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Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability?

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[1] The ~60 year Pacific Decadal Oscillation (PDO) is a major factor controlling streamflow in the northern Rocky Mountains, causing dryness during its positive phase, and wetness during its negative phase. If the PDO's influence is not incorporated into a trend analysis of streamflows, it can produce detected declines that are actually artifacts of this low-frequency variability. Further difficulties arise from the short length and discontinuity of most gauge records, human impacts, and residual autocorrelation. We analyze southern Alberta and environs instrumental streamflow data, using void-filled datasets from unregulated and regulated gauges and naturalized records, and Generalized Least Squares regression to explicitly model the impacts of the PDO and other climate oscillations. We conclude that streamflows are declining at most gauges due to hydroclimatic changes (probably from global warming) and severe human impacts, which are of the same order of magnitude as the hydroclimate changes, if not greater. **Citation:** St. Jacques, J.-M., D. J. Sauchyn, and Y. Zhao (2010), Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability?, *Geophys. Res. Lett.*, *37*, L06407, doi:10.1029/2009GL042045.

1. Introduction

[2] Under anthropogenic global warming scenarios, southern Alberta, Canada, is projected to see decreased streamflow, and northern Alberta increased streamflow in the next century (see *Intergovernmental Panel on Climate Change* (*IPCC*) [2007, Figure 10.12] for multi-model mean run-off changes). Detection of any developing trends in the observed instrumental streamflow records is complicated by the fact that the Alberta hydroclimate, like that of much of northwestern North America, displays strong periodic cycles linked to the low-frequency Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997; *Stewart et al.*, 2005]. The PDO is a pattern of climate variability that shifts phases on an inter-decadal time scale, usually at about 20 to 35 years [*Minobe*, 1997; *Mantua and Hare*, 2002]. In 1890, the PDO entered into a predominately cool (negative) phase, which continued until 1925 when a warm (positive) phase began. In 1947, the PDO shifted back into a cool phase, which lasted until 1977, whereupon a warm phase began. Winter precipitation in Alberta is higher when the PDO is in a negative phase [*Mantua et al.*, 1997; *Comeau et al.*, 2009]. A strong negative relationship exists between the PDO and streamflow in south and central Alberta, while a weak positive relationship exists in northwestern Alberta (Figure 1). Therefore, south and central Alberta are wetter when the PDO is in its negative phase and drier when the PDO is positive.

[3] The ~60 year low frequency cycle of the PDO [*Minobe*, 1997] can potentially generate a declining linear trend in short instrumental streamflow records. Like much of the western North American high-density hydrological monitoring network, many Alberta instrumental streamflow records begin in the 1950s (a period of strongly negative PDO, hence high Alberta streamflow), or omit the 1930s and early 1940s (periods of high positive PDO, hence low Alberta streamflow). If the influence of the PDO (i.e., high flows 1947–1976, low flows 1977–2007) is not taken into account in an analysis of northwestern North American instrumental hydroclimatic records, declines could be detected and linked to global warming, while they are actually artifacts of the sampling period and the PDO phase changes [e.g., *Chen and Grasby*, 2009].

[4] There are additional difficulties with using the instrumental records to reach a conclusion of declining surface water supplies in the northern Rocky Mountains. These records are short, typically having periods of record of ~40–50 years in northern Alberta and ~95 years in southern Alberta. They are frequently discontinuous with gaps, especially in the 1930s (due to economic collapse) and the 1940s (due to war). Heavy human impact from water consumption, diversion and storage, especially in southern Alberta, obscures the natural hydrology. Less obvious, but very serious statistically, is the frequent autocorrelation in the fitted residuals from regression using hydrometric data, which results in the overestimation of the effective sample size [*Zheng et al.*, 1997]. Therefore, classical linear regression and Mann-Kendall non-parametric methods can disproportionately reject a null hypothesis of no trend [*Zheng et al.*, 1997; *Zhang et al.*, 2001; *Burn and Hag Elnur*, 2002; *Yue et al.*, 2002]. In this paper, we examine instrumental streamflow records from the northern Rocky Mountains for trends, while addressing these important issues.

