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A Multi-Millennial Drought Reconstruction for West-Central New Mexico Using Rocky Mountain Juniper (*Juniperus scopulorum*, Sarg.)

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A MULTI-MILLENNIAL DROUGHT RECONSTRUCTION FOR WEST-CENTRAL NEW MEXICO USING ROCKY MOUNTAIN JUNIPER (*JUNIPERUS SCOPULORUM*, SARG.)

by

Joshua S. Oliver

A Thesis
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and the Department of Geography and Geology
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ABSTRACT

A MULTI-MILLENNIAL DROUGHT RECONSTRUCTION FOR WEST-CENTRAL NEW MEXICO USING ROCKY MOUNTAIN JUNIPER (*JUNIPERUS SCOPULORUM*, SARG.)

by Joshua S. Oliver

May 2017

A new multi-millennial tree-ring record from living and remnant Rocky Mountain juniper (*Juniperus scopulorum*, Sarg.) wood from Candelaria in west-central New Mexico is used to determine the temporal and spatial variability of scPDSI over the past two millennia (B.C. 492 to A.D. 2014). Our record indicates extreme drought events found within other hydroclimatic proxy records in the Colorado Plateau region spanning the time period (16th century and 2nd century megadroughts). By ranking the extreme drought events by magnitude, duration, intensity, and overall score, the most extreme drought events of this record are compared to drought events illustrated within the proxy records of the region. Our new record contains a 100-year drought period, 850–950 A.D. not documented within these records. We hypothesize that this drought period is equally severe as the 2nd century and 16th century droughts and was restricted to the southern portions of the Colorado Plateau and in low elevation areas of the region. Published hydroclimatic research help designate the severity of these drought events, and our findings suggest that the American Southwest should anticipate comparable drought events in the predicted warmer and drier future.

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DEDICATION

I want to dedicate this research to the love of my life, Sarah, my mother, Angela, my father, Kenny, my two sisters, Ashleigh and Brittany and finally my best friends, Layne Dillon, Dustin Plaster, and Darren Doyle. You all have been my driving force pushing me to be the best I can be and I could not have done any of this without you. A special dedication to my late grandfather, Charles Albert Pence, and my late grandmother, Helen Sue Pence, may you forever rest in peace.

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1.1 Project Summary

1.1.1 The Proposed Study

The overarching goal of this research is to develop a multi-millennial tree-ring chronology using Rocky Mountain juniper (*Juniperus scopulorum*, Sarg.) that will provide a long-term perspective of past drought variability in a core region of the American Southwest. This research is unique due to the proposed length of the tree-ring chronology, 2000+ years, and how this research will produce a tree-ring based drought proxy record that surpasses the length of previous drought reconstructions in this arid region. This research will investigate relationships between the growth increments of a Rocky Mountain juniper site in west-central New Mexico and climatic variables that influence water availability (self-calibrated Palmer Drought Severity Index (a drought metric widely used to assess drought conditions; scPDSI) (Wells, Goodard, & Hayes 2004). These potential relationships will be evaluated and obtained through correlations reflected in drought variability documented by climate data stations.

1.1.2 Intellectual Merit

This research will create the first multi-millennial Rocky Mountain juniper tree-ring chronology within the American Southwest. The creation of such a chronology will provide a valuable proxy record of hydroclimate within the region prior to the introduction of instrumental records [*ca.* ~1900 AD (depending on the actually climate station for the exact starting date of record)]. The strength of this research is embedded in the persistent and well-established theories on the relationship between climatic variables and tree growth; however, the science of dendroclimatology relies on the functionality of biological organisms. The individualistic nature of trees and stand dynamics can alter growth patterns thus disregarding the climate-growth relationship expressed. The understanding of these strengths and weaknesses of the science is vital for properly identifying a species' relationship with biotic and abiotic factors before attempting to reconstruct past phenomena.

1.1.3 Broader Impacts

1.1.3.1 Benefits to Society

By producing a multi-millennial reconstruction of drought, this research will provide historic context to the extreme drought experienced in the American Southwest over recent decades. This will support regional and local government agencies to develop future sustainable environmental and socio-economic policies that effectively address water allocation, water use, water production, and long-term water management in the American Southwest.

1.1.3.2 Collaboration and Distribution of Results

Upon completion of this research, the tree-ring time series will be uploaded to the International Tree-Ring Data Bank (ITRDB) and reconstruction uploaded to the NOAA Paleoclimate Database. Once submitted, all findings of this research can be viewed, downloaded, and shared to the scientific, governmental, and public communities for any fair use. The findings of this research will also be disseminated in the form of peer-reviewed publications in sequential years following the conclusion of this study.

1.2 Problem Statement

The current drought in the American Southwest (States of New Mexico, Arizona, Utah, Nevada, and California) is exceptional and arguably the most severe drought recorded in the instrumental period (since ca. 1895 CE) (MacDonald, 2010). Current climate projections express that the next 100 years will be significantly drier and the intensity and duration of droughts within the American Southwest will increase considerably (National Drought Mitigation Center, 2016). The current drought was first put into perspective in 2001 when the Colorado River, the vast contributor of potable water in the region, transformed from a lively river into a trickle of water twenty miles short of the Gulf of Mexico (MacDonald, 2010). Every year following this event, the region has experienced annual precipitation levels 20–25% below its 20th century average with Arizona receiving 40% less annual precipitation in 2002 and 2009 (MacDonald, 2010). The drought that has been looming over the American Southwest for the past 15 years has also been the hottest drought on record (National Drought Mitigation Center, 2016; Udall & Overpeck, 2017). The increase in annual temperature within the period has increased the evaporation rates throughout the region only accelerating drought conditions further (National Drought Mitigation Center, 2016).

Population growth within the region has increased steadily despite of the growing concern of drought conditions. Current population projections convey that 65 million people will reside in the region by 2030 (United States Census Bureau, 2010). At the same time, the amount of irrigated farmland will reduce by 12–18% most likely to be replaced by suburban centers (MacDonald, 2010). At first glance this reduction of agriculture practices would elevate some drought conditions; however, additions of a growing population and the need of potable water for urban lawns and gardens is predicted to negate the positive effects of the removal of irrigated farmland (National Drought Mitigation Center, 2016). The increased demand for providing water to growing urban centers presents concerns for rural communities and food production in the region. The shift of allocating water to urban areas could have long-term effects on smaller, rural, or agricultural-based municipalities which in turn could socio-economically strain these communities. This strain will become more apparent as environmental concerns of the river systems and their associated ecosystems limit the transferability of water across the region (MacDonald, 2010). The implementation of a long-term water policy that adheres to technological innovation and drought projections would provide water to all citizens without sacrificing the environmental or socio-economical integrity of the American Southwest.

1.2.1 Research Objectives and Questions

The main objective of this research is to identify the relationships between climate variables (scPDSI) and Rocky Mountain juniper growth within in west-central New Mexico. The relationship between Rocky Mountain juniper growth and climate variables illustrates a temporal and spatial signal that can offer vital insight to drought conditions presently active in the American Southwest (Cook, Meko, Stahle, & Cleaveland, 1999; Stahle et al., 2009; Swetnam & Betancourt, 1990; Woodhouse, Meko, Griffin, & Castro, 2013; Woodhouse, Meko, MacDonald, Stahle, & Cook, 2010). The ability to present a multi-millennial reconstruction of drought will be accomplished by exploring the following research questions:

1. To which climate variables are Rocky Mountain junipers responding at the study site? Is this relationship stable through time?

2. Will the reconstruction uncover climatic patterns not illustrated in past studies involving tree-ring based climate reconstructions in the American Southwest? If so, what temporal characteristics are expressed by such discovery?
3. Can the achieved drought reconstruction aid in providing an extended context for understanding hydroclimatic resources in the American Southwest? If so, how?

1.2.2 Research Outcomes

An important outcome of this project will be a greater understanding on the relationship between climate variables associated with drought and Rocky Mountain juniper growth. Other outcomes will include (1) the development of a multi-millennial Rocky Mountain juniper chronology, (2) the development of a multi-millennial tree-ring based reconstruction of drought conditions within the American Southwest, (3) proving a longer perception of drought conditions within the region, (4) the investigation of past millennia to offer insights on current drought conditions, and (5) providing a multi-millennial reconstruction of drought to local and regional water resource managers to aid in examining the complexity and temporal patterning of drought conditions in the American Southwest. This research will also accompany the ongoing and current scientific research on the temporal and spatial aspects of drought phenomena in efforts to better understand the dynamic nature of droughts.

CHAPTER II REVIEW OF PAST LITERATURE

2.1 Brief Overview of Dendroclimatic Research

The use of dendroclimatic techniques in the American Southwest has become a staple for understanding relationships between atmospheric conditions and tree growth (Grissino-Mayer, 1996; Speer, 2010; Woodhouse et al., 2010, 2013). These techniques have their grassroots in 1929 within A.E. Douglass's *The Secret of the Southwest Solved by Talkative Tree Rings;* a creative title for the first description of dendroclimatic research within the American Southwest. Within the paper, Douglass proposed that climate variables such as precipitation shared a relationship with annual tree-rings and that the pattern of tree-ring width could provide context to past changes in climate conditions (Douglass, 1929). The dendroclimatic studies and written books on the dendroclimatic techniques that followed Douglass, (1929) would provide an avenue for modern day dendroclimatic research in the American Southwest (Cook & Holmes, 1986; Cook & Peters, 1981; Douglass, 1941; Fritts, 1976; Holmes, 1983; Schulman, 1954; Stokes & Smiley, 1968). The advancements of computer technology during the late 20th century allowed for the development of computer-based software such as COFECHA and ARSTAN to aid in measuring, crossdating, standardizing, and statistically testing the agreements between climate variables and tree growth (Cook & Holmes, 1986; Cook & Peters, 1981; Holmes, 1983). The development of this software would allow longer and more accurate tree-ring chronologies to be produced. One of the most notable and only multi-millennial chronology developed in the American Southwest, the El Malpais Long Chronology (ELMA), may have not been produced without the aid of these newly established computer-based programs (Grissino-Mayer, 1996). This 2,129-year chronology was one of the first multi-millennial tree-ring chronology produced specifically for reconstructing climate variables (precipitation) in the American Southwest. Other multi-millennial chronology had been produced before; however, they were not used to reconstruct climate variables. In the years that followed, research on long chronologies and relationships with climatic variables was conducted (Briffa, Jones, Schweingruber, Karlen, & Shiyatov, 1996;Cook, D'Arrigo, & Mann, 2002; Cook et al., 1999; Cook, Palmer, Cook, Hogg, & D'Arrigo, 2002; Cook, Palmer, & D'Arrigo, 2002; Hughes & Graumlich, 1996; Nakamura, Lin, & Yamagata, 1997; Villalba & Veblen, 1996). As these studies were produced, a shift in isolating certain climate variables became popular. By the early 2000's, research responding to climate projections of increased drought and powerful swings in atmospheric-oceanic oscillations would alter the dendroclimatic studies within the American Southwest.

2.2 Tree-Ring Based Drought Reconstructions within the American Southwest

The focus of drought conditions with the American Southwest is apparent in Stahle et al. (2000). The study examines the "megadroughts" within the 16th century as being the worse drought experienced in North America in terms of intensity and persistence (Stahle et al., 2000). However, the "megadrought" found in the 16th century has been disregarded as being the worse drought by dendroclimatic research more recently studied (Cook, Anchukaitis, Touchan, Meko, & Cook, 2016; Hoekema & Sridhar, 2011; Q. Li, Nakatsuka, Kawamura, Liu, & Song, 2011; Stahle et al., 2009, 2011; Stahle, Fye, Cook, & Griffin, 2007; Woodhouse et al., 2010). The studies focused heavily on the current drought conditions of the American Southwest. These studies provided 1,200 years of valuable climate data within the region and concluded that the current 2000's drought has been the worse within the 1,200-year time period (Cook et al., 2016; Hoekema & Sridhar, 2011; Li et al., 2013; Li et al., 2011; Stahle et al., 2007, 2009, 2011; Woodhouse et al., 2010). However, these studies do lack longevity. ELMA indicated a period within the 4th century that expressed a drought that would indicate the worse drought reconstructed by tree-ring analysis (Grissino-Mayer, 1996). Unfortunately, ELMA was produced before the Turn of the 21st-century drought of the American Southwest.

During the same period, tree-ring based reconstructions of atmospheric-oceanic oscillations were conducted and as projection models suggested an increase in intensity of the positive and negative stages of the Pacific Decadal Oscillation (PDO), El Niño-Southern Oscillation (ENSO), and La Niña Oscillation (LNO), dendroclimatic research on these oscillations became well-known in the field of study. The relationship between atmospheric-oceanic oscillations and tree growth is well established (D’Arrigo & Wilson, 2006;Li et al., 2013; MacDonald & Case, 2005; Stahle, D’Arrigo, Krusic, & Cleaveland, 1998; Trouet & Taylor, 2010; Verdon & Franks, 2006; Wilson et al., 2010). From these studies, 600 years of reconstructed climate values were produced. The main conclusions of these studies were that (1) tree-ring growth correlates with the positive and negative phases of atmospheric-oceanic oscillations, (2) the relationship found could indicate the timing and magnitude based on reconstruction values, and (3) the intensity of these oscillations have been intensifying since 1950 (D’Arrigo & Wilson, 2006;Li et al., 2013; MacDonald & Case, 2005; Stahle et al., 1998; Trouet & Taylor, 2010; Verdon & Franks, 2006; Wilson et al., 2010).

Widespread drought condition starting in the early 2000s brought on the innovation of improved software to provide higher accurate modeling, error assessment, and crossdating methods (Biondi & Qeadan, 2008; Braker, 2002; Bunn, 2010;Cook & Pederson, 2011; Grissino-Mayer, 2001; Woodhouse et al., 2010). Woodhouse et al., (2010) studied the uses of different regression based models during tree-ring based climate reconstruction. They concluded that linear regression models were best suited for reconstructions when they are based solely on one chronology and that stepwise or multivariate regressions were more accurate with reconstructions involving more than one climate variable or chronology. As the development of higher accurate reconstruction modeling, laboratory methods were becoming more precise. Maxwell, Wixom, and Hessl (2011) discusses two of the most common techniques for measuring tree-ring width, WinDendro and a measuring platform based software, Tellevo. They concluded that WinDendro illustrated that the program was based on brightness values between earlywood and latewood. Maxwell et al. (2011) provided that WinDendro was most accurate with species that provided an abrupt change in brightness values between latewood and earlywood. Spond, van de Gevel, and Grissino-Mayer (2014) supported the above conclusion in a study of Rocky Mountain juniper. The researchers found that the use of WinDendro was best useful in the measuring of each annual ring width due to the species' sudden transition from earlywood to latewood (Spond et al., 2014).

2.3 Gaps in Current Dendroclimatic Research in the American Southwest

Even though the relationship between climate variables and tree growth is well established the current research of the past 20 years lacks in the number of millennial length reconstructions. There has only been 3 main tree-ring reconstructions of drought-related variables since 1996 (precipitation, temperature, and PDSI) (Cook et al., 2008; Knight, Meko, & Baisan, 2010; Routson, Woodhouse, & Overpeck, 2011), Routson et al.

