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New reconstructions of streamflow variability in the South Saskatchewan River Basin from a network of tree ring chronologies, Alberta, Canada

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[1] In western Canada growing demand for water resources has increased vulnerability to hydrological drought. The near full allocation of water supplies in the Oldman and Bow River subbasins of the South Saskatchewan River Basin has resulted in a moratorium on new surface water licenses. In this region, short instrumental records limit the detection of long-term hydrological variability. To extend the historical record, we collected 14 new moisture-sensitive tree ring chronologies and reconstructed the average October through September flow of the Oldman (1618–2004) and South Saskatchewan (SSR) (1400–2004) rivers. Our SSR proxy record updates a previously published reconstruction. While the 20th century is representative of drought frequency over the long term, droughts are of greater severity and duration in the preinstrumental proxy record. A spectral analysis of the reconstructed flows revealed quasiperiodic cycles at interannual to multidecadal scales.

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1. Introduction

[2] Demand for water supplies in the Prairie Provinces of western Canada is rising with growth in population and economic activity [*Schindler and Donahue*, 2006]. This growing dependence on the water resources has increased vulnerability to hydrological drought. Prairie drought is Canada's most costly climate hazard; the drought of 2001–2002 cost the prairie agricultural sector an estimated $3.6 billion [*Wheaton et al.*, 2005] and, during the drought of 1988, energy providers sustained up to $73 million in economic losses [*McKay et al.*, 1989; *Wheaton et al.*, 1992]. Future water scarcity would be a significant constraint on economic development including expansions of irrigated lands and oil sands production.

[3] The most serious risk from recent and projected climate warming in western Canada is a shift in the amount and timing of streamflow [*Pietroniro et al.*, 2006; *Sauchyn and Kulshreshtha*, 2008]. The snow-dominated basins of midlatitudes to high latitudes are losing the advantage of a cold winter; snow and ice are the most reliable, predictable and abundant sources of spring and summer runoff [*Barnett et al.*, 2005]. Sensitivity analysis of mountain snowmelt hydrology demonstrates that regional warming shifts stream hydrographs earlier into the winter and spring at the expense of summer runoff [*Brubaker and Rango*, 1996; *Nijssen et al.*, 2001]. The earlier loss of the annual snowpack contributes to negative glacier mass balance, which is among the strongest signals of the impacts of global warming in the Rocky Mountains of western Canada [*Sauchyn et al.*, 2009].

[4] Coupled with the sensitivity of the human and natural systems to climate variability is a highly variable hydroclimate. The coefficient of variation (standard deviation divided by mean) in annual precipitation in the populated (monitored) region of Canada reaches maximum values (>25%) in the central prairies over an area roughly corresponding to the South Saskatchewan River Basin [*Longley*, 1953]. Despite documented variability over a range of time scales, from annual to decadal to millennial [*St. George and Sauchyn*, 2006; *Michels et al.*, 2007), resource management practices and policies have assumed a stationary hydrological regime. Western water use, policy and management were established during a period of fairly stable and reliable water supplies as compared to the recent past and near future [*Sauchyn et al.*, 2009]. Paradigms and practices of water management must be adjusted to manage a hydrological cycle that may be increasingly sensitive to the timing and frequency of precipitation events with less of a buffer from glacier ice and late lying snow at high elevations.

[5] The Prairie Provinces of Alberta, Saskatchewan and Manitoba share the water resources of the Saskatchewan River Basin (SRB) according to the 1969 Master Apportionment Agreement, whereby each province is allocated a percentage of the 'natural' flow from the SRB. With climate change, water managers will increasingly have to manage for conditions outside the short historical experience. Managing for the greater range of hydrologic variability evident in proxy and projected, versus gauged, hydrometric records can prepare water managers for adaptation to climate

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change. Centuries long tree ring reconstructions of streamflow capture hydroclimatic variability at annual to multidecadal scales [*Stockton and Jacoby*, 1976; *Meko et al.*, 1991; *Woodhouse*, 2001; *Case and MacDonald*, 2003; *Gedalof et al.*, 2004].

[6] Tree rings are well suited for hydrological reconstructions as they have annual resolution and wide distribution, and climate conditions causing decreased watershed runoff (low precipitation, high evapotranspiration) also cause decreased water potential in trees [*Loaiciga et al.*, 1993; *Meko et al.*, 1995]. Tree ring indices correlate with hydrologic variables in a range of hydroclimatic regimes [*Schulman*, 1945; *Stockton and Jacoby*, 1976; *Smith and Stockton*, 1981; *Cook*, 1985; *Cleaveland and Stahle*, 1989] and particularly with streamflow data that integrate runoff over space and among events [*Loaiciga et al.*, 1993; *Meko et al.*, 1995; *Hidalgo et al.*, 2001]. Tree ring signals are coherent over hundreds of kilometers reflecting a regional (basin) hydroclimatic signal. In western Canada, tree ring reconstructions of streamflow have been developed for the Athabasca [*Bonin and Burn*, 2005], Churchill [*Beriault and Sauchyn*, 2006], Bow [*Watson and Luckman*, 2005a], and Saskatchewan rivers [*Case and MacDonald*, 2003]. Other tree ring studies in the region have investigated lake levels in the Athabasca Basin [*Stockton and Fritts*, 1973; *Meko*, 2006] and floods in the Red River Basin [*St. George and Nielsen*, 2002a, 2002b].

