

## Article

# Dendrochronological Reconstruction of January–September Precipitation Variability (1647–2015A.D) Using *Pinus arizonica* in Southwestern Chihuahua, Mexico

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## Abstract

Climate projections suggest ecosystems could face drastic changes due to global climate change, including more severe and frequent droughts than those recorded in the last century. Paleoclimatic series provide more extensive information than that available with instrumental records, allowing for the analysis of trends and recurrence of extreme events over a longer time periods. The objective of this research was to reconstruct the precipitation variability for southwestern Chihuahua, based on the tree-ring records of *Pinus arizonica* Engelm. and to assess the influence of ocean atmospheric circulations like El Niño Southern Oscillation (ENSO) and the North American Monsoon (NAM) on both low- and high-frequency climate variability. We developed three dendrochronological series covering 214 years (1802–2015), 265 years (1750–2014) and 369 years (1647–2015), for the Talayotes (TAL), Predio Particular Las Chinas (PPC) and El Cuervo (CUE) sites, respectively. The 369-year regional chronology was significantly related to cumulative precipitation variability between January and September. Recurring droughts were observed at approximately 50-year intervals. This regional climate variability was significantly related ( $p < 0.05$ ) to Niño 3 SST and PDSI (JJA) indices. Maximum and minimum extreme events reconstructed in the last 369 years were synchronized with ENSO events, both in the El Niño warm phase and the La Niña cold phase. These results suggest that *P. arizonica* tree rings record shared a common response to the regional climate that was significantly modulated by ENSO and the NAM. This is the first dendroclimatic study to reconstruct summer precipitation patterns in northern Mexico, which is valuable given the importance of this seasonal precipitation on the regional economy.

**Keywords:** tree rings; summer precipitation; ENSO; drought; NAM



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## 1. Introduction

The direct impacts of climate change on precipitation and temperature are of great interest to the human populations that depend on natural systems [1,2]. The report of the

Intergovernmental Panel on Climate Change (IPCC) has projected a decrease in precipitation and an increase in temperature [3], which have been linked to structural changes in forested ecosystems and the mass mortality of trees [4,5]. Studies using tree-ring width indices have suggested that the impact of extreme drought on productivity can last up to several years and that the impacts are the greatest in semi-arid forests in the Northern Hemisphere [6,7]. Droughts are of concern worldwide, especially in arid and semi-arid regions [8], where droughts are expected to increase both in frequency and extend over time [9,10]. These effects are especially important in the region that serves as the focus of this study.

Precipitation in most of Mexico occurs in the summer season [11] and is influenced by ocean temperatures. Most (>70%) of the annual precipitation is recorded in the warm season between May and October, and less than 30% during the remaining months of the year [12]. Precipitation in northern Mexico is seasonal and strongly influenced by the North American Monsoon [13–15], which pulls moisture from both the Gulf of Mexico and the Pacific Ocean. Similarly, climate patterns in northern Mexico are influenced by El Niño Southern Oscillation (ENSO) that affects climates worldwide, with a strong influence in areas with subtropical humid climates [16,17]. Interannual climate variability across Mexico is, therefore, largely determined by ENSO [18–20].

Understanding how regional climate patterns vary over time and what causes this variability is important for economies that rely on this water. Worldwide, observational climate records are relatively short (150 years) and even shorter in Mexico (less than 80 years) [21]. Therefore, assessing whether ENSO behavior in the 20th century is not possible using observational records [22–28]. However, tree-ring-based paleoclimate reconstructions provide a long-term (several centuries) perspective for understanding the influence of ENSO on the regional precipitation pattern [29].

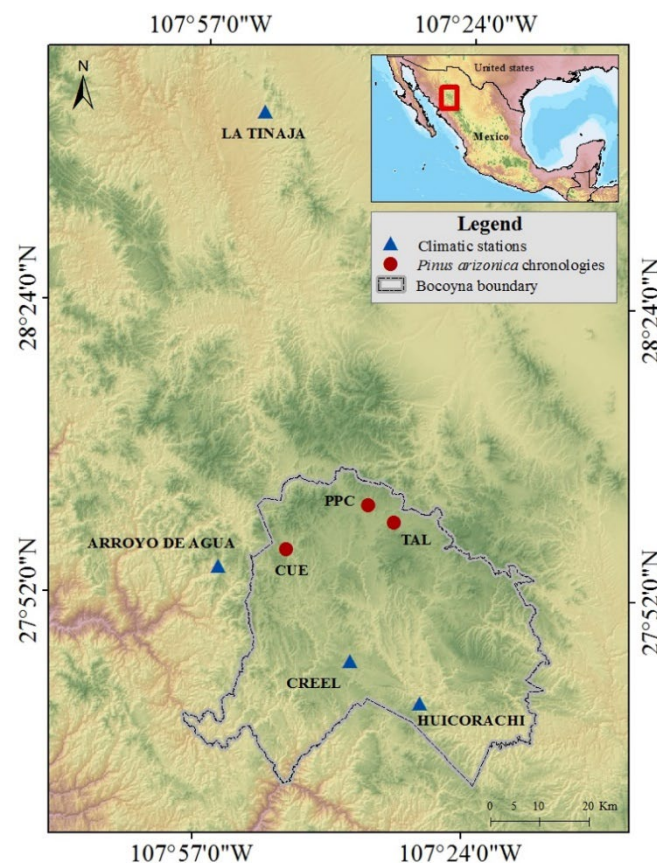
Tree ring information is crucial due to high temporal resolution, sensitivity to climate, and wide spatial distribution [30]. Large-scale or regional climate patterns for the past hundreds-to-thousands of years have been reconstructed using tree ring data worldwide [30–33]. Important progress has also been achieved in the development of paleoclimatic series during the last decades in this region, including the state of Chihuahua [34,35]. However, these studies have only reconstructed winter–spring precipitation, and few have managed to develop reconstructions that include part of the summer rainfall [36] and streamflow reconstruction [37]. Reconstructions that capture the variability of the entire summer monsoon rainfall season are lacking. Summer rainfall in Mexico is vital for agriculture and from an economic perspective, which many rural communities depend on. Significant decreases in summer precipitation affect human populations due to crop loss and public health, as there are many diseases associated with drought cycles [38–40].

Given these circumstances and the importance of summer rain patterns on social and economic aspects, it is important to understand precipitation variability at broad time scales and how this variability is influenced by climatic phenomena such as ENSO. To understand precipitation patterns and the factors that influence precipitation, the objectives of this study were to (1) generate dendrochronological series based on the tree ring growth patterns of *Pinus arizonica* Engelm., (2) reconstruct summer precipitation patterns based on the chronologies of *P. arizonica*, and (3) analyze the influence of ENSO on the variability of the reconstructed summer precipitation for northern Mexico. We tested the following research hypotheses: (1) tree ring growth variability of *P. arizonica* is a response to regional precipitation patterns, and (2) high- and low-frequency historical climate variability is significantly modulated by ENSO climate patterns.

## 2. Materials and Methods

### 2.1. Study Area

The study area was located in the Alta Sierra Tarahumara, within the municipality of Bocoyna, Chihuahua, at  $27^{\circ}50'25''$  N and  $107^{\circ}35'21''$  W, with an elevation of 2300–2800 masl (Figure 1). The municipality is part of a national forest reserve, called “Papigochi” Flora and Fauna Protection Area [41]. The climate in the study area is predominantly subhumid semi-cold with summer rains [42]. The area experiences cold temperatures and heavy snowfalls during the winter, with a maximum temperature of  $31.1^{\circ}\text{C}$  and a minimum of  $-17.8^{\circ}\text{C}$ . The average annual rainfall is 683.3 mm, most of it occurring in the summer season [39].



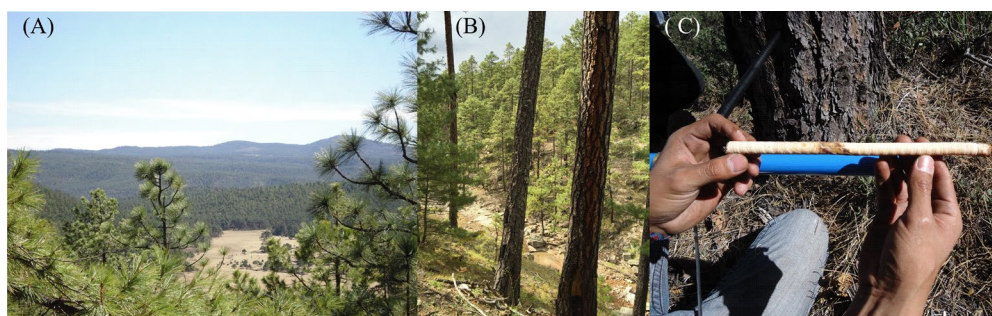
**Figure 1.** Location of the study site in the municipality of Bocoyna, Chihuahua and the geographical distribution of the tree ring chronologies and climatic stations used in the study.