(2011) provided 2000+ years of drought information. However, tree-ring based reconstruction since has not been able to reach BC to compare that drought period with the current drought of the 2000's. The longest tree-ring reconstruction of an atmospheric-oceanic oscillation, Li et al. (2011) does provide an accurate representation of climate; however, this study is lacking longevity due to the reconstruction is only 700-years long. In Grissino-Mayer, Swetnam, and Adams (1997) and Spond et al. (2014) the researchers concluded that Rocky Mountain juniper is a much longer lived species than Douglas fir, the species used in the making of ELMA. Their conclusions provide that the species could be used to provide a multi-millennial tree-ring chronology; a chronology that would be longer and report more accurate results (Grissino-Mayer et al., 1997; Spond et al., 2014). By developing a multi-millennial tree-ring reconstruction of drought variability in this research, the unknown gaps in the previous drought studies will be filled. By reconstructing drought at a multi-millennial time frame, the drought events found in Cook et al. (2008), Grissino-Mayer (1996), Knight et al. (2010), and Routson et al. (2011), as well as current drought conditions, could be evaluated. This proposed study will have the ability to indicate the time period of significant droughts within the American Southwest for the past 2000+ years; aiding previous dendroclimatic research on the severity and magnitude of past droughts within the region.

CHAPTER III METHODOLOGY

3.1 Study Area

The chosen site location, Candelaria, is a 500-acre privately owned track of land adjacent to the northern extent of El Maplais National Monument outside Grants, New Mexico, U.S.A. (Figure 3.1). The property encompasses the Bandera Crater and is recognizable by the basalt formation produced during past volcanic eruptions. Candelaria is at located approximately 2365 m.a.s.l. and is uniform in elevation throughout the site; however, the basalt formations are sharp and uneven which can lead to micro-changes in elevation (< 1 m). The Candelaria site is located close to the border of Climate Division 4 (Southwestern Mountains) and New Mexico Climate Division 1 (Northwestern Plateau) (United States Department of Commerce National Oceanic and Atmospheric Administration, 2011). Over the period 1902–2014, the summers, on average, were hot (maximum > 30°C) and winters were cold (average January temperatures < -10°C) (United States Department of Interior National Park Service, 2011). The region receives an average annual precipitation of 400mm (United States Department of Interior National Park Service, 2011). The vast majority of precipitation received in this region is linked to the North American Monsoon during July, August, and September (Griffin, Meko, Touchan, Leavitt, & Woodhouse, 2011; Stahle et al., 2009; Woodhouse et al., 2010, 2013). Annual precipitation is distributed bimodally, with a maximum level of precipitation occurring during summer months with a secondary apex occurring between December and March (Spond et al., 2014). Tree species diversity on the Candelaria lava field is greater than that of surrounding areas. The trees living on such basalt include Rocky Mountain juniper, Douglas-fir (*Pseudotsuga menziesii,* Mirb.), and some sparse populations of quacking aspen (Populus tremuloides Michx). The forests encircling Candelaria are comprised almost entirely of youthful stands of Ponderosa Pine (*Pinus ponderosa*, Doug.)

(Grissino-Mayer & Swetnam, 1995; Rother, 2010). The forests surrounding Candelaria had been once used for animal grazing and was profoundly logged (Rother, 2010). Because of the trees located on the basalt are asymmetrical shaped with sparsely foliated crowns, their use in commercial timber operations would have been minimal (Schulman, 1954; Stahle & Chaney, 1994). Even though this site has been owned by the Candelaria family for generations, the site is untouched from any timber operations. The potential for old standing Rocky Mountain juniper as well as remnant Rocky Mountain juniper samples is exceptional in this pristine landscape.

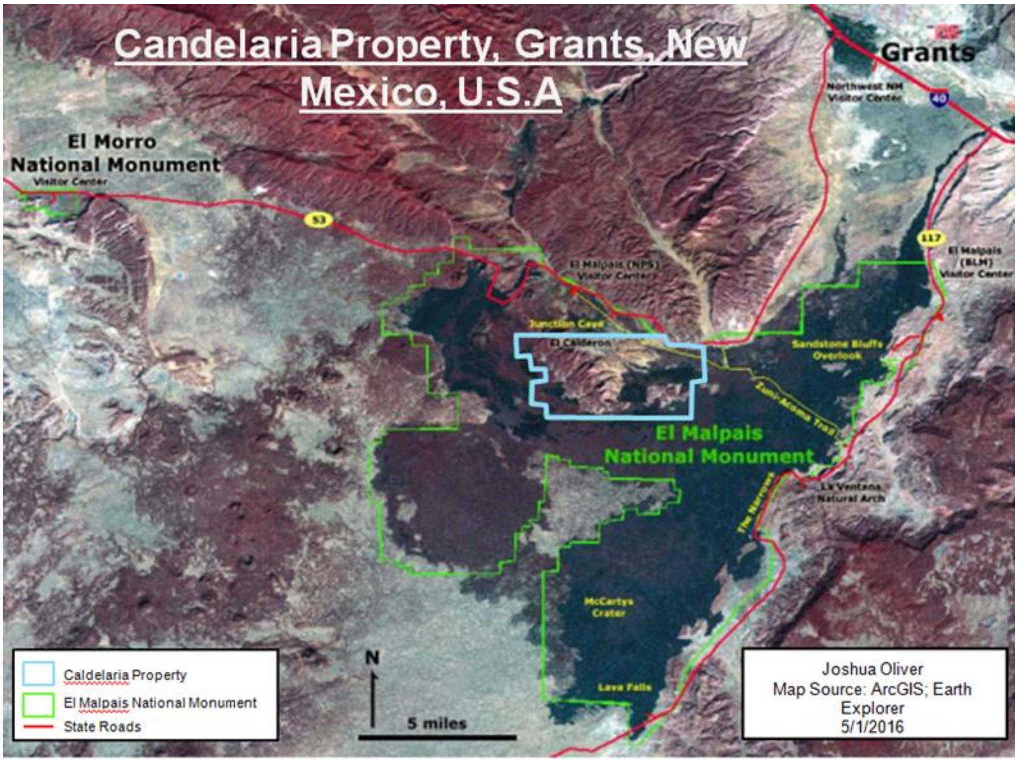

Figure 3.1 This satellite image shows the boundary of the Candelaria Property, El Malpais National Monument, and a portion of Cibola National Forest (north of the Caldelaria property)

3.2 Development of a Mult-Millennial Tree-Ring Chronology

The development of a tree-ring chronology is considered the key component of any dendroclimatic research (Speer, 2010; Stokes & Smiley, 1968). There are different approaches, both field, and laboratory, to accomplish this goal. Variations in sampling approaches have been used within dendrochronological research such as random sampling and stratified sampling based on stand structure or size of tree (diameter at breast height, DBH) (Nehrbass-Ahles et al., 2014); however, the most used sampling method is a targeted approach (Speer, 2010). Despite the targeted approach being most popular for dendrochronological research, the approach has had been criticized due to its user bias. For dendroclimatic research pertaining to climate reconstruction, this inherent bias is justified due to the necessity of selecting long-lived individuals to reconstruct past climatic variability. To accurately measure and crossdate individual tree rings within the initial laboratory portion of dendrochronological research it is important to (1) determine the appropriate measuring platform, (2) provide a standard for how each individual ring will be measure, (3) describe areas of each sample to denote each individual ring boundaries, (4) implement COFECHA to determine interseries correlation, and (5) indicate areas of low interseries correlation and determine if any measuring mistakes were made, micro-rings or missing rings were unrepresented, or false rings were included as true rings (Sieg, Meko, DeGaetano, & Ni, 1996; Spond et al., 2014; Stokes & Smiley, 1968).

The main objectives of this goal are to: (1) collect living and remnant samples of Rocky Mountain juniper capable of producing a multi-millennial chronology from Candelaria (2) crossdate samples by determining the interseries correlation of all samples within COFECHA and (3) validate areas of low correlation to determine possible misidentified rings or inclusions of false rings.

3.2.1 Field Methods for Developing a Multi-Millenial Tree-Ring Chronology

At Candelaria, the construction of the field design was focused around the sampling techniques used in similar dendrochronological studies (Grisssino-Mayer, 1995, 1996; MacDonald & Case, 2005; Rother, 2010; Stahle et al., 2009; Swetnam & Belancourt, 1990;

Woodhouse et al., 2010, 2013) These studies have highlighted a necessary sampling technique when performing dendroclimatic research within the American Southwest, on volcanic substrate such as cindered rock and basalt fields, or performing research on Rocky Mountain juniper. The sample technique described is a targeted sampling method in the attempt to collect the oldest Rocky Mountain juniper samples. Rocky Mountain juniper, like many conifer species in the Southwest United States, offer clues in regards to estimating the age of an individual tree. These old age characteristics were targeted on site within the surveying portion of the field study and geo-tagged with a GPS to ensure the location of each targeted tree or remnant wood sample was identified correctly. Each targeted sample was then processed using a complementary 6 digit alphabetical and numerical code based on the site name and the number of each sample (i.e., CAN001).

Once the initial surveying portion of the field study was conducted and all samples have been given a precise codename, each tree was revisited and samples were collected. For collecting samples from living trees, an incremental bore was used. An incremental bore is a handheld tool with a hollow shaft and a sharp screw-like bit (the bore) used in collecting a 4mm cylinder of wood. This cylinder of wood represented one radius or core of the tree, the total width of the sample tree from the outermost bark to the center ring of the tree known as the pith. Two individual cores were oppositely taken from each sample to represent an “A” and a “B” portion of the tree. This is not attended to enhance the overall sample size but to minimize the effects of irregular growth and missing/false rings that could be apparent on one side of the tree and absent on the opposite side (Stokes & Smiley, 1968). For remnant, woody debris, a cross section of wood representing the entire log or highly decomposed sample was collected using a forestry grade chainsaw. Most cross sections were thin entire samples of decomposing woody debris that was identified as being the correct species; however, woody debris that no longer had any resembling characteristics was only be recognized as Rocky Mountain juniper after the sample had been processed in the laboratory portion of this study.

As stated by Spond et al. (2014), there was a 50 percent chance of samples not correlating with other samples collected due to the species' irregular growth forms and formations of pinched/missing rings. To combat this failure rate, double the appropriate amount of samples was collected at Candelaria to ensure an adequate sample size. The maximum sample size for any dendrochronological research, as stated in Grissino-Mayer (2001), is 50 individual samples to represent every 50-year segment within the crossdating portion of the research. Grissino-Mayer discusses that the additional of more samples past this threshold will not result in an increase in interseries correlation (Grissino-Mayer, 2001). The attended sample size during this study was aimed at this threshold to maximize the interseries correlation throughout the time series to provide the best possible chronology to be used as a proxy of climate.

3.2.2 Laboratory Methods for Developing a Multi-Millennial Tree-Ring Chronology

3.2.2.1 Preparation and Measurement of Tree-Rings

All samples were transported back to the USM Dendron Laboratory and prepared using traditional dendrochronological techniques (Stokes & Smiley, 1968). Each sample core was mounted (the process of gluing samples on a base material to protect samples from breaking) and polished using an industrial sander with progressively finer sandpaper, initially with 120-grit and ending with 400-grit. The samples were hand sanded with 1000 and 1500-mircogrit sandpaper to ensure all possible rings are visible. All samples were scanned using an EPSON Expression 1100XL, a high-resolution digital scanner. Each annual tree-ring width was measured using the software WinDendro to the nearest 0.001mm. WinDendro was used as the measuring platform due to the abrupt changes in brightness values between earlywood and latewood of Rocky Mountain juniper discussed in Maxwell et al. (2011), to provide the most accurate measurements of each annual tree-ring.

3.2.2.2 Crossdating Procedures

The principle of crossdating is vital to all dendrochronological research. The correlating values of annual tree-ring width within a sample population convey the necessary growth relationships throughout space. The correlation coefficients gathered in this research was gained through the computer software, COFECHA (Grissino-Mayer, 2001). COFECHA provides a user-friendly interphase that allows measurement values to be used to determine inter-sample correlation between all samples. COFECHA uses a running interval correlation algorithm to determine certain measurement patterns within the uncrossdated base chronology. The base interval is set to express 50-year segments that are lagged by 25 years in determining measurement patterns (Grissino-Mayer, 2001). The output is a matrix of correlation coefficients that express the statistical relationship between an individual series (one sample) and COFECHA predicted chronology (based on correlating patterns within a majority of samples) at each interval (known as interseries correlation).This allows for the user to quality check the sample for measuring mistakes and identify potential irregular growth forms such as false and missing rings that the user did not account for in the measuring process (Grissino-Mayer, 2001). It was only then when all samples had been quality check throughout the entire time frame that the chronology was able to undergo validation and calibration related tests within the climate analysis/reconstruction portion of this study.

3.3 Development of a Multi-Millennial Drought Reconstruction

The phases associated with the development of a tree-ring climate reconstruction are debatably the most technical portions of any study stemming from dendrochronology (Speer, 2010). Even though it may be technical, there are many models, programs, and methods that accomplish the same goal. There is one standard, however; every tree-ring based climate reconstruction begins with identifying any relationship between climate variables and the growth widths of tree-rings at an annual resolution. Furthermore, if such relationships do exist the following should be completed to develop a tree-ring climate reconstruction: (1) testing the expressed relationship based on other statistical measures or parameter based algorithms, (2) produce an unbiased regression-based model to calculate estimated values for climate variables before the introduction of instrumental records, and (3) indicate and correspond the error within the produced model (Cook et al., 2013).

The main objectives of this of goal was to (1) standardize the produced chronology, (2) evaluate the climate-growth relationship between Rocky Mountain juniper growth at Candelaria and a chosen instrumental record within the region, (3) test the relationship using statistical parameters, (4) produce the reconstructed values of past drought variability, and (5) indicate the amount of error within the produced model.

3.3.1 Detrending and Standardization of the Chronology

During this process, we attempted to maximize the studied climate single and limit the amount of noise (values that do not pertain to the pattern expressed) found in the Candelaria (CAN) chronology produced in the crossdating portion of the study (Speer, 2010). The chronology that was produced in COFECHA did not indicate a true signal of any variable that could influence growth on the trees studied; however, it did express the overall pattern of tree-ring width measurements throughout the full-time series. (Grissino-Mayer, 2010). By detrending and standardizing the chronology produced in COFECHA, the most limiting factor (the variable contributing to the majority of growth of the trees studied) was isolated. The computer software, ARSTAN, was used to detrend and standardize the chronology produced. ARSTAN uses a robust estimation of mean value function to remove the effects of geometric amplitude (the size of the trunk gets larger as a tree ages which causes the tree to naturally put on less wood due to the size of the trunk. Because of this, the ring will appear and measure as if it was smaller than it is in reality) (Cook & Holmes; 1986). We detrended using a negative any slope standardized produce to remove these effects within the chronology produced at Candelaria. By standardizing the effects of these naturally occurring variables, all values throughout the time series was evaluated at the same level without any influences that would be considered outliers in the dataset. The result of this procedure was a chronology that has limited the effects of potential outliers (noise) and has standardized all tree-ring measurements to provide a maximized signal.