2. Statistical Methodology

[5] We analyzed instrumental streamflow records from southern Alberta and environs to determine if significant trends existed which could be attributable to 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 given the associated severe socio-economic and ecological impacts of prolonged drought. High-frequency variability in precipitation and streamflow can be accommodated via conventional hazard

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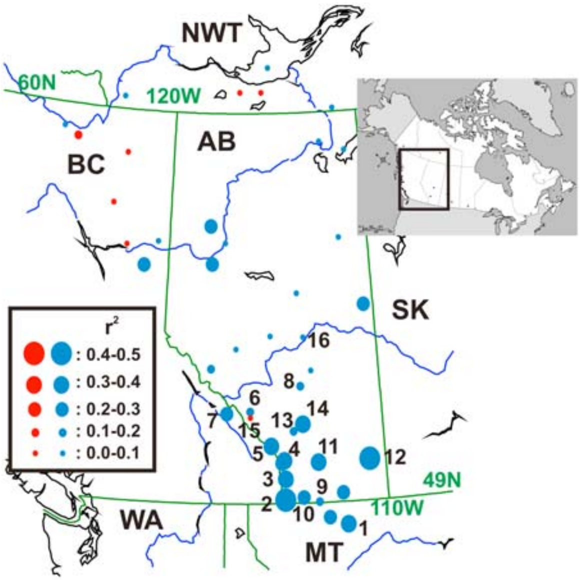

Figure 1. Pearson's correlation coefficients between Alberta and environs mean daily streamflows and the November–March Pacific Decadal Oscillation index (PDO) of the same year. Both streamflows and PDO were smoothed by a 5-year binomial filter. Gauges used were those with the longest continuous records. Dark red (light blue) circles denote positive (negative) correlation. Numbers denote the gauge locations of Table 1 (for regulated flows, the actual flow record and the naturalized record have the same gauge location).

mitigation strategies (insurance, reservoir storage, etc.), but not low frequency variability (i.e., sustained drought), which is a much more challenging climate hazard. Furthermore, if a trend were absent in the low-pass filtered data, it would be absent in the original data, as the particular filter used, a binomial smoother of five years, passes a linear trend without distortion [*Brockwell and Davis*, 2002].

[6] The above problems with streamflow data were addressed as follows: We extracted the longest and most complete streamflow records for southern Alberta and its near environs from the Water Survey of Canada (HYDAT) (http://www.wsc.ec.gc.ca/) and the National Water Information System (http://waterdata.usgs.gov/nwis/sw) databases. In addition to gauge records from unregulated streams, a streamflow database produced by Alberta Environment provided naturalized daily flows and void-filled records to overcome the effects of human impacts and gaps in the time series [*Seneka*, 2004]. Mean daily flows averaged over the year were used, because annual averaging normalizes the data by the Central Limit Theorem [*Wilks*, 2006], which allowed the use of more powerful parametric statistics. Shapiro-Wilks tests confirmed that most records were normally distributed, and that departures from normality were mild, except in two cases: the observed flows of the Spray and Red Deer Rivers.

[7] Generalized Least Squares (GLS) computes time series regression with serially correlated residuals and is therefore suitable for hydrological data [*Brockwell and Davis*, 2002]. Autoregressive-moving-average (ARMA(p,q)) models were fit to the residuals using a Maximum Likelihood Estimator. Open-source software from the R statistical programming language was used (http://www.r-project.org/).

[8] If there is a significant response of Alberta streamflow to any atmospheric-oceanic circulation anomaly at inter-annual 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 internal forcing 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]. Also, if the PDO is not included in the model, its effect on precipitation and runoff can be mistaken for a linear trend extending over several decades. We also explored the influence of the North Atlantic Oscillation (NAO), as a proxy for the short-duration Arctic Oscillation record, and the El Nino-Southern Oscillation (ENSO). The climate indices used are the winter averaged (November–March) PDO, the winter averaged (December–March) 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/). A linear trend and the PDO, NAO and SOI were included as predictors in the GLS regression models. 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 were 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. The climate indices and their lags showed only minor collinearity.

