The North American Monsoon in the U.S. Southwest: Potential for investigation with tree-ring carbon isotopes

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Abstract

The North American Monsoon (NAM) contributes critical summer moisture to the U.S. Southwest from July through September, but instrumental records of monsoon precipitation are limited to 100 years or less. Tree-ring investigation offers a means of improving our understanding of its long-term spatial and temporal variability. Available evidence indicates the stable-carbon isotopic composition ($\delta^{13}C$) of tree rings in this region is strongly linked to moisture. In addition to latewood width as a precipitation proxy, the $\delta^{13}C$ of latewood also appears to be a strong proxy, largely manifesting water stress effects on stomatal conductance and their consequence to isotopic discrimination against $^{13}CO_2$. In one promising study, the $\delta^{13}C$ of 11 years of latewood from 8 sites regressed against their corresponding precipitation exhibited a coefficient of -0.061‰ per cm of July+August+September precipitation (r^2 = 0.41). Long latewood $\delta^{13}C$ chronologies are currently being developed from tree rings of ponderosa pine and Douglas-fir at several sites in NAM core regions in the Southwest to evaluate its usefulness in supplementing precipitation reconstructions derived from latewood widths. Among planned

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outcomes, the improved monsoon precipitation records can be used to better evaluate natural variability of NAM precipitation and its linkage to winter precipitation, document the character of monsoon season droughts, and test accuracy of regional climate models.

Keywords: precipitation; southwest monsoon; dendrochronology; stable-carbon isotopes; latewood

1. Introduction

The large-scale North American Monsoon (NAM) advects moist air from both the Gulf of Mexico and the Gulf of California/Pacific into North America during the summer months (Douglas et al., 1993; Adams and Comrie, 1997; Higgins et al., 1997). The western arm of this system delivers moisture into the U. S. Southwest, where in southern Arizona and New Mexico, the NAM-associated summer rains typically begin in early July, and continue through mid-September (Higgins et al., 1999). This summer precipitation in southwestern North America has provided much-needed moisture over past millennia to agricultural efforts of prehistoric peoples and retains importance now in light of the increasing water demands of the burgeoning regional population. More generally, this moisture contributes to both agroecosystems and natural ecosystems. Understanding the long-term variability of NAM moisture may be even more important given projections of future drying and warming in the Southwest and because the dynamics of the NAM are poorly replicated in the IPCC general circulation models presently being used for climate change projection (IPCC, 2007).

Given the importance of the NAM to southwestern water resources for human and natural ecosystems, a project has been recently initiated employing U.S. Southwest tree rings to reconstruct NAM precipitation. One element of the project involves the use of stable-carbon isotopes ($\delta^{13}C$) to supplement moisture estimates based on latewood ring-width measurements. The $\delta^{13}C$ values contain a moisture signal via an ecophysiological link between stomatal conductance and carbon isotope fractionation, which is particularly strong in arid and semi-arid regions (Warren et al., 2001). Previous work (Leavitt et al., 2002) exploring moisture-$\delta^{13}C$ relationships in a 500-km transect in southern Arizona and New Mexico indeed revealed promising correlations of latewood $\delta^{13}C$ and summer moisture, but the series were only 11-years long. This new initiative, however, is aimed at reconstructing moisture several centuries into the past.

This paper describes the characteristics and importance of the southwestern NAM and how tree-ring methodologies for both tree-ring widths and stable-carbon isotopes are particularly suitable for reconstruction of associated moisture. The basis for application of stable-carbon isotope tools in the study is emphasized. Preliminary studies demonstrate the potential value of including isotopic measurements in a spatial/temporal study of the NAM, and its suitability for inclusion in the focused multi-proxy study of the southwestern NAM over several centuries.

2. The North American Monsoon in the U.S. Southwest

NAM precipitation falls predominantly in July, August and September, and it accounts for ca. 30%-50% of annual precipitation in the southwestern U.S. (Figure 1). In contrast to the more widespread nature of winter precipitation associated typically with synoptic-scale mid-latitude cyclones, distribution of individual summer convective precipitation events is more spatially discontinuous, reflecting the localized nature of monsoon thunderstorms.

This summer monsoon system is associated with a summertime ridge of high pressure over the Colorado Plateau and mountains of Mexico, a shift in upper level winds, and convective precipitation fed by surges of moisture channeled by low-level jets from the Gulf of California and to a lesser degree, the Gulf of Mexico (Adams and Comrie, 1997). Monsoon precipitation is related to meso-scale, terrain-induced diurnal convection. Synoptic-scale transient disturbances, such as inverted troughs, and low-level moisture surges can enhance the diurnal cycle of convection and allow thunderstorms to organize and propagate off the elevated terrain. The position of the southwestern U.S. on the northern-most fringe of the NAM results in greater dependence on synoptic-scale disturbances to generate rainfall as compared to Mexico (Hales, 1972, Brenner, 1974, Castro et al., 2007a). Influx of low-level moisture is contributed from the northern Gulf of California, but also mid-level moisture appears to be contributed from the Gulf of Mexico (Carleton, 1986; Adams and Comrie, 1997; Higgins et al., 1997). An analysis of a 17-year record of H and O-isotopes in summer precipitation collected at Tucson, Arizona, suggests NAM moisture linkage to the eastern tropical Pacific Ocean (Wright et al., 2001). The intense heating in late May and June, which contributes to development of a southwestern thermal low in advance of the NAM moisture influx, also results in hyper-aridity that influences plant growth and is particularly fortuitous for tree-ring studies. The timing of onset is linked to the positioning and strength of an upper-level (monsoon) ridge over western North America. The monsoon ridge position during the onset period (late June, early July) is tied to a Pacific SST-forced teleconnection response (e.g. Castro et al., 2001; Schubert et al., 2004; Castro et al., 2007b). It may also be linked to the amount of antecedent winter/spring moisture present in the Southwest as well, which may influence the land-ocean temperature gradient (e,g,, Gutzler, 2000; Grantz et al., 2007) so the challenge is in separating out the cool and warm season precipitation response in tree rings.

