Security of western water supplies under a changing climate

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Abstract

Despite the dry climate of the Canadian plains, water supplies seem relatively secure, at least from the short perspective of our non-aboriginal history and period of instrumental monitoring. A longer view, over the past millennium and to the end of current century, presents a somewhat different perspective. In the past 70 years, western Canadians have been exposed to water deficits that are shorter and less severe than droughts in preceding centuries. For example, in May 1796 at Fort Edmonton, furs could not be moved "there being no water" in the North Saskatchewan River. Tree rings, a reliable proxy of available soil water, show drought lasting decades prior to European settlement of the western plains. Since the 1930s, droughts have been of relatively short duration and western rivers have carried surplus runoff from retreating glaciers. The gauge records, that are the scientific basis for water management and planning, are mostly from this recent period and do not capture the full range of regional hydroclimatic variability both in the past and expected in the future with climate change. The longer inferred hydrology indicates that 1) declining trends in measured surface water levels may represent low-frequency variability: climate cycles that approximate or exceed the length of the gauge records, and 2) the hydrologic regime is not stationary as assumed, that is, there are shifts in the mean and variance. This natural variability underlies the trends imposed by global warming and the resulting shift in water resources between seasons, years and watersheds. Integrated water management to ensure water security under a shifting hydrologic regime may rely less on major infrastructure for water diversion and storage and more on source water protection and conservation including restoration of stream channels and riparian ecosystems, on-farm and off-stream water storage, restoration of wetlands and terrestrial ecosystems, and more efficient use of agricultural, industrial and domestic water supplies.

Introduction

Recent national (Sauchyn and Kulsthretha, 2008) and provincial (Sauchyn et al., 2007, 2009) assessments of climate change impacts and adaptation have identified shifts in the distribution of water resources, between seasons, years and watersheds, as the major risk from climate change in the Canadian Prairies. Adaptation to avoid or reduce adverse impacts on communities, economies, and managed ecosystems requires knowledge of trends and variability in surface and soil water balances in the past and projections for the future. Most of the current information on water supply trends is from analyses of streamflow records and the expected shifts in mean conditions from the recent past (usually 1961-90) to a future 30-year period, such as 2040-69 (the “2050s”).

In this paper we describe how previous analyses of recent and future hydroclimatic trends have limitations for supporting adaptation to climate change and variability. We address the most serious knowledge gap: the nature and forcing of the inter-annual to multi-decadal variability that characterizes the regional hydroclimate and underlies streamflow trends and the shifts in water levels projected using climate models. While trends in mean water levels and future average conditions for 30-year periods is useful information, without a knowledge of annual departures from the mean, it is insufficient to address most of the climate impact and adaptation issues in the Prairie Provinces. In the Prairies, most climate hazards and risks are related to extreme events and departures from mean conditions, especially drought. Most of the vulnerability to climate change is exposure to increased variability rather then to shifts or trends in mean conditions.

The Hydroclimate of the Recent Past

Western Canada's short non-aboriginal history, and period of instrumental monitoring, provides a short perspective on the variability of our climate and water resources. Various natural archives record a measureable response to variations in hydroclimate over decades to millennia. Tree rings are among the proxies of highest resolution. A tree-ring record is both a climate proxy and chronology of annual resolution. Tree growth at dry sites records the local water balance because the main growth limiting factor is available soil moisture. Therefore there is often a statistically significant correlation between ring-width indices and hydroclimate variables; especially streamflow and lake and ground water levels since they represent, like soil moisture, the balance between inputs of precipitation and outputs by evaporation. Long wet and dry cycles, that are evident in tree-ring records, approximate or exceed the length of instrumental water and weather records, giving the impressions of trends in these decadal length records.

At the University of Regina Tree-Ring Lab, we archive collected old wood from more than 120 dry sites in Alberta, Saskatchewan, the Northwest Territories and Montana. The focus of this research program is an improved understanding of the nature and causes of hydroclimatic variability in this region as a context for detecting changes in the hydrosphere imposed by global warming (Axelson and Sauchyn, *in press*; Sauchyn *et al.* 2008). The tree-ring index chronologies are calibrated using instrumental hydroclimate data that correlate with standardized ring-width time series. The tree rings are an especially good proxy of drought; low water levels correspond to narrow tree rings. On the other hand, the tree rings tend to underestimate high stream flows, since there is a limit to amount of water used by trees and in wet years other factors become growth limiting.

Figure 1 is a preliminary reconstruction of the flow of the North Saskatchewan River (NSR) at Edmonton (gauge 05DF001) for the period 1616 to 2005. The reconstruction model has five predictor tree-ring chronologies and was calibrated using naturalized streamflow data from Alberta Environment for the period 1912-2007. Both the gauged and reconstructed flow records are plotted in Figure 2 for the calibration period. This plot reveals that the tree-rings capture reasonably well the low flows and low frequency variability. The tree-ring model explains about 50% of the variance in observed annual flow. Most of the unexplained variance is from the underestimation of high flows. On the other hand, the tree-ring reconstruction captures the severity, timing and duration of drought. Prior to gauge record starting in 1912, there were periods of low flow of longer duration and greater severity than the lowest gauged flows in the 1930s. Specifically, in the early to mid 1700s and early 1800s, there are 10 to 15 year periods that have few if any years of above average flow. While the 15-year weighted average flow has been below average and declining in recent decades, annual flows have fluctuated above and below the long-term mean, such there have been no sustained droughts since the 1930s. This long proxy streamflow record provides a historical context for the recorded flows and for the following analysis of trends and variability in southern Alberta stream gauge records.

