 1976, 1990). The climate variables analyzed represented regionalized monthly temperature, precipitation, Palmer Drought Severity Index (PDSI), and Palmer Hydrological Drought Index (PHDI) values developed for NOAA Climate Divisions Four (Southwestern Mountains), Five (Central Valley), and Six (Central Highlands) for New Mexico. Analyses were conducted first on individual climate divisions, then on averaged climate variables for divisions four and five, four and six, five and six, and for all three divisions combined. These combinations were necessary because our study sites spanned locations in all three climate divisions: El Malpais in division four, the Magdalena Mountains in division five, and the Sandia Mountains in division six. Furthermore, all analyses included monthly values lagged by one year to investigate the effects of previous year's climate upon current year's tree growth (Fritts 1976; Grissino-Mayer and Butler 1993). Because trees respond to climate over a period often extending to the previous growing season, various seasonal climate variables were also constructed for correlation analyses by averaging or grouping monthly values (Briffa *et al*. 1990; Grissino-Mayer and Butler 1993; Grissino-Mayer 1995).

Developing the Calibration Equation

We chose the climate variable with the highest and most significant coefficient when correlated with the tree-ring chronology for reconstruction. Ordinary least squares regression techniques were used to generate an equation with the tree-ring chronology as the predictor and the selected climate variable as the predictand. Generation of the equation followed an iterative process to remove outliers that adversely affected the calibration (*i.e.*, reduced the model sum of squares and the resulting *F*-value). The model was inspected for outliers by identifying observations with significant studentized residuals (–2.0 > *t* > 2.0) and Cook's *d* values (*d* $ .01) (Cook 1977; Schlotzhauer and Littell 1987; Burt and Barber 1996). Any outlier observation deemed significant was removed, and the model was then re-specified and re-inspected for additional outliers in the new model. This process continued until no statistical outliers were observed in the final data set. We used the entire period to develop the calibration equation rather than half-sample subsets because previous studies in the Four Corners region of the American Southwest have clearly demonstrated the stability of the climate-tree growth relationship during the historical period (1895–present) (Rose *et al*. 1981; D'Arrigo and Jacoby 1991; Grissino-Mayer 1995, 1996). Furthermore, use of the entire data set during the calibration maximizes the degrees of freedom used in the final regression equation (Briffa *et al*. 1990).

Analyzing Past Trends in Climate

A major goal of this research was to analyze both short-term, decadal trends as well as long-term, century scale trends in past climate. To partition decadal and century scale climate episodes from the original reconstruction, we fit both a 10-year and 100-year cubic smoothing spline (Cook and Peters 1981) through the reconstructed climate variable chosen (see Grissino-Mayer 1995; Grissino-Mayer *et al*. 1997b). To objectively determine significant climate episodes, we first converted the annual observations for reconstructed time series into standard deviation units (*i.e.*, z-scores). This was accomplished by first subtracting the mean for the entire series from each annual observation, and then dividing the resulting value by the standard deviation of the overall series (Burt and Barber 1996). Several archaeological studies have previously used the "1.1 standard deviation (sd) level to delimit those climate episodes that represented significant departures from mean climate (Dean *et al.* 1985; Dean 1988). These levels delimit the 25% most extreme climate episodes (12.5% above and 12.5% below the mean) considered potentially significant to the physical environment and to native populations (Dean 1988; Grissino-Mayer 1995).

To identify a specific short-term or long-term period when climate deviated significantly from the average, we first isolated those drought or wet periods that had at least four consecutive years when the standard deviation levels from the 10-year spline fell below the –1.1 sd level (for dry years) or above the +1.1 sd level (for wet years). For those periods identified using the shorter 10-year spline, we termed these "severe multi-year drought periods" (SMYD) and "extreme multi-year wet periods" (EMYW). The beginning/ending year for each period was initially determined by noting the first/last year when the reconstructed climate variable fell below the –0.5 sd level (for dry years) or above the +0.5 sd level (for wet years). The actual beginning/ending year of the SMYD or EMYW period was pinpointed precisely by inspection of the values for the actual reconstructed climate variable. Multi-year drought or wet episodes do not require the reconstructed climate variable be below or above a certain value for every year in the episode, as noted by Palmer (1965). More likely, the climate episode may contain one or several years where the climate variable represents an opposite departure from the majority of years in that episode (*i.e.*, a few wet years scattered within a multi-year drought period).

Because effects of climate can be exacerbated by the length of the drought or wet period, each period was also weighted by its duration, using a modification of the formulae used by Grissino-Mayer (1995). To rank the most severe drought periods, an index was calculated by first standardizing (mean subtracted, then divided by the standard deviation) both the reconstructed climate variable per year and the duration (in years) for each period. The absolute value of the lowest (negative) standard value in either data set was then added to all values to ensure only positive indices. The index for the climate variable was then combined with the index for duration to derive a final ranking. In this way, duration of a climate episode is equally weighted along with the magnitude of the climate episode. For example, the magnitude of a particular drought or wet episode was "penalized" if the period was of short duration. Similarly, the magnitude of a drought/wet period was "rewarded" if the episode was of longer duration.

Previous studies have shown that changes in the variability of climate are strong indicators of long-term climate change, and may be as important as changes in mean climate (Katz and Brown 1992). Furthermore, changes in climate variability have been used to explain certain behavioral responses by the Anasazi. High temporal variability likely produced differences in resource availability that caused interactions among groups within the Four Corners area (Plog *et al.* 1988) and favored long-term food storage to prevent starvation during frequent and intense drought periods (Dean *et al.* 1994). Low temporal variability meant stable climatic conditions and perhaps less interaction among groups. We analyzed changes in variance of the reconstructed climate variable by computing the running variance for overlapping 25 year periods (Grissino-Mayer 1995). We then compared these changes in variability with changes in short- and long-term climate as determined by the 10-year and 100-year splines fit through the reconstructed climate series.

Results

Crossdating and Quality Control

After checking crossdating accuracy with program COFECHA and filtering the raw ring measurement files through program SAMDEP, the final chronology was based on 239 measurement series averaging 480.4 years each (Table 1). The series intercorrelations by site

Table 1. Descriptive statistics for the chronologies developed at all three sites used in this study.

	El Malpais National Monument	Sandia Mountains	Magdalena Mountains
Range	136 BC–AD 1992	AD 174–1995	AD 622–1995
Number of series	94	73	72
Average length	495.0	489.1	457.8
Series intercorrelation	0.856	0.768	0.773
Avg mean sensitivity	0.526	0.438	0.437
Avg standard deviation	0.306	0.179	0.275
Total segments tested	1853	1409	1307
Problem segments	1	5	2

Table 2. Outliers isolated using the regression diagnostics, and deleted from the calibration model. All outlier observations had Studentized residuals –2.0 > *t* > 2.0. Note how the F-value for the model increases as each outlier is deleted from the analysis. The initial model with all observations had a model r^2 of 0.54.

Step	Outlier Year	Actual PDSI	Pred PDSI	Residual	Studentized Residual	Cook's d	model F	model r^2
1	1973	6.76	1.19	5.57	2.90	0.06	114.36	0.56
2	1967	1.44	–3.06	4.50	2.37	0.09	132.07	0.58
3	1908	–1.93	2.14	–4.07	–2.28	0.06	142.74	0.60
4	1931	5.04	1.09	3.95	2.20	0.04	145.08	0.61
5	1947	–3.66	–0.13	–3.53	–2.06	0.02	150.56	0.62
6	1970	–1.84	1.54	–3.38	–2.01	0.04	159.02	0.64

Table 3. Standard descriptions of dry and moist conditions corresponding to values of the Palmer Drought Severity Index (Hayes, 2001).

PDSI Value	Description
+4.00 and above	Extremely moist
+3.00 to +3.99	Very moist
+2.00 to +2.99	Unusually moist
+1.00 to +1.99	Slightly wet
+0.50 to +0.99	Incipient wet conditions
–0.49 to +0.49	Average conditions
–0.50 to –0.99	Incipient dry conditions
–1.00 to –1.99	Mild drought
–2.00 to –2.99	Moderate drought
–3.00 to –3.99	Severe drought
–4.0 and below	Extreme drought

were very high by dendrochronological standards (0.77, 0.77, and 0.86), attesting to the high quality of crossdating found at all three sites. The average mean sensitivities (0.44, 0.44, and 0.53) and standard deviations (0.18, 0.28, and 0.31) for each site were also very high, indicating trees at these sites were responding strongly to a macroenvironmental signal.

COFECHA tested 4,569 50-year segments for crossdating accuracy and flagged only eight segments (0.17%) as having significantly low correlations (< 0.32). Re-inspection of these segments indicated anomalous mid-series ring patterns that likely reflected influence from a local disturbance to individual trees, *e.g.* a tree fall that may have damaged growth on one side of a sampled tree. Because of the large number of samples per year, these rings added little noise to the final chronology, and were retained to ensure the affected series remained continuous.

Climatic Analyses

To ensure no one site chronology dominated the final master chronology, all subsequent analyses were conducted on the period common to all three chronologies, 622–1992. Furthermore, we found few differences between the chronology generated by simple averaging of the three individual site chronologies and the chronology developed using principal components analysis. Climatic analyses indicated a slightly stronger climate signal was actually retained in the site-average chronology, and this chronology was selected for all further analyses. We hypothesize that the chronology derived using PCA presented no additional information over the chronology derived using standard techniques because the observed variability is common to all three series. PCA-derived chronologies are more effective when one or more series contains variability not seen in the other series.

Correlation analyses revealed statistically significant associations between the tree-ring index chronology and monthly rainfall totals spanning from the previous year's August to the current year's July (Figure 5, top). These results indicate trees in this region of New Mexico are responding strongly to a water year annual rainfall signal (see Rose *et al*. 1981 and Grissino-

Mayer 1995, 1996 for examples). An improved relationship between precipitation and tree growth was generated by combining the August through July monthly totals into one water year rainfall total (r-value = 0.56, p < 0.0001).

In general, temperature effects were weaker based on the monthly analyses. We expected, however, some influence from temperature on tree growth in our study because we collected samples at the Sandia and Magdalena Mountains, where temperature has a greater effect at higher elevations than at lower elevations (Grissino-Mayer and Fritts 1995; Buckley *et al*. 1997; Salzer 2000). This probable influence of temperature is reflected in the highly significant monthly correlations of tree growth with PDSI values. The synergistic effects of temperature and precipitation are combined in the calculation of this index (Palmer 1965; Alley 1984). The best relationship between climate and tree growth was found using June PDSI values for Climate Division Five (Figure 5, bottom, r-value = 0.73, p < 0.0001). Significant autocorrelation is present in PDSI because its calculation in any given month depends on antecedent climatic conditions (Alley 1984). Therefore, we used reconstructed June PDSI as a proxy for summer drought conditions. Furthermore, reconstruction of summer drought using PDSI values for Climate Division Five is appropriate because this division contains the Middle Rio Grande Valley of interest in this study.

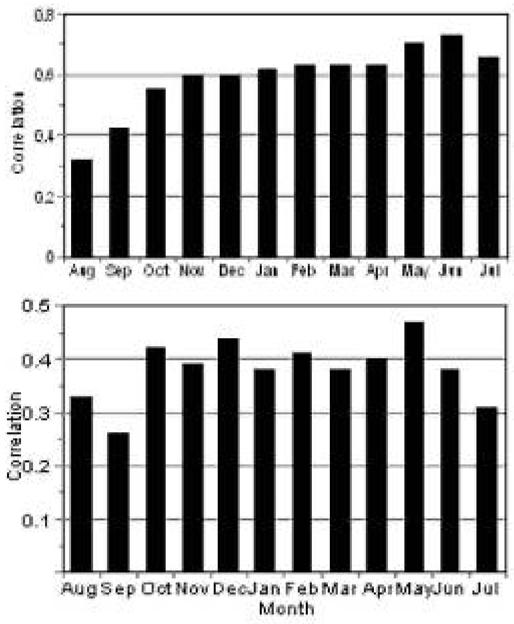

Figure 5. Correlation coefficients between the master tree-ring chronology and monthly precipitation (top) and monthly PDSI (bottom), from the previous year's August value to the current year's July value. All coefficients are significant at the 0.05 level.

Climate Reconstruction

The initial model (all observations kept) that predicted summer drought from tree growth for the period 1895–1992 yielded an r^2 value of 0.54, indicating that tree growth could explain 54% of the variance in the climate data over this period. An iterative process identified outliers in the years 1973, 1967, 1908, 1931, 1947, and 1970 (Table 2). Outliers are often connected with severe weather events in specific years that are not recorded in the tree growth record. For example, late summer and early fall of 1972 saw unusually high amounts of rainfall, perhaps due to an unusually strong El Niño event (Quinn and Neal 1992) that may have enhanced rainfall during the fall and winter seasons. Most of this rainfall obviously occurred as runoff in central New Mexico, and was not made readily available for tree growth. Hence, the tree rings for the following year show an otherwise average width compared to a very high PDSI value, providing a climatically reasonable explanation for removal of this yearly observation from the calibration equation. After removal of these six outlier observations, the final model r^2 value was 0.64, indicating 64% of the climate variance could be explained by the tree-ring indices. This value is comparable to other r^2 values obtained in previous studies (Rose *et al*. 1981, D'Arrigo and

Jacoby 1991; Grissino-Mayer 1995). The final equation used to reconstruct summer PDSI took the form:

$$(\text{predicted June PDSI})_t = -6.472 + 6.075(\text{tree-ring index})_t$$

where t is a particular year. Both parameter estimates (–6.472 and +6.075) were statistically significant ($p < 0.0001$). The F-value of the model was 159.02 ($p < 0.0001$), indicating variability attributable to the model was 159 times that attributable to error variance. The Durbin-Watson D statistic was 2.125, indicating no significant autocorrelation (–0.12) in the model residuals. This lack of residual autocorrelation affirms that the tree growth model is capturing the majority of climate variability. Had some aspect of climate not been accounted for in the model, the residual autocorrelation would likely have been high and statistically significant.