Systematic research on the NAM continues with the North American Monsoon Experiment (NAME) project (Higgins et al., 2006; Higgins and Gochis, 2007), which began in 2004 with an intensive field campaign to gather data, and has evolved into a post-field phase of diagnostic and modeling studies to improve predictive capabilities. A lack of long instrumental records or reanalysis data, however, prevents an assessment of long-term variability of the NAM and its association with multidecadal-scale ocean variability. Proxy precipitation on longer time scales would be particularly helpful in this regard, but few are available. Poore et al. (2005) reported promising results showing enhanced NAM in the middle Holocene (ca. 6500–4500 ^{14}C yr B.P.) based on high abundance of a warm-water foraminifer species (*Globigerinoides sacculifer*) in the western Gulf of Mexico, seemingly supported by a decrease in packrat midden abundance at that time (Betancourt et al. 1993) perhaps caused by higher humidity dissolving away midden binding agents. The foraminifer proxy also generally compared well with a reconstruction of water-year precipitation from tree rings at a site in north-central New Mexico over the past 2000 years where summer precipitation dominates (Grissino-Mayer 1996). For revealing both high-resolution and spatial variability of NAM, however, precipitation reconstructions from systematic tree-ring networks extending back centuries are needed.

It is also anticipated that subsequent use of high-resolution general circulation models (GCMs) or regional climate models (RCMs), will be able generate long-term simulations resolved enough to represent the NAM as a salient feature. Current GCMs cannot capture interactions between surface forcing and large-scale atmospheric dynamics, which organize terrain-induced convective rainfall, so any projections of future NAM summer climate variability may be invalid (Castro et al. 2007b). Tree-ring reconstructions could then be compared with such model data from the RCMs to verify they provide a reasonable representation of past climate and are thus valid tools for climate projection.

Furthermore, because the NAM region is experiencing high population growth, increasing urbanization, and greater demands on water supplies, it is especially vulnerable to natural climatic variability and climate change (Ray et al., 2007). Both environmental and social infrastructures in the Southwest U.S. and northwest Mexico are particularly susceptible to drought stresses that can result from both cool season and warm season precipitation deficits. Although not a large component of the water supply in large metropolitan areas in the southwest like Tucson and Phoenix, variability in the NAM is very closely linked to summer water usage. Improved understanding of NAM behavior through tree-ring reconstructions may therefore contribute to more effective water resource management and drought planning.

3. Coherency in spatial variability of Southwest U.S. monsoon precipitation

In considering analysis of tree-ring data collected over the geographic area of the U.S. Southwest, it is important to know the spatial coherency of precipitation variability. Namely, do tree-ring data collected from the various sites in Fig. 1 exhibit the same signal with respect to large-scale climate variability? Or is there significant sub-regional variability? The answer to this question should consider the dominant synoptic-scale features responsible for the climatology and interannual variation in monsoon precipitation. Climatologically, as the monsoon ridge develops in the early to mid-summer, precipitation decreases in the central U.S. and increases in the Southwest (e.g., Higgins et al., 1997). As the monsoon ridge position and strength is influenced by Pacific SST-associated teleconnections in early summer, the out-of-phase relationship in summer precipitation between the central U.S. and Southwest is also present interannually (e.g., Castro et al., 2001, 2007b).

To characterize the spatial coherency of precipitation in the southwestern U.S. as a region, we performed a preliminary rotated empirical orthogonal function (EOF) analysis on the early summer (June and July) standard precipitation index (SPI), computed from PRISM climate data (http://www.prism.oregonstate.edu). Early summer is selected because that is the period when Pacific SST-associated teleconnections are most apparent and affect vegetation greening in the Southwest (Castro et al. 2001, 2007a, 2009). The dominant mode of this analysis (Fig. 2a) reveals the same sign of loading throughout virtually the entire southwestern U.S. study domain where tree-ring sites are located (Fig. 1) and the expected out-of-phase relationship with precipitation in the central U.S. In addition, correlation analyses with 500-mb height anomalies (Fig. 2c) from the NCEP-NCAR global atmospheric reanalysis (Kalnay et al., 1996) and global sea surface temperature anomalies (Fig. 2b) described by Kaplan et al. (1998), clearly show the atmospheric teleconnection response governing monsoon ridge position and the tie to Pacific-SST variability, as in Castro et al. (2007b). Thus, it is expected that the tree-ring data being collected should generally exhibit a consistent latewood precipitation signal.