3.3.2 Choosing an Instrumental Record and Testing the Agreement with the Tree-Ring Index

In dendroclimatic research, choosing an instrumental record is based upon three factors: (1) the overall completeness of the climate record (potentially data gaps can be expressed throughout the years of data collection), (2) the overall length of the instrumental record (how long has the station been measuring a particular climate variable), and (3) the proximity of the climate station in regards to the study site. The best scenario in dendroclimatic research is to obtain instrumental climate data recorded from a station that is nearby the study site (< 30 km) and for the station to have a continuous record for at least 50 years from present (Cook et al., 1999). For this study, instrumental records of scPDSI variability was collected from a climate station that adheres to the three parameters above.

The instrumental record obtained was first tested against the tree-ring index produced from Candelaria during the instrumental period (time period when climate variables have been recorded by man-made instruments). The Pearson's correlation, *r*, was used to test the agreement between the values of the tree-ring index and the values of the instrumental record for all four climate variables. The expressed *r* value denotes a value between -1 and 1 determining the overall agreement to be negatively correlated, values closer to -1, positively correlated, values closer to 1, or no to weak correlations, values closer to zero. The instrumental period was then split into two equal time periods (equal by the number of years) to determine the overall agreement between the climate variable record and tree-ring index in both time periods (the expressed correlation is used later during the calibration and verification portion of the study). Two statistics were used to determine if the expressed correlation between the climate variable record and the tree-ring index has the ability to withhold an accurate reconstruction (Cook et al., 1999). The two limiting statistic parameters were the average reduction of error (RE) and the average coefficient of efficiency (CE).

3.3.3 Validation of Agreement by a Split-Calibration/Verification Procedure

To validate the relationships expressed further, the split time periods were used to calibrate and verify the reconstruction model. The time periods were labeled as either the calibrating or verifying period of the model based on the overall agreement, *r*, of both time periods. The higher correlating time period was used as the verifying period as the lower correlating time period was used as the calibrating period (Cook et al., 1999). The two limiting parameters, RE and CE were then used to calibrate and verify the agreement expressed between the tree-ring index and the climate record. RE, the average reduction of error, describes the amount of difference between that of the actual climate values and the predicted tree-ring values during the verification period in regards to the actual values during the calibration period. From this statistic, a value ranging from 1 to negative infinity will be produced. A RE value > 0 demonstrates that the model possesses a high predictive skill during the calibration period, meaning that the values estimated/predicted by the tree-ring index are similar to that of the actual value recorded by the climate instrument during this period (Cook et al., 1999). The average coefficient of efficiency, CE, describes the amount of difference between actual and estimated values during the verification period in regards to the actual values during the verification period. Just like RE, CE generates a value ranging from 1 to negative infinity. A CE value > 0 demonstrates that the model possesses a high predictive skill during the verification period. Once both RE and CE have been calculated, a cross-calibration/verification process was used. By cross-calibrating/verifying the two periods were switched meaning that the verification period became the calibration period and the initial calibration period into the verification period. The process allowed RE and CE to be obtained from the newly changed periods. The result of this and the normal split periods, are CVRE, VRE, and VCE values that represented both the present half and the latter half of the instrumental period (Cook et al., 2013). If any of the 3 parameters' values are negative, the tree-ring index cannot serve as a proxy for that particular climate variable and does not have the ability to withhold an accurate reconstruction. RE and CE values >0 indicate that the tree-ring index can serve as a proxy and does have the ability to withhold an accurate reconstruction (Cook et al., 1999).

3.3.4 Reconstruction and Error Assessment

If the agreements (climate variable tested and the instrumental climate record) are found to be statistically valid during the calibration and verification procedure, the agreements were used to produce estimated values for each climate variable pre-instrumental period. The application of a linear regression was used. This is supported by a conclusion from Woodhouse et al. (2010) that states linear regression models are most useful in single chronology based reconstructions. The equation for such linear regression, $\hat{Y}= bX+ A$, was used to calculate the estimated values of the past climate variable. This regression provides the notion that a particular value of X, representing the average tree-ring width of a particular year during the instrumental period equals a particular value of the climate variable, $\hat{Y}$ during the same year. This relationship was applied based on the average tree-ring width, X, in every year before the instrumental period, to predict the estimated value of the climate variable tested, $\hat{Y}$. The result of this process was an index of predicted climate values before the instrumental period.

To assess the error of the model, the maximum entropy bootstrapping method, MEBoot, was used due to its ability to preserve the overall temporal order of the time series without disrupting the bootstrapping process (Cook et al., 2013). By not randomizing the time series and replacing values with randomly chosen values, this bootstrapping method allowed the predicted error intervals to be calculated while keeping the regression model and temporal aspects intact (Cook et al., 2013). The amount of error calculated by the MEBoot process was applied to every year that is reconstructed to denote that the value obtained through the linear regression-based model does not serve as the true climate value expressed in a given year. Rather, MEBoot ensures a range of values that indicated the predicted climate value as the median and the error amount added as a maximum value and subtracted as a minimum value for that given year. The result of was a range of predicted climate values for every year in the time series to serve as the multi-millennial tree-ring based reconstruction of scPDSI of west-central New Mexico.

3.4 Testing the Reconstruction Stability and Climatic Response

One of the fundamental steps towards the development of a robust dendroclimatic model is the testing the stability of the reconstruction through time (during the instrumental period) and to further test the annual growth of series within the chronology to monthly climatic information (scPDSI) (Biondi, 1997). To test the reconstruction stability and related climatic response, the program DENDROCLIM2002 was used to identify the reconstruction’s stability through the calibration period of the reconstruction (1956–2013) and to recognize the correlation between all annual growth rings within the period and monthly scPDSI. DEDROCLIM2002 was used to determine bootstrapped correlation and response functions of annual tree-ring growth towards the climatic variable used (scPDSI in this study) in identified intervals (Biondi & Waikul, 2004).

To indicate these correlation and response functions, a forward moving interval analysis was used. The forward moving interval analysis considered the calibration period of the model and tested the climate-growth relationship within nested intervals through the period (Biondi & Waikul, 2004). The produced agreement was also tested further by using 1000 Monte Carlo simulations throughout the time period to provide the most statistical representation of each annual correlation between tree-ring growth and climatic variability. The result of this procedure indicated the temporal stability within the calibration period and ensured that the reconstruction was stable throughout the full-time series. This procedure also provided monthly correlation values between tree-ring growth and scPDSI variability to indicate the timeframe at which Rocky Mountain juniper is most sensitive to or limited by scPDSI.

3.5 Evaluation of Drought and Pluvial Events

The evaluation of drought (events below the mean of the reconstruction) and pluvial (events above the mean of the reconstruction) is a necessity within any dendroclimatic reconstruction. The reconstruction can be evaluated based on many different techniques or observations; however, there are two main techniques that have been common in recent literature. These two being the comparison of drought and pluvial events occurring pre-instrumental with those events obtained within the instrumental period and to compare the reconstruction’s drought and pluvial events to other reconstructions pertaining to water availability in the same region of study. The result of this evaluation often reveals important climatic information within the reconstruction itself and within the other reconstructions within the area. In Stahle et al. (2007), by evaluating many different climatic reconstructions, they were able to suggest, on two separate occasions, the occurrence of a megadrought that outweighed previous drought records of the past. Without this comparison, these droughts may have never been evaluated upon and would not be contained within the present drought record (Stahle et al., 2007).

The main objective of this evaluation was to (1) determine the overall variability of drought and pluvial events by indicating running averages above and below mean scPDSI based on different time intervals (5, 10, 25, and 50 years), (2) compare the drought and pluvial events within the entire reconstruction by analyzing the magnitude, duration, and intensity of each event and rank the events based on these criteria, (3) compare and contrast the drought and pluvial events of the past within other reconstructions of the region to determine the differences and similarities between those and the produced reconstruction.

3.5.1 Determining the Magnitude, Duration, and Intensity of Drought and Pluvial Events

To determine the magnitude, duration, and intensity of drought and pluvial events throughout the entire reconstruction period, a run analysis was first used. A runs analysis is a simple binary process where each annual reconstruction value for scPDSI is given a 1 or 0 depending on the nature of each value (given a 0 if less than the reconstructed scPDSI average; given a 1 if above-said average) (Gray, Lukas, & Woodhouse, 2011). This process indicates the years in which are similar throughout a certain timeframe. For example, the years 100 to 110 AD could appear as '00011111000', this, in turn, translates into 3 years below the mean, 5 years above, and 3 years below. These continuous 'runs' are then coded as the time period in which they are a part of. Continuing the example above, the interval 100-102 AD expresses a three-year run that is below the reconstructed mean of scPDSI. This binary process is conducted for every year of the reconstruction; however, only runs consisting of 2 or more years was used during the next steps of this analysis. This was to eliminate time periods that illustrated sole years of drought and pluvial conditions which in turn eliminated potential climatic outliers or outliers caused by non-climatic factors (endogenous/exogenous conditions) (Bekker, DeRose, Buckley, Kjelgren, & Gill, 2014).

Once all runs had been identified and coded based on the time period each run represents, magnitude, duration, and intensity was calculated for each run (time period). Magnitude illustrated the cumulative flow (sum) of all values within the given time period (Bekker et al., 2014; Gray et al., 2011). To compute magnitude, the values within the run were summed to provide the total in which this time period was below or above the mean scPDSI. Magnitude was calculated for every run to determine cumulative flow (sum, total) for the entire reconstructed period. Duration expressed the number of years in which each run represents (Bekker et al., 2014;

Gray et al., 2011). The duration was a simple counting process to evaluate the number of years in each run both below or above the mean scPDSI within the reconstructed timeframe. Intensity was the quotient of magnitude by the duration or the respected yearly average below or above the mean within the time period (Bekker et al., 2014; Gray et al., 2011). The result of this process was that every run 2 years or more in duration and either below or above the reconstructed mean scPDSI were given a magnitude, duration, and intensity that was used to determine the overall score (rank) of every drought and pluvial event during the reconstructed period.

Before determining the overall score of each drought or pluvial event (runs) runs below the reconstructed mean scPDSI were separated from runs illustrating values above the mean. By separating these runs into drought and pluvial events, they were ranked and given an overall score based on their respected category (two separate ranking procedures; one including all drought events and one including all pluvial events). To determine the overall score, the runs were ranked on their magnitude from lowest to highest. The lowest score was given a 1 and the highest magnitude was given the highest rank possible (depended on the number of events per category). The same process was achieved with the duration of the events. If any ties occurred, the same rank was given to all events that had tied (e.g. 3 events with a duration of 7 years would receive the same rank). The result of this process was that every event was given a respected magnitude rank and duration rank that was summer together to provide an overall score. The highest overall scores indicated time periods of exceptional values below or above the mean, a long-term duration below or above the mean, or a combination of both. This ranking process was completed twice; once with the drought events and again with the pluvial events. The final result of this analysis was the identification of the most exceptional drought and pluvial events within the entire reconstructed time period (Bekker et al., 2014; Gray et al., 2011).

3.5.2 Comparison of Other Drought Records in the American Southwest

To compare the produced reconstruction between that of other drought reconstruction in the region, a temporal evaluation was conducted. The temporal evaluation was a basic assessment of expressed drought and pluvial events during certain time periods of the produced reconstruction and other hydroclimatic reconstructions. The assessment was aimed to determine any region-scale climatic variability and to gauge the predictive power of the both reconstructions. For example, if the produced reconstruction illustrates a newly found megadrought within a certain time period this drought phenomenon will be checked against the other climatic reconstructions in the area. The same can be said about past research and drought or pluvial events within those reconstructions not found in the one produced from this study. This portion of the assessment was not to deem one reconstruction over the other but to simply compare these found differences and to add to the hydroclimatic research within the American Southwest.

To further examine the similarities and differences between the produced reconstruction and selected reconstructions (e.g. ELMA, Grissino-Mayer, 1996), the spatial correlation of both reconstructions was analyzed. To test the spatial correlation, gridded scPDSI was used to determine the correlation values of the reconstructions between that of every scPDSI grid point within the American Southwest. This illustrated the spatial range of each reconstruction and provided the area at which the reconstruction could be used within the region; thus, aiding in determining the robustness of each reconstruction spatially. By analyzing the reconstructions spatially, the ability for the reconstruction to indicate regional climatic variability was represented. For example, if a reconstruction had a spatial range that only surrounded the study area than the trees used to produce such a reconstruction may be limited by small-scale climatic variability compared to a broad spatially ranged reconstruction may be limited by more large-scale climatic variability. From this, the ability to demonstrate the spatial limits of selected reconstructions provided a necessary counterpart to the temporal capability of the reconstructions to better under the hydroclimatic variability within the American Southwest.

CHAPTER IV – RESULTS

4.1 CAN Chronology

At Candelaria, 63 Rocky Mountain juniper samples were collected within two field seasons in 2015 and 2016. The collection consisted of 27 living (cores) and 46 remnant (cross sections) samples. We acquired 43 Rocky Mountain juniper samples on loan from the Laboratory of Tree-Ring Science at the University of Tennessee and the Laboratory of Tree-Ring Research at the University of Arizona to aid this study and provided a total of 106 samples of Rocky Mountain juniper. From those 106 samples collected or given, 68 samples were used in the development of this chronology. By using Windendro and COFECHA, the preparation and crossdating procedures within section 3.2.2.1. and 3.2.2.2. above, each individual ring was measured and crossdated across all other series of the chronology. Samples that were unable to be accurately dated based on irregular growth and other informalities such as the inability to precisely date cross sections were discarded. The final chronology depicted in Table 4.1, illustrates a Rocky Mountain juniper chronology with a total of 68 series spanning 492 BC to 2014 AD with a interseries correlation of .755 and a mean sensitivity of .614. The chronology also had 4 segment problems (50 years of low correlation values, below .3250) and a mean series length of 450.7 years.

Table 4.1

Descriptive statistics for CAN Chronology used to reconstruct scPDSI of west-central New Mexico

Site Name	**Species**	**Time Span (year A.D)**	**No. Series**	**Interseries Correlation**	**Mean Sensitivity**	**No. Segment Problems**	**Mean Length of Series (yrs)**
CAN	JUSC	-492–2014	68	0.755	0.614	4	450.7

4.2 CAN Pre-Reconstruction Analyses

The standardization used to normalize the CAN chronology produced was a negative any slope. The negative any slope was used to normalize the described long-term decline in ring width due to geometric amplitude (reduction of tree-ring size as the tree grows in circumference). The standardized chronology produced was used for all other analyses in this study due to its ability to maintain the low-frequency variation needed for analyses of long-term hydroclimatic trends. The standardized negative any slope CAN chronology was tested against monthly scPDSI and found that the chronology was significantly correlated throughout the period of previous March through current December (with the exception of previous May) (Figure 4.1). Because of this finding, total water-year mean scPDSI (previous October to current September) was used for all following analyses.The CAN chronology effectively modeled the water-year scPDSI and yielded a reconstruction that extends from 80 BC to 2013 AD. The chronology explained 51.5 percent of the variance of scPDSI in the instrumental period. The reconstruction successfully illustrates the interannual and lower frequency variation of the period (Figure 4.2). The model does effectively predict the 1925, 1996, and 2014 extreme drought events; however, the model underestimates other extreme drought events including 1918, 1922, 1951, and 1990. Calibration and verification statistics of the reconstruction did demonstrate a robust model although the model performed better when calibrated on the early part of the record (1902 to 1956; Table 4.2). The EPS (expressed population signal) retains a 0.85 throughout the entire record; however, the reconstruction was truncated at 80 BC due to the chronology beyond that time period was solely comprised of one individual tree (0.85 is the threshold used to indicate robust signal strength (Wigley, Briffa, & Jones, 1984)). The results of the forward moving interval analysis (refer to section 3.4.) indicated a highly correlated and stable scPDSI signal throughout the calibration period (Figure 4.3). The forward moving interval analysis also showed a significant moving correlation with water-year scPDSI through the period (previous October to current September). Because of the model explained 51.5 percent of the variance in scPDSI, high calibration and verification statistics, and demonstrated a stable signal for water-year scPDSI throughout the instrumental record we proceeded to reconstruct scPDSI back to -80 BC.