The equation generated predicted values for climate that simulated both high- and low-frequency trends during the 20th century calibration period (Figure 6), which illustrates the accuracy of tree rings to predict climate. For example, an average index value of 1.0 indicates summer PDSI was –0.4, very close to the average PDSI of 0.0. A tree-ring index of 1.5 indicates June PDSI for that year was 2.6, indicating a very wet year. Likewise, a very low tree-ring index value of 0.5 indicates a summer PDSI value of –3.4, indicating a severe drought year. Corresponding descriptions of drought using the PDSI are given in Table 3 (Hayes, 2001).

This equation was used to reconstruct summer drought for northern New Mexico for every year since 622 based on the millennial-length tree-ring chronologies developed in this study (Figure 7). Long-term trends become more apparent when the reconstructed values for summer drought were converted to standard deviation units (Figure 8) and fit with both a 10-year (Figure 9) and 100-year (Figure 10) smoothing splines. The variances of the 10-year and 100-year smoothing splines fit to the reconstruction were adjusted to reflect the variability seen within the original reconstruction, and to accentuate the extreme wet and dry periods.

Climate Trends Since AD 622

Short-term, multi-year periods of extremely wet and severe drought conditions occurred numerous times throughout the 1,371 year reconstruction. The five periods with the wettest conditions occurred between (1) 1553–1557 (5 years, average June PDSI = 3.60), (2) 1627–1653 (27 years, average June PDSI = 1.45), (3) 1978–1992 (15 years, average June PDSI = 1.90), (4) 724–733 (10 years, average June PDSI = 2.34), and (5) 1377–1396 (20 years, average June PDSI = 1.29) (Table 4). The five periods with the most severe multi-year droughts were (1) 1571–1593 (23 years, average June PDSI = –1.99), (2) 1272–1297 (26 years, average June PDSI = –1.30), (3) 1945–1963 (19 years, average June PDSI = –1.62), (4) 701–712 (12 years, average June PDSI = –1.95), and (5) 1131–1151 (21 years, average June PDSI = –1.38) (Table 5).

Five major long-term drought periods and five major wet periods occurred since 622 in the Middle Rio Grande Basin (Table 6). The first drought began *ca*. 600 and lasted to 715 (Figures 7–10). During this drought, an extremely dry string of years occurred from 638–648 (Table 5), with the year 645 having one of the lowest June PDSI values (–4.60) in the entire reconstruction. The 600–715 drought was followed by a major wet interval that lasted from 716–

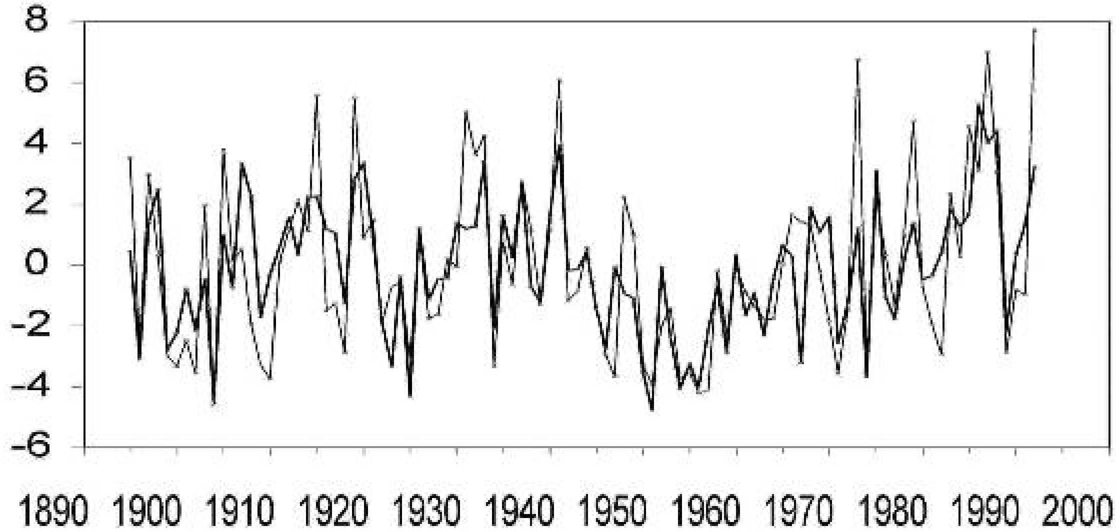

Figure 6. Comparison of predicted June PDSI (bold line, predicted from the calibration equation) with actual June PDSI (lighter line) over the historical period 1895 – 1992. The model is able to simulate both high-frequency, year-to year changes, as well as lower-frequency decadal scale changes.

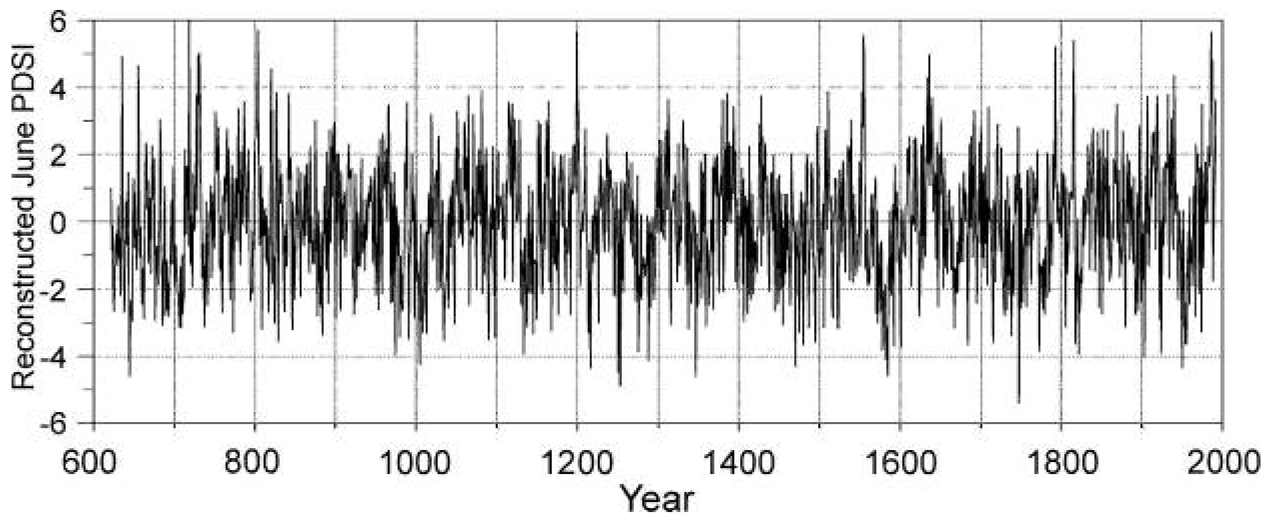

Figure 7. Reconstructed summer drought (June PDSI), AD 622–1992, for the Middle Rio Grande Basin. Table 3 describes drought or wet conditions associated with the PDSI values.

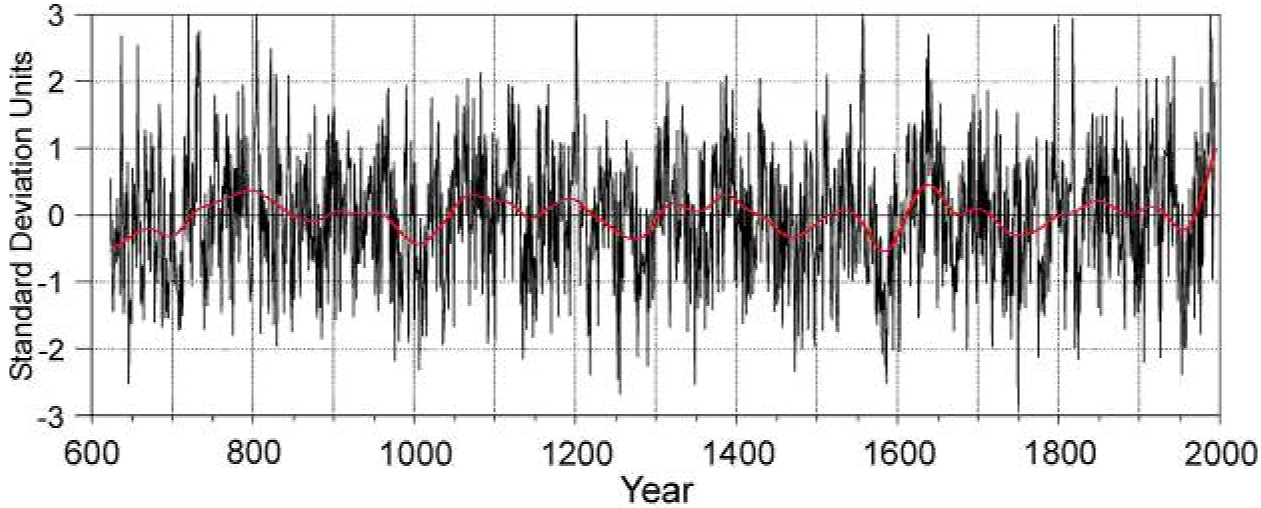

Figure 8. Reconstructed summer drought (June PDSI), AD 622–1992, expressed as dimensionless standard deviation units. The smooth curve represents a cubic smoothing spline calculated using a 100-year window to accentuate longer-term trends.

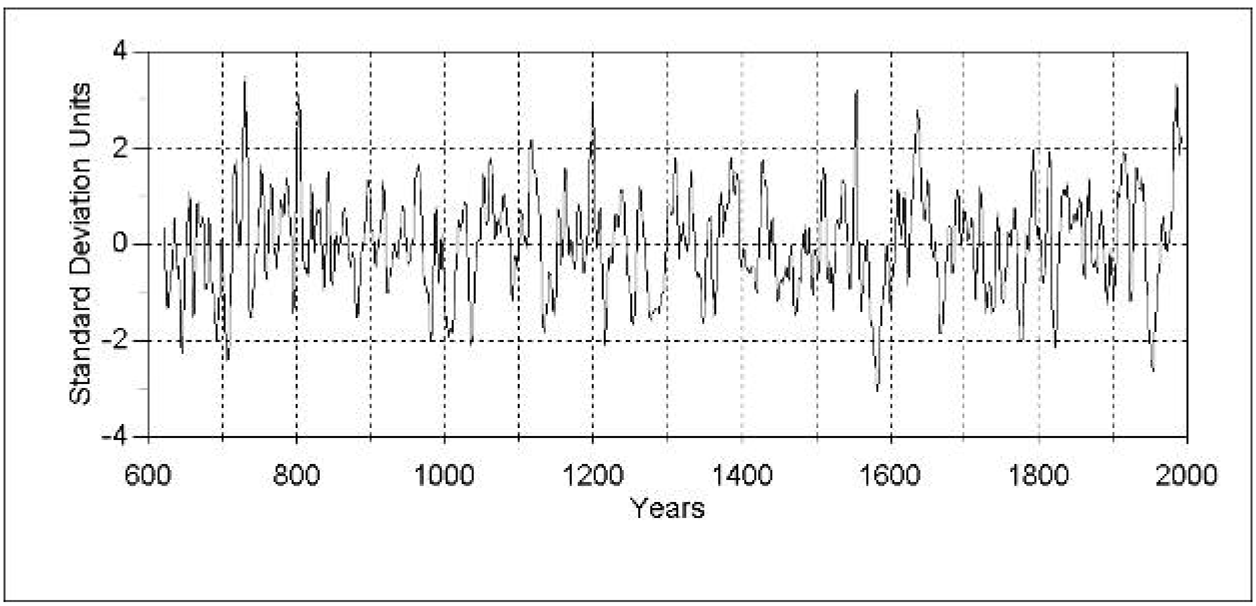

Figure 9. The reconstruction of June PDSI, AD 622–1992, in standard deviation units, filtered with a 10-year smoothing spline to accentuate interannual- to decadal-scale trends.

834, and ranks as the second wettest period in the entire reconstruction. This century-long wet period was capped by a short-term, extremely wet period between 800–808 (Table 4), when summers (and likely all seasons) were exceedingly wet. The year 804 ranks as one of the top five wettest years in the entire reconstruction (June PDSI = 5.79). After 834, a period of rather benign climate occurred until 961. Few notable extreme events occurred during this period.

A major long-term drought began 962 that lasted until 1042, accentuated by a 17 year period of well below-average rainfall between 999 and 1015 (Table 5). No positive June PDSI value occurred during this 17-year period, making this one of the severest short-term periods of drought in the entire reconstruction. Beginning in 1043, a long-term period of above-average rainfall began that lasted until 1203 (Table 6). Two notable extremes occurred in this period. First, a very wet year occurred in 1200 with a reconstructed June PDSI of 5.68. Second, although the period between 1043–1203 was generally wet, it was broken by a 21-year period of extremely dry conditions that lasted between 1131–1151 (Table 5; Figure 9). Exceptionally dry years (PDSI < –2.00) within this period occurred in 1131 (June PDSI = –2.45), 1134 (–3.93), 1138 (–3.12), 1140 (–2.10), 1143 (–2.13), 1146 (–3.33), and 1150 (–2.90).