4. Physical expression of NAM precipitation in tree rings

Annual tree-ring widths in the U.S. Southwest and northern Mexico have generally been used to reconstruct annual or "cool season" (winter/spring) precipitation (e.g., Grissino-Mayer 1996; Villanueva-Diaz and McPherson, 1996; Diaz et al., 2001; Ni et al., 2002). Fortunately, the formation of latewood in the second half of the growing season generally corresponds to the NAM period. Additionally the separation of the annual bimodal precipitation winter/spring and summer peaks by hyper-arid conditions in May/June, contributes to another ring feature that helps to better identify the timing of NAM onset and subsequent ring growth. Consequently, rather than the more typical growth ring couplet of earlywood (large cells with thin cell walls) and latewood (small cells with thick walls), tree rings in the Southwest can sometimes show earlywood, a "false latewood" band formed during the hyper-arid period, and then the final latewood (Figure 3). The lack of moisture during the hyper-arid period can contribute to dormancy in tree growth and hence the "false" latewood formation, but the NAM precipitation that follows can reactivate growth so that the first cells formed after the false ring even have the appearance of earlywood until the growing season concludes with formation of final latewood.

Research in Mexico and the southwestern U.S. has shown that measurements of the latewood portion of the annual ring reflect summer moisture variability (Meko and Baisan, 2001; Therrell et al., 2002). Evidence suggests the latewood signal for summer precipitation in southern Arizona can be enhanced by statistical removal of the dependence of latewood width on the preceding earlywood width (Meko and Baisan, 2001). This dependence, which presumably derives from improved tree vigor, increased food storage, foliage growth, etc., associated with a wet winter, can be effectively removed by linear regression. An "adjusted" latewood index is accordingly defined as the residual of latewood index on earlywood index. From analysis of daily precipitation records, the summer precipitation signal in adjusted latewood width was found to be sharply focused on roughly a 75-day window from late June to mid-August, the heart of the NAM season. Meko et al. (2003) found that adjusted latewood is vastly superior to total-width index as a predictor of summer precipitation in southern Arizona, potentially explaining more than half the variance of summer precipitation. Adjusted latewood-width was similarly found to be a useful summer precipitation proxy in western New Mexico, with a seasonal signal focused on the month of July (Stahle et al., 2007, 2009).

5. Tree-ring carbon isotopes and moisture

Stomatal opening in leaves of trees form the gateway for transfer of CO_2 from the atmosphere into the plant to support photosynthesis, as well as for the conveyance of plant water to the atmosphere. Diffusion and photosynthetic enzyme processes in the leaves discriminate against fixation of $^{13}CO_2$ in favor of $^{12}CO_2$, with stomatal conductance being an important factor determining the final amount of discrimination (Farquhar et al., 1982). In principle, under conditions of water stress or reduced humidity, the stomata close down and the reservoir of CO_2 available for continued photosynthesis is reduced, proportionately more $^{13}CO_2$ is fixed, and the $^{13}C/^{12}C$ ratio of sugars eventually incorporated into tree rings increases (i.e., $\delta^{13}C$ increases, where $\delta^{13}C$ (‰) = $[^{13}C/^{12}C_{sample} \div {}^{13}C/^{12}C_{PDBstandard} - 1] \times 1000$)). During moist conditions conductance is higher and photosynthetic enzymes are more selective against fixation of $^{13}CO_2$.

Furthermore, parameters influencing the rate of photosynthesis (and hence rate of consumption of CO_2) also influence discrimination against ^{13}C and contribute to the final $\delta^{13}C$ value. These include parameters such as temperature and sunlight. The full model for carbon isotope fractionation in plants was developed by Farquhar et al. (1982) and first interpreted with respect to tree-ring records by Francey and Farquhar (1982). The $\delta^{13}C$ link to stomatal conductance and moisture, however, seems to dominate over other influences under arid and semi-arid conditions (Warren et al., 2001).

Numerous studies have found strong linkage of $\delta^{13}C$ with moisture, even in environments that would be considered more mesic than arid. These include $\delta^{13}C$ linkage with various moisture indicators, such as drought indices (e.g., Leavitt, 1993, 2007; Leavitt et al., 2002; Liu et al., 2008), precipitation (e.g., Saurer et al., 1995; Hemming et al., 1998; Gagen et al., 2004; Liu et al., 2004; Anderson et al., 2006), soil moisture (e.g., Dupouey et al., 1993; Kagawa et al., 2003) and relative humidity (e.g., Saurer and Siegenthaler, 1989). In fact, one of the early studies with $\delta^{13}C$ and moisture involved a network of pinyon pine trees (*Pinus edulis* and *Pinus monophylla*) at 14 sites in six southwestern U.S. states (Leavitt and Long, 1989) and measurement of $\delta^{13}C$ of cellulose in 5-year ring sequences. As exemplified in the $\delta^{13}C$ series at the site in Northeast Arizona (converted to an "isotope drought index" by fitting a spline curve to the series and then calculating residuals), tree-ring $\delta^{13}C$ is strongly correlated to average annual precipitation and even more so to July Palmer Drought Severity Index (PDSI) (Fig. 4). Because moisture and plant growth are generally so strongly intertwined in the Southwest, it is not surprising that pinyon pine $\delta^{13}C$ in this network has even been found closely related to satellite-based "greenness" of regional vegetation (Leavitt et al., 2008)

