North American monsoon precipitation reconstructed from tree-ring latewood

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[1] The North American monsoon is a major focus of modern and paleoclimate research, but relatively little is known about interannual- to decadal-scale monsoon moisture variability in the pre-instrumental era. This study draws from a new network of subannual tree-ring latewood width chronologies and presents a 470-year reconstruction of monsoon (June–August) standardized precipitation for southwestern North America. Comparison with an independent reconstruction of cool-season (October–April) standardized precipitation indicates that southwestern decadal droughts of the last five centuries were characterized not only by cool-season precipitation deficits but also by concurrent failure of the summer monsoon. Monsoon drought events identified in the past were more severe and persistent than any of the instrumental era. The relationship between winter and summer precipitation is weak, at best, and not time stable. Years with opposing-sign seasonal precipitation anomalies, as noted by other studies, were anomalously frequent during the mid to late 20th century.
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1. Introduction

[2] The North American monsoon is a fundamental climate component in the Southwest that provides moisture relief and modulates ecosystem structure, wildfire, agricultural productivity, public health, and water resources supply and demand [*Ray et al.*, 2007]. Interannual monsoon moisture variability, which is pronounced over the southwestern United States, has been the focus of numerous studies using instrumental observations [e.g., *Higgins and Shi*, 2000; *Seager et al.*, 2009; *Turrent and Cavazos*, 2009; *Arias et al.*, 2012]. The North American monsoon is also a research focus for paleoclimatology [e.g., *Asmerom et al.*, 2007; *Barron et al.*, 2012], but relatively little is known about pre-instrumental monsoon variability at interannual to decadal timescales. Understanding the plausible range of monsoon variability is critical because model projections of monsoon response to anthropogenic greenhouse gas forcing remain unclear [*Castro et al.*, 2012; *Bukovsky and Mearns*, 2012; *Cook and Seager*, 2013]. The American Southwest has a rich history of dendroclimatology, but the vast majority of tree-ring reconstructions from the region reflect only cool-season or annual-scale moisture variability. This is epitomized by the North American Drought Atlas, which, for the Southwest, principally reflects the influence of cool-season precipitation on annual water balance [*St. George et al.*, 2010].

[3] Annual tree-ring records do not reflect monsoon moisture variability, but subannual chronologies created from the summer-forming "latewood" component of tree rings can contain strong, monsoon-specific precipitation signal [see *Griffin et al.*, 2011, and references therein]. However, to date, relatively few latewood width (LW) width chronologies and monsoon reconstructions have been generated for the southwestern United States. Targeting a small area in southeastern Arizona, *Meko and Baisan* [2001] used a set of five *Pseudotsuga menziesii* (PSME) LW chronologies and a nonlinear binary recursive classification model to estimate the probability of dry monsoons for the period 1791–1992. *Stahle et al.* [2009] conducted LW analysis of the multimillennial PSME record from El Malpais [*Grissino-Mayer*, 1996] and produced a July precipitation reconstruction for northwestern New Mexico, which was interpreted as a record of onset and early monsoon precipitation. Comparing the July estimate with a November–May precipitation reconstruction, *Stahle et al.* [2009] found that years with winter precipitation extremes tended to have an opposing-sign July moisture anomaly. That phenomenon, also identified in instrumental studies, may be dynamically linked to a negative land-surface feedback [e.g., *Gutzler*, 2000; *Zhu et al.*, 2005; *Notaro and Zarrin*, 2011] and atmospheric teleconnections to Pacific sea surface temperature variability [e.g., *Castro et al.*, 2001].

[4] The present study offers several advancements on prior research. It uses a new multispecies LW chronology network to reconstruct monsoon (June–August) precipitation for a large region in the Southwest. Following the *Stahle et al.* [2009] analytic, the paleomonsoon record is compared with an October–April precipitation reconstruction developed from chronologies of tree-ring earlywood width (EW). These reconstructions provide novel perspective on monsoon paleoclimatology and reveal instability in the relationship between winter and summer precipitation through time.

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2. Methods and Results

[5] This study focuses on monsoon region 2 (NAM2), as defined by the North American Monsoon Experiment Forecast Forum (Figure 1) [*Gochis et al*., 2009]. NAM2 is a region of spatially coherent variability in monsoon precipitation that approximates regions identified by other studies. Interannual monsoon variability is strong over NAM2, which includes critical waterways, major metropolitan areas, and more than 550 km of the United States–Mexico border. NAM2 is a target for seasonal climate forecasts and has been the focus of dynamically downscaled regional climate model projections [*Castro et al*., 2012]. Monthly precipitation data are from a 0.5° gridded product developed by NOAA that extends across North America and uses a terrain-sensitive algorithm to interpolate between available instrumental station records for the period 1895–2010. NAM2 grid point data were averaged to produce time series of monthly precipitation and correlation analysis was used to assess relationships to the subannual tree-ring chronologies. October–April (cool season) and June–August (monsoon) were selected as the seasons for reconstruction, and precipitation totals for these seasons were converted to standardized precipitation indices (SPI).