[7] In this paper we present two reconstructions of mean water year flow (October through September) inferred from a network of 14 new tree ring chronologies collected throughout the upper western regions of the South Saskatchewan River Basin (SSRB). The flow of the South Saskatchewan River (SSR) was previously reconstructed by *Case and MacDonald* [2003] using tree ring chronologies from two sites in the SSRB. The two chronologies were from moisture-sensitive limber pine (*Pinus flexilis* James) at exposed xeric sites. We collected tree rings from limber pine at four sites, but also from Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) at 10 sites, to produce robust reconstructions of the flow of the SSR and one of the main tributaries, the Oldman River. Douglas fir occupies a greater variety of sites than limber pine, and thus a network of Douglas fir chronologies encompasses a greater range of local hydroclimatic conditions throughout the upper reaches of the SSRB, where about 80% of the runoff in the entire basin is generated [*Prairie Provinces Water Board* (*PPWB*), 1962]. The larger network of tree ring sites used in this study also enables the reconstruction of streamflow at a subbasin scale, and the analysis of hydroclimatic variability among basins at interannual to multidecadal scales. Recent studies [*Rood et al.*, 2005; *Schindler and Donahue*, 2006] have examined trends in the recorded flow of the SSR and conclude or imply that global warming is causing a reduction in water supplies. The longer perspective, provided by tree ring reconstructions of stream flow, can address the degree to which recent trends represent components of long-term low-frequency variability in the regional hydroclimate.

2. Study Area

[8] The South Saskatchewan River Basin (SSRB) of Alberta and Saskatchewan (Figure 1) is Canada's largest (167,765 km^2) dryland watershed. The major subbasins (and contributions to mean annual flow) are the Bow (43%), Red Deer (18%), and Oldman (38%) River basins [*Alberta Environment*, 2002]. Highest peak annual flow occurs in the snowmelt runoff season of March through June, receding to base flow conditions in July–August [*Hauer et al.*, 1997; *Marshall and Schut*, 1999]. All of the major tributaries of the SSR have large-scale water extractions and impoundments, such that summer flows in the Oldman River are 40–60% below their historical values, and in the SSR summer flows have been reduced by 84% since the early 20th century [*Schindler and Donahue*, 2006]. More than 70% of licensed surface water withdrawals in Alberta are for irrigation [*Alberta Environment*, 2005].

3. Tree Ring and Streamflow Data

[9] Of the eleven tree ring chronologies previously collected in the SSRB (International Tree Ring Data Bank, 2006, http://www.ncdc.noaa.gov/paleo/treering.html) nine predate 1992. Given the lack of current tree ring data for the SSRB, we established a network of new tree ring chronologies for the major runoff-generating areas of the basin. Douglas fir and limber pine are common throughout the region as open canopy stands at dry sites and near the eastern edge of their range. Both species are long lived, with 800-year-old limber pine and 700-year-old Douglas fir known to occur in the SSRB [*Case and MacDonald*, 2003; *Watson and Luckman*, 2006].

[10] Tree rings were collected from at least 20 trees per site at 14 sites on low-elevation dry south and southwest facing slopes where soil moisture is limited (Table 1). The densest sampling occurred in the Oldman River subbasin, where the montane landscape, fescue prairie and well drained soils are ideal conditions for open canopy stands of long-lived and moisture-sensitive coniferous trees. In the Red Deer River Basin, on the other hand, young closed canopy forests predominate and the only suitable site we located was near the headwaters of the Red Deer and James rivers at Ya Ha Tinda Ranch (YHT) (Figure 1).

[11] Sample preparation, cross dating and chronology construction followed standard dendrochronological methods [*Stokes and Smiley*, 1968; *Cook et al.*, 1990]. Tree ring width was measured to within 0.001 mm using a 40X stereomicroscope, Velmex uniSlide digitally encoded traversing table, AcuRite III digital counter, and the measuring program J2X. Cross dating ensured that exact calendar years were assigned to every tree ring, and was verified using the program COFECHA [*Holmes*, 1983]. The program ARSTAN [*Cook*, 1985] was used to standardize the measured tree ring series using conservative detrending methods: a negative exponential curve, which removes the juvenile biological growth trends in the tree ring series; or a cubic smoothing spline, a low-pass digital filter with a 50% frequency response cutoff, where the cutoff is the frequency at which 50% of the amplitude of the signal is retained [*Cook et al.*, 1990]. Chronologies ranged in length from 290 to 786 years (Table 1). Where individual chronologies were used as predictors of streamflow, the length of each chronology was limited to the segment with an expressed population signal (EPS) $\geq$0.85, minimizing inflation of variance associated with decreasing sample size [*Wigley et al.*, 1984; *Briffa and Jones*, 1990]. The standardized ring width series of various lengths were