The 13th century clearly represents a period of diminished rainfall in the American Southwest (Figure 9), culminating in the drought between 1272–1297, known as the "Great Drought" in this portion of the American Southwest (Douglass 1929; Baldwin 1935). After the very wet year of 1200, very few wet years occurred that exceeded the 2.0 PDSI level, indicating very dry conditions (Figure 9). Dry periods occurred between 1204–1208, 1213–1221, and 1246–1258 (Table 5). This century also had the greatest number of extremely severe drought years (June PDSI < –3.0) of any century: 1214 (–3.30), 1217 (–4.36), 1227 (–3.00), 1251 (–4.48), 1254 (–4.89), 1276 (–3.86), and 1288 (–4.13). Therefore, the "Great Drought" was actually preceded by two very dry years during the 1250s and many other years of mild drought during the 1250s and 1260s (Figures 7–9). Surprisingly, this number of severe drought years during the 13th century would not be matched again until the 20th century. Average June PDSI for the 26 year period between 1272–1297 was only –1.30. Only four years in this period saw average or above average rainfall.

The 14th century, in contrast, experienced generally above-average rainfall conditions (Figures 7–9). Several extreme multi-year wet periods occurred in this century. The first occurred between 1298–1314, followed soon after by the wet period between 1330–1337 (Table 4). Between 1298 and 1337, only one year (1316) experienced a severe drought with a June PDSI value below –2.0. Unusually moist years (June PDSI > 2.0) occurred in 1302, 1305, 1310, 1311, 1313, 1314, 1325, 1331, 1332, and 1333. Given the two wet years that preceded 1315 and 1316, it is doubtful the drought during these two years had a major impact on native human populations. A period of mild drought then occurred between 1338 – 1369, punctuated by the severe drought years of 1338 (June PDSI = –3.19), 1347 (June PDSI = –4.62), and 1360 (June PDSI = –3.12). Very wet climatic conditions returned beginning 1370 that lasted until 1407. During this decades-long wet interval, a very wet period occurred between 1377–1396 (Table 4). Nearly every year in this 20 year period experienced average to very wet conditions.

Most of the 15th century was generally unfavorable climatically (Figure 9). Beginning with the very dry multi-year drought between 1407–1423 (Table 5), drier conditions prevailed, interrupted only by a very wet, short-term period between 1426–1435 (Table 4; Figures 7–9). After 1435, only one year during the 15th century could be classified as an unusually moist year, 1498, with a reconstructed June PDSI value of 2.87. An extended period of very dry conditions occurred between 1445–1465, and again between 1470–1480 (Table 5). During this period, several years saw dry conditions (PDSI < –2.0): 1449 (–2.45), 1450 (–2.17), 1452 (–2.01), 1455 (–3.07), 1464 (–2.48), 1471 (–4.28), 1475 (–3.30), and 1480 (–3.65), followed later by dry years in 1487 (–3.12) and 1495 (–3.59). These drought years, interspersed within the decades-long drought, rank the latter half of the 15th century as one of the top five longer-term drought periods in the entire reconstruction (Figure 9).

The 16th century began with a return to favorable climate conditions. In general, climate from 1507–1556 was mildly wet, with a brief period of well below average rainfall between 1516–1525. After 1525, no single year of moderate to severe drought (PDSI < –2.0) occurred until 1571 (June PDSI = –2.71). Furthermore, this period was accentuated by two of the wettest years in the entire reconstruction: 1555 (June PDSI = 5.56) and 1556 (June PDSI = 5.06), embedded within the wettest multi-year wet period in the entire reconstruction between 1553–1557 (Table 4). Beginning in the late 1550s, however, climate conditions in the Middle Rio Grande Basin deteriorated, culminating in the worst decades-long drought in the entire reconstruction. During the 50-year period from 1558 to 1607, the average June PDSI was –1.18. This 50-year period witnessed 14 years with moderate to severe drought conditions (June PDSI < –2.0): 1571 (–2.71), 1573 (–3.00), 1575 (–2.03), 1576, (–2.68), 1579 (–3.81), 1580 (–2.04), 1581 (–2.56), 1583 (–4.10), 1584 (–3.08), 1585 (–4.59), 1589 (–2.20), 1590 (–2.07), 1593 (–3.69), and 1601 (–3.74). The average June PDSI for the period between 1571–1593 was –1.99, indicating that virtually every year for this 23-year duration (Table 5) experienced severe drought conditions, broken only by an occasional, rare year of slightly wetter conditions.

The recovery from this very long and intense drought period was equally remarkable, and represents the greatest swing from severe drought to severe wet conditions in the entire reconstruction (Figure 9). Beginning in 1606 and lasting until 1713, the Middle Rio Grande Basin experienced very favorable climate (Table 6), highlighted by an extremely wet period from 1627–1653 (Table 4; Figure 9). The average June PDSI for this 27-year period was 1.45, indicating each year received abundant rainfall. Only one PDSI value below 0.0 (1645, June PDSI value = –1.11) occurred during this interval. Five extremely wet years occurred in 1634 (4.30), 1637 (4.97), 1639 (2.36), 1640 (3.72), and 1646 (2.37). The 17th century experienced dry conditions for only a brief period between 1664–1674 (Table 4).

The 18th century was generally very dry, and witnessed one of the worst longer-term droughts in the entire reconstruction (Table 6). Beginning with 1714 and lasting until 1789, 23% of all years (17 of 76 years) are classified as having moderate to severe droughts (PDSI < 2.0). Notable among these years is 1748, which likely witnessed the most severe drought of any year during the 1,371 year reconstruction. The June PDSI value for this year was a remarkably low –5.40, and was followed by severe drought years in 1750 (–2.58) and 1752 (–2.40). Severe multi-year droughts occurred on three occasions (Table 5): 1727–1740, 1748–1757, and 1772–1782. The 11-year period between 1772–1782 was especially dry (average June PDSI was only –1.83), and ranked as one of the top ten multi-year droughts in the entire record. Five of these eleven years would be classified as moderate to severe drought years: 1773 (–3.88), 1777 (–2.61), 1779 (–2.17), 1780 (–2.76), and1782 (–2.24). A shift to generally wetter conditions occurred between 1790–1797 (Table 4), highlighted by the very wet year of 1793 (June PDSI = 5.21).

Table 4. Extreme multi-year wet periods in the central Rio Grande Basin, AD 622–1992. "Avg PDSI" is the average reconstructed June PDSI value each year during that period. See Table 3 for an explanation of PDSI values.

Rank	Period	Avg PDSI	Duration
1	1553–1557	3.60	5
2	1627–1653	1.45	27
3	1978–1992	1.90	15
4	724–733	2.34	10
5	1377–1396	1.29	20
6	1112–1130	1.38	19
7	1193–1203	2.09	11
8	800–808	2.27	9
9	1907–1921	1.65	15
10	1049–1066	1.36	18
11	1298–1314	1.17	17
12	1930–1944	1.30	15
13	959–968	1.62	10
14	1426–1435	1.60	10
15	713–720	1.63	8
16	1810–1817	1.60	8
17	1866–1869	1.95	4
18	1507–1515	1.44	9
19	751–756	1.72	6
20	1790–1797	1.53	8
21	1830–1841	1.13	12
22	776–789	0.93	14
23	1159–1165	1.55	7
24	893–899	1.53	7
25	1534–1541	1.41	8
26	1845–1858	0.80	14
27	1235–1245	0.99	11
28	1330–1337	1.18	8
29	1618–1622	1.45	5
30	1688–1693	1.35	6
31	914–918	1.43	5
32	763–769	1.21	7
33	1608–1613	1.25	6
34	1259–1265	1.08	7

Table 5. Severe multi-year drought periods in the central Rio Grande Basin, AD 622–1992. "Avg PDSI" is the average reconstructed June PDSI value each year during that period. See Table 3 for an explanation of PDSI values.

Rank	Period	Avg PDSI	Duration
1	1571–1593	–1.99	23
2	1272–1297	–1.30	26
3	1945–1963	–1.62	19
4	701–712	–1.95	12
5	1131–1151	–1.38	21
6	1818–1826	–2.03	9
7	999–1015	–1.54	17
8	1772–1782	–1.83	11
9	1522–1525	–2.25	4
10	685–696	–1.55	12
11	638–648	–1.57	11
12	972–985	–1.39	14
13	1445–1465	–0.93	21
14	1031–1041	–1.48	11
15	1213–1221	–1.57	9
16	1899–1904	–1.72	6
17	1664–1674	–1.43	11
18	1727–1740	–1.23	14
19	1246–1258	–1.28	13
20	1470–1480	–1.37	11
21	1338–1352	–1.13	15
22	658–663	–1.69	5
23	1748–1757	–1.37	10
24	877–886	–1.28	10
25	735–743	–1.32	9
26	1360–1367	–1.37	8
27	1407–1423	–0.76	17
28	794–799	–1.38	6
29	1089–1093	–1.41	5
30	1889–1896	–1.12	8
31	1598–1607	–0.93	10
32	921–927	–1.08	7
33	624–631	–1.01	8

The shift at 1790 signaled a change to wetter conditions that prevailed for much of the 19th century (Table 6; Figure 9). The beginning of this century, however, was marked by a pronounced shift from two very wet years (1815, June PDSI = 3.10, and 1816, June PDSI = 5.40) to three severe drought years: 1818 (–3.63), 1819 (–2.68), and 1822 (–3.94). The period between 1818–1826 ranks as the sixth worst drought period in the entire reconstruction (Table 5). Following these highly variable beginning years, the 1800s were generally wet with only an occasional dry year (*e.g.*, 1880, June PDSI = –3.12). In fact, three extreme multi-year wet periods occurred during this century (Table 4): 1830–1841, 1845–1858, and 1866–1869. Severe multi-year drought conditions returned in the latter decade of the 1800s (Table 5): 1889–1896 and again between 1899–1904. This period of generally unfavorable climate was marked by a series of moderate to severe drought years in 1892 (–2.15), 1893 (–2.76), 1896 (–2.65), 1899 (–2.39), and 1904 (–4.01).

The 20th century is remarkable for having three distinct climate periods (Figure 9). The first half of the 20th century saw a continuance of the wetter conditions that prevailed during the previous century. Between 1905 and 1945, only two severe drought years occurred: 1923 (–2.91) and 1925 (–3.89). In contrast, this 41 period witnessed numerous years of abundant rainfall (June PDSI > 2.0): 1907 (3.74), 1908 (2.67), 1914 (2.65), 1915 (2.66), 1919 (3.22), 1920 (3.76), 1933 (3.81), 1935 (2.02), 1937 (3.08), and 1941 (4.35). In fact, the multi-year wet period between 1930–1944 ranks as one of the wettest in the entire reconstruction (Table 4). This decades-long period of very wet conditions was rapidly followed by another major drought period, however.

Beginning in 1945, severe droughts became more common, with extremely dry years occurring in 1946 (–2.32), 1950 (–3.10), 1951, (–4.35), 1954 (–3.64), 1955 (–2.85), 1956 (–3.62), 1959 (–2.44), 1967 (–2.81), 1971 (–2.14), and 1974 (–3.27). The multi-year dry period between 1945–1963, commonly called the "1950s Drought" (Betancourt *et al*. 1993; Swetnam and Betancourt 1998), ranks as the third worst drought in the last 1,371 years (Table 5). Beginning in 1975, though, favorable climate conditions returned, representing one of the wettest periods in the entire reconstruction. This period was highlighted by a string of six consecutive extremely wet years in 1983 (2.25), 1984 (1.64), 1985 (2.10), 1986 (5.68), 1987 (4.43), and 1988 (4.83). The multi-year wet period between 1978–1992 ranks as the third wettest period in the entire 1,371 year reconstruction (Table 5). Remarkably, the last 50 years of the 1900s saw the third worst multi-year drought (1945–1963) followed soon by the third wettest multi-year wet period (1978–1992).

Climate Variability Since AD 622

The plot of 25-year running variance for the reconstruction (Figure 11) clearly shows periods when climate was fairly stationary over time (*i.e.*, low variance) or highly variable from year to year (*i.e.*, high variance). The most notable feature in this plot are two distinct periods of variability. First, the period 622–1000 was characterized by periods of variance that spanned decadal and longer time scales. In other words, once climate became highly variable or highly stationary year to year, it stayed in this mode for several decades or longer. In addition, this period was characterized by extreme and rather rapid shifts from periods of high variability (*e.g.*, 790–845) to periods of low variability (*e.g.*, 845–955). The most extreme periods of high and low variability at any time in the reconstruction occurred in this earlier 380-year period.

Table 6. Long-term periods (> 50 years) of above- average and below-average climate conditions in the central Rio Grande Basin, AD 622–1992.

Period of Below-Average Rainfall	Period of Above-Average Rainfall
AD 622–715	
	AD 716–834
AD 962–1042	
	AD 1043–1203
AD 1204–1300	
	AD 1301–1427
AD 1428–1605	
	AD 1606–1713
AD 1714–1800	
	AD 1801–1992

Second, the variability of climate became more stationary beginning AD 1000, although at times displayed a "choppy" behavior. Climate variability tended to remain fairly uniform year to year, broken only by an occasional but short-lived fluctuation in the reverse direction. We interpret both periods to be a real property of past climate, primarily because this reconstruction is based on numerous samples from three sites, each sample averaging over 400 years in length. Because our methods were designed to consider both sample depth and sample length, we are certain these changes in variability are not artifacts of low sample size in the earlier period (< AD 1000) or due to changing sample depth in the latter period (> AD 1000).