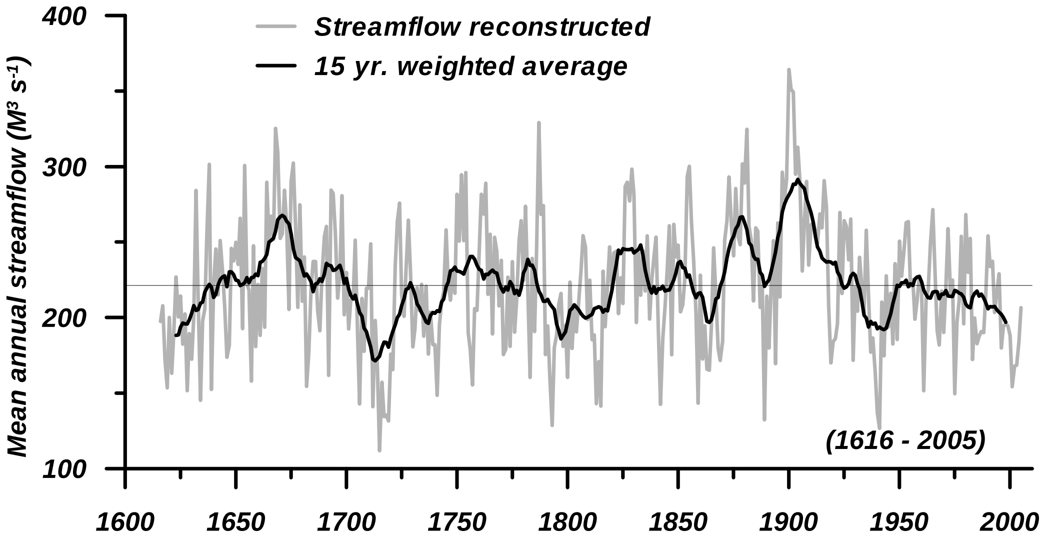


Figure 1. A preliminary reconstruction of the flow of the North Saskatchewan River at Edmonton for the period 1616-2005.

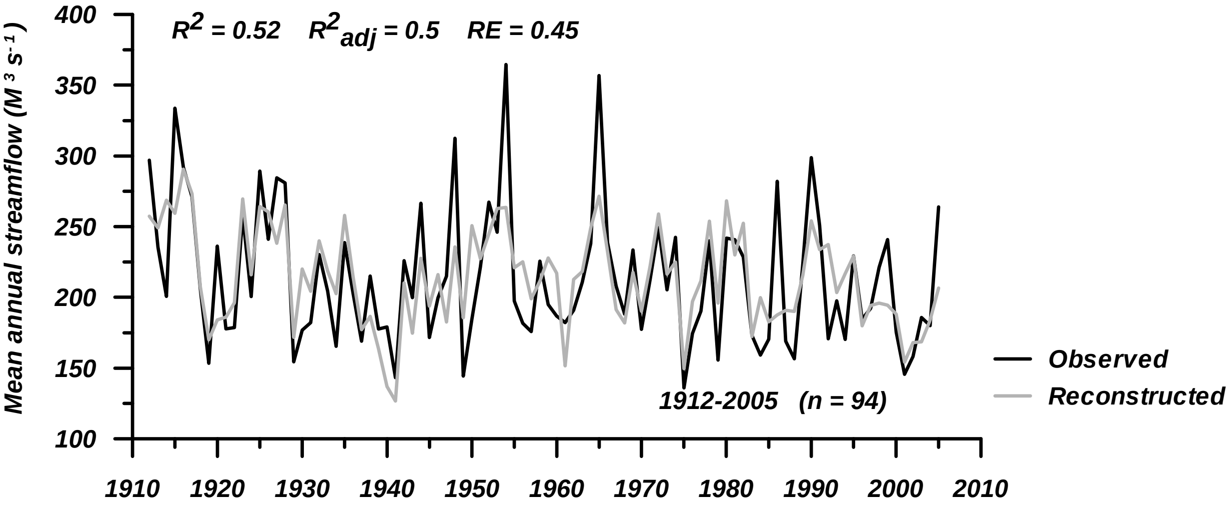


Figure 2. The gauged and reconstructed flows of the North Saskatchewan River at Edmonton for the calibration period, 1912-2007.

Southern Alberta Streamflow Records: Global Warming Trends or Natural Variability

Under Anthropogenic Global Warming (AGW) scenarios, southern Alberta is projected to see decreased streamflow and northern Alberta increased streamflow in the next 100 years (Figure 10.12, IPCC 4). Because of the moderate resolution of global climate models (GCMs), it is uncertain exactly where the transition between the two hydrological states will occur. Using the observed instrumental records, there has been much recent research on the detection and projection of climate change trends in Alberta and in western Canadian streamflow (i.e. Rood *et al.*, 2005; Schindler and Donahue, 2006; Rood *et al*., 2008). The conclusion of this latter research is that Alberta, particularly southern Alberta, is running out of water due to global warming. In this paper, we critically examine this interpretation of the instrumental records in Alberta.