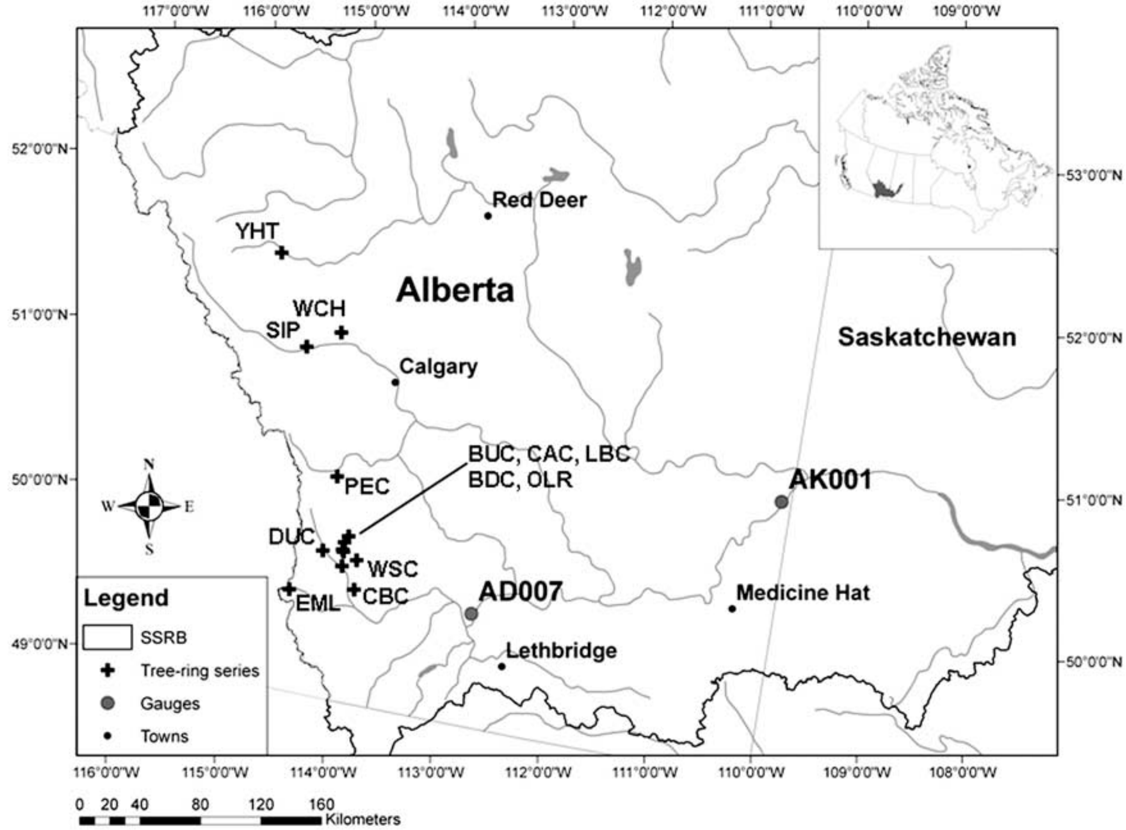

Figure 1. The South Saskatchewan River Basin (SSRB) in the Prairie Provinces of Alberta and Saskatchewan (top right inset) and locations of the tree ring chronologies and streamflow gauges in the major runoff-generating subbasins of the SSRB.

averaged for each site, using a mean value function that minimizes the effect of outliers [*Cook et al.*, 1990], producing a dimensionless stationary index time series with a defined mean of 1.0 and a relatively constant variance.

[12] Streamflow data for the SSRB were provided by Alberta Environment who derived naturalized flows from streamflow records, reservoir data, recorded and estimated irrigation withdrawals, and climate data using the Streamflow Synthesis and Reservoir Regulation (SSARR) model from U.S. Army Corps of Engineers [*Alberta Environment*, 1998]. These natural flow data for the period 1912–2001 are suitable for water management planning on the scale of the SSRB [*Alberta Environment*, 1998]. We focused on two hydrometric gauges, which integrate streamflow at different spatial scales: (1) the Oldman River near Lethbridge, Alberta (ID 05AD007), and (2) the South Saskatchewan River below the confluence with the Red Deer River, 16 km west of the Alberta-Saskatchewan border (ID 05AK001) (Table 2).

Table 1. Properties of New Tree Ring Chronologies Sampled in the South Saskatchewan River Basin, Alberta, Canada

Site Name	Code[a]	Species[b]	North Latitude	West Longitude	Elevation (m)	Number of Dated Samples	Chronology Interval	Interseries Correlation	Mean Sensitivity	Year EPS >0.85
Beaverdam Creek	BDC	PsMe	49°55′	114°12′	1661	42	1482–2004	0.736	0.363	1584
Burto Creek	BUC	PsMe	50°1′	114°11′	1536	21	1442–2004	0.681	0.332	1605
Callum Creek	CAC	PsMe	49°59′	114°12′	1677	45	1513–2004	0.744	0.310	1596
Cabin Creek	CBC	PsMe	49°42′	114°1′	1395	39	1373 –2004	0.791	0.425	1440
Dutch Creek	DUC	PsMe	49°54′	114°24′	1648	42	1618–2004	0.808	0.353	1639
Emerald Lake	EML	PiFl	49°37′	114°38′	1384	39	1450–2004	0.602	0.291	1688
Little Bob Creek	LBC	PsMe	49°56′	114°13′	1602	47	1493–2004	0.775	0.399	1607
Oldman River	OLR_1	PiFl	49°50′	114°11′	1458	60	1218–2004	0.608	0.419	1436
Oldman River	OLR_2	PsMe	49°50′	114°11′	1458	21	1490–2004	0.736	0.479	1577
Pekisko Creek	PEC	PiFl	50°22′	114°24′	1515	36	1563–2004	0.624	0.358	1640
Stoney Indian Park	SIP	PsMe	51°7′	114°58′	1300	21	1597–2003	0.788	0.354	1698
Wildcat Hills	WCH	PsMe	49°53′	114°3′	1351	35	1341–2004	0.863	0.499	1399
West Sharples Creek	WSC	PsMe	51°15′	114°40′	1575	63	1525–2004	0.767	0.374	1589
Ya Ha Tinda	YHT	PiFl	51°40′	115°25′	1529	12	1711–2001	0.477	0.230	1712

[a]Chronologies referred to by abbreviations herein.
[b]Species coded as follows: PIFL, Limber pine (*Pinus flexilis*); PSME, Douglas fir (*Pseudotsuga menziesii*).

Table 2. Information on Hydrometric Gauges in the South Saskatchewan River Basin, Alberta, Canada

Gauge ID"05"	Gauge Name	North Latitude	West Longitude	Gross Drainage Area (km^2)	Length of Record
AD007	Oldman River near Lethbridge	49°42′	112°52′	17,031	1912–2001
AK001	South Saskatchewan River at Hwy. 41	50°44′	110°5′	66,000	1912–2001

These annual streamflow time series have a Gaussian frequency distribution according to a robust nonparametric Lilliefors test of normality.

4. Methods of Streamflow Reconstruction

[13] The 14 tree ring chronologies were examined for correlations with climate and streamflow data to restrict the pool of predictors to those with a physical relationship to hydrologic variability. Correlation coefficients were calculated between residual chronologies [*Cook*, 1985] and mean monthly temperature and total monthly precipitation, using the full record from Pincher Creek, Alberta (1895–1962), in the year t and in $t - 1$ for July and August, and between the standard, residual and arstan chronologies [*Cook*, 1985] and average monthly, annual, and water year flows, using the naturalized streamflow data for the period 1912 to 2001.

