

**A Multicentury Reconstruction of Precipitation
for Great Sand Dunes National Monument, Southwestern Colorado**

Henri D. Grissino-Mayer

Dept. of Physics, Astronomy & Geosciences
Valdosta State University
Valdosta, GA 31698-0055

and

Christopher H. Baisan

Thomas W. Swetnam

Laboratory of Tree-Ring Research
The University of Arizona
Tucson, AZ 85721

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1.0 Introduction

1.1 Objectives of the research

Our knowledge about past environmental changes in the Four Corners area of the American Southwest comes primarily from tree-ring data, which offer a resolution (annual) unmatched by other chronological dating techniques. In addition, these data can provide information about both high frequency and low frequency trends in past climate (Grissino-Mayer 1995). The study of climate change has been particularly important for developing a better understanding about behavioral attributes and adaptations by local Native American groups, such as the ancient Anasazi (pre-1400) and the Utes, Navajo, and Puebloan groups of more modern periods (post-1500). Archaeologists have long speculated that changes in environmental conditions may have caused or contributed to changes in Native American lifestyles, such as the collapse of the Chacoan system *ca.* AD 1150, the sudden abandonment of many sites in the upper Southwest *ca.* AD 1300, and the hypothesized migration of the inhabitants of Mesa Verde to the Rio Grande basin (Jorde 1977; Dean 1988; Fritts and Dean 1992; Ahlstrom *et al.* 1995). Only recently have large-scale multidisciplinary studies shown that long-term (> 100 years) changes in climate may indeed have precipitated concurrent changes in the behavior of ancient Native Americans (Euler *et al.* 1979; Dean *et al.* 1985; Grissino-Mayer 1995).

The objectives of this study were to:

- (1) collect increment cores from living trees and partial and/or full cross sections from dead and downed low-elevation ponderosa pine and Douglas-fir trees growing within the monument, and from high-elevation limber pine trees growing adjacent to the monument,
- (2) process all samples, then crossdate, measure, and standardize all tree rings to develop a tree-ring chronology local to GSDNM,
- (3) analyze the climate/tree growth relationship and isolate to which climate variables these trees are responding,
- (4) develop a robust, statistically-calibrated climate reconstruction from the master tree-ring chronology, and
- (5) evaluate past multicentury trends in climatic change for the Great Sand Dunes area.

These objectives were possible because the area in and around the sand dunes harbors many species of trees known to be long-lived (Swetnam and Brown 1992; Brown 1996), such as ponderosa pine (*Pinus ponderosa* Douglas ex. C. Lawson), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Colorado pinyon (*Pinus edulis* Engelm.), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.). These species have yielded reconstructions of past climate in other portions of the American Southwest, but never one in southwestern Colorado that exceeded 500 years in length.

The value of tree-ring data collected for GSDNM goes far beyond archaeological applications and interpretations. Tree rings are essentially “nature’s recorder” because any environmental (whether natural or anthropogenic) factor able to affect tree growth is aptly recorded in the growth-ring record. Hence, the collection and use of tree-ring data often assumes a multidisciplinary role not entirely limited to any one application. Once tree-ring data are gathered, analyzed, and properly archived, they can contribute valuable information for future generations of researchers. For Great Sand Dunes National Monument, these tree-ring data should prove invaluable

for better understanding the past and present surface and subsurface hydrologic regime, as tree-ring data have often been used to analyze past streamflow patterns of important Southwestern rivers and their subsurface water supply characteristics (Stockton 1990; Webb *et al.* 1991).

1.2 Previous Tree-Ring Research at Great Sand Dunes National Monument

Great Sand Dunes National Monument (GSDNM) occupies approximately 55 square miles of the San Luis Valley along the western flank of the Sangre de Cristo Mountains. This dune field consists of barchan, climbing, transverse, longitudinal, and parabolic dunes originating from aeolian sand derived from alluvium laid down by the Rio Grande as it emerges from the San Juan Mountains to the west (Johnson 1971). Prevailing southwesterly winds drive the sand from the San Luis Valley to the northeast where the steep Sangre de Cristo Mountains decrease wind speeds, causing sand to be deposited. The dune fields are home to a surprising variety of tree species, such as ponderosa pine, Douglas-fir, and pinyon. In the higher elevations to the east along the flanks and crests of the Sangre de Cristo Mountains, Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.), subalpine fir (*Abies lasiocarpa* Nutt.), and limber pine (*Pinus flexilis* James) occur (Dixon 1971).

Previous tree-ring research was conducted in GSDNM by Mangimelli (1981, 1990), who investigated the past climate of the area using local tree-ring data. This study was limited, however, by the number of samples collected (only 24 cores from 12 trees), and (perhaps) by the species investigated. Although pinyon is generally regarded as a species “sensitive” to climatic conditions (Fritts *et al.* 1965; Betancourt *et al.* 1993), it is also regarded as more difficult to crossdate than the other species present within the monument (ponderosa pine and Douglas-fir). In addition, more information on past climate could perhaps have been gained using at least one other local species, because different species growing in close proximity have been shown to respond differently to climate (Graumlich 1989; Grissino-Mayer and Fritts 1995).

Finally, the length of the tree-ring record could have been extended further into the past by using tree-ring data from dead trees. Mangimelli (1990) reported that dune movement covered and subsequently exposed entire stands of ponderosa pine trees, and that these trees could be dated against the local derived master. The exhumed ponderosa pine trees, however, were not older than the local pinyon. During our field trips to GSDNM in 1990 and 1996, we observed numerous stumps in and around active dunes that appeared much older than living trees in the area. More importantly, we observed dead and/or downed Douglas-fir trees that were short (< 30 feet tall), and shaped like “inverted carrots.” This shape is characteristic of extremely long-lived Douglas-fir trees growing in other locations of the Southwest (Schulman 1937, 1947), such as El Malpais National Monument where living Douglas-fir trees in excess of 1,000 years were found (Grissino-Mayer 1995; Grissino-Mayer *et al.* 1997b) and the Magdalena Mountains of central New Mexico (Grissino-Mayer *et al.* 1997a).

More importantly, remnant pieces of wood, presumably of limber pines, were previously observed at or near treeline on the flanks of the Sangre de Cristo Mountains to the east above the monument. The longevity of this pine species (Swetnam and Brown 1992) indicated that a climate reconstruction in excess of 700 years (and perhaps longer) was possible for the GSDNM area. The numerous wood remnants within and around the monument suggested the possibility of extending the tree-ring chronology derived from living trees back several more hundred years, thereby gaining additional information on past long-term trends in climate.

GSDNM also is home to an impressive number of ponderosa pine trees that have had their bark peeled by Native Americans for various purposes. Tree-ring data have been used previously to obtain exact dates for such peeling events, thus providing archaeologists with important information on site occupancy, possible migration routes, and probable reasons why Native Americans peeled such trees (Swetnam 1984; Hicks 1985; Bergland 1992). Martorano (1990) and Martorano and Beardsley (1993) conducted tree-ring studies on peeled ponderosa pine trees within GSDNM, and concluded that the Ute Native American group was likely responsible for peeling these trees. They further concluded that the peeling events most likely coincided with times of environmental stress, causing the Utes to use the inner bark of pine trees as emergency food during times of starvation. In addition to providing an additional dating control for the peeling events themselves, a reconstruction of precipitation for the local area could be used to test the hypothesis that peeling events coincided with periods of stress to Native American groups. A lack of correspondence between peeling dates and adverse climate would suggest additional and alternative uses for inner bark other than emergency food.

2.0 Field Methods and Collections

2.1 1990 Field Season

In September 1990, increment cores had been obtained from two sites within and adjacent to the monument. Jeanne DeLanois and Henri D. Grissino-Mayer, visiting the monument as part of Ms. DeLanois's master's palynology research into the paleoclimate of the San Luis Valley, collected cores from numerous ponderosa pine trees along the Little Medano Trail, designated as site "MCT." These cores were taken from trees that exist in the same proximity as the Great Sand Dunes (GSD) collection described below, but duplication of specimens taken in the 1996 collection was avoided by carefully examining the site and sample cards. Numerous cores were also collected from limber pine trees up nearby Morris Gulch to the south of the monument, designated as site "MGA," eventually culminating near treeline at approximately 10,500 feet. We took this opportunity to incorporate these extensive collections into the overall project for the reconstruction of precipitation for the GSDNM area.

2.2 1996 Field Season

24 September 1996: We began our field collections on the northern end of the monument in Indian Grove, a stand of large, old-aged ponderosa pine trees, many of which had been peeled. We collected increment cores and small cross-sections from 17 dead and downed ponderosa pine trees, and recorded all relevant information (e.g. specific location, diameter at breast height, crown condition) for each tree sampled. Cores were placed in paper straws to avoid breakage during transport back to the laboratory and appropriately labeled. Cross-sections were wrapped with plastic wrap and labeled to facilitate reassembly back in the laboratory.

25 September 1996: We began our collection near Sawmill Canyon next to the Little Medano Trail (west side). Here, we collected cores from our first Douglas-fir trees, although we were disappointed in not finding more trees of this species. We collected increment cores and cross-sections from numerous ponderosa pine trees, both living and downed logs. After sampling the

“General Smith” tree along the road that traverses through the sand dunes, we hiked westward across the dunes and sampled nine ponderosa pines, culminating about 500 yards from the “General Smith” tree. We returned to the Little Medano Trail and hiked northward until we reached a grove of trees at the base of another canyon. Here, we sampled Douglas-fir trees that looked exceptionally old, taking both cores and cross-sections. In addition, we sampled, for the first time, two dead Rocky Mountain juniper trees. One juniper tree, GSD033, appears to be very old, and may have tree rings that could possibly extend prior to AD 1000.

During these two days, we obtained increment cores and cross-sections from 36 ponderosa pine and Douglas-fir trees, as well as cross-sections from two Rocky Mountain junipers, designated as site “GSD.” Although we did not collect enough material from Douglas-fir trees to develop a master tree-ring chronology from this species outright, we will combine the tree-ring sequences from the pines and Douglas-firs into one master chronology as these two species should have similar responses to the climate of this area.