### 2.2. Tree Ring Sampling

Within the study area we selected three sample sites (Figure 1, Table 1), including the following: Talayotes (TAL), Predio Particular Las Chinas (PPC) and El Cuervo (CUE). At each site, we collected increment cores from live trees using a Pressler increment borer Hagl f Sweden of 5 and 12 mm in diameter (Figure 2). We also collected cross-sections from stumps using a chainsaw Stihl MS-382 Germany. A total of 155 *P. arizonica* trees were sampled; at the PPC and CUE sites, we collected two-to-three samples per tree, and three samples per tree were collected at the TAL site (Table 1), which is the number of samples that meet the minimum recommended per site for dendroclimatic studies [43]. The elevation of the three sites ranged from 2400 to 2700 m asl (Table 1).

**Table 1.** Geographic and sampling characteristics of the three sample sites within the study area in southwest Chihuahua, Mexico.

| Site Name                    | Site Code | Long W    | Lat N   | Elevation (m) | No. of Trees | No. of Samples Collected | No. of Samples Crossdated/% |
|------------------------------|-----------|-----------|---------|---------------|--------------|--------------------------|-----------------------------|
| Predio Particular las Chinas | PPC       | −107.6004 | 28.0384 | 2536          | 52           | 129                      | 107/83                      |
| El Cuervo                    | CUE       | −107.7756 | 27.9492 | 2458          | 58           | 133                      | 118/89                      |
| Talayotes                    | TAL       | −107.5486 | 27.9902 | 2648          | 45           | 135                      | 134/99                      |
| Regional                     | REG       | ---       | ---     | ---           | 155          | 397                      | 359/90                      |

**Figure 2.** Panoramic view of *Pinus arizonica* forest (A), old trees selected (B), and samples taken from *P. arizonica* using Pressler increment borer of a 12 mm diameter (C).

Areas with the least possible disturbance were selected: PPC is a private, unmanaged area with a 30% slope. The CUE site is a forest with a 60%–70% slope under conservation due to the recording of individuals of *Picea chihuahuana* Martínez, a species listed as threatened or endangered in Mexico (Norma Oficial Mexicana 059). The TAL site is a managed forest with a 20–30% slope. However, despite the variability in conditions for each of the three study areas, the least disturbed and longest-lived individuals were selected as much as possible.

### 2.3. Laboratory Work

The samples were prepared for dating at the INIFAP CENID-RASPA Dendrochronology Laboratory. The increment cores were mounted in wood moldings and polished with sandpaper ranging from 40 to 600 grit to achieve a uniform surface to facilitate the visibility of individual tree rings under the microscope. The samples were dated using standard pattern matching techniques by comparing the growth patterns [44] to determine the exact year of formation for each annual ring. Dead trees and stumps were dated using the master chronology developed using living trees. After pre-dating, tree ring widths of all samples were measured using the Velmex measuring system, with 0.001 mm accuracy [45]. The quality of the dating was verified using COFECHA software [46]. To standardize the tree ring widths and highlight the climatic signal, biological–geometric detrending operations were performed using ARSTAN software [47]. This generated a series of standardized indices (chronology) with a mean of 1.0 and homogeneous variance [48].

### 2.4. Data Analysis

To determine similarities among the three sites we created a correlation matrix using the tree-ring width chronologies from each of the three sampled sites. This relationship was also verified using Principal Component Analysis (PCA) in order to merge the three site chronologies into a single “regional” chronology representative of climate variability for the southwest region of Chihuahua. Both analyses were conducted using STATISTICA Kernel program ver. 10.0 [49]. Based on the PCA results, dendrochronological series associated

with the first component (PC 1), and which explained the most variance, were merged to create a single tree-ring-based series [50]. Based on the PCA results, we also used the full extent of the dendrochronological series grouped in PC1 to develop the regional chronology, and we discarded the eigenvalues obtained by PCA to avoid reducing the length of the regional chronology. In addition, we estimated the expressed population signal (EPS), which describes how well-replicated a chronology is compared to an infinitely replicated chronology. We used a minimum EPS value of 0.85 as suggested by Wigley et al. [51] to identify the best replicated portions of the chronologies (individual and regional).

The influence of climate on the tree ring growth of *P. arizonica* was analyzed using response function analysis. For this analysis, we used precipitation and temperature records from weather stations near the sample sites including data from the National Water Commission (CONAGUA) and the National Meteorological Service (SMN) (Table 2). The total tree-ring width indices of the residual chronologies were compared using correlation analysis with monthly and seasonal precipitation records from weather station in Creel, Chihuahua and grid points E46182, E47137 and E50658 (interpolated precipitation records) from the precipitation gridded dataset for Mexico [52], which were points located near the towns of Huicorachi, Arroyo de Agua, and Tinaja, respectively. Temperature records, however, were only available from the Creel weather station. We used the response function analysis to determine the correlation between *P. arizonica* tree-ring width index and both monthly climate variables, as well as cumulative values between January and the corresponding month. The climate variables analyzed included precipitation, minimum temperature and maximum temperature. The period of analysis was between 1981 and 2015, based on records from weather stations in Creel, Huicorachi, Arroyo de Agua and La Tinaja in Chihuahua, Mexico. Climate data were selected based on its completeness and proximity to the tree-ring sample sites. Therefore, although the selected climate records do not cover an extensive period, they are high-quality data that do not contain missing records, a common problem in many of the climate records observed in this region of the country. Furthermore, the relatively short calibration period provided valuable results. Analyses were conducted using the STATISTICA Kernel ver. 10.0 program [49].

**Table 2.** Geographic characteristics of the four climate stations in southwest Chihuahua, Mexico used in the analysis.

| Climate Station                                   | Long W   | Lat N  | Elevation (m) | Total Period | No. of Years |
|---------------------------------------------------|----------|--------|---------------|--------------|--------------|
| Creel, Bocoyna                                    | −107.634 | 27.755 | 2345          | 1981–2015    | 35           |
| Huicorachi, Bocoyna (E46182) <sup>a</sup>         | −107.491 | 27.666 | 2281          | 1981–2015    | 35           |
| Arroyo de Agua, Maguarichic (E47137) <sup>a</sup> | −107.966 | 27.938 | 2198          | 1981–2015    | 35           |
| La Tinaja, Temósachic (E50658) <sup>a</sup>       | −107.871 | 28.937 | 2065          | 1981–2015    | 35           |

<sup>a</sup> Grids of precipitation points.

We used the Climate Explorer web application to statistically analysis climate data. This web-based application for climatic research is managed by the Royal Netherlands Meteorological Institute (KNMI). Specifically, we used the ERA5 Near-Surface Air Temperature gridded dataset (European Centre for Medium-Range Weather Forecasts) [53] from 1979 to 2015 to determine correlation between the near-surface temperature and the reconstructed tree ring chronology.

To understand the relationship between tree ring growth and precipitation, we generated a linear regression model based on the observed precipitation data and the total tree-ring width index from the regional residual chronology using the STATISTICA 10.0 program. We used the VERIFY 5 subroutine from the University of Arizona’s Dendrochronological Program Library (DPL) to run the Calibration and Verification statistical tests for the common observed data period (50% of the data were used for calibration and the rest for

verification). The calibration test examines the relationship between two variables, while the verification test validates the reconstruction model [54]. Once the model was validated, we applied it to the complete chronology period. Lastly, we fitted a decadal smoothing spline to the reconstruction time series to emphasize low-frequency extreme events such as dry and wet periods [55].

To analyze the influence of ENSO on the reconstructed regional precipitation patterns, we compared the Niño 3 SST Index (1400–1978) [56] to the reconstructed cumulative January–September precipitation. We used the MATLAB 6.5 program [57] to create annual resolution graphics of time–frequency and their potential wavelet spectra. For the years with the most severe drought and the highest precipitation, we generated maps, based on the Mexican Drought Atlas (MXDA) [58], Palmer Drought Severity Index (PDSI) for the months of June–August to analyze the affected area and degree of severity in relation to the study region.