The problems with previous analyses

There are many problems with using the instrumental streamflow records simplistically to reach a conclusion of declining surface water supplies. First, these records are short. They typically have periods of record of ~40-50 years in northern Alberta and ~95 years in southern Alberta. Second, these records are frequently discontinuous with gaps especially in the 1930s (due to economic collapse) and the 1940s (due to war). The gauge record for Pembina River at Entwhistle (Figure 3) is typical of this problem. The record begins during 1915-1922; there is a hiatus spanning 1916-1954; and then the record recommences in 1955 and continues until the present. The third problem with the Alberta streamflow dataset is the frequent serial autocorrelation in the fitted residuals which results in the overestimation of the effective sample size of the residuals (Zheng *et al.* 1997). Therefore classical linear regression and Mann-Kendall non-parametric methods such as those used by Rood *et al.* (2005, 2008) will disproportionately reject a null hypothesis of no trend (Zheng *et al.,* 1997; Zhang *et al.,* 2000, 2001; Burn and Hag Elnur, 2002; Yue *et al.,* 2002). The fourth difficulty arises from the heavy human impact from water consumption, diversion and storage, especially in southern Alberta. This overlays and obscures the natural hydrology as illustrated in Figure 4 for the South Saskatchewan River at Medicine Hat. The increasing difference between the naturalized flow (Alberta Environment) and the actual flow is readily apparent. The Oldman River at Lethbridge shows even larger differences between naturalized flows and recorded flows.

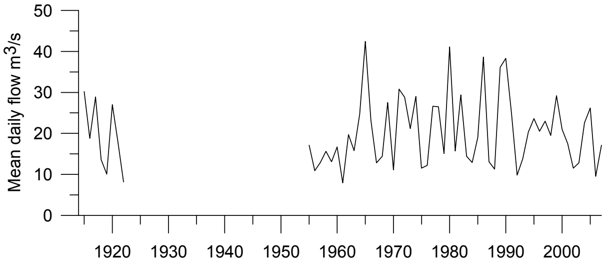
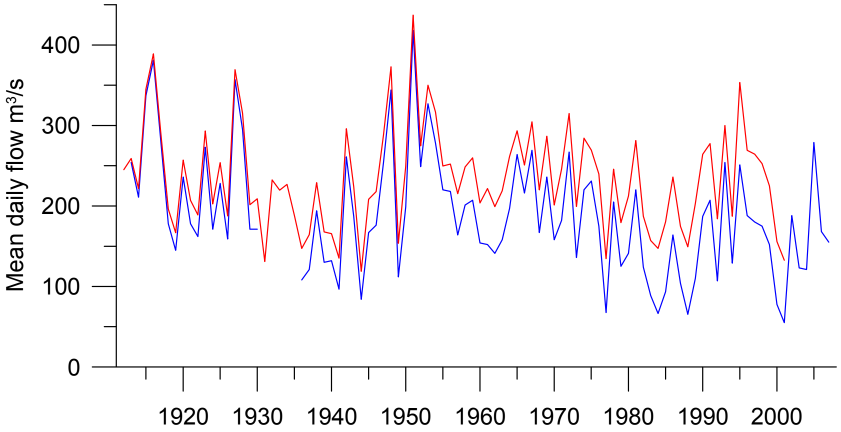


Figure 3. Mean daily flow (m^3/s) for the Pembina River at Entwhistle, Alberta (HYDAT gauge AB07BB002).

(A)



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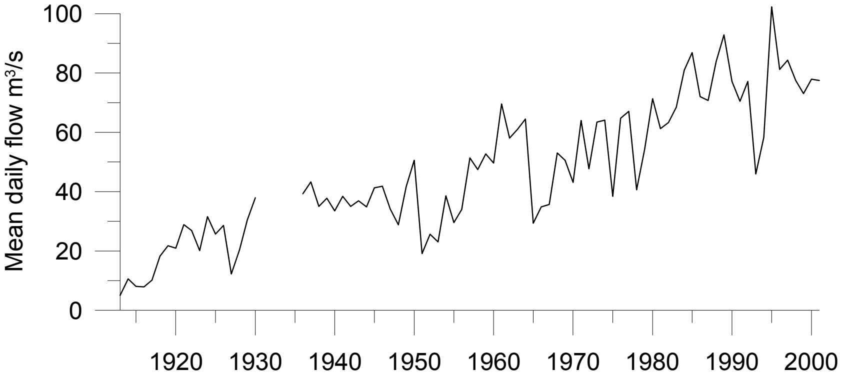

Figure 4. (A) Mean daily recorded (blue line) and naturalized (red line) flows (m^3/s) for the South Saskatchewan River at Medicine Hat, Alberta (HYDAT gauge AB05AJ001). **(B)** The difference (m^3/s) between the mean daily recorded and naturalized flows. Naturalized flows courtesy of Alberta Environment.

