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Teleconnected ocean forcing of Western North American droughts and pluvials during the last millennium

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ABSTRACT

Western North America (WNA) is rich in hydroclimate reconstructions, yet questions remain about the causes of decadal-to-multidecadal hydroclimate variability. Teleconnection patterns preserved in annually-resolved tree-ring reconstructed drought maps, and anomalies in a global network of proxy sea surface temperature (SST) reconstructions, were used to reassess the evidence linking ocean forcing to WNA hydroclimate variability over the past millennium. Potential forcing mechanisms of the Medieval Climate Anomaly (MCA) and individual drought and pluvial events—including two multidecadal-length MCA pluvials—were evaluated. We show strong teleconnection patterns occurred during the driest (wettest) years within persistent droughts (pluvials), implicating SSTs as a potent hydroclimate forcing mechanism. The role of the SSTs on longer timescales is more complex. Pacific teleconnection patterns show little long-term change, whereas low-resolution SST reconstructions vary over decades to centuries. While weaker than the tropical Pacific teleconnections, North Atlantic teleconnection patterns and SST reconstructions also show links to WNA droughts and pluvials, and may in part account for longer-term WNA hydroclimate changes. Nonetheless, evidence linking WNA hydroclimate to SSTs still remains sparse and nuanced—especially over long-timescales with a broader range of hydroclimatic variability than characterized during the 20th century.

1. Introduction

Annually resolved tree-ring records have shown that Western North America (WNA) has experienced a wide range of hydroclimatic conditions over the past millennium. Most remarkable has been the occurrence of megadroughts: multidecadal-length droughts more persistent than any observed during the instrumental record (Woodhouse and Overpeck, 1998). Megadroughts, defined as prolonged drought lasting more than two decades, occurred throughout the last millennium, but were more frequent during the Medieval Climate Anomaly (MCA, ~900–1400 AD), (Cook et al., 2004, 2007, 2010b; Meko et al., 2007; Routson et al., 2011; Woodhouse and Overpeck, 1998). Multidecadal-length pluvials, or megapluvials, are also documented throughout the last millennium, but have received less attention than megadroughts despite their comparable societal importance. Here, we reassess the evidence linking these past WNA megapluvials and megadroughts to global sea surface temperature (SST) variations.

Observational records (up to ~100 years), document strong causal linkages known as teleconnections between SSTs and WNA climate (e.g., Cayan et al., 1999; Cook et al., 2010a,b; Kam et al.,

Abbreviations: WNA, Western North America; SST, Sea Surface Temperature; MCA, Medieval Climate Anomaly; ENSO, El Niño Southern Oscillation; PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAM, Northern Hemisphere annular mode; PDSI, Palmer Drought Severity Index; NADA, North American Drought Atlas.

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2014; McCabe et al., 2004, 2008; Tootle et al., 2005; Wang and Mehta, 2008). Because ocean-driven SSTs have a longer memory or persistence than the atmosphere alone, SST variability is the most likely cause of persistent multidecadal-to-centennial hydroclimate variability. WNA climate is strongly connected to SSTs in the tropical Pacific, as characterized by the impact of the El Niño Southern Oscillation (ENSO) (Redmond and Koch, 1991). During La Niña events, cool conditions in the eastern equatorial Pacific tend to displace westerly, mid-latitude, storm tracks northward, resulting in reduced cool season precipitation in southwestern North America (e.g., Cayan et al., 1999; Redmond and Koch, 1991; Schubert et al., 2009). The opposite tends to be true for El Niño events. Persistent ENSO conditions have been linked to decadal-scale WNA hydroclimate variability over the past ~150 years (Seager et al., 2005). On decadal to multidecadal timescales, the Pacific Decadal Oscillation (PDO) reflects the dominant mode of SST in the North Pacific (Mantua et al., 1997). Linked with tropical Pacific variability (Newman et al., 2003), the PDO also has demonstrated connections with WNA climate (McCabe et al., 2004, 2008; Tootle et al., 2005). The Indian Ocean works in concert with the Pacific whereby warming in the western Pacific and Indian oceans drives deep atmospheric convection that influences the rising limb of the Walker Cell, and ultimately affecting the mean position of storm tracks and WNA cool season rainfall (Wang and Mehta, 2008). ENSO, PDO, and Indian Ocean all tend to modulate anti-phased precipitation in a well-known dipole between southwestern (Southwest) and northwestern North America (Northwest).