### 3. Results

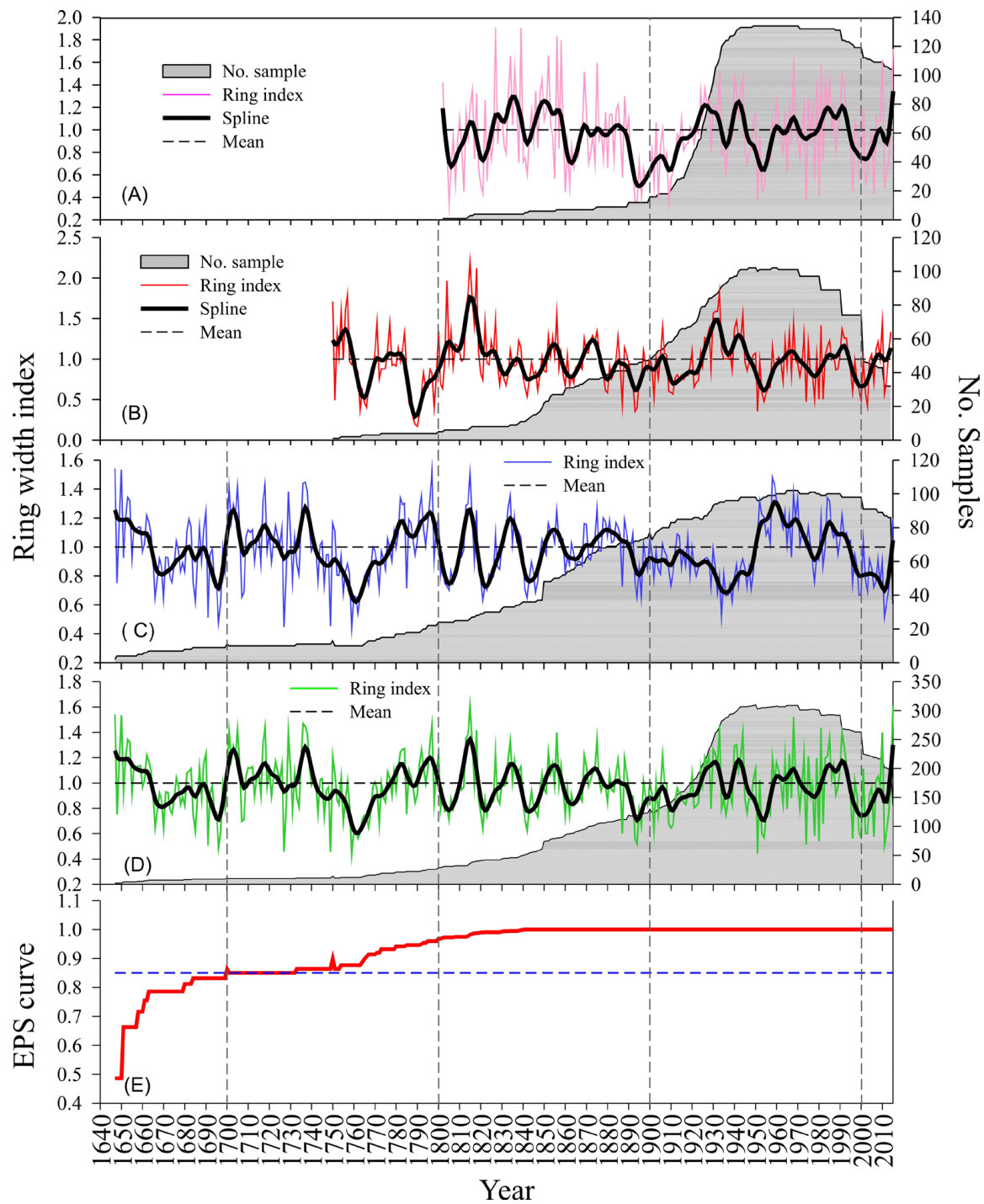
#### 3.1. Growth Rings and Common Response of the Chronologies

We dated a total of 359 increment cores from 155 *P. arizonica* trees (Table 1) and generated three chronologies with different temporal lengths (Figure 3, Table 3). The 10% of the samples (38) could not be dated due to growth problems and advanced wood rotting. The PCA results suggest that the three chronologies shared similar variability. That is, the first two principal components explain 86.8% of the variance in growth for the past two centuries (TAL chronology: CP1 = 0.86; CP2 = 0.14; PPC chronology: CP1 = 0.80; CP2 = −0.69 and CUE chronology: CP1 = 0.70; CP2 = 0.45). The three chronologies were grouped into PC1, which explained 63% of the variance (Figure 4). The correlation analysis between tree-ring series ( $r = 0.58$ ,  $p < 0.01$ ) also indicated similar response patterns between chronologies, allowing for the integration of the three site chronologies into a single regional chronology spanning 369 years, between 1647 and 2015 (Figure 3D, Table 3). The regional chronology showed high inter-annual and multi-year tree-ring variability for the southwest region of the state of Chihuahua.

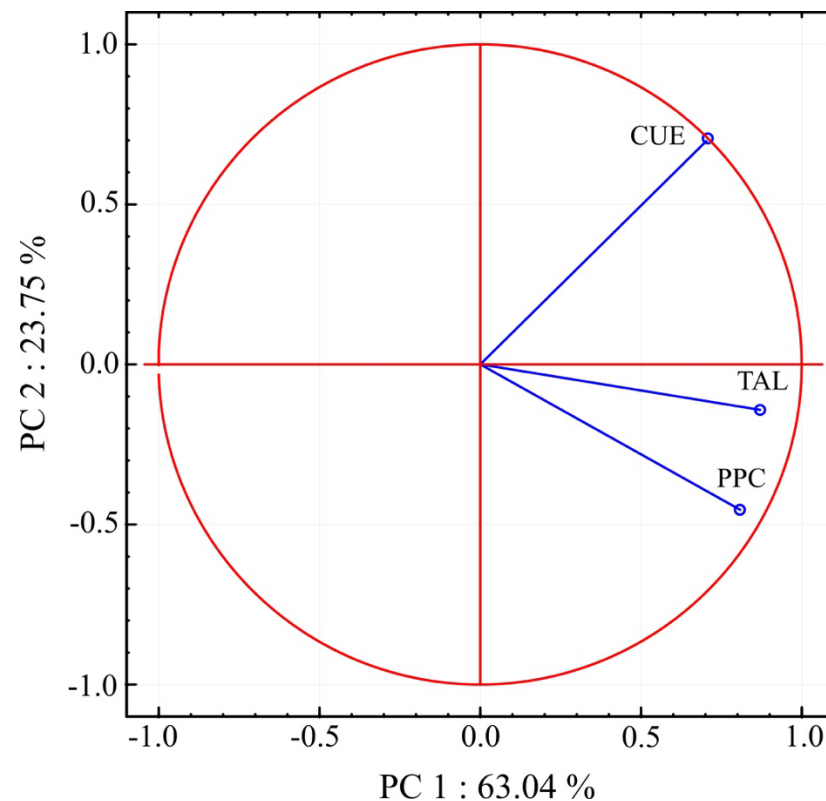
**Table 3.** Temporal length and correlation statistics between the three sites and regional chronology based on *P. arizonica* tree ring-width series from Chihuahua, Mexico.

| Site     | Span (Years)    | Avg $r^a$           | MS <sup>b</sup> | EPS <sup>c</sup> |
|----------|-----------------|---------------------|-----------------|------------------|
| PPC      | 1750–2014 (265) | 0.66 ( $p < 0.01$ ) | 0.40            | 1803             |
| CUE      | 1647–2015 (369) | 0.46 ( $p < 0.01$ ) | 0.29            | 1700             |
| TAL      | 1802–2015 (214) | 0.71 ( $p < 0.01$ ) | 0.45            | 1843             |
| Regional | 1647–2015 (369) | 0.58 ( $p < 0.01$ ) | 0.38            | 1700             |

<sup>a</sup> Average correlation between all series and the master chronology determined using 50-year blocks; all correlations are significant. <sup>b</sup> Mean sensitivity is the average percentage of change in chronology indices between years [45]. <sup>c</sup> First year each chronology exhibited a 0.85 expressed population signal statistic [51].