The above four problems are frequently encountered in any study of instrumental streamflow variability anywhere. However, the hydroclimatology of Alberta is distinct with its strong periodic cycles and relationship with the low-frequency Pacific Decadal Oscillation (PDO). The PDO is a pattern of climate variability that shifts phases on an inter-decadal time scale, usually about 20 to 30 years (Mantua *et al.,* 1997; Mantua and Hare, 2002) (Figure 5). The PDO is manifested as warm or cool extratropical Pacific surface waters (i.e., north of 20° N). During a warm or positive phase, the west Pacific becomes cool and part of the eastern ocean warms; during a cool or negative phase, the opposite occurs. In 1905, the PDO entered into a predominately warm phase, which continued until 1946 when a predominately cool phase began (Figure 5). In 1977, the PDO changed back into a warm phase. It is speculated that a succeeding cool phase has begun in 2008. The PDO is a major factor controlling streamflow in Alberta; a strong negative relationship exists between the two in south and central Alberta, while a weak positive relationship exists in northwestern Alberta (Figure 6). Up to 48% of the low frequency variability of some southern Alberta rivers can be accounted for by the PDO (Figure 6). Therefore, south and central Alberta are drier when the PDO is in its positive phase, and wetter when the PDO is negative.

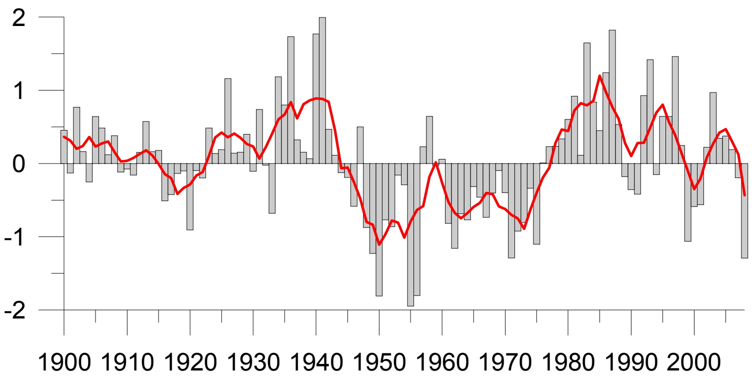

Figure 5. Annual Pacific Decadal Oscillation index (PDO) smoothed by a 5-year running mean (red line). Data source: Earth System Research Laboratory, National Oceanic and Atmospheric Administration, http://www.cdc.noaa.gov/data/climateindices/list/.

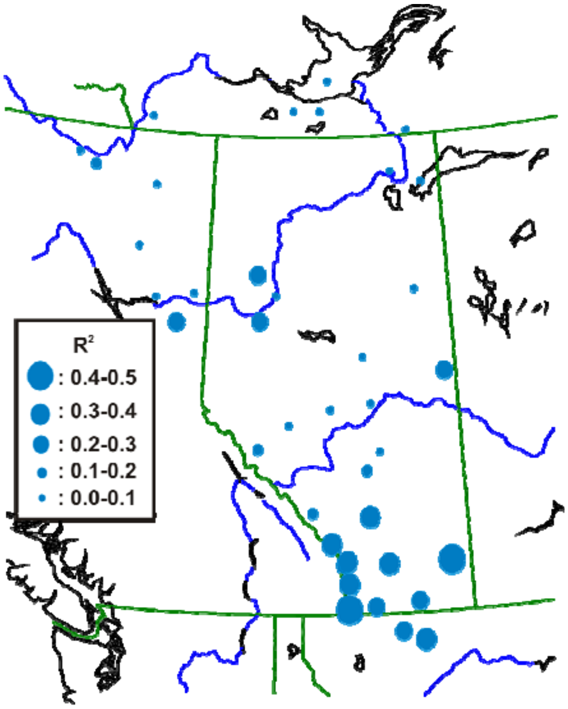

Figure 6. Pearson's correlation coefficients between Alberta and environs mean daily streamflow and the winter Pacific Decadal Oscillation index (PDO) of the same year. Both streamflow and winter (November-March) PDO index were smoothed by a 5-year binomial filter. Streamflows used were the longest continuous flows at selected sites.

The ~65 year low frequency cycle of the PDO can potentially generate a declining linear trend in short instrumental streamflow records. To illustrate this, we use the daily mean flow of the Waterton River near Waterton Park over the period 1950-2007 (Figure 7A). The data are normally distributed and an ordinary least squares regression line (with uncorrelated residuals) can be fitted showing a significantly declining trend (*p-value = 0.004*). However, from 1950-1976 the PDO was in the negative phase and streamflow was consequently high. From 1977-2007 the PDO was in the positive phase and streamflow was decreased. Hence, the trend could be solely due to the PDO phase changes, and not due to global warming or other human impact. If we examine the entire Waterton River record from 1912 to 2007, spanning an initial positive PDO phase, then a negative phase, then a positive phase again, the trend disappears (*p-value = 0.290*) (Figure 7B).

Many Alberta instrumental streamflow records begin in the 1950s (a period of strongly negative PDO, hence high Alberta streamflow), or omit the 1930s and 1940s (periods of high positive PDO, hence low Alberta streamflow). If the influence of the PDO is not taken into account in an analysis of Alberta instrumental hydroclimatic records, this could produce detected declines that could be attributed to global warming, while they are actually artifacts of the sampling period and the PDO phase changes. To the best of our knowledge, no published analysis takes this into account.