[6] Tree-ring data are from a new network of subannual chronologies developed using EW and LW measurements on collections from more than 50 sites in the southwestern United States and Baja California (Figure 1). EW and LW indices were standardized with the protocol described by *Griffin et al*. [2011]. Chronologies more than 450 years long from NAM2 that exhibited significant ($p<0.01$) correlations with the instrumental SPI variables were submitted as candidate predictors to forward stepwise multiple linear regression. Model skill was verified with standard methods. Periods of persistent drought and wetness were identified as consecutive-year runs of negative or positive SPI and using ranked values in the time series smoothed with a 5-year cubic spline. The reconstructions were analyzed to determine when both seasons were wet (positive SPI) or dry (negative SPI) or when one season was wet and the other was dry. Cross-wavelet analysis [*Grinsted et al*., 2004] was used to summarize spectra and coherence of the reconstructions through time. Details on the study area, data, methods, analyses, and rationale are provided in the Supporting Information.

[7] Seasonal SPI reconstruction models included PSME and *Pinus ponderosa* predictor chronologies that were well distributed across NAM2 (Figure 1; Tables S1 and S2 in Supporting Information). The assumptions of the regression approach were met and verification statistics indicate that both models exhibit robust predictive skill (Table S3 in Supporting Information). Relationships between the instrumental and reconstructed variables were highly significant, linear, positive, and stable through time (Figure 2). The cool-season estimate exhibits moderately superior regression statistics, but the LW reconstruction does capture nearly half of the variance in instrumental monsoon SPI. This is an important and somewhat unexpected result given the spatial heterogeneity of monsoon precipitation and its subordinate role in annual water balance.

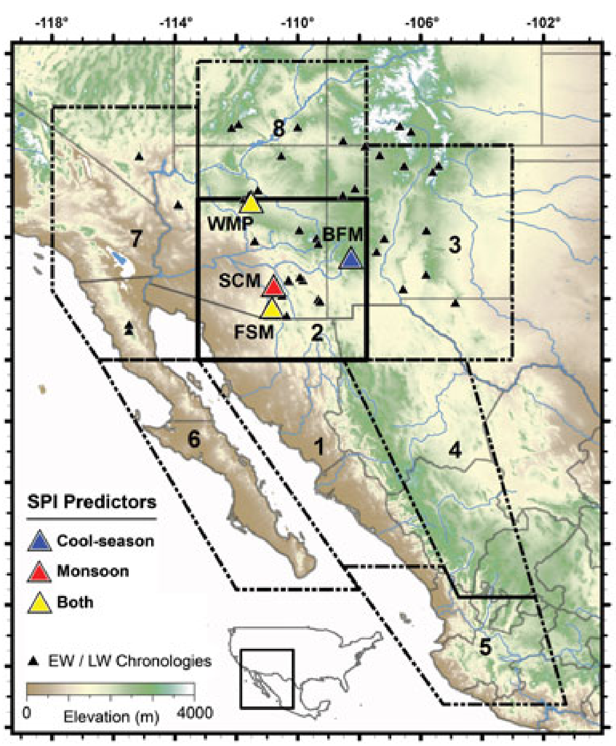

Figure 1. The North American monsoon domain, monsoon regions 1–8, and the new network of EW and LW chronologies. Colored triangles denote tree-ring predictor locations for the region 2 SPI reconstructions.

