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

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Abstract

Recent research on the detection of climate change trends in the northern Rocky Mountains has concluded that the region is running out of water due to global warming. Reaching such a conclusion from the analysis of instrumental streamflow records is problematic, given the short length and discontinuity of most gauge records, human impacts, and residual autocorrelation. Furthermore, the ~65 year Pacific Decadal Oscillation (PDO) is a major factor controlling streamflow in south-central Alberta and environs, causing dryness during its positive phase, and wetness during its negative phase. If the PDO's influence is not incorporated into an analysis, it can produce detected declines that are actually artifacts of this low-frequency variability. We analyze south-central Alberta and environs instrumental streamflow data, using a void-filled and naturalized streamflow dataset, 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.

Index terms: 1833 Hydroclimatology, 1860 Streamflow, 1872 Climate impacts, 1834 Human impacts, 1872 Time series analysis.

Key words: Alberta, Canada; anthropogenic global warming; human impacts; Pacific Decadal Oscillation (PDO); streamflow trends.

Introduction

Under anthropogenic global warming (AGW) scenarios, southern Alberta, Canada, is projected to see decreased streamflow, and northern Alberta increased streamflow in the next century [Figure 10.12, IPCC 4]. Because of global climate models' (GCMs) moderate resolution, 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 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 the northern Rocky Mountains.

There are many problems with using the instrumental streamflow records simplistically to reach a conclusion of declining surface water supplies. These records are short, typically having periods of record of ~40-50 years in northern Alberta and ~95 years in southern Alberta. These records are frequently discontinuous with gaps, especially in the 1930s (due to economic collapse) and the 1940s (due to war). There 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 will 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]. Lastly, there is heavy human impact from water consumption, diversion and storage, especially in southern Alberta, which overlays and obscures the natural hydrology.

The above problems are frequently encountered in any study of instrumental streamflow variability. However, in addition, the hydroclimate of Alberta displays strong periodic cycles and is linked to 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 35 years [*Mantua et al.,* 1997; *Mantua and Hare*, 2002]. In 1905, the PDO entered into a predominately warm phase, which continued until 1946 when a predominately cool phase began. In 1977, the PDO shifted back into a warm phase. 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 (Fig 1). Therefore, south and central Alberta are drier when the PDO is in its positive phase and wetter when the PDO is negative.

The ~65 year low frequency cycle of the PDO can potentially generate a declining linear trend in short instrumental streamflow records. 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 artefacts of the sampling period and the PDO phase changes [e.g., *Chen and Grasby*, 2009].

Statistical methodology

We analyzed the southern Alberta instrumental streamflow record to determine if significant trends exist which could be attributable to AGW, 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 of the associated severe socio-economic and ecological impacts of prolonged drought. High-frequency variability in precipitation and streamflow can be accommodated via conventional hazard 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. A trend is indistinguishable from an oscillation with wavelength greater than twice the period of record.

The above problems with streamflow data are 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. 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. 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.

Generalized Least Squares (GLS), used in econometric forecasting, computes time series regression with serially correlated residuals [*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/).

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]. Also, if the PDO is not included in the model, its influence can be mistaken for a linear trend extending over several decades. We also explored the influence of the North Atlantic Oscillation (NAO) [*Hurrell*, 1995], as a proxy for the short-duration Arctic Oscillation record, and the El Nino-Southern Oscillation. The climate indices 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/). 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.

Sixteen stream gauges in southern Alberta and its environs were chosen for analysis based on the length and completeness of their records and their natural flow regimes [*Alberta*

Environmental Protection, 1998] (Table 1, and Supplemental Fig. 1 and Table 1). Eight of the gauges are on unregulated or slightly regulated river runs. Eight of the gauges measure regulated flows and in these cases, both the observed actual flows and the reconstructed naturalized flows compiled by Alberta Environment were separately analyzed, providing an additional 16 records. Fourteen of the gauge locations are in Alberta, one in adjacent Montana, and one nearby in British Columbia. Most records (21 out of 24) span at least 90 years.