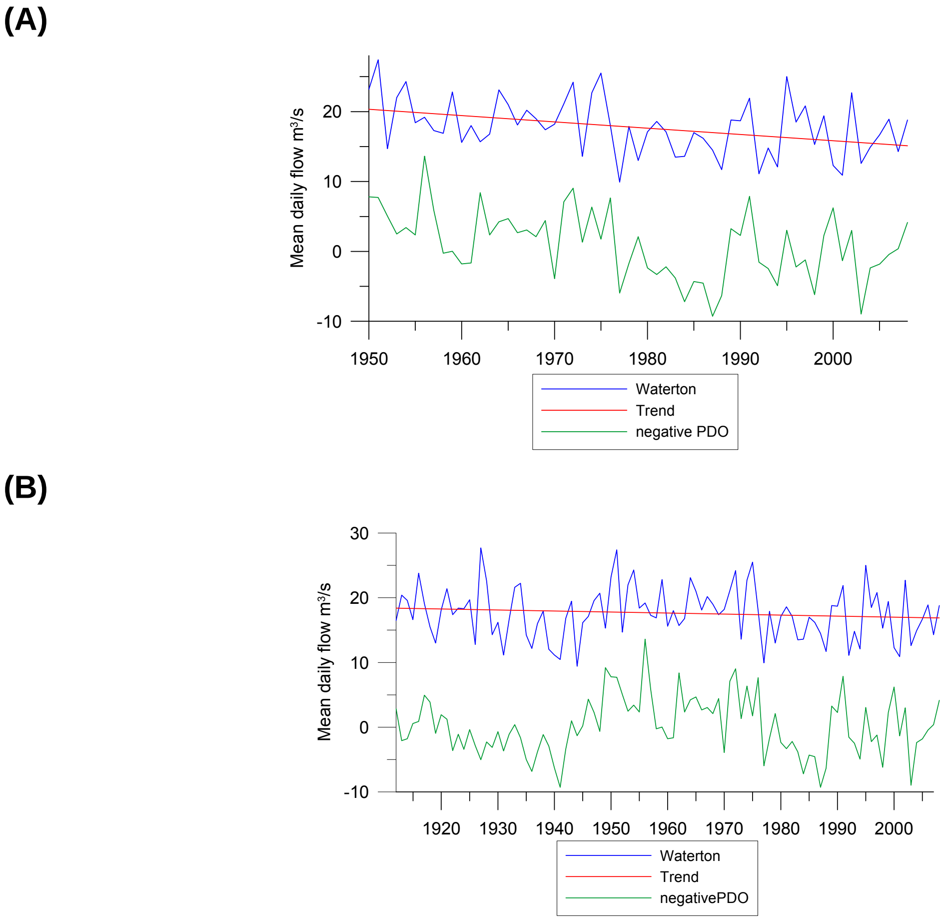

Figure 7. Mean daily flow (m^3/s; blue) for the Waterton River near Waterton, Alberta (AB05AD003) for (A) 1950-2007 and (B) 1912-2007. Shown also are ordinary least squares fitted trends (red) and in is the negative winter (Nov.-Mar.) Pacific Decadal Oscillation index (green) (scale exaggerated 5x for comparison). Waterton River void-filled data courtesy of Alberta Environment.

Statistical methodology

We analyzed the southern Alberta instrumental streamflow record, with the goal of determining if significant trends exist which could be attributable to anthropogenic global warming, while explicitly including the possible effects of the PDO and other interannual regional circulation anomalies to account for hydroclimatic variability. Low-frequency variability (i.e. slightly smoothed data) was analyzed because if a trend were absent in the smoothed data, it would be absent in the original data. Another rational for a focus on low-frequency variability was the associated severe socio-economic and ecological impacts of prolonged drought. High-frequency variability in precipitation and streamflow can be accommodated via financial insurance, reservoir storage, etc., but not low frequency variability.

We addressed the above data problems as follows: We extracted the longest daily streamflow records for southern Alberta and its near environs from the Water Survey of Canada (HYDAT) database (http://www.wsc.ec.gc.ca/). Mean daily flows were used, because annual averaging normalizes the data by the Central Limit Theorem (Wilks, 2006), which allowed the use of more powerful parametric statistics. In addition to gauge records from unregulated streams, we had a naturalized streamflow database produced by Alberta Environment. Void-filled streamflow records produced by M. Seneka (Alberta Environment) were used to infill missing data.

Generalized Least Squares (GLS) computes time series regression with serially correlated residuals. Autoregressive-moving-average (ARMA(p,q)) models were fit to the residuals using a Maximum Likelihood Estimator (MLE). Open-source software from the R statistical programming language was used (Venables and Ripley, 1999; Shumway and Stoffer, 2006). In previous studies (e.g. Rood *et al.*, 2005; Schindler and Donahue, 2006; Rood *et al.*, 2008), it was assumed that the annual mean daily streamflow time series was made up of a long-term trend component and a residual component that is assumed to be white noise. If the residuals were serially correlated, the effective sample size of the residuals was thereby overestimated (Zheng *et al.* 1997; Zheng and Basher, 1999). Some studies (e.g. Bloomfield 1992; Bloomfield and Nychka 1992; Zheng *et al.,* 1997) have used regression models with stationary and serially correlated residuals to correct this.