Table 4.2

Calibration and verification statistics for reconstruction

Calibration Period	**R^2**	**CVRE**	**VRE**	**VCE**	**RMSE**
1957–2013	0.487	0.444	–	–	1.217
1902–1956	0.543	–	0.556	0.285	1.217
1902–2013	0.515	–	–	–	1.217

R^2 = calibration/verification period coefficient of determination; CVRE = Calibration period reduction of error calculated by cross-validation; VRE = validation period reduction of error; VCE = validation period coefficient of efficiency; RMSE = root mean square error

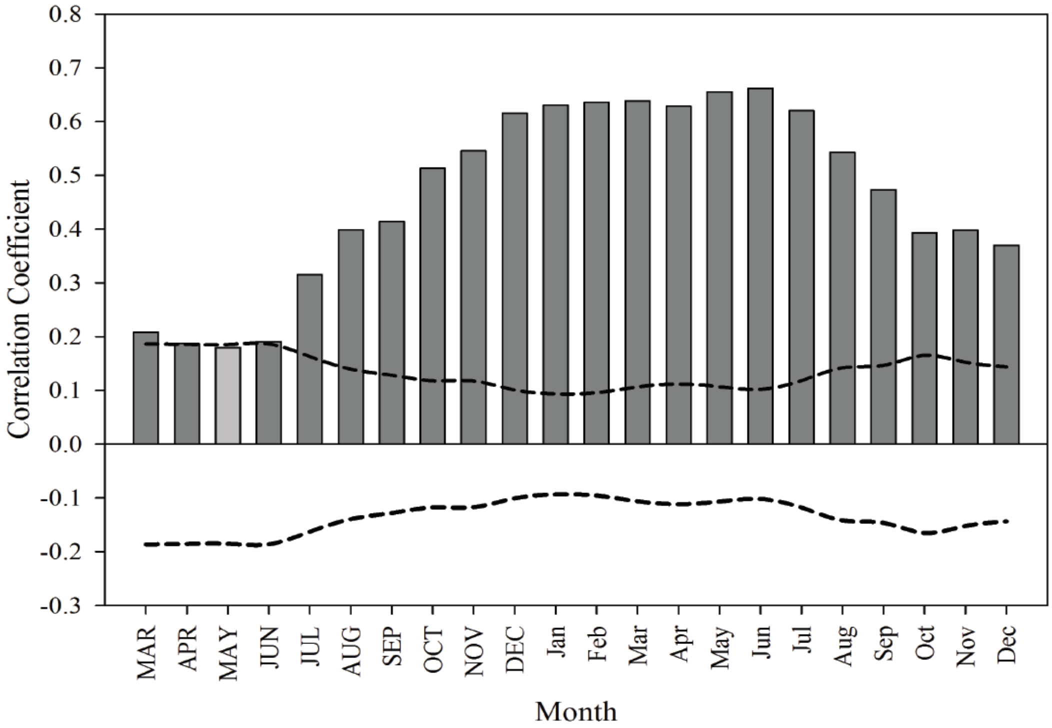

Figure 4.1 Correlation coefficients (y-axis) showing the relationship between the CAN chronology and monthly scPDSI from previous March to current December (1902–2013)

Significant correlations shown in dark grey; insignificant correlations show in light grey.

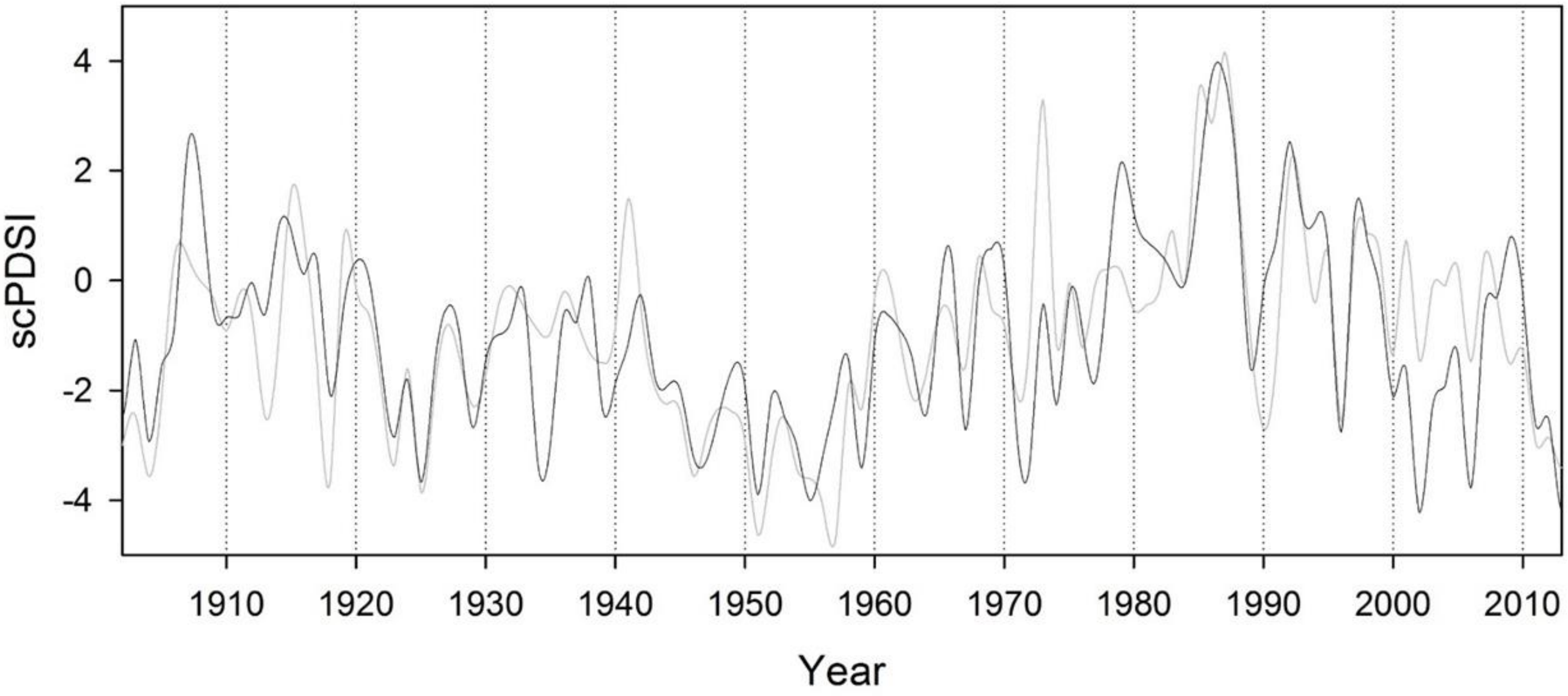

Figure 4.2 Modeled (black line) and observed (gray line) water year (October-September) scPDSI from 1902 to 2013

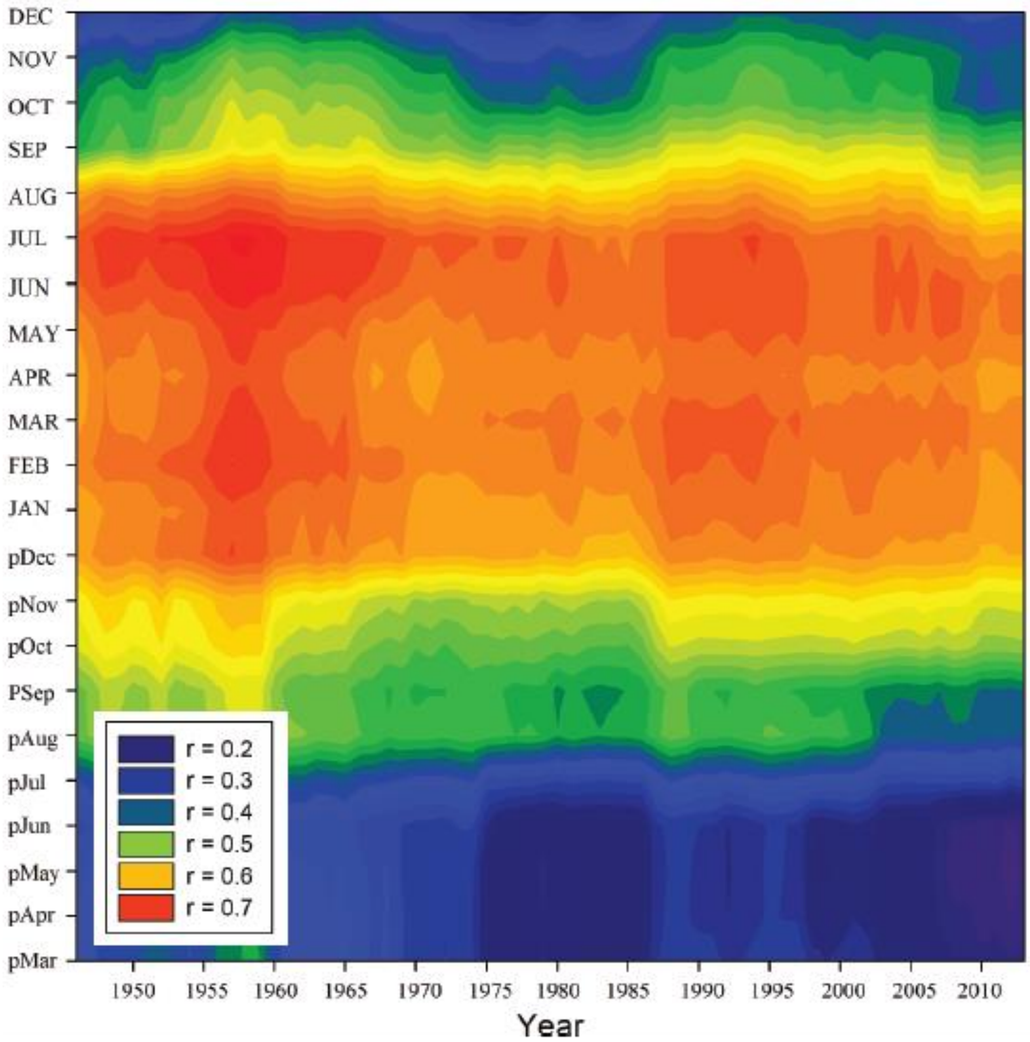

Figure 4.3 Forward moving interval analysis between CAN chronology and scPDSI from previous March to current December

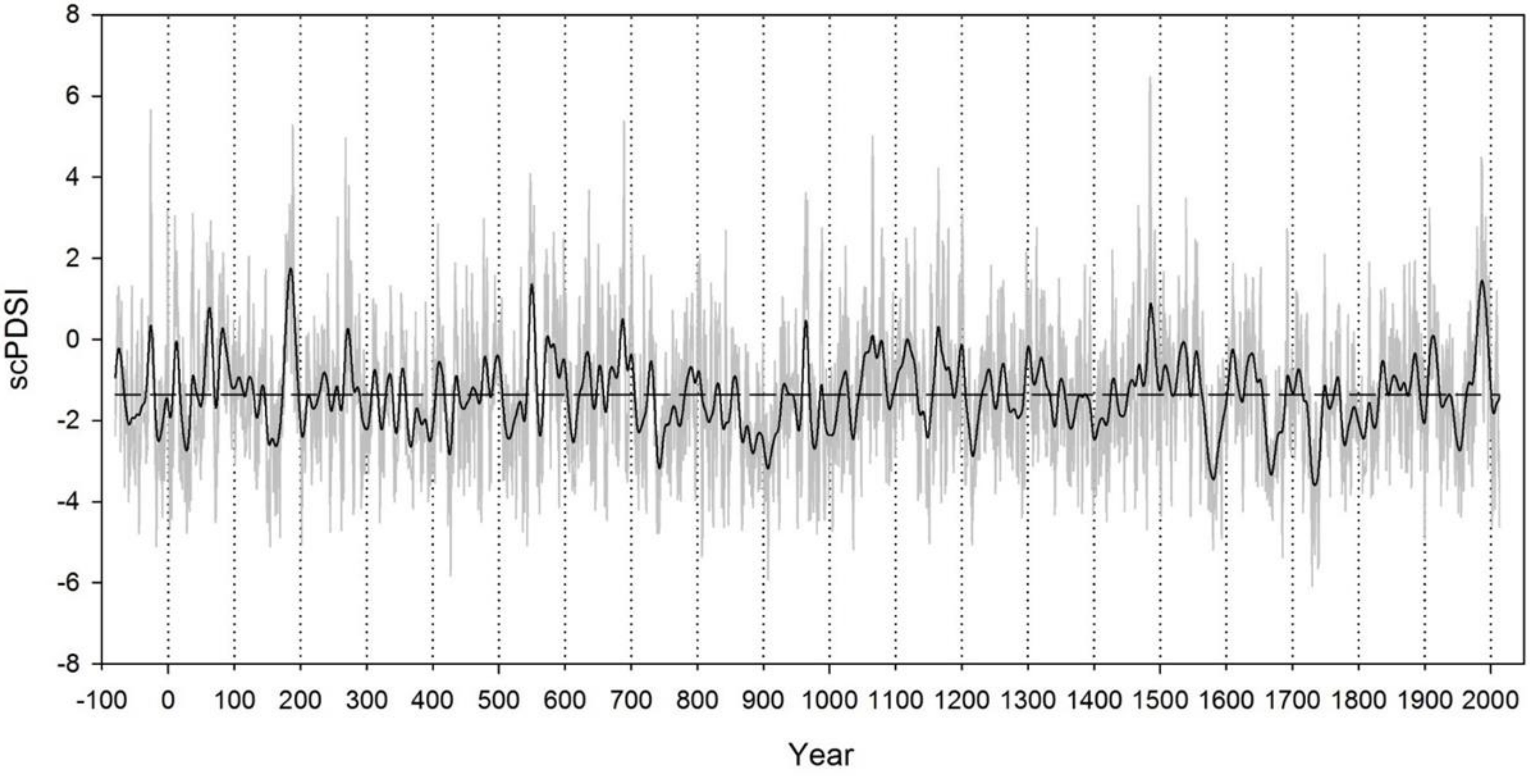

Figure 4.1 Reconstruction of water-year scPDSI for west-central New Mexico from 80 BC to 2013 AD

Showing MEBoot confident intervals (grey line) and a 25-year smoothing spline (black line). Reconstruction mean = -1.362 (dashed black line)

4.3 CAN scPDSI Reconstruction and Past Extreme Events

The ability for the CAN reconstruction to demonstrate strong interannual, decadal and multidecadal-scale variability over the past two millennia is shown in Figure 4.4 above. The reconstruction spans a 2,093-year period (80 BC to 2013 AD) and exhibits a mean scPDSI of -1.362 and a RMSE of 1.217. The reconstruction displays persistent and/or severe droughts within the 100s, 500s, 700s, 800s, 900s, 1200s, 1500s, 1600s, 1700s, and 1900s. The results of the runs analysis of drought also identified several less persistent and/or severe dry periods of 2+ years in duration (total of 219 drought events). During the instrumental record (1902–2013), only one extreme drought event based on overall score (Table 4.3) was discovered; 1943-1959, tied for 5th most severe. Comparatively, other centuries including the 100s, 500s, 800s, and 1700s were found to have more severe droughts (within the top 25), than any other century within the 2,093-year period. The longest drought 1724–1746 (duration of 23 years) was also the most severe drought in terms of magnitude (cumulative flow below the mean) at -40.09 with the highest overall of 235. The 2-year drought of 951–952 was found to be most intense drought of the reconstruction; however, it places as the 89th most severe with an overall score of 136.