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 $\{\varepsilon_t\}$ 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 minimal ARMA(p,q) residual model was chosen using the corrected Akaike Information Criterion (AICc) 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 AICc 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.

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 1 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 the rates of change, trend lines were calculated based upon the fitted multiple regressions with the climate indices set to zero. The change per year is expressed as a percentage of the smoothed mean daily flow, averaged over the entire period of record, for those records with a significant linear trend term [*Rood et al.*, 2005].

Results and discussion

As suggested by previous studies of streamflow trends [*Rood et al.*, 2005; *Schindler and Donahue*, 2006; *Rood et al.*, 2008], surface water supplies are indeed becoming scarcer in southern Alberta. Unlike previous studies, however, our modeling of streamflow trends also accounted for interannual to interdecadal variability, autocorrelated residuals and human impacts on water levels. We found fifteen significant decreasing linear trends in the streamflow records, versus only two increasing linear trends and seven null trends (Table 1). There were no strong differences between the eight unregulated headwater gauges with three detected declining trends, and the eight naturalized flow records (generally at downstream gauges), five with declining trends, but the numbers of available long records are limited. There was a geographical pattern, with the gauges in the Bow River watershed more likely to show declining flow. The effect of human impacts was strong. More actual flow records showed declines than their corresponding naturalized records; and actual flow declines were greater than naturalized flow declines (except for the Belly River, where neither record showed a significant trend). The actual flow declines were at least twice that of the naturalized flow declines at the St. Mary, Oldman near Lethbridge, South Saskatchewan, Elbow and Spray gauges. The plots of the actual and naturalized flows of the Oldman River near Lethbridge, together with their fitted multiple linear regressions and trend lines, show the severity of human impacts, primarily water storage and diversion for irrigation, in this watershed (Fig. 2).

The current year PDO or a lead or lag, is 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 (Table 1). The PDO's strong influence is also shown by box plots of the individual stream records divided into the three phases of the PDO over the past century: lower flows during the early warm phase (1905-1945), higher flows in the cold phase (1946-1976) and lower flows again during the last warm phase (1977-2007) (Supplemental Fig. 2). Because we explicitly modelled the influence of the PDO, and used longer records that include at least one full PDO cycle, we can factor out the PDO's effect and conclude that the detected declining surface water supplies are due to hydroclimatic changes (probably from AGW) and severe human impacts. The human impacts are of the same order of magnitude as the hydroclimate changes, if not greater.

Rood et al. [2005], *Schindler and Donahue* [2006] and *Chen and Grasby* [2009] showed declining trends in southern Alberta streamflows, but did not address the issue of serially correlated residuals. If the residuals were serially correlated, which is typical of streamflow data [our observations; *Zhang et al*., 2001; *Yue et al*., 2002], the effective sample size of the residuals will be overestimated, causing disproportionate rejection of the 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. *Rood et al.* [2005] noted the strong relationship between the PDO and regional streamflow, but provided no method of including the PDO in their models, and thereby no method of factoring out its effect and determining if a trend remained. Much current research has linked declining flow in Rocky Mountain rivers to reduced snowpack accumulation and the associated wastage of glaciers, although the later 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].

The low-pass filtered streamflow data comprise a large percentage (a mean of 46.8%) of the total variability, confirming that low-frequency variance is an important component of the hydroclimatic variability. There was no particularly favoured ARMA(p,q) model fit to the residuals, with 15 (out of 24) having relatively low complexity with $p + q \leq 5$. 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 Red Deer record was not well modeled, and should be interpreted cautiously.