**Figure 3.** Total tree-ring width residual chronologies generated based on growths for *P. arizonica*, at (A) Talayotes (TAL), (B) Predio Particular Las Chinas (PPC), (C) El Cuervo (CUE), (D) merged regional chronology based on the three site chronologies from Chihuahua, Mexico and (E) expressed population signal (EPS) curve. The red line shows the variability of the EPS, and the blue dashed line indicates the EPS value = 0.85. The period 1700–2015 of the regional chronology indicates an EPS > 0.85.



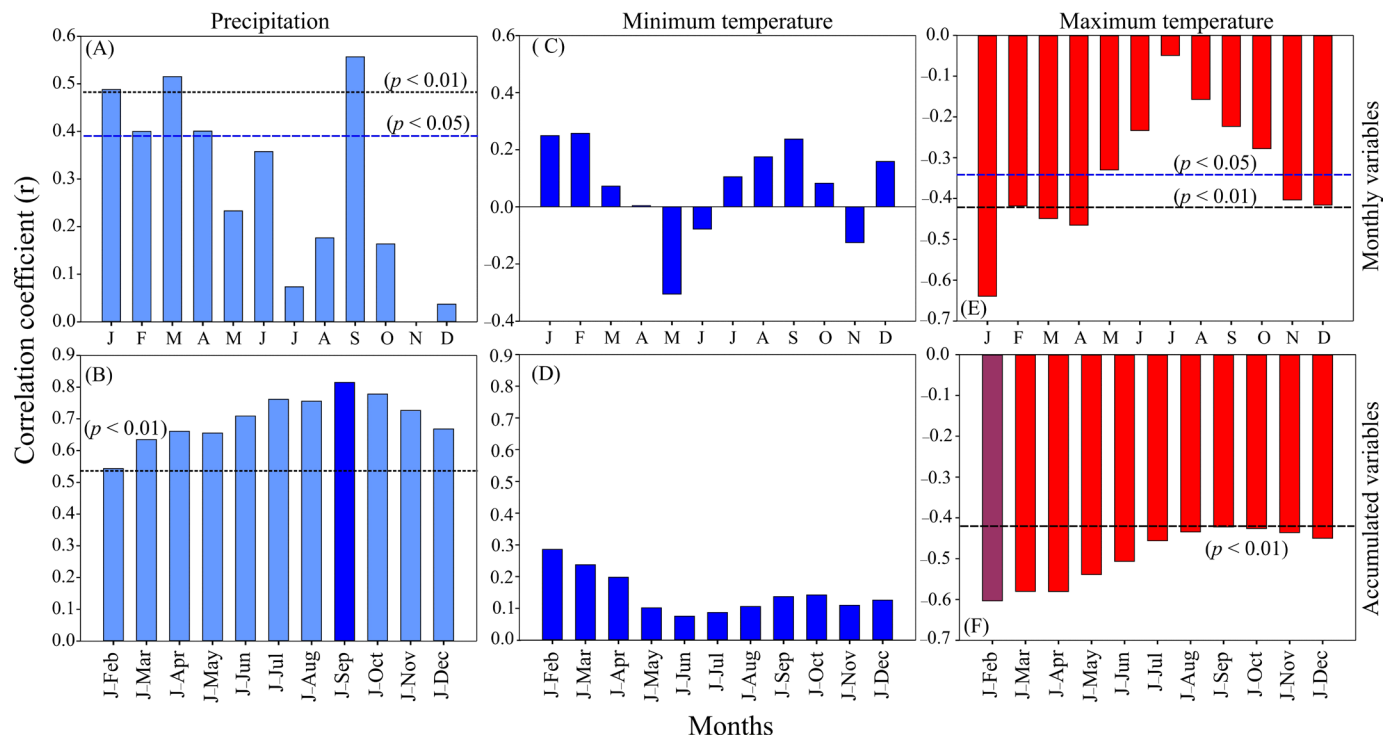
**Figure 4.** Principal components analysis (PCA) grouped all three site chronologies in PC1, indicative of a common variability.

### 3.2. Response Function

We found high correlation between residual tree ring-width chronology and observed precipitation (1981–2015). In general, there was a positive relationship between tree-ring growth and monthly precipitation (Figure 5). That is, we found a positive correlation for all the individual months except November. However, statistically significant correlations ( $p < 0.05$ ) were only detected for the individual months of January through April and September. While a highly significant relationship ( $p < 0.01$ ) was detected individually for three months for January, March and September (Figure 5A).

Tree-ring growth and cumulative monthly precipitation was significantly correlated ( $p < 0.01$ ) though out the year (Figure 5B); however, the correlation peaked for cumulative precipitation between January and September ( $r = 0.814$ ,  $p > 0.01$ ) (Figure 5B). Therefore, the reconstruction period that explains the greatest variability in rainfall was January–September. Conversely, the relationship between tree-ring growth and minimum monthly temperature varied throughout the year, with a positive relationship during most months except May, June and November, but none were significant (Figure 5C). We also found a non-significant positive relationship ( $p > 0.05$ ) between total ring growth and average minimum accumulated temperature (Figure 5D), the highest correlation was recorded in January–February.

Maximum monthly temperatures did significantly influence tree-ring growth. In particular, we found a highly significant negative relationship ( $p < 0.05$ ) for the winter and spring months from November through April (Figure 5E). We found a significant negative relationship ( $p < 0.05$ ) between tree ring growth and average maximum accumulated temperature, mainly for the months January–February (Figure 5F).



**Figure 5.** Correlation between *P. arizonica* tree-ring width index and both monthly as well as cumulative values between January and the corresponding month for average regional precipitation (A,B), minimum temperature (C,D) and maximum temperature (E,F). The period of analysis was between 1981 and 2015, based on records from weather stations in Creel, Huicorachi, Arroyo de Agua and La Tinaja in Chihuahua, Mexico.

### 3.3. Precipitation Reconstruction

For the 35-year period (1981–2015), when we had both tree ring and recorded precipitation, we found a significant correlation between cumulative precipitation from January to September and tree ring-width index ( $r = 0.814$ ;  $p < 0.01$ ) (Figure 6A). The residual chronology indicated the potential to develop a regression model and reconstruct the January–September precipitation variability for previous years within the chronology (369 years). The linear regression model developed for the reconstruction (Figure 6B) was considered statistically significant ( $p < 0.0001$ , Tables 4 and 5) and was as followed:

$$Y_t = 204.794 + 348.904 * X_t$$

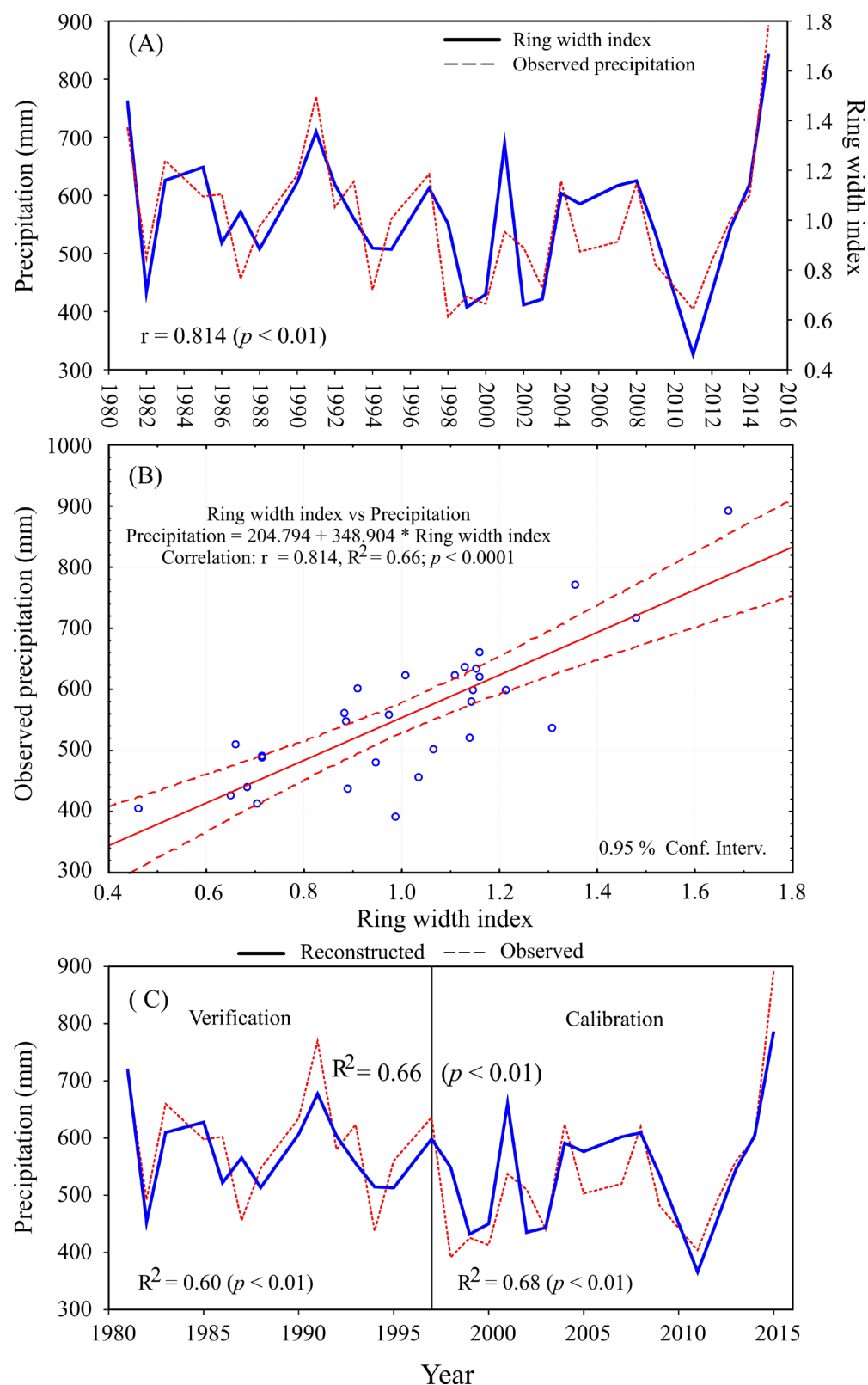
where:

$Y_t$  = precipitation in millimeters for a specific year;

$X_t$  = tree-ring width index for a specific year.

**Table 4.** Calibration of reconstructed of January–September precipitation for Chihuahua, Mexico based on *P. arizonica* ring-width residual chronologies.

| Period    | $R^2_{Adj}$ | Coefficient |           | Standard Error |           | <i>t</i> -Statistic |           | Probability |           |
|-----------|-------------|-------------|-----------|----------------|-----------|---------------------|-----------|-------------|-----------|
|           |             | $\beta_0$   | $\beta_1$ | $\beta_0$      | $\beta_1$ | $\beta_0$           | $\beta_1$ | $\beta_0$   | $\beta_1$ |
| 1981–1997 | 0.60        | 221.26      | 348.86    | 88.89          | 81.83     | 2.48                | 4.26      | 0.028       | 0.001     |
| 1998–2015 | 0.68        | 207.34      | 331.28    | 61.66          | 61.35     | 3.36                | 5.39      | 0.004       | 0.000     |
| 1981–2015 | 0.66        | 204.79      | 348.90    | 48.99          | 46.94     | 4.17                | 7.43      | 0.000       | 0.000     |



**Figure 6.** Relationship between the seasonal precipitation between January and September, and the regional index of ring width that includes the period of 1981–2015 (A), linear regression model between the two variables based on the program STATISTICA Kernel Release 5.5 [49] (B), and comparison of the reconstructed seasonal precipitation January–September (solid line) and observed precipitation (dotted line) for the period 1981–2015 (35 years), verification and calibration of the regression model (C).

**Table 5.** Verification statistics for the tree-ring reconstruction January–September precipitation in Chihuahua, Mexico from three *P. arizonica* ring-width residual chronologies. The verification procedure used the climate estimates derived in the calibration period, e.g., verification against observed data 1981–1997 used climate estimated by regression 1998–2015.

| Period    | Pearson Corr. (r) | Reduction <sup>a</sup> of Error | Signs Test <sup>b</sup> | <i>t</i> -Value <sup>c</sup> | First <sup>d</sup> Significant Difference |
|-----------|-------------------|---------------------------------|-------------------------|------------------------------|-------------------------------------------|
| 1981–1997 | 0.776 *           | 0.44 *                          | 4 ns                    | 2.41 *                       | 6 ns                                      |
| 1998–2015 | 0.824 *           | 0.59 *                          | 2 *                     | 2.32 *                       | 3 *                                       |
| 1981–2015 | 0.814 *           | 0.49 *                          | 8 *                     | 2.94 *                       | 9 *                                       |

ns = Not significant. \* = Significant  $p < 0.05$  <sup>a</sup> There is no formal test of significance for this statistic, but any positive result indicates that the reconstruction contributes unique paleoclimatic information [48]. <sup>b</sup> Signs of departures from the mean of each series [48]. Means are subtracted from each series and the residuals are multiplied. A positive product is a ‘hit’. If either observed or reconstructed data are similar to the mean, the year is omitted from the test. <sup>c</sup> Comparison of the relative magnitude of hits/misses in the sign test above. <sup>d</sup> Observed and reconstructed data-first differences ( $t-t-1$ ); the transformation removes trends that may affect the Pearson correlation coefficient. The sign of the first differences measures the association at high frequencies between observed and predicted values. The number of positive signs (agreement) expected by chance follows a binomial distribution and is  $1/2n$ , where  $n$  is the total number of observations. The test is significant whenever the number of signs exceeds the number expected from random [54].

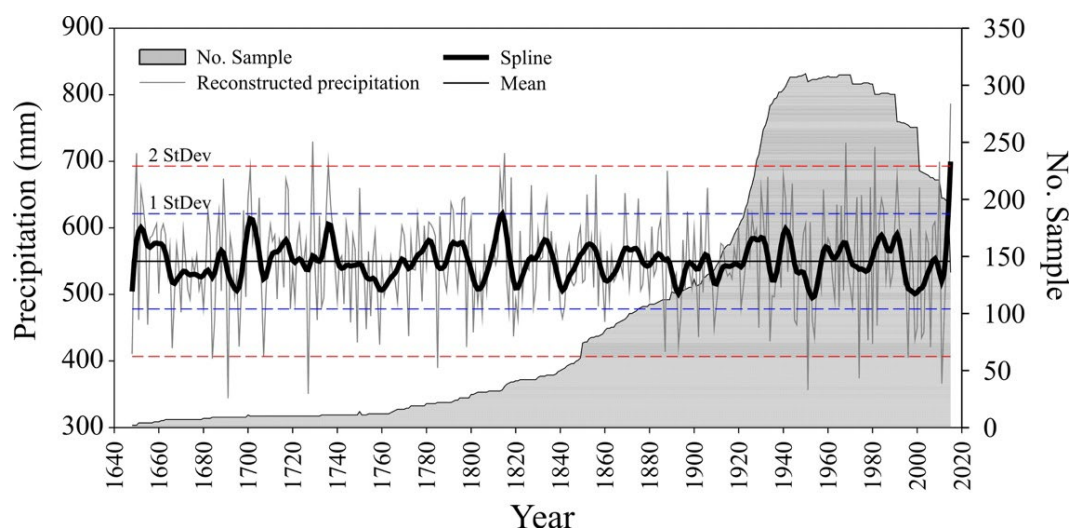
### 3.4. Calibration and Verification

The regression model was then applied to the total period of observation (1981–2015,  $n = 35$  years), the verification period between 1981 and 1997, and the calibration period was 1998–2015 (Tables 4 and 5). Despite the relatively short validation period, the model had good predictive power ( $r = 0.824$ ;  $R^2 = 0.68$ ;  $p < 0.05$ ) between the observed and reconstructed precipitation with the regression model explaining 68% of the rainfall variability in the calibration period. The verification test resulted in an  $r = 0.776$  ( $R^2 = 0.60$ ;  $p < 0.05$ ), explaining 60% of the seasonal precipitation variability (Figure 6C). For the total calibration period (1981–2015), the model resulted in an  $r = 0.814$  ( $R^2 = 0.66$ ;  $p < 0.01$ ) between observed and reconstructed precipitation, which explained 66% of the rainfall variability (Figure 6C). The results of the calibration and verification tests were significant ( $p < 0.05$ ) regarding the correlation, error reduction, *t*-value, and first significant difference (Table 5). The linear regression model, for the 1981–2015 period, was considered statistically valid and was, therefore, used to reconstruct annual precipitation for the complete period covered by the tree-ring width index chronology (1647–2015).