Long-term pluvial events are also apparent within the reconstruction. The reconstruction illustrates persistent and severe pluvial events within the 1st century BC, 100s, 200s, 300s, 500s, 1000s, 1100s, 1400s, and 1900s. The runs analysis of pluvial events throughout the reconstructed period identified 208 2+ year events that sustained a value greater the -1.362 (reconstructed mean of scPDSI). 3 of the top 25 pluvial events occurred within the instrumental period (Table 4.4): (1)1979–1988, 4th most severe pluvial event; (2) 1906–1917, tied 6th; (3); 1990–1995, tied 15th. Compared to other centuries represented within the top 25 severe pluvial events, the 1900s was rivaled only by the 1st century AD; both having 3 top 25 pluvial events. The most continuous pluvial event occurred from 176 to 190, a duration of 15 years. The same event had the greatest magnitude (cumulative flow above the mean) at 42.39 and the highest overall score possible of 215; thus, being ranked 1st of the most severe pluvial events obtained from this reconstruction. In terms of intensity, the pluvial event that occurred from 1481 to 1486 was found to be most severe at an intensity of 3.37 per year above the reconstructed mean of scPDSI and ranked 9th with an overall score of 200.

Table 4.3

Periods of the reconstruction with consecutive years below the reconstructed mean, including duration, magnitude (CFBM= cumulative flow below the mean), and intensity (magnitude/duration)

Period	**Duration (years)**	**Magnitude (CFBM–scPDSI)**	**Intensity (CFBM–scPDSI /yr)**	**Score**
1724–1746	23	-40.09	-1.74	235
1567–1587	21	-35.72	-1.70	233
900–916	17	-27.95	-1.64	231
1661–1674	14	-25.80	-1.84	229
1943–1959	17	-20.63	-1.21	228
738–751	14	-22.77	-1.63	228
420–432	13	-18.27	-1.41	224
878–889	12	-18.72	-1.56	224
24–34	11	-18.01	-1.64	221
361–371	11	-16.19	-1.47	220
1773–1782	10	-15.59	-1.56	218
1819–1831	13	-13.48	-1.04	217
864–872	9	-13.52	-1.50	214
557–567	12	-13.12	-1.09	213
391–400	10	-13.25	-1.32	213
149–154	6	-15.10	-2.52	213
1146–1151	6	-13.72	-2.29	212
21–12	10	-12.61	-1.26	209
1213–1219	7	-13.14	-1.88	209
512–521	10	-12.59	-1.26	208
1–8	8	-13.01	-1.63	208
1030–1039	10	-12.50	-1.25	207
158–167	10	-12.39	-1.24	205
1397–1405	9	-12.48	-1.39	205
341–348	8	-12.22	-1.53	202

The top 25 drought events with the highest overall scores are shown, sorted by highest to lowest score. Maximum score of 235, Bold represents periods in the instrumental record and italicized indicates periods AD

Table 4.4

Periods of the reconstruction with consecutive years above the reconstructed mean, including duration, magnitude (CFAM= cumulative flow above the mean), and intensity (magnitude/duration)

Period	**Duration (years)**	**Magnitude (CFAM–scPDSI)**	**Intensity (CFAM–scPDSI /yr)**	**Score**
176–190	15	42.39	2.83	215
55–68	14	27.72	1.98	211
545–556	12	32.48	2.71	211
1978–1988	11	30.71	2.79	209
683–691	9	23.86	2.65	205
1906–1917	12	19.51	1.63	204
960–968	9	23.31	2.59	204
77–87	11	19.31	1.76	202
30–22	9	20.18	2.24	202
491–505	15	14.77	0.98	201
1112–1125	14	16.88	1.21	201
1481–1486	6	20.21	3.37	200
9–16	8	17.94	2.24	198
569–577	9	16.93	1.88	197
1525–1537	13	13.79	1.06	196
475–484	10	14.32	1.43	195
1162–1167	6	17.63	2.94	195
1603–1613	11	13.62	1.24	192
271–278	8	13.69	1.71	190
1990–1995	6	14.14	2.36	190
1549–1557	9	13.30	1.48	189
592–602	11	12.55	1.14	187
1297–1303	7	13.06	1.87	185
1063–1067	5	13.13	2.63	184
697–702	6	13.01	2.17	183

The top 25 pluvial events with the highest overall scores are shown, sorted by highest to lowest score. Maximum score of 215. Bold represents periods in the instrumental record and italicized indicates periods AD

CHAPTER V DISCUSSION

5.1 Evaluation of Other Drought Reconstructions within the American Southwest

The newly reconstructed record of scPDSI illustrates how moisture availability within west-central New Mexico has varied on an annual, decadal, and centurial timescale over the past 2,093 years. The 5-year running average in Figure 5.1 shows this variability, in the finest detailed, of persistent and severe drought and pluvial events. The variability on a decadal time frame (10-year running average; Figure 5.1) still illustrates this variability with the most persistent and severe drought and pluvial events governing the variability throughout the reconstructed period. Figure 5.2 demonstrates the running averages of 25 and 50-year intervals and displays the most persistent and severe events on a centurial time scale. The reconstructed record reveals several persistent drought and pluvial events that corresponds with recent literature within the 2093-year period. The CAN reconstruction of scPDSI displays 'megadroughts' (persistent and severe dry periods), within the more recent time period; 1700s, 1600s, and 1500s. The most severe dry period within these centuries 1724–1746 (ranked 1st; refer to Table 3 above) is not well documented within the recent literature. The time period is illustrated as below the reconstructed mean within Bekker et al. (2014), Gray et al. (2011), Grissino-Mayer (1996), Routson et al. (2011), and Stahle et al. (2007); however, the time period is not normally as severe within in other records. Bekker et al. (2014), a tree-ring reconstruction of the Weber River streamflow in Utah, does rank the year 1729 as the 22nd worse drought year within their 576-year reconstruction. The time period. 1735 –1737, of the Weber River streamflow reconstruction, was ranked as the 14th most severe drought event within the record (Bekker et al., 2014). Although these records do not show this time period as being very severe, the time period is illustrated as below mean values within other tree-ring reconstructions regarding drought variability within the American Southwest.

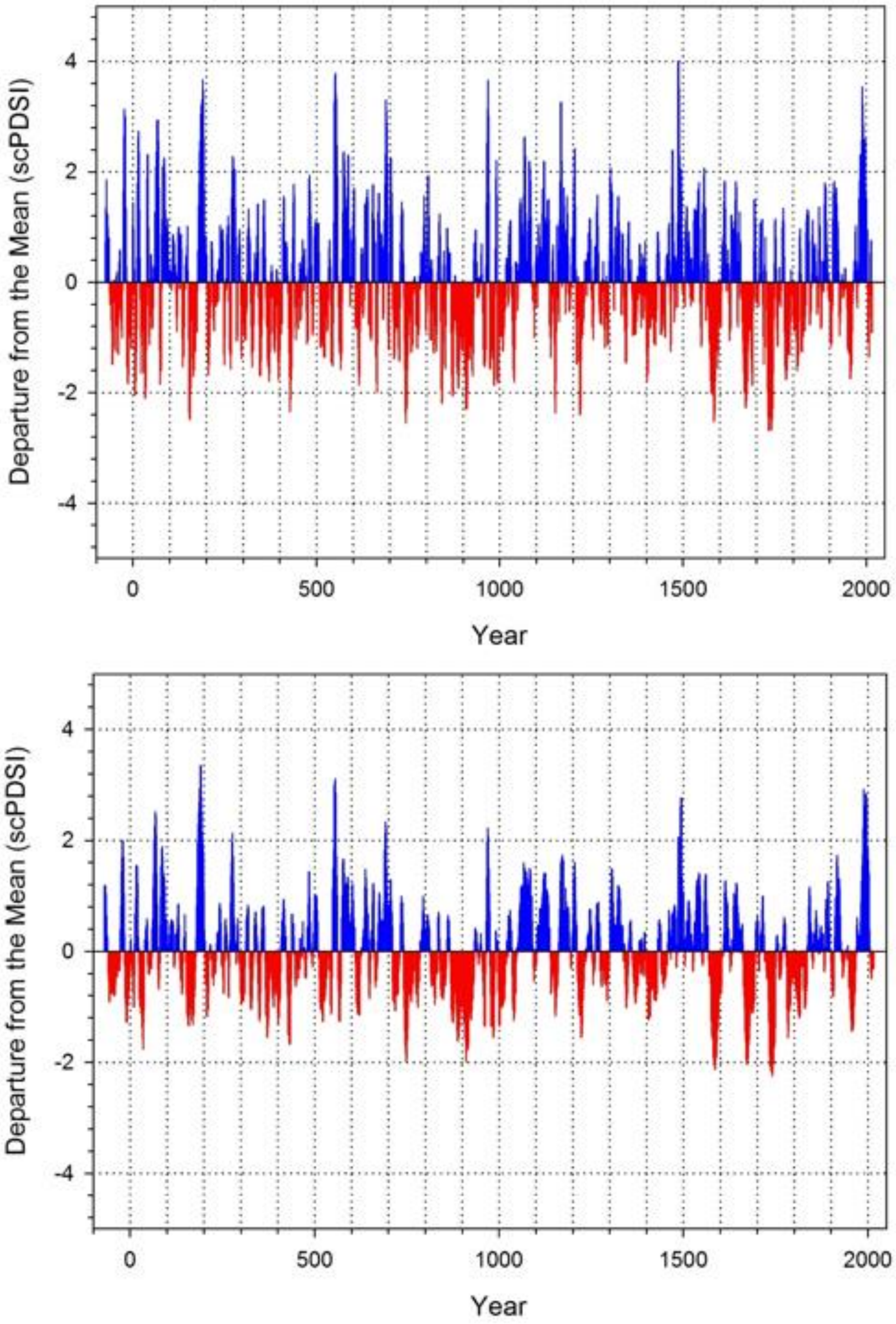

Figure 5.1 5-year (top) and 10-year (bottom) running averages of scPDSI during the reconstructed period (80 BC–2013 AD).

Below reconstructed average shown in red and above-reconstructed average in blue

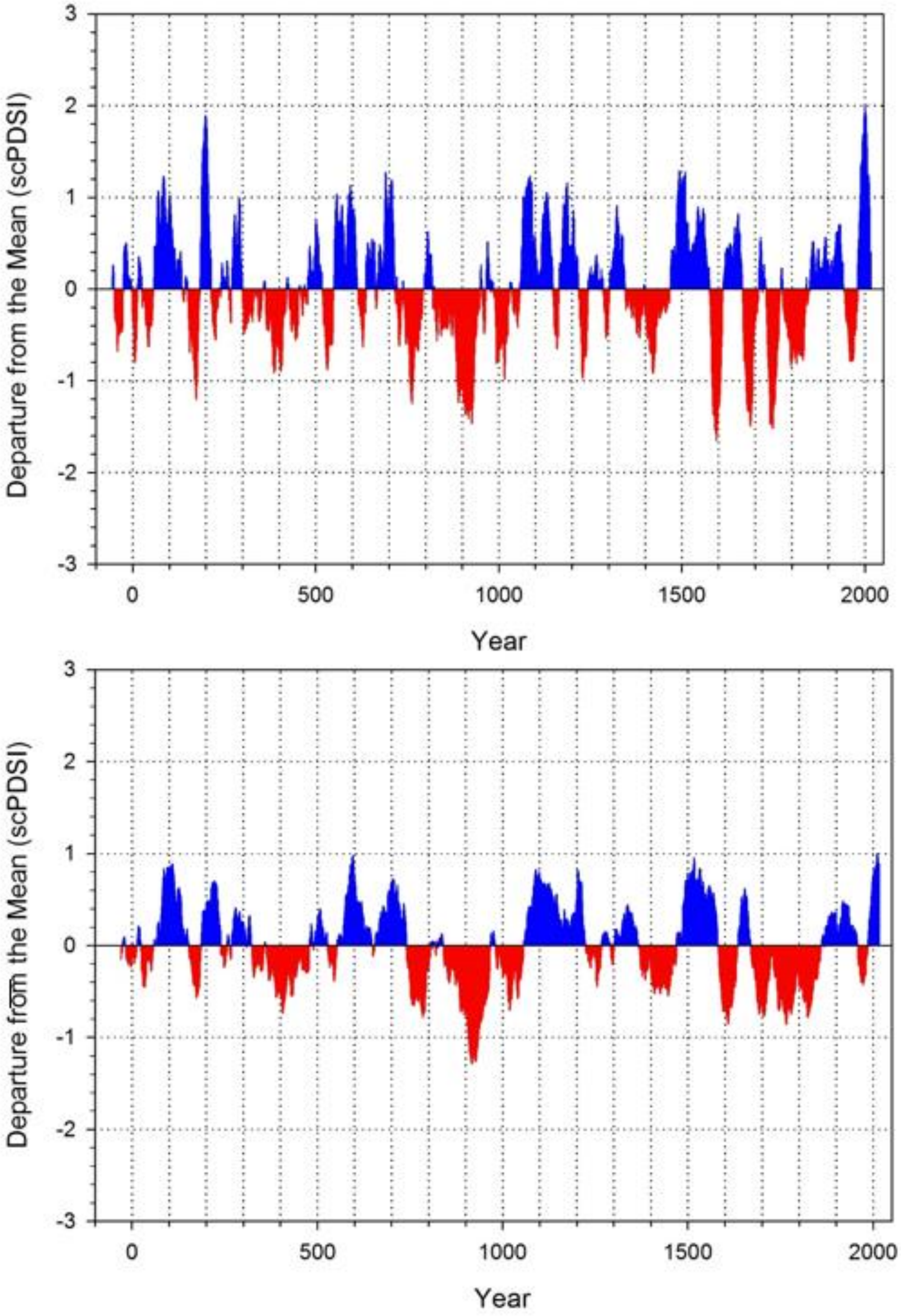

Figure 5.2 25-year (top) and 50-year (bottom) running averages of scPDSI during the reconstructed period (80 BC–2013 AD)

Below reconstructed average shown in red and above-reconstructed average in blue

The megadrought found within the 16th century has been well documented within other dendroclimatic studies (Bekker et al., 2014; Stahle et al., 2007). The PDSI reconstruction of all 286 grid points across North America, Stahle et al. (2007) illustrates the time period of 1571–1586 as being the worse drought within the American Southwest during the century. Bekker et al. (2014) ranked two events, within the period of the megadrought, as the top 25 most severe drought events on record in the streamflow reconstruction of the Weber River, Utah: 1579–1581, 1583–1586 (tied for 6th). The scPDSI reconstruction from Candelaria corresponds extremely well with these drought events, indicating the period of 1567–1587 as the 2nd most severe drought event in the entire 2,093-year record (refer to Table 3 in section 4.3.).