We used ARMA processes, rather than the more general ARIMA processes [*Brockwell and Davis*, 2002]. If $\{Q_t\}$ is modelled with ARMA residuals, but really has ARIMA residuals, then erroneous trends may be found [*Woodward and Grey*, 1993]. If a process actually is ARIMA($p,1,q$) and an ARMA($p+1, q$) model is fitted to the series, its characteristic autoregressive equation is likely to have a near-unit root x (i.e., $| x - 1 | < 0.2$) [*Zheng et al*., 1997; *Brockwell and Davis*, 2002]. We therefore examined the characteristic autoregressive roots of our fitted models. Only the actual Spray River at Banff record had a near unit root, which suggests that an ARIMA($p,1,q$) residual model might be better. All other records had no near-unit autoregressive roots, which suggested that ARMA residuals are appropriate.

According to this analysis of instrumental streamflow records, the future of water availibility for 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. Tree-ring inferred streamflow reconstructions for the South Saskatchewan basin show a PDO-like signal for the past six centuries, including prolonged 20-35 year low-flow regimes, further underlining the PDO’s regional importance [*Axelson et al.*, *in press*]. Because of its influence on Alberta streamflow, the status of the PDO in a warmer world due to AGW 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 Niño (La Niña) drives the positive (negative) phase of the PDO. The majority of the most recent GCMs show that a greenhouse-gassed warmer world will see relatively more El Niños [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.

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References

Alberta Environmental Protection (1998), South Saskatchewan River basin historical weekly natural flows 1912 to 1995. Technical Report Alberta Environment.

Axelson, J., D. J. Sauchyn and J. Barichivich (*in press*), New reconstructions of streamflow variability in the South Saskatchewan River basin from a network of tree-ring chronologies, Alberta, Canada, *Water Resour. Res.*

Brockwell, P.J. and R.A. Davis (2002), *Introduction to time series and forcasting*, 2nd *ed*., Springer-Verlag, New York.

Burn, D.H., and M.A. Hag Elnur (2002), Detection of hydrologic trends and variability, *J. Hydrol.,* 255, 107-122.

Chen, Z. and S.E. Grasby (2009), Impact of decadal and century-scale oscillations on hydroclimate trend analyses, *J. Hydrol.,* 365, 122-133.

Comeau, L.E.L., A. Pietroniro and M.N. Demuth (2009), Glacier contribution to the North and South Saskatchewan Rivers, *Hydro. Proc.,* 23, 2640-2653.

Hurrell, J.W. (1995), Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation, *Science,* 269, 676-679.

Hurvich, C.M. and C.L. Tsai (1989), Regression and time series model selection in small samples, *Biometrika,* 76, 297-307.

IPCC4 (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.)], Cambridge Univ. Press, Cambridge, UK.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Amer. Meteorol. Soc.,* 78, 1069-1079.

Mantua, N. J., and S.R. Hare (2002), The Pacific Decadal Oscillation, *J. Oceanogr.,* 58, 35-44.

Newman, M., G.P. Compo, and M.A. Alexander (2003), ENSO-forced variability of the Pacific Decadal Oscillation, *J. Clim.,* 16, 3853-3857.

Rood, S.B., G.M. Samuelson, J.K. Weber, and K.A. Wywrot (2005), Twentieth-century decline in streamflows from the hydrographic apex of North America, *J. Hydrol.,* 306, 215-233.

Rood, S.B., J. Pan, K. M. Gill, C. G. Franks, G. M. Samuelson, and A. Shepherd (2008), Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests, *J. Hydrol.,* 349, 397-410.

Schindler, D.W., and W. F. Donahue (2006), An impending water crisis in Canada's western prairie provinces, *PNAS,* 103, 7210-7216.

Seneka, M. (2004), *Trends in historical annual flows for major rivers in Alberta*, Technical Report Alberta Environment, http://environment.gov.ab.ca/info/library/6792.pdf

Wilks, D.S. (2006), *Statistical Methods in the Atmospheric Sciences, 2nd ed.*, Academic Press, New York.

Woodward, W.A. and H.L. Gray (1993), Global warming and the problem of testing for trend in time series data, *J. Clim.,* 6, 953-962.

Yue, S., P. Pilon, B. Phinney, and G. Cavadias (2002), The influence of autocorrelation on the ability to detect trend in hydrological series, *Hydro. Proc.,* 16, 1807-1829.