[14] Principal components analysis (PCA) was used to reduce the tree ring indices to a set of independent predictors for chronologies from the Oldman River subbasin. Chronologies were grouped into two common periods: 1400–2004 (2 chronologies) and 1618–2004 (8 chronologies). Principal components (PCs) were extracted using a covariance matrix, where no more than three components were retained for further analysis. Limiting the number of potential predictors minimizes the probability of overfitting the regression model.

[15] Multiple linear regression was used to estimate streamflow from a set of potential tree ring predictors, index chronologies and PCs, for the growth year and at forward lags of 1, 2 and 3 years. The lagged predictors account for current conditions that affect tree growth in succeeding years [*Fritts*, 1976]. Reconstruction models were calibrated using a forward stepwise procedure with a cross-validation stopping rule. They were validated using a cross-validation leave-*n*-out method, where observations are left out sequentially through the length of the streamflow record allowing maximum use of the data [*Hughes et al.*, 1982].

[16] For the calibration period (1912–2001) we reported the strength of the regression models using the adjusted R^2, which quantifies the explanatory power of the regression and accounts for lost degrees of freedom [*Fritts*, 1976]. For the verification period we used the reduction of error (RE) statistic, a rigorous measure of association between a series of actual values and their estimates. The theoretical limits of the RE range from a maximum of +1 to negative infinity. Any positive value indicates that the model has some predictive capacity [*Fritts*, 1976; *Fritts et al.*, 1990]. The F level of the regression model was computed as a goodness-of-fit test. The standard error (SE) and root-mean-square error of validation ($RMSE_v$) are measures of the uncertainty in predicted values over the calibration period and validation period, respectively. Both error terms have the same units as the predictand so are used as a measure of uncertainty in the regression estimates. Regression residuals were tested for autocorrelation using the Durbin-Watson test [*Ostrom*, 1990]. The mean variance inflation factor (VIF) was calculated to identify multicollinearity in the matrix of predictor values [*Haan*, 2002].

[17] The hydroclimatic variability inherent in the streamflow reconstructions was characterized by the timing and frequency of moderate and extreme hydrological drought, defined as reconstructed flows in the lowest 25th and 10th percentiles, respectively, and by the main modes of variability identified using a multitaper method (MTM) of spectral analysis [*Mann and Lees*, 1996] and continuous wavelet transform (CWT) analysis [*Grinsted et al.*, 2004]. The MTM is a powerful and widely used nonparametric method of spectral estimation providing high resolution while minimizing spectral leakage and reducing the variance of spectral estimates by using orthogonal tapers [*Ghil et al.*, 2002]. It is particularly well suited for short and noisy time series. With a frequency resolution suitable for resolving distinct climate signals, and improved spectral estimation properties over classical methods, the MTM has been widely applied to instrumental records of atmospheric and oceanic variables. We implemented MTM using the SSA-MTM Toolkit available at http://www.atmos.ucla.edu/tcd/ssa/. The CWT analysis is a powerful tool for the identification of nonstationary signals because it decomposes the time series into frequency components. Most traditional mathematical methods that examine periodicities in the frequency domain, such as Fourier analysis, have implicitly assumed that the underlying processes are stationary in time. Wavelet transforms expand time series into time frequency space and can therefore find localized intermittent periodicities [*Grinsted et al.*, 2004].

5. Results

[18] Residual tree ring chronologies were significantly ($p < 0.05$) and positively correlated to precipitation and negatively correlated to temperature (Figure 2). The correlation with precipitation was strongest in previous August and the current spring season (May, June, July). Seven chronologies, two limber pine and the five highest elevation Douglas fir chronologies (1536 to 1677 m asl), were significantly and positively correlated to late fall and winter (November and February) precipitation, but averaged across all chronologies these correlations failed to meet the 95% confidence threshold (Figure 2). The correlation between temperature and tree ring width was predominately negative and strongest in June, July and September of the current year (Figure 2). Correlations with streamflow data (results not shown) were significant ($p < 0.05$) for all flow observation intervals: monthly, annual and water year. Standard chronologies and average water year (October–September) flows were most strongly correlated ($r = 0.30$ to 0.61; $p < 0.05$). Of the 14 potential predictor tree ring chronologies, 11 exhibited significant correlations with hydroclimatic variables; the three chronologies (EML,