The medieval warming or aridity period documented within Cook, Woodhouse, Eakin, Meko, and Stahle (2004), Meko et al. (2007), Routson et al. (2011), and Woodhouse and Overpeck (1998), describes the period of ~1050–1350 that was found to be considerably warmer and dryer within the 2nd millennia AD. The period expressed persistent drought events exacerbated by higher than average temperatures (Meko et al., 2007). During the medieval warming period, the CAN reconstruction of scPDSI found 2 drought events (within the top 25 drought events) within the period; 1146–1151 and 1213–1219 (ranked 13th and tied for 14th, respectively). The CAN reconstruction, however, does show much more variability within this time period than other dendroclimatic records of the recent past. The reconstruction indicates 4 periods of extreme pluvial activity: (1) 1063–1067; ranked 22nd, (2) 1112–1125, ranked 9th, (3) 1162–1167, ranked 15th, (4) 1297–1303, ranked 21st (refer to Table 4.4 in section 4.3). The 25-year and 50-year running average of the reconstructed scPDSI (Figure 5.2 above) demonstrates this variability within larger timeframes and illustrates that the medieval warming period had both persistent drought and pluvial events. Although the warming period exacerbated drought conditions due to higher than average temperatures, the warming period could have been responsible for accelerated evaporation rates. The variable rate at which stored water could have evaporated could be responsible for the decadal shifts in drought and pluvial events within the medieval period of this reconstruction.

Comparatively, the medieval warming period is rivaled by an extreme drought event in the 1st millennia found in recent publications (Cook et al., 2008; Grissino-Mayer, 1996; Knight et al., 2010; Routson et al., 2011). The period, *ca.* 100–400, has been found to have excessive lower yearly values in gridded PRISM (monthly precipitation and temperature; Rio Grande headwaters hydrologic unit) (Routson et al., 2011), precipitation (Grissino-Mayer, 1996; Knight et al., 2010), and PDSI (Cook et al., 2008) (Figure 5.3).

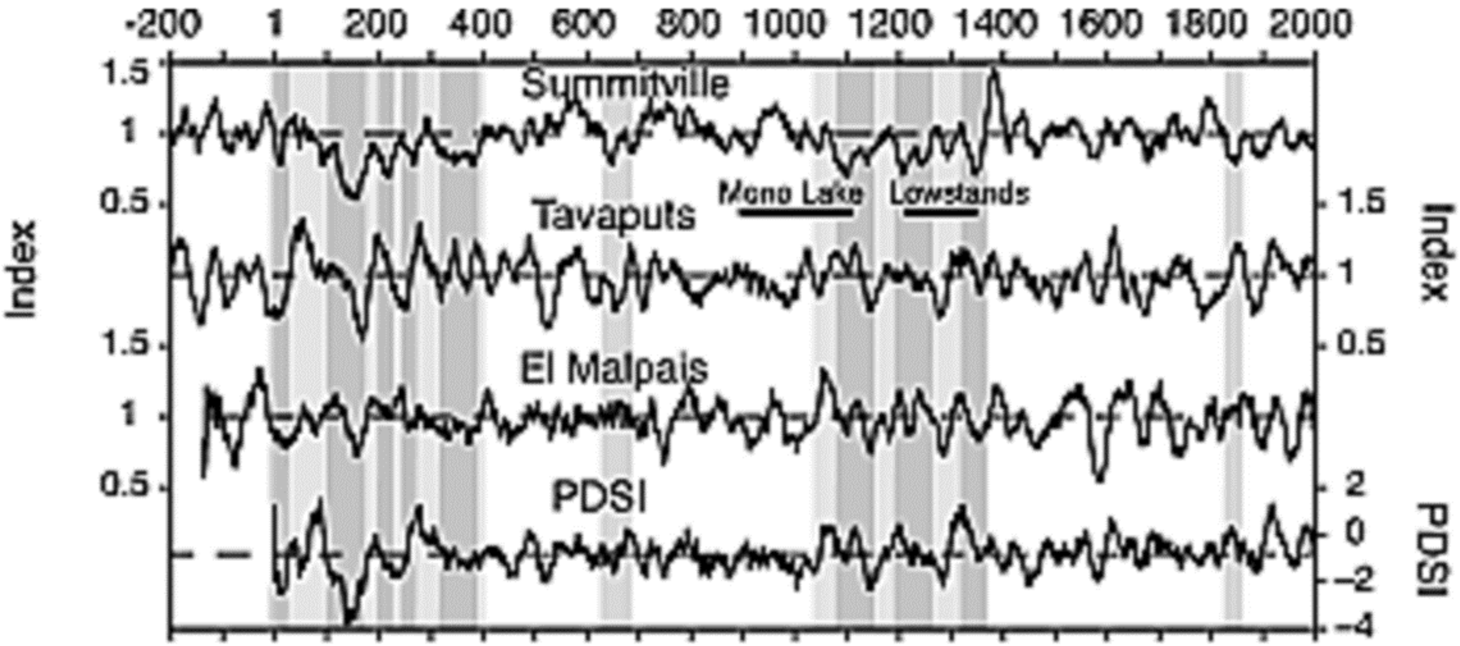

Figure 5.1 Colorado Plateau region moisture records.

Included Summitville, CO (Routson et al., 2011), Tavaputs, UT (Knight et al., 2010), El Malpais NM (Grissino-Mayer, 1996), PDSI (Cook et al., 2008).

Shaded areas reflect the 1st millennia warming period and the medieval warming period. Figure retrieved from Routson et al., 2011

All four records above in Figure 5.3 demonstrate a period of extreme drought within the 2nd century AD. The newly scPDSI reconstruction highlights this drought event within the period and ranks 2 events in particular within the top 25 most severe drought events of the past 2,093 years; 149–154 and 158–167 (ranked 15th and 23rd, respectively). The precipitation records from El Malpais (Grissino-Mayer, 1996), and Tavaputs, Utah (Knight et al., 2010) along with the PDSI reconstruction from gridded points throughout the Colorado Plateau region (Cook et al., 2008) show a steep incline in year to year variability within the later portion of the 2nd century (~170–199) which compliments the sharp increase of scPDSI of the newly produced reconstruction from Candelaria (refer to Figure 5.3 above and Figure 4 introduced in section 4.3.). Importantly, the most severe pluvial event found in the 2,093-year CAN reconstruction based upon overall score was during the period of 176–190. The 1st century AD within all four records displayed in Figure 5.3 demonstrate elevated levels of water availability. Comparatively, the CAN reconstruction illustrates this shift from 1st century pluvial to 2nd-century drought. Tied for the most recorded pluvial events in a single century, within the top 25 of all pluvial events, occurred in the 1st century AD (Ties with the 6th century). 3 individual events, accounting for 33 years of pluvial activity, are among the highest pluvial events within the past two millennia; (1) 9–16 (ranked 10th), (2) 55–68 (tied for 2nd), (3) 77–87 (tied for 6th). This shift from the 1st century 'megapluvial' to 2nd century megadrought displayed among the records, across space (many different parts of the Colorado Plateau region), across elevation, and differences in tree species used to reconstruct (*Juniperus scopularum, Pseudotsuga menziesii*, and *Pinus aristata*) provides the needed confirmation on the timing and severity of these events.

Droughts of the most recent period, ~1895 –2016, have worsened due to higher than average annual and/or sub-annual temperatures (Breshears et al., 2005; Routson et al., 2011; Weiss, Castro, & Overpeck, 2009; Woodhouse et al., 2010). Comparatively, the medieval warming period indicated a rise in reconstructed annual temperatures within a temperature reconstruction of the Colorado Plateau (Salzer & Kipfmuellur, 2005). The rise in temperature demonstrated throughout this period possibly influenced the emergence of these megadroughts. However, in the same study, the 2nd century had few positive shifts towards higher temperatures (Salzer & Kipfmuellur, 2005). Illustrated in Figure 5.4, the 11-year scPDSI anomalies from the produced reconstruction of Candelaria provides the influx of solar radiation in terms of scPDSI within the time period. During both the 16th and 2nd century AD, the reconstruction demonstrates strong negative shifts in scPDSI corresponding with positive phases of solar flux. This can also indicate that regional temperature anomalies may be a common influence on megadroughts within the American Southwest. Much more global or hemispheric-scale shifts in temperature may have predisposed the region's 'normal' circulation of temperature and climatic phenomena (Cook et al., 2010; Routson et al., 2011).

Multiproxy reconstructions of the Northern Hemispheric temperatures have found differing standpoints during the 2nd century AD. Moberg, Sonechkin, Holmgren, Datsenko, and Karlen (2005) illustrated no apparent warming throughout the century; however, a recent study Ljungqvist (2010), shows a hemispheric-scale shift in higher annual temperatures within the period of ~1–300 AD in which could have influenced the severity of this megadrought. Both multiproxy records did show similar variability within the 16th century, illustrating that the 16th-century megadrought was most likely exacerbated by abnormally higher temperatures. Relatively, a ~4,000-year geological reconstruction of past climatic variability can be found within the work of Polyak and Asmerom (2001). The study aimed to determine past water availability by evaluating the rate at which annual banding of stalagmites (partially analogous of annual tree-ring formation) occurred within the karst environment of the Guadalupe Mountains located within southeast New Mexico. The study also describes the apparentness of both the 16th century and 2nd-century megadroughts, as within both periods 'growth' of stalagmites with the study site fell well below the reconstructed mean (Polyak & Asmerom, 2001). Due to these past research efforts within the American Southwest, we are confident that the tree-ring reconstruction of scPDSI at Candelaria rightly identifies the timing and duration of these 'once-in-a-millennia' drought events throughout its 2,093-year timeline.

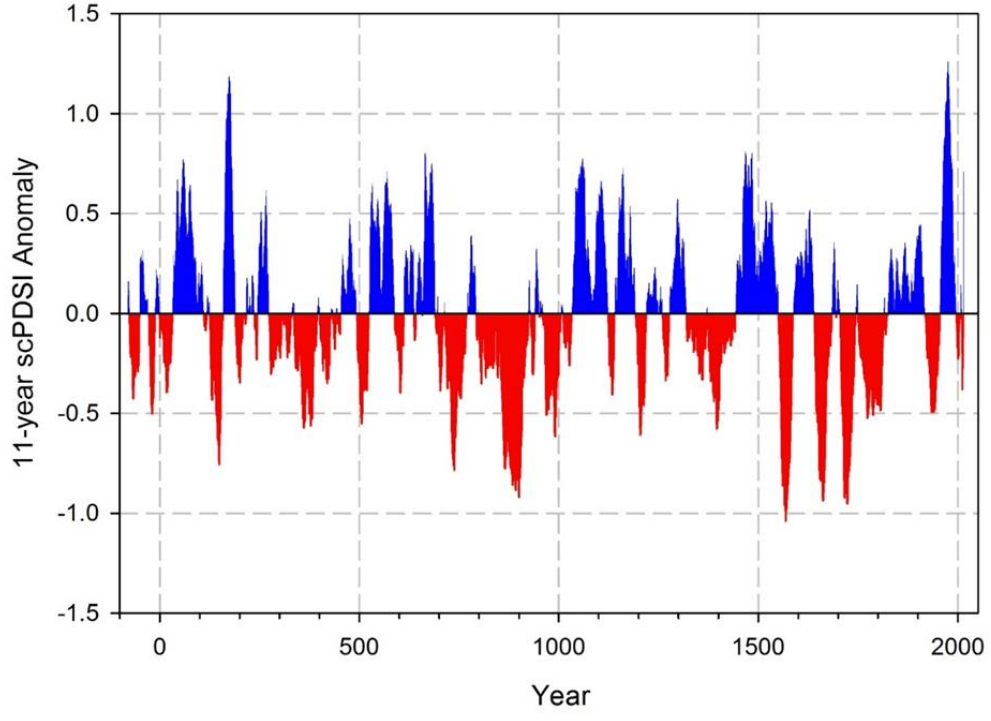

Figure 5.2 11-year scPDSI anomalies during the reconstructed period (80 BC–2013 AD)

Below reconstructed average shown in red and above-reconstructed average in blue

5.2 Evaluation of CAN Reconstruction and El Malpais Precipitation Reconstruction

Of the most dramatic differences among the tree-ring reconstructions (Refer to 5.1. and Figure 5.3 above) within the Colorado Plateau region against the reconstruction of scPDSI of this study is the absence of the megadrought event within the late 800s to mid-900s found at Candelaria. The reconstructions that had the ability to reach this time period within the region offers little information on this drought event. The PRISM reconstruction of Summitville, Colorado indicates the period to be slightly below average alongside the precipitation reconstruction of Tavaputs, Utah (Knight et al., 2010; Routson et al., 2011). The PDSI reconstruction of the Colorado Plateau showed average values within the time period; however, interestingly, the ELMA precipitation reconstruction expressed the most negative shift towards drought conditions during the period (Cook et al., 2010; Grissino-Mayer, 1996). This time period is well represented within the top 25 severe drought events within this new reconstruction of scPDSI. Three individual severe drought events took place within the period: (1) 864–872 (ranked 12th), (2) 878–889 (ranked 7th), (3) 900–916 (ranked 3rd). More severe drought events are found within this period and ranked higher in terms of overall score than that of the 2nd-century megadrought discussed previously.

The differences between the CAN reconstruction of scPDSI and the ELMA precipitation reconstruction lies in the chronologies used as the base of these two reconstructions. Figure 5.5 illustrates the sample depth throughout the entire length of both chronologies. The chronologies have roughly the same amount of samples within the period; however, the mean sample length varies between the CAN chronology and the El Malpais Long Chronology. The CAN chronology during these periods consist of samples above 470 years in length; comparatively, the ELMA chronology consists of series much less than the CAN counterpart. Mean series length is often depicted as one of the most important determinants of preserving low-frequency climatic variability. To best preserve, this variability throughout a time period, the reconstruction, and its base chronology must maintain a mean segment length greater than 470 years (Cook, Briffa, Meko, Graybill, & Funkhouser, 1995). The result of reconstructing climatic information with shorter series is usually the misrepresentation of extreme events and hinders the reconstruction's ability to produce an accurate interpretation of past climatic variability. Also, the cohort-like progression throughout the ELMA reconstruction, absent from the CAN reconstruction, could further misrepresent extreme events. The areas where these cohorts of series overlap are only comprised of ~200–300 years which could exacerbate this problem and misrepresent extreme events that occur in these 'transitional' periods. Most notably, the ELMA chronology's EPS would drop off well below .85 during one of these periods; this being the period of 501–457 AD. Within the period the chronology consists of 1 sample, halting the reconstruction at year 501 although sample depth springs back up within the early centuries of the 1st millennia AD.

