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Tree-ring reconstructed hydroclimate of the Upper Klamath basin

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SUMMARY

This work presents the first tree-ring reconstructions of hydroclimate for the Upper Klamath River basin, which stretches from northern California into southern Oregon. The extended record provides a centuries-long perspective on the region's hydroclimatic variability and context for water-related political issues that have erupted in recent years. Reconstructions of water-year precipitation for Klamath Falls, Oregon (extending 1564–2004 and 1000–2010 CE) were developed to compare past drought severity with drought severity of the instrumental record (extending 1896–2011). The reconstructions suggest that variability exhibited during the instrumental period captures extremes of moderate-to-long-duration (6-, 10-, and 20-year) droughts, but not of short (single-year and 3-year) and very long (50-year) droughts, which were more severe during the 11th–13th centuries. The late-16th-century "mega drought" is present in the Klamath River basin, though with less strength than in the neighboring Sacramento River basin. Cool-season storm tracks appear to be a direct driver of hydroclimatic variability, leading to instances of see-saw like relationships with neighboring regions, such as in the mid-14th century. In contrast, the larger area of drought in the 12th century is suggestive of a long-term northward shift in cool-season storm tracks.

1. Introduction

The Klamath River basin is host to a wealth of biodiversity and human development. It has been the focus of heated discourse around water rights, resource allocation, and economic development (Levy, 2003; Service, 2003). These issues are linked to the Klamath River's natural hydroclimatic variability.

The basin is located in northern California and southern Oregon, in the transition zone of a cool-season precipitation dipole between the Pacific Northwest and Southwest US (Brown and Comrie, 2004). This dipole has been found to correspond to different phases of the El Niño/La Niña-Southern Oscillation (ENSO; Redmond and Koch, 1991; Cayan, 1996; Brown and Comrie, 2004). Consequently, the Klamath Basin has a variable relationship to dipole and ENSO phasing (Dettinger et al., 1998; Wise, 2010). Basin precipitation appears to have a strong relationship with Pacific/North American-like (PNA) patterns and Pacific cool-season storm track position (Wallace and Gutzler, 1981; Dettinger et al., 1998).

The drought of 2001–2002 is often cited as one of the worst droughts on record, throughout the western US. In the Klamath basin, snowpack and cumulative precipitation were 50% of average in January and February of 2001, with about 32% of normal cool-season precipitation (October, 2000–March, 2001) at Klamath Falls, Oregon (Risley et al., 2005; Braunworth et al., 2002). In the spring of 2001, the US Fish and Wildlife Service and the National Marine Fisheries Service issued opinions which noted a dramatic decline in local populations of endangered fish species over the past decades and recommended minimum levels in the Klamath River and Upper Klamath Lake (Service, 2003). As a result, the US Bureau of Reclamation reduced availability of water for irrigating agricultural lands in the Upper Klamath basin. Damages in 2001 from resulting agricultural losses in the surrounding communities were estimated at over $200 million (Levy, 2003). Tensions that followed saw the birth of an effort to negotiate differences between farmers, fishermen, environmentalists, and local tribes. The focus of this effort has been the development of a formal plan to manage the basin, and the launch of a river restoration project with the potential to become the largest such project in US history (US Department of the Interior, 2010).

Effective resource management requires understanding the range of variability possible in this natural system. Most water management decisions and planning are based on existing gauge records that extend, at best, into the early 20th century, and thus assume that the hydroclimatic variability exhibited over this time period is a fair representation of what may be expected in the future (e.g. Jain et al., 2002; Meko et al., 2012). One way to assess this assumption is to extend hydroclimatic records back in time using tree-ring data.

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Tree-ring data have been used to reconstruct a variety of hydroclimatic variables, including streamflow, precipitation, salinity, drought, and snowpack (e.g. Stockton and Jacoby, 1976; Stahle et al., 2001; Woodhouse, 2003; Cook et al., 2004; Touchan et al., 2011). Reconstructions have been developed for the neighboring Columbia and Sacramento River basins (Earle and Fritts, 1986; Meko et al., 2001; Gedalof et al., 2004), but not yet for the Klamath basin. Previous dendrochronological work in the region includes the development of tree-ring chronologies from sites in northern California, southern Oregon, and the Klamath River basin (e.g. Meko et al., 2001; Stahle et al., 2001). Research indicates that the species *Juniperus occidentalis*, *Quercus douglasii*, *Pinus ponderosa*, and *Pinus jeffreyi*, are sensitive to cool-season moisture in this region (e.g., Meko et al., 2001, 2011). These tree species can achieve hundreds of years of age. Existing chronologies extend as far back as 530 CE (Table 1), with the incorporation of remnant material (dead wood on the landscape). These chronologies are useful for developing reconstructions of Klamath basin moisture variability. The drought of the 21st century can then be examined in light of a multi-century record of hydroclimatic variability.

This paper examines Upper Klamath basin hydroclimatic variability with reconstructions of Klamath basin precipitation. The droughts documented in the reconstructions are used to evaluate the representativeness of drought events in the instrumental record. Large scale implications of these reconstructions are then discussed, such as how long-term hydroclimatic variability in the Klamath basin fits within our larger understanding of western US hydroclimate.