Zhang, X., K.D. Harvey, W.D. Hogg, and T.R. Yuzyk (2001), Trends in Canadian streamflow, *Water Resour. Res.,* 37, 987-998.

Zheng, X., R.E. Basher, and C.S. Thompson (1997), Trend detection in regional-mean temperature series: maximum, minimum, mean, diurnal range, and SST, *J. Clim.,* 10, 317-326.

Zheng, X., and R.E. Basher (1999), Structural time series models and trend detection in global and regional temperature series, *J. Clim.,* 12, 2347-2358.

Figure captions

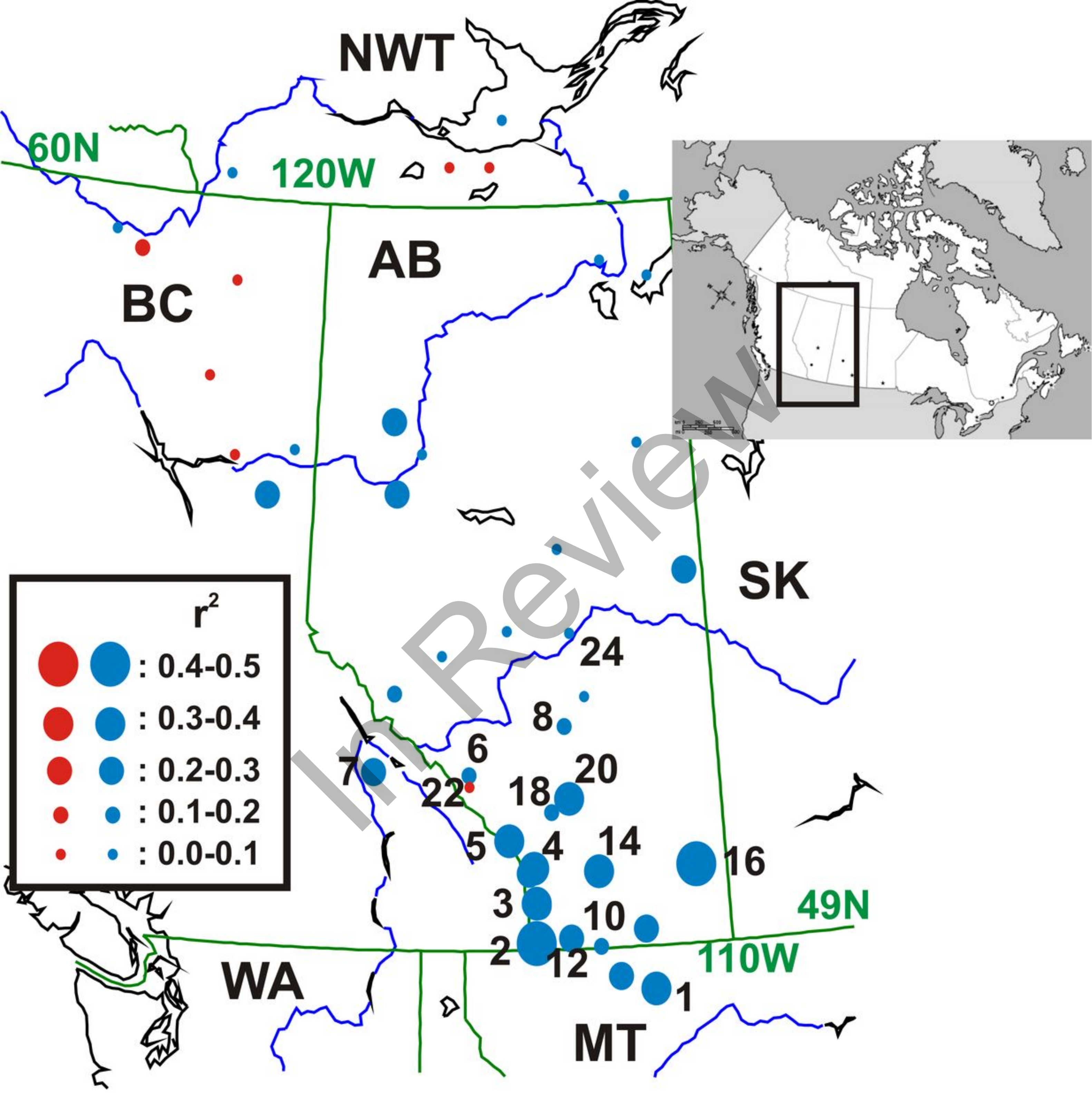
Figure 1. Pearson's correlation coefficients between Alberta and environs mean daily streamflows and the November-March Pacific Decadal Oscillation index (PDO) of the same year. Both streamflows and PDO were smoothed by a 5-year binomial filter. Streamflows used were the longest continuous flows from gauges with the longest 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).

