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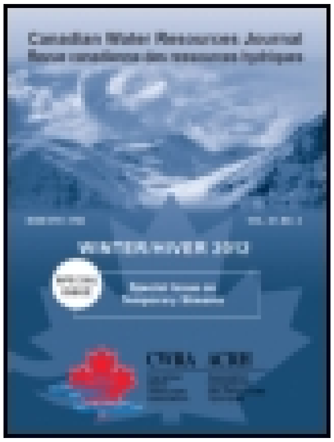

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Detection and attribution of variability and trends in streamflow records from the Canadian Prairie Provinces

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Emerging period of record trends and low frequency (i.e. centennial-scale) variability were examined in streamflow records over the entire Canadian Prairie Provinces. The average record length was 52 years, with the longest record spanning 1911–2010. A modified Mann-Kendall trend analysis showed decreasing flows in Alberta and in southwestern Saskatchewan, no significant trends in the central Prairies and increased flows in Manitoba. Using composite analysis, this study also detected the impacts of the Pacific Decadal Oscillation (PDO), the North Pacific Index (NPI), the El Niño-Southern Oscillation (ENSO) and the Pacific North American mode (PNA) on mean daily discharge. There are increased flows during the negative phases of the PDO and PNA, La Niña events and weak Aleutian lows, and decreased flows during the positive phases of the PDO, El Niño and strong Aleutian lows. A much weaker effect of the Arctic Oscillation (AO) was detected. The ~60-year cycle of the PDO has important implications for the recognition of emerging trends in streamflow in response to global climate change. Separation of an emerging consistent trend from the confounding transient trend from PDO phase was greatly facilitated by streamflow time series that span at least one and a half PDO cycles.

Les tendances émergentes de la période de relevé et la variabilité de fréquence basse, ou de l'échelle centenaire, ont été examiné dans les dossiers de débits de l'intégralité des provinces des Prairies canadiennes. La longueur d'enregistrement moyenne était de 52 ans, avec le plus long enregistrement s'étendant de 1911 à 2010. Une analyse Mann-Kendall modifiée des tendances des débits des Prairies a montré la diminution des flux en Alberta et dans le sud-ouest de la Saskatchewan, aucune tendance significative dans le centre des Prairies et des flux accrus au Manitoba. En utilisant une analyse composite, cette étude a aussi détecté les impacts de l'oscillation décennale du Pacifique (ODP), de l'Index Pacifique Nord (NPI), du phénomène El Niño-oscillation australe (ENSO) et du mode Pacifique-nord-américain (PNA) sur le débit quotidien moyen des ruisseaux et rivières des provinces des Prairies canadiennes. Il y a des débits plus importants pendant les phases négatives de l'ODP et du PNA, la Niña et les faiblesses de la dépression des Aléoutiennes, et une diminution des flux durant les phases positives de l'ODP, El Niño et de forces de la dépression des Aléoutiennes. Un effet beaucoup plus faible de l'oscillation arctique (OA) a été détecté. En raison du cycle de 60 ans de l'ODP, il y a des implications importantes pour la reconnaissance des tendances émergentes dans les débits en réponse au changement climatique mondial. La séparation de tendance constante émergente de la tendance passagère de l'effet de confusion de la phase de l'ODP a été grandement facilitée par les séries chronologiques des débits qui s'étendent sur plus d'un cycle et demi de l'ODP.

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Introduction

Surface water supplies in the semi-arid Canadian Prairie Provinces, Canada's major agricultural region, are important economically and their continued availability under global warming is of serious concern to stakeholders (Rood et al. 2005; Schindler and Donahue 2006; Rood et al. 2008; St. Jacques et al. 2010). However, any analysis of emergent trends in regional streamflows is hampered by the short length of continuous records (typically being 35–50 years), with a few exceptions in southern Alberta (Rood et al. 2005; Water Survey of Canada 2011). There are heavy human impacts from water consumption, diversion and storage, which obscure the natural hydrology. On the Prairies, there are no naturally-flowing medium or large rivers; all have been heavily modified. Although emerging trends in and large-scale forcings of the hydrology of British Columbia and southern Alberta have been well studied recently (e.g. Stewart et al. 2005; Gobena and Gan, 2006, 2009; Fleming et al. 2007; St. Jacques et al. 2010), streamflow trends in the Canadian Prairie Provinces as a whole have been examined much less comprehensively (although see Gan 1998; Zhang et al. 2001; Woo and Thorne 2003; Burn et al. 2008).