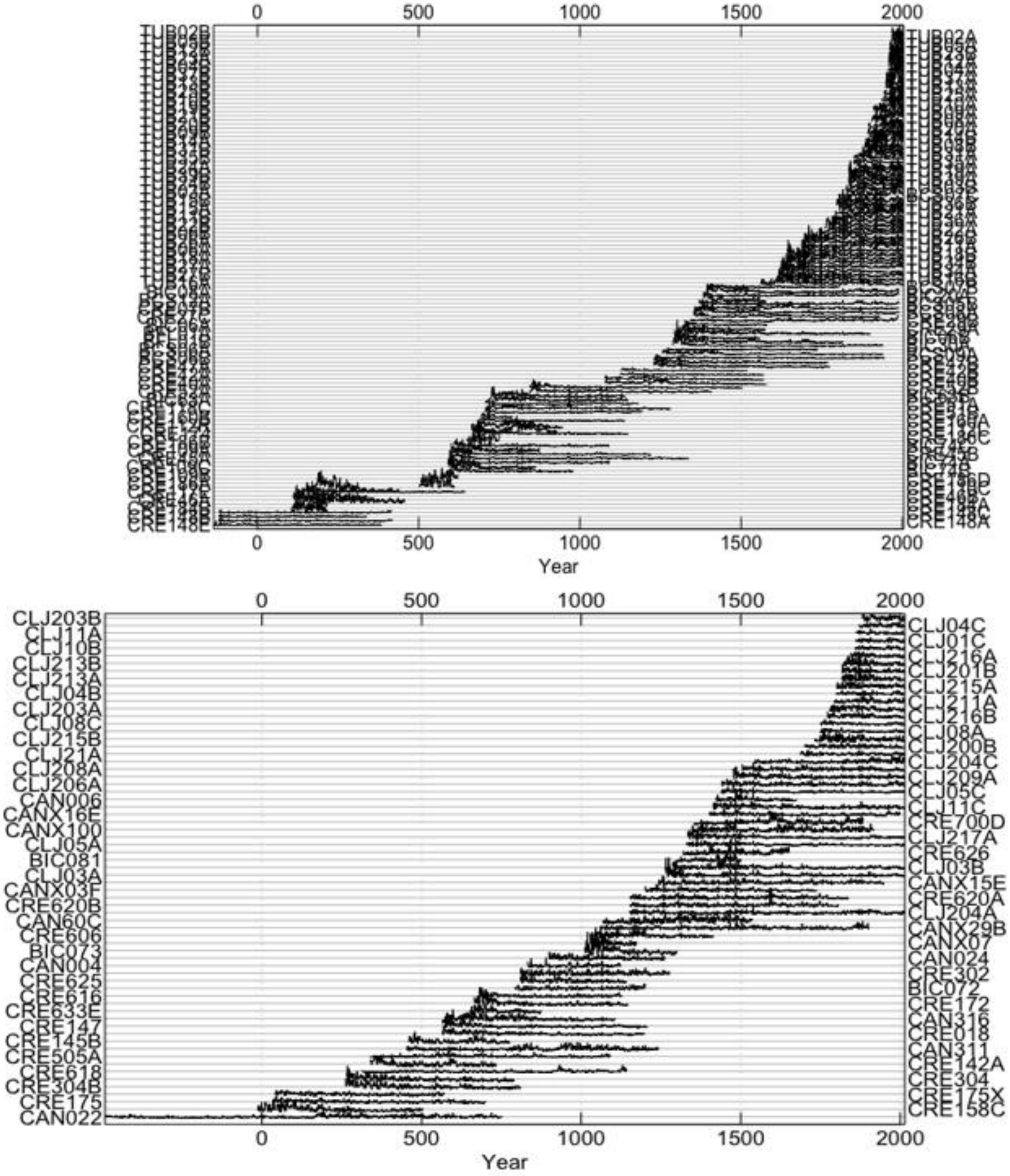

Figure 5.3 Sample depth of El Malpais Long Chronology (top) and CAN chronology (bottom)

The trees on which these reconstructions are based upon are also vital to understanding the variability in annual tree-ring growth. Rocky Mountain juniper, the species used to reconstruct scPDSI at Candelaria, is a well-known anisohydric species. Anisohydric species have a tendency of being more productive under drought conditions due to their ability to maintain higher CO_2

assimilation and stomatal conductance (Sade, Gebremedhin, & Moshelion, 2012). Douglas fir, the species used to reconstruct precipitation at EL Malpais, is a known isohydric species and does not maintain full productivity during times of drought. This inability for the individual trees sampled at El Malpais to maintain productivity at mildly dry periods would not reveal the magnitude of extreme droughts. For example, if the Douglass fir is exposed to drought conditions, roughly the same reduction of growth occurs no matter the magnitude or intensity of the drought, and consequently, neglecting the severity of extreme drought events if the chronology made from this species is used to reconstruct hydroclimatic variability. Because Rocky Mountain juniper is an anisohydric species, it has the inherent ability and sensitivity to produce annual rings during periods of drought where annual growth corresponds more accurately to the severity of the drought event.

The Summitville reconstruction of southwest Colorado was produced from bristlecone pine, a well-known temperature sensitive and anisohydric species. Stated previously, the reconstruction showed slight drought conditions within this ~850–950 megadrought period. Since the CAN reconstruction corresponds well with the year-to-year variability of this reconstruction, the 850–950 megadrought event may have been a more local occurrence within the more southern portion of the Colorado Plateau region and affected the lower elevation regions of the American Southwest. Although this newly found drought might have been a more local event, Figure 5.6 illustrates the spatial significance of Rocky Mountain juniper in regards of gridded scPDSI. The reconstruction positively correlates with the entire American Southwest radiating out from west-central New Mexico further suggesting regional-scale hydroclimatic shifts comparative to a much more centralized or localized spatial correlation of the ELMA precipitation reconstruction (Figure

5.6). Due to correlations of annual hydroclimatic variability between the 4 records discussed previously, the timing and severity of well-documented megadroughts and the inherent drought sensitivity of this species, these findings signify that the Rocky Mountain juniper growing at Candelaria have been affected by both local and regional-scale severe drought events throughout the past 2,093 years, and rightly reconstructs drought variability in the American Southwest within the past two millennia.

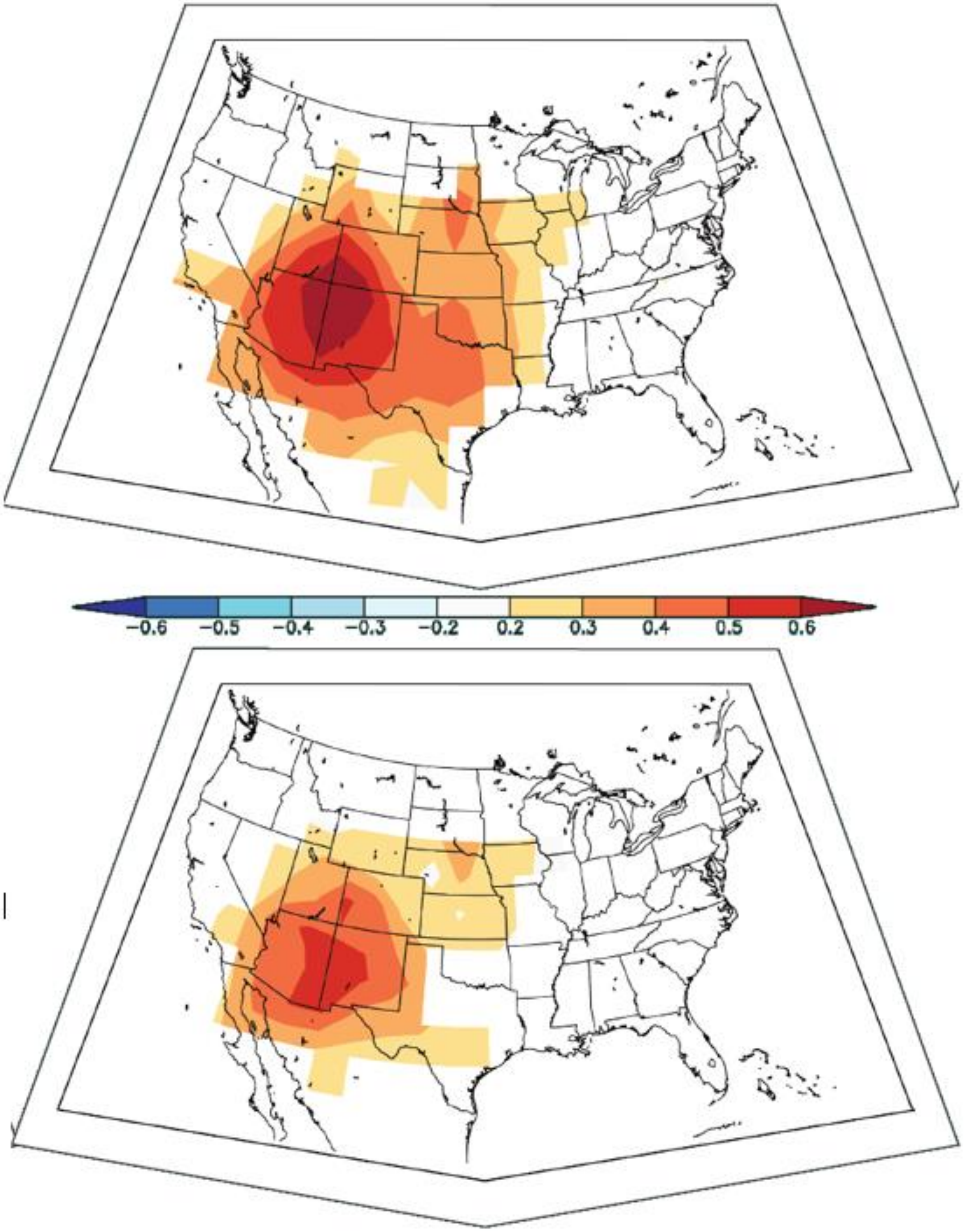

Figure 5.4 Visual comparison of spatial correlation of gridded scPDSI between CAN chronology (top) and El Malpais Long Chronology

CHAPTER VI – CONCLUSION AND IMPLICATIONS

The first multi-millennial length drought-sensitive Rocky Mountain juniper chronology produced from this research provides insight on the moisture availability and change in overall aridity of the past 2000-year period in the southwestern United States. Our record extends back confidently to 80 BC (492 BC; however, lack of sample depth caused us to truncate the record) and shows a wide-ranging drought variability throughout. The record was able to identify periods of persisting drought events that corresponds with other millennial-scale moisture-sensitive records within the Colorado Plateau region (Cook et al., 2008; Grissino-Mayer, 1996; Knight et al, 2010; Routson et al., 2011) such as the 16th century and 2nd-century megadroughts. The record also corresponds with the year-to-year variability and dramatic shifts of moisture availability found in previous tree-ring reconstructions of the area. Importantly, the CAN chronology parallels the extreme events found within large-scale multi-proxy and geological reconstructions of temperature and precipitation (Ljungqvist, 2010; Polyak & Asmerom, 2001; Salzer & Kipfmuellur, 2005) which offers insights to the scale of these drought events. The record also found major differences in drought variability across these reconstructions during ~850–950 and based on our findings, we hypothesize that extreme drought events are not unique to the medieval warming period, ~1050–1350, 16th century AD, and the 2nd century AD.

Our record also showed significant differences against our neighboring chronology, ELMA. The ELMA precipitation reconstruction was found to lack sample depth during transitional periods between cohort-like series throughout its reconstructed time period. Because of this, and alongside of a poor mean series length, the reconstruction would have misrepresented extreme drought events. Furthermore, the species used for this reconstruction, Douglas fir, is an anisohydric species and ceases growth during times of drought no matter the intensity or magnitude. This would lead to even more underestimation of extreme drought events throughout the past 2,000-year period. Because the CAN chronology was developed from a isohydric, moisture-sensitive species, Rocky Mountain juniper, had a mean series well above 470 years long in within in the time period, and closely corresponded with the year-to-year variability of other records in the area, we hypothesize that the extreme drought events including the ~850–950 events were as persistent and severe as the 16th and 2nd century 'megadroughts'.

Due to the recent effects of the Turn of the 21st Century drought on terrestrial and aquatic ecosystems and water resources in the American Southwest (Breshears et al., 2005; Udall & Overpeck, 2017), the ability to test our claims and hypotheses that rivalling drought events of the 16th and 2nd century could have occurred. To test these claims, a better network of drought-sensitive millennial-length proxy records is needed. These records will need to be able to retain short- and long-term climatic variability throughout the entirety of the record, and also be able to correlate with large-scale climate patterns. Until the climatic variability and timing and magnitude of severe drought events are thoroughly understood, water and natural resource managers should be mindful of potential extreme drought that could persist for more than 30 years and could reoccur warmer, drier, and more severe as the last.

REFERENCES

Bekker, M. F., DeRose, R. J., Buckley, B. M., Kjelgren, R. K., & Gill, N. S. (2014). A 576-year Weber River streamflow reconstruction from tree-rings for water-resource risk assessment in the Wasatch Front, Utah. *Journal of the American Water Resources Association*, *50*(5), 1338-1348. doi:10.1111/jawr.12191

Biondi, F. (1997). Evolutionary and moving response functions in dendrochronology. *Dendrochronologia*, *15*, 139-150. Retrived from http://wolfweb.unr.edu/homepage/fbiondi/Biondi1997.pdf

Biondi, F., & Qeadan, F. (2008). A theory-driven approach to tree-ring standardization: defining the biological trend from expected basal area increment. *Tree-Ring Research*, *64*(2), 81-96. doi:10.3959/2008-6.1

Biondi, F., & Waikul, K. (2004). Dendroclim2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers & Geosciences*, *30*(3), 303-311. doi:10.1016/j.cageo.2003.11.004

Braker, O. U. (2002). Measuring and data processing in tree-ring research–a methodological introduction. *Dendrochronologia*, *20*(1-2), 203-216. doi:10.1078/1125-7865-00017

Breshears, D. D., Cobb, N. S., Rich, P. M., Price, K. P., Allen, C. D., Balice, R. G., … & Anderson, J. J. (2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Science of the United States of America*, *102*(42), 15144-15148. doi:10.1073/pnas.0505734102

Briffa, K. R., Jones, P. D., Schweingruber, F. H., Karlen, W., & Shiyatov, S. G. (1996). Tree-ring variables as proxy-climate indicators: problems with low-frequency signals. In *Climatic Variations and Forcing Mechanisms of the Last 2000 Years* (pp. 9-41). Berlin Heidelberg: Springer.

Bunn, A. G. (2002). Statistical and visual crossdating in R using the dplR library. *Dendrochronologia*, *28*(4), 203-216. doi:10.1016/j.dendro.2009.12.001

Cook, B. I., Anchukaitis, K. J., Touchan, R., Meko, D. M., & Cook, E. R. (2016). Spatiotemporal drought variability in the Mediterranean over the last 900 years. *Journal of Geophysical Research: Atmospheres*, *121*(5), 2060-2074. doi:10.1002/2015JD023929

Cook, E. R., Briffa, R., Meko, D. M., Graybill, D. A., & Funkhouser, G. (1995). The "segment length curse" in long tree-ring chronology development for palaeoclimatic studies. *The Holocene*, *5*(2), 229-237. doi:10.1177/095968369500500211

Cook, E. R., Cleaveland, M. K., Eakin, C. M., Meko, D. M., Stahl, D. W., Woodhouse, C. A. (2008), North American summer PDSI reconstructions, version 2a. *IGBP PAGES World Data Center. Paleoclimate. Data Contribution Series # 2008-046*. Paleoclimatology Program, NGDC, NOAA, Boulder, CO, USA.