Furthermore, these significant linkages of $\delta^{13}C$ with moisture emerge despite additional complexities in tree-ring isotope systematics, particularly as related to allocation of carbon. Hill et al. (1995) found evidence for derivation of the carbon in earlywood from photosynthesis in the previous growing season, so it would reflect environmental conditions at that time rather than the beginning of the growing season where the earlywood cells were located. Such reallocation of photosynthates in and out of a storage pool has been confirmed in pulsed ^{13}C tracer experiments by Kagawa et al. (2006). Helle and Schleser (2004) found evidence for this storage and carryover effect in earlywood of very finely resolved seasonal tree-ring subsamples of several species, and suggested that latewood should be sampled for dendroclimate studies to best obtain an unambiguous climate signal. Another study with finely sampled seasonal tree-ring samples (Skomarkova et al. 2006) further suggested storage and reallocation effects on $\delta^{13}C$ at both the beginning and end of the growing season so that the mid-ring wood best reflected a contemporaneous environmental signal. In a study tracking newly photosynthesized sugars from leaves to tree rings, however, Gessler et al. (2009) found good coherence between the isotopic composition of the sugars and ring wood over about 8 months of growth. Multi-parameter mechanistic models of ring formation by Hemming et al. (2001) and Ogee et al. (2009) include storage terms of varying complexity, but they improve the fit between modeled versus actual isotopic results. Generally, storage effects on tree-ring $\delta^{13}C$ seem to be greater for angiosperms (such as oak) than for conifers, and species differences even among conifers or angiosperms may further influence the degree of expression of these effects.

Even in a case where photosynthate storage is not important, newly fixed carbon will be simultaneously allocated to both initiate formation of new wood cells and to complete the cell formation of older cells at various stages of development, i.e., the duration of formation of individual cells may be days to weeks (Skene, 1969), and thus each cell will contain carbon fixed over that time period under the various corresponding environmental circumstances. Thus the tree-ring isotope system has further justification for "fuzziness" in environmental relationships, but as described above and below, the fidelity of relationships of tree-ring $\delta^{13}C$ with moisture is often quite high.

6. Isotopic expression of NAM precipitation in tree rings

The greatest promise for the use of tree-ring $\delta^{13}C$ for NAM precipitation reconstruction is seen in the findings of Leavitt et al. (2002) who analyzed the stable-carbon isotope composition of ring formation pre- and post-onset of monsoon (as represented by growth before and after an intra-annual or false band) in ponderosa pine (*Pinus ponderosa* and *Pinus arizonica*) at eight sites over a 500-km transect in southern Arizona and New Mexico. Cellulose from ring subdivisions pooled from 5-6 trees at each site was analyzed to generate $\delta^{13}C$ chronologies for ca. 10-11 years within the period 1985-1996. The pre-monsoon $\delta^{13}C$ chronologies correlated well with the Southern Oscillation Index (i.e., El Niño, primarily a winter-spring phenomenon), whereas the post-false latewood $\delta^{13}C$ chronologies correlated well with summer (monsoon) precipitation amount.

Indeed, when the latewood $\delta^{13}C$ values from all sites are regressed against corresponding total July through September precipitation of the nearest climate stations a strong relation is apparent ($r^2 = 0.41$) (Fig. 5a). At the site closest to the corresponding climate station (within ca. 1 km), the relationship was remarkably strong ($r^2 = 0.81$) (Fig. 5b). With respect to stored photosynthates, the latewood $\delta^{13}C$ was not significantly correlated with the earlywood $\delta^{13}C$ of the next ring at this site ($r= 0.37$, $n=10$, $p=0.30$), suggesting storage carryover effects not important to any climate signal in the earlywood at this site.

Coherence among $\delta^{13}C$ chronologies was greater across the transect during the period represented by earlywood (mean inter-series correlation among the eight sites, $r = 0.73$) than in the latewood (summer monsoon) time period (mean inter-series correlation, $r = 0.39$) (see also Fig. 4 of Leavitt et al. (2002)). This presumably results from the greater spatial homogeneity of precipitation from winter mid-latitude cyclones relative to summer monsoon thunderstorms.

The results from this pilot study demonstrate the strong influence of moisture on the $\delta^{13}C$ of tree rings, and thus useful for extracting a precipitation seasonal signal in sub-annual isotope measurements in the southwestern NAM region. The study of Leavitt et al. (2002), however, used only trees with false latewood bands to more clearly define the monsoon period in the ring.

Testing rings with latewood alone (and no false latewood bands) will be important to see if these relationships are still as strong, as is the case when latewood widths are used (Meko and Baisan, 2001). Likewise, latewood widths of Douglas-fir (*Pseudotsuga menziesii*) have been found strongly related to southwestern NAM precipitation (Meko and Baisan, 2001), but a systematic exploration of this species with stable-carbon isotopes remains to be done.

7. Monsoon tree-ring project and its isotope component

We initiated a project in late 2008 to reconstruct southwestern monsoon precipitation for the past three centuries using tree-ring measurements. Latewood width is the primary parameter being featured in the study, supplemented with a smaller but important isotope component. The project is targeting at least 30 tree-ring chronologies around the southwestern NAM monsoon, with a focus on the core southeastern Arizona/southwestern New Mexico region (Fig. 2). Collections from the core and fringe regions will be used to evaluate both temporal and spatial characteristics of monsoon precipitation. The latewood width chronologies are being developed primarily from existing sample collections archived at the Laboratory of Tree-Ring Research, University of Arizona. New collections are being used to update archive-based chronologies to the present from their original collection dates several decades ago. We are also building on existing chronologies because the variability of latewood widths decreases with the age of the tree, so it is necessary to sample young and middle-aged trees to obtain useful latewood width variability up to the present.