Any regional trend analysis must also take into account the natural forcings of the hydroclimate. The

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hydroclimate of Canada's western interior is heavily influenced by recurring large-scale climate patterns, i.e. the Pacific Decadal Oscillation (PDO), the Pacific North American mode (PNA), the North Pacific Index (NPI), the El Niño-Southern Oscillation (ENSO) and the Arctic Oscillation (AO) (Wallace and Gutzler 1981; Trenberth and Hurrell 1994; Mantua et al. 1997; Shabbar et al. 1997). Much of western North America displays strong periodic hydroclimate cycles linked to the low-frequency PDO, an integrated or rectified measure of the North Pacific atmosphere-ocean system (Mantua et al. 1997; McCabe and Dettinger 2002; Stewart et al. 2005; St. Jacques et al. 2010). The PDO is a pattern of North Pacific Ocean variability that shifts phases on an inter-decadal time scale, usually about 20 to 35 years (Minobe 1997, 1999). Winter precipitation in the northern Rocky Mountains is higher when the PDO is in a negative phase (approximately 1890–1924 and 1947–1976), and lower when the PDO is in a positive phase (approximately 1925–1946 and 1977–2007) (Mantua et al. 1997; Comeau et al. 2009; Wise 2010). Hence, a strong negative relationship exists between the PDO and precipitation and streamflow throughout Alberta, British Columbia and Montana. The PNA is a prominent mode of low-frequency atmospheric variability in the Northern Hemisphere extratropics (Wallace and Gutzler 1981). The PNA pattern is associated with strong fluctuations in the strength and location of the East Asian jet stream. The positive phase of the PNA pattern is associated with above-average temperatures over western Canada and lower-than-average precipitation anomalies in the Gulf of Alaska, extending into the Pacific Northwest. The NPI is a measure of the intensity of the Aleutian Low, which is a possible driving mechanism of the PDO (Trenberth and Hurrell 1994; Lapp et al. 2012). When the NPI is high (low), the intensity of the Aleutian Low is weak (strong), a state consistent with the negative (positive) phase of the PDO. The tropical Pacific ENSO also affects the hydroclimatology of this region as precipitation and streamflow are decreased during El Niño events and increased during La Niña events (Shabbar and Khandekar 1996; Shabbar et al. 1997; Bonsal and Lawford 1999; Bonsal et al. 2001; Shabbar and Skinner 2004; Bonsal and Shabbar 2008). The AO is a measure of the intensity of the polar vortex and is closely related to, if not the same as, the North Atlantic Oscillation (NAO) (Wallace and Gutzler 1981). A negative relationship exists between winter precipitation in the central Prairie Provinces and the AO, as the positive AO (and NAO) allows more frequent outbreaks of cold, dry Arctic air to this region (Bonsal and Shabbar 2008).

The purpose of this study is to examine the emerging period of record trends and low frequency or centennial-scale variability in streamflow records over the entire Prairie Provinces, including as many records as possible from the little-studied east and north. To meet this objective, the longest, most complete naturally-flowing mean daily streamflow records with the broadest geographical coverage were examined for trends, using a Mann-Kendall trend test adjusted for the problem of autocorrelation according to Yue and Wang (2004). However, the detection of lower-frequency variability can be confounded by the presence of higher-frequency variability. Therefore, this study also examined prairie streamflow records for the impacts of the higher-frequency climate oscillations of the PDO, PNA, NPI, ENSO and AO by means of composite analysis with permutation *t*-tests. In particular, if impacts of the PDO are present, they can have a confounding effect on emerging long-term trend detection because of the PDO's 50–60 year quasi-periodicity (Minobe 1997, 1999), which is the same length as many of the longer streamflow records in the region. Any trends were then interpreted using the composite analysis results in order to distinguish emerging consistent trends from the confounding transient trend of the low-frequency PDO cycle of approximately a half-century.

Datasets and methods

Hydroclimatic datasets

The streamflow records were extracted from the Water Survey of Canada (HYDAT) 2011 database, augmented with unpublished data supplied by the Saskatchewan Watershed Authority, Alberta Environment and Manitoba Hydro (Figure 1, Table 1). The two longest, most continuous naturally flowing streamflow records in each drainage sub-basin were selected, thus attempting geographical coverage across the Prairies. This was not always possible due to lack of gauges, particularly in the north. In total, 86 naturally flowing stream discharge records were analyzed by trend and composite analysis: 37 from Alberta and environs (including Pine River, BC and Hay River, NWT), 27 from Saskatchewan, and 22 from Manitoba; most were from active gauges (Table 1, Figure 1). Mean daily flow was averaged over 1 January 1–30 December or 1 March–30 October (the gauges on the smaller Prairie streams do not record in winter as there is no flowing water due to freezing). The "calendar year" will be used to refer to these annualizations. This is equivalent to analyzing total annual discharge. Because the climate oscillations' effects are most pronounced upon winter snowpack, and since October–December streamflow is more related to the current calendar year's conditions than to the subsequent winter snowpack, streamflow was analyzed according to the calendar year. However, water year (1 October–30 September) was also analyzed. The