The reconstruction of running variance revealed that climate variability declined steadily during the 600s, coincident with a period of very dry conditions. The first half of the 8th century, however, witnessed a major shift to high year to year variability, suggesting the period from 700–750 was marked by unpredictable year-to-year weather. The latter half of the 8th century was very wet, one of the wettest long-term periods in the entire reconstruction (Figures 7–9). Furthermore, this period also experienced a shift to low variability (Figure 11), indicating the wet conditions that dominated year to year became more stationary and predictable. The 9th century overall saw generally average rainfall, but the first half of this century did witness major shifts from years of low rainfall to years of high rainfall. The latter half of the 9th century saw very stationary conditions from year to year as indicated by a period with one of the lowest values of variance in the entire reconstruction.

This trend in climate variability continued into the 10th century, which saw the lowest values of running variance in the entire reconstruction. The first 62 years of the 900s saw generally average amounts of rainfall, with little variability about the mean for the period. The century ended, however, with a major swing to rainfall totals well below average (Figures 7–9). Variability of climate during the major drought period from 962–1042 was fairly stable with no major shifts from one extreme to the other. In general, the variability of climate during the 11th century was rather benign, with no period exceeding the 1.1 sd level (Figure 11). Essentially, once wet conditions returned after 1042, the rainfall was fairly uniform from year to year with little fluctuation. Beginning near 1100, however, rainfall became less predictable year to year, indicated by three distinct periods of high variability during the 12th century. The 13th century generally had very stationary climate from year to year as indicated by very low values of variance. This suggests that the deteriorating climate conditions beginning *ca*. 1270 were further augmented by very little fluctuation about the already low precipitation values. Essentially, once the "Great Drought" was underway, annual rainfall remained low year after year.

The 1300s were clearly a period of favorable climatic conditions as indicated by both the high annual amounts of rainfall (Figures 7–9) and by the low variability about the mean rainfall (Figure 11). Rainfall was abundant during this century, and fluctuated little about the mean. The 1400s also saw little variability about the mean, but was also a century of very low rainfall totals overall. The 16th century began with above-average rainfall conditions and low variability about this mean. Beginning around 1530, however, climate became extremely unpredictable, indicated by the highest values of running variance witnessed in over 300 years. This shift to unpredictable climate was followed by (1) the most severe drought in the entire reconstruction between 1558–1607, and (2) a return to less variable year to year climate. This indicates that this intense, long-lasting drought was also characterized by little variability about these low mean values.

The first half of the 17th century saw very wet conditions, but year-to-year variability was also high, indicating that climate was not stationary. Climate during the latter half of this century, however, was very stable from year to year, with one of the lowest values for running variance occurring in the 25-year period 1656–1680 (Figure 11). Rather benign climate conditions occurred between 1680–1735. Beginning in the late 1730s, however, climate became more unstable, fluctuating between periods of high variability and periods of low variability until 1835. The 1800s were marked by an extended period of low year-to-year variability that lasted between 1830–1890, indicating climate was not only very wet during the 1800s, but these wet conditions persisted from year to year. Beginning *ca*. 1890, climate became very unstable. The 20th century, in general, was a period of high climate variability, with some of the highest values of variance recorded at any time in the reconstruction (Figure 11). For much of this century, running variance has exceeded the +1.1 sd level, and has three times reached or exceeded the +2.0 sd level. The 20th century has therefore been a century of unpredictable year-to-year weather for the Middle Rio Grande Basin.

Discussion

Several significant features of this 1,371 year reconstruction warrant additional discussion. While similarities exist between this reconstruction of drought with a reconstruction of precipitation for southern and central New Mexico (Grissino-Mayer *et al*. 1997b), differences also occur indicating some regionalization of climate patterns, perhaps forced by shifts in dominant atmospheric circulation patterns. We point out that our reconstruction of drought for the Middle Rio Grande Basin and the previous reconstruction of precipitation for southern New Mexico have one data set common to both, namely the tree-ring data from the Magdalena

Mountains. Similarities that may arise in these separate reconstructions can not, however, be explained solely by the inclusion of the Magdalena Mountains data set in both. The Southern Rio Grande reconstruction is based on equally-weighted tree-ring data from the Organ Mountains and from the San Mateo Mountains, as well as data sets from Colorado pinyon obtained from 12 archaeological sites in southern and central New Mexico. The reconstruction for the Middle Rio Grande Basin is based on equally-weighted tree-ring data from El Malpais National Monument and from the Sandia Mountains.

Shifts in climate variance ca. AD 960

The variability in reconstructed drought was generally high prior to *ca*. 960, with periods of high and low variability often lasting for decades (Figure 11). Beginning around 960, however, climate variability entered a new mode vastly different from the pre-960 mode. Decades-long periods of high and low variability ceased to occur, and climate was instead marked by rapid alternations between short-term periods of high/low variability. Furthermore, these shifts between periods were very rapid. For example, the early 1800s were marked by high variability (*i.e*. unstable) climate, but were immediately followed by an extended period of low variability (*i.e.*, stable) climate between 1830–1890. This period of low variability was then followed by a decades-long period of highly variable, unstable climate during the 20th century (Figure 11), reminiscent of the variability that occurred prior to 960. As mentioned previously, climate during the 20th century was the most variable and most unstable of any century since 622.

This change in variance also can not be attributed to decreases in sample size prior to 1000, a common problem that causes changes in variance over time in tree-ring chronologies (Sheppard 1991). Furthermore, the shift in variance *ca*. 960 was coincident with a marked and dramatic shift to below-average rainfall conditions that lasted for *ca*. 80 years (Table 5; Figures 9 and 10). Interestingly, a similar climate change scenario occurred in southern New Mexico beginning at nearly the same period (Grissino-Mayer *et al*. 1997b). Reconstructed precipitation there revealed a major change in oscillatory behavior *ca*. 950, when climate switched from a highly variable mode to a less variable mode. These shifts strongly suggest that a major change in climate occurred in the Middle Rio Grande Basin, and perhaps for most of New Mexico, generally between 950–1000. This change in regional climate may be related to the onset of the more spatially-extensive climate period for the northern hemisphere known as the Medieval Warm Period, generally acknowledged as having occurred between 950–1400 (Lamb 1977). Because two of our sites exist at higher elevations (the Sandia Mountains and the Magdalena Mountains), our reconstruction for the Middle Rio Grande Basin may have a greater temperature expression that other reconstructions for New Mexico based on trees collected at lower-elevation sites. This observation is supported by the overall response by our sampled trees to the Palmer Drought Severity Index, an index that combines information from both precipitation and temperature data (Palmer 1965; Alley 1984).

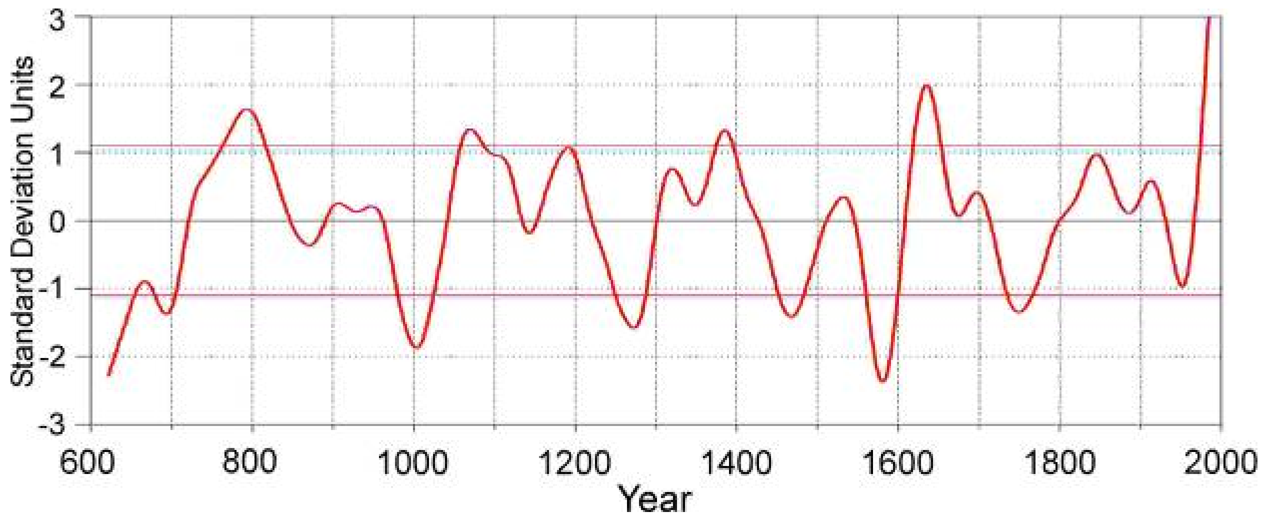

Figure 10. Major wet and dry periods between AD 622–1992 for the Middle Rio Grande Basin, filtered with a 100-year smoothing spline, expressed as standard deviation units. The ± 1.1 sd units are depicted as well. Any periods above or below these lines denote extreme wet and dry periods, respectively.

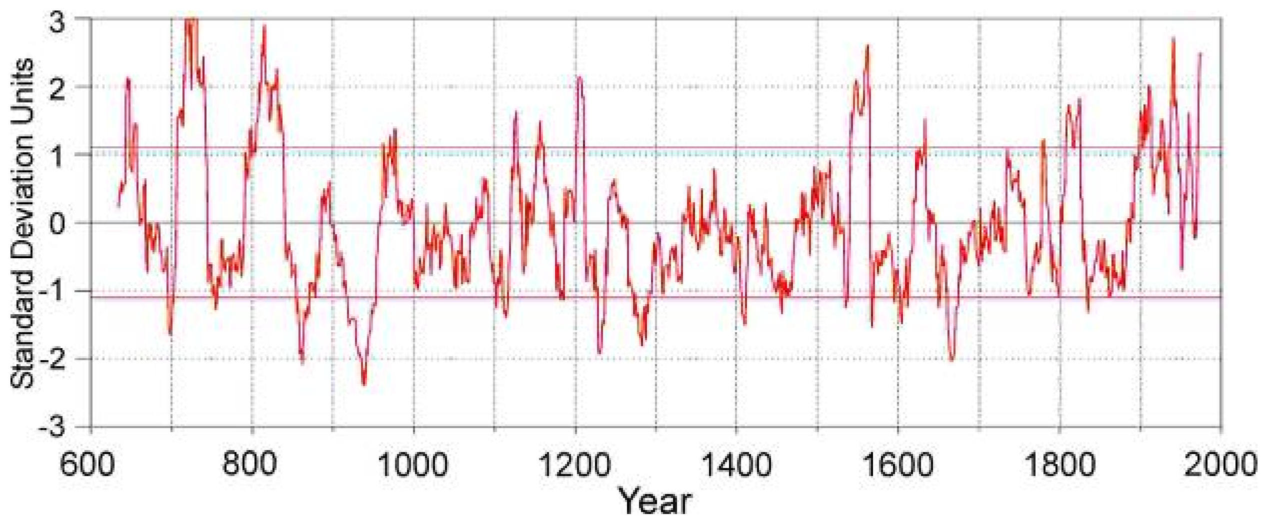

Figure 11. Running variance calculated for 25-year periods lagged by one year, then converted to standard deviation units to highlight periods of unusually high or low variability.

An unusual and detrimental climate situation between AD 1100–1150

The Chacoan cultural system, located in the San Juan Basin of northwestern New Mexico, reached its apex of achievement and social organization between 1000–1150 (Gumerman and Gell-Mann 1994). Concurrently in southern New Mexico, the Classic Mimbres period occurred between 1000–1150. Strangely (or perhaps not), both the Chacoan and the Classic Mimbres cultures foundered by 1150 (LeBlanc 1989; Dean *et al*. 1985; Gumerman and Gell-Mann 1994). Was climate change a factor in these broad-scale cultural changes?

The reconstruction for the Middle Rio Grande Basin reveals that a multidecadal period of above-average rainfall (inferred using PDSI) occurred between 1043–1131 (Figure 9), remarkably similar to the period of abundant rainfall reconstructed for southern New Mexico between 1040–1120 (Grissino-Mayer *et al*. 1997b). In fact, the sixth wettest multi-year period occurred in the Middle Rio Grande Basin between 1112–1130 (Table 4, average June PDSI = +1.38 for 19 years), while the period 1100–1120 was by far the most extreme multi-year wet period in the Southern Rio Grande area (Grissino-Mayer *et al*. 1997b; average total rainfall per year = 10.97 inches for 21 years compared to the average of 9.34 inches).

These favorable climate conditions would have contributed to improvements in Chacoan and Mimbres agriculture, behavior, social organization, and life styles, and likely facilitate increases in population. For example, changes in farming practices are evident in the archaeological record. The Mimbres took advantage of increased runoff by building checkdams, and, perhaps, irrigation systems (LeBlanc 1989). For the first time, rooms solely dedicated to food storage were constructed, indicating successful farming and an abundance of provisions. Minnis (1985) was one of the first to suggest that the favorable responses and advances made by the Mimbres during this period likely resulted from favorable rainfall patterns, which allowed marginal areas to be utilized for farming. The Anasazi of Chaco Canyon constructed sophisticated irrigation systems that likely took advantage of the increased rainfall and runoff, thus ensuring successful dry-farming agriculture (Gumerman and Gell-Mann 1994). Native American populations increased dramatically between 1040–1100 as construction of new pueblos or within existing pueblos increased or continued without abatement (Dean *et al*. 1994). Mimbres populations increased steadily until *ca*. 1130 (Dean *et al*. 1994).