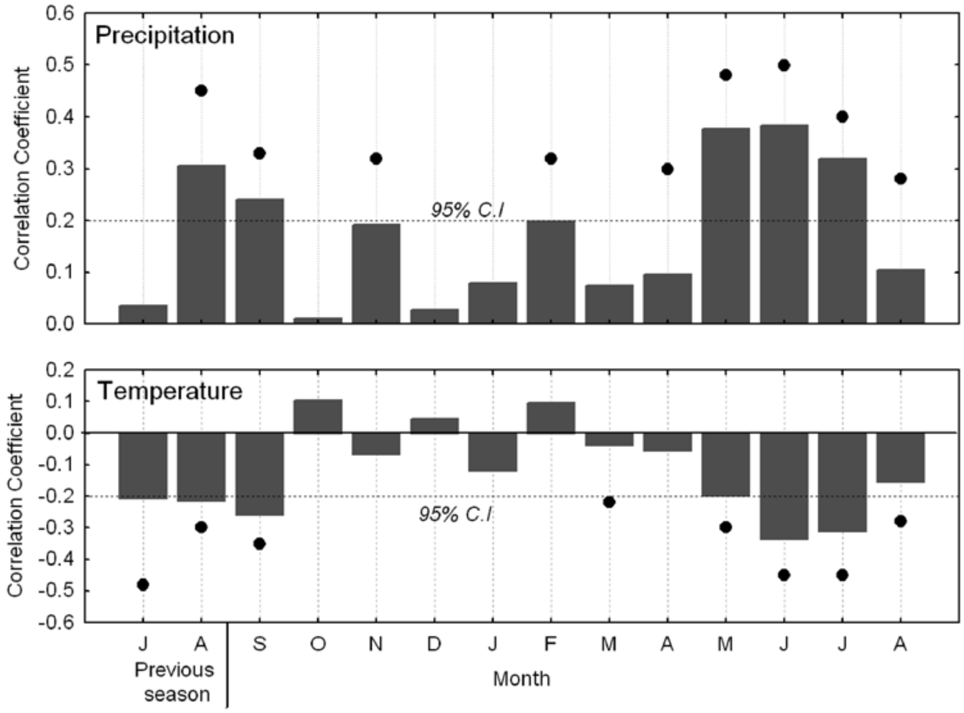

Figure 2. Average (solid bars) and maximum (dots) correlation coefficients between tree ring width indices and monthly total precipitation (mm) and mean temperature (°C) for the period 1895–1962, the length of the record from Pincher Creek, Alberta. The dotted line is the 95% confidence interval.

OLR2 and YHT) that did not were removed from the pool of predictors.

[19] The PC data sets from the Oldman River subbasin were used in conjunction with the standard chronologies to reconstruct streamflow. For the 1400–2004 common period two PCs were retained (604-PC1 and 604-PC2) and accounted for 84.3% and 15.6% of the variance in standardized tree ring width. For the 1618–2004 common period, one PC was retained (386-PC1) accounting for 77.7% of the variance (Table 3).

[20] We reconstructed average water year flow for the Oldman River at Lethbridge (AD007) and the South Saskatchewan River at Medicine Hat (AK001), to capture hydroclimatic variability at subbasin and basin scales, respectively. Calibration and verification statistics for the two regression models indicated skillful reconstructions of water year flow (Table 4). The models accounted for 37% and 43% of the instrumental variance and had significant skill when subjected to cross validation (Table 4). Regression residuals were normally distributed and behaved as a white noise process. The calibration models captured the low-frequency and low-flow variability well but underestimated high flows throughout the calibration period (Figure 3). Tree ring reconstructions typically underestimate high flows as other environmental conditions become limiting during wet years [*Fritts*, 1976]. This accounts for much of the unexplained variance. The low flows in the instrumental record during the 1930s were under represented by both models (Figure 3), but not to the extent that high flows are underestimated. Plotted with the full reconstructions of average water year flow (Figure 3) are 95% confidence levels based on the root-mean-square-error estimates from the verification period [*Jain et al.*, 2002], the calibration mean; the lowest 10th and highest 90th flow percentiles, and sample depth through time against the right *y* axis. A 25-year spline with a 50% frequency cutoff, the frequency at which 50% of the amplitude of signal is retained, highlights low-frequency variability in the reconstruction.

[21] Sustained wet and dry intervals were identified for each reconstruction using flows in the 75th and 25th percentiles, respectively. For the 387-year Oldman River record, the longest wet interval occurred from 1897 to 1913, the period when most Euro-Canadian settlers arrived in the region; and the longest dry interval was from 1862 to 1876, shortly prior to settlement. For the South Saskatchewan River, the longest wet interval was from 1825 to 1841 and longest dry interval was during 1552 to 1571. The SSR record extending to 1400 is characterized by low flows from the 1470s to the 1570s, with extreme drought in the 1560s (Table 5). Severe hydrological droughts, defined as flows in the lowest 10th percentile,

Table 3. Principal Components Analysis of Standard Chronologies From the Oldman River Subbasin for Two Common Periods Using the Covariance Matrix Method[a]

Common Period	Predictors	Extracted Principal Components[b]
1400–2004	CBC and OLR_1	604-PC1 (84.3) 604-PC2 (15.6)
1618–2004	BDC, BUC, CAC, CBC DUC, LBC, OLR_1, WSC	386-PC1 (77.7)

[a]Standard chronologies.
[b]Explained variance. Percentages are given in parentheses.