26 September 1996: We began our sampling at the higher elevations on the western slopes of the Sangre de Cristo mountain range overlooking GSDNM, sampling at the radio towers near Mosca Pass, designated as site “MOS.” At this site, we found living limber pine trees that appeared exceptionally old, exhibiting the growth forms and stunted stature characteristic of long-lived trees. More importantly, we found numerous examples of remnant (i.e., “subfossil”) limber pine wood lying on the ground in a natural state as most of the site surrounding the radio tower had remained minimally altered and disturbed. At this first site, we collected increment cores and cross-sections from 20 limber pine trees, and we were hopeful that tree rings from these samples would extend prior to AD 1400. We sampled a second site near the trail head to the Mosca Pass Trail where more limber pine trees exist that again appeared to be exceptionally old. We obtained numerous cross-sections from dead and downed logs that were in an excellent state of preservation. One limber pine log, designated MOS022, was five feet in diameter with branches larger than most living trees, which we believed could easily extend prior to AD 1300. At this site, we collected tree-ring material from an additional 20 trees, making a total of 40 sampled for the day.

27 September 1996: Based on our observations from the previous day, we again sampled at the upper elevations of Mosca Pass, this time to explore the possibility that long-lived conifers may exist along or near the trail itself as it descends to the monument in the valley below. We sampled an additional 12 trees, obtaining only increment cores on this trip as we had entered the wilderness boundary where chain saw use was not permitted. In general, the trees along the trail did not exhibit the growth characteristics distinguishing them as being particularly old. We did, however, find a few limber pine trees growing in rocky outcrops along the north side of the trail, and these looked quite promising. Further down the trail, we found one limber pine about 30 meters above the trail to the north (designated as sample MOS047) that exhibited an impressive twist in its spiral grain, but unfortunately this sample had decay. Another impressive and quite large living limber pine tree, designated sample MOS052, is growing right alongside the trail and has exposed roots. Again, we hit decay on the inside of this tree and it is unlikely we will be able to age this tree accurately.

This concluded four days of sampling in and around GSDNM. We collected tree-ring material from a total of 90 trees. The majority of these were ponderosa pine trees within the monument itself, and limber pine trees from the upper elevations to the east. The majority of these samples were increment cores, but we also procured several cross-section samples that aided the crossdating process and most likely will extend the living tree chronologies considerably back in

time. In addition, we collected several cross-sections from Rocky Mountain juniper trees and pinyons that had been cut by Park Service personnel during construction near the Headquarters. The four sites collected for this project were: (1) Morris Gulch (MGA), (2) Great Sand Dunes (GSD), (3) Medano Creek Trail (MCT), and (4) Mosca Pass (MOS).

3.0 Laboratory Methods

3.1 Sample Preparation

In the laboratory, all increment cores were glued to wooden core mounts, while the cross-sections were mounted to plywood for stability (if necessary). Once dry, all surfaces were sanded with a 4" X 24" belt sander beginning with a coarse grit size (usually 40 grit) to plane the surface, then we progressed to finer sandpaper until we were eventually using a 320 grit. This technique produced a surface on which the cellular structure of the wood is readily visible under 7–10X magnification.

3.2 Crossdating, Quality Control, and Standardization

Each core and cross-section will be crossdated, assigning each tree ring the exact calendar year in which that ring was formed (Stokes and Smiley 1968; Swetnam *et al.* 1985). To facilitate this process, we used master reference tree-ring chronologies developed previously this century for the northern Rio Grande by A.E. Douglass and Edmund Schulman of the Laboratory of Tree-Ring Research (Schulman 1938). We also used a more recent tree-ring chronology from nearby Wagon Wheel Gap on the other side of the San Luis Valley. All tree-ring widths were then measured on a moving stage micrometer interfaced with a microcomputer running measurement software (Robinson and Evans 1980). We used the computer program COFECHA to ensure the accuracy of both crossdating and measurements (Holmes 1983). All measurements in all individual ring series were then standardized to a mean of 1.0 using program ARSTAN (Cook 1985) by fitting linear or log-linear expressions to each series to produce predicted values of tree growth. This process was intended to remove undesirable growth trends due to normal physiological aging processes, while increasing the desired climatic signal. Indices were generated by averaging by year across all series to produce the final master tree-ring chronology for climate reconstruction (Fritts 1976).

3.3 Climate/Tree Growth Analyses

Before generating the climate reconstruction, we first determined to which climate variables the trees in and around the monument were responding using correlation and response function analyses (Fritts 1976; Grissino-Mayer 1995). We compared the final index chronologies with monthly precipitation and temperature records from individual weather stations in the region (Del Norte, Durango, and Manassa), as well as with regionalized values developed for the Rio Grande Basin area in southern Colorado by the National Climatic Data Center in Asheville, North Carolina. Because trees often allocate carbon and food reserves for use during the following year's growing season (Fritts 1976), all analyses included monthly values lagged by one year to investigate the effects of previous year's climate upon current year's tree growth. Because trees respond to climate

over a period often extending to the previous growing season, various seasonal climate variables were constructed for correlation analyses by averaging or grouping monthly values (Grissino-Mayer 1995).

3.4 Developing the Climate Reconstruction

Once the climate variable for reconstruction had been isolated, we used half-sample subsets of the period 1941–1995 to calibrate the climate records with the index chronologies (Fritts 1976). In this analysis, a calibration equation was generated for the period 1968–1995 that predicted climate from the tree-ring data using least squares analysis and proper regression diagnostics, and compared with the actual climate data for the period 1941–1967. We chose these periods because preliminary analyses of the regional precipitation data with the tree-ring data indicated a noticeable breakdown in the climate/tree growth association in all years prior to 1941. This breakdown likely occurred because of (1) the paucity of high-quality climate data prior to 1940 in the region, or (2) the low number of climate stations that existed in the area prior to 1940. The preliminary analyses showed remarkably low levels of annual rainfall totals in the 1930s which the tree-ring data failed to capture, instead showing average to above-average rainfall levels. Similar low levels of rainfall in the 1940s–1950s were reliably captured by the tree-ring data, suggesting the regional precipitation data for the Rio Grande Basin in southern Colorado may in fact be in error rather than the tree-ring data. This situation warrants additional investigation to resolve because a major drought did indeed occur in the 1930s in the central United States. Furthermore, the tree-ring data indicate that the annual rainfall totals prior to 1930 are all underestimated to some degree. The fact that the tree-ring data and the precipitation data are well-associated after 1940 further indicate that the precipitation data may in fact be unreliable prior to 1941.

After the model had been specified, we used verification statistics (e.g. correlation coefficients, product moment t-tests, and the reduction of error statistic) to verify the fidelity of the calibration equation to predict climate by comparing predicted values with actual values withheld from the original analyses (Fritts 1991; Grissino-Mayer 1995). The verification ensured the stationarity of the climate/tree growth relationship over the entire period 1941–1995 so that the entire period could be used for the final calibration and climate reconstruction.

3.5 Analyzing Changes in Past Climate

Long-term (> 25 years) climate episodes will be classified as above average or below average with respect to the reconstructed mean calculated over the entire period of record. To help quantify the magnitude of past climatic fluctuations, we converted reconstructed values to standard deviation units (z-scores) by first subtracting the series mean and then dividing by the standard deviation of the overall series (Dean 1988; Grissino-Mayer 1995). However, directional changes in climate over both time and space can occur not only in mean climate, but also in the variability of past climate, which can be a more sensitive indicator of environmental change than changes in the mean (Dean 1988; Katz and Brown 1992). Because variance is a measure of dispersion, periods of high variability indicate periods when climate varied greatly about the mean from one year to the next, while periods of low variability indicate periods in which climate fluctuated very little (Grissino-Mayer 1995).

We assessed trends in mean climate by calculating a 10-year spline fit to the reconstruction, and calculated a running variance for overlapping 25-year periods to assess whether significant long-term trends in climate occurred over the length of the precipitation reconstruction. If precipitation has remained unchanged for the length of the reconstruction, no unidirectional changes in either the mean or variance should be observed. If directional changes are observed in either, then we must reject the null hypothesis that climate has remained unchanged.

4.0 Results

4.1 *The Visitor Center Peeled Tree*

In November 1996, the peeled tree in the Visitor Center was successfully dated, along with the peeling event itself. The peeling event is confidently dated to the year 1800, more precisely sometime between October 1799 and April 1800, because the scar was created in the dormant season. This means the peel was made after the growing season of 1799, but before the growing season of 1800. Most likely, the peel event took place in the spring of 1800 as this was the traditional season for peeling by the Utes. Secondly, the outer ring date of the tree is 1985. No sign of trauma is evident during the last few years of tree growth, suggesting its death was rather sudden, perhaps due to a lightning strike, logging, or sudden windthrow. It could have died anytime after October 1985, as no cells were formed whatsoever for 1986.

4.2 *Dating the Morris Gulch (MGA) 1990 Collection*

In September 1990, we collected 42 increment cores from 21 limber pine trees along an elevational gradient up Morris Gulch, culminating approximately at 10,500 feet. Of these 42 cores, 32 were crossdated successfully. This site gave us an indication of the longevity of the trees growing in and around the monument itself. The oldest living limber pine sampled in Morris Gulch has an inside date of AD 1278 (on Core A, while Core B extends to AD 1280) which is very exceptional by dendrochronological standards. This one tree, MGA009, has lived over 700 years during which time it has recorded climate variability through both the Medieval Warm Period and the Little Ice Age. Amazingly, this was *not* the only limber pine tree from the Morris Gulch that extended to the 1200s. Tree MGA013 has an inside date of AD 1290, thus making a total of three cores that extend to the 13th century, already a remarkable achievement. Sample depth to the 14th century is also excellent, strengthened by trees MGA001 (AD 1378) and MGA002 (AD 1336). It is worth pointing out that over half of these living limber pine trees sampled extended before the AD 1650 inside date of the pinyon chronology developed by Mangimelli (1981).