If there is a significant response of Alberta streamflow to any atmospheric-oceanic circulation anomaly at interannual to multi-decadal scales, and this response is not modeled, the ratio of trend signal to noise is reduced and a real trend, if present, may not be detectable. However, where the circulation influence can be represented by a linear response to some explanatory variable (e.g., the PDO), the variable can be included in the model to reduce the noise level and improve the detection of any existing trend (Zheng *et al.,* 1997; Zheng and Basher, 1999). Additionally, if the PDO is not included in the model, its influence can be mistaken for a linear trend. A linear trend and the PDO and other interannual regional circulation anomalies were included as predictors in GLS regression models and the regression coefficients were tested to determine if they were significantly different from zero. An optimum minimal subset of significant predictors and an optimum minimal ARMA(p,q) model for the residuals was chosen using the Akaike Information Criterion (AIC) goodness-of-fit statistic (Choudhury *et al.,* 1999).

In addition to the PDO, we explored the influence of the North Atlantic Oscillation (NAO) (Hurrell, 1995) and the El Nino-Southern Oscillation. The climate datasets used are the winter averaged (Nov.-Mar.) PDO, the winter averaged (Dec.-Mar.) NAO, and the annually averaged Southern Oscillation Index (SOI), obtained from Earth Systems Research Laboratory (National Oceanic and Atmospheric Administration, 2009, http://www.cdc.noaa.gov/ClimateIndices/). Since streamflow is naturally lagged and smoothed from precipitation by surface and subsurface hydrology, and large-scale climatic phenomena act most prominently at inter-annual time scales, the stream observations was lagged relative to the climate indices by 0, ±1, and +2 years, and a binomial smoother of five years was applied to both the stream and climate data.

Results

Thirteen stream gauges in southern Alberta and its environs were chosen for analysis based upon the length and completeness of their records and their natural flow regimes (Alberta Environmental Protection, 1998) (Table 1). Five of the gauges are on unregulated or slightly regulated rivers. Eight of the gauges measure regulated flows and in these cases naturalized flows compiled by Alberta Environment were used. Eleven of the gauge locations are in Alberta, one in adjacent Montana, and one nearby in British Columbia. All record periods were at least 90 years. Mean daily discharge Q ranged from 7.7 to 210.0 m^3/s and the drainage area ranged from 319.2 to 56,368.6 km^2.

The statistical model used in this study is

$$Q_t = \mu + \lambda T_t + \beta_1 x_{1,t} + \ldots + \beta_k x_{k,t} + \varepsilon_t , \qquad t = 1,\ldots, L,$$

where $\{Q_t\}$ is mean daily streamflow, index t runs over L years; μ is the mean streamflow over these years; T_t is a linear trend with coefficient λ representing the trend to be detected; $\{x_{i,t},\ t = 1,\ldots,L\}$ is the i^{th} explanatory variable; k is the number of explanatory variables; β_i is the coefficient for the i^{th} explanatory variable; and $\{\varepsilon_i\}$ is the residual time series, which is an autoregressive-moving average process of order (p,q) [ARMA(p,q)].

An optimum subset of significant predictors and an optimum ARMA(p,q) model for the residuals was chosen using the AIC goodness-of-fit statistic applied to all predictor subsets of size 6 or less and for all $p + q \leq 5$. The explanatory variables included were a linear trend, the same-year PDO, the same-year SOI and the same-year NAO, together with their ±1 and +2 year lags. The climate indices and their lags showed only minor collinearity. The non-zero significance of the trend coefficient λ was tested by the Neyman-Pearson statistic (RP) (Zheng *et al.*, 1997) using the null model of the optimum set of explanatory variables (minus the trend variable if included in the optimum set;

Table 2) versus the alternative model of the optimum set of explanatory variables together with the linear trend (if not already added). The RP is asymptotically distributed as a chi-square distribution with 1 degree of freedom. If the estimated RP is greater than the 0.05 percentile of $\chi^2(1)$, the trend is significant at the 95% level.

The results of the trend detection are shown in Table 2. The most important result is that there were no increasing linear trends in southern Alberta streamflows. There were seven significant decreasing linear trends and eight no trends. Shown as an example in Figure 8 is the naturalized mean daily flow (m^3/s) of the Oldman River near Lethbridge, together with the fitted reconstruction with ARMA(3,2) residuals, and with the fitted significantly decreasing trendline. There were no differences in detected trend between the unregulated flows (generally at headwaters) and the naturalized flows (generally at downstream gauges). There was no particular geographical pattern in the declining streamflows, except perhaps a concentration in the Bow River watershed. The second most important result is the constant occurrence of some lead or lag of the PDO in the optimum predictor set. Only one river, the Red Deer River at Red Deer, failed to include the PDO in its optimum predictor set.

The percentage of the total variability comprised by the low-pass filtered streamflow data is high, ranging between 37.8 to 51.6%, with a mean of 43.9%, which confirms that low frequency variance is an important component of the total variability in Alberta mean daily streamflow. The ARMA(3,2) model was fit most often to the residuals, although ARMA(2,q) for $q \geq 1$ and ARMA(1,3) models were also fit. Only one autoregressive ARMA(3,0) model was fit, but the moving average ARMA(0,2) model was fit 3 times. More complex residuals were needed to model hydrological data with its long persistence, than for regional and global temperature data which can be typically well-modeled using low-order autoregressive AR(1) residuals (Zheng *et al.*, 1997, Zheng and Basher, 1999). The proportion of the variability explained by the fitted GLS regression was high, with a mean $R^2 = 0.63$, ranging from 0.42 to 0.74 (omitting the Red Deer which was not well modeled at all).