No one could have foretold the impending changes in climate about to happen. In the Middle Rio Grande Basin, drought began in 1131 and would not abate until the wet year of 1152 (Table 5; Figure 9). During this 21-year period, June PDSI averaged only –1.38 per year. In the Southern Rio Grande Basin, a major 16-year period of drought began slightly earlier and ended earlier (1125–1140; Grissino-Mayer *et al*. 1997b), but was amazingly concurrent with the drought in the northern region. Previous studies have clearly shown that possible deleterious and degrading environmental conditions are likely agents that contribute to large-scale shifts in ancient Native American populations (Dean *et al*. 1985; Gumerman and Gell-Mann 1994; Salzer 2000). There can be little doubt that much of New Mexico witnessed a major drought between ca. 1125–1150 that prompted major changes in human populations, *e.g.*, changes in migration and settlement patterns, agricultural practices, and cultural interaction. We agree with LeBlanc (1989), however, that changes in the environment *allowed* for these changes to occur, rather than directly causing them.

The Native American populations that lived and thrived in New Mexico between 1000–1120 were essentially "set up" by the environment. In summary, four climatic events eventually contributed to or facilitated the collapse of both the Chacoan and Mimbres cultures. First, a long-term period of below-average rainfall occurred between 940–1040 of considerable severity (Figure 10) that may have contributed to keeping population densities low in both the San Juan Basin and Mogollon regions. Second, a period of above-average rainfall followed between 1040–1100 may have contributed to population increases and changes in settlement patterns that reflected greater use of peripheral areas. Food provisions were therefore plentiful. Third, this multi-decadal period of above-average rainfall culminated with one of the wettest multi-year periods in the entire reconstruction for both regions between 1100–1125. Rainfall was abundant year to year. Finally (and quite abruptly), an extended 25-year period of unprecedented below-average rainfall occurred between 1125–1150 for which the Chaco and Mimbres peoples were unprepared. By 1150, both cultures had collapsed.

Effects of the "Great Drought" between ca. AD 1272–1297

Following the devastating drought between 1125–1150, generally wetter conditions prevailed between 1150–1200 for the Middle Rio Grande Basin (Figure 9). In fact, no significant multi-year drought occurred during this 50-year period (Table 5), whereas two extreme multi-year wet periods occurred between 1159–1165 (average June PDSI = 1.55) and 1193–1203 (average June PDSI = 2.09). This latter 11-year period ranks as the seventh wettest multi-year period in the entire 1,371 year reconstruction (Table 4). This climate scenario would not last, however.

The 13th century is reconstructed as the driest century in the last 1,371 years, marked by three severe multi-year droughts: 1213–1221 (average June PDSI per year = –1.57 for 9 years), 1246–1258 (average June PDSI per year = –1.28 for 13 years), and 1272–1297 (average June PDSI per year = –1.30 for 26 years) (Table 5). No other century averaged such severe longer-term drought conditions for its entire duration (Figure 10), although a more severe drought occurred in the late 1500s. Furthermore, the 13th century also experienced the lowest levels of climate variability since the major shift *ca*. 960. Not only was the Middle Rio Grande Basin experiencing very dry conditions during the 1200s, but the variability indicates that drought conditions prevailed year to year, interrupted only by the occasional wet episode (*e.g.*, 1235–1245 and 1259–1265).

Beginning *ca*. 1272, climate changed dramatically. The variance of drought plunged rapidly to very low conditions, indicating that year-to-year rainfall fluctuated very little about the very low annual totals. Between 1272–1297, the Middle Rio Grande Basin of New Mexico experienced a severe drought that also had the longest duration of low variance in the entire reconstruction. This drought, also called the "Great Drought" (Douglass 1931; Baldwin 1935; Jett 1964; Dean *et al*. 1985), was detrimental to Anasazi populations. Prior to 1270, the Anasazi practiced water control for both irrigation farming and domestic use to take advantage of the unpredictable rainfall (Dean *et al.* 1985). Population densities peaked in nearly all areas *ca*. 1250. Climate between 1272–1297, however, was very unfavorable. According to Dean *et al.* (1985), this drought "undoubtedly contributed substantially to the widespread abandonment and population redistributions of the late thirteenth century."

Climate conditions in the Southern Rio Grande Basin were not much better. Grissino-Mayer *et al*. (1997b) found that average annual precipitation between 1272–1296 was only 7.88 inches, compared to 9.34 inches over the entire 1,373 year length of the reconstruction, representing an average 16% reduction in rainfall for each of the 25 years in the drought. This drought was the most severe of any multi-year drought in southern/central New Mexico, suggesting this drought may have been regional in scope and not confined to a specific geographic area. Grissino-Mayer *et al*. (1997b) proposed that these decaying environmental conditions were perhaps too difficult for the Mimbres who could not adjust as rapidly as the environment was changing. This may have set the stage for the cultural disintegration that no doubt followed due to the much-reduced precipitation. Again, the environment may have "set up" the Native American populations in the late 1200s for major shifts in population and cultural patterns that could have contributed to cultural collapse. High population densities and agricultural intensification, coupled with deteriorating hydrologic conditions and below normal rainfall, may have combined to cause depopulation around 1300 of major Anasazi and Mogollon occupation areas (Dean *et al*. 1985; Plog *et al.* 1988; Dean *et al*. 1994). LeBlanc (1989) acknowledged the probable effect of climate change on the southern Mogollon: "Environmental factors may have been involved in some of the changes, for example, favorable rainfall regimes may have resulted in population growth in the A.D. 1000s, or drought in the late 1200s affecting the Casas Grandes collapse."

The North American "Megadrought" of the late 16th Century

The 1500s were enigmatic. The first half of this century was very wet, with extreme multi-year wet episodes occurring between 1507–1515 (average June PDSI = 1.44), 1534–1541 (average June PDSI = 1.41), and 1553–1557 (average June PDSI = 3.60) (Table 4). This latter period represents the most extreme wet period in the entire reconstruction. Although several wet periods occurred that were of longer duration, none matched the intensity of this wet episode. Grissino-Mayer *et al*. (1997b) found a similar climate scenario for the Southern Rio Grande Basin, noting that "the first 50 years of the 1500s saw generally above average rainfall conditions, especially between 1526–1543."

The latter half of the 16th century, however, ushered in what Stahle *et al*. (2000) have called the "megadrought." The intensity, duration, and even the spatial extent of this drought across North America can not be over-emphasized. This drought lasted between 1571–1593 (Table 5) although less severe drought years occurred in years prior to and after this period. The duration (23 years) and average June PDSI for each year (–1.99) make this drought the most severe multi-year drought during the last 1,371 years in the Middle Rio Grande Basin. Interestingly, a drought of similar length (17 years, from 1571–1587) and magnitude (average annual rainfall = 7.60 inches) occurred in the Southern Rio Grande Basin, suggesting that this also was a region-wide climate phenomenon.

Unlike other droughts, however, the 16th century "megadrought" appears to be unparalleled in its spatial extent. Stahle *et al*. (2000) analyzed tree-ring reconstructions of PDSI or precipitation and found that the megadrought was strongly apparent in Durango, Mexico, throughout the Sierra Madre Occidental, extending up through the Rocky Mountains (New Mexico, Arizona, Colorado, Wyoming, and Montana), and into western Canada (Alberta). More importantly, this drought is also apparent from California longitudinally across the United States, into Missouri and the Mississippi Valley region, and along the eastern seaboard into Virginia. Woodhouse and Overpeck (2000) confirmed the existence of this drought in the Great Plains, the Great Basin, and in California. Biondi *et al*. (2000) employed singular spectral analysis on varves extracted from the Santa Barbara Basin off the California Coast and found a dramatic shift in oscillation *ca*. 1600. The difference in timing between the tree-ring and varve records could be due to a delayed shift in the response by reduced vegetative cover that would allow an influx of increased terrigenous materials into the basin (Biondi *et al*. 2000).

The effects on human populations of this drought may have been considerable. In northern New Mexico, widespread abandonment of Anasazi areas occurred after *ca*. 1300. Large settlements, however, in the Mogollon Highlands area, Hopi Mesas, Middle Little Colorado area, Zuni, and Rio Grande areas became established or increased in size, perhaps as a means for local populations to cope with unfavorable environmental conditions. Therefore, native populations had, by the late 1500s, aggregated to central locations with more reliable sources of water, such as the Zuni Pueblo and areas near the Rio Grande (Cordell and Gumerman 1989; Ahlstrom *et al*. 1995), thus lessening the impact by this drought. Nonetheless, this long dry period may have contributed to hardships for both the Native American and Spanish populations at the time, and strained relations between both groups. For example, food stress may have led to events that precipitated the brutal encounter between the Spanish and Acoma Puebloans in 1599 where hundreds of Puebloans were killed by the Spaniards (Forbes 1960; Spicer 1962). Between 1540–1598, several pueblos were permanently abandoned, but "not from causes attributable to the Spaniards" (Shroeder 1968). Rather, food stress is a more likely candidate for abandonment and out-migration. Stahle *et al*. (2000) reported a likely link between drought-mediated pestilence and an epidemic among native Mexicans that killed 12–15 million during the late 1500s (see also Showstack 2001). Swetnam and Brown (1992) suggested the late-1500s drought may be responsible for the proliferance of tree-ring chronologies throughout the Southwest that extend back only to 1600. Furthermore, the megadrought of the late 1500s may have been severe enough to cause major ecotonal shifts in the dominant vegetation types of New Mexico. For example, the precipitation isohyet that demarcates grassland from pinyon-juniper woodland could have shifted upward in elevation, causing expansion of grasslands at the expense of woodland and forest tree species.

The "Wet-Dry-Wet" Trifecta of 17th, 18th, and 19th Century Climate

The return to more favorable climate conditions in the 1600s was nearly as rapid and dramatic as was the decline to the late 1500s drought. In fact, the 17th century claims the greatest number (four) of EMYW periods: 1608–1613 (average June PDSI = 1.25 for 6 years), 1618–1622 (average June PDSI = 1.45 for 5 years), 1627–1653 (average June PDSI = 1.45 for 27 years), and 1688–1693 (average June PDSI = 1.35 for 6 years) (Table 4; Figure 9). The period 1627–1653 actually represents the wettest period in the entire 1,371-year reconstruction, although it was eclipsed in magnitude by the shorter wet episode from 1553–1557. Only one SMYD period occurred during the 1600s between 1664–1674 (average June PDSI = –1.43 for 11 years; Table 5; Figure 9). A similar severe drought was reported for the Southern Rio Grande Basin between 1666–1674 (Grissino-Mayer *et al*. 1997b).

Again, changes in the environment may have prompted significant changes in human populations during the 1600s by providing a false sense of "environmental stability." Crop failures and widespread starvation attributable to the late 1600s drought are well documented (Vivian 1975), and Betancourt *et al*. (1993) further suggested that this drought may have induced the well-known (and surprisingly successful) Pueblo Revolt of 1680 (Knaut 1995). This drought is believed to have prompted the abandonment of Gran Quivira (Betancourt *et al*. 1993), a large pueblo at the foot of Chupadera Mesa in central New Mexico occupied from the 13th to the 17th centuries, and believed to have served as a hub for regional activity. Changes in the ecosystems of New Mexico may have occurred as well. In central and southern New Mexico (where this drought appears to have been more intense), this drought may have caused widespread mortality of conifers that would again explain the difficulty in locating living-tree sites that extend prior to the mid-1600s. More intense, longer-lasting droughts have occurred throughout the 1,371-year reconstruction, but few were preceded by such extreme wet conditions like those that occurred in the first half of the 1600s. Essentially, the floral (and possibly faunal) populations of the Rio Grande Basin in New Mexico were similarly "set up" by a rapid change in climate for a ruinous collapse as were human populations.

In marked contrast to the 1600s, the 1700s were considerably dry. Three SMYD periods occurred: 1727–1740 (average June PDSI = –1.23 for 14 years), 1748–1757 (average June PDSI = –1.37 for 10 years), and 1772–1782 (average June PDSI = –1.83 for 11 years) (Table 5; Figure 9). The latter period ranks as the eighth most severe drought in the last 1,371 years. This century would not experience a wet episode until the period 1790–1797, when June PDSI averaged 1.53 for eight years. This EMYW period, however, ranks only 20th (Table 4). Furthermore, the variability of climate during this century was rather benign (Figure 11), with no 25-year period showing extremes in variance like those found in previous centuries.

Climate during the 1800s was considerably wetter, preceded by the 8-year wet episode between 1790–1797. EMYW periods during the 19th century occurred in three episodes: 1830–1841 (average June PDSI = 1.13 for 12 years), 1845–1858 (average June PDSI = 0.80 for 14 years), and 1866–1869 (average June PDSI = 1.95 for 4 years). Another wet period occurred between 1881–1885 (average June PDSI = 1.06 for 5 years; Figure 9), but did not qualify as an extreme episode. Two noteworthy SMYD periods also occurred during this century, the first between 1818–1826 (average June PDSI = –2.03 for 9 years) and a second between 1889–1896 (average June PDSI = –1.12 for 8 years). The first period was coincident with a period of high variability (Figure 11), suggesting climate fluctuated considerably between severe drought years and extreme wet years, a pattern evident in the tree-ring record between 1816 and 1830 (Grissino-Mayer 1995). The second period beginning in 1889 was coincident with a major, well-documented livestock starvation event throughout the Southwest between 1892–1893 (Allen 1989; Bahre 1991).