4.3 *Dating the Medano Creek Trail (MCT) 1990 Collection*

Also in September 1990, we collected increment cores from 17 trees along the Little Medano Trail as it winds its way north from the Pinyon Flats Campground. We measured 34 cores from this site, although not all trees were able to be crossdated successfully. Most of the inner rings from these trees date between the period AD 1550 to 1850, hence these are younger trees than those found in Morris Gulch. Nonetheless, the inner date for the oldest tree, MCT008 a Douglas-fir found growing

along the fence line to the wilderness boundary north of the campground, is AD 1387. Like the Morris Gulch site, the MCT trees average approximately 300 years in length, hence long-term centennial-scale trends in past climate should be discernible.

4.4 Dating the Great Sand Dunes (GSD) 1996 Collection

In September 1996, we obtained increment cores and cross-sections from 36 ponderosa pine and Douglas-fir trees, as well as cross-sections from two Rocky Mountain junipers. The oldest tree sampled was a Douglas-fir, GSD030, found near the previous long-lived Douglas-fir collected in 1990 along Little Medano Trail. The inside date for this tree is AD 1260, and marks the oldest tree yet dated within the monument boundary itself. In general, the ponderosa pine trees sampled all have inner ring dates between AD 1600 and 1800. Hence the sample depth prior to 1600 is not as desirable as we would like. However, coupled with cores and sections from the other three sites, the sample depth should be adequate to develop a well-replicated master tree-ring chronology for the Great Sand Dunes area.

4.5. Dating the Mosca Pass (MOS) 1996 Collection

This collection is almost exclusively limber pine trees, although a few ponderosa pines were collected as well. During this collection, we sampled the oldest *living* tree yet discovered around Great Sand Dunes National Monument, a limber pine (designated MOS047), along the trail leading down to the monument, with an inside ring date of AD 1265. More importantly, we sampled cross sections from several dead logs that yielded tree ring dates prior to the oldest samples from the other three sites: (1) MOS004A – AD 1179, (2) MOS009A – AD 1242, (3) MOS012A – AD 1257, (4) MOS020B – AD 1083, and (5) MOS054A – AD 1253. However, one immense log, designated MOS022, yielded the oldest tree ring dates yet attained from the GSDNM area: MOS022A – AD 1035, MOS022B – AD 1040, and MOS022C – AD 1039. These six trees collected from the Mosca Pass site ensured that sample depth would be more than adequate and well replicated to reconstruct precipitation back to AD 1035. This is a remarkable achievement which will strengthen the network of centuries-long tree-ring chronologies for the northern portion of the American Southwest. More importantly, we are hopeful that these trees will reveal century-scale trends in past climate not readily observable in most archeological tree-ring chronologies developed for this area of the western United States.

4.6 Quality Control in Crossdating

Crossdating, which provides precise assignment of yearly dates to annual rings, was accomplished using two techniques. The skeleton plot procedure is the most graphically accurate method. Narrow rings (as well as any anomalous ring features that would aid in crossdating) were plotted on graph paper and compared between cores of the same and different trees, as well as with a master reference chronology developed for a nearby site, such as Mesa Verde National Park. Once crossdated and measured, the ring series were further tested for crossdating accuracy using COFECHA. The veracity of the crossdating accuracy can be assessed in two ways. First, investigators should inspect the number of 50-year segments flagged by COFECHA as being

probable dating errors. The program occasionally suggests alternative dating positions for a 50-year segment that are improbable, a situation that occurs simply because the correlation coefficient calculated for the alternative position can be significant by chance when calculating so many coefficients. Second, the correlation of the individual series with the master used by COFECHA should all be high if crossdating is precise. A low correlation relative to those calculated for the other series would suggest crossdating problems. The mean interseries correlation (the average of all the correlations for all series with the master chronology) also should be very high, generally above 0.50.

For this study, 53,129 individual rings from cores collected at all four sites were crossdated and measured. For the MCT site located within the monument, 359 50-year segments from the measured ring series were tested and only four were flagged (1.1%). The lowest correlation for any individual series with the master series was 0.48 while the highest was 0.93, with the average interseries correlation being a very high 0.80 (34 series). For the GSD site, also located within the monument, only eight of 519 50-year segments were flagged by COFECHA as being problematic (1.5%). The lowest correlation with the master was 0.51 while the highest was 0.84. The mean interseries correlation was again very high at 0.73 (48 series). Series from the Mosca Pass site (MOS) had 15 of 794 segments flagged as being probable errors (1.9%), which is not unusual given the length of these series (the chronology extends back to AD 1035). The lowest correlation by any individual series with the master was 0.44 while the highest was 0.86. The mean interseries correlation was 0.74. Finally, the Morris Gulch site, located to the southeast of the monument, remarkably had only one of 417 50-year segments flagged by COFECHA (0.2%). The lowest and highest correlations with the master were 0.66 and 0.88, respectively, while the overall interseries correlation was again very high at 0.81.

In summary, of 2089 50-year ring series segments tested for this project, only 28 (1.3%) were flagged as being problematic. Inspection of these segments revealed that the crossdating was accurate. Alternative positions suggested by the software were found to be unlikely, while segments flagged without alternative positions were simply problematic because of erratic, short ring sequences that arise due to tree injury or some other environmental factor. Such anomalous ring sequences were retained to provide length and continuity to the individual series, and their effects on the overall chronology were minimized due to the averaging in of many samples without anomalous sequences during these periods.

4.7 Developing the Final Tree-Ring Chronology

Our original objective was to attempt two separate climate reconstructions, one from the low-elevation tree-ring samples collected within GSDNM which extend back to AD 1260 (Figure 1), and another based on the high-elevation tree-ring samples collected near the crest of the Sangre de Cristo Mountains which extend back to AD 1035 (Figure 2). We assessed these two data sets separately by analyzing their relationship and strength with monthly total precipitation, average monthly temperature, and monthly Palmer Drought Severity Indices for NOAA Climate Division Five of Colorado. Not surprisingly, the high-elevation data (Figure 2) set had a much weaker relationship with climate, both monthly and seasonal. The highest correlation coefficients were found with April–June precipitation ($r = 0.45$, $n = 101$, $p < 0.0001$), July PDSI ($r = 0.43$, $n = 101$, $p < 0.0001$), and June–July average temperature ($r = -0.44$, $n = 101$, $p < 0.0001$). None of these correlations

suggested the possibility of a high-quality climate reconstruction using divisional climate data, as these coefficients suggested that only 20% of the variance in climate data could initially be explained by the upper-elevation tree-ring data. However, this situation is not unique as nearly all high-elevation tree-ring data sets used in dendroclimatic reconstructions are limited by the use of climate data collected at low-elevation stations.

Examination of the low-elevation tree-ring data (Figure 1) and the divisional climate data revealed much stronger relationships, as expected. The samples collected within the monument had very high correlations with monthly precipitation totals from the previous August to the current year's June precipitation, with eight monthly values being significant at the 0.05 level. The strongest relationship was found by seasonalizing the precipitation data from previous August to current July ($r = 63$, $n = 100$, $p < 0.001$). Unfortunately, the low-elevation tree-ring data had adequate sample depth only back to AD 1600, with only a few Douglas-fir series extending back to the 1200s. We were therefore faced with the following dilemma: we had a long tree-ring data set from the upper-elevation site with which to reconstruct climate, but which had a poor climate signal. We also had a low-elevation tree-ring data set with a strong climate signal but which was short in length. It seemed reasonable to us, then, to combine the tree-ring data from both the high and low elevation sites into one tree-ring chronology, with the following caveat. Because the early part of the combined tree-ring chronology would be primarily composed of samples from high-elevation limber pine which had a weaker climate signal, the period prior to AD 1600 would be a tentative reconstruction of precipitation pending further sampling from the low-elevation sites to increase the sample depth. Future sampling should therefore concentrate on collecting material from within the monument itself, especially focusing on Douglas-fir trees, to build a longer chronology which will have a stronger climate signal for reconstructing precipitation on a millennium time scale.

4.8 Analyzing the Climate/Tree Growth Relationship

We inspected all climate data sets from nearby weather stations for reconstruction purposes, and concluded that the divisional precipitation data set for the Rio Grande Basin in southern Colorado (NOAA Climate Division 5) was most appropriate. Data from individual nearby weather stations often contained incomplete data in recent periods, or were too short to be useful for this project. We found statistically significant correlations between our final GSDNM tree-ring chronology with monthly total precipitation (Figure 3) from the previous year's August value (0.21 , $p < 0.05$) to the current year's June value (0.38 , $p < 0.0001$). Based on these correlations, the variable chosen for reconstruction was annual precipitation spanning the period from previous August to the current July, often called a "water year" by hydrologists. It must be remembered that this period is the most logical based on physiological mechanisms of trees which fix carbon for growth in later months using available water from the previous calendar year. This hydrologic "water year" has also been reconstructed from tree-ring data for other portions of the Southwest, including El Malpais National Monument (Grissino-Mayer 1995, 1996) and Arroyo Hondo near Santa Fe, New Mexico (Rose *et al.* 1981). The correlation between water year total precipitation and the GSDNM tree-ring chronology over the period 1896–1995 was highly significant ($r = 0.61$, $n = 100$, $p < 0.0001$).

4.9 Calibration and Verification for Climate Reconstruction

The precipitation and tree-ring data were calibrated first over the period 1968–1995. The final equation took the following form (F-value = 48.112, $p < 0.0001$, $n = 23$):

$$\text{PPT}_t = (14.327I_t) - 1.475 + e_t$$

where PPT_t represents the predicted water year rainfall for year t , I_t represents the tree-ring index for year t , and e_t represents the error term used in all regression equations. This equation showed that the tree-ring data could account for 69% of the variability in the climate data over the period 1968–1995 after removal of four outlier observations (1969, 1970, 1979, and 1988). The effects of outlier observations on tree-ring based regression equations were emphasized by the amount of model variance increased by exclusion of these four observations. The adjusted r-squared dramatically increased from 0.34 to 0.69, *i.e.*, inclusion of these four years would have reduced the model variance 35%.