Figure 1. The 86 naturally flowing streamflow records (squares) from the Canadian Prairie Provinces used in this study (Lambert equal area projection).

average record length was 52 years, but the distribution is skewed with a few long records (the longest spanned 1911–2010) and many relatively short ones (Figure 2a). The full period of whatever records were available was analyzed because this study was focused on the detection of long-term trends in the presence of high natural variability. The continuous streamflow records restricted to 1972–2010 and 1962–2010 were also analyzed. In the dry and heavily human-modified landscape of the southern Prairies, most naturally flowing streams are relatively small, with correspondingly small watersheds (Table 1, the left-hand side of Figure 2b). In the relatively unpopulated northern half of the provinces, the naturally flowing rivers are large (Table 1, the right-hand side of Figure 2b).

The monthly PDO time series of sea surface temperature (SST) residuals (Mantua et al. 1997) was obtained from the Joint Institute for the Study of the Atmosphere and Ocean (2011). The 500 hPa height-based December–February PNA was obtained from the Earth Systems Research Laboratory (2011). The November–March averaged NPI index of sea level pressures (SLP) was obtained from Hurrell (2011). The SLP-based monthly Southern Oscillation Index (SOI) of Ropelewski and Jones (1987), i.e. the normalized difference between monthly mean SLP at Tahiti, French Polynesia, and Darwin, Australia, was used for an ENSO metric. The SOI was also obtained from the Earth Systems Research Laboratory. The SLP-based December–March averaged AO index, also called the Northern Annular Mode (NAM), was also obtained from James Hurrell. All climate time series began by 1901, except for the PNA, which commenced by 1950 (Figure 3).

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Table 1. Eighty-six naturally flowing river discharge records from the Prairie Provinces, including Water Survey of Canada (WSC) station codes.

Station name	WSC code	Station name	WSC code
Sage Creek at Q Ranch	11AA026	Notukeu Creek above Admiral Res.	05JB004
Waterton River near Waterton Park	05AD003	Swift Current Creek, below Rock Creek	05HD036
Rolph Creek near Kimball	05AE005	Bridge Creek at Gull Lake	05HA015
Manyberries Creek	05AF010	Cottonwood Creek near Lumsden	05JF011
Pincher Creek at Pincher Creek	05AA004	Stony Creek near Kamsack	05MD010
Prairie Blood Coulee	05AD035	Opuntia Lake West Inflow	05GC007
Trout Creek near Granum	05AB005	Maloneck Creek near Pelly	05LE011
Blood Indian Creek near the mouth	05CK001	Quill Creek near Quill Lake	05MA020
Jumpingpound Creek	05BH009	Lilian River near Lady Lake	05MC003
Bow River at Banff	05BB001	Red Deer River near Erwood	05LC001
Rosebud River	05CE006	Overflowing River near Hudson Bay	05LD003
Mistaya River	05DA007	Sturgeon River near Prince Albert	05GF002
Threehills Creek	05CE018	Shell Brook near Shellbrook	05GF001
Prairie Creek	05DB002	Carrot River near Smoky Burn	05KC001
Bigknife Creek near Gadsby	05FC002	Beaver River near Dorintosh	06AD001
Buffalo Creek at Highway 41	05FE002	Churchill River above Otter Rapids	06CD002
Athabasca River at Hinton	07AD002	Haultain River above Norbert River	06BD001
McLeod River above Embarras	07AF002	Gelkie River below Wheeler River	06DA004
Pembina River	07BB002	Waterfound River below Theriau Lake	07LB002
Waskatenau Creek	05EC002	MacFarlane River at Outlet Davy Lake	07MB001
Beaver River at Cold Lake Reserve	06AD006	Fond du Lac River **	07LE001¸07LE002
Athabasca River at Athabasca	07BE001	Mowbray Creek near Mowbray	05OB021
Little Smoky River near Guy	07GH002	Antler River near Melita	05NF002
Saddle River near Woking	07FD006	Graham Creek near Melita	05NF008
Smoky River at Watino	07GJ001	Shannon Creek near Morris	05OF014
Pine River at East Pine, BC	07FB001	S. Tobacco Creek near Miami	05OF017
Heart River near Nampa	07HA003	Whitemouth River	05PH003
Clearwater River at Draper	07CD001	Brokenhead River near Beausejour	05SA002
Athabasca River below McMurray	07DA001	Little Saskatchewan River	05MF001
Notikewin River	07HC001	Pelican Creek S. Tributary	05LL027
Birch River below Alice Creek	07KE001	Shell River near Inglis	05MD005
Richardson River near the mouth	07DD002	Icelandic River near Riverton	05SC002
Boyer River near Ft.Vermilion	07JF002	Ochre River at Ochre River	05LJ005
Ponton River above Boyer River	07JF003	Fisher River near Dallas	05SD003
Sousa Creek near High Level	07OA001	Waterhen River near Waterhen	05LH005
Chinchaga River	07OC001	Pigeon River at Outlet of Round Lake	05RD008
Hay River near Hay River	07OB001	Overflowing River at Overflowing R.	05LD001
Rock Creek below Horse Creek	11AE009	Island Lake River	04AC007
Poplar River at Intern. Bd.	11AE008	God’s River below Allan Rapids	04AC005
Long Creek at W. Crossing*	05NA003	Grass River above Standing Stone Falls	05TD001
Lyons Creek at International Boundary	11AB075	Kettle River near Gillam	05UF004
Lightning Creek near Carnduff	05NF006	Little Beaver River near the mouth	06FB002
Antler River near Wauchope	05NF010	Seal River below Great Is.	06GD001

