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 five regions during the late 16th century megadrought. Consistent oscillatory modes in the 30–70 yr domain persisted until the mid-19th century in two of the five 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 unusually 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 subtropical North Atlantic, marked a substantial reorganization of climate variation 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, western U. S., 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*(0), XXXX, 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 [*Meko*, 1992; *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 some optimism that once understood, this oscillatory behavior could help extend severe drought prediction beyond seasonal forecasts. To date, much of the focus on low-frequency oscillations has been at decadal (mostly ~15–25 years) time scales, even though multidecadal (>30–70 yr) periodicities are evident in many records.

[3] Tree rings, which offer the primary synoptic means for evaluating long-wave variations in precipitation, present important yet surmountable challenges. Long-wave patterns may be confounded by segment-length issues [*Cook et al.*, 1995], or may be removed inadvertently by the statistical detrending used to correct for size-related growth artifacts [*Cook and Kairiukstis*, 1990]. Most of these uncertainties can be eliminated, however, through proper selection and treatment of tree-ring chronologies, and by examining periodicity and phasing of multiple chronologies from different tree species and geographic areas.

[4] 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 two regions experience different precipitation seasonality and interannual variability, historically they have suffered prolonged catastrophic droughts at the same times (e.g., the 1950s). Hence, we also consider the strength, persistence and coherency of possible multidecadal oscillatory modes within and among these regions. Finally, we explore possible climatic sources of multidecadal oscillations in the central and southern Rocky Mountains.

2. Methods

[5] We examined 15 ring-width series (Supplemental Appendix 1) used in previous reconstructions of drought [*Grissino-Mayer*, 1996; *Cook et al.*, 1999] for evidence of low-frequency variation in precipitation of the central and southern Rocky Mountains (Figure 1). 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.

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

[7] We grouped sites with similar modes of low-frequency behavior into five separate regions by averaging standard 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 the dual winter and July–August precipitation peaks and dry May–

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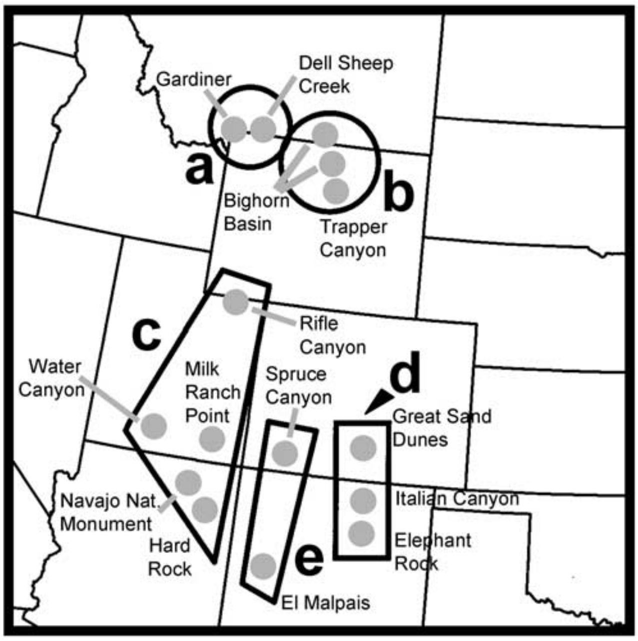

Figure 1. Map of study sites showing individual chronologies (gray dots) used in the wavelet analyses. Areas in enclosed by thick black lines represent sites included in the regional composite chronologies: A. Yellowstone; B. Bighorn Basin; C. Colorado Plateau; D. Southeast Rocky Mountains; E. Southwest Rocky Mountains.

June typical of the Southwest or Arizona monsoon pattern. The SE Rocky Mountain Region shows similarities to the Colorado Plateau and SW Rockies, but may also receive significant precipitation in late spring and early summer.

3. Results

[8] All of the 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 (Figure 2). 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. In addition, the Bighorn Basin chronology alone shows significant energy in a band near 128 yrs. from ~1300–1400 AD.