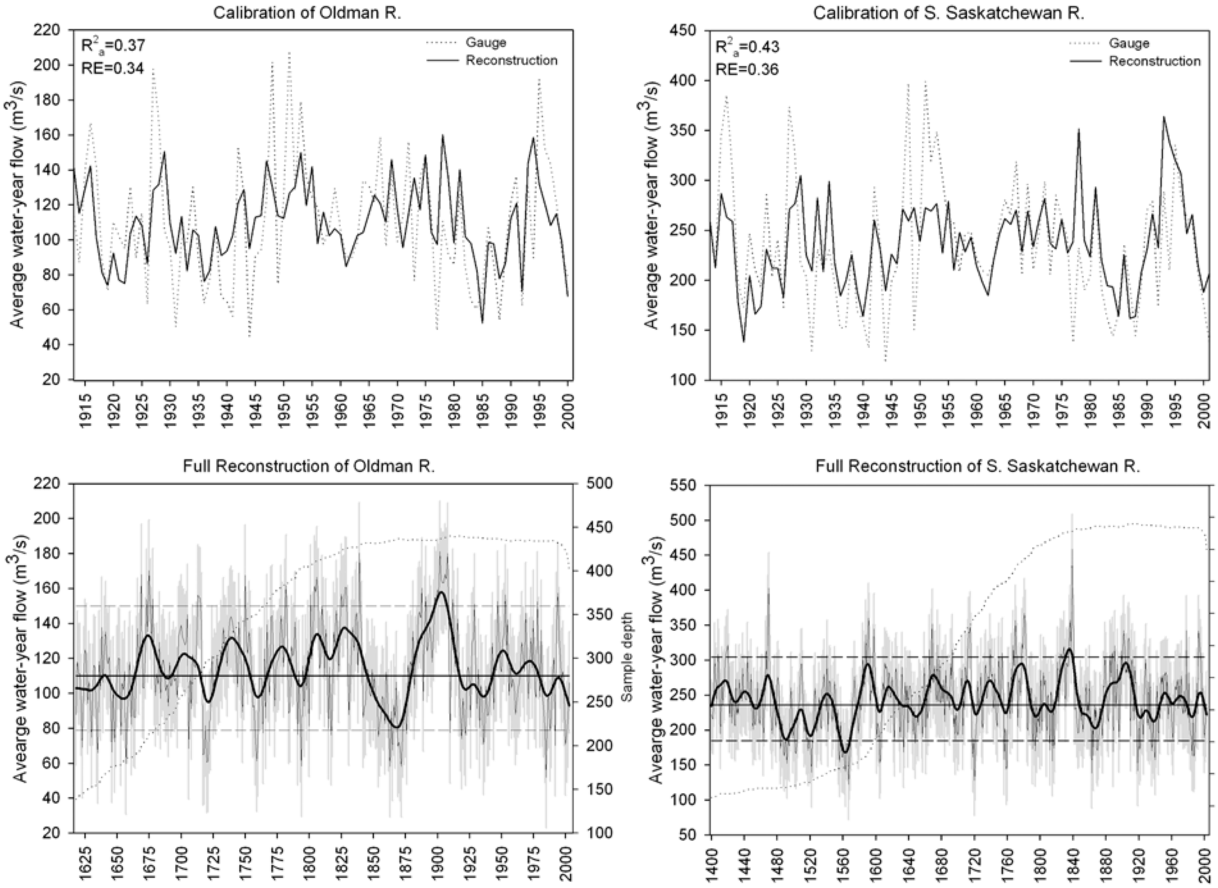

Figure 3. (top left) Oldman River and (top right) South Saskatchewan River gauge and reconstructed water year flows (previous October to current September) for the calibration period (1912–2001). (bottom) The full reconstruction (black lines) of water year flows for (left) the Oldman River for the period of 1618–2003 and (right) South Saskatchewan River for the period of 1400–2003; gray lines are the 95% confidence interval calculated from the root-mean-square error estimates from the verification period, the heavy black line is a 25-year spline with 50% frequency response, the solid horizontal line is the calibration mean, and dashed horizontal lines represent the 10th and 90th percentiles. Sample depth through time is plotted on the right-hand y axis.

were identified and the top ten worst droughts were compiled by reconstruction (Table 5). The earliest severe drought common to both reconstructions occurred from 1717 to 1721, when at least one of these years was ranked as one of the ten driest years. Another severe drought year common to both reconstructions was 1863, which ranked second and third for the Oldman and South Saskatchewan rivers, respectively. Both reconstructions had only one drought year in the postsettlement (instrumental) period; 1985 (first) and 1919 (sixth) in the Oldman River and SSR records, respectively (Table 5). Although the 1930s are considered one of the worst droughts periods in memory in western North America, it does not appear as an extreme drought in either reconstruction.

[22] The results of the single-spectrum MTM analysis (Figure 4) of the reconstructions show a highly significant multidecadal (~65 years) component of variability in both reconstructions together with significant variability at interannual time scales (2–6 years) in the El Niño-Southern Oscillation (ENSO) band. The results of the wavelet power spectrum mirror those of the MTM spectrum, but with the additional context of the time frequency domain. The significant multidecadal (~65 years) component is evident in the wavelet spectrum during sustained low flows in the 1500s for the South Saskatchewan reconstruction, corresponding to the "megadrought" identified in the western United States [*Stahle et al.*, 2000]; and during the 1800s in both reconstructions (Figure 4). Significant interannual variability is evident throughout the wavelet power spectrum for both reconstructions. Previous studies [e.g., *Shabbar and Skinner*, 2004; *Gobena and Gan*, 2006] identified significant modes of

Table 4. Regression Statistics of Tree Ring-Based Reconstructions of Streamflow

Gauge ID	Reconstruction Period	Predictors in Model	R^2	Adjusted R^2	RE	F Ratio	SE	$RMSE_v$
AD007	1618–2003	386-PC1, PEC, WCH	0.394	0.373	0.34	13.51	28.52	28.92
AK001	1400–2003	604-PC1, 604-PC2	0.443	0.430	0.36	22.51	47.93	50.35

Table 5. Top Ranked Extreme Dry Years for Both Reconstructions[a]

Rank	Oldman River	South Saskatchewan River
1	1985	1567
2	1863	1720
3	1872	1863
4	1794	1522
5	1657	1563
6	1720	1919
7	1721	1759
8	1759	1760
9	1717	1721
10	1718	1568

[a]Extreme dry years are <10th percentile.

interannual and interdecadal variability in the observed hydroclimate of western Canada, and associated sea surface temperature (SST) forcing, specifically the ENSO and Pacific Decadal Oscillation (PDO). While, our tree ring series have an interdecadal (∼13 years) peak, the multidecadal component is stronger; a finding similar to previous tree ring studies [e.g., *Gedalof and Smith*, 2001; *Gray et al.*, 2003]. A difference in dominant modes between proxy and instrumental records could point to the limitation of the shorter records for capturing low-frequency signals and to the nonstationarity of SST forcing, whereby for example interdecadal variability may be recently more energetic.