To ensure the ability of the calibration equation to accurately predict climate from the tree-ring data, the actual climate data for the period 1941–1967 were compared to the predicted climate data using verification statistics commonly used in dendroclimatic reconstructions. All verification statistics were significant at the 0.05 level (Table 1), suggesting the calibration equation above could predict annual precipitation with reasonable accuracy. The calibration model was then re-specified over the entire period 1941–1995, and took the following form (F-value = 122.107, $p < 0.0001$, $n = 51$):

$$\text{PPT}_t = (10.922I_t) + 1.996 + e_t$$

In this model, only three outlier observations were identified as adversely affecting the regression: the years 1965, 1970, and 1979. After removal of these three observations from the calibration equation, the tree-ring data captured 70% of the variance found in the water-year precipitation totals over the period 1941–1995. Comparison of actual versus predicted precipitation totals confirms that the tree-ring data were able to capture both high-frequency variability (*i.e.*, year to year) as well as low-frequency variability (*i.e.*, decadal) (Figure 4).

5.0 Discussion

The regression equation above was then used to predict water-year total precipitation for the full length of the master chronology back to AD 1035. Values of reconstructed annual rainfall in the early portion of the record, *i.e.* prior to *ca.* 1215, are not as reliable as later values due to the low sample depth (five series) between AD 1035 and 1240. To reduce the effects of low sample depth on reconstructed values, the variance of the series between AD 1035 to 1233 was stabilized to equal the variance of the latter portion. This was accomplished by first subtracting the mean of the period from the individual values, then multiplying the result by a ratio equal to (pre-1233 standard deviation/post-1233 standard deviation) before adding the mean back to the series (Cook *et al.* 1988; Grissino-Mayer *et al.* 1989). However, any inferences made concerning long-term trends through this period should be interpreted cautiously. Appendix 1 contains a full listing of the annual precipitation values calculated from the master tree-ring chronology developed for this study.

The reconstruction (Figure 5) clearly shows several apparent trends about the mean value of 12.92 inches, which become more apparent when a 10-year spline is fit through the reconstruction and standardized to a mean of zero and standard deviation of one (Figure 6). The longest and most

intense drought during the reconstruction occurred between AD 1570–1600, a dry period also reconstructed for northwestern New Mexico (Rose *et al.* 1981; D'Arrigo and Jacoby 1991; Grissino-Mayer 1995, 1996) and central/southern New Mexico (Grissino-Mayer *et al.* 1997a). The “Great Drought” of the Colorado Plateau (Douglass 1929; Baldwin 1935; Dean *et al.* 1985; Ahlstrom *et al.* 1995) and south-central New Mexico (Grissino-Mayer *et al.* 1997a), which occurred between AD 1273–1299, appears *not* to have been a period of major drought in this region. This finding places an eastern limit on the probable extent of this drought in the American Southwest.

A major feature of the precipitation reconstruction is the striking change in decadal variability that occurred *ca.* 1400. Prior to 1400, the variability was high, indicating rapid fluctuations between decadal periods of above and below average rainfall (Figure 6). An examination of the running variance for overlapping 25 year periods (Figure 7) also reveals a major change in precipitation *ca.* AD 1400 when variance dropped below the zero level and stayed that way for 200 years, until the early 1600s. The period from AD 1400–1570 was therefore one of fairly stable precipitation, with few extreme fluctuations about the mean, as shown in the reconstructed values themselves (Figure 5). The one exception was the very wet year for 1521, with nearly 21 inches of rainfall, followed by 1522, when only 9.7 inches of rainfall fell. This period of relative stability in rainfall terminated with the major drought between AD 1570–1600. Because numerous limber pine samples from the upper elevation site, as well as several continuous Douglas-fir samples from the low-elevation site, extend continuously through AD 1400, we can rule out that this change may be species or sample size related. Hence, the change in variance *ca.* 1400 is likely related to a change in precipitation patterns. The timing of this change is also coincident with changes in long-term century-scale precipitation noted elsewhere in the American Southwest (Grissino-Mayer 1995, 1996; Grissino-Mayer *et al.* 1997b), and bears a remarkable resemblance to the change in variance observed near AD 1400 reconstructed for southern/central New Mexico (Grissino-Mayer *et al.* 1997a).

Another major change in precipitation variability occurred beginning with this major drought in the late 1500s. Decadal-length precipitation patterns became more oscillatory (Figure 6), perhaps indicating a phase change in precipitation patterns, from one of low periodicity to strong periodicity. Spectral analysis of the reconstruction after 1570 indicates a strong periodicity with cycles evident at 40–50 year wavelengths (Figure 8), a periodicity not observed in the pre-1570 period. Inspection of the high and low elevation tree-ring chronologies (Figures 1 and 2) indicated no obvious phase change in the high-elevation limber pine samples, while the phase change does appear in the low-elevation samples beginning in the early 1600s. However, ponderosa pine samples dominate the low-elevation site back to the 1600s, with only a few Douglas-fir samples extending prior to AD 1600. Therefore, we should question whether the phase change observed in the reconstruction of precipitation is due to the species included in the final tree-ring chronology rather than being due to a distinct phase change in rainfall patterns. Construction of a millennium-length tree-ring chronology exclusively of Douglas-fir from the climate-sensitive low-elevation site within the monument would clarify whether such a phase change did occur in precipitation patterns beginning *ca.* AD 1600.

Another noteworthy feature of the precipitation reconstruction is the declining variability over the past 1000 years (Figure 7). This decreasing variance suggests that overall precipitation patterns have become more stable from year to year and from decade to decade since AD 1035, with a declining number of extreme fluctuations as those observed early in the record. This decreasing

variability is not likely an artifact due to species, sample size, or the ages of trees used in construction of the master chronology, because such declining variance was also observed in other millennium-length tree-ring data sets for the Southwest, such as El Malpais National Monument (Grissino-Mayer 1995) and the Pinaleño Mountains of southeastern Arizona (Grissino-Mayer, *unpublished data*). The lowest amount of variability occurred in the late 1800s, similar to findings from previous studies, suggesting that year-to-year rainfall during this period was very stable, and perhaps contributed to the success of the Southwestern livestock industry at the time (Love 1916; Denevan 1967; Allen 1989; Bahre 1991).

The period of low variability abruptly terminated when a very wet period signaled a return to wide decadal fluctuations at the beginning of the 20th century (Figure 6). This wet episode lasted until approximately 1930, and is similar to early 20th century wet periods reconstructed at other sites in the Southwest, clearly a regional phenomenon. Beginning in 1931, the climate record shows a very dry period began that lasted until 1941, a drought not captured by the trees at Great Sand Dunes National Monument, as previously discussed. Beginning in 1949, however, the climate record and the trees at GSDNM clearly show a major decadal drought began that did not subside until approximately 1965. This drought, termed the “50s drought,” is ubiquitous in the American Southwest (Betancourt *et al.* 1993; Grissino-Mayer 1995, 1996; Grissino-Mayer *et al.* 1997a), and may have been strongest in the central and southern portions of the Southwest (Grissino-Mayer *et al.* 1997a). At GSDNM in southern Colorado, this drought ranks as one of the worst droughts within the last 1000 years in terms of both severity and duration (Figure 6), and places northern and eastern limits on the extent of this drought.

After the 1950s drought, a period of above average rainfall began, culminating in one of the wettest 15-year periods during the last 1000 years for this part of Colorado. The tree-ring record indicates that rainfall averaged 14.02 inches in the period between 1981 and 1995 (this value is much lower than the actual value of 18.56 inches that fell per year between 1981–1995, but still higher than the 12.92 inches averaged per year since AD 1035). Other reconstructions in the Southwest also suggest a period of unprecedented rainfall during the last 15–20 years (Grissino-Mayer 1995; T.W. Swetnam and J.L. Betancourt, *personal communication*), although the climatic mechanisms responsible for this increased rainfall are unknown. A dramatic change in ocean-atmosphere circulation in the western Pacific Ocean in 1976–1977 (Ebbesmeyer *et al.* 1991; Miller *et al.* 1994; Hayward 1997) is believed to have caused changes in the frequency and intensity of El Niño-Southern Oscillation events, which may have caused changes in precipitation frequency in the American Southwest.

6.0 Conclusions and Recommendations

The tree-ring samples collected in and around Great Sand Dunes National Monument yielded two tree-ring chronologies, one at lower elevations within the monument itself, and another at high-elevation in the nearby Sangre de Cristo Mountains to the east. The high elevation site, composed exclusively of limber pine samples, yielded material back to AD 1035, and shows great promise of eventually leading to development of a 1000–1500 year long tree-ring chronology. However, the climate response by this species is weaker than that found in material at lower elevations, perhaps because the climate data used to analyze the tree-ring data were all collected from low-elevation stations. The low-elevation tree-ring samples, composed primarily of material collected from

ponderosa pine trees, showed a very strong relationship to water-year annual rainfall from the previous year's August to the current year's July. This water-year variable was chosen for reconstruction purposes, and the reconstruction itself provided new insights on past rainfall patterns for this portion of southern Colorado. For example, a major phase change in precipitation variability was observed around *ca.* AD 1400, concurrent with major changes in precipitation observed elsewhere in the Southwest.

Recommendation #1: *A systematic and long-term effort should be exerted by researchers and National Park Service personnel to collect and preserve these Douglas-fir tree-ring samples before they are lost due to wildfires, fuelwood collection, and normal physiological decay.* We strongly believe that the Douglas-fir trees found within and around the monument at lower elevations hold the key to developing a high-quality millennium-length reconstruction of precipitation, and future collections should specifically target this species. Numerous downed Douglas-fir logs and remnant pieces of wood were observed within the monument at the interface with the basal slopes of the mountains to the east, and in the nearby wilderness area adjacent to the monument. The few Douglas-fir tree-ring samples collected for this study extended back continuously to the 1200s, remarkable for this low-elevation area composed predominantly of ponderosa pine trees.

