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The seasonality of precipitation signals embedded within the North American Drought Atlas

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Abstract

We examine how the seasonality of precipitation signals embedded within the North American Drought Atlas varies across the continent. Instrumental records of average summer (JJA) Palmer Drought Severity Index (PDSI) are characterized by major regional differences in the relative importance of precipitation during summer and winter (DJF). The Atlas, which is based on a network of drought-sensitive tree-ring records, is able to reproduce the main geographic patterns of these biases, but tree-ring reconstructions exaggerate the influence of seasonal precipitation anomalies in the southwestern United States and northern Mexico (towards a stronger winter signal) and western Canada (towards a stronger summer signal). Drought reconstructions from the Southwest and Tex-Mex regions are tuned mainly to winter precipitation and display strong teleconnections to both El Niño and La Niña. In contrast, winter precipitation signals are either weak or absent in drought reconstructions from northwestern North America, and tree-ring estimates of PDSI show a much less robust association with the El Niño-Southern Oscillation. Geographical differences in the relative strength of seasonal precipitation signals are likely due to (i) local factors that influence tree growth but are not incorporated into the PDSI algorithm and (ii) real differences in regional climatology. These seasonal biases must be taken into account when comparing drought reconstructions across North America, when comparing tree-ring PDSI to drought records developed from other proxies or when attempting to use the Drought Atlas to link past droughts to potential forcing mechanisms.

Keywords

dendrochronology, drought, North America, paleoclimatology, precipitation, seasonality

Introduction

The North American Drought Atlas (Cook and Krusic, 2004; Cook *et al*., 1999, 2007) uses a network of moisture-sensitive tree-ring records from Canada, the United States and Mexico to estimate changes in drought conditions across the continent during the past two millennia. In its primary application, the Atlas has been used to place recent dry and wet intervals within a context of long-term variability and to identify droughts that were more persistent or more severe than historical droughts (Cook *et al*., 2004; Fye *et al*., 2003; Woodhouse *et al*., 2005). Partially because of the Atlas's excellent replication and rigorous quality-control procedures, it has also been used to corroborate or compare drought conditions inferred from independent tree-ring reconstructions (Watson *et al*., 2008; Woodhouse *et al*., 2006), historical documents (Mendoza *et al*., 2006) and other biological or geological proxies (Booth *et al*., 2006; Conroy *et al*., 2009; Neff *et al*., 2008; Sridhar *et al*., 2006). The Atlas has helped clarify the impact of drought on wildfire (Hessl *et al*., 2004; Kitzberger *et al*., 2007; Westerling and Swetnam, 2003) and ecological dynamics (Gray *et al*., 2006), provided a framework to test the stability of relationships between remote climate forcings and North American drought (Cole and Cook, 1998; Hidalgo, 2004; Herweijer *et al*., 2007) and served as a real-world target for climate model simulations (Meehl and Hu, 2006; Seager *et al*., 2005, 2009; Yoshimori *et al*., 2005).

The specific drought metric described by the Drought Atlas is the Palmer Drought Severity Index (PDSI) (Palmer, 1965). The PDSI incorporates historical records of precipitation and temperature into a Thornthwaite water-balance model to estimate the amount of water available in the soil relative to average conditions and is typically produced at a monthly time step (Alley, 1984; Cook *et al*., 2007). Calculating the PDSI is quite involved; in his critique of the index's construction, Alley (1984)'s description of its computation takes up nearly four pages. The index applies the water balance model to compute four values – potential loss to evaporation, potential evapotranspiration, potential recharge and potential runoff – that are combined into a set of coefficients that reflect local climate conditions. The model also requires latitude (potential evapotranspiration depends partially on day length) and soil-water capacity to be specified. A moisture anomaly index, *Z*, is calculated from the difference between

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actual precipitation and CAFEC (Climatically Appropriate For Existing Conditions) precipitation, with a weighting factor that standardizes the index across different areas and different months. The PDSI at time *i* is calculated as:

$$\text{PDSI}_{(i)} = 0.897\text{PDSI}_{(i-1)} + \tfrac{1}{3}Z_{(i)} \quad (1)$$

The index has relatively high month-to-month persistence because of soil moisture carryover in the water balance and the strong autocorrelative term imposed by the computation algorithm. As a consequence, PDSI for a given month reflects drought conditions for that month and several months prior. Values for the PDSI commonly range between −4 (extreme drought) and +4 (extreme wet) but the index does not have a prescribed upper or lower limit (Cook *et al*., 2007). The PDSI is a key element of national and international drought monitoring efforts including Agriculture and Agri-Food Canada's DroughtWatch program (http://www.agr.gc.ca/pfra/drought), the United States National Weather Service's Climate Prediction Center (http://www.cpc.noaa.gov) and the North American Drought Monitor (Lawrimore *et al*., 2002).