According to this analysis, simply based upon the observed instrumental records, the future water availibility for southern Alberta does not look encouraging, even without including the expected increasing water demands of a growing economy and population. The PDO was shown to have a major impact on surface water availibility. Because of its influence on Alberta streamflow, the status of the PDO in a warmer world due to anthropogenic global warming is of serious interest. Newman *et al.* (2003) argue that the PDO is a reddened response to ENSO (i.e., shifted to lower frequencies), or that ENSO drives the PDO. In particular, they consider that El Nino drives the positive phase of the PDO, and La Nina drives the negative phase of the PDO. The majority of the most recent GCMs show that a greenhouse-gassed warmer world will see relatively more El Ninos (Figure 10.16, IPCC4, 2007). If the relationship posited by Newman *et al.* (2003) holds under these conditions, the PDO will be in its positive phase more often and southern Alberta will see even drier conditions.

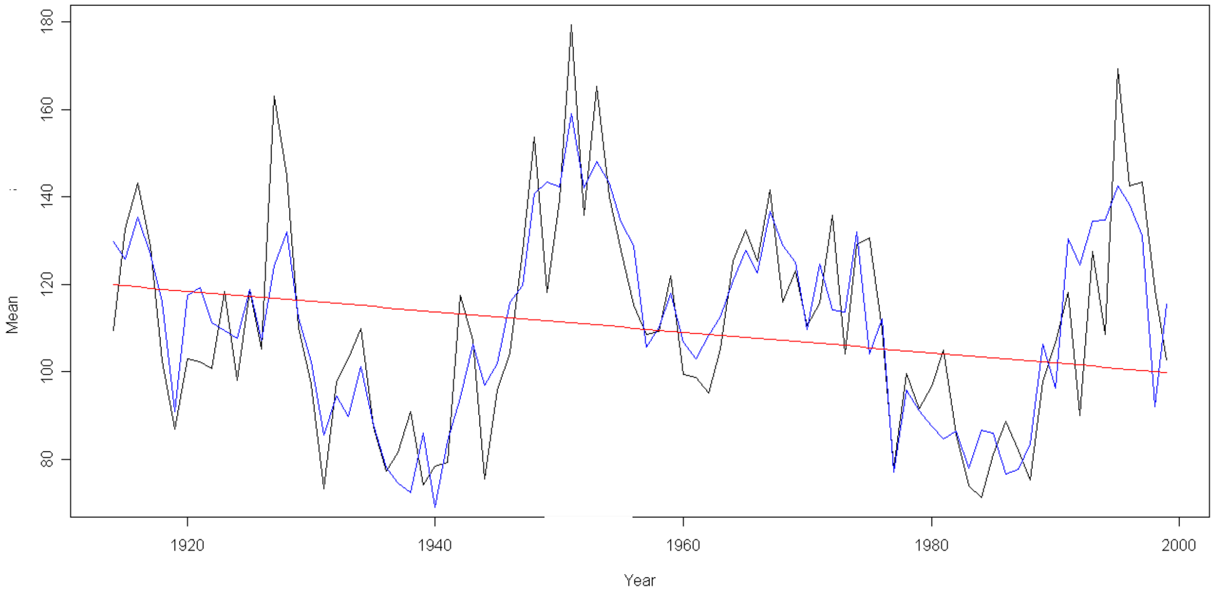

Figure 8. Oldman River near Lethbridge naturalized mean daily flow (m^3/s) (black line) (smoothed by a 5-yr binomial filter), with reconstruction with ARMA(3,2) residuals (blue line), and with fitted significantly decreasing trendline (red line) . $R^2 = 0.71$.

Table 1. Southern Alberta and environs rivers and their characteristics. For the regulated rivers, naturalized flows were used in the analysis.

River	HYDAT (USGS) code	Record period	Record length (years)	Mean daily *Q* (m^3/s)	Gross drainage (km^2)	Flow regime
Marias River near Shelby, MT	06099500	1912-2007	96	25.1	8,396.8	Free-flowing
Waterton River near Waterton Park	05AD003	1912-2008	97	18.0	612.7	Free-flowing
Bow River at Banff	05BB001	1911-2008	98	39.2	2,209.6	Free-flowing
Columbia River at Nicholson, BC	08NA002	1917-2007	91	108.0	6,660.0	Free-flowing
Red Deer River at Red Deer	05CC002	1913-2007	95	47.9	11,608.8	Free-flowing
St. Mary River at International Boundary	05AE027	1912-2001	90	20.3	1,206.4	Regulated
Belly River near Mountain View	05AD005	1912-2001	90	8.62	319.2	Regulated
Oldman River near Lethbridge	05AD007	1912-2001	90	80.6	17,045.6	Regulated

South Saskatchewan River at Medicine Hat	05AJ001	1912-2001	90	188.0	56,368.6	Regulated
Elbow River below Glenmore Dam	05BJ001	1912-2001	90	7.9	1,235.7	Regulated
Bow River at Calgary	05BH004	1912-2001	90	90.2	7,868.2	Regulated
Spray River at Banff	05BC001	1912-2001	90	7.7	750.6	Regulated
North Saskatchewan River at Edmonton	05DF001	1911-2007	97	210.0	28,096.0	Regulated

Table 2. Identification of the optimum set of trend, explanatory variables and residual models for Southern Alberta streamflow. Percent (%) variance in filtered stream data refers to what percentage the low-pass filtered streamflow data comprises of the total variability. AIC: Akaike Information Criterion. RP: Neyman-Pearson statistic. ±1, +2 year lags of climate indices included in analysis. P1: climate leads streamflow 1 year. P2: climate leads streamflow 2 years. N1: climate lags streamflow 1 year.