[9] Sixteen stream gauges in southern Alberta and its environs were chosen for analysis based on the length and completeness of the records and natural flow regimes [*Alberta Environmental Protection*, 1998] (Table 1, and auxiliary material Figure S1 and Table S1).[1] Eight of the gauges are on unregulated or slightly regulated river runs. Eight of the gauges measure regulated flows and in these cases, the observed actual flows and the reconstructed naturalized flows compiled by Alberta Environment were separately analyzed, providing an additional 16 records. Fourteen of the gauges are located in Alberta, one in adjacent Montana, and one nearby in British Columbia. Most records (21 out of 24) span at least 90 years.

[10] The statistical model used in this study is

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

where $\{Q_t\}$ is mean daily streamflow for year t, index t runs over L years; μ is the mean streamflow over all L of 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 $\{\varepsilon_t\}$ is the residual time series, which is an autoregressive-moving average process of order (p,q) [ARMA(p,q)]. An optimum minimal subset of significant predictors and an optimum

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL042045.

Table 1. Trends in Southern Alberta and Environs Streamflows[a]

	Actual flow record			Naturalized flow record			
Flow Record	Record period	Significant linear trend?	Change %/yr	Record period	Significant linear trend?	Change %/yr	Human impact/yr
1. Marias R. near Shelby, MT	1912–2007	**decreasing**	**−0.26**	n.a.	n.a.	n.a.	n.a.
2. Waterton R. near Waterton Park	1912–2007	none	−0.05	n.a.	n.a.	n.a.	n.a.
3. Castle R. near Beaver Mines	1945–2007	none	−0.04	n.a.	n.a.	n.a.	n.a.
4. Oldman R. near Waldron's Corner	1950–2007	**increasing**	**0.43**	n.a.	n.a.	n.a.	n.a.
5. Highwood R. at Diebel's Ranch	1952–2007	none	0.11	n.a.	n.a.	n.a.	n.a.
6. Bow R. at Banff	1911–2007	**decreasing**	**−0.12**	n.a.	n.a.	n.a.	n.a.
7. Columbia R. at Nicholson, BC	1917–2007	none	−0.001	n.a.	n.a.	n.a.	n.a.
8. Red Deer R. at Red Deer	1912–2007	**decreasing**	**−0.22**	n.a.	n.a.	n.a.	n.a.
9. St. Mary R. at International Boundary	1903–2007	**decreasing**	**−0.46**	1912–2001	none	0.006	−0.47
10. Belly R. near Mountain View	1912–2007	none	0.02	1912–2001	none	0.02	−0.002
11. Oldman R. near Lethbridge	1912–2007	**decreasing**	**−0.76**	1912–2001	**decreasing**	**−0.18**	−0.58
12. S. Saskatchewan R. at Medicine Hat	1912–2007	**decreasing**	**−0.36**	1912–2001	**increasing**	**0.05**	−0.41
13. Elbow R. below Glenmore Dam	1911–2007	**decreasing**	**−0.70**	1912–2001	**decreasing**	**−0.34**	−0.36
14. Bow R. at Calgary	1912–2007	**decreasing**	**−0.16**	1912–2001	**decreasing**	**−0.16**	−0.01
15. Spray R. at Banff	1911–2007	**decreasing**	**−2.20**	1912–2001	**decreasing**	**−0.11**	−2.09
16. N. Saskatchewan R. at Edmonton	1912–2007	**decreasing**	**−0.14**	1911–2007	**decreasing**	**−0.10**	−0.04

[a]The first eight records are from unregulated rivers, therefore only the actual flow records exist. The last eight rivers are regulated and both actual flow and naturalized flow records exist, giving a further 16 records. Change%/yr calculated as 100x trend line slope/mean daily flow averaged over record period (bold denotes significant). Human impact/yr is the difference between the Change%/yr of the actual and the corresponding naturalized flows.

minimal ARMA(p,q) residual model were chosen using the corrected Akaike Information Criterion ($\mathrm{AIC_c}$) goodness-of-fit statistic [*Brockwell and Davis*, 2002] applied to all predictor subsets of size ≤ 6, and for all $p \leq 8$ and $q \leq 5$. Simulation results by *Hurvich and Tsai* [1989] suggested that the $\mathrm{AIC_c}$ outperforms many other model selection criteria, including the AIC and the BIC, when the number of total estimated parameters is more than 10% of the sample size.