The reconstructions in the Drought Atlas estimate average PDSI during summer (June to August) on a 2.5° grid across most of North America. By estimating the same parameter (summer PDSI) at each location in its network, the Drought Atlas provides a uniform set of proxy records that are directly comparable across its entire domain. At the same time, certain applications of the Atlas, such as examining potential connections between North American drought and atmospheric or oceanic forcings, are complicated by the fact that summer PDSI can be influenced by a variety of climatic factors and the relative importance of these factors differs from place to place. Real differences in the climatology of summer PDSI may also be exacerbated by the varying ability of tree rings across North America to reproduce certain climate signals. In this study, we examine how the seasonality of precipitation signals embedded within the North American Drought Atlas varies across the continent. By showing that the Atlas is biased towards precipitation anomalies during either winter or summer in some regions, we highlight an important aspect of proxy drought records derived from tree rings that must be considered when assessing the dynamics and impacts of past droughts at the regional or continental scale.

Data and methods

Instrumental records of average summer PDSI were obtained from the North American data set developed by Cook *et al.* (2004, 2007), available online at the World Data Center for Paleoclimatology (http://www.ncdc.noaa.gov/paleo/pdsidata.html). These data (hereafter, 'observed PDSI') are based on high-quality monthly PDSI records for stations in the United States (Cook *et al*., 1999) and Canada (Skinner *et al*., 2001) and gridded PDSI estimates from Mexico (Dai *et al*., 1998). The complete data set covers most of North America at a resolution of 2.5° (excluding only the Yucatan, Alaska, and northern Canada) and spans the interval 1900 to 2003. Tree-ring estimates of summer PDSI (hereafter, 'tree-ring PDSI') are derived from Version 2a of the North American Drought Atlas (http://www.ncdc.noaa.gov/paleo/pdsi.html) (Cook and Krusic, 2004; Cook *et al*., 2004). This version of the Atlas incorporates more tree-ring chronologies than its 2004 release and extends the reconstructions further back in time (in some regions, the records cover the last 2000 years). Because observed PDSI data was used to extend tree-ring PDSI records for gridpoints in the United States after 1979 (Cook *et al*., 2004), our analysis was restricted to the period extending from 1900 (or 1901, for seasons that span the calendar year) to 1978 so that we could assess the characteristics of the observed and tree-ring PDSI data sets separately over the same reference period.

Seasonal precipitation records for summer (JJA) and winter (DJF) were computed from the University of East Anglia Climatic Research Unit's TS 2.1 gridded data set of monthly climate observations (Mitchell and Jones, 2005). We also performed additional tests for select climate divisions in the United States using monthly precipitation, temperature and PDSI data downloaded from NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgr.html). An index describing the El Niño-Southern Oscillation (the 'Cold-Tongue Index') was downloaded from the Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu), and averaged to produce cold-season (October to March) means. The Cold Tongue Index (CTI) is the average sea surface temperature (SST) anomaly over the region bounded by 6°N–6°S and 180°–90°W minus global mean SST (Deser and Wallace, 1990) and is very similar to the more commonly used NINO-3 time series (Zhang *et al*., 1997).

We tested the connection between seasonal precipitation and PDSI using point-to-point correlations – correlating observed and tree-ring PDSI records at each gridpoint with precipitation data from the same location. Correlation tests were adjusted for the loss of degrees of freedom due to temporal autocorrelation (Dawdy and Matalas, 1964). We also mapped the correlation between the CTI and both observed and tree-ring PDSI across the domain and used a compositing approach to identify regional PDSI anomalies during the positive (El Niño) or negative (La Niña) phase of ENSO (index values more than one deviation above or below the mean).

Results

In most parts of North America, observed PDSI is related to precipitation during both seasons (Figure 1a and c). Correlations are overwhelmingly significant and positive for both summer (257/286 gridpoints) and winter (222/286 gridpoints) precipitation. The summer signal is strong over Canada and most of the United States east of the Rocky Mountains but is absent over Arizona, southern California, Sonora, Chihuahua and Baja California (hereafter, 'the Southwest'). In this region, observed summer PDSI is highly correlated ($0.4 < r < 0.7$) with precipitation during winter. The connection between observed PDSI and winter precipitation is weaker outside the Southwest but is still significant. The main exception is the northern limit of the Great Plains, as the winter signal in observed PDSI is generally missing from gridpoints in Manitoba, Saskatchewan and the Dakotas.