Recommendation #2: *We believe a systematic and long-term project should be initiated in which the peeling dates of the numerous ponderosa pine trees are dendrochronologically determined in a non-destructive manner, utilizing both GIS (Geographic Information Systems) and GPS (Global Positioning Systems) technology to accurately map the locations of the peeled trees themselves.* Additional research should also be conducted on the numerous peeled ponderosa pine trees found throughout the monument and in the nearby mountain range to the east. The few peeling events analyzed to date provided some insights into the occupational history of the area by the local Ute Native American tribe, as well as information on probable uses of the inner bark of these pine trees. Additional questions could be answered by an in-depth and extensive analysis of these peeling events. For example, were these peeling events contemporaneous with major drought episodes? Does a spatio-temporal pattern exist in the peeling events themselves, thereby providing additional information on the occupational history of the San Luis Valley, and on the migration patterns of the local Indian peoples? Was ponderosa pine the preferred species because of its abundance, or were other species, such as limber pine at higher elevations, utilized? We encourage the National Park Service to consider funding such a valuable and timely study.

Recommendation #3: *The initiation and temporal sequences on the development of adventitious root systems can be dendrochronologically dated, and can therefore provide information on the timing of dune movement. Furthermore, the cessation of adventitious root development in these trees would place a terminal date on dune stabilization.* Great Sand Dunes National Monument further provides a unique environment that could lead to potential research not possible anywhere else in the United States. The sand dunes provide information on wind direction and intensity, erosion rates, dune development, and sand dune encroachment and migration. The sand dunes themselves could easily provide information on the resistance of ponderosa pine and Douglas-fir trees to dune encroachment and eventual overtopping and covering by the dunes. For

example, in several locations within the monument, sand dunes have stabilized around both ponderosa pine and Douglas-fir trees which subsequently sprouted adventitious roots, root systems emerging from higher up on the trunks of the trees that develop to ensure an adequate water supply for the tree under these new hydrologic conditions (Filion and Marin 1988; Bégin *et al.* 1991; Strunk 1997). The significance of these adventitious roots can not be over-emphasized. By analyzing the timing of the initiation of these root systems, we could perhaps determine whether dune stabilization was concurrent with major changes in past climate as revealed in the precipitation reconstruction, or whether stabilization is more related to geomorphic phenomena and topographic barriers.

Recommendation #4: *The Rocky Mountain juniper trees (*Juniperus scopulorum* Sarg.) found throughout the monument are perhaps the longest-lived of all tree species in the immediate area, and are likely to yield a tree-ring chronology in excess of 1,500 years, and quite possibly 2,000 years in length. Future collections should target select specimens of living and remnant junipers.* Tree-ring sequences from this species from living-tree samples collected near the Park Service headquarters during building construction indicated the ring patterns can be crossdated against the local master chronologies, with one juniper tree dating back to approximately AD 1600. In the vicinity of the Douglas-fir trees near the wilderness boundary, we located dead, standing juniper trees with a gnarled, stunted appearance indicative of great age in trees. We were not successful in dating these remnant juniper samples against the master chronology which currently extends to AD 1035, suggesting tree-ring samples from these trees extend prior to AD 1000. Successful dating of Rocky Mountain junipers was accomplished at El Malpais National Monument (Grissino-Mayer *et al.* 1997b), with many remnant logs having continuous tree-ring sequences in excess of 1,500 years. While not as abundant as they are at El Malpais, the junipers within GSDNM could quite easily yield tree-ring dates in excess of 1,500 years, and provide a low-elevation, climate-sensitive species with which to reconstruct past rainfall, perhaps providing intra-annual information on past precipitation to supplement the annual water-year rainfall possible from the Douglas-fir trees.

Recommendation #5: *The exhumed “ghost forests” of ponderosa pine trees within the monument should be carefully and non-destructively investigated to determine the dates these forests were over-run by the sand dunes. Information from the tree-ring record would provide dates of tree mortality, thus providing initiation dates of dune encroachment, and could potentially extend the living-tree ponderosa pine chronology.* Ponderosa pine trees at low-elevations within the monument are prone to encroachment and overtopping by shifting sand dunes, thus killing the trees. This results in “ghost forests,” entire intact stands of pine trees exhumed by the removal of sand by blowing winds. Occasionally, only the very tops of these pine trees are evident. These “ghost trees” could potentially provide a means for extending the living-tree ponderosa pine tree-ring chronology from the low-elevation areas, a species already shown to be superior in regards to climate sensitivity when compared to the high-elevation tree species. Increment cores were successfully extracted from two of these exhumed trees, proving that these trees could be non-destructively sampled (*i.e.*, cross sections would not have to be obtained using a chain saw). The cores from these trees were intact, much like cores taken from the peeled ponderosa pine trees, which suggest this “ghost forest” (located near the Medano Creek Trail) may not be exceedingly old. Nonetheless, even if the “ghost forest” was over-run by sand dunes a few hundred years ago, tree-

ring dates should still be older than any thus far obtained from the living tree samples.

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Table 1. Summary of verification statistics used to assess the fidelity of the calibration equation to predict climate from tree-ring data.

Reduction of error	≥ 0.101	0.171
T-value	≥ 1.710	2.710
Sign-products	≥ 9	9
Negative first differences	≤ 8	6

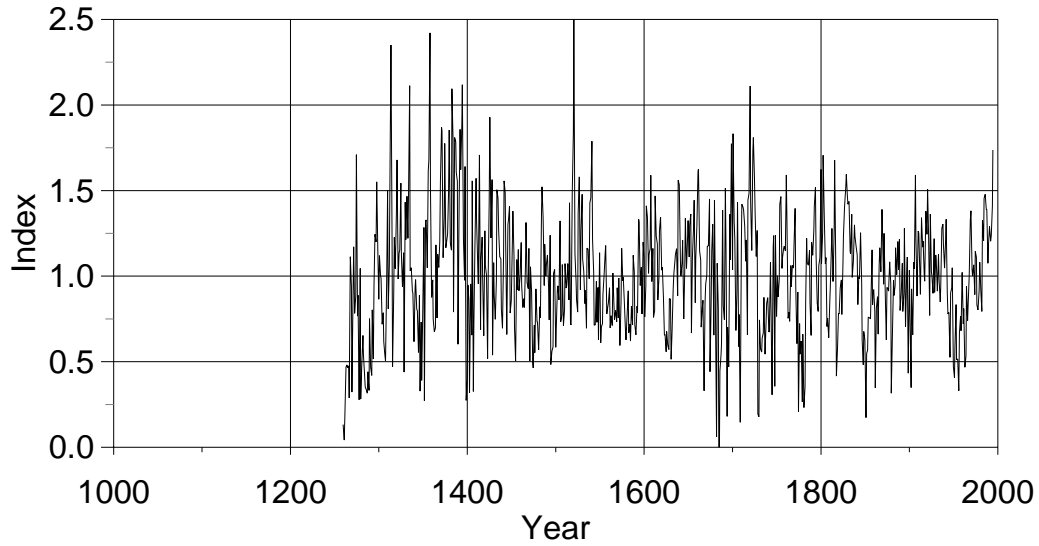


Figure 1. The tree-ring chronology developed from samples collected at the lower elevation sites within the monument itself, composed primarily of ponderosa pine samples. A distinct phase change in oscillation is observed beginning in the early 1600s when the tree-ring series switch between a period of low variability to one of high variability.

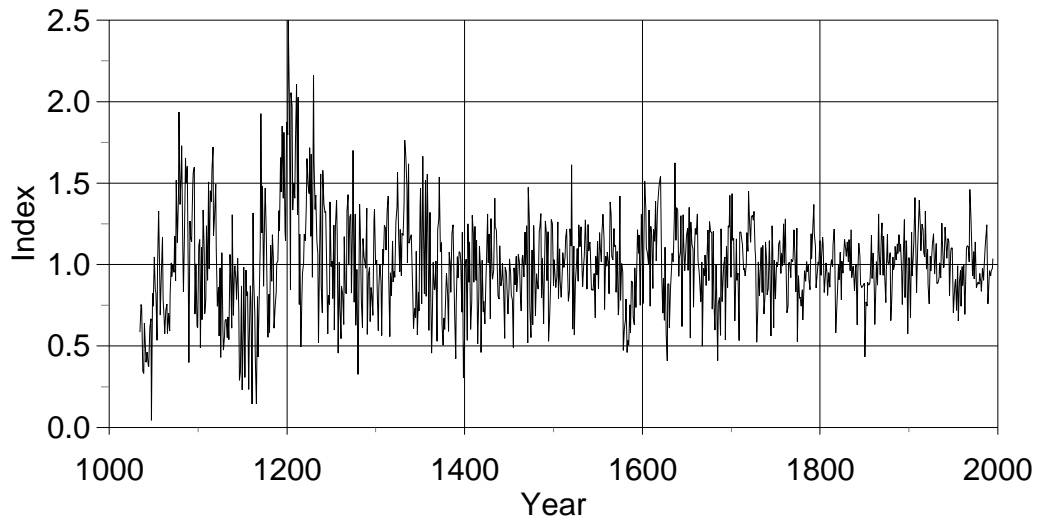


Figure 2. The tree-ring chronology developed for the high elevation site in the Sangre de Cristo Mountains to the east of the monument, composed exclusively of limber pine samples. The late 1500s drought is much more obvious in this data set than in the low elevation samples.

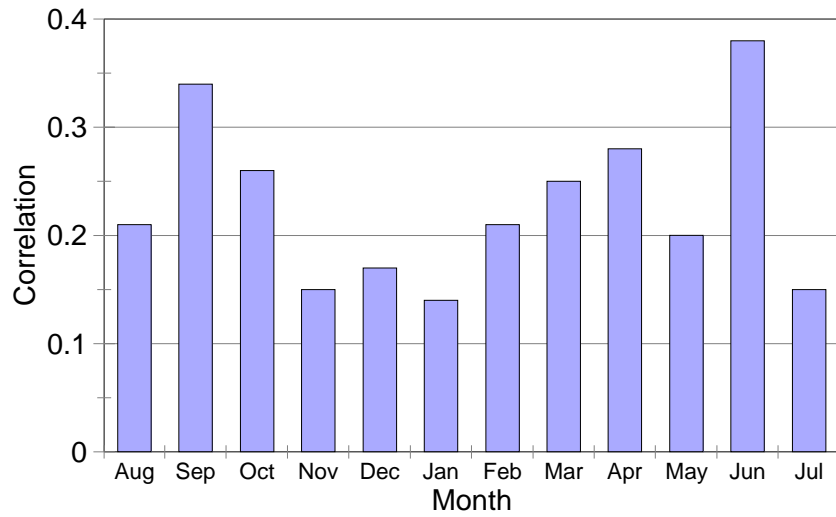


Figure 3. Correlation coefficients between monthly total precipitation and the final GSDNM master tree-ring chronology from previous August to current July. Any coefficient at or above 0.20 is significant at the 0.05 level.