### 3.5. Climate Variability

Using the calibrated model, we reconstructed annual cumulative precipitation between January and September from 1647 to 2015 (369 years). The reconstructed precipitation patterns had high inter-annual, decadal, and multi-decadal variability (Figure 7), including 14 different dry periods with below-mean precipitation that stand out due to their amplitude and intensity (Table 6). Similarly, we reconstructed six individual years with precipitation  $< 400$  mm (below 2 standard deviations) (Figure 7, Table 6).

Wet periods with precipitation above average were also reconstructed (Table 6), including six years with precipitation  $> 700$  mm (above 2 standard deviations) (Figure 7, Table 6). Recent decades (1981–2015) had years with the highest recorded precipitation including 1991, 2001, 2010 and 2015, with 2015 standing out with nearly 800 mm of precipitation, the largest amount within the 369-year reconstruction period for this site.



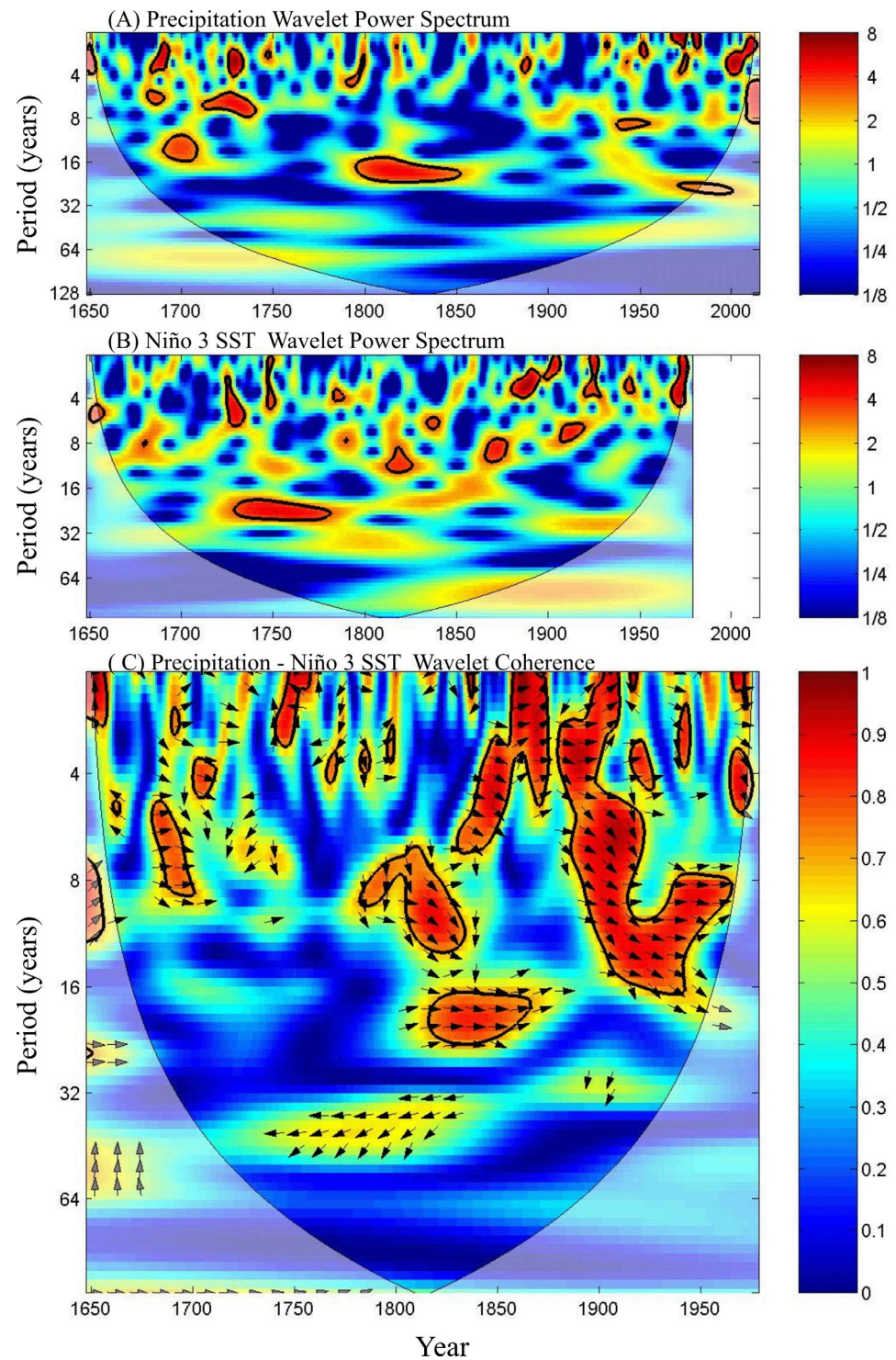
**Figure 7.** Reconstructed winter–spring precipitation (January–September) from 1647 to 2015. The thin gray line indicates the annual variability, while thick black represents decadal smoothing spline fitted to the annual data emphasizes low frequency variance in the reconstruction. The black horizontal line represents the mean (550 mm) and the gray background area indicates the sample size in each segment of the series. The dotted horizontal lines above and below the mean in blue and red color indicate one and two standard deviations, respectively. The wettest years (>700 mm) and driest years (<400 mm) are marked in red.

**Table 6.** Reconstructed periods with minimum and maximum records of precipitation in the last 369 years for the southwestern Chihuahua region.

| Duration (Years)                      | Dry Periods                                | Wet Periods                                |
|---------------------------------------|--------------------------------------------|--------------------------------------------|
| 2                                     | 1707–1708                                  |                                            |
| 3                                     | 2011–2013                                  |                                            |
| 4                                     | 1934–1937                                  | 1735–1738, 1812–1815, 1958–1961, 1990–1993 |
| 5                                     | 1801–1805, 1839–1843, 1907–1911            | 1830–1834, 1924–1928, 1940–1944            |
| 6                                     |                                            | 1700–1705, 1779–1784                       |
| 7                                     | 1691–1697, 1890–1896, 1951–1957, 1994–2000 |                                            |
| 8                                     | 1673–1680, 1819–1826                       |                                            |
| 9                                     | 1759–1767, 1859–1867                       |                                            |
| Driest years (Precipitation < 400 mm) |                                            | Wettest years (Precipitation > 700 mm)     |
|                                       | 1691 (343.9)                               | 1650 (712.1)                               |
|                                       | 1727 (350.7)                               | 1729 (729.8)                               |
|                                       | 1785 (389.4)                               | 1815 (712.3)                               |
|                                       | 1951 (356.3)                               | 1968 (727.4)                               |
|                                       | 1974 (374.2)                               | 1981 (721.5)                               |
|                                       | 2011 (365.7)                               | 2015 (786.7)                               |

### 3.6. ENSO Influence on Rainfall Variability

The wavelet analysis for the reconstructed precipitation (Figure 8A) found significant ( $p < 0.05$ ) one- and two-year oscillatory periods after 1950. Slightly longer oscillatory periods of three and four years were scattered across the period of analysis between 1650 and 2010. Early in this period, we also found significant periods of 6–8 years and 11–16 years, while longer significant periods between 17 and 24 years were found between 1800 and 1850. On the other hand, the ENSO wavelet spectrum (Figure 8B) had significant ( $p < 0.05$ ) areas of irregular cyclicity which ranged from 1 to 7 years mainly after 1725, and from 8 to 14 years after 1810. Longer periods ranging from 20 to 28 years occurred from 1730 and 1770.

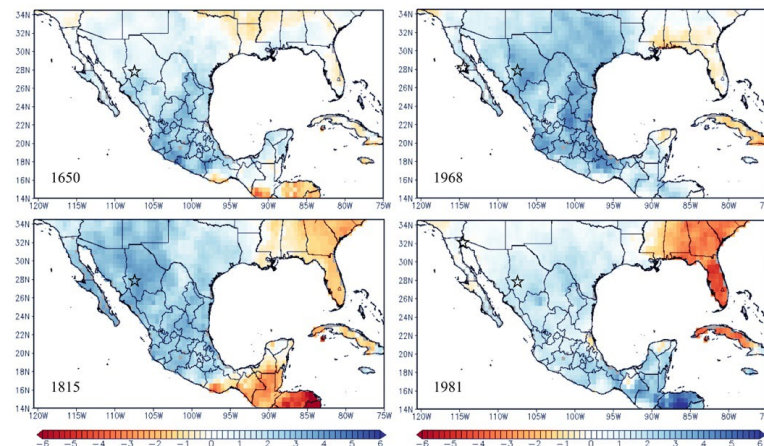


**Figure 8.** Continuous annual wavelet power spectrum for January–September reconstructed precipitation (A), Niño 3 SST index (B,C) represents the Wavelet Coherence domain between the reconstructed precipitation series and the Niño 3 SST index. The red spots delineated in black represent periods with significant frequencies ( $p < 0.05$ ), and the arrows pointing to the right indicate that both phenomena are in phase (positive correlation).