The spatial patterns of correlation of seasonal precipitation with tree-ring PDSI (Figure 1b and d) broadly resemble those present in observed PDSI. Tree-ring PDSI also reproduces the strength of the correlation patterns relatively accurately, although there are several important regional exceptions. The winter precipitation signal in the Southwest is stronger and more extensive in the tree-ring estimates than in observations, while the summer signal is weaker. Tree rings also underestimate the correlation with summer precipitation in the central and southeastern United States, and while observed PDSI in British Columbia and Alberta is

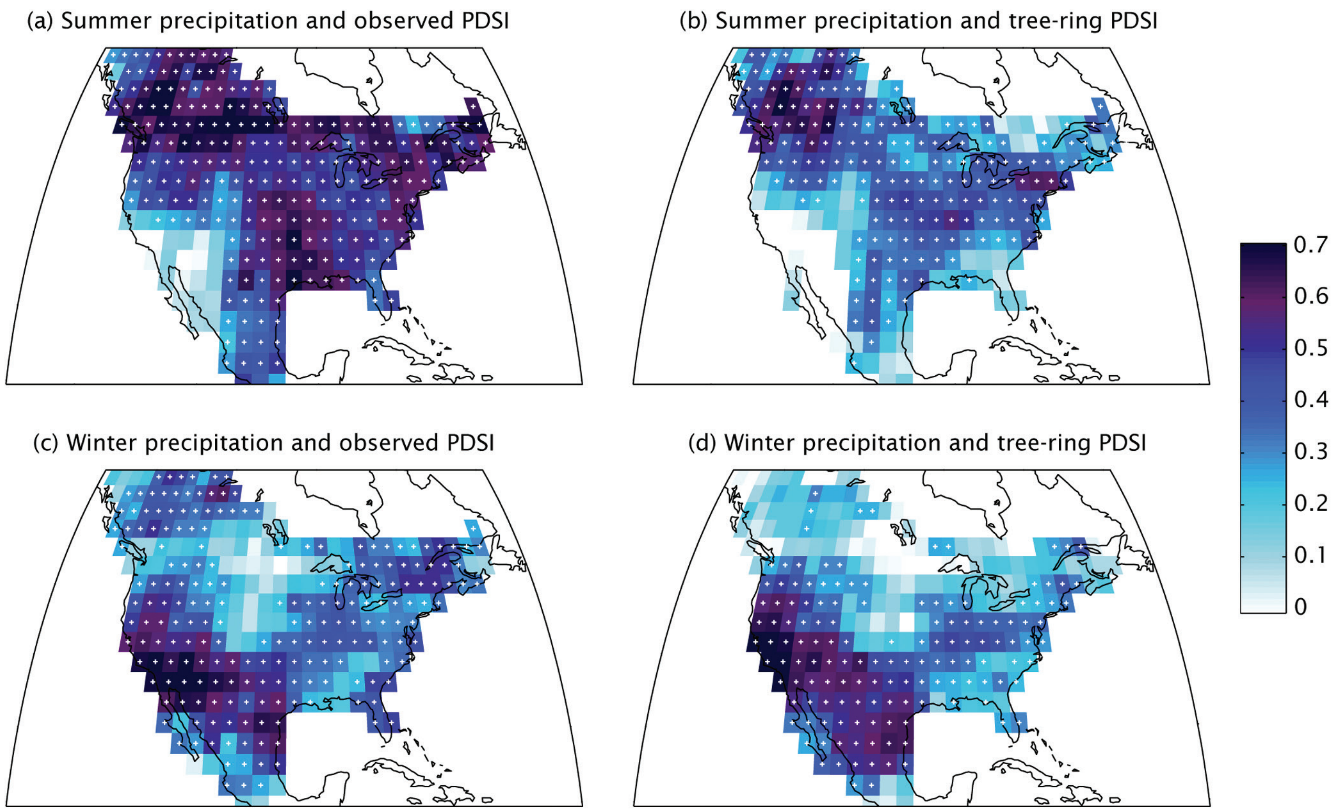

Figure 1. Point-to-point correlations between (i) summer (JJA) and winter (DJF) precipitation and (ii) observed and tree-ring PDSI across North America for the period 1900 (or 1901) to 1978. Gridpoints with significant (p = 0.05) correlations are marked with white crosses

significantly correlated with winter precipitation, tree-ring PDSI does not show a winter signal over most of western Canada.