*Slightly regulated;
**Two nearby gauge records merged by drainage area ratio.

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Trend analysis

Trends in annual mean daily flow (m^3s^{-1}) for the 86 naturally flowing flow Prairie streamflows over their individual periods of record were assessed by the non-parametric Mann-Kendall (MK) statistical test. The MK test needs data to be serially independent (Kulkarni and von Storch 1995), a condition often not met with hydrological data. To remove the effect of serial correlation on the MK test, the variance correction (VC) approach of Yue and Wang (2004) was used, as recommended by Khaliq et al. (2009). Significance levels of $p \leq 0.05$ and $0.05 < p \leq 0.10$ were used in trend detection.

Because of the possibility of random significant results from either modified MK trend tests or permutation *t*-tests at multiple streamflow gauges across the Canadian Prairies, the field significance, *P*, of obtaining a given fraction of significance results, *f*, at the $\alpha = 0.10$ significance level was tested against a binomial distribution (Livezey and Chen 1983; Wilks 2006; Luce and Holden 2009), where

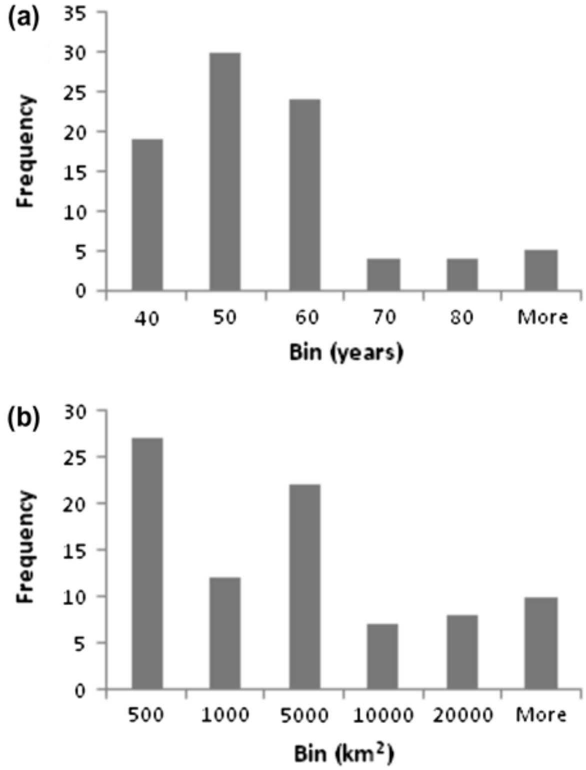

Figure 2. (a) Histogram of the 86 Canadian Prairie Provinces' naturally flowing streamflow record lengths (years) from Table 1. (b) Histogram of the drainage areas (km^2) of the 86 naturally flowing streams. The *x*-axis numbers list the potentially largest number in that bin.

$$P = 1 - \sum_{i=0}^{\lfloor n_{ef} f \rfloor} (\lfloor n_{ef} \rfloor_i) \alpha^i (1-\alpha)^{\lfloor n_{ef} f \rfloor - i} \quad (1)$$

Although $n = 86$ gauges were analyzed, the effective sample size represented by n_{ef} will be lower because streamflow across a geographical area is spatially correlated. Following Bretherton et al. (1999), n_{ef}, the effective number of gauges, was estimated to be the number of leading principal components necessary to explain 86% of the variance in the streamflow matrix.