River	**% variance in filtered stream data**	**AIC**	**Predictors**	**Residual model**	***R^2***	**RP (*p*-level)**	**Significant trend present?**
Free-flowing rivers (at least only slightly regulated)							
Marias River near Shelby	45.3%	530.2	Trend, SOI, **PDO$_{\text{P1}}$,** NAO$_{\text{P2}}$, **PDO$_{\text{P2}}$**, SOI$_{\text{P2}}$	ARMA(2,3)	0.72	19.2 (1.2xe^{-5})	**decreasing**
Waterton River near Waterton Park	40.5%	352.7	SOI, **PDO**, SOI$_{\text{N1}}$, NAO$_{\text{P2}}$, SOI$_{\text{P2}}$, **PDO$_{\text{P2}}$**	ARMA(3,2)	0.70	0.8 (0.37)	**none**
Bow River at Banff	40.6%	446.0	Trend, **PDO, PDO$_{\text{N1}}$, PDO$_{\text{P2}}$**, SOI$_{\text{P2}}$	ARMA(0,2)	0.46	7.2 (0.007)	**decreasing**
Columbia River at Nicholson	42.8%	617.0	**PDO**, **PDO$_{\text{N1}}$**	ARMA(0,2)	0.42	0.1 (0.8)	**none**
Red Deer River at Red Deer	51.6%	670.8	Trend	ARMA(3,0)	0.07	2.0 (0.15)	**none**
Naturalized flows							
St. Mary River at International Boundary	38.9%	391.2	**PDO**, SOI, SOI$_{\text{P1}}$, NAO$_{\text{P2}}$, **PDO$_{\text{P2}}$**, SOI$_{\text{P2}}$	ARMA(2,1)	0.67	0.1 (0.8)	**none**

Belly River near Mountain View	41.8%	226.2	NAO, **PDO**, SOI, SOI$_{N1}$, NAO$_{P2}$, **PDO**$_{P2}$	ARMA(2,3)	0.67	0.2 (0.62)	**none**
Oldman River near Lethbridge	44.1%	716.8	Trend, **PDO**, NAO$_{P2}$, **PDO**$_{P2}$, SOI$_{P2}$	ARMA(3,2)	0.71	14.9 (0.0001)	**decreasing**
South Saskatchewan River at Medicine Hat	47.0%	810.9	NAO, **PDO**, **PDO**$_{N1}$, SOI$_{N1}$, NAO$_{P2}$, **PDO**$_{P2}$	ARMA(3,2)	0.74	0.4 (0.54)	**none**
Elbow River below Glenmore Dam	49.3%	320.0	Trend, **PDO**, NAO$_{N1}$, SOI$_{N1}$, SOI$_{P1}$, NAO$_{P2}$	ARMA(2,2)	0.70	23.9 (1.0xe^{-6})	**decreasing**
Bow River at Calgary	48.8%	603.4	Trend, **PDO**, NAO$_{P2}$, **PDO**$_{P2}$, SOI$_{P2}$	ARMA(0,2)	0.62	4.1 (0.04)	**decreasing**
Spray River at Banff	42.8%	255.8	Trend, NAO, **PDO**$_{P1}$, NAO$_{P2}$, **PDO**$_{P2}$, SOI$_{P2}$	ARMA(1,3)	0.65	9.6 (0.002)	**decreasing**
North Saskatchewan River at Edmonton	37.8%	859.0	Trend, NAO, **PDO**, **PDO**$_{P2}$	ARMA(3,2)	0.51	11.7 (0.0006)	**decreasing**

Conclusions

In this paper, we examine the historical and potential future variability in Alberta's hydroclimate with a focus on streamflow measured by gauges and reconstructed from moisture-sensitive tree-ring chronologies. Our analysis of these records highlights the strong interannual to multi-decadal variability that can be linked to atmospheric-oceanic circulation anomalies, and in particular the Pacific Decadal Oscillation. Quasi-periodic wet and dry cycles of varying intensity and duration can have profound effects on natural and human systems. An understanding the potential impact of climate change requires analyses of both trends and shifts in mean conditions associated with global warming and of systematic departures from mean conditions (climate variability).

In this paper we demonstrated the degree and significance of low-frequency variability in instrumental stream flow records and a tree-ring reconstruction of the flow of the North Saskatchewan River for the past five centuries. This natural hydroclimate variability underlies the impacts climate change including the modulation of hydrologic regimes. While global and regional climate models (GCMs and RCMs) are the only reliable source of projections of future climate, the most robust outputs from GCMs are trends over several decades and large (continental) regions. Further research is required to develop projections of future hydroclimate variability using outputs from climate models that best simulate the quasi-periodic cycles described in this paper. RCMs of higher resolution provide data for smaller regions and time spans and thus should more reliably simulate interannual to multi-decadal hydroclimatic variability. The spatial domain of the Canadian Regional Climate Model (CRCM) has been recently expanded to provide much more model output for western Canada. CRCM outputs and our long proxy reconstructions of the regional hydroclimate could be the source of the reliable scenarios of future hydroclimatic variability and probabilities of departures (e.g. drought) from mean conditions.

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