Latewood $\delta^{13}C$ chronologies will be developed on ponderosa pine at three of the sites, and additionally a Douglas-fir $\delta^{13}C$ chronology will be developed at one of these sites for direct comparison. For each site, the latewood of each ring from 4-5 trees per site will be separated with a razor knife under a binocular microscope. To represent the mean $\delta^{13}C$ time series at each site, the latewood from the trees will be pooled for most years, after which cellulose will be extracted and analyzed to achieve highest signal fidelity (McCarroll and Loader, 2004). Approximately every 20 years, the latewood of each tree will be analyzed separately to assess general inter-tree $\delta^{13}C$ variability for each chronology. Effects of declining atmospheric $\delta^{13}C$ composition will be removed from the tree-ring time series by applying incremental corrections such as those in McCarroll and Loader (2004), and effects of increasing atmospheric CO_2 concentration on $\delta^{13}C$ will explored with corrections as described in McCarroll et al. (2009). Using regression and correlation analysis between these $\delta^{13}C$ chronologies (also latewood width chronologies) and respective climate data, the following questions will be addressed:

1) To what extent do the $\delta^{13}C$ chronologies reflect NAM instrumental precipitation measurements at their respective sites?
2) How do the $\delta^{13}C$-precipitation relationships compare to latewood width-precipitation relationships? Do the $\delta^{13}C$ values provide supplemental NAM information not contained in the latewood widths? To what extent could the addition of a $\delta^{13}C$ term improve multiple regressions with precipitation in calibration models?
3) Can latewood $\delta^{13}C$ measurements from ponderosa pine and Doug-fir be used interchangeably?

In addition to possible confirmation of precipitation reconstruction from latewood widths, the $\delta^{13}C$ chronologies could expand precipitation reconstruction if they are better able to track late season (September) precipitation, which is not captured well by latewood width. Furthermore, $\delta^{13}C$ series from fewer trees are likely needed to represent the environmental record of a site, so isotopic analysis could be particularly useful in extending chronologies back in time when fewer samples may be available.

The collective set of isotope and latewood width measurements from the Southwest network of sample sites will be used to address a broader set of questions, including:

1) How does the strength of the monsoon signal in tree vary with elevation, aspect and distance from the core monsoon region?
2) What are the spatial and temporal characteristics of the reconstructions over the past 300-500 years?
3) What are the relationships between monsoon precipitation, winter precipitation, and circulation, and what influence do these relationships have on the frequency, timing, duration and spatial extent of droughts?

We anticipate several applications of these data to other fields of study. As a part of this project, we will use the temporal and spatial characteristics of reconstructed NAM precipitation to help verify whether the regional circulation model (RCM) downscaling of IPCC general circulation models (GCMs) can adequately capture NAM climatology and range of inter-annual variability that exists in the tree-ring records. Another key part of this project is collaborative interaction with local and regional water management agencies to develop data and information that is useful to water resource management and drought planning. Several agencies, who already use tree-ring proxies for water supply, have expressed interest in understanding the demand component, largely represented by the NAM, as well as the long-term relationship between winter and summer precipitation.

8. Conclusions

Like sub-continent scale circulation of summer monsoon moisture in India and East Asia, the North American Monsoon delivers precious moisture into the U.S. Southwest. With a growing population stressing regional water resources, it is becoming even more important to improve our understanding of the NAM, particularly in regard to its spatial variability and temporal stability over centuries and its relationship with winter precipitation. According to models of plant carbon isotope fractionation, the stable-carbon isotope composition of tree rings can be influenced by moisture (among other factors), a relationship that seems to be particularly strong in arid/semi-arid regions such as the Southwest. This is seen quite conspicuously in $\delta^{13}C$ studies with pinyon pine whole rings from around the Southwest and with latewood of ponderosa pine in southern Arizona and New Mexico.

This relationship forms the basis for development of long latewood $\delta^{13}C$ records from ponderosa pine (and Doug-fir) tree rings in several core regions of the southwestern NAM. It is anticipated that the $\delta^{13}C$ will supplement latewood width chronologies for reconstructing NAM precipitation and therefore contribute to a more comprehensive historical understanding of NAM and its association with multidecadal-scale ocean variability. Results of this project will provide assistance to long-term water management and contribute to validation of RCM models dynamically downscaled from GCM models.

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Fig. 1. Map of percent summer precipitation (JAS) during the NAM period around the Southwest and location of tree-ring sites for monsoon study.