[11] 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 1) 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 one degree of freedom. If the estimated RP is greater than the 0.10 percentile of $\chi^2_{(1)}$, the trend is significant at the 90% level. To assess rates of change, trend lines were calculated based upon the fitted multiple regressions with the climate indices set to zero (i.e., $Q_t = \mu + \lambda T_t$). The rate of change per year (Change%/yr) was expressed as a percentage of the mean daily flow, averaged over the entire period of record (i.e., $100\lambda/mean(Q_t)$) [*Rood et al.*, 2005]. Human impact could be estimated as the difference between the Change%/yr of the actual and the corresponding naturalized flows.

3. Results and Discussion

[12] Surface water supplies are indeed becoming scarcer in southern Alberta even when the confounding effects of the PDO and other sources of natural variability are factored out. We found fifteen significant decreasing linear trends in the streamflow records, versus only two increasing linear trends and seven null trends (Figure 2a, Table 1 and Table S1). There were no strong differences between the eight unregulated headwater gauges with three detected declining trends, and the eight naturalized flow records (at downstream gauges), five with declining trends, although the number of available long records is limited. There was a geographical pattern, with the gauges in the Bow River watershed more likely to show declining flow.

[13] The current year PDO or a lead or lag was the explanatory variable that appeared most consistently in the optimum predictor set, with only two exceptions: the actual flows of the Elbow and Spray Rivers (Figure 2b and Table S1). The PDO's strong influence was also shown by box plots of the individual stream records divided into the four phases of the PDO over the past century: higher flows in the cold phases (1900–1924 and 1946–1976) and lower flows during the warm phases (1925–1945 and 1977–2007) (Figure S2). Because we explicitly modelled the influence of the PDO, and used longer records that include at least one full PDO cycle, we could factor out the PDO's effect and conclude that the detected declining trends in surface water supplies are due to hydroclimatic changes (probably from global warming) and/or severe human impacts, and are not merely PDO phase artifacts.

[14] The effect of human impacts was strong. More actual flow records showed declines than did their corresponding naturalized records; and declines were greater in actual flows than in naturalized flows. The declines in the naturalized and unregulated gauge records reflect only hydroclimatic changes, whereas fluctuations in the actual regulated gauge records reflect both global warming effects and direct human impacts. Hence, human impact could be estimated by the difference in annualized decline rates between the actual and naturalized flows. The human impacts were typically of the same order of magnitude as the hydroclimate changes, if not greater (Table 1), confirming concerns raised by *Schindler and Donahue* [2006]. The plots of the actual and naturalized flows of the Oldman River near Lethbridge, together with their fitted multiple linear regressions and trend lines, showed the severity of human impacts in this watershed (Figure S3).

[15] Previous seminal work, *Zhang et al.* [2001], *Rood et al.* [2005, 2008], *Schindler and Donahue* [2006] and *Chen*

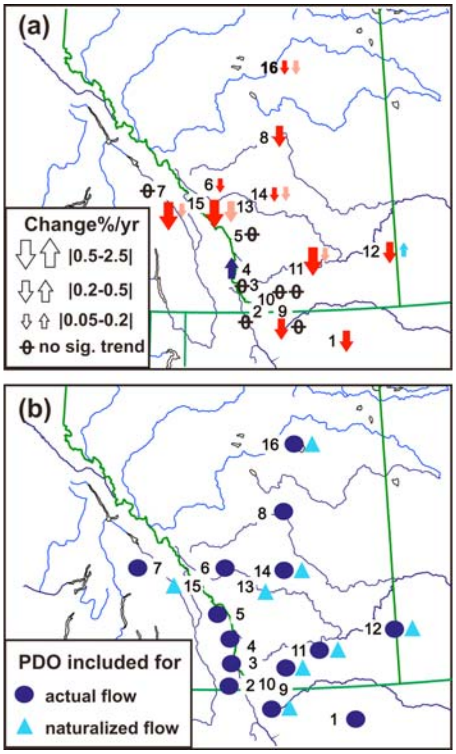

Figure 2. (a) Trends in southern Alberta mean daily streamflows. Numbers denote gauge locations named in Table 1. Red and blue arrows denote trends in actual recorded flows, pink and light blue denote trends in naturalized flows. (b) Occurrences of a PDO 0, ±1, +2 lag in the optimum subset of predictor variables. Dark blue circle (light blue triangle) denotes that the PDO was used in predicting actual (naturalized) streamflow.

