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Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains

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[1] Tree-ring records spanning the past seven centuries from the central and southern Rocky Mountains were studied using wavelet analysis to examine multidecadal (>30–70 yr) patterns of drought variation. Fifteen tree-ring series were grouped into five regional composite chronologies based on shared low-frequency behavior. Strong multidecadal phasing of moisture variation was present in all regions during the late 16th century megadrought. Oscillatory modes in the 30–70 yr domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought. The 16th/17th century pattern of severe multidecadal drought followed by decades of wet conditions resembles the 1950s drought and post-1976 wet period. The 16th century megadrought, which may have resulted from coupling of a decadal (~20–30 yr) Pacific cool phase with a multidecadal warm phase in the North Atlantic, marked a substantial reorganization of climate in the Rocky Mountain region. *INDEX TERMS:* 1812 Hydrology: Drought; 1833 Hydrology: Hydroclimatology; 1854 Hydrology: Precipitation (3354); 9350 Information Related to Geographic Region: North America; *KEYWORDS:* drought, tree-rings, multi decadal variability, Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation. **Citation:** Gray, S. T., J. L. Betancourt, C. L. Fastie, and S. T. Jackson, Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, *Geophys. Res. Lett.*, *30*(6), 1316, doi:10.1029/2002GL016154, 2003.

1. Introduction

[2] Oscillatory modes on >10-yr timescales have been identified in instrumental and proxy records of precipitation across western North America [*Cayan et al.*, 1998; *McCabe and Dettinger*, 1999; *Dettinger et al.*, 2001; *Biondi et al.*, 2001; *Gedalof and Smith*, 2001; *Villalba et al.*, 2001]. There is optimism that once understood, this behavior could help extend drought prediction beyond seasonal forecasts. To date, much of the focus on low-frequency oscillations has been at decadal (mostly ~15–25 years) scales, though multidecadal (>30–70 yr) periodicities are evident in many records.

[3] Here, we use wavelet analyses to investigate multidecadal oscillations in precipitation across tree-ring records from Douglas-fir (*Pseudotsuga menziesii*) and ponderosa (*Pinus ponderosa*), limber (*Pinus flexilis*), and piñon (*Pinus edulis*) pines that extend back to at least A.D. 1400 from the central (Montana, Wyoming) and southern (Utah, Colorado, New Mexico) Rocky Mountains. Although these regions experience different precipitation seasonality and interannual variability, they have suffered catastrophic droughts at the same times (e.g., the 1950s). Hence, we also consider the strength, persistence and coherency of multidecadal modes within and among these regions. Finally, we explore possible sources of multidecadal oscillations in the central and southern Rocky Mountains.

2. Methods

[4] We examined 15 ring-width series (Supplemental Appendix 1) used in previous reconstructions of drought for evidence of low-frequency variation in precipitation of the central and southern Rocky Mountains (Figure 1a). We selected ring-width series based on length (extend to or before 1400 AD), replication (n $\geq$ 20) and average segment length (>300 years). We relaxed these criteria in three cases (Dell Sheep Creek, MT, low sample size; Gardiner, MT and Great Sand Dunes, CO, short segment length) to maximize site density.

[5] We used the ARSTAN program [*Cook*, 1985] to create tree-ring chronologies that preserve long-wave patterns (negative exponential or linear regression detrending). We then used wavelet analysis [*Torrence and Compo*, 1998] to examine low-frequency modes of these chronologies and how these modes vary over time.

[6] We grouped sites with similar low-frequency behavior into five regions by averaging chronologies with similar wavelet characteristics. The Yellowstone and Bighorn Basin regions are characterized by May-June precipitation peaks, while the Colorado Plateau and SW Rocky Mountain regions exhibit dual winter and July–August precipitation peaks and dry May–June typical of the Southwest monsoon. The SE Rocky Mountain Region shows similarities to the Colorado Plateau and SW Rockies, but also receives significant precipitation in late spring and early summer.

3. Results

[7] All wavelet spectra for the regional-composite chronologies show effective moisture varying at significant multidecadal periodicities, particularly in the >40 yr domain. The frequency and strength of these multidecadal signals, however, vary through time and among regions (Figures 1b–f). In particular, chronologies from Yellowstone and the SW Rocky Mountains have strong moisture signals in a band from 30 to 70 years around 1250–1400 AD, but these modes are absent from other regions.