Perhaps the most remarkable feature of climate during the 19th century is its variability (Figure 11). Beginning with the 25-year period centered *ca*. 1830, the variance in climate reaches its lowest levels since the late 1200s–early 1300s, extended over much of the 19th century. The shift to low variance was also coincident with a change to wet conditions *ca*. 1830 (Table 4), indicating that climate varied little year-to-year once these wet conditions returned. Two well-documented events are possibly associated with these changing climate conditions. First, the fire regime in the American Southwest appears to have changed significantly in the early 1800s from one marked by patchy and relatively frequent fires to one marked by more widespread, less frequent fires (Grissino-Mayer and Swetnam 2000). Second, the stable climate conditions may have again provided a false sense of "environmental stability" that possibly led to the overstocking of livestock on Southwestern rangelands.

The Turbulent 20th Century

Climate during the 20th century is best described as "volatile," especially in terms of climate variability. The 20th century clearly experienced the most variable climate in the last 1,371 years (Figure 11), with most climate episodes surpassing the +1.1 sd level. In fact, no period during the 20th century fell below the =1.1 sd level, indicating a climate regime for the 20th century that was highly unstable from year to year. This highly variable climate exists in stark contrast to the very stable climate regime that existed during the 19th century, especially between 1830–1890 (Figure 11). Hence, the period that experienced the most stable, long-lasting climate (the late 1800s) was immediately followed by the period with the most unstable climate (the 20th century).

The wet conditions of the 19th century abated with the severe multi-year drought that commenced *ca*. 1889. This drought was soon followed by another well-documented drought between 1899–1904 (average June PDSI = –1.72 for 5 years; Table 5). This drought appears to have been more severe, however, in the central and northern portions of New Mexico (Grissino-Mayer *et al* 1997b). Abruptly, this drought ended and was soon followed by an extended period of very wet conditions between 1907–1921 (average June PDSI = 1.65 for 15 years) which ranks as one of the ten wettest multi-year periods in the last 1,371 years in central New Mexico (Table 4). Following a few years of mild drought between 1922–1925, another EMYW period occurred between 1930–1944 (average June PDSI = 1.30 for 15 years; Table 4; Figure 9). Many of the "dog-hair" thickets of ponderosa pine stems common in New Mexican forests today likely established during these two wet episodes (see Pearson 1923). Globally, a general cooling in temperatures occurred beginning in the 1930s and lasted into the 1940s (IPCC 1990). These cooler temperatures would have lowered soil moisture loss due to evapotranspiration, thus making more water available for uptake by plants. These generally favorable conditions would have enhanced tree growth, widely reflected in the very wide tree rings produced by trees growing in and around the Central Rio Grande Basin in the first half of the 20th century.

These favorable climate conditions between *ca*. 1907–1944 again likely set the stage by creating a false sense of "environmental stability," similar to the changes in human populations and ecosystem dynamics that accompanied the climate scenarios (exceedingly wet followed by exceedingly dry) in the late 1500s, late 1600s, and late 1800s. A severe multi-year drought episode began *ca*. 1945, and did not abate until the early 1960s, ranking this as the third worst SMYD period in the entire 1,371-year reconstruction (Table 5). The average June PDSI per year during this 19-year SMYD period was –1.62. Schulman (1956) observed early on that the "1950s drought" (as it became known) was major in magnitude and perhaps spatially extensive as the effects were clearly felt as far south as southern Arizona and as far north as the Colorado River Basin. In the Southern Rio Grande Basin, Grissino-Mayer *et al*. (1997b) found that precipitation was 28–57% lower during this period when compared to the long-term average, ranking this as the second most SMYD behind the late 1200s drought. The 1950s drought extended into the lower Rio Grande Basin, then into western portions of Texas, until "all but ten of Texas' 254 counties were declared federal drought disaster areas" by 1957 (Jensen 1996). In some portions of the American Southeast, the extremely dry years of 1954 and 1955 are especially well-known, while very narrow tree rings for 1949–1950 are plainly obvious in longleaf pine (*Pinus palustris* Mill.) samples from the Gulf Coast region.

Betancourt *et al*. (1993) observed extensive dieback in the pinyon-juniper woodlands of central New Mexico and elsewhere occurred due to this drought: 90% of pinyons living in 1940 at the Sevilleta Long-Term Ecological Research Station had died by 1956. This drought is particularly significant to studies that analyze the effects of natural (and human) disturbances on ecosystems. For example, the 1950s drought can be used as a "tracer" for tracking the impacts of (and recovery from) a catastrophic drought (Betancourt *et al*. 1993), providing necessary background information for assessing the ability of ecosystems to recover from natural catastrophes that occur only on century time scales. Combined with information from the Southern Rio Grande Basin (Grissino-Mayer *et al*. 1997b), the 1950s drought can be placed in historical and spatial perspective – this drought was as severe and nearly as long lasting of any drought during the past 1,371 years, equaled in its magnitude and duration only by the "Great Drought" between 1272–1296 and the "Megadrought" between 1571–1593.

The reconstruction of precipitation for El Malpais National Monument (Grissino-Mayer 1995), however, ranks this drought 19th in severity and duration, suggesting that the tree-ring chronologies from the Sandia and Magdalena Mountains are the data sets that express this drought most clearly. Several reasons could account for this. First, El Malpais National Monument is located further to the west than the other two chronologies by approximately 112 kilometers. Despite the strong statistical relationship between the three chronologies, the trees at El Malpais may experience a slightly different climate regime than trees at the other two sites, especially in times of severe drought. Dean and Funkhouser (1995) demonstrated using principal components (PCs) analysis how the normal climate systems of unimodal (summer precipitation dominant) and bimodal (summer monsoonal rainfall augmented by winter frontal rainfall) precipitation patterns in New Mexico break down dramatically during severe drought years. El Malpais National Monument exists exactly on the edge of and in-between the zones demarcated by these PCs. Second, the trees at El Malpais grow in a unique substrate material (porous basalt) unlike any other tree-ring site collected in the American Southwest (Grissino-Mayer 1995, 1996; Grissino-Mayer and Swetnam 2000). The substrate material likely makes these trees more responsive to hydrological drought conditions rather than meteorological drought conditions. This hypothesis is supported by the long climatic response of El Malpais trees to water-year rainfall rather than to seasonal rainfall (Grissino-Mayer 1995, 1996). Finally, the trees of El Malpais grow at a much lower elevation (2,280 meters) than the trees growing at both the Sandia Mountains site (3,250 meters) or the Magdalena Mountains site (3,225 meters). Dendrochronologists have well established that trees growing at higher elevations are likely to contain a stronger temperature response than trees growing at lower elevations where precipitation may be the dominant limiting factor on tree growth (see LaMarche 1974; Graumlich 1993; Salzer 2000; Van West and Dean 2000). The temperature response by trees growing at El Malpais may be muted when compared to trees growing at the other two higher elevation sites. Hence, the 1950s drought would not be expressed at El Malpais as well as other sites where temperature plays a greater influence.

The roller-coaster climate ride of the 20th century did not end with the 1950s drought, however. A remarkable switch to very wet conditions occurred in the mid-1970s, ushering in the third wettest extreme multi-year period in the entire 1,371-year reconstruction between 1978–

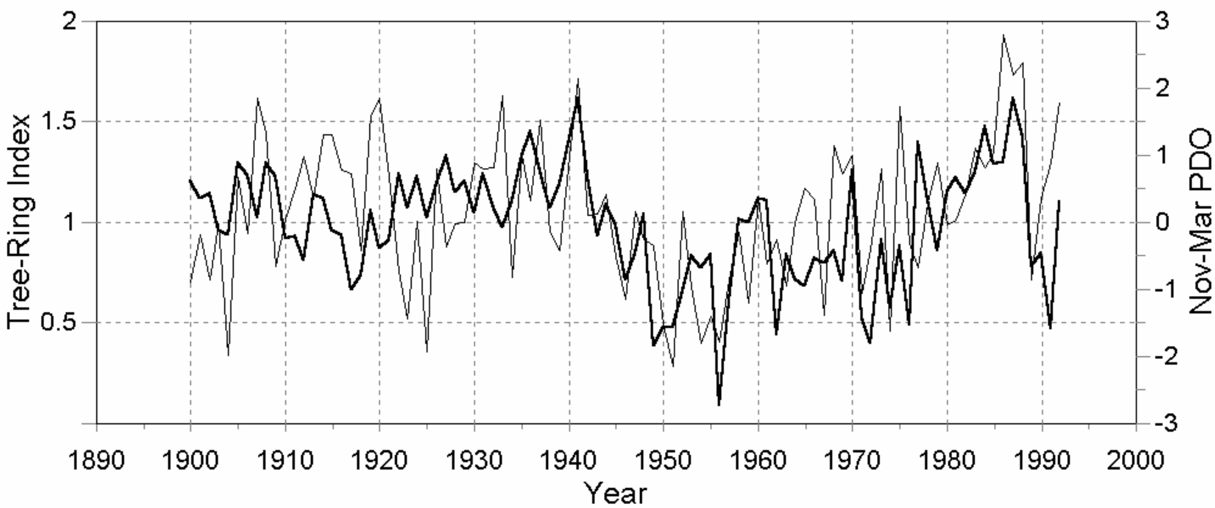

Figure 12. Comparison of Nov–Mar PDO (thin line) and the tree-ring indices developed for this study (bold line). The correlation is 0.36 ($p < 0.001$) between the two series.

1992 (Table 4; Figure 9). The 20th century is therefore unique in having a SMYD period that ranked third in its severity and duration, followed soon by an EMYW period that also ranked third in its severity and duration (Tables 4 and 5). Grissino-Mayer (1995) and Swetnam and Betancourt (1998) document a dramatic change in tree growth rates beginning *ca*. 1976–1977 in many Southwestern tree-ring chronologies. This change in growth rates may have been triggered by increased activity in ocean-atmosphere circulation patterns in the tropical (and possibly extratropical) Pacific Ocean (see Ebbesmeyer *et al*. 1991; Miller *et al*. 1994; Hayward 1997). A change to an increased frequency of El Niño-Southern Oscillation events may have triggered a change in the annual amount and seasonal distribution of precipitation, causing enhanced rainfall in winter and spring months while summer rainfall remained the same or may have been slightly diminished. The increase in annual rainfall may have facilitated an increase in growth rates of Southwestern trees to levels that may be unprecedented for at least the last 1,371 years (Grissino-Mayer 1995) (Figure 10).

New findings, however, may provide insights into possible forcing mechanisms of 20th century climate. Recent research on the temporal properties of northern Pacific Ocean sea surface temperature patterns has revealed an extratropical, longitudinal phase-switching similar to the ENSO phenomenon, except these phases last approximately 15–25 years (Minobe 1999). Termed the Pacific Decadal Oscillation (PDO; see Trenberth and Hurrell 1994; Mantua *et al*. 1997; Zhang *et al*. 1997), this phenomenon exists in either a warm (positive) phase (where northerly flowing warm ocean waters exist off western North America) and a cold (negative) phase (where southerly flowing cold ocean waters exist off the west coast of North America) (Figure 12). Evidence also suggests a possible modulation by the PDO on ENSO activity (Gershunov and Barnett 1989; Smith *et al*. 2001). The temporal stability of PDO has been questioned, however. Knapp *et al*. (2002, in press) analyzed single-year drought events in tree rings of western junipers (*Juniperus occidentalis* Hook.) growing in central Oregon, and found that the influence of the PDO on climate in the Pacific Northwest may have been nonexistent or minimal during the period 1717–1923. Biondi *et al.* (2001) also observed that the variability of the PDO during the 1900s was anomalous compared to reconstructed indices for the three previous centuries.

A time series of the PDO indices clearly shows three major alternations between warm and cold phases: (1) a warm phase between *ca*. 1923 and *ca*. 1948; (2) a cold phase between *ca*. 1949 and *ca*. 1976; and (3) a warm phase between *ca*. 1977 and *ca*. 1998 (Figure 12). The effects of PDO on regional precipitation patterns are much like the effects of ENSO. Enhanced precipitation occurs in the southern tier of the US and northern Mexico during warm phase PDO (ENSO) events, while diminished precipitation occurs during cold phases. In the Pacific Northwest and Great Lakes regions, enhanced precipitation (and snowpack) is associated with cold phase events, while reduced precipitation is associated with warm phase events (Mantua 1999). The warm phase PDO event between 1923 and 1948, when we would expect enhanced rainfall in the Southwest, was contemporary with the above-average rainfall conditions (inferred from PDSI) that occurred between 1930–1944. The cold phase PDO event between 1949–1976, when we would expect lowered rainfall amounts, was contemporary with the 1950s drought between 1945–1963. The warm phase PDO event between 1977 and 1998 was contemporary with a period of enhanced rainfall between 1978–1992.

It is clear that climate patterns in the Middle Rio Grande Basin (and likely throughout the American Southwest) have been modulated to some degree by the extratropical Pacific Decadal Oscillation. If this modulation is real, then a direct relationship should exist between the tree-ring chronology developed for this study and the PDO index over the common period of record 1900–1992. We found a statistically significant correlation coefficient ($r = 0.36$, $p < 0.001$) between the two series (Figure 12). Not only did the two series match in the high frequency, year-to-year variation, but the two series also showed remarkable coherence in the lower-frequency, decadal variation. This relationship strongly corroborates our hypothesis that variability in northern Pacific Ocean sea surface temperatures modulates precipitation patterns in the American Southwest. Furthermore, the PDO index is calculated solely using sea surface temperature information; precipitation values are not used whatsoever. Hence, this relationship suggests additional variability (perhaps up to 10–20%) in tree growth in New Mexico can be explained by a climate variable derived using only temperature. Historical precipitation in the American Southwest traditionally accounts for between 40–60% of the variability in many tree-ring chronologies over the 20th century. Our study suggests a large proportion of the remaining variability could be explained by PDO-driven moisture patterns. Finally, we point out that the relationship between our tree-ring chronology and PDO is notably weak prior to *ca*. 1925 (Figure 12). This also corroborates the findings by Knapp *et al*. (2002, in press) and Biondi *et al*. (2001) that the PDO may have been weakened or non-existent prior to the 20th century.