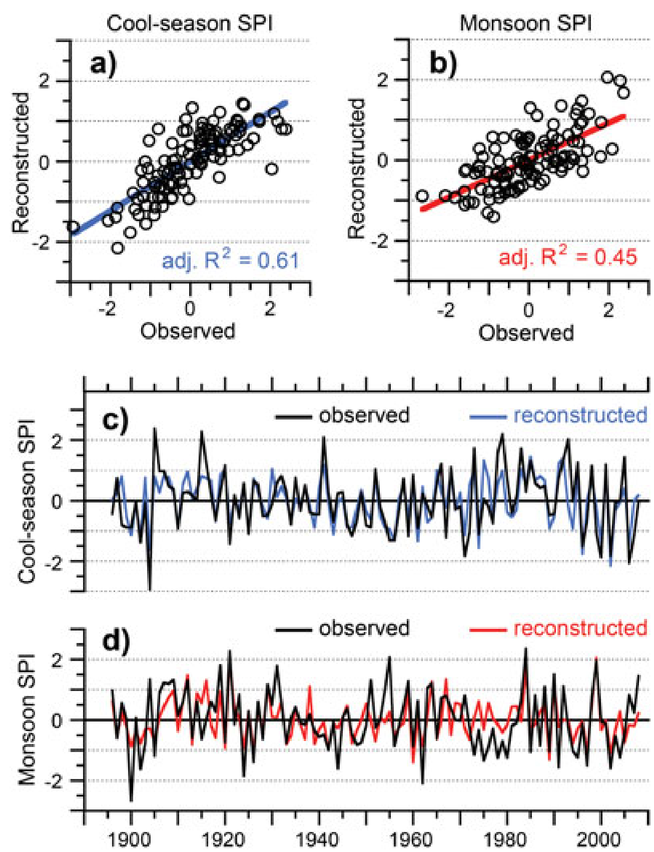

Figure 2. Scatterplots (a and b) and time-series graphs (c and d) of observed and reconstructed SPI for the cool season and monsoon.

[8] The monsoon and cool-season SPI reconstructions are uncorrelated for the 1539–2008 common period (r=0.02; p=0.67) and the 1896–2008 instrumental period (r=0.06; p=0.53), although the monsoon and cool-season SPI instrumental data exhibit weak negative correlation (r=-0.19; p=0.04). Wavelet analysis indicates that both reconstructions are dominated by high-frequency variability (Figure S5 in Supporting Information). Low-frequency covariability between the two seasonal reconstructions is visually evident (Figure 3a and b). Cross-wavelet squared coherence, analogous to correlation between the reconstructions as a function of time and frequency, is variable and time unstable at periods less than 32 years (Figure S5 in Supporting Information). At longer periods, the reconstructions generally exhibit in-phase coherence. Potential sources of the low-frequency reconstruction coherence include long-term changes in tree physiology related to root and crown mass [*Fritts*, 2001], standardization of the ring-width time series, or true low-frequency coherence between the seasonal climate regimes. Diagnosing the source (s) of this coherence is considered important but also beyond the brief scope of the present study.

3. Seasonal Precipitation History for NAM2

[9] Several persistent periods of anomalous SPI stand out in the instrumental records (Figure 2). Both seasons had negative SPI near the turn of the 20th century and again in the early 21st century. Precipitation was consistently above average in both seasons during the early 20th century pluvial, as recently noted by *Cook et al*. [2011]. These persistent variations are tracked remarkably well by the tree-ring reconstructions. Monsoon SPI was negative from 1972 to 1982, the longest run of dry monsoons in the instrumental record. This episode is not particularly well matched by the LW reconstruction, possibly because it contained several notably wet May and June months that would have differentially benefitted summer tree growth. Visual comparison indicates that cool-season SPI contains more middle- to low-frequency variability than monsoon SPI and that the EW-based reconstruction tracks these frequency components well.

[10] The reconstructions offer an expanded perspective, revealing seasonal drought events more persistent and severe than those of the instrumental era (Figure 3). The period of most persistent summer drought was 1882–1905, when 19 of 24 years had negative monsoon SPI. In the 1890s and early 1900s, this monsoon failure was complemented by severe and persistent cool-season drought. This dual-season drought event factors importantly into the socioenvironmental history of the region. Arrival of the Southern Pacific Railroad in the early 1880s ushered an expansion of the Arizona cattle population from ~40,000 to 1.5 million individuals [*Sheridan*, 1995]. By the early 1890s, however, an estimated 50–75% of the herd starved and perished from drought-induced rangeland failure [*Sayer*, 1999]. Cattle overgrazing triggered landscape-scale vegetation change that remains evident today. Environmental consequences of the 1890s drought were also severe in northern Mexico, as discussed by *Seager et al*. [2009]. Ironically, this decades-long drought was immediately followed by the well-known early 20th century pluvial, which included the highest frequency of dual-season wetness in the entire reconstruction (Figure S4 in Supporting Information).

[11] Other dual-season drought events are evident in the early 1820s and the 1770s. Yet more severe was the 17th century "Puebloan Drought," an event *Parks et al*. [2006] implicate as one factor leading to the Pueblo Revolt of 1680. In northwestern New Mexico, *Stahle et al*. [2009] found that this drought included below-average precipitation during both the cool season and July. For NAM2, the period from 1666 to 1676 included a seven-year run of drier-than-average monsoons and six years with below-average SPI in both seasons. According to the smoothed record, this was the most extreme monsoon drought episode of the last 470 years. This result, coupled with the finding by *Stahle et al*.