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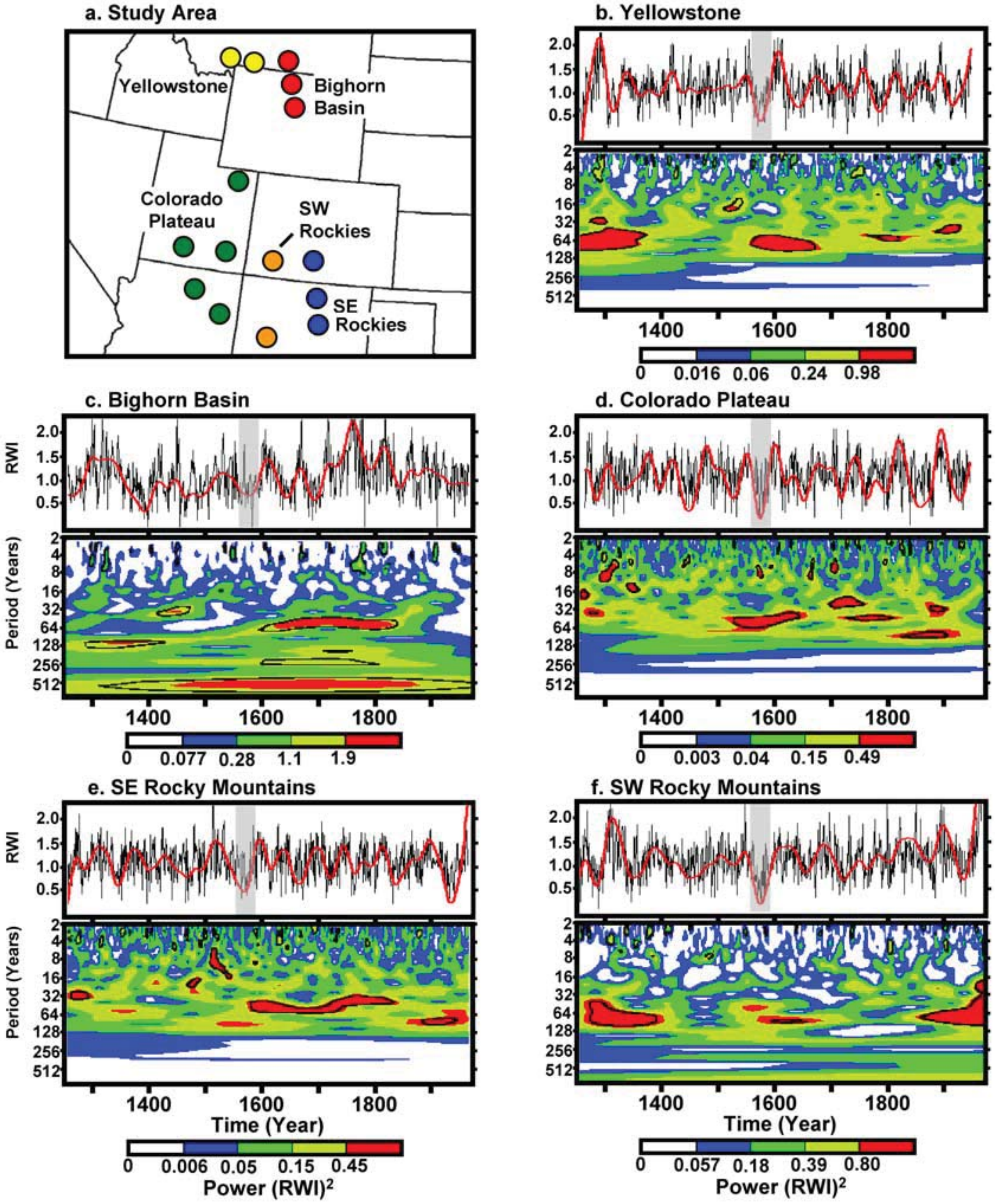

Figure 1. (a) Map showing tree-ring sites in the regional composite chronologies (see Supplemental Appenidx 1). (b-f) Plots of average ring with index (RWI) values (top) and wavelet power spectra (bottom) for the regional composite chronologies. The colored intervals represent 75, 50, 25, and 5% of the wavelet power, respectively. Black contours in the spectra represent the 95% confidence level (compared to red-noise). All analyses employed the Morlet wavelet and zero-padding [*Torrence and Compo*, 1998]. Red lines through the RWI plots show a cubic spline set to capture 50% of the variance at a wavelength of 50 years. Gray shading represents the late 16th century megadrought of *Stahle et al.* [2000]. Wavelet software was provided by C. Torrence and G. Compo, and is available at http:/paos.colorado.edu/research/wavelets/.