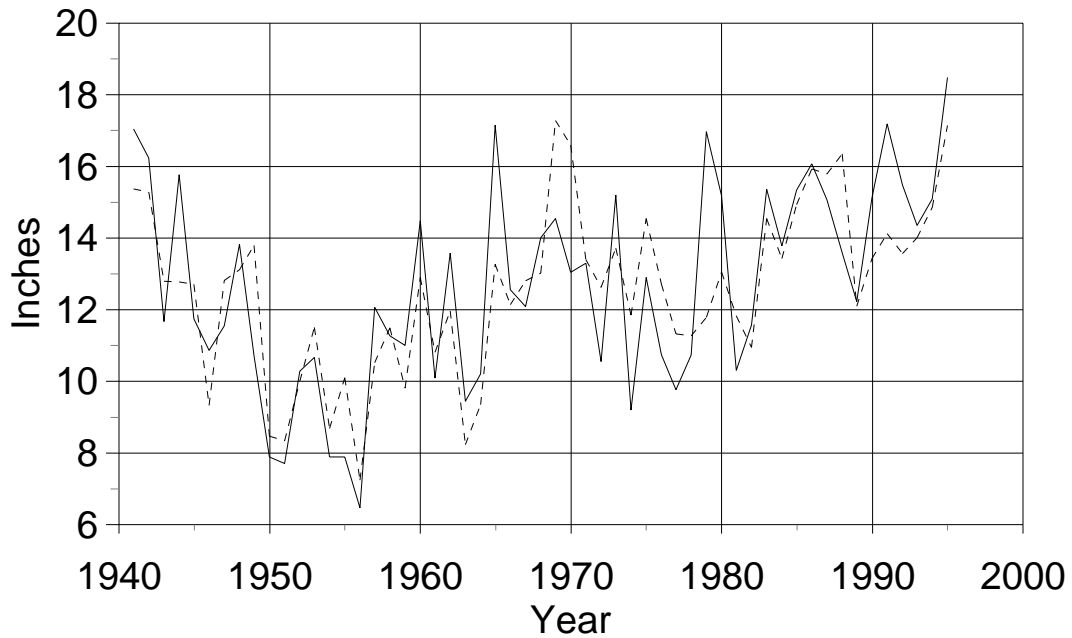


Figure 4. Comparison of actual annual precipitation values (dark solid line) to those predicted from the calibration equation (dashed line) calculated over the period 1941–1995.

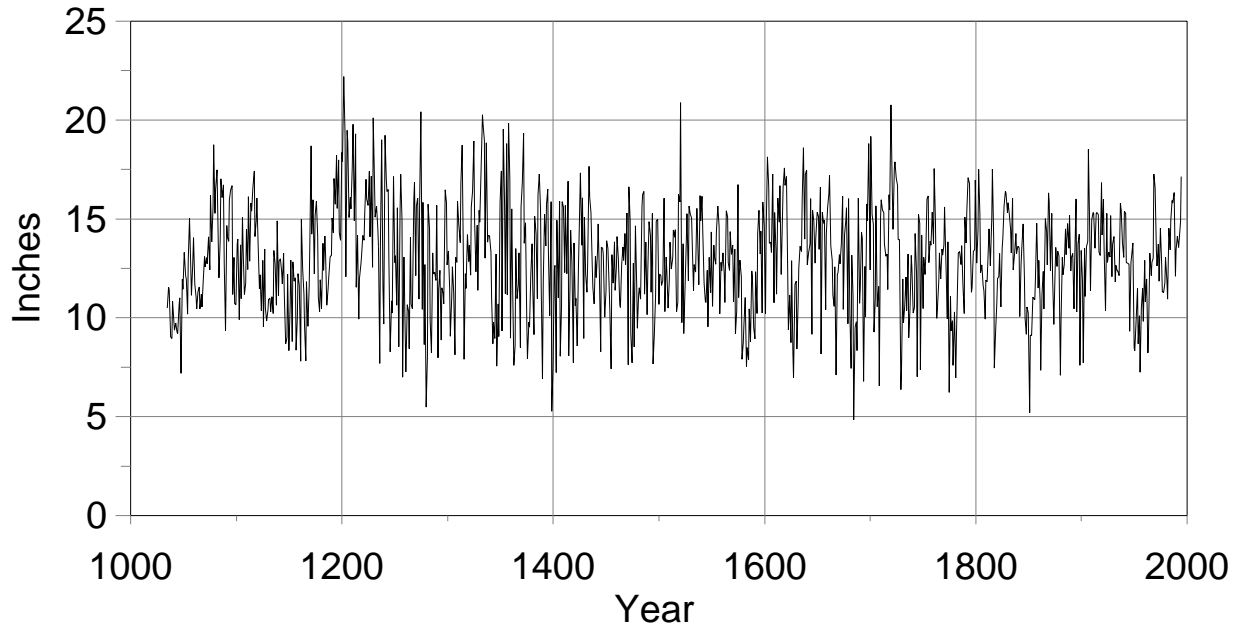


Figure 5. Reconstruction of annual water-year (previous August to current July) precipitation for the Great Sand Dunes area, southern Colorado. The variance between 1035–1233 was stabilized to equal the 1234–1995 variance to minimize effects of a low sample size on the final reconstruction.

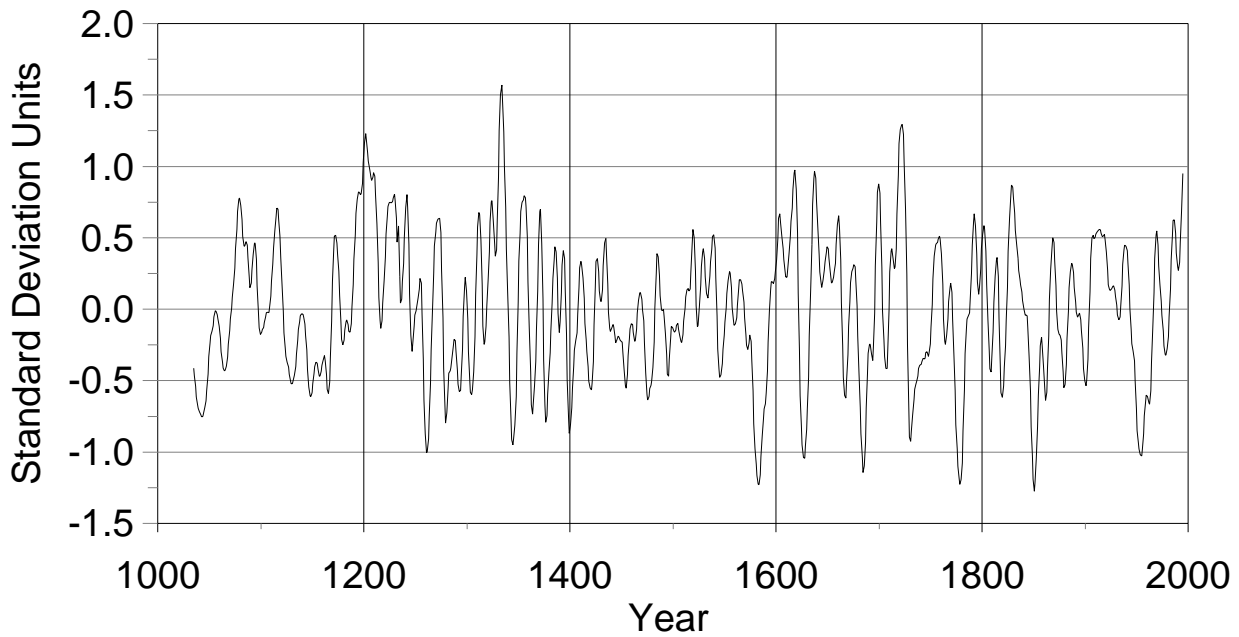


Figure 6. The precipitation reconstruction for Great Sand Dunes National Monument, depicted as a 10-year cubic spline to accentuate decadal scale trends in past rainfall. The data have been standardized to a mean of zero and standard deviation of one. The variance between 1035–1233 was stabilized to equal the 1234–1995 variance to minimize effects of a low sample size on the final reconstruction.

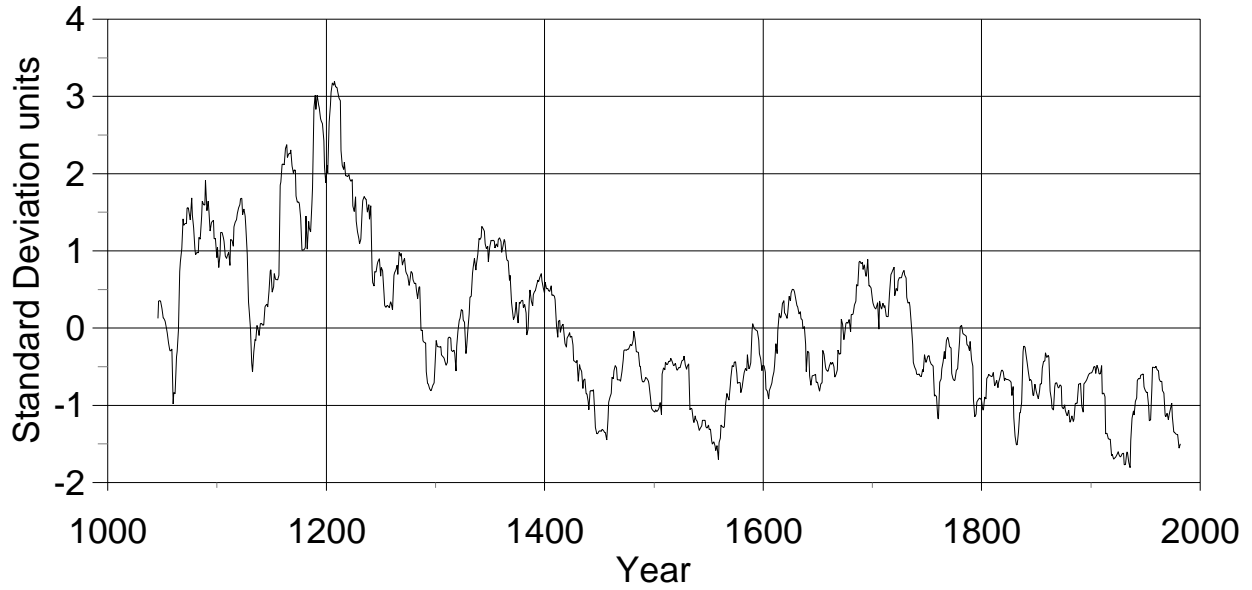


Figure 7. Running variance for the precipitation reconstruction calculated for overlapping 25-year periods, represented as a 10-year cubic smoothing spline. The graph clearly shows declining variability in precipitation during the past 1000 years in this part of southern Colorado.