Differencing the summer and winter maps shows major geographic differences in the seasonality of precipitation signals that influence summer PDSI across North America (Figure 2a). Southwest of a transect cutting between Oregon and the Louisiana coast, summer PDSI is dominated by winter precipitation. Towards the northeast, the summer signal is more prominent. The North American Drought Atlas reproduces the geographic patterns of these biases towards either summer or winter precipitation quite accurately (Figure 2b), but the tree-ring estimates exaggerate their magnitude in the Southwest (enhancing the winter signal) and western Canada (enhancing the summer signal) relative to the observed PDSI.

Geographic differences in the seasonality of precipitation signals that influence summer PDSI also affect the teleconnection patterns produced when comparing the Drought Atlas with the El Niño-Southern Oscillation (ENSO). In agreement with results obtained using an earlier version of the Atlas (Cole and Cook, 1998), the regional correlation with ENSO is higher and more extensive (expanding farther south into central Mexico) in tree-ring PDSI than in observations (Figure 3a). Composites indicate that strong El Niños (La Niñas) are associated with anomalously wet (dry) conditions across Texas and northern Mexico (the 'Tex-Mex' region) and parts of the Southwest. In Mexico, El Niño has a greater impact than La Niña on both observed and tree-ring PDSI. The drought response to ENSO in the Pacific Northwest and western Canada (dry during El Niño, wet during La Niña) is opposite to the relationship observed in the Southwest, but the correlation and composite results are

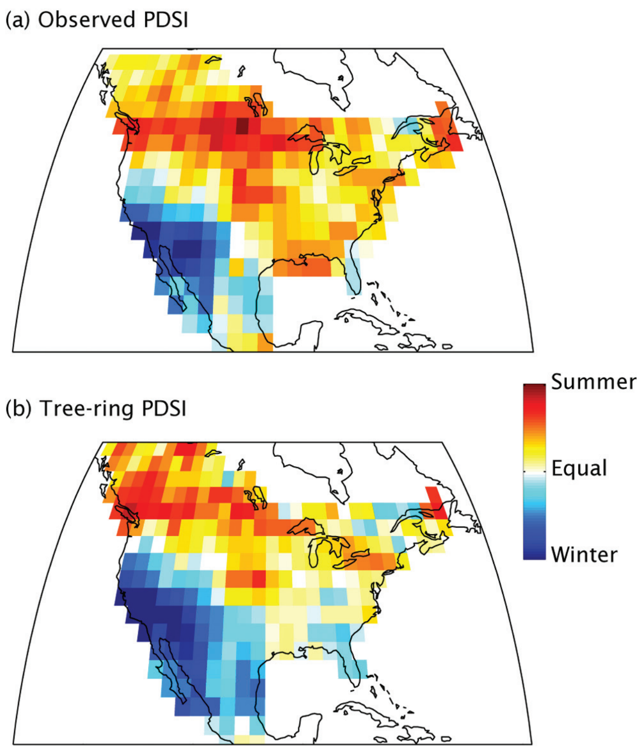

Figure 2. Dominant seasonal precipitation signals in (a) observed and (b) tree-ring PDSI. Shading represents the difference of correlation coefficients calculated between (i) summer PDSI and summer precipitation and (ii) summer PDSI and winter precipitation at each gridpoint for the period 1901 to 1978