[8] Significant and coherent modes of multidecadal precipitation variability are first observed during a prolonged dry event experienced throughout much of North America from 1575–1595 AD [*Stahle et al.*, 2000], followed by a wet period from 1600–1625 AD (Figures 1b–f). In the Bighorn Basin and SE Rocky Mountains, a pattern of strong dry events alternating with strong wet events continuing from the late 1500s drought to the mid 1850s (Figures 1b–f) results in significant energy in the 30–60 yr domain over the same period (Figures 1c and 1e). Precipitation modes at 30–60 yr do not persist after ~1650 AD in Yellowstone or the Colorado Plateau as the difference between extreme events becomes dampened after this time. The SW Rockies show a strong periodicity in precipitation variability around

1600 AD, but only in the ~70 year domain. Strong phasing of chronologies from the Colorado Plateau, SE and SW Rocky Mountain, and Bighorn Basin regions is not seen again after 1650 until the 1950s drought (Figures 1b–f). The 1950s drought does not produce strong multidecadal energy in the wavelet diagrams. However, zero padding may reduce significance (power) near the ends of these records [*Torrence and Compo*, 1998]. In any case, the 1950s drought represents the most coherent event in these records after 1650 AD.

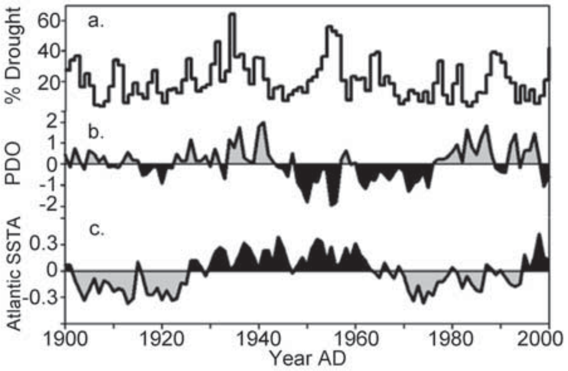

Figure 2. (a) Annual % of contiguous United States experiencing drought (PDSI< −2). (b) Average annual Pacific Decadal Oscillation (PDO) index [*Mantua and Hare*, 2002]. (c) Detrended sea surface temperature anomalies (SSTA) for the Atlantic Ocean from 0–70° North.The Atlantic Multidecadal Oscillation (AMO) index is a ten-year running mean of this series [*Enfield et al.*, 2001].

4. Discussion

[9] Significant multidecadal precipitation modes appear in the wavelet power-spectrum analyses for all regions (Figure 1). Furthermore, strong multidecadal phasing of moisture variation was present in all five regions during the late 16th century megadrought, and persisted at some sites until the mid-19th century. Such low-frequency variations in these regions are generally thought to originate in the Pacific Basin, involving interaction of ENSO modes with longer-term fluctuations in North American climate [*Dettinger et al.*, 2001; *McCabe and Dettinger*, 1999]. Similar low-frequency variations in SST's in the northern Atlantic [*Delworth et al.*, 1993; *Enfield et al.*, 2001] may also interact, in poorly understood ways, with those emanating from the Pacific to produce coherent precipitation anomalies spanning the Rockies and the entire U.S. Low-frequency variability in both northern oceans apparently modulates ENSO teleconnections over the U.S., rendering them non-stationary [*Enfield et al.*, 2001].

[10] In the North Pacific, much of the sea surface temperature variance occurs in a mode with decadal (~15–25 years) time scales, and is accompanied by variability in the strength and position of the Aleutian Low in winter. These variations are most often referred to as the Pacific Decadal Oscilliation (PDO) [*Mantua and Hare*, 2002]. Though PDO variations are typically linked to anomalies in U.S. wintertime precipitation [*Cayan et al.*, 1998; *Dettinger et al.*, 2001], low-frequency variability in Pacific SST's may modulate summer rainfall, particularly over the Great Plains [*Barlow et al.*, 2001]. The positive, warm phase of the PDO is associated with greater precipitation in all seasons throughout the central and southern Rockies.