Cook, E. R., D'Arrigo, R. D., & Mann, M. E. (2002). A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation Index since ad 1400. *Journal of Climate*, *15*(13), 1754-1764. doi:10.1175/15200442(2002)015<1754:AWVMRO>2.0.CO;2

Cook, E. R., & Holmes, R. L. (1986). Users manual for program ARSTAN. *Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA*. Retrieved from https://www6.nancy.inra.fr/foret-boislerfob/content/.../1/.../Manuel_ARSTAN.pdf

Cook, E. R., Meko, D. M., Stahle, D. W., & Cleaveland, M. K. (1999). Drought reconstructions for the continental United States. *Journal of Climate*, *12*(4), 1145-1162. doi:10.1175/1520-0442(1999)012<1145:DRFTCU>2.0.CO;2

Cook, E. R., & Pederson, N. (2011). Uncertainty, emergence, and statistics in dendrochronology. In *Dendroclimatology* (pp. 77-112). Rotterdam, Netherlands: Springer.

Cook, E. R., & Peters, K. (1981). The smoothing spline: a new approach to standardizing forest interior tree-ring series for dendroclimatic studies. *Tree-Ring Bulletin*, *41*, 45-53. Retrieved from http://arizona.openrepository.com/arizona/bitstream/10150/261038/1/trb-41-045-053.pdf

Cook, E. R., Palmer, J. G., Ahmed, M., Woodhouse, C. A., Fenwick, P., Zafar, M. U., … & Khan, N. (2013). Five centuries of Upper Indus River flow from tree rings. *Journal of Hydrology*, *486*, 365-375. doi:10.1016/j.jhydrol.2013.02.004

Cook, E. R., Palmer, J. G., Cook, B. I., Hogg, A., & D'Arrigo, R. D. (2002). A multi-millennial palaeoclimatic resource from Lagarostrobos colensoi tree-rings at Oroko Swamp, New Zealand. *Global and Planetary Change*, *33*(3), 209-220. doi:10.1016/S0921-8181(02)00078-4

Cook, E. R., Palmer, J. G., & D'Arrigo, R. D. (2002). Evidence for a 'Medieval Warm Period' in a 1,100-year tree-ring reconstruction of past austral summer temperatures in New Zealand. *Geophysical Research Letters*, *29*(14), 12-1-12-4. doi:0.1029/2001GL014580

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. W. (2004). Long- term aridity changes in the western United States. *Science*, *306*(5698), 1015-1018. doi:10.1126/science.1102586

D'Arrigo, R. D., & Wilson, R. (2006). On the Asian expression of the PDO. *International Journal of Climatology*, *26*(12), 1607-1617. doi:10.1002/joc.1326

Douglass, A. E. (1929). The secret of southwest solved by talkative tree rings. *National Geographic Magazine*, *56*(6), 736-770. Retrieved from http://isu.indstate.edu/jspeer/dendro/Douglass1929.pdf

Douglass, A. E. (1941). Crossdating in Dendrochronology. *Journal of Forestry*, *39*(10), 825-831. Retrieved from http://www.ingentaconnect.com/content/saf/jof/1941/00000039/00000010/art00006#expand/collapse

Fritts, H. C. (1976). *Tree Rings and Climate*. New York, NY: Academic Press Inc.

Gray, S. T., Lukas, J. J., & Woodhouse, C. A. (2011). Millennial-length records of streamflow from three major Upper Colorado River tributaries. *Journal of the American Water Resources Association*, *47*(4), 702-712. doi:10.1111/j.1752-1688.2011.00535.x

Griffin, D., Meko, D. M., Touchan, R., Leavitt, S. W., & Woodhouse, C. A. (2011). Latewood chronology development for summer moisture reconstruction in the US Southwest. *Tree-Ring Research*, *67*(2), 87-101. doi:10.3959/2011-4.1

Grissino-Mayer, H. D. (1996). A 2129-year reconstruction of precipitation for northwestern New Mexico. In *Tree Rings, Environment, and Humanity* (pp. 191-204). Tucson, AZ: University of Arizona Press.

Grissino-Mayer, H. D. (2001). Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research*, *57*(2), 205-221. Retrieved from http://arizona.openrepository.com/arizona/handle/10150/251654

Grissino-Mayer, H. D. & Swetnam, T. W. (1995). Effects of habitat diversity on fire regimes in El Malpais National Monument, New Mexico. *General technical report INT (USA)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=US9730850

Grissino-Mayer, H. D., Swetnam, T. W., & Adams, R. K. (1997). The rare old-aged conifers of El Malpais: their role in understanding climate change in the American Southwest. *New Mexico Bureau of Mines & Mineral Resources, Bulletin*, *156*, 155-161. Retrieved from http://www.ltrr.arizona.edu/~tswetnam/tws-pdf/malpaisclimate97.pdf

Hoekema, D. J., & Sridhar, V. (2011). Relating climatic attributes and water resources allocation: a study using surface water supply and soil moisture indices in the Snake River Basin, Idaho. *Water Resources Research*, *47*(7). doi:10.1029/2010WR009697

Holmes, R. L. (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, *43*(1), 69-78. Retrieved from http://arizona.openrepository.com/arizona/handle/10150/261223

Hughes, M. K., & Graumlich, L. J. (1996). Multimillennial dendroclimatic studies from the western United States. In *Climatic Variations and Forcing Mechanisms of the Last 2000 Years* (pp. 109-124). Berlin, Germany: Springer.

Knight, T., Meko, D., & Baisan, C. (2010). A bimillenial-length tree-ring reconstruction of precipitation for the Tavaputs Plateau, Northeastern Utah. *Quaternary Research*, *73*(1), 107-117. doi:10.1016/j.yqres.2009.08.002

Li, J., Xie, S. P., Cook, E. R., Morales, M. S., Christie, D. A., Johnson, N. C., … & Fang, K. (2013). El Niño modulations over the past seven centuries. *Nature Climate Change*, *3*(9), 822-826. doi:10.1038/nclimate1936

Li, Q., Nakatsuka, T., Kawamura, K., Liu, Y., & Song, H. (2011). Hydroclimate variability in the North China Plain and its link with El Niño–Southern Oscillation since 1784 AD: Insights from tree- ring cellulose δ18O. *Journal of Geophysical Research: Atmospheres*. *116*(D22). doi:10.1029/2011JD015987

Ljungqvist, F. C. (2010). A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geographical Analysis*, *92*(3), 339-351. doi:10.1111/j.1468-0459.2010.00399.x

MacDonald, G. M. (2010). Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences*, *107*(50), 21256-21262. doi:10.1073/pnas.0909651107

MacDonald, G. M., & Case, R. A. (2005). Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters*, *32*(8). doi:10.1029/2005GL022478

Maxwell, R. S., Wixom, J. A., & Hessl, A. E. (2011). A comparison of two techniques for measuring and crossdating tree rings. *Dendrochronologia*, *29*(4), 237-243. doi:10.1016/j.dendro.2010.12.002

Meko, D. M., Woodhouse, C. A., Baisan, C. H., Knight, T., Lukas, J. J., Hughes, M. K., & Salzer, W. (2007). Medieval drought in the Upper Colorado River Basin. *Geophysical Research Letters*, *34*(10). doi:10.1029/2007GL029988.

Moberg, A. E., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., & Karlen, W. (2005). Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature*, *433*(7026), 613-617. doi:10.1038/nature03265

Nakamura, H., Lin, G., & Yamagata, T. (1997). Decedal climate variability in the North Pacific during the recent decades. *Bulletin of the American Meteorological Society*, *78*(10), 2215-2225. doi:10.1175/1520-0477(1997)078<2215:DCVITN>2.0.CO;2

Nehrbass-Ahles, C., Babst, F., Klesse, S., Notzli, M., Bouriaud, O., Neukom, R., … & Frank, D. (2014). The influence of sampling design on tree- ring- based quantification of forest growth. *Global Change Biology*, *20*(9), 2867-2885. doi:10.1111/gcb.12599

National Drought Mitigation Center. (2016). U.S. Drought Monitoring Center. Retrieved from http://www.drought.unl.edu

Polyak, J. & Asmerom, Y. (2001). Late Holocene climate and cultural changes in the southwestern United States. *Science, 294*(5540), 148-151. doi:10.1126/science.1062771

Rother, M. T. (2010). *Influences of Climate and Anthropogenic Disturbances on Wildfire Regimes of the Zuni Mountains, New Mexico, USA*. Unpublished master's thesis, The University of Tennessee, Knoxville, Tennessee.

Routson, C. C., Woodhouse, C. A., & Overpeck, J. T. (2011). Second-century megadrought in the Rio Grande headwaters, Colorado: how unusual was medieval drought? *Geophysical Research Letters*, *38*(22). doi:10.1029/2011GL050015.

Sade, N., Gebremedhin, A., & Moshelion, M. (2012). Risk-taking plants: anisohydric behavior as a stress-resistance trait. *Plant Signal Behavior*, *7*(7), 767-770. doi:10.4161/psb.20505

Salzer, M. W., & Kipfmueller, K. F. (2005). Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau. *Climate Change*, *70*(3), 465-487. doi: 10.1007/s10584-005-5922-3

Schulman, E. (1954). Longevity under adversity in conifers. *Science*, *119*(3091), 396-399. Retrieved from http://wmrc.edu/history/docs/science-1954.pdf

Sieg, C. H., Meko, D. M., DeGaetano, A., & Ni, W. (1996). Dendroclimatic potential in the northern Great Plains. In *Tree Rings, Environment, and Humanity* (pp. 295-302). Tucson, AZ: University of Arizona Press.

Speer, J. (2010). *Fundamentals of Tree-Ring Research.* New York, NY: Springer.

Spond, M. D., van de Gevel, S. L., & Grissino-Mayer, H. D. (2014). Climate-growth relationships for Rocky Mountain juniper (Juniperus scopulorum Sarg.) on the volcanic badlands of western New Mexico, USA. *Dendrochronologia*, *32*(2), 137-143. doi:10.1016/j.dendro.2014.03.001

Stahle, D. W., & Chaney, P. L. (1994). A predictive model for the location of ancient forests. *Natural Areas Journal*, *14*(3), 151-158. Retrieved from http://www.jstor.org/stable/43911437

Stahle, D. W., Cleaveland, M. K., Therrell, M. D., Gay, D. A., D’Arrigo, R. D. Krusic, P. J., … & Moore, M. D. (1998). Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bulletin of the American Meteorological Society*, *79*(10), 2137-2152. doi:10.1175/1520-0477(1998)079<2137:EDROTS>2.0.CO;2

Stahle, D. W., Cook, E. R., Cleaveland, M. K., Therrell, M. D., Meko, D. M., Grissino-Mayer, H. D., . . . & Luckman, B. H. (2000). Tree-ring data document 16th century megadrought over North America. *Eos*, *Transactions*, *American Geogphysical Union*, *81*(12), 121-125. doi:10.1029/00EO00076

Stahle, D. W., Cook, E. R., Villlanueva-Daiz, J., Fye, F. K., Burnette, R., Griffin, D., … & Heim Jr., R. R. (2009). Early 21st-century drought in Mexico. *Eos Transactions*, *American Geophysical Union*, *90*(11), 89-90. doi:10.1029/eost2009EO11

Stahle, D. W., Fye, F. K., Cook, E. R., & Griffin, D. (2007). Tree-ring reconstructed megadroughts over North America since AD 1300. *Climatic Change, 83*(1-2), 133. doi:10.1007/s10584-006-9171-x

Stahle, D. W., Villanueva-Diaz, J., Burnette, D. J., Paredes, J., Heim, R. R., Fye, F. K., … & Stahle, D. K. (2011). Major Mesoamerican droughts of the past millennium. *Geophysical Research Letters*, *38*(5). doi:10.1029/2010GL046472

Stokes, M., & Smiley, T. (1968). *An Introduction to Tree-Ring Dating.* Tucson, AZ: University of Arizona Press.

Swetman, T. W., & Betancourt, J. L. (1990). Fire-southern oscillation relations in the southwestern United States. *Science, 249*(4972), 1017-1020. doi:10.1126/science.249.4972.1017

Trouet, V., & Taylor, A. H. (2010). Multi-century variability in the Pacific North American circulation pattern reconstructed from tree rings. *Climate Dynamics, 35*(6), 953-963. doi:10.1007/s00382-009-0605-9

Udall, B., & Overpeck, J. (2017). The 21st century Colorado River drought and implications for the future. *Water Resources Research*, *53*. doi:10.1002/2016WR019638

United States Census Bureau. (2010). US Population Projections. Retrieved from http://www.census.gov/population/www/projections/stproj.html.

United States Department of Commerce National Oceanic and Atmospheric Administration. (2011). National Climatic Data Center, Ashville, North Carolina. Retrieved from www.ncdc.noaa.gov

United States Department of Interior National Park Service. (2011). El Malpais National Monument, New Mexico. Retrieved from https://www.nps.gov/elma/index.htm

Verdon, D. C., & Franks, S. W. (2006). Long-term behavior of ENSO: interactions with the PDO over the past 400 years inferred from paleoclimate records. *Geophysical Research Letters*, *33*(6). doi:10.1029/2005GL025052

Villalba, R., & Veblen, T. (1996). A tree-ring record of dry spring-wet summer events in the forest-steppe ecotone, northern Patagonia, Argentina. In *Tree-Rings, Environment, and Humanity* (pp. 107-116). Tucson, AZ: University of Arizona Press.

Weiss, J. L., Castro, C. L., & Overpeck, J. T. (2009). Distinguishing pronounced droughts in the southwestern United States: seasonality and effects of warmer temperatures. *Journal of Climatology*, *22*(22), 5918-5932. doi:10.1175/2009JCLI2905.1

Wells, N., Goddard, S., & Hayes, M. J. (2004). A self-calibrating Palmer Drought Severity Index. *Journal of Climate*, *17*(12), 2335-2351. doi:10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2

Wigley, T. M., Briffa, K. R., & Jones, P. D. (1984). On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology*, *23*(2), 201-213. doi:10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2

Wilson, R., Cook, E. R., D'Arrigo, R. D., Riedwyl, N., Evans, M. N., Tudhope, A., & Allen, R. (2010). Reconstructing ENSO: the influence of method, proxy data, climate forcing, and teleconnections. *Journal of Quaternary Science*, *25*(1), 62-78. doi:10.1002/jqs.1297

Woodhouse, C. A., Meko, D. M., Griffin, D., & Castro, C. L. (2013). Tree rings and multi season drought variability in the lower Rio Grande Basin, USA. *Water Resources Research, 49*(2), 844-850. doi: 10.1002/wrcr.20098

Woodhouse, C. A., Meko, D. M., MacDonald, G. M., Stahle, D. W., & Cook, E. R. (2010). A 1,200-year perspective of 21st-century drought in southwestern North America. *Proceedings of the National Academy of Sciences, 107*(50), 21283-21288. doi:10.1073/pnas.0911197107

Woodhouse, C. A., & Overpeck, J. T. (1998). 2000 years of drought variability in the central United States. *Bulletin of the American Meteorology Society*, *79*(12), 2693-2714. doi:10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2