6. Discussion

[23] Research in dendrohydrology has been characterized by the use of increasingly dense networks of moisture-sensitive tree ring chronologies for constructing proxy records of regional hydroclimate. For example, there has been a series of reconstructions of the paleohydrology of the Colorado River [*Stockton and Jacoby*, 1976; *Hidalgo et al.*, 2001; *Woodhouse et al.*, 2006; *Timilsena et al.*, 2007] as chronologies are added to the network of tree ring sites in the basin and new statistical methods are applied to tree ring and hydroclimatic data. By developing a network of new moisture-sensitive tree ring chronologies in the runoff-generating upper reaches of the South Saskatchewan River Basin (SSRB), we were able to produce the first reconstruction of the annual flow of the Oldman River and a second reconstruction of the annual flow of the South Saskatchewan River (SSR). The initial reconstruction for the SSR by *Case and MacDonald* [2003] (CM) was based on tree ring data from limber pine at only two sites in the SSRB that were both xeric. Our new network of 14 sites in

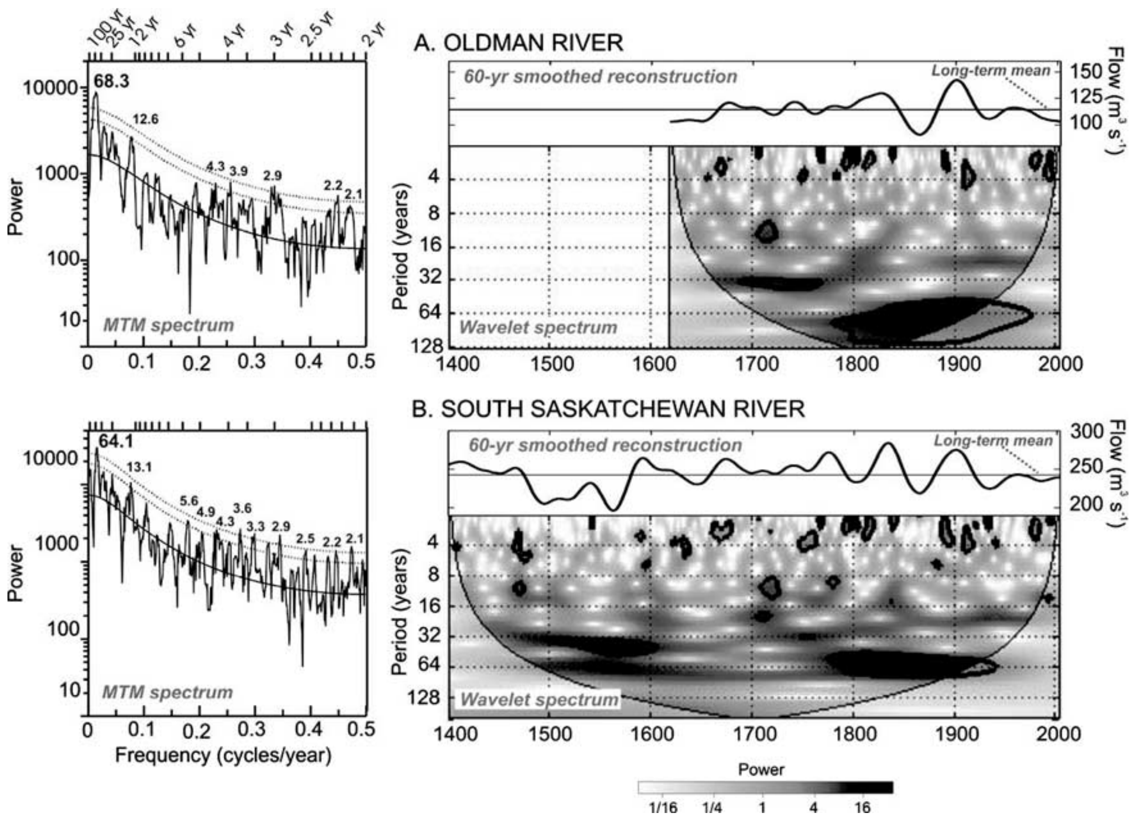

Figure 4. (left) The results of the single-spectrum MTM analysis showing a highly significant multidecadal (∼65 years) component of variability in both reconstructions together with significant variability at interannual time scales (2–6 years). The dotted lines represent the median and 95 and 99% levels of significance. The significant spectral peaks are labeled. (right) The wavelet power spectrum and a 60-year low-pass-filtered version of the streamflow reconstructions for (a) Oldman River and (b) South Saskatchewan River show a prominent multidecadal mode of variability. In the wavelet plots, the thick black contour designates the 5% significance level against red noise, and a lighter shade is used to show the cone of influence where edge effects might be important.

the SSRB includes Douglas fir at 10 mesic sites and thus encompasses a range of local hydroclimatic conditions, including signals of late fall and midwinter precipitation. Our results are not directly comparable to *Case and MacDonald* [2003] because, in an attempt to produce more robust models and reconstructions, we used somewhat different methods to create, calibrate and validate the tree ring models of streamflow. These methods included PCA, enabled by dense sampling in the Oldman River basin, and various methods and statistics (e.g., expressed population signal, leave-*n*-out cross validation) to measure and express the validity and predictive capacity of the models. Foremost, we were able to achieve much more replication, a basic principle of dendrochonology, and thus a longer record for the SSR (605 years versus 522 years for CM) but more importantly much greater sample depth in the early years.

[24] Similarities between the CM reconstruction of the SSR and ours presented here reflect some common signals between the two sets of tree ring chronologies. Both reconstructions include 1717, 1718, 1720, 1721 and 1815 among the 10 worst drought years. In the CM record, however, severe droughts occurred mainly during the 18th and 19th centuries, while in our reconstructions severe droughts occurred mainly in the16th and 18th centuries in the South Saskatchewan River (Figure 3) and the 18th century in the Oldman River (Figure 3). The megadrought of the 16th century that extended from northwestern Canada [*Szeicz and MacDonald*, 1996] to Mexico [*Stahle et al.*, 2000] and the Atlantic Coast [*Stahle et al.*, 1998] was captured in our SSR reconstruction, where the period from 1552 to 1571 had the longest sustained low flow on record, and 3 years (1563, 1567 and 1568) ranked in the top 10 worst drought years (Table 5). Another sustained drought, from the 1850s to the early 1870s, is prominent in all reconstructions of streamflow [*Case and MacDonald*, 2003; *Bonin and Burn*, 2005; *Watson and Luckman*, 2005a; *Beriault and Sauchyn*, 2006] and precipitation [e.g., *Sauchyn et al.*, 2003; *Watson and Luckman*, 2005b] from the western interior and cordillera. It also appears in historical archives; specifically in the journals of the Palliser expedition that contained the infamous remark that the region corresponding to the SSRB "will forever be comparatively useless" [*Sauchyn et al.*, 2003, p. 163; *Rannie*, 2006].