[9] Significant and coherent modes of multidecadal precipitation variability are first observed during a severe and prolonged dry event experienced throughout much of North America from roughly 1575–1595 AD [*Meko et al.*, 1995; *Stahle et al.*, 2000], followed by an unusually wet period in at least the central and southern Rockies from 1600–1625 AD (Figure 2). In the Bighorn Basin and SE Rocky Mountains, a marked pattern of strong dry events alternating with strong wet events continuing from the late 1500s drought to the mid 1850s (Figure 2) results in significant multidecadal energy in the 30–60 yr domain over the same period (Figure 2b and 2d). Multidecadal precipitation modes at 30–60 yr do not persist after ~1650 AD in either 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, and this multidecadal energy does not persist past the 1650s. Strong phasing of chronologies from the Colorado Plateau, SE and SW Rocky Mountain, and to some degree Bighorn Basin regions is not seen again after 1650 until the 1950s drought (Figure 3). Unlike the late 16th century dry event, the 1950s drought does not produce strong multidecadal energy in the wavelet diagrams. However, this may be due to the effects of zero padding reducing significance (power) near the ends of these records [*Torrence and Compo*, 1998]. In any case, the 1950s drought represents the most widely coherent event in these records after 1650 AD.

4. Discussion

[10] Significant multidecadal precipitation modes appear in the wavelet power-spectrum analyses (Figure 2) for all regions investigated. Furthermore, strong multidecadal phasing of moisture variation was present in all five regions during the late 16th century continental megadrought, and persisted at some sites until the mid-19th century (Figures 2 and 3). Such low-frequency climatic 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 during both winter and summer [*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].

[11] 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 have been defined as the North Pacific Oscillation (NPO) [*Gershnov and Barnett*, 1998] if referring only to anomalies in the North Pacific, or Pacific Decadal Oscillation (PDO) if they also extend into the tropics [*Mantua and Hare*, 2002]. The two oscillations have overlapping geographic domains and share similarities in their patterns. The PDO has variously been attributed to stochastic atmospheric forcing, atmospheric teleconnections, midlatitude ocean-atmosphere interactions, tropical-extratropical interactions, oceanic teleconnections, and intrinsic ocean variability [see *Dettinger et al.*, 2001; *Mantua and Hare*, 2002]. Though PDO variations are typically linked to anomalies in U.S. wintertime precipitation [*Cayan et al.*, 1998; *Cayan et al.*, 1998; *Dettinger et al.*, 2001], low-frequency variability in Pacific SST's also appear to 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.

[12] The 20th century was marked by two full PDO cycles (Figure 4a and 4b). The 'cool' or negative PDO (more La Niña-like) regime prevailed from 1890-1924 and