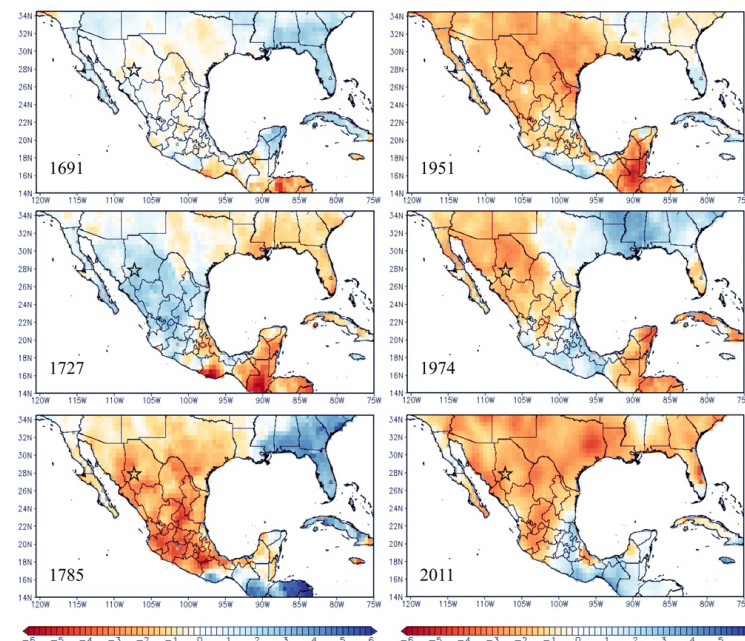
Using cross-wavelet analysis of our site seasonal reconstructed precipitation and the Niño 3 SST index, we found significant coherence ( $p < 0.05$ ) between 1647 and 1978 at frequencies ranging from 1 to 4 years (Figure 8C). The reconstructed precipitation from January to September and the Niño 3 SST Index coincide in phase during the periods of 1680–1700, 1830–1860, 1890–1920 and 1935–1965 at frequencies between 5 and 9 years.

Similar phase coinciding occurred from 1800 to 1830 and 1890 to 1965 at frequencies between 10 and 14 years, and from 1810 to 1870 at frequencies between 16 and 24 years, and finally from 1647–1800 at frequencies of approximately 100 years (Figure 8C). These results suggest that the most severe drought periods (Table 6) reconstructed for our study area in Chihuahua were significantly modulated ( $p < 0.05$ ) by ENSO.

The years with the highest and lowest precipitation for the last three and a half centuries within our study area in southwest Chihuahua were synchronized with ENSO events (Figure 7). These events occurred both in the El Niño warm phase and in the La Niña cold phase, respectively (Figures 9 and 10). Both ENSO and North American Monsoon are the main contributors to precipitation variability in the Chihuahua region.



**Figure 9.** Maps of the climatic condition (PDSI, JJA) for the four years with the highest precipitation records ( $>700$  mm) in the reconstructed period (1647–2015) in southwestern Chihuahua. In each of the four years analyzed, there was synchrony with the warm phase of ENSO (El Niño). The maps were generated based on the MXDA [58].



**Figure 10.** Drought maps (PDSI, JJA) for the six years with the lowest precipitation records ( $<400$  mm) in the reconstructed period (1647–2015) in southwestern Chihuahua. In each of these six years analyzed, there was a synchrony with the cold phase of ENSO (La Niña). The maps were generated based on the MXDA [58].

## 4. Discussion

### 4.1. Growth Ring Response to Climatic Variables

Previous dendroclimatic studies in northern Mexico have reconstructed winter–spring precipitation variability based on different species like *Pseudotsuga meziensisii* (Mirb.) Franco [35,59,60], *Pinus durangensis* Martínez [61], *Pinus cooperi* C. E. Blanco [61], and *Pinus lumholtzii* Robinson et Fernald [61,62]. However, summer precipitation, which represents a higher percentage of annual rainfall, has not been reconstructed using dendrochronological methods. In this study, we have reconstructed cumulative precipitation for the period January–September that includes the critical summer period and captures most of the variability in annual rainfall.

This study, based on *P. arizonica* annual tree rings, represents the first to analyze the dendroclimatic potential of this species in Mexico. Our analysis confirms that this species has the potential to develop extensive chronologies in this region of northern Mexico. Tree ring growth patterns across the study area had high inter-annual variability, suggesting high sensitivity to environmental variations, and the tree-ring series had high intercorrelation between trees. These parameters characterize conifers sensitive to precipitation variability in this region [63]. The correlation between series for each of the three chronologies we analyzed (Table 3) exceeded COFECHA's minimum acceptable correlation of 0.328 ( $p < 0.01$ ), meaning that they were appropriately dated [46]. These results indicate synchronous variability of annual growth that allows annual to interannual resolution and their potential use in reconstructions of climate variables.

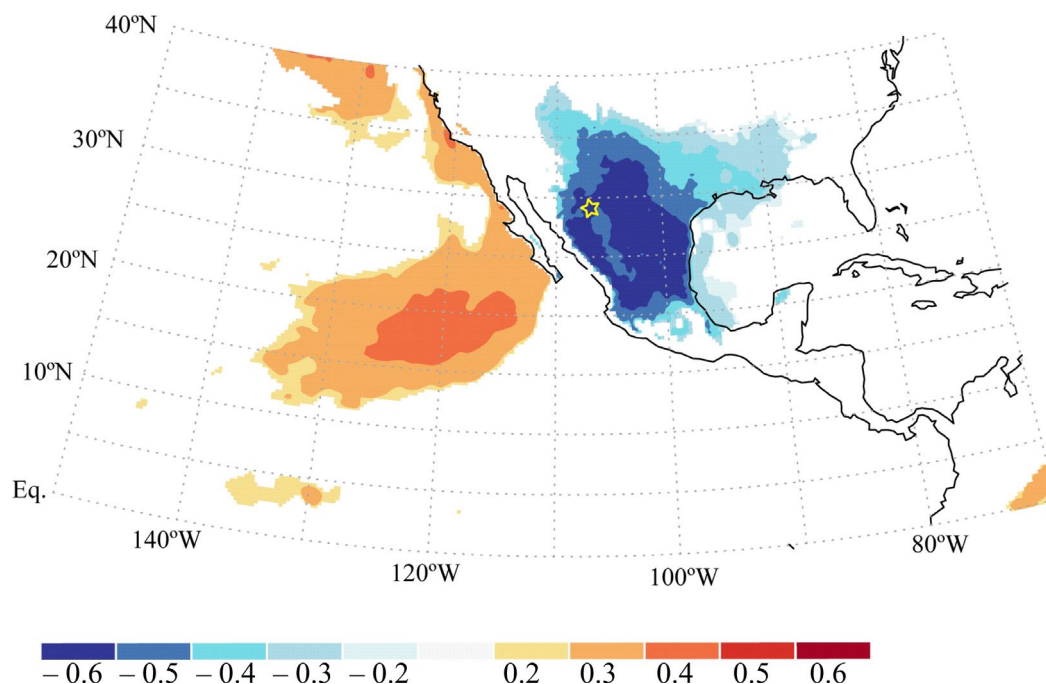
The chronologies used in this study had similar shared interannual variability during their common period (1802–2014) which was captured in PC1 and explained 63.04% of the variance (Figure 4). This common variability among the three sites captures the dominant pattern of tree growth throughout the region, and is a direct response to precipitation, the most limiting growth factor in this region and elsewhere. Similar results have been reported in different studies across northern Mexico [37,62]. Our regional chronology also recorded an EPS value above 0.85 after 1700, which is generally cited as an acceptable threshold for dendroclimatic reconstructions [64].