Figure 2. (a) Naturalized and **(b)** actual flows of the Oldman River near Lethbridge, smoothed by 5-point binomial filters (black lines), together with fitted multiple linear GLS regressions (blue) and trend lines (red) **(c)** inverted Pacific Decadal Oscillation index (PDO) smoothed by a 5-point binomial filter. Data source: http://www.cdc.noaa.gov/data/climateindices/list/.

Table 1. Identification of the optimum set of trend, explanatory variables and residual models for Southern Alberta streamflow. AICc: corrected Akaike Information Criterion. 0, ±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. RP: Neyman-Pearson statistic (results significant at the 10% level in bold). Change%/yr calculated as 100x trend line slope/ smoothed mean daily flow averaged over record period.

Flow Record	Record period	AICc	Predictors	Residual model	RP (*p*-level)	Significant linear trend?	Change% /yr
Free-flowing rivers (at least only slightly regulated)							
1. Marias R. near Shelby, MT	1912-2007	534.8	trend, SOI, **PDO$_{P1}$**, NAO$_{P2}$,**PDO$_{P2}$**, SOI$_{P2}$	ARMA(2,3)	**19.2 (1.2e^{-5})**	**decreasing**	-0.26
2. Waterton R. near Waterton Park	1912-2007	360.6	**PDO**, SOI, SOI$_{N1}$, NAO$_{P2}$, **PDO$_{P2}$**, SOI$_{P2}$	ARMA(3,2)	0.7 (0.40)	none	n.a.
3. Castle R. near Beaver Mines	1945-2007	221.2	NAO, **PDO**, SOI$_{N1}$, SOI$_{P2}$	ARMA(2,5)	0.26 (0.61)	none	n.a.
4. Oldman R. near Waldron's Corner	1950-2007	228.9	trend, **PDO**, **PDO$_{P2}$**, SOI$_{P2}$	ARMA(2,2)	**17.2 (3.4e^{-5})**	**increasing**	0.43
5. Highwood R. at Diebel's Ranch	1952-2007	197.9	**PDO**, SOI$_{N1}$	ARMA(2,1)	1.1 (0.29)	none	n.a.
6. Bow R. at Banff	1911-2007	447.6	trend, **PDO**, SOI$_{P2}$	ARMA(0,2)	**6.7 (0.01)**	**decreasing**	-0.12
7. Columbia R. at Nicholson	1917-2007	616.7	**PDO**, **PDO$_{N1}$**, NAO$_{P1}$	ARMA(4,2)	0 (1.0)	none	n.a.
8. Red Deer R. at Red Deer	1912-2007	678.7	trend, NAO, **PDO**, **PDO$_{N1}$**, NAO$_{P1}$,NAO$_{P2}$	ARMA(2,4)	**18.7 (1.5e^{-5})**	**decreasing**	-0.22
Regulated flows							
9. Naturalized St. Mary R. at International Boundary	1912-2001	394.7	**PDO**, SOI, SOI$_{P1}$, NAO$_{P2}$, **PDO$_{P2}$**, SOI$_{P2}$	ARMA(2,1)	0 (1.0)	none	n.a.
10. Actual St. Mary R. at International Boundary	1903-2007	496.5	trend, NAO, **PDO**, NAO$_{P2}$, **PDO$_{P2}$**, SOI$_{P2}$	ARMA(2,1)	**11.6 (0.0007)**	**decreasing**	-0.46
11. Naturalized Belly R. near Mountain View	1912-2001	222.4	**PDO**, SOI$_{N1}$, NAO$_{P2}$, **PDO$_{P2}$**, SOI$_{P2}$	ARMA(0,1)	0.14 (0.71)	none	n.a.
12. Actual Belly R. near	1912-	244.4	NAO, **PDO**, SOI, SOI$_{N1}$,	ARMA(2,3)	0.64	none	n.a.