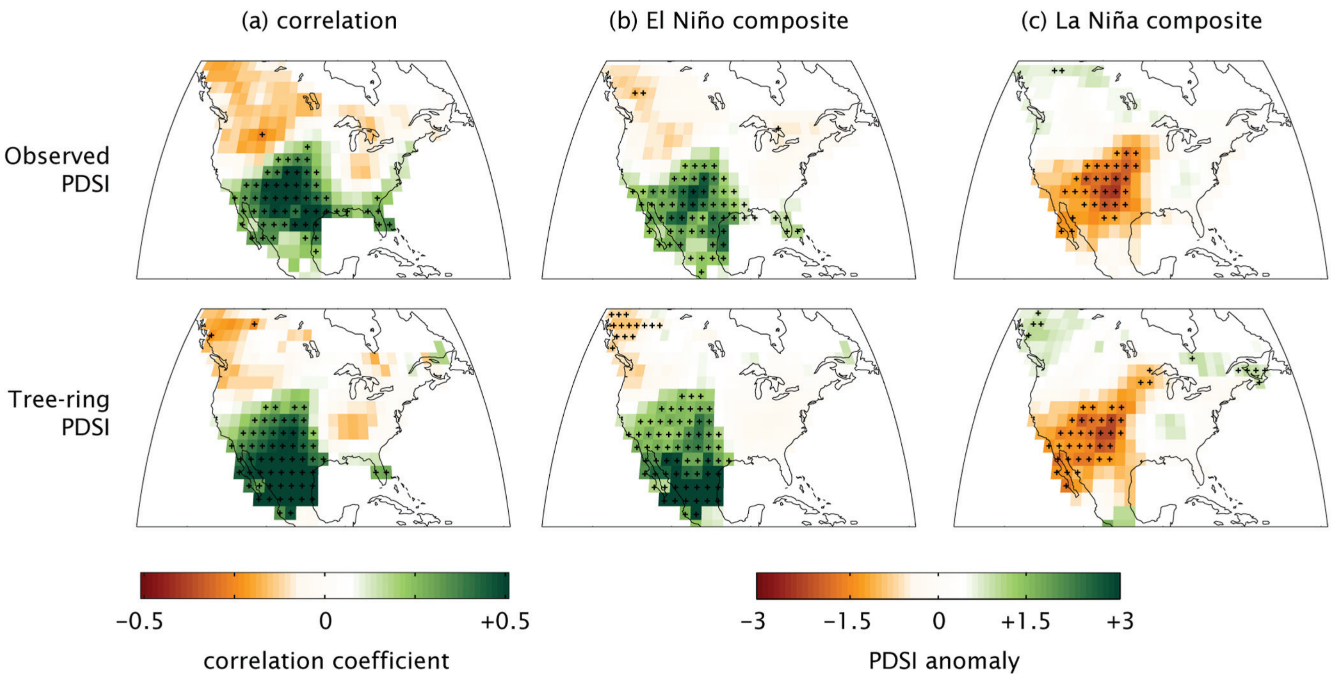

Figure 3. Observed and tree-ring PDSI compared with the El Niño-Southern Oscillation (as represented by the Cold Tongue Index) during the period 1900 to 1978 using correlation (a) and composite (b and c) analysis. The composite maps show PDSI anomaly averaged over years when the index was either one standard deviation above (El Niño) or below (La Niña) its 1900–1978 mean. Black crosses denote significant ($p = 0.05$) correlations in (a) while in (b) and (c), they highlight gridpoints where PDSI anomalies in high or low index years are significantly ($p = 0.05$) different from anomalies in all other years

significant at only a few gridpoints in either the observed or tree-ring PDSI data sets. Because of the absence of a strong northwestern response, the overall patterns described by the Drought Atlas do not resemble the classic dipole structure of ENSO teleconnections in western North America (Redmond and Koch, 1991).

Discussion and conclusion

Despite being targeted at the same drought parameter across the continent, the reconstructions that make up the North American Drought Atlas still show major regional differences in the relative influence of seasonal precipitation. To a large degree, these differences are real and reflect aspects of local climatology and the construction of the PDSI. Even in observations, summer PDSI is mainly tuned to winter precipitation in the southwestern United States and northern Mexico, while in western Canada, the same index is linked primarily to summer rainfall (Figure 2). It may be somewhat counter-intuitive that, across the Southwest, summer PDSI is not significantly correlated with summer precipitation, but this result is due to the importance of winter precipitation to the overall water budget, either because winter is the rainy season (as in southern California) or because monsoon rains in summer coincide with high evaporative losses (as occurs in Arizona and western Mexico). Because the PDSI integrates soil moisture anomalies over several prior months, strong precipitation anomalies during winter can be carried over to influence summer conditions. In addition, in parts of the Southwest, precipitation has more interannual variability in winter than in summer (McDonald, 1956; Sellers, 1960), which further strengthens the impact of cool-season moisture on the summer PDSI. In western Canada, summer PDSI is strongly linked to summer precipitation because rainfall between June and August makes up 40 to 50% of annual precipitation and evaporative demand during summer is relatively low (compared with warmer regions in North America), which allows the summer season to have a major influence on the PDSI's water balance.