Table 1
Tree-ring chronologies in predictor pools for reconstructions. Species codes (spp.): *Juniperus occidentalis* (JUOC), *Pinus ponderosa* (PIPO), *Pinus jeffreyi* (PIJE), and *Quercus douglasii* (QUDG). Period is the time coverage of site chronology after parsing and cropping such that a sample depth ⩾5. ITRDB sites annotated with "*" indicate sites recollected and updated for this study.

	Series	spp.	Period	ITRDB site
AGU	Arrow Gap Update	JUOC	530–2011	OR062*
ALU	Antelope Lake Update	PIPO	1493–2010	CA067*
BCC	Bear Creek Canyon	QUDG	1582–2004	CA648
BCU	Boles Creek Update	JUOC	1235–2010	CA629*
DIB	Dibble Creek	QUDG	1531–2004	CA652
DPR	Don Pedro Res. Update	QUDG	1564–2005	CA616
DRU	Dalton Reservoir Update	JUOC	1449–2010	CA065*
FBK	Frederick Butte Update	JUOC	936–2010	OR060*
FEA	Feather River Lake Oroville Update	QUDG	1585–2004	CA618
HRK	Horse Ridge Update	JUOC	1000–2010	OR061*
KAW	North Fork Kaweah River	QUDG	1503–2004	CA659
LCU	Lemon Canyon Update	PIJE	1535–2010	CA064*
LJK	Little Juniper Mt.	JUOC	1493–2010	OR018*
LTU	Log Cabin – Tioga Pass Update	PIJE	1422–2010	CA505*
LVU	Lakeview Update	PIPO	1560–2010	OR002*
PPP	Pacheco Pass State Park Update	QUDG	1549–2003	CA625
PUT	Putah Creek, Lake Berryessa	QUDG	1584–2004	CA663

2. Hydroclimatology of the Klamath River basin

The Klamath River drains a 40,795 km^2 basin and runs 423 km from its source in southern Oregon (elevation 1247 m), through northern California to the Pacific Ocean (Fig. 1). The Klamath River's total annual discharge (average 482 $m^3 s^{-1}$) is influenced by strong seasonal precipitation (Fig. 2), with peak discharge from January to March. Surface runoff from Upper Klamath cool-season precipitation is the primary source for Klamath River flow.

The main gage on the Upper Klamath River is at Keno, Oregon. The US Bureau of Reclamation has developed estimated natural streamflow at this gage, but the series extends to only 1949, leaving a relatively short period of overlap between tree-ring and natural flow gage data. There is some uncertainty regarding the estimated flow values due to the region's complex land use (US Bureau of Reclamation, 2004). Klamath Falls water-year (WY; October–September) precipitation is adopted as a proxy for Upper Klamath basin streamflow and hydroclimate because of these uncertainties in the flow record. The long Klamath Falls precipitation record is suitable for training and validating a reconstruction since precipitation in the Upper Klamath basin is the primary contributor to Klamath River flow and Klamath Falls precipitation is strongly and linearly related to flow (Fig. 3).

The atmospheric circulation pattern most closely associated with Klamath Falls precipitation is a mid-latitude wave train across the Northern Hemisphere (Fig. 4). This points to the importance of a cool-season PNA-like circulation pattern, guiding moisture from the Pacific across the region (Wallace and Gutzler, 1981). The PNA pattern guides and displaces cool-season jets and storms, and is a consistent control of interannual and decadal precipitation transport across the west coast of North America, especially in northern California and southern Oregon (Cayan, 1996; Dettinger et al., 1998; Abatzoglou, 2011). Klamath Falls WY precipitation is inversely correlated ($r = -0.38$, $n = 52$, $\alpha = 0.05$) with cool-season (November–April) 500 mb geopotential height anomalies off the northwest coast of North America, reflecting the influence of strong blocking ridges during cool-season droughts.

Klamath Falls WY precipitation shows no significant correlation with equatorial Pacific sea surface temperatures (SST; Fig. 4). This is not surprising given the Klamath Basin's transitional position between north and south ends of the ENSO precipitation dipole (Haston and Michaelsen, 1997; Cayan et al., 1998; Dettinger et al., 1998). Although there appears to be little direct and consistent association with ENSO variability, cool-season precipitation in this transition zone may be influenced by ENSO if the dipole boundary shifts north or south (Cayan et al., 1998; Dettinger et al., 1998; Brown and Comrie, 2004; Woodhouse et al., 2009; Wise, 2010).

3. Methods

3.1. Hydroclimatic reconstructions

The Klamath Falls WY-total precipitation record (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html), which extends from WY 1896–2011, was selected as the target variable for reconstruction. A set of strategies was employed to develop a pool of candidate tree-ring chronology predictors for precipitation reconstruction. First, existing *Juniperus occidentalis*, *Pinus ponderosa*, *Pinus jeffreyi*, and *Quercus douglasii* chronologies from California and Oregon were obtained from the International Tree-Ring Databank (ITRDB; http://www.ncdc.noaa.gov/paleo/treering.html) and parsed. Initial screening excluded sites outside a 450 km buffer around the Klamath basin to emphasize chronologies related to Klamath basin climate variability directly, rather than through teleconnections. The network was not strictly delineated by the