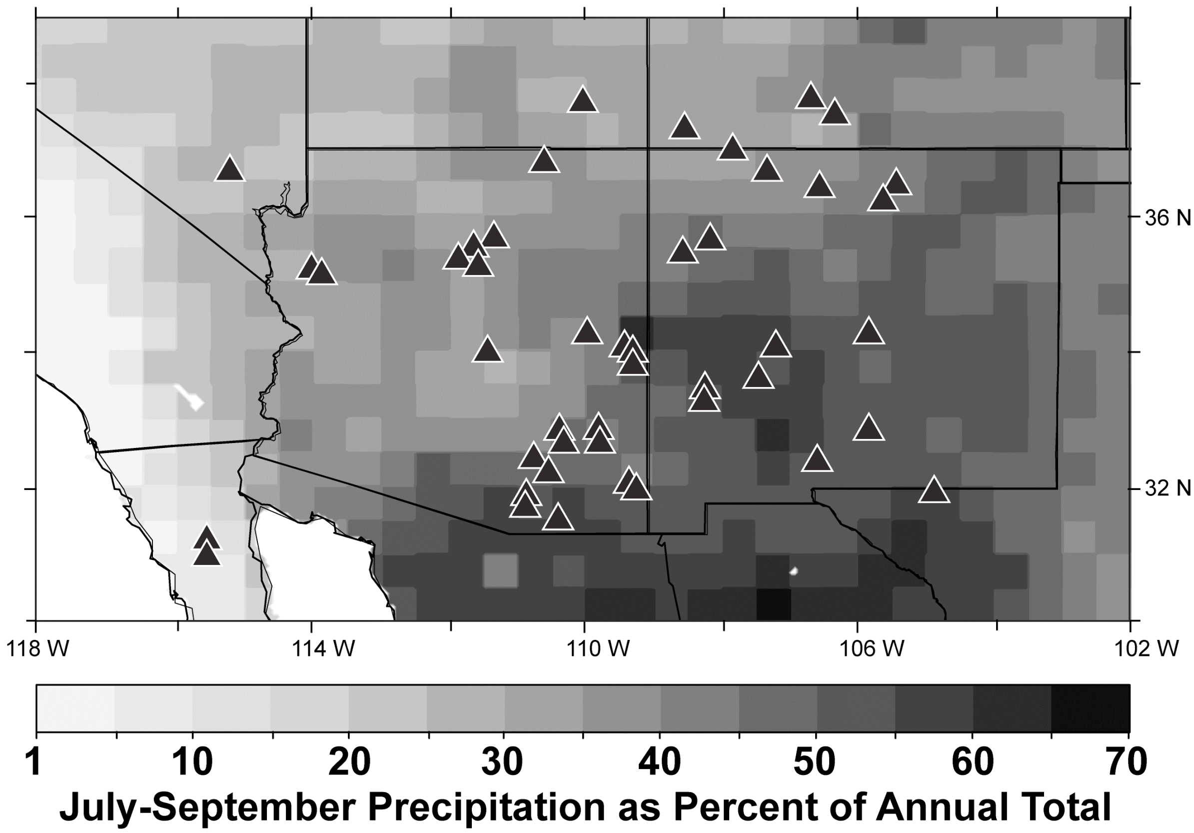


Figure 2. Maps of (a) first rotated EOF (Varimax rotation) computed using June-July SPI, (b) the first June-July rotated PC time series correlated with the Kaplan average June-July SST anomalies, and (c) the first June-July rotated PC time series correlated with NCEP/NCAR global reanalysis average June-July 500-mb geopotential height anomalies.

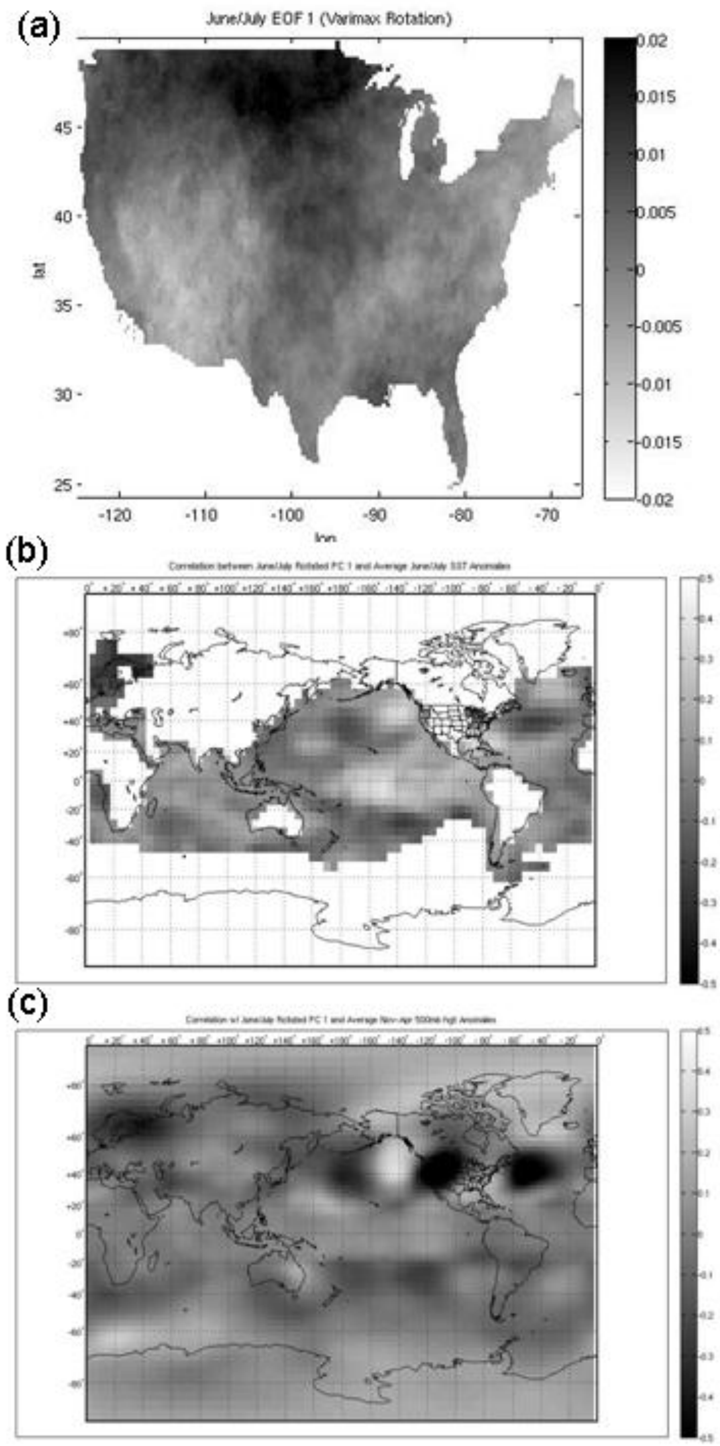


Fig. 3. Photomicrograph illustrating a series of Douglas-fir tree rings from Black Mountain in southwestern New Mexico. Note the independent variability in earlywood-width (light color), latewood-width (dark color), and total ring-width. Also note the presence of "false latewood bands" in 1871 and 1872. These tangential bands of increased wood density are likely related to reduced soil moisture during the very dry "foresummer" season that leads up to the onset of the NAM. With the onset of the NAM rains, tree growth resumes with less dense latewood formation.