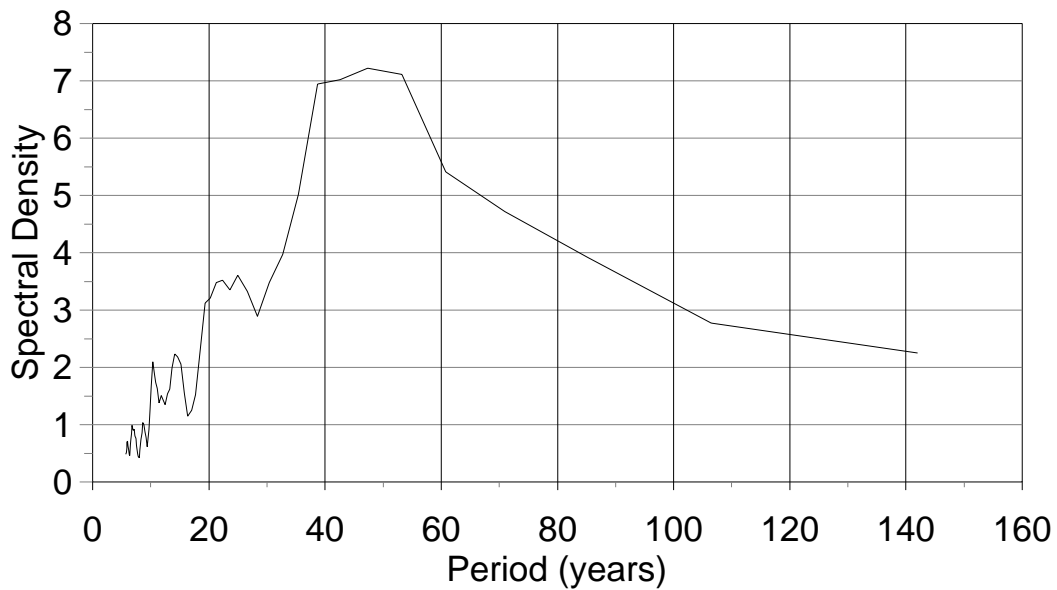


Figure 8. The smoothed spectral density function of the climate reconstruction for the post-1570 period, indicating a strong cyclicity between 40-50 years. This cyclicity is not apparent for the pre-1570 period, but may be related to the inclusion of ponderosa pine samples from the lower-elevation site rather than to a distinct change in climate patterns.

Appendix 1. Reconstructed values (in inches) of annual water-year (previous August to current July) precipitation for Great Sand Dunes National Monument, southern Colorado.

1035	10.50	1081	16.52	1127	13.49	1173	15.98
1036	11.55	1082	17.49	1128	10.50	1174	12.23
1037	11.43	1083	13.63	1129	9.84	1175	15.17
1038	9.04	1084	12.02	1130	10.39	1176	15.90
1039	8.96	1085	14.02	1131	10.93	1177	14.15
1040	10.84	1086	17.04	1132	10.99	1178	11.04
1041	9.86	1087	16.09	1133	10.31	1179	10.32
1042	9.38	1088	16.72	1134	11.08	1180	11.93
1043	9.75	1089	12.73	1135	10.22	1181	10.48
1044	9.27	1090	9.37	1136	13.42	1182	13.77
1045	9.21	1091	14.67	1137	12.73	1183	12.42
1046	10.67	1092	14.09	1138	10.66	1184	14.15
1047	11.01	1093	13.88	1139	14.90	1185	13.29
1048	7.20	1094	15.95	1140	11.14	1186	10.65
1049	11.95	1095	16.48	1141	12.90	1187	11.45
1050	11.46	1096	16.69	1142	12.99	1188	12.02
1051	13.32	1097	11.18	1143	12.32	1189	13.10
1052	12.10	1098	13.07	1144	11.73	1190	13.16
1053	11.98	1099	10.72	1145	13.28	1191	15.06
1054	10.19	1100	10.67	1146	11.31	1192	14.29
1055	12.92	1101	13.76	1147	8.69	1193	17.05
1056	15.05	1102	13.98	1148	9.00	1194	15.76
1057	12.50	1103	9.91	1149	12.23	1195	18.23
1058	11.15	1104	13.69	1150	8.34	1196	15.53
1059	12.70	1105	10.98	1151	10.61	1197	18.00
1060	14.06	1106	15.09	1152	12.94	1198	14.31
1061	11.72	1107	13.51	1153	8.80	1199	13.93
1062	11.07	1108	11.19	1154	12.83	1200	18.37
1063	10.45	1109	11.74	1155	11.86	1201	17.91
1064	11.34	1110	14.49	1156	12.03	1202	22.20
1065	11.56	1111	12.45	1157	8.36	1203	19.27
1066	10.46	1112	16.13	1158	10.03	1204	12.09
1067	11.20	1113	12.87	1159	12.25	1205	19.48
1068	10.55	1114	15.81	1160	11.64	1206	18.96
1069	11.94	1115	15.40	1161	7.81	1207	15.08
1070	13.10	1116	16.57	1162	14.97	1208	16.10
1071	12.59	1117	17.44	1163	12.51	1209	15.53
1072	13.05	1118	14.12	1164	11.22	1210	17.60
1073	12.75	1119	14.92	1165	9.56	1211	19.79
1074	14.11	1120	16.06	1166	7.82	1212	14.90
1075	12.43	1121	13.66	1167	11.84	1213	19.31
1076	16.20	1122	11.47	1168	9.58	1214	11.55
1077	13.86	1123	12.19	1169	11.59	1215	14.18
1078	15.59	1124	10.37	1170	13.78	1216	9.95
1079	18.76	1125	12.91	1171	18.70	1217	11.99
1080	15.29	1126	9.56	1172	14.23	1218	12.70

1219	13.10	1269	16.86	1319	14.22	1369	8.51
1220	14.17	1270	12.14	1320	12.85	1370	15.62
1221	13.93	1271	15.65	1321	13.67	1371	16.85
1222	15.28	1272	16.06	1322	12.17	1372	19.33
1223	17.01	1273	10.95	1323	15.61	1373	13.78
1224	16.02	1274	15.72	1324	16.41	1374	14.81
1225	15.69	1275	20.43	1325	18.96	1375	9.78
1226	17.42	1276	10.44	1326	14.83	1376	7.95
1227	14.10	1277	15.84	1327	12.33	1377	9.78
1228	17.17	1278	8.66	1328	14.69	1378	9.53
1229	12.56	1279	12.70	1329	11.39	1379	12.20
1230	20.12	1280	5.49	1330	15.44	1380	13.76
1231	16.94	1281	8.07	1331	14.84	1381	11.58
1232	15.10	1282	15.75	1332	17.39	1382	9.16
1233	15.64	1283	14.52	1333	20.27	1383	15.15
1234	14.51	1284	9.87	1334	19.76	1384	14.28
1235	13.63	1285	8.25	1335	18.97	1385	10.97
1236	7.69	1286	13.29	1336	13.02	1386	16.23
1237	13.64	1287	12.22	1337	18.86	1387	17.29
1238	19.01	1288	12.31	1338	13.84	1388	15.46
1239	11.53	1289	11.90	1339	14.17	1389	11.61
1240	9.69	1290	15.70	1340	14.15	1390	6.94
1241	19.24	1291	7.99	1341	13.33	1391	11.85
1242	16.95	1292	11.43	1342	11.01	1392	15.26
1243	16.41	1293	12.42	1343	8.70	1393	13.65
1244	16.49	1294	8.88	1344	9.78	1394	15.74
1245	12.97	1295	11.54	1345	8.96	1395	16.52
1246	8.29	1296	11.24	1346	13.24	1396	13.36
1247	10.87	1297	10.71	1347	7.57	1397	10.12
1248	10.25	1298	16.48	1348	10.70	1398	15.88
1249	17.14	1299	15.82	1349	9.06	1399	5.29
1250	12.80	1300	12.68	1350	15.87	1400	7.53
1251	13.14	1301	13.40	1351	17.43	1401	12.44
1252	10.65	1302	11.47	1352	9.34	1402	12.67
1253	15.58	1303	9.08	1353	19.55	1403	7.23
1254	8.55	1304	11.07	1354	15.76	1404	14.94
1255	15.46	1305	12.58	1355	11.23	1405	11.02
1256	17.26	1306	11.30	1356	18.82	1406	15.91
1257	14.97	1307	8.13	1357	11.17	1407	8.06
1258	7.00	1308	13.09	1358	19.85	1408	10.54
1259	13.08	1309	12.82	1359	17.00	1409	15.89
1260	9.26	1310	15.91	1360	8.99	1410	15.61
1261	7.27	1311	14.71	1361	15.52	1411	12.29
1262	10.66	1312	13.81	1362	11.87	1412	15.70
1263	10.34	1313	16.80	1363	7.61	1413	12.24
1264	8.45	1314	18.74	1364	8.59	1414	16.91
1265	14.08	1315	12.73	1365	13.50	1415	8.08
1266	10.68	1316	7.91	1366	10.97	1416	11.62
1267	10.47	1317	12.24	1367	11.66	1417	14.45
1268	16.02	1318	11.49	1368	13.29	1418	12.80