Future Climate Possibilities for the Middle Rio Grande Basin

The relationship between PDO and drought in the Middle Rio Grande Basin raises another important question: what will climate be like in the coming 20 years or so? Currently in the Middle Rio Grande Basin (as of mid-May 2002), an extreme drought situation is occurring (PDSI between –4.00 and –4.99), causing great alarm concerning the hazard of wildfires.

Furthermore, this situation is expected to continue until at least September 2002, causing "serious drought impacts" over much of New Mexico (Climate Prediction Center 2002). A recent study (Lagerloef and Cummins 2002) has uncovered strong evidence that a major phase shift has occurred in the Pacific Decadal Oscillation *ca.* 1998–1999 based on satellite-derived sea level and wind stress curl anomalies. Some scientists believe this shift may have occurred earlier in 1988–1989 (Yasunaka and Hanawa 2002), a view supported by the dramatic shift to negative values (*i.e.*, a cold phase) *ca*. 1988 (Figure 12). Nonetheless, researchers now strongly believe a cold-phase PDO is in effect (Jet Propulsion Laboratory 2002). If true, then New Mexico (and much of the Southwest) could be in for a 20-year extended period of drought, possibly similar to the 1950s drought, because the cold phase of the PDO results in diminished rainfall for the Southwest (Mantua 1999). Such a drought will have dire consequences for agriculture and water resources, and possibly cause high amounts of stress on the environment from large human populations that have flourished in times of increased precipitation. Reaches of the Rio Grande itself became dry during the drought of the 1950s, and this is a real possibility should an extended PDO-driven drought occur again in the Middle Rio Grande. More importantly, wildfires can be expected to increase in frequency, severity, and spatial extent because of the increased dryness that may be expected should this drought occur. These wildfires, however, will also be driven in part by physical fuel dynamics and fire exclusion practices that have caused unprecedented high levels of fuels in Southwestern forests that are more homogeneous across the landscape (USDA Forest Service 1993; Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000).

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Appendix 1. Actual values for reconstructed June Palmer Drought Severity Index, AD 622–1992.

622	1.00	674	0.63	726	-0.27	778	1.29
623	-0.82	675	1.89	727	0.58	779	-0.57
624	-0.12	676	0.68	728	3.78	780	3.39
625	-1.98	677	-2.93	729	0.35	781	1.27
626	-2.66	678	-1.23	730	4.93	782	-1.27
627	-0.74	679	-0.71	731	3.51	783	-0.53
628	-0.35	680	-1.87	732	5.03	784	2.08
629	-0.73	681	-0.48	733	3.61	785	-0.06
630	-1.29	682	-0.14	734	0.28	786	0.45
631	0.48	683	3.05	735	-1.68	787	3.57
632	-1.13	684	2.19	736	-0.73	788	1.85
633	-0.50	685	-0.89	737	-0.68	789	0.22
634	-2.17	686	-3.09	738	-3.11	790	-0.35
635	0.93	687	-1.25	739	-1.42	791	0.60
636	4.92	688	-1.09	740	0.60	792	2.16
637	0.28	689	1.04	741	-1.73	793	0.74
638	-2.68	690	-2.81	742	-2.47	794	-0.70
639	-2.23	691	-1.17	743	-0.69	795	-2.35
640	-0.42	692	-2.62	744	0.30	796	-1.96
641	0.60	693	-1.83	745	0.18	797	-2.10
642	-0.68	694	-2.81	746	1.08	798	-0.29
643	1.47	695	-1.64	747	-1.66	799	-0.86
644	-0.72	696	-0.48	748	-0.30	800	1.95
645	-4.60	697	0.64	749	0.84	801	2.44
646	-2.78	698	-1.26	750	-0.79	802	2.45
647	-2.31	699	0.92	751	0.13	803	3.16
648	-2.96	700	1.65	752	3.29	804	5.69
649	-0.04	701	-1.90	753	1.48	805	2.13
650	1.29	702	-0.68	754	1.54	806	1.61
651	-0.79	703	-1.32	755	2.79	807	-0.68
652	0.86	704	-1.65	756	1.09	808	1.66
653	-0.20	705	-2.16	757	-1.41	809	-3.22
654	-1.42	706	-2.14	758	0.19	810	0.70
655	-0.02	707	-3.14	759	-1.27	811	-0.39
656	4.66	708	-1.35	760	-2.69	812	-0.43
657	2.14	709	-3.12	761	0.79	813	0.41
658	-1.05	710	-0.99	762	-0.39	814	-1.15
659	-0.16	711	-2.75	763	1.33	815	0.18
660	-2.43	712	-2.22	764	0.60	816	-1.28
661	-2.26	713	0.74	765	1.05	817	-0.17
662	-1.36	714	2.16	766	2.76	818	-2.69
663	-2.86	715	-0.38	767	-0.34	819	-1.04
664	0.20	716	1.61	768	2.18	820	3.16
665	2.35	717	1.66	769	0.90	821	4.57
666	2.13	718	-0.73	770	-2.31	822	1.97
667	0.37	719	5.98	771	-0.62	823	-1.82
668	1.24	720	1.96	772	1.68	824	-1.04
669	-1.23	721	-1.28	773	0.73	825	-3.00
670	0.71	722	0.17	774	-3.28	826	-0.07
671	0.37	723	-1.94	775	-0.83	827	3.85
672	-1.53	724	1.43	776	1.28	828	3.52
673	2.27	725	0.44	777	0.09	829	-3.57

830	0.34	885	-0.82	940	-0.54	995	2.04
831	1.87	886	-0.30	941	0.85	996	0.02
832	0.53	887	1.07	942	0.43	997	0.81
833	1.20	888	-0.69	943	1.08	998	0.22
834	1.41	889	-1.45	944	0.60	999	-2.86
835	-0.15	890	2.07	945	1.36	1000	1.43
836	-1.52	891	-0.01	946	1.06	1001	-1.77
837	-2.67	892	-2.44	947	-1.21	1002	-1.13
838	-0.40	893	2.75	948	-0.61	1003	-1.57
839	-0.06	894	-0.62	949	1.61	1004	-1.48
840	-1.32	895	0.04	950	0.12	1005	-4.24
841	0.29	896	2.25	951	-2.17	1006	-1.20
842	2.09	897	0.74	952	-0.71	1007	-0.08
843	3.83	898	2.58	953	1.97	1008	-1.06
844	1.28	899	2.97	954	-2.61	1009	-3.30
845	1.88	900	-0.98	955	0.28	1010	-2.40
846	-2.00	901	-2.87	956	2.47	1011	-1.66
847	-3.20	902	2.04	957	-1.26	1012	-0.54
848	0.61	903	-0.04	958	-2.14	1013	-0.26
849	-0.10	904	2.04	959	1.15	1014	-3.30
850	-2.30	905	0.99	960	2.63	1015	-0.81
851	-0.64	906	-2.22	961	0.93	1016	0.86
852	0.90	907	-2.64	962	1.34	1017	-0.37
853	0.22	908	1.52	963	2.18	1018	0.11
854	1.63	909	-0.52	964	0.77	1019	-0.19
855	0.20	910	0.49	965	0.06	1020	3.23
856	-0.70	911	0.53	966	3.27	1021	-0.57
857	-2.23	912	0.87	967	3.48	1022	-1.13
858	1.49	913	-1.05	968	0.35	1023	-0.07
859	-0.02	914	-0.79	969	-2.41	1024	1.01
860	0.05	915	0.43	970	1.21	1025	1.34
861	-0.71	916	1.69	971	0.33	1026	1.54
862	0.94	917	2.31	972	-2.37	1027	-2.07
863	1.39	918	1.29	973	1.48	1028	2.08
864	-0.43	919	1.30	974	-1.13	1029	2.58
865	1.71	920	1.58	975	-3.98	1030	0.83
866	1.66	921	-0.98	976	0.47	1031	-1.96
867	-0.41	922	-1.68	977	0.07	1032	-0.66
868	-1.50	923	-1.43	978	-1.01	1033	0.61
869	2.24	924	-2.76	979	-0.06	1034	-0.83
870	-0.65	925	1.42	980	-3.43	1035	-3.55
871	0.16	926	0.13	981	-2.18	1036	-2.67
872	-1.23	927	-2.29	982	-1.02	1037	-1.77
873	-0.57	928	0.28	983	-2.41	1038	-1.77
874	-1.27	929	0.13	984	-2.63	1039	-1.38
875	-0.70	930	-1.30	985	-1.27	1040	0.23
876	3.02	931	-1.32	986	-0.18	1041	-2.57
877	-0.61	932	0.58	987	1.76	1042	0.76
878	-2.80	933	1.87	988	0.99	1043	-0.05
879	-0.64	934	-0.59	989	3.55	1044	-0.77
880	0.32	935	-0.92	990	-0.53	1045	1.03
881	-1.71	936	-0.07	991	-1.36	1046	1.24
882	-2.53	937	-1.43	992	-3.48	1047	-0.19
883	-0.33	938	0.67	993	-1.04	1048	-3.05
884	-3.38	939	0.30	994	-0.28	1049	0.96

1050	2.21	1105	0.78	1160	0.51	1215	-2.59
1051	0.79	1106	0.48	1161	-0.83	1216	-0.83
1052	3.29	1107	0.21	1162	3.01	1217	-4.36
1053	1.82	1108	-0.54	1163	2.09	1218	-1.20
1054	-0.49	1109	1.15	1164	1.34	1219	0.19
1055	1.59	1110	0.09	1165	3.58	1220	-0.06
1056	-0.38	1111	-1.71	1166	-1.77	1221	-1.22
1057	0.52	1112	0.10	1167	0.70	1222	-0.01
1058	-0.73	1113	1.23	1168	-0.48	1223	0.77
1059	0.30	1114	0.83	1169	-3.23	1224	-0.95
1060	2.70	1115	2.06	1170	1.47	1225	-0.54
1061	2.98	1116	3.58	1171	2.07	1226	0.33
1062	0.93	1117	2.96	1172	-1.25	1227	-3.00
1063	1.92	1118	0.74	1173	1.63	1228	0.72
1064	0.04	1119	1.22	1174	-1.18	1229	1.89
1065	3.76	1120	3.52	1175	-1.44	1230	0.38
1066	2.23	1121	-1.78	1176	0.33	1231	1.34
1067	-2.46	1122	3.05	1177	-2.76	1232	0.82
1068	-0.24	1123	1.50	1178	1.16	1233	-0.29
1069	-0.39	1124	2.46	1179	1.43	1234	-0.91
1070	0.95	1125	0.49	1180	1.99	1235	1.22
1071	-0.49	1126	-0.02	1181	0.08	1236	-0.31
1072	3.20	1127	0.29	1182	-0.17	1237	1.57
1073	0.05	1128	0.78	1183	1.17	1238	2.61
1074	0.27	1129	3.04	1184	1.98	1239	1.17
1075	-2.02	1130	0.24	1185	-0.49	1240	-0.91
1076	1.66	1131	-2.45	1186	-2.15	1241	1.57
1077	0.44	1132	-0.84	1187	-0.58	1242	1.51
1078	0.17	1133	-1.64	1188	-0.15	1243	1.03
1079	2.17	1134	-3.93	1189	-0.95	1244	1.02
1080	0.97	1135	-0.49	1190	0.08	1245	0.38
1081	-0.09	1136	-0.54	1191	1.91	1246	-2.20
1082	3.91	1137	-1.80	1192	-2.75	1247	-2.10
1083	-2.15	1138	-3.12	1193	0.93	1248	0.56
1084	1.70	1139	0.24	1194	0.97	1249	1.19
1085	-1.56	1140	-2.10	1195	0.82	1250	-0.67
1086	-0.06	1141	1.09	1196	2.24	1251	-4.48
1087	2.22	1142	-0.21	1197	2.29	1252	-1.31
1088	1.56	1143	-2.13	1198	1.09	1253	0.37
1089	-0.24	1144	-0.43	1199	0.85	1254	-4.89
1090	-3.50	1145	0.91	1200	5.68	1255	1.22
1091	-2.79	1146	-3.33	1201	3.82	1256	-1.73
1092	0.52	1147	-1.15	1202	2.93	1257	-0.54
1093	-1.05	1148	-1.13	1203	1.36	1258	-2.10
1094	-0.08	1149	-1.24	1204	-1.89	1259	1.16
1095	-0.23	1150	-2.90	1205	-0.31	1260	0.86
1096	2.26	1151	-1.74	1206	-0.32	1261	0.06
1097	-2.20	1152	3.01	1207	0.32	1262	2.07
1098	0.35	1153	2.34	1208	-0.30	1263	1.37
1099	-3.44	1154	-0.64	1209	0.81	1264	1.57
1100	0.11	1155	2.91	1210	1.10	1265	0.49
1101	1.45	1156	-1.13	1211	2.76	1266	-0.01
1102	2.10	1157	-2.15	1212	0.25	1267	-0.63
1103	-0.22	1158	-1.75	1213	-0.74	1268	1.75
1104	0.66	1159	1.13	1214	-3.30	1269	-1.08