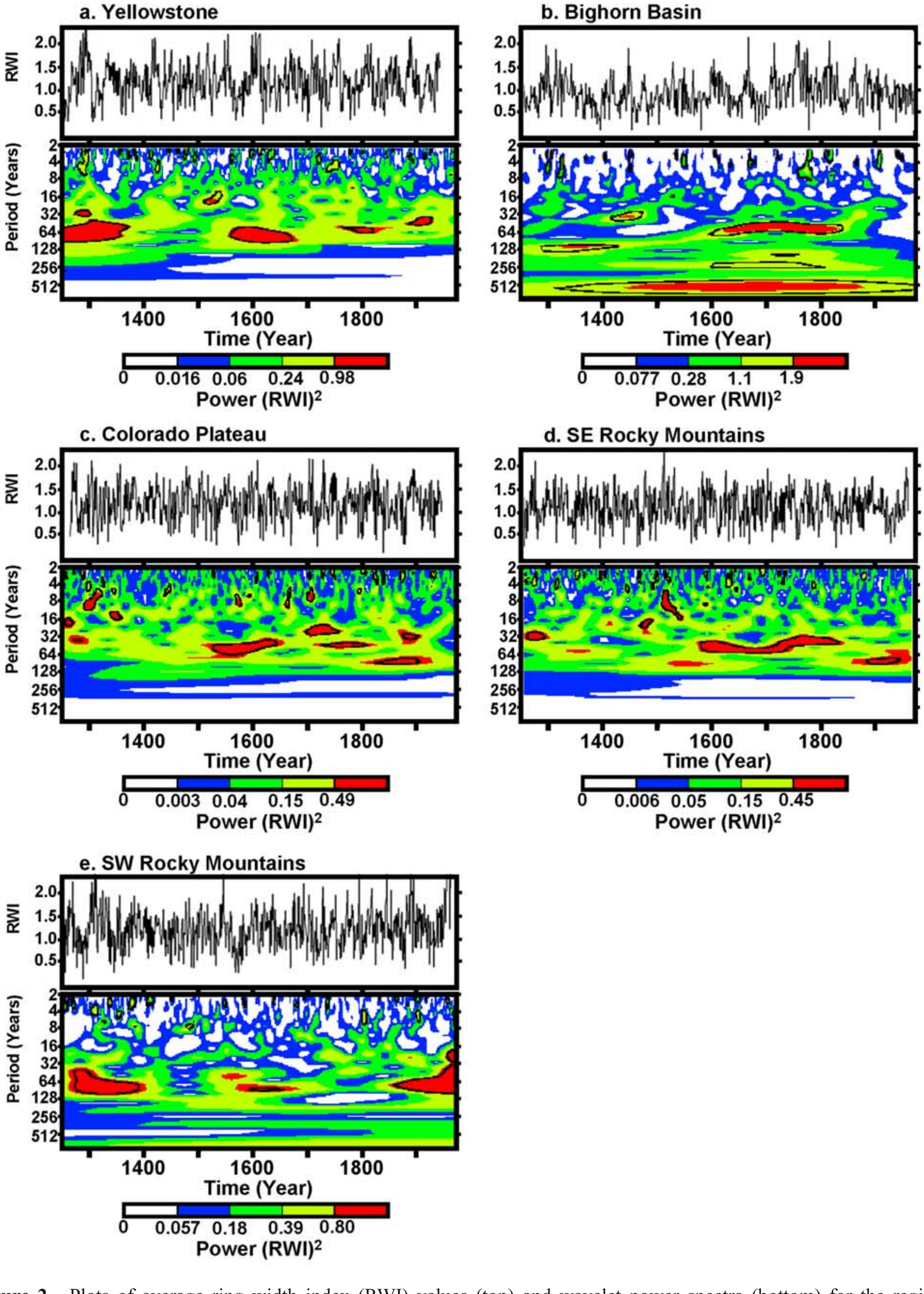

Figure 2. Plots of average ring width index (RWI) values (top) and wavelet power spectra (bottom) for the regional composite chronologies. The colored contour intervals represent 75, 50, 25, and 5% of the wavelet power, respectively. Black contours in the wavelet power spectra represent the 95% confidence level using a red-noise background spectrum. All analyses employed the Morlet wavelet and zero-padded series [*Torrence and Compo*, 1998].