1419	7.73	1469	12.68	1519	16.25	1569	13.22
1420	13.80	1470	15.31	1520	15.86	1570	13.68
1421	10.63	1471	7.64	1521	20.88	1571	10.82
1422	11.00	1472	16.64	1522	9.76	1572	13.48
1423	8.58	1473	14.90	1523	13.76	1573	9.19
1424	12.66	1474	9.23	1524	9.22	1574	10.36
1425	14.14	1475	7.73	1525	11.52	1575	16.74
1426	17.35	1476	12.78	1526	13.90	1576	11.04
1427	13.68	1477	8.54	1527	15.27	1577	12.94
1428	16.08	1478	14.66	1528	11.88	1578	12.07
1429	8.96	1479	11.60	1529	15.66	1579	7.91
1430	15.10	1480	9.48	1530	15.25	1580	8.75
1431	12.18	1481	11.18	1531	15.06	1581	9.66
1432	11.30	1482	11.53	1532	13.77	1582	11.04
1433	12.61	1483	10.95	1533	11.38	1583	7.54
1434	17.66	1484	15.65	1534	12.71	1584	8.50
1435	16.12	1485	16.25	1535	12.32	1585	7.88
1436	15.32	1486	16.40	1536	15.53	1586	10.46
1437	12.65	1487	11.20	1537	14.37	1587	8.79
1438	11.53	1488	13.83	1538	11.68	1588	12.37
1439	10.71	1489	10.18	1539	16.20	1589	12.08
1440	13.13	1490	12.31	1540	14.90	1590	9.51
1441	12.04	1491	14.86	1541	16.16	1591	8.95
1442	13.36	1492	14.15	1542	14.33	1592	12.33
1443	14.75	1493	11.31	1543	11.78	1593	10.23
1444	12.06	1494	15.29	1544	10.84	1594	14.27
1445	8.30	1495	7.68	1545	10.78	1595	15.45
1446	13.59	1496	9.13	1546	12.41	1596	13.24
1447	13.52	1497	11.15	1547	9.55	1597	14.39
1448	13.22	1498	14.91	1548	13.07	1598	10.25
1449	10.04	1499	14.99	1549	11.28	1599	15.86
1450	11.35	1500	10.69	1550	14.35	1600	14.61
1451	13.91	1501	12.23	1551	10.60	1601	10.21
1452	13.53	1502	12.15	1552	13.67	1602	14.37
1453	11.50	1503	11.65	1553	13.06	1603	18.15
1454	10.40	1504	11.87	1554	12.72	1604	16.65
1455	7.42	1505	16.05	1555	14.37	1605	13.77
1456	13.20	1506	10.33	1556	15.65	1606	13.84
1457	11.76	1507	13.08	1557	14.62	1607	13.32
1458	13.86	1508	12.41	1558	10.21	1608	17.29
1459	11.39	1509	10.50	1559	12.81	1609	10.76
1460	12.56	1510	11.97	1560	12.39	1610	15.33
1461	14.12	1511	13.83	1561	13.30	1611	13.51
1462	13.03	1512	12.48	1562	12.24	1612	11.20
1463	10.68	1513	13.02	1563	10.78	1613	16.06
1464	10.53	1514	14.44	1564	15.43	1614	14.85
1465	12.73	1515	14.08	1565	15.11	1615	16.68
1466	13.59	1516	14.46	1566	12.79	1616	12.20
1467	12.91	1517	10.32	1567	12.42	1617	15.14
1468	14.28	1518	10.79	1568	14.36	1618	16.64

1619	17.59	1669	12.22	1719	15.47	1769	13.18
1620	16.71	1670	12.27	1720	20.77	1770	13.68
1621	17.14	1671	13.20	1721	16.57	1771	15.62
1622	12.09	1672	12.74	1722	14.48	1772	12.66
1623	9.41	1673	13.76	1723	17.55	1773	9.96
1624	11.17	1674	16.15	1724	17.90	1774	13.86
1625	8.76	1675	10.44	1725	17.08	1775	6.24
1626	12.90	1676	14.22	1726	16.71	1776	11.11
1627	8.29	1677	14.93	1727	13.96	1777	9.34
1628	6.97	1678	15.58	1728	13.96	1778	9.86
1629	11.71	1679	9.72	1729	6.37	1779	7.61
1630	11.85	1680	16.03	1730	7.42	1780	10.31
1631	8.42	1681	10.33	1731	11.98	1781	6.97
1632	10.83	1682	7.44	1732	9.75	1782	8.96
1633	12.53	1683	13.18	1733	10.60	1783	11.99
1634	13.62	1684	11.14	1734	12.07	1784	13.30
1635	13.36	1685	4.84	1735	10.36	1785	13.36
1636	15.91	1686	9.54	1736	13.24	1786	12.71
1637	18.60	1687	9.81	1737	9.00	1787	13.66
1638	13.99	1688	8.35	1738	10.44	1788	11.63
1639	17.26	1689	16.06	1739	13.17	1789	10.23
1640	17.48	1690	10.75	1740	12.49	1790	15.10
1641	12.68	1691	11.46	1741	10.24	1791	13.80
1642	13.27	1692	14.33	1742	10.53	1792	15.37
1643	13.73	1693	14.02	1743	14.28	1793	17.09
1644	16.04	1694	6.79	1744	12.25	1794	16.81
1645	9.17	1695	12.61	1745	7.02	1795	14.19
1646	15.44	1696	10.05	1746	15.23	1796	11.31
1647	14.88	1697	15.76	1747	14.79	1797	11.54
1648	12.77	1698	14.90	1748	7.38	1798	13.37
1649	14.03	1699	18.81	1749	14.20	1799	13.45
1650	15.35	1700	12.43	1750	10.47	1800	16.97
1651	15.13	1701	19.19	1751	13.07	1801	12.77
1652	13.46	1702	15.23	1752	12.20	1802	14.42
1653	16.61	1703	14.73	1753	13.00	1803	17.51
1654	8.18	1704	9.28	1754	16.01	1804	15.21
1655	15.35	1705	10.97	1755	16.18	1805	12.29
1656	14.79	1706	15.68	1756	12.80	1806	12.68
1657	14.95	1707	10.58	1757	13.88	1807	11.64
1658	10.42	1708	11.59	1758	13.67	1808	11.37
1659	14.23	1709	6.56	1759	15.35	1809	9.94
1660	15.58	1710	15.08	1760	13.76	1810	11.92
1661	16.28	1711	15.98	1761	17.55	1811	11.84
1662	17.20	1712	15.45	1762	14.88	1812	13.63
1663	13.64	1713	15.35	1763	9.97	1813	14.51
1664	12.92	1714	13.76	1764	10.43	1814	12.65
1665	11.17	1715	13.12	1765	11.87	1815	14.99
1666	10.59	1716	13.24	1766	13.30	1816	17.53
1667	12.59	1717	11.44	1767	11.97	1817	14.04
1668	7.13	1718	16.22	1768	13.49	1818	7.47

1819	9.31	1869	16.33	1919	16.84	1969	17.29
1820	10.82	1870	15.88	1920	14.20	1970	16.60
1821	11.99	1871	12.39	1921	16.00	1971	13.40
1822	12.08	1872	15.29	1922	13.57	1972	12.63
1823	13.25	1873	12.12	1923	10.37	1973	13.73
1824	10.56	1874	9.67	1924	15.29	1974	11.86
1825	13.53	1875	12.42	1925	12.81	1975	14.55
1826	13.98	1876	13.56	1926	13.34	1976	12.73
1827	15.67	1877	12.60	1927	13.09	1977	11.33
1828	16.40	1878	13.40	1928	15.17	1978	11.28
1829	16.33	1879	13.15	1929	12.09	1979	11.79
1830	15.33	1880	7.11	1930	13.72	1980	13.06
1831	15.82	1881	9.87	1931	14.12	1981	11.83
1832	15.23	1882	13.07	1932	11.82	1982	10.95
1833	14.44	1883	12.18	1933	12.67	1983	14.55
1834	13.29	1884	12.69	1934	12.38	1984	13.44
1835	16.05	1885	14.51	1935	12.38	1985	14.94
1836	12.43	1886	13.20	1936	12.15	1986	15.94
1837	13.29	1887	14.78	1937	15.81	1987	15.80
1838	14.27	1888	13.53	1938	15.45	1988	16.35
1839	13.25	1889	15.20	1939	13.77	1989	12.10
1840	13.63	1890	12.37	1940	13.07	1990	13.44
1841	13.56	1891	13.06	1941	15.38	1991	14.13
1842	10.07	1892	13.26	1942	15.29	1992	13.57
1843	12.69	1893	10.45	1943	12.80	1993	14.01
1844	13.59	1894	12.75	1944	12.78	1994	14.86
1845	14.76	1895	16.01	1945	12.72	1995	17.15
1846	12.09	1896	10.31	1946	9.33		
1847	10.01	1897	13.73	1947	12.82		
1848	9.17	1898	14.23	1948	13.12		
1849	10.55	1899	7.60	1949	13.80		
1850	10.26	1900	13.41	1950	8.48		
1851	5.20	1901	11.86	1951	8.35		
1852	9.14	1902	7.73	1952	10.01		
1853	9.12	1903	13.53	1953	11.51		
1854	11.06	1904	11.09	1954	8.69		
1855	11.00	1905	13.61	1955	10.11		
1856	10.91	1906	13.87	1956	7.25		
1857	12.00	1907	18.53	1957	10.52		
1858	14.80	1908	14.51	1958	11.50		
1859	11.51	1909	11.37	1959	9.82		
1860	12.92	1910	14.96	1960	12.91		
1861	10.92	1911	15.33	1961	10.82		
1862	7.36	1912	15.31	1962	11.98		
1863	11.21	1913	13.53	1963	8.24		
1864	12.36	1914	15.30	1964	9.35		
1865	10.46	1915	15.33	1965	13.27		
1866	15.02	1916	15.23	1966	12.15		
1867	14.36	1917	13.34	1967	12.81		
1868	12.69	1918	13.16	1968	13.03		