North Atlantic SSTs, as characterized by the Atlantic Multidecadal Oscillation (AMO), may also influence WNA drought, although less directly and to a lesser degree than the Pacific (Cook et al., 2010a,b; Feng et al., 2010; Kam et al., 2014; McCabe et al., 2004; McCabe and Wolock, 2013; Schubert et al., 2009; Tootle et al., 2005). Warm North Atlantic SSTs are associated with warmer WNA temperatures. Regional warming associated with a positive AMO was shown to decrease runoff efficiency and streamflow in the Upper Colorado River Basin (Nowak et al., 2012). The impact of the North Atlantic may not be limited, however, to regional temperature effects on the water cycle (Feng et al., 2010; Kam et al., 2014; McCabe et al., 2004; Schubert et al., 2009). Pacific forcing appears to influence atmospheric circulation patterns driven by the AMO during some seasons (Hu and Feng, 2012). Instrumental records and climate models also suggest the largest precipitation anomalies in WNA tend to occur when Pacific and Atlantic SSTs are opposite in sign (Feng et al., 2010; Kam et al., 2014; McCabe et al., 2004, 2008; Schubert et al., 2009), reflecting a combined influence of ocean basins on global atmospheric circulation.

The inference that past megadroughts were caused by an extension or enhancement of the processes influencing WNA climate today is prevalent in the literature, although the proposed mechanisms driving this inference vary. The predominant hypothesis is that tropical Pacific SSTs drove sustained WNA aridity, in which extended La Niña-like conditions forced medieval megadroughts (e.g., Conroy et al., 2009a; Graham et al., 2007; Herweijer et al., 2007; Seager et al., 2007; Stahle et al., 2000). Links also have been drawn between the AMO and past WNA drought over the past ~500 years as established by tree rings (Gray et al., 2004; Hidalgo, 2004). North Atlantic SSTs are less well-constrained before ~1500 AD, but some SST proxy records indicate tenuous multidecadal to centennial-scale relationships between North American climate and the North Atlantic (Conroy et al., 2009a; Feng et al., 2008, 2010; Oglesby et al., 2012).

Various general circulation model studies support the paleoclimatic evidence and interpretations for the causes of megadroughts. A cool tropical Pacific has been shown to simulate WNA megadroughts in several studies (Burgman et al., 2010; Graham et al., 2007; Seager et al., 2008), and some modeling results indicate a warm North Atlantic plays a role in modulating drought in the Southwest and Midwest (e.g., Feng et al., 2010; Oglesby et al., 2012). Some evidence suggests that ocean teleconnections with recent North American droughts may be weakening, while atmospheric teleconnections are strengthening (Kam et al., 2014; Kumar et al., 2013; Seager et al., 2014; Wang et al., 2014). Though this recent shift may be related to greenhouse warming, it is conceivable that similar shifts, from oceanic to atmospheric controls of North American droughts and pluvials, also have happened in the past.

Traditionally, most paleoclimatic studies have focused on the causes of WNA megadroughts over megapluvials, and have not fully evaluated the associations of both to global SST anomalies over past millennium. For example, because background conditions may vary at longer time scales, the drivers for two known pluvials embedded in the generally droughty period of the MCA could differ substantially from those during the wetter post-MCA. Here we extend previous work, using a multiproxy approach to assess the evidence linking SSTs to persistent wet and dry periods in WNA over the past millennium. We use teleconnection patterns embedded in gridded drought reconstructions (Cook and Krusic, 2008), and a screened network of global SST proxy records to explore the following research questions:

1) Are differences in WNA hydroclimate between the MCA and post-MCA linked to SSTs?
2) What evidence links WNA megadroughts and megapluvials to SST forcing during the past millennium?
3) Do SST/pluvial associations vary with multidecadal variability, for example, within the MCA?

2. Materials and methods

2.1. Defining droughts and pluvials

Droughts and pluvials over the period 900–2006 AD were characterized with the North American Drought Atlas (NADA, Cook and Krusic, 2008). The NADA is a gridded network of tree-ring reconstructed drought as defined by the Palmer Drought Severity Index (PDSI, Palmer, 1965). Although the NADA reconstructed drought metric is summer season PDSI (Cook et al., 2004), tree rings have inherent seasonal climate sensitivities, and for this reason, the WNA portion of the NADA used here primarily reflects winter precipitation (St. George et al., 2010). PDSI grid points used for WNA (27.5°N to 50° N, 97.5°W to 125°W, after Cook et al., 2004) were averaged and smoothed with a 50-year cubic smoothing spline to highlight regional multidecadal variability (Fig. 1). Pluvial and drought periods were identified as intervals during which the smoothed series exceeded 0.2 PDSI units above or below the series mean (−0.17) respectively. This threshold was chosen qualitatively as one that encompasses all relatively severe droughts and pluvials with low frequency components that persisted for multiple decades. We also looked at two subset regions, the Southwest and Northwest (32°N to 40° N, 105°W to 115°W and 42°N to 50° N, 110°W to 125°W, respectively, after Cook et al., 2014) for comparison of droughts and pluvials.

2.2. Teleconnection patterns

Correlation maps were used to investigate relationships between drought and pluvial patterns and the teleconnections documented by circulation modes. First, instrumental circulation