The *P. arizonica* chronology developed in this study explained nearly 70% of the precipitation variability of instrumental climate records (January–September). In a similar study using *P. durangensis*, others [36] reconstructed precipitation for the January–August period in Presidio-San Pedro watershed in the state of Durango, Mexico, but their results only explain 51% of the precipitation variability and did not include the entire summer period. An accurate reconstruction of summer precipitation is important because according to instrumental climate records for this region, precipitation between January and September accounts for 90% of the annual total and includes summer precipitation which accounts for more than 70% [40,65]. Therefore, this study represents the first to reconstruct the entire summer period for this region. The analysis of trends, recurrence of extreme events, and the influence of climatic phenomena on the variability of summer precipitation, provides technical and scientific information that is critical to economic activities such as forest management and agriculture.

Maximum temperatures ( $>31\text{ }^{\circ}\text{C}$ ) in this region occur between March and April, and are associated with low relative humidity that characterizes the most significant fire risk. High temperatures and low humidity increase the water vapor deficit, which induces a reduction in stomatal conductance to avoid water loss. This period of low precipitation reduces photosynthesis [66], likely explaining the negative relationship we found between maximum temperature and tree ring growth. However, a decrease in growth is generally related to a decline in water availability limiting cell expansion [67–69]. Therefore, the relationship between temperature and tree ring growth, in this case, is explained by the

close relationship between regional temperature and water availability (rainfall) where cooler temperatures are related to higher humidity and vice versa. Overall, maximum temperatures have a negative effect on growth since increasing temperatures also increase vapor pressure deficit leading to decreases in tree-ring growth [70,71].

At larger scales, temperature and precipitation are related in different ways. That is, the correlation between the reconstructed precipitations is positively correlated to the eastern Pacific Ocean's near-surface temperature and negatively correlated to the continental temperature. That is, warm oceans result in increased humidity (humid air currents to the continent), increasing rainfall potential and reducing temperatures inland. Therefore, the precipitation reconstruction is positively correlated to the ocean temperatures and negatively to the regional land temperature. This ocean–land relationship emphasizes the importance of ENSO and NAM atmospheric circulations as the main contributors to precipitation in northern Mexico. Our study suggests that these two sources are integrated into tree ring-width in the region (Figure 11). Low temperatures are related to lower potential evaporation, which favors a positive water balance, as greater soil moisture is available during the growing season [48,72]. This positive growth response at minimum temperature is consistent with previous studies on other conifers [73,74].



**Figure 11.** Spatial correlation values between the January–September near-surface temperature ERA5 1979–2015 and the precipitation reconstruction, positively correlated to the eastern Pacific Ocean's near-surface temperature and negatively correlated to the continental temperature. The yellow star represents the study area.

#### 4.2. Precipitation Variability

The influences of ENSO vary across continental scales. For example, northern and southern Mexico have opposite climatic responses to El Niño and La Niña phases of the oscillation, a phenomenon known as the dipole [58,75,76]. During the El Niño phase, northern Mexico receives above average precipitation while drought tends to occur in southern Mexico. Precipitation patterns typically switch between these two regions during La Niña events. Therefore, it is no surprise that within the 369 years of precipitation reconstructed in this study in northern Mexico, the six individual years the lowest precipitation (<400 mm)

occurred during the La Niña, cold ENSO phase [23,77]. Conversely, the six wettest years (>700 mm) occurred during the warm ENSO phase of El Niño [23,77] (Figure 7, Table 6).

Studies in this region have shown that the growing season for conifer species occurs mostly during the spring and summer [69], suggesting that summer monsoon precipitation is an important factor for tree ring development and growth. Moreover, the relationship between the ENSO and the NAM is complex [78–80]. This is because each phenomena influences precipitation patterns within different seasons. That is, ENSO influences winter precipitation, while NAM is active during the summer. However, studies have shown that ENSO can indirectly affect the NAM by influencing the atmospheric and oceanic conditions prior to the monsoon season [15,81,82]. Elsewhere, the ENSO phenomenon strongly influences U.S. precipitation and temperature patterns, especially extreme events. For example, the record El Niño event of 1997–1998 produced extreme rainfall and flooding in California in February 1998.

The links between summer tropical sea surface temperatures and summer climate variability in North America are not as pronounced. However, the extraordinarily wet summer of 1983 in our study area may have been an aftermath of the significant 1982–1983 El Niño. During the summer of 1983, an unusually high number of Pacific hurricanes tracked northward into the Gulf of California, contributing to the rainfall totals. Therefore, ENSO patterns and summer precipitation in our study area may be related, at least in part, to the effects of decadal variability in sea surface temperatures and surface pressure in the North Pacific [58,83].

Our reconstructed precipitation patterns (Table 6) indicate a cycle of approximately 50 years, between intense droughts and negative Niño 3 SST indices (Figure 8C). The most severe regional droughts vary in intensity; however, these episodes also tend to be recorded more broadly at the national level (Figures 9 and 10), which might be attributed to global climatic phenomena that modulate climate at larger scales [58,76,84]. Our findings suggest a significant relationship between ENSO and the NAM that influences precipitation variability. Our results also suggest that these low-frequency events at 50-year intervals are significantly modulated by the La Niña the cold-phase of ENSO in northern Mexico (Figure 8). This low-frequency variability coincides with similar studies from northern [85] and central Mexico, which have found droughts at the beginning, middle, and end of every century [86]. In the Sierra Madre Occidental (SMO), other studies have documented the relationship between La Niña phase and extreme droughts that have caused water shortages [35,37].

There have been contradictory studies on the relationship between ENSO and total summer precipitation, which might be partly due to variable definitions used to identify the timing of El Niño or La Niña events [82]. On the one hand, Arizona and New Mexico have been shown to receive significantly higher monsoon precipitation in July during El Niño years compared to La Niña years [87]. On the other hand, El Niño is thought to reduce the number of monsoonal storms in Arizona [88]. In another study, La Niña events have been associated with below-average monsoon rainfall in Arizona and New Mexico, but El Niño events have resulted in normal rainfall [15]. Despite this variability in outcomes, ENSO and the NAM are broad climate patterns that strongly influence water availability in northern Mexico [37]. Climate studies indicate that the influence of the NAM in the Sonora region is weak during El Niño summers, but higher during the winter in the warm phases of ENSO, which generates higher runoff [15]. La Niña events cause storm tracks to move northwards, drying out northern Mexico and the Southwestern US [89], and this impacts NAM rainfall production in the summer [79].

Our ability to reconstruct the accumulated influence of January–September precipitation on tree-ring growth suggests that the growing season of these forests is relatively

long. This could provide new opportunities to explore the differential water use between January–September and summer along the growing season using intra annual isotope records [90].

## 5. Conclusions

Our dendrochronological study of *P. arizonica*, has shown that this species was an excellent source of paleoclimatic records for nearly four centuries which allowed us to reconstruct seasonal cumulative January–September precipitation over the same period. We found that *P. arizonica* tree rings recorded a common growth pattern in response to climatic variability at regional levels; therefore, the first hypothesis is accepted. These findings are novel because they reconstruct precipitation beyond the commonly reported winter or winter–spring periods, to also include the summer months, which account for 90% of the annual precipitation. Within the reconstruction, we found six major drought events and six mesic events, synchronized with ENSO in its La Niña and El Niño phases, respectively. A higher frequency of major events was identified in recent decades, as well as major droughts approximately every 50 years, modulated by ENSO events. Therefore, the second hypothesis is also accepted, suggesting that historical high- and low-frequency climate variability was modulated this circulatory phenomenon.

Understanding the influence of ENSO on climate patterns in northern Mexico is critical to better predict water availability and planning. Given our current abilities to predict ENSO event months in advance using remotely sensed technologies, our findings could be used to predict how those patterns could influence future regional precipitations, which would be of great use in a region where water is such an important resource. Similarly, our 369-year reconstruction provides a baseline of natural climate variability that can be used to compare with future climate change projections to evaluate both current and future droughts.

Although our study is focused on northern Mexico. Similar climate patterns have been observed at other latitudes such as central Mexico, which is attributed to the modulation of the climate by general circulation climate phenomena. It is important to better understand how climate change is influencing the frequency and intensity of phenomena like ENSO and their effects on natural resources at regional scales. These results highlight the opportunity for future researchers to develop new work or lines of research that generate information on the influence of ENSO at different latitudes and the ENSO-NAM relationship in northern Mexico. They also provide an opportunity to analyze the influence of other climate phenomena such as the PDO and the AMO.

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**Data Availability Statement:** The raw data (chronologies) presented in this study are available on request from the corresponding author, without undue reservation.

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