Mountain View	2007		NAO_{P2}, **PDO_{P2}**		(0.42)		
13. Naturalized Oldman R. near Lethbridge	1912-2001	720.8	trend, **PDO**, NAO_{N1}, NAO_{P2}, **PDO_{P2}**, SOI_{P2}	ARMA(9,2)	**31.1 $(2.4e^{-8})$**	**decreasing**	-0.24
14. Actual Oldman R. near Lethbridge	1912-2007	777.4	trend, **PDO**, NAO_{N1}, NAO_{P2}, **PDO_{P2}**, SOI_{P2}	ARMA(7,5)	**44.9 $(2.0e^{-11})$**	**decreasing**	-0.76
15. Naturalized S. Saskatchewan R. at Medicine Hat	1912-2001	800.8	trend, **PDO**, **PDO_{N1}**, SOI_{N1}, NAO_{P1}, NAO_{P2}	ARMA(6,4)	**23.9 $(1.0e^{-6})$**	**increasing**	0.05
16. Actual South Saskatchewan R. at Medicine Hat	1912-2007	897.0	trend, **PDO**, NAO_{N1}, **PDO_{N1}**, SOI_{N1}, NAO_{P2}	ARMA(6,2)	**43.2 $(4.9e^{-11})$**	**decreasing**	-0.36
17. Naturalized Elbow R. below Glenmore Dam	1912-2001	323.2	trend, NAO, **PDO**, SOI, NAO_{N1}, **PDO_{N1}**	ARMA(6,2)	**37.5 $(9.0e^{-10})$**	**decreasing**	-0.35
18. Actual Elbow R. below Glenmore Dam	1911-2007	368.6	trend, SOI_{P2}	ARMA(1,0)	**3.7 (0.06)**	**decreasing**	-0.70