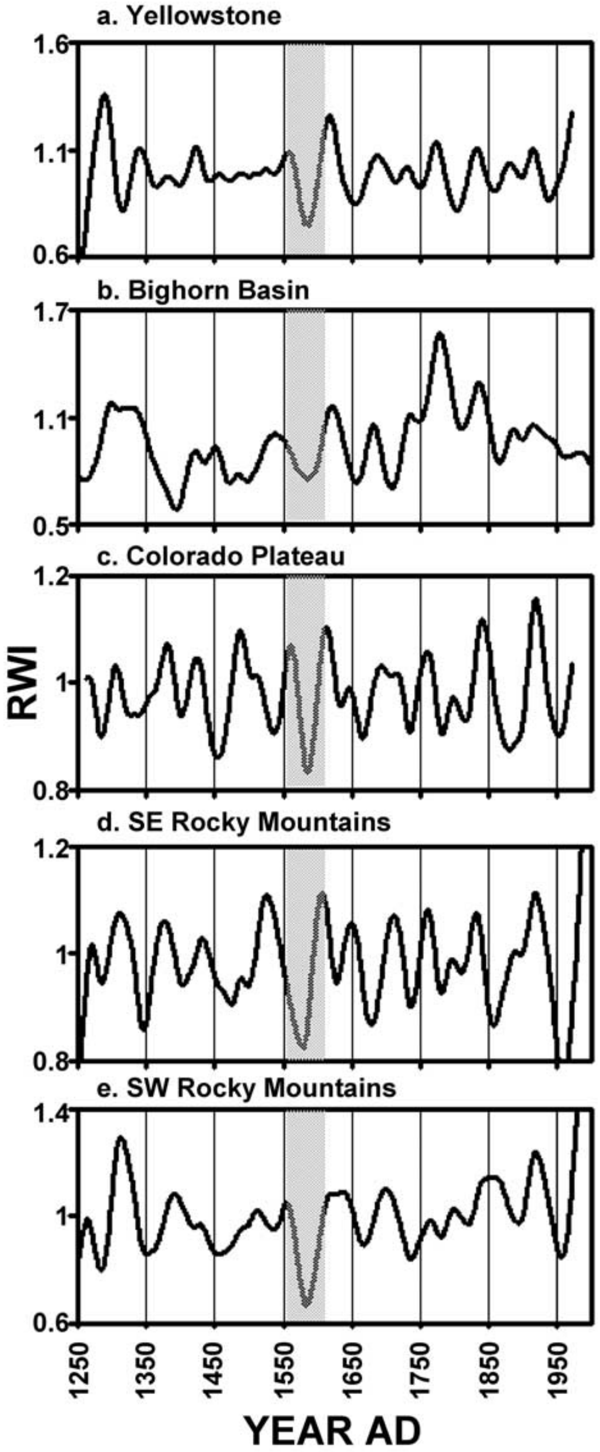

Figure 3. 50-yr smoothed ring-width index (RWI) values for the regional composite chronologies. Gray shading represents the late 16th century megadrought of *Woodhouse and Overpeck* [1998] and *Stahle et al.* [2000]. Smoothed values were produced by applying a cubic spline set to capture 50% of the variance at a wavelength of 50 years.

1947–1976, while the 'warm' or positive PDO (more El Niño-like) regime prevailed from 1925–1946 and from 1977–1998. Using wavelet analysis, *Minobe* [1999] found that fluctuations in North Pacific sea surface temperatures, sea level pressures and North American tree-ring based temperature reconstructions were most energetic at periodicities in the 15–25 (for boreal winter) and 50–70-yr bands (for boreal winter and spring). According to *Minobe* [1999], 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] used an intervention detection algorithm to identify 11 PDO shifts (1662, 1680, 1696, 1712, 1734, 1758, 1798, 1816, 1923, 1946, and 1977) in Pacific Northwest tree-ring chronologies since 1600.

[13] 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), which has a 0.4°C range, and is linked to fluctuations in the intensity of thermohaline circulation [*Schlesinger and Ram-*