and Grasby [2009], showed declining trends in southern Alberta streamflows, but did not fully address important statistical issues. *Rood et al.* [2005] noted the strong relationship between the PDO and regional streamflow, but provided no numerical method of factoring out its effect and determining if a trend remained. *Zhang et al.* [2001] and *Schindler and Donahue* [2006] did not address the issue of trend detection in the presence of the confounding effects of the PDO. Only *Zhang et al.* [2001] addressed the issue of serially correlated residuals. If the residuals are serially correlated, which is typical of streamflow data (see our observations, *Zhang et al*. [2001], and *Yue et al*. [2002]), the effective sample size of the residuals can be overestimated, causing disproportionate rejection of a no trend null hypothesis. Some climate studies [e.g., *Zheng et al.*, 1997] have used regression models with stationary and serially correlated residuals to correct this. Much current research has linked declining flow in Rocky Mountain rivers to reduced snowpack accumulation and the associated wastage of glaciers, although the latter may account for declining or augmented summer flow depending on the recent rate of glacier runoff relative to the historical contribution. Data on glacier mass balance and runoff are insufficient to determine whether the streamflow trends examined here are influenced by recent rates of glacier wastage [*Comeau et al*., 2009].

[16] The low-pass filtered streamflow data comprised a large percentage (a mean of 46.8%) of the total variability in annual flows, confirming that low-frequency variance is an important component of the hydroclimatic variability (see Table S1 for modelling details). There was no particularly favoured ARMA(p,q) model fit to the residuals, with 17 (out of 24) having relatively low complexity with $p + q \leq 5$. More complex residuals are 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 Red Deer record was not well modeled, and should be interpreted cautiously. Although there is measurement error in these southern Alberta river discharges, ice conditions of only three to four months, HYDAT's use of ice correction coefficients and frequent peak discharge measurements in this accessible region, and our time-aggregation over the year combine to keep errors relatively low [*Shiklomanov et al*., 2006].

[17] According to this analysis of instrumental streamflow records, future water availability in southern Alberta does not look encouraging, even without considering the expected increasing water demands of a growing economy and population. The PDO is shown to have a major impact on present-day surface water supplies. The PDO's regional importance is further underlined by tree-ring inferred streamflow reconstructions for the South Saskatchewan River Basin which show a PDO-like signal for the past six centuries, including prolonged 20–35 year low-flow regimes [*Axelson et al.*, 2009]. Because of its influence on Alberta streamflow, the status of the PDO in a warmer world under anthropogenic climate change is of serious interest. The majority of the most recent GCMs show that a warmer world will have relatively more El Niños [*IPCC*, 2007, Figure 10.16]. For instance, *Newman et al.* [2003] argued that the PDO is a reddened response to ENSO (i.e., shifted to lower frequencies), or that ENSO drives the PDO. In particular, they considered that El Niño (La Niña) drives the positive (negative) phase of the PDO. If their posited relationship holds under global warming conditions, the PDO will be in its positive phase more often and southern Alberta will see more frequent drier conditions. However, other researchers [e.g., *Zhang et al*., 1996, *Yu et al*., 2007] considered the PDO to be independent of ENSO, but that re-enforcing interactions could occur between the two oscillations. *Yu et al.* [2007] found that there occurred an enhanced response of the Pacific-North American mode when the PDO and ENSO were in the same phase; that is, when the PDO was in a positive phase and an El Niño occurred, southern Alberta experienced even warmer conditions, and presumably more evapotranspiration, than normal in a positive PDO. Hence, in this case, under global warming conditions, southern Alberta will see more severe drier conditions. Thus, regardless of the exact relationship between the PDO and ENSO, the change to a more El Niño-dominated world is expected to have major impacts (probably decreases) on southern Alberta river flow, given its strong connection to the PDO.

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