19. Naturalized Bow R. at Calgary	1912-2001	602.4	trend, **PDO**, **PDO_{P2}**, SOI_{P2}	ARMA(1,0)	**3.1 (0.08)**	**decreasing**	-0.16
20. Actual Bow R. at Calgary	1912-2007	645.2	trend, **PDO**, **PDO_{P2}**, SOI_{P2}	ARMA(1,0)	**3.4 (0.07)**	**decreasing**	-0.16
21. Naturalized Spray R. at Banff	1912-2001	259.6	trend, **PDO_{P1}**, NAO_{P2},**PDO_{P2}**, SOI_{P2}	ARMA(1,3)	**7.5 (0.006)**	**decreasing**	-0.11
22. Actual Spray R. at Banff	1911-2007	300.6	trend, SOI, SOI_{P2}	ARMA(1,0)	**8.0 (0.005)**	**decreasing**	-2.20
23. Naturalized N. Saskatchewan R. at Edmonton	1911-2007	861.2	trend, **PDO**	ARMA(4,3)	**8.7 (0.003)**	**decreasing**	-0.10
24. Actual North Saskatchewan R. at Edmonton	1912-2007	849.3	trend, NAO, **PDO**, **PDO_{P2}**	ARMA(3,2)	**15.4 $(8.9e^{-5})$**	**decreasing**	-0.14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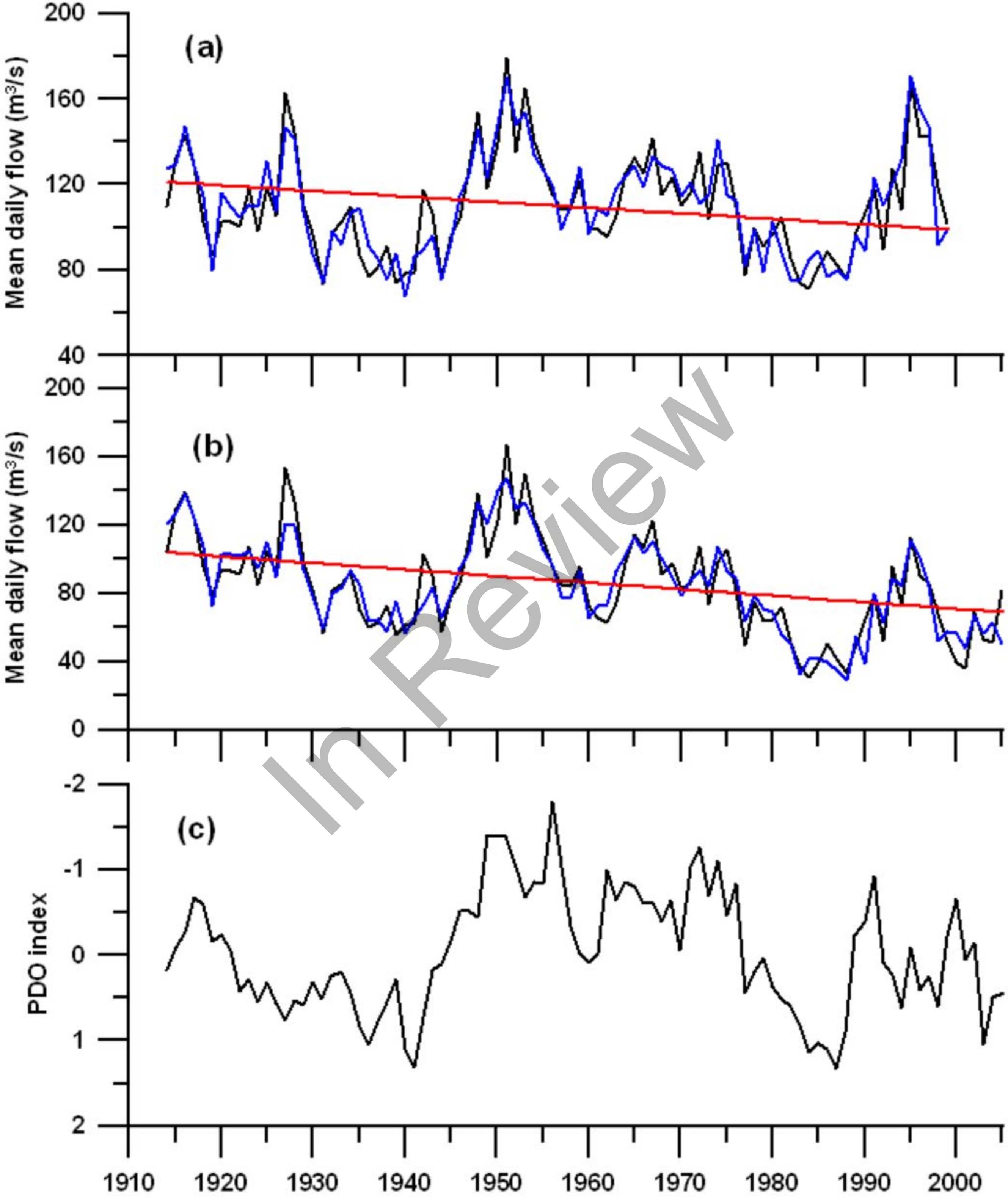
(a)
Mean daily flow (m3/s)
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(b)
Mean daily flow (m3/s)
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PDO index
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