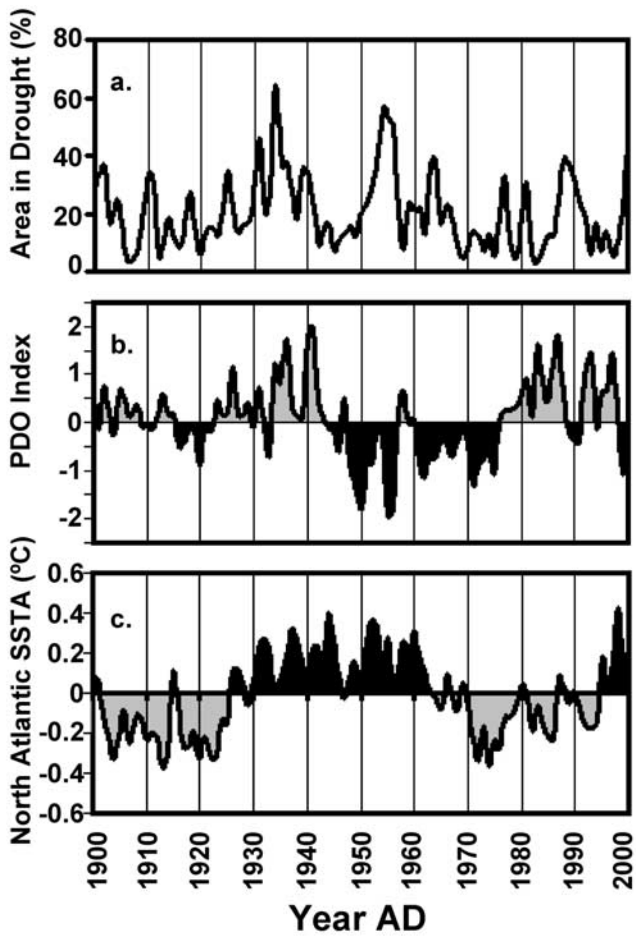

Figure 4. (a) Annual plot showing % of contiguous United States experiencing drought conditions (PDSI< −2). (b) Plot of average annual Pacific Decadal Oscillation (PDO) index values [*Mantua and Hare*, 2002]. (c) Detrended sea surface temperature anomalies (SSTA) for the Atlantic Ocean from 0–70° North.The Atlantic Multidecadal Oscillation (AMO) index is a ten-year running mean of this annual series [*Enfield et al.*, 2001].

ankutty, 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 4c). 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].

[14] Severe drought conditions (e.g., the 1950s) across consecutive seasons and years in the central and southern Rockies, and in the contiguous U.S. (Figure 4a), may ensue from coupling of the cold phase of the PDO with the warm phase of the AMO [*Cayan et al.*, 1998; *Barlow et al.*, 2001; *Enfield et al.*, 2001]. During the 1950s drought, for example, 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 (February–April) over most of the western states were succeeded in the central and southern Rockies by failures in both the early summer (May–June) and late summer (July–August) monsoon moisture that originates in the Gulf of Mexico. The 1950s drought, which in the southwestern U.S. actually persisted from 1942 to 1972, was followed by an unusually warm, wet period after 1976 [*Swetnam and Betancourt*, 1998].

[15] We envision a similar pattern of intraseasonal drought for the late 16th century megadrought, which affected most of North America from northwestern Canada [*Szeicz and MacDonald*, 1996] to the Valley of Mexico [*Stahle et al.*, 2000] and the Atlantic Coast [*Stahle et al.*, 1998]. Like the 1950s drought, the late 16th century megadrought was followed by an unusually wet period in the early 17th century, and both events were associated with intense and prolonged La Niña episodes typical of southwestern U.S. and Great Plains droughts [*Cole et al.*, 2002]. Such continental-scale droughts may be symptomatic of major reorganizations in both Pacific and Atlantic climate. In the Santa Barbara Basin, California, oscillations of annual varve thickness during the last millennium show an abrupt change in frequency and amplitude beginning in 1600 [*Biondi et al.*, 1997]. This change is matched to the south in the Santa Monica Basin by a shift to anoxic conditions, presumably linked to a change in SST, and preservation of laminated, marine sediments [*Christiensen et al.*, 1994]. Tree-ring chronologies in both North and South America exhibited greater decadal to multidecadal (interdecadal) energy after 1600 [*Villalba et al.*, 2001; *Gedalof and Smith*, 2001; *Biondi et al.*, 2001]. Interdecadal energy did not remain coherent across the central and southern Rockies after the 17th century, however (Figure 2), although it persisted in some areas (Bighorn Basin, SE Rockies).

[16] There is considerable discussion about the steady state vs. chaotic behavior of interdecadal variability, and thus about its predictability. An optimistic view is that knowledge about the present phase of the long-term modes (e.g., PDO or AMO) can be used to forecast climate more than a year in advance. Some recent forecasts are already taking into account the possible regime shift in both the Pacific and Atlantic SSTs during 1995–1998, which could signal prolonged drought in the central and southern Rockies [*Dettinger et al.*, 2000; *Schneider and Miller*, 2001; *Enfield et al.*, 2001]. 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, and uncertainty in how they might be affected by anthropogenic forcing, argue against extending the forecasting window much beyond 2–3 years. At the very least, however, recent shifts to the cool phase of the PDO and the warm phase of the AMO provide little reason for optimism about ongoing drought in the Rockies.

[17] 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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