[11] The 20th century was marked by two full PDO cycles (Figures 2a and 2b). The 'cool' or negative PDO (La Niña-like) regime prevailed from 1890-1924 and 1947–1976, while the 'warm' or positive PDO (El Niño-like) regime prevailed from 1925–1946 and from 1977–1998. Using wavelet analysis, *Minobe* [1999] found that fluctuations in North Pacific SST's, SLP's and North American tree-ring based temperature reconstructions were strongest in the 15–25 (for boreal winter) and 50–70-yr bands (for boreal winter and spring). The two periodicities synchronize with a relative period of three cycles, and produce a 'regime shift' in North Pacific climate when they reverse phase (e.g., in the 1920s, 1940s and 1970s). Another such 'regime shift' may have started in 1998 when the PDO index turned sharply negative ('cool' mode). Using Pacific Northwest tree-ring chronologies, *Gedalof and Smith* [2001] identify 11 PDO shifts since 1600.

[12] Such North Pacific decadal variability may be teleconnected with low-frequency variations in the North Atlantic via low-level wind anomalies associated with the Arctic Oscillation. North Atlantic SST's exhibit a 65–80 yr cycle termed the Atlantic Multidecadal Oscillation (AMO) and are linked to fluctuations in the intensity of thermohaline circulation [*Schlesinger and Ramankutty*, 1994; *Delworth and Mann*, 2000; *Enfield et al.*, 2001]. Warm phases occurred during 1860–1880 and 1930–1960 and cold phases during 1905–1925 and 1970–1990 (Figure 2c). The AMO shifted to its warm phase around 1995, coincident with the apparent recent shift to the negative, cool phase of the PDO. During the warm phase of the AMO, the central U.S., including the central and southern Rockies, receives less than normal rainfall, particularly in summer [*Enfield et al.*, 2001].

[13] Severe drought conditions (e.g., the 1950s) across consecutive seasons and years in the central and southern Rockies, (Figure 2a), may ensue from coupling of the cold phase PDO with the warm phase AMO [*Cayan et al.*, 1998; *Barlow et al.*, 2001; *Enfield et al.*, 2001]. During the 1950s drought, cool SSTs in the tropical Pacific and warm SSTs in the North Atlantic generated anomalously high geopotential heights above the northern oceans and North America in both cool and warm seasons [*Namias*, 1983]. Dry springs (Feb–April) were succeeded in the central and southern Rockies by failures in both the early summer (May–June) and late summer (July–Aug) monsoon moisture that originates in the Gulf of Mexico. The 1950s drought was followed by an unusually warm, wet period after 1976.

[14] We envision a similar pattern of intraseasonal drought for the late 16th century megadrought, which affected most of North America [*Stahle et al.*, 2000]. Like the 1950s drought, the late 16th century megadrought was followed by a wet period, and both events were associated with intense La Niña episodes typical of southwestern U.S. and Great Plains droughts [*Cole et al.*, 2002]. Such continental-scale droughts may be symptomatic of reorganizations in both Pacific and Atlantic climate. Pacific basin marine sediments and tree-ring records throughout North and South America show an abrupt change in frequency and amplitude beginning around 1600 [*Christiansen et al.*,

1994; *Biondi et al.*, 1997, 2001; *Gedalof et al.*, 2001; *Villalba et al.*, 2001]. Interdecadal energy did not remain coherent across the central and southern Rockies after the 17th century, however (Figures 1b–1f), although it persisted in some areas (Bighorn Basin, SE Rockies).

[15] There is considerable discussion about the steady vs. chaotic behavior of interdecadal variability, and thus its predictability. An optimistic view is that knowledge about the present phase of long-term modes (e.g., PDO or AMO) can be used to forecast climate more than a year in advance. Although there is plenty of decadal to multidecadal persistence in western North America climate, the instabilities of periodicities exhibited in long (>300 yr) tree-ring chronologies argue against extending the forecasting window much beyond 2–3 years.

[16] It is probable that multidecadal variations in North American climate, specifically the occurrence of prolonged, continental-scale drought, involve complex interactions between the Atlantic and Pacific Oceans. Unraveling these relationships will require development of multi-century, annually-resolved SST proxies from the Atlantic, to match the pace of proxy development in the Pacific Basin.

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