The fact that reconstructions from the Drought Atlas strongly mimic the patterns exhibited by PDSI observations confirms that tree growth integrates or filters seasonal precipitation anomalies in a way that is very similar to that specified in the calculation of the drought index. At the same time, the Drought Atlas is not able to accurately reproduce the observed seasonality of summer PDSI everywhere. Some of these differences may be due to trees imposing their own biases on the drought reconstructions. For example, the enhanced winter-precipitation signal observed in tree-ring PDSI records from the Southwest may reflect the importance of snowmelt as a source of water for trees from this region. At high-elevation sites, an unusually deep snowpack can linger and effectively irrigate the trees through the spring, reducing moisture stress in this hot, semi-arid region during the period of early-season growth. In contrast, the PDSI algorithm treats all precipitation as rainfall and is not able to carry over moisture stored as snow beyond its influence on the monthly water balance accounting. As a consequence, drought reconstructions derived from Southwestern tree-ring records may be expected to record the influence of winter precipitation more strongly than the observed PDSI itself.

The apparent connections between summer PDSI and seasonal precipitation may also be influenced by other aspects of the Drought Atlas. The lack of a significant summer signal in either observed or tree-ring PDSI records from the interior Southwest is somewhat surprising given that summer precipitation delivered by the North American Monsoon (NAM) can make up more than half the annual precipitation. This result may be a product of the relatively modest spatial coherence exhibited by precipitation anomalies in this region during summer and the smoothing required to match the gridded CRU data to the 2.5° × 2.5° grid used by the Drought Atlas. Using higher-resolution divisional-average climate data, we found that summer PDSI in southern Arizona is indeed significantly ($p < 0.01$) correlated with both winter and summer precipitation ($r = 0.67$ for winter, $r = 0.31$ for summer; $n = 97$). Therefore, we emphasize that our findings apply to the relatively course spatial scale described by this version of the Drought Atlas and they may not hold for investigations conducted at a more local level.

Tree-ring reconstructions of PDSI for the Southwest and western Canada are tuned almost exclusively to precipitation anomalies during winter or summer, respectively. These geographic differences appear to be particularly relevant when the Drought Atlas is used to illustrate associations between tree-ring PDSI in North America and ENSO. ENSO affects the climate of North America most strongly during winter (Redmond and Koch, 1991), so drought reconstructions that are tuned primarily to winter precipitation, such as those from the Southwest and Tex-Mex regions, display connections that are strong and symmetrical for both El Niño and La Niña. In other parts of North America, the winter precipitation signal in tree-ring PDSI is either weak or absent and, as a consequence, the association with ENSO is less robust. These results confirm that the Southwest is the most promising location in North America to search for ENSO signals in tree-ring series (Stahle *et al*., 1998). They also indicate that researchers should be cautious when examining potential connections between the ENSO system and individual drought-sensitive tree-ring records from other regions.

The reconstructions in the Drought Atlas are based on tree-ring records that have been screened for at least a modest correlation with summer PDSI. This criterion could serve to exclude records that might track moisture conditions that are unrelated to summer PDSI, so the seasonality of moisture signals in the Drought Atlas is not, strictly speaking, equivalent to the seasonality of signals in all tree-ring chronologies across North America. There are several examples that have shown total ring-width records to be linked to seasonal precipitation signals beyond those contained in the Atlas, including northwestern trees that are connected to winter precipitation (e.g. Peterson and Peterson, 2001; St. George *et al*., 2009) and trees in the Southwest and central Mexico that track rainfall delivered by the summer monsoon (Biondi, 2001). Partial-width and stable isotope measurements have shown promise as recorders of summer-rainfall signals in the NAM region (e.g. Meko and Baisan, 2001; Stahle *et al*., 2009). However, total-width tree-ring chronologies from the Southwest are most commonly interpreted as proxies of cool-season precipitation (Fritts, 1966; Ni *et al*., 2002) and studies in western Canada have demonstrated that tree-ring records from that region primarily reflect summer rainfall (St. George *et al*., 2009; Watson and Luckman, 2002), so the Drought Atlas does appear to provide a reasonable approximation of the dominant patterns in the seasonality of moisture-sensitive tree-ring records from North America. Because the relative strength of seasonal precipitation signals in the Drought Atlas varies markedly across the continent, these biases must be taken into account when comparing drought reconstructions across North America, when comparing tree-ring PDSI to drought records developed from other proxies or when attempting to link past droughts to potential forcing mechanisms.

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