1270	0.63	1325	2.33	1380	3.63	1435	1.35
1271	0.25	1326	-0.09	1381	-0.34	1436	-0.04
1272	-1.19	1327	-1.28	1382	-2.07	1437	-1.35
1273	-2.36	1328	-0.13	1383	2.17	1438	-2.09
1274	-0.65	1329	-0.59	1384	-0.40	1439	-0.14
1275	1.36	1330	0.82	1385	3.50	1440	1.20
1276	-3.86	1331	3.01	1386	3.83	1441	1.47
1277	-1.59	1332	2.05	1387	0.02	1442	-0.26
1278	-2.19	1333	2.30	1388	2.37	1443	0.95
1279	0.22	1334	0.63	1389	0.22	1444	2.01
1280	-2.30	1335	-1.86	1390	-0.05	1445	-2.63
1281	-1.50	1336	0.27	1391	0.62	1446	-1.02
1282	-1.04	1337	2.21	1392	2.26	1447	1.28
1283	-1.27	1338	-3.19	1393	0.84	1448	-1.74
1284	-1.62	1339	0.59	1394	3.43	1449	-2.45
1285	-1.35	1340	0.28	1395	0.66	1450	-2.17
1286	-1.22	1341	-2.41	1396	2.10	1451	1.41
1287	0.19	1342	-0.34	1397	-1.78	1452	-2.01
1288	-4.13	1343	-1.06	1398	0.68	1453	-0.17
1289	-0.58	1344	0.27	1399	-1.97	1454	0.85
1290	-0.03	1345	0.32	1400	-0.35	1455	-3.07
1291	-2.53	1346	-0.12	1401	-0.20	1456	-0.17
1292	-0.72	1347	-4.62	1402	0.17	1457	-1.86
1293	0.16	1348	-0.34	1403	-0.43	1458	0.82
1294	-0.45	1349	-1.42	1404	1.61	1459	-1.50
1295	-2.31	1350	-2.54	1405	-1.83	1460	0.83
1296	-1.99	1351	-0.85	1406	1.28	1461	-0.84
1297	-0.89	1352	-1.50	1407	-2.96	1462	0.23
1298	1.93	1353	1.79	1408	-0.31	1463	-1.60
1299	0.71	1354	1.47	1409	0.76	1464	-2.48
1300	-0.34	1355	-2.26	1410	0.23	1465	-1.16
1301	0.76	1356	1.49	1411	-2.73	1466	2.03
1302	2.44	1357	-0.31	1412	0.67	1467	0.96
1303	-0.31	1358	2.02	1413	-2.16	1468	-0.29
1304	-0.29	1359	2.01	1414	2.25	1469	-0.12
1305	2.40	1360	-3.12	1415	-2.30	1470	-1.53
1306	0.49	1361	-0.46	1416	-0.86	1471	-4.28
1307	-0.41	1362	-0.99	1417	0.83	1472	0.02
1308	-0.56	1363	-2.48	1418	-0.13	1473	-0.65
1309	1.87	1364	-1.48	1419	-2.14	1474	-1.15
1310	2.72	1365	-1.60	1420	-0.57	1475	-3.30
1311	2.39	1366	0.06	1421	-0.76	1476	-0.65
1312	0.36	1367	-0.89	1422	-1.30	1477	0.41
1313	3.65	1368	1.64	1423	-1.49	1478	0.89
1314	2.00	1369	-2.59	1424	-0.14	1479	-1.22
1315	-1.78	1370	1.92	1425	-0.26	1480	-3.65
1316	-3.06	1371	1.69	1426	2.92	1481	0.55
1317	0.25	1372	0.76	1427	2.29	1482	0.01
1318	0.41	1373	1.99	1428	3.75	1483	-1.56
1319	0.95	1374	1.82	1429	-1.29	1484	2.01
1320	0.61	1375	-1.27	1430	2.52	1485	1.87
1321	1.42	1376	-2.10	1431	-0.40	1486	1.55
1322	0.30	1377	0.83	1432	1.28	1487	-3.12
1323	-0.73	1378	1.38	1433	2.35	1488	-1.48
1324	-1.78	1379	0.76	1434	1.24	1489	-0.54

1490	1.45	1545	-1.05	1600	-1.38	1655	1.90
1491	1.77	1546	-1.58	1601	-3.74	1656	0.38
1492	1.29	1547	-1.26	1602	-0.20	1657	-1.33
1493	-0.87	1548	-0.35	1603	0.37	1658	-0.19
1494	-1.18	1549	-0.45	1604	0.01	1659	-1.54
1495	-3.59	1550	1.79	1605	-0.49	1660	0.73
1496	-1.39	1551	-1.31	1606	-0.91	1661	0.94
1497	-0.85	1552	-0.32	1607	-1.03	1662	0.01
1498	2.87	1553	3.86	1608	0.50	1663	0.00
1499	1.19	1554	2.82	1609	0.50	1664	-1.41
1500	-1.54	1555	5.56	1610	2.18	1665	0.46
1501	-1.64	1556	5.05	1611	1.43	1666	-1.93
1502	-0.77	1557	0.73	1612	2.53	1667	-1.32
1503	-0.97	1558	-1.41	1613	0.35	1668	-3.17
1504	0.08	1559	-0.21	1614	-1.92	1669	-1.37
1505	0.55	1560	-1.86	1615	-0.02	1670	-2.12
1506	-3.15	1561	-1.89	1616	0.18	1671	-0.58
1507	2.74	1562	-1.38	1617	-0.12	1672	-2.09
1508	2.23	1563	-1.83	1618	2.44	1673	-0.92
1509	1.09	1564	0.82	1619	-0.30	1674	-1.25
1510	-0.24	1565	-0.08	1620	2.52	1675	1.15
1511	3.88	1566	-0.69	1621	2.06	1676	-1.18
1512	1.43	1567	-1.32	1622	0.56	1677	0.12
1513	0.79	1568	0.64	1623	-0.42	1678	-1.18
1514	0.29	1569	0.94	1624	-2.81	1679	0.72
1515	0.74	1570	1.33	1625	-2.32	1680	1.50
1516	-2.64	1571	-2.71	1626	-0.59	1681	0.05
1517	-2.85	1572	0.32	1627	2.29	1682	0.88
1518	0.31	1573	-3.00	1628	-1.41	1683	0.18
1519	0.00	1574	-0.69	1629	2.86	1684	-1.78
1520	1.30	1575	-2.03	1630	2.39	1685	-3.68
1521	1.26	1576	-2.68	1631	-0.80	1686	2.31
1522	-2.04	1577	-0.58	1632	-1.04	1687	-0.19
1523	-3.14	1578	-0.78	1633	1.87	1688	0.25
1524	-3.18	1579	-3.81	1634	4.30	1689	2.54
1525	-0.62	1580	-2.04	1635	1.79	1690	0.51
1526	1.54	1581	-2.56	1636	1.72	1691	-1.05
1527	0.21	1582	-1.85	1637	4.97	1692	3.32
1528	-0.91	1583	-4.10	1638	1.08	1693	2.51
1529	1.62	1584	-3.08	1639	2.36	1694	-0.35
1530	1.81	1585	-4.59	1640	3.72	1695	-0.53
1531	0.12	1586	-1.10	1641	1.94	1696	-2.41
1532	-1.50	1587	-1.91	1642	0.30	1697	0.96
1533	-0.32	1588	0.30	1643	0.86	1698	0.05
1534	1.34	1589	-2.20	1644	1.47	1699	2.37
1535	1.77	1590	-2.07	1645	-1.11	1700	-0.62
1536	2.26	1591	0.55	1646	2.37	1701	2.90
1537	2.10	1592	-1.59	1647	0.99	1702	-1.06
1538	-1.73	1593	-3.69	1648	-2.53	1703	1.47
1539	1.83	1594	1.70	1649	2.03	1704	-0.38
1540	3.04	1595	0.51	1650	0.79	1705	-1.37
1541	0.66	1596	0.00	1651	3.06	1706	1.67
1542	-1.80	1597	0.90	1652	1.56	1707	-0.65
1543	0.84	1598	-1.20	1653	1.33	1708	0.70
1544	0.14	1599	-0.78	1654	-1.95	1709	-1.86

1710	3.42	1765	-0.51	1820	-0.69	1875	-1.22
1711	0.01	1766	1.50	1821	0.10	1876	-0.33
1712	0.43	1767	0.96	1822	-3.94	1877	2.69
1713	0.35	1768	0.24	1823	-1.56	1878	-0.74
1714	-0.81	1769	0.66	1824	-2.68	1879	-1.39
1715	-1.87	1770	0.88	1825	-1.36	1880	-3.12
1716	-3.60	1771	2.14	1826	-1.81	1881	0.42
1717	0.64	1772	-0.61	1827	0.21	1882	2.04
1718	0.10	1773	-3.88	1828	0.77	1883	-0.05
1719	-1.79	1774	-1.21	1829	-0.69	1884	1.09
1720	2.17	1775	-1.54	1830	0.29	1885	1.82
1721	1.80	1776	-1.29	1831	1.00	1886	-1.12
1722	2.91	1777	-2.61	1832	0.23	1887	0.26
1723	0.04	1778	-1.11	1833	1.37	1888	1.04
1724	-0.51	1779	-2.17	1834	2.28	1889	-0.70
1725	-0.88	1780	-2.76	1835	1.66	1890	-1.25
1726	2.21	1781	-0.76	1836	-1.41	1891	1.32
1727	-0.27	1782	-2.24	1837	1.29	1892	-2.15
1728	-1.64	1783	2.06	1838	0.87	1893	-2.76
1729	-2.55	1784	1.94	1839	2.36	1894	-1.61
1730	-2.78	1785	0.63	1840	2.78	1895	0.86
1731	0.66	1786	-2.08	1841	0.89	1896	-2.65
1732	-0.99	1787	-0.02	1842	-1.46	1897	1.82
1733	-2.62	1788	-0.24	1843	-0.33	1898	2.89
1734	1.35	1789	-1.29	1844	0.01	1899	-2.39
1735	-1.59	1790	2.00	1845	0.79	1900	-1.81
1736	0.44	1791	0.65	1846	2.68	1901	-0.38
1737	-2.19	1792	1.33	1847	-2.53	1902	-1.72
1738	-0.58	1793	5.21	1848	1.55	1903	-0.05
1739	-3.38	1794	0.98	1849	2.16	1904	-4.01
1740	-1.05	1795	1.16	1850	0.91	1905	1.36
1741	-0.08	1796	-0.03	1851	-2.74	1906	-0.34
1742	-2.20	1797	0.91	1852	2.76	1907	3.74
1743	1.38	1798	-0.33	1853	-0.46	1908	2.67
1744	0.27	1799	-0.22	1854	1.08	1909	-1.32
1745	0.71	1800	0.44	1855	0.90	1910	0.10
1746	1.76	1801	-0.49	1856	1.90	1911	1.01
1747	2.81	1802	1.50	1857	-0.49	1912	1.97
1748	-5.40	1803	0.45	1858	2.71	1913	0.73
1749	1.43	1804	1.43	1859	-1.12	1914	2.65
1750	-2.58	1805	-1.16	1860	1.06	1915	2.66
1751	0.98	1806	-3.12	1861	-1.75	1916	1.59
1752	-2.40	1807	1.03	1862	-1.41	1917	1.46
1753	-1.53	1808	-1.56	1863	-0.83	1918	-0.84
1754	-0.88	1809	-0.80	1864	0.02	1919	3.22
1755	-0.63	1810	0.24	1865	-0.52	1920	3.76
1756	-0.18	1811	0.87	1866	1.86	1921	1.35
1757	-2.53	1812	0.65	1867	1.13	1922	-1.47
1758	1.21	1813	0.89	1868	1.28	1923	-2.91
1759	1.55	1814	0.69	1869	3.52	1924	0.05
1760	-0.73	1815	3.10	1870	-0.23	1925	-3.89
1761	0.35	1816	5.40	1871	-0.63	1926	1.61
1762	1.65	1817	0.97	1872	1.54	1927	-0.72
1763	-1.85	1818	-3.63	1873	-1.64	1928	-0.05
1764	-0.44	1819	-2.68	1874	-0.80	1929	-0.02

1930	1.78	1946	-2.32	1962	-0.52	1978	0.58
1931	1.60	1947	0.34	1963	-1.90	1979	1.78
1932	1.67	1948	-0.52	1964	-0.00	1980	-0.07
1933	3.81	1949	-0.69	1965	1.04	1981	0.06
1934	-1.67	1950	-3.10	1966	0.69	1982	0.82
1935	2.02	1951	-4.35	1967	-2.81	1983	2.25
1936	0.65	1952	0.33	1968	2.30	1984	1.64
1937	3.08	1953	-1.95	1969	1.48	1985	2.10
1938	-0.30	1954	-3.64	1970	2.00	1986	5.68
1939	-0.84	1955	-2.85	1971	-2.14	1987	4.43
1940	1.97	1956	-3.62	1972	-0.82	1988	4.83
1941	4.35	1957	-1.73	1973	1.61	1989	-1.75
1942	0.23	1958	-0.28	1974	-3.27	1990	0.74
1943	0.27	1959	-2.44	1975	3.51	1991	1.78
1944	0.84	1960	0.73	1976	-0.63	1992	3.63
1945	-1.04	1961	-1.24	1977	-1.37		