Statistical analysis of the relationship between streamflow and climate indices

The relationships between streamflow and the climate oscillations were examined by composite analysis. For each climate oscillation and for each Prairie stream, mean daily discharges were composited into two classes corresponding to the strong positive versus strong negative climate oscillation events. The differences in average discharge between the two classes were then assessed by a permutation *t*-test (10,000 iterations) (Manly 2007) using Matlab©. The one-tailed significance was assessed

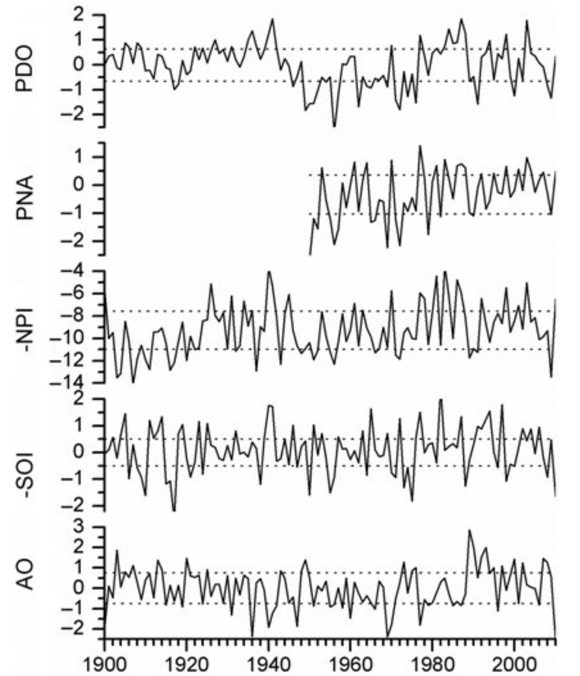

Figure 3. Plots of the November–March Pacific Decadal Oscillation (PDO), December–February Pacific North American mode (PNA), negative November–March North Pacific Index (NPI), negative June–November Southern Oscillation Index (SOI) and December–March Arctic Oscillation (AO) for 1900–2010. The dotted lines mark the strong positive and strong negative climate oscillation events (see Table 2).

at the 5 and 10% levels. One-tailed *t*-tests can be justified from prior knowledge as there are known relationships between the climate oscillations and precipitation for the region (Mantua et al. 1997; Wallace and Gutzler 1981; Trenberth and Hurrell 1994; Shabbar et al. 1997). It is assumed that for any given watershed, when winter precipitation is heavier over the watershed (as known in the literature and verified by the correlation plots between the climate oscillations and winter precipitation in Figure 4), that subsequent year streamflow should also be higher, and vice versa for less winter precipitation and lower flow. Correlation plots were constructed between the climate oscillations and the 0.5 by 0.5° gridded (1950–2005) precipitation data from the Canadian Forest Service Climate Dataset (McKenney et al. 2006) (Figure 4). For example, when a strong negative correlation exists between winter precipitation falling on a watershed and the PDO, a one-sided *t*-test can be used between streamflow magnitude at a gauge in that watershed and the PDO, testing whether flow is indeed higher during negative PDO years and lower during positive PDO years, in order to detect the impact of the PDO on streamflow. For each river and each climate oscillation, a watershed map was compared to the