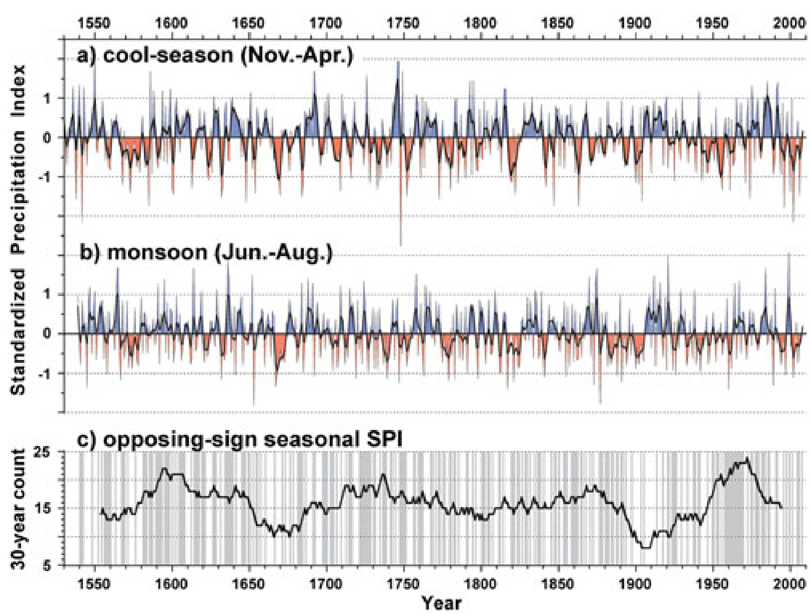

Figure 3. Time-series graphs of reconstructed SPI for the cool season (a) and monsoon (b) with a 5-year cubic spline plotted in black. Vertical gray bars denote years with opposing-sign SPI anomalies and the black line represents a centered 30-year running count of these events (c).

[2009], indicates that monsoon failure during the 17th century Puebloan Drought was robust and widespread across the Southwest.

[12] The late 16th century "megadrought" is evident in both the monsoon and cool-season SPI reconstructions for NAM2 (Figure 3). This event, among the most severe droughts of the last millennium, drove landscape-scale ecosystem change across the Southwest [e.g., *Swetnam and Betancourt*, 1998]. From 1566 to 1579, 11 of 14 monsoons were drier than average. Monsoon SPI rebounded to average or near average in the 1580s, but cool-season drought persisted through that decade. From 1566 to 1587, 21 of 22 years were reconstructed to include at least one season of below-average SPI and 10 of those years had negative SPI in both seasons. July dryness was previously noted in northwestern New Mexico [*Stahle et al*., 2009], but this is the first time that persistent monsoon failure has been connected with the megadrought in the NAM2 region. Several exceptionally dry monsoons in the late 1560s reveal that the megadrought may have first manifest as a warm-season phenomenon. This idea is lent some support by spatial analysis of the megadrought through time (Figure 6 in *Stahle et al*. [2007]), which mapped the 1560s drought center over northwestern Mexico, where the monsoon provides more than 70% of annual precipitation.

[13] These reconstructions offer a novel opportunity to assess the relationship between cool-season and monsoon precipitation in NAM2. Years with opposing-sign SPI anomalies, plotted in Figure 3c, appear to be randomly distributed through time. There are brief periods when these events appear to congregate (e.g., 1960s and 1720s) and others when they were rare (i.e., the decadal drought and wet events described above). A 30-year running count illustrates some temporal variability and indicates that the mid to late 20th century was characterized by a relatively high frequency of such events. These results are congruent with instrumental data analysis by *Gutzler* [2000] and by *Zhu et al*., who found that the "linkage is strong from 1965–1990 and weak otherwise" [2005]. Opposing-sign years were also relatively frequent in the mid-18th and early 17th centuries. In contrast, the period centered near the turn of the 20th century contained relatively few of these events. Wavelet analysis reveals no time-stable coherence at subdecadal to decadal timescales, indicating that the NAM2 seasonal precipitation relationship is dominated by noise (Figure S3 in Supporting Information).

4. Summary

[14] This study provides a high-quality, precisely dated, seasonally resolved geochronology for the NAM2 region. The reconstructions represent a plausible range of interannual- to decadal-scale variability in multiseason precipitation for the past 470 years. These precipitation estimates are suitable for comparison with paleoproxy, historical, modern, and projected climate data and should be useful for a more precise interpretation of the social and environmental history in the American Southwest. Decadal drought events in this region over the past five centuries (e.g., 1570s, 1660s, 1770s, 1820s, 1890s, and early 2000s) were characterized not only by cool-season precipitation deficits but also by consistent failure of the summer monsoon. Monsoon drought events in the past were more persistent (e.g., late 19th century) and extreme (e.g., mid-17th century) than any during the instrumental era to date. With the exception of the ongoing early 21st century drought, the instrumental era lacks the persistent dual-season drought episodes common to centuries past. The NAM2 seasonal precipitation relationship is weak at best and is not time stable. The mid to late 20th century experienced a relatively high frequency of years with opposing-sign precipitation anomalies. These results indicate that the instrumental era, especially the later half of the 20th century, may not be the ideal period for characterizing NAM2 monsoon precipitation climatology, its relationship to the cool-season climate regime, and potential connections to the coupled ocean-atmosphere system.

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