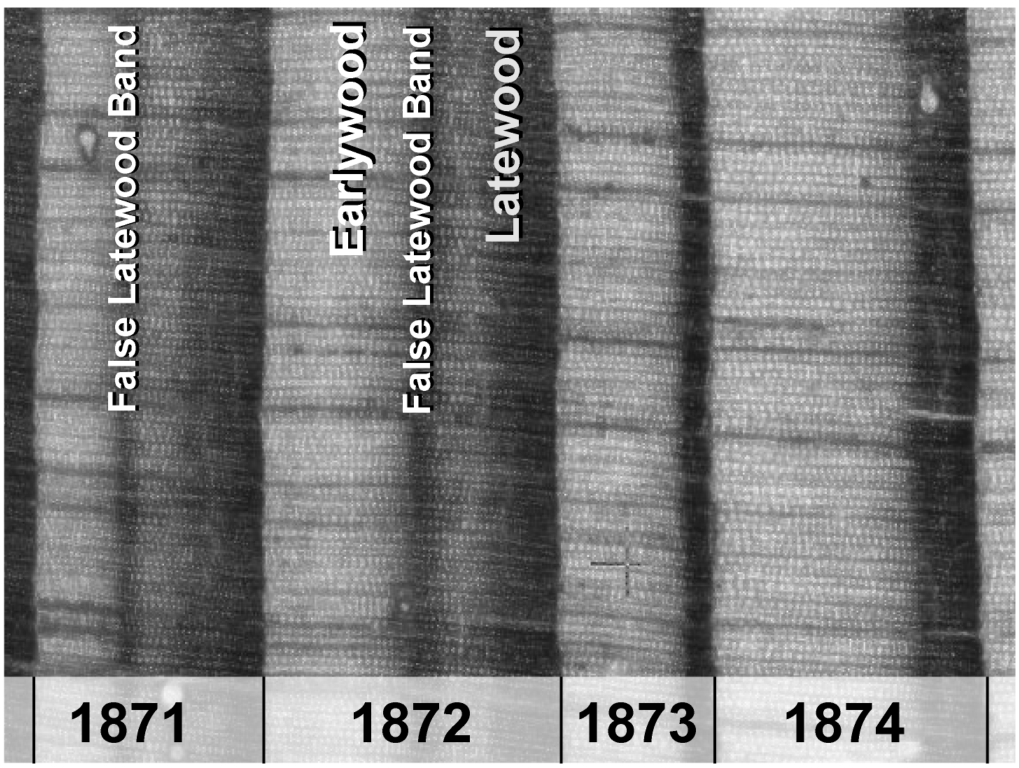
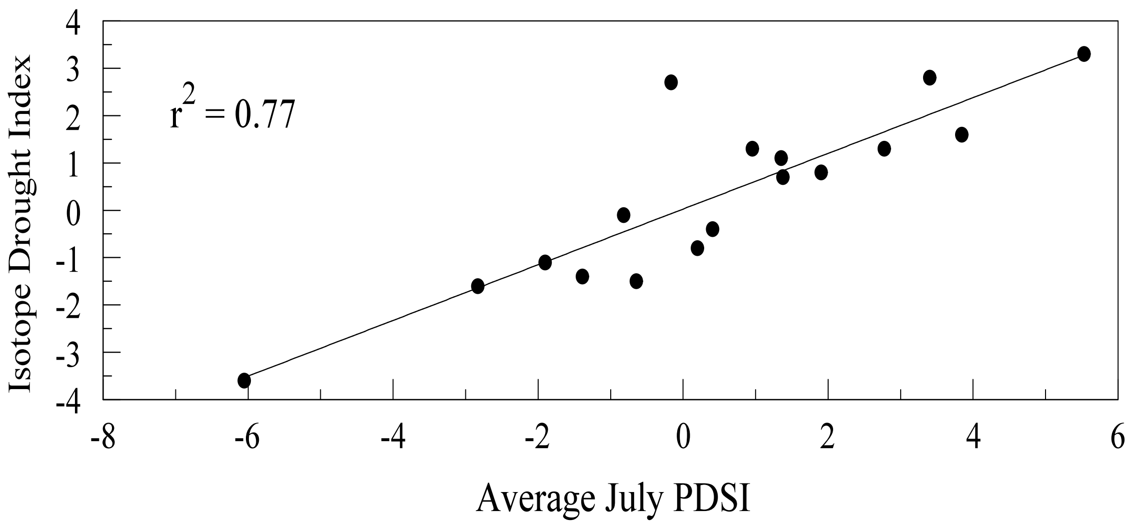