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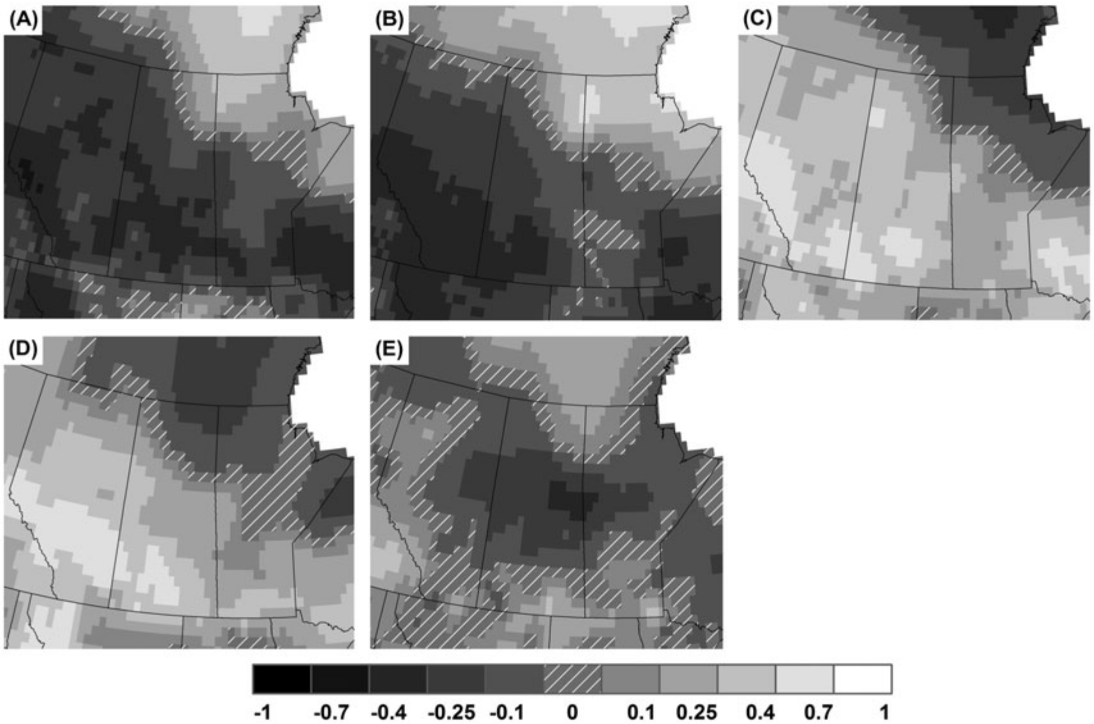

Figure 4. (a) Correlation plot between same year winter (November–March) mean Pacific Decadal Oscillation (PDO) and concurrent precipitation for 1950–2005. (b) Correlation plot between same year winter (December–February) mean Pacific North American mode (PNA) and concurrent precipitation. (c) Correlation plot between same year winter (November–March) mean North Pacific Index (NPI) and concurrent precipitation. (d) Correlation plot between June–November mean Southern Ocean Index (SOI) and following year winter (December–March) precipitation. (e) Correlation plot between same year winter (December–March) mean Arctic Oscillation (AO) and concurrent precipitation.

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correlation plot between the climate oscillation and precipitation (Figure 4) to determine which one-sided test should be used.

The composite analyses required identifying individual strong positive and negative climate oscillation events. Strong positive (negative) PDO events are defined as those years in which the winter-averaged (November–March) PDO was greater or equal (less than or equal to) to 0.75 standard deviations from its mean (Table 2). Strong PNA, NPI and AO events are defined analogously using the December–February PNA, November–March NPI and December–March AO (Table 2). The definitions of the PDO, NPA, NPI and AO were followed according to the initial literature (Trenberth and Hurrell 1994; Mantua et al. 1997; Wallace and Gutzler 1981; Hurrell 2011). The 0.75 standard deviation threshold was chosen in order to have at least four strong oscillation events in each phase during the shortest record period. However, the same analysis was also performed using 1.0, 0.9, 0.8 and 0.5 standard deviations and using all years when the climate oscillation was negative, versus all years when it was positive, in order to determine how stable the effects (if any) were. The winter values of the PDO, PNA, NPI and AO are used because the oscillations are strongest in winter, and their downstream teleconnections are strongly correlated to Prairie winter precipitation (Figures 4a,b,c,d). Winter snowfall is the source of most of the water flowing in the local rivers (Pham et al. 2009). Even if the season of analysis started in November or December, it was assigned to the year corresponding to the following January, i.e. a strong negative PDO event during November and December 2007, and continuing January through March 2008, was assigned the year 2008, and similarly for the PNA, NPI and AO.

Strong El Niño events were defined as when the averaged June–November SOI < –0.5, and a La Niña event was when the averaged June–November SOI > 0.5 (Table 2), following Redmond and Koch (1991) who examined how to detect the lagged impact of ENSO on Pacific Northwest winter hydroclimatology. They found better correlations between the SOI and winter climate when the SOI leads by a few months, as the teleconnection between the tropical Pacific Ocean and the downstream Pacific Northwest operates at a multi-monthly lag. Hence, the leading SOI (June–November) event was compared to the following year's streamflow, as it is the winter after an El Niño/La Niña event that is drier/wetter on the Prairies (Figure 4d) (Shabbar et al. 1997; Bonsal and Shabbar 2008, their Figure 2).

Table 2. Classification of years into strong positive and negative climate oscillation events for the Pacific Decadal Oscillation (PDO), Pacific North American mode (PNA), North Pacific Index (NPI), Southern Oscillation Index (SOI) and Arctic Oscillation (AO).

Climate oscillation	Phase	Strong event years
PDO	positive	1905, 1906, 1908, 1909, 1922, 1924, 1927, 1931, 1935, 1936, 1937, 1940, 1941, 1942, 1970, 1977, 1981, 1983-1988, 1994, 1998, 2003
	negative	1917, 1918, 1946, 1949, 1950, 1951, 1952, 1954, 1956, 1957, 1962, 1964, 1965, 1969, 1971, 1972, 1974, 1976, 1991, 2000, 2008, 2009
PNA	positive	1953, 1961, 1964, 1970, 1977, 1981, 1983, 1986, 1987, 1988, 1992, 1995, 1998, 2001, 2003, 2004, 2007, 2010
	negative	1950, 1951, 1952, 1955, 1956, 1957, 1965, 1966, 1969, 1971, 1972, 1979, 1982, 1990, 2009
NPI	low	1900, 1926, 1931, 1934, 1936, 1940, 1941, 1945, 1961, 1963, 1970, 1977, 1978, 1981, 1983, 1984, 1986, 1987, 1992, 1998, 2001, 2003, 2010
	high	1903, 1904, 1907, 1908, 1910, 1911, 1916, 1917, 1920, 1922, 1932, 1937, 1943, 1948, 1951, 1952, 1955, 1956, 1966, 1971, 1972, 1989, 1991, 2009
SOI	negative El Niño	1902, 1904, 1905, 1911, 1912, 1913, 1914, 1918, 1919, 1923, 1925, 1932, 1939, 1940, 1941, 1944, 1946, 1951, 1953, 1957, 1963, 1965, 1969, 1972, 1976, 1977, 1982, 1987, 1991, 1992, 1993, 1994, 1997, 2002, 2004, 2006, 2009
	positive La Niña	1906, 1908, 1909, 1910, 1915, 1916, 1917, 1921, 1924, 1938, 1945, 1947, 1950, 1955, 1956, 1964, 1970, 1971, 1973, 1974, 1975, 1988, 1996, 1998, 2000, 2008
AO	positive	1903,1905, 1907, 1913, 1914, 1920, 1925, 1943, 1948, 1949, 1973, 1975, 1976, 1989, 1990, 1992, 1993, 1995, 1997, 2000, 2002, 2007, 2008
	negative	1900, 1915, 1919, 1931, 1936, 1940, 1941, 1942, 1947, 1951, 1955, 1956, 1958, 1960, 1966, 1969, 1970, 1977, 1979, 1985, 1987, 1996, 2006, 2010

Because the PDO has a large effect on winter prairie precipitation and the subsequent year's streamflow (e.g. Mantua et al. 1997; St. Jacques et al. 2010; Whitfield et al. 2010), the effect of PDO phase on the probability of two successive years of low or high flows of Prairie streamflow was further examined. This analysis required long continuous mean daily flow (annualized) records that spanned at least one PDO cycle, i.e. included 1946–2007. There were nine such records in the initial streamflow compilation (Table 3). Thirteen records from regulated gauges with long continuous records were added to improve the numbers and geographical coverage (Table 3, Figure 5). An additional reason for focusing on the probability of two years of extreme flow is because reservoir storage in the Saskatchewan River basin is estimated to be two years in case of drought (pers. comm. Michael Seneka, Alberta Environment and Sustainable Development). For each gauge, the mean daily flow magnitudes were ranked into quartiles. The numbers of two successive years of least quartile streamflows were tallied and examined according to PDO phase. The PDO was in its positive phase for 1925–1946 and 1977–2007, and in its negative phase for 1890–1924 and 1947–1976. The probability of two successive years of least quartile flow in a given PDO phase is estimated by the number of these events divided by the total number of two successive years with streamflow data occurring in that phase. The probability of two successive years of highest quartile flow in a given PDO phase is estimated similarly. A paired permutation *t*-test was used to determine the significance of the mean Prairie-wide difference between the probability of two successive years of least quartile flow in a given river during the positive PDO phase versus the probability of two successive years of least quartile flow in the same river during the negative PDO phase (Manly 2007). Likewise, a paired permutation *t*-test was used to determine the significance of the mean Prairie-wide difference between the probability of two successive years of highest quartile flow in a given river during the positive PDO phase versus the probability of two successive years of highest quartile flow in the same river during the negative PDO phase. The exactRankTests package in the R programming language was used for the paired permutation *t*-tests (R Development Core Team 2008).

Results

Streamflow trend analysis

The modified MK trend tests demonstrate a distinct geographical pattern with significant declines in the west and significant increases in the east, using the calendar year streamflow records over their entire period of record (Figure 6a). There are 12 declining trends (nine significant at the $p \leq 0.05$ level) throughout Alberta (34% of the gauges), which extend into western Saskatchewan as three further declining trends (two significant at the $p \leq 0.05$ level). On the other hand, there are three significant increasing trends (two significant at the $p \leq 0.05$ level) in southern Manitoba, and one increasing trend ($p \leq 0.05$) at Seal River and one decreasing trend ($p \leq 0.10$) at Gods River, both in northern Manitoba.

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Table 3. Empirical probabilities of two successive years of least quartile and highest quartile flows composited according to the Pacific Decadal Oscillation (PDO) phase for the long Prairie records. The Water Survey of Canada (WSC) codes are given for the added regulated flow records.

	2 successive yrs least 1/4 flow in +PDO phase	2 successive yrs least 1/4 flow in –PDO phase	2 successive yrs highest 1/4 flow in +PDO phase	2 successive yrs highest 1/4 flow in –PDO phase
Bow R. at Banff	0.115	0.000	0.078	0.071
Highwood R. [05BL019]	0.194	0.000	0.033	0.042
Oldman R. at Waldron's [05AA023]	0.167	0.000	0.033	0.077
Castle R. [05AA022]	0.097	0.034	0.000	0.138
Elbow R. [05BJ001]	0.176	0.048	0.059	0.190
Bow R. at Calgary [05BH004]	0.176	0.024	0.039	0.195
Waterton R. near Waterton	0.118	0.000	0.039	0.122
Red Deer R. [05CC002]	0.098	0.122	0.039	0.171
Belly R. [05AD005]	0.098	0.000	0.039	0.122
N. Saskatchewan R. at Edmonton [05DF001]	0.118	0.024	0.078	0.122
St. Mary R. [05AE027]	0.157	0.020	0.020	0.160
Athabasca R. at Athabasca	0.136	0.000	0.091	0.075
Rolph Creek	0.200	0.000	0.050	0.138
Oldman R. at Lethbridge [05AD007]	0.196	0.000	0.020	0.146
S. Saskatchewan R. [05AJ001]	0.196	0.000	0.020	0.171
Sage Creek	0.122	0.000	0.049	0.034
Lyons Creek	0.061	0.034	0.102	0.000
N. Saskatchewan R. at Prince Albert [05GG001]	0.137	0.049	0.039	0.122
Poplar Creek	0.111	0.000	0.044	0.172
Long Creek	0.078	0.024	0.059	0.098
Saskatchewan R. at the Pas [05KJ001]	0.137	0.025	0.059	0.175
Antler R. near Melita	0.091	0.069	0.030	0.276
Mean	0.135	0.022	0.046	0.128

R., river.

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Four principal components were needed to explain 86% of the variance in the streamflow records; hence, $n_{ef} = 4$. The binomial test (Equation 1) showed a lack of field significance over all the 86 records for $\alpha = 0.10$. The results from the same analysis using the water year records are almost identical.

The results from the analyses restricted to those streamflows with continuous records for 1972–2010 and 1962–2010 are comparable to those from the full period, for both the calendar and water year records. The restrictions curtailed the number and geographic coverage of the analyses as only 65 (rather than 86) streams had continuous records for 1972–2010, and only 36 streams had continuous records for 1962–2010, very few of which are located in Saskatchewan and Manitoba (Table 1, Figure 6b). For the 1972–2010 calendar year streamflow records, seven of the 31 Alberta gauges show a decline (34%), as does one southwestern Saskatchewan gauge (full results not shown). Five of the southern Manitoba gauges show an increase, as does one southeastern Saskatchewan gauge on the Manitoba border. For the 1962–2010 calendar year streamflow records, 10 of the 17 Alberta gauges show a decline (59%), as does one southwestern Saskatchewan gauge (Figure 6b). Two of the 11 southern Manitoba gauges show an increase (Figure 6b). The results from the analyses using the 1972–2010 and 1962–2010 water year records are almost identical (full results not shown). The Bow, Little Smoky, Smoky, Athabasca below Fort McMurray, Notikewin Rivers and Rock Creek show significant declines and Mowbray Creek shows a significant increase for all time periods examined: the full period of record, 1962–2010 and 1972–2010, and for both the calendar year and water year records.

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