[25] Our tree ring reconstructions of streamflow in the SSRB provide a long-term context for the gauge records that are basis for water supply planning in the watershed. The Prairie Provinces Master Agreement on Apportionment, governing interprovincial streamflows, was based on computed natural flows from 1912 to 1967 [*PPWB*, 1969], while allocations in Alberta are based on the computed natural flow from 1919 to 2001 [*Alberta Environment*, 2005]. There are approximately 200,000 water licenses and registrations in the SSRB, where irrigation accounts for 75% of water allocations, as compared to 0.99% for preserving aquatic environments. The Oldman River accounts for 87% of irrigation allocations and the volume allocated at times exceeds natural flow [*Alberta Environment*, 2005]. The nearly full allocation of surface water in the Oldman and Bow River basins has led to a moratorium on the granting of new surface water licenses [*Alberta Environment*, 2005]. This level of demand for the water resources of the SSRB suggests that an awareness of interannual to multidecadal variation in hydroclimate is essential for water resource management and planning in the basin. This study has clearly documental long-term low-frequency variability in regional hydroclimate that must be considered in any interpretation of recent trends in gauged streamflow and projections of future water supplies in the basin.

[26] The energy provider, Manitoba Hydro, uses the basin wide hydrological drought of 1937 to 1944 to represent the worst-case scenario for their operations on the basis of water supplies from the Saskatchewan-Nelson, Churchill, Red and Winnipeg River basins [*Girling*, 2006]. Placing this "worst-case scenario" in the context of our reconstruction, by expressing streamflow as a percentage difference from the full reconstruction mean, the 1937–1944 drought represents a 10% negative departure for the Oldman River and a 16% flow deficit for the South Saskatchewan River. If we apply the same analysis to the most severe drought in the reconstruction, 1717–1721, there was a 40% deficit for the Oldman River, and a 32% negative departure for the South Saskatchewan River. Thus, the most severe drought in the tree ring reconstruction represents flows that are roughly four times lower than the institutional worst-case scenario.

[27] A significant decreasing trend in the annual flow of the South Saskatchewan River is documented in recent analyses of gauge records [*Rood et al.*, 2005; *Schindler and Donahue*, 2006]. Much of this declining flow can be attributed to water storage, diversion and consumption but it is also consistent with projections of future flows derived by coupling hydrologic models and climate change scenarios [*Pietroniro et al.*, 2006]. This trend will level off at mean annual future flows according to changes in demand versus supply, where future raw water supplies will be determined by global warming impacts on the hydrology of the headwater basins and imposed on the interannual to multidecadal variability revealed in our tree ring reconstructions. The significant multidecadal ($\sim$65 year) mode of variability in our reconstructed flows of the Oldman and South Saskatchewan rivers suggest that trends inferred from decades-long instrumental records could represent low-frequency variability inherent in the regional hydroclimate.

7. Conclusion

[28] The objective of this research was to examine long-term hydroclimatic variability in the South Saskatchewan River Basin (SSRB) by deriving robust reconstructions of streamflow at two scales from a network of new tree ring chronologies in the major runoff producing subbasins. Average water year flow was reconstructed for gauges on the Oldman and South Saskatchewan rivers. The tree ring models accounted for 37% and 43% of the instrumental variance, respectively. These proxy streamflow records, extending to 1400, reveal the timing, duration and relative severity of sequences of high and low flows. Because much of the unexplained variance in the calibration period is the underestimation of high flows, we have more confidence in the interpretation of the low flows which consistently correspond to narrow tree rings, capturing the timing and duration of drought. While the 20th century is representative of drought frequency over the long term, there are droughts of greater severity and especially duration in the

proxy record. Thus the 605 years of reconstructed flow presented in this paper provide an important context for institutional worst-case scenarios which rely on instrumental records that are generally shorter than the significant low-frequency variability captured by our tree ring records. In particular, the significant interdecadal variability in our tree ring reconstructions of streamflow provide an alternative interpretation of trends in gauge records that are decades in length.

[29] Despite the amount of new tree ring data and processing that we applied to skilful reconstructions of streamflow in the SSRB, tree ring width indices still account for less than 50% of the variance in the gauge records. In snow dominated basins, spring snowmelt and precipitation in the cooler months are the major contributors to streamflow. Soil moisture recharged from winter precipitation is available for use by trees at the beginning of the growing season, and biological processes important for the overall water and energy balances of the trees are not restricted to cambial growing season but continue year round [*Fritts*, 1976; *Meko et al.*, 1995]. Thus to some extent, our tree ring records have a snowmelt signal; there are significant correlations with February precipitation at some sites and with spring soil water availability at most sites. However, despite developing a new network of tree ring chronologies in the upper reaches of the SSRB to capture a wider range of local hydroclimate conditions, the underestimation of high annual flows persists. Therefore this study also has verified that tree growth at lower elevations does not capture the full magnitude of snowmelt infiltration and runoff despite some correlation between tree ring and winter precipitation data. Adding higher-elevation snowpack sensitive tree ring chronologies to the pool of predictors of streamflow [*Watson and Luckman*, 2006] should produce models that account for a larger percentage of the variance in the instrumental records.

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