Fig. 4. Plot of the $\delta^{13}C$-derived "isotope drought index" (IDI) for the NEAZ pinyon pine site (Leavitt and Long, 1989; Leavitt et al., 2008) versus (a) the Palmer Drought Severity Index ($p<0.00001$), and (b) average annual precipitation, for the Northeast Arizona climate division, 1900 to 1984 ($p<0.0001$). The $\delta^{13}C$ chronology was developed on cellulose of 5-year ring groups and the PDSI values are the mean July values of the corresponding 5 years in each isotope pentad. IDI's were derived by fitting a spline to the raw $\delta^{13}C$ values and calculating the indices as the offset between the raw values and the spline. The relationships using $\delta^{13}C$ directly were considerably weaker ($\delta^{13}C$ with July PDSI and $\delta^{13}C$ with annual precipitation both $r^2=0.38$, $p<0.01$) as were relationships with Jul-Aug-Sep precipitation (IDI with JAS precipitation $r^2=0.49$, $p<0.002$; $\delta^{13}C$ with JAS precipitation $r^2=0.22$, $p=0.06$).



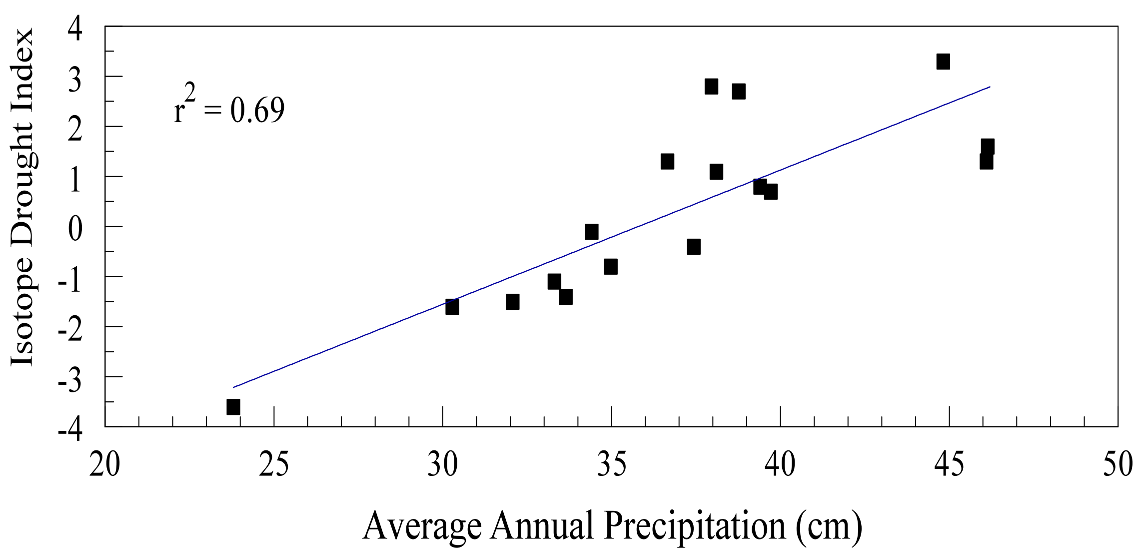
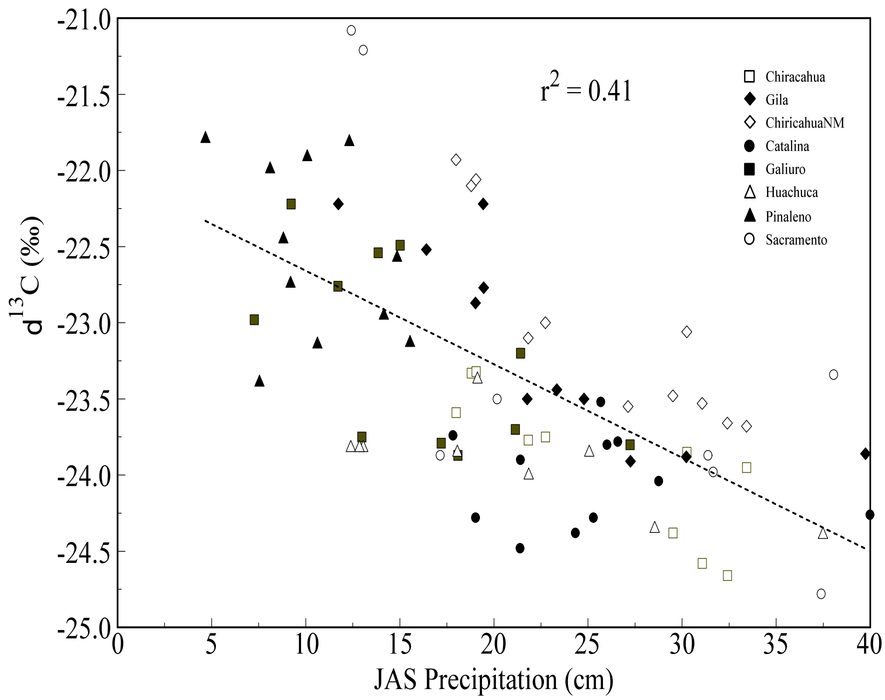


Fig. 5. Relation between $\delta^{13}C$ of post-false latewood bands with total July-August-September precipitation for years in the 1986 to 1996 period for (a) eight ponderosa pine sites over a 500-km transect in southern Arizona and New Mexico ($\delta^{13}C = -0.061 \times$precipitation(cm) $- 22.045$; $p<0.00001$) using precipitation data from the closest stations with highest correlations, and (b) for the Chiricahua Mts. site with the closest climate station within 1 km ($p<0.0002$). Data from Leavitt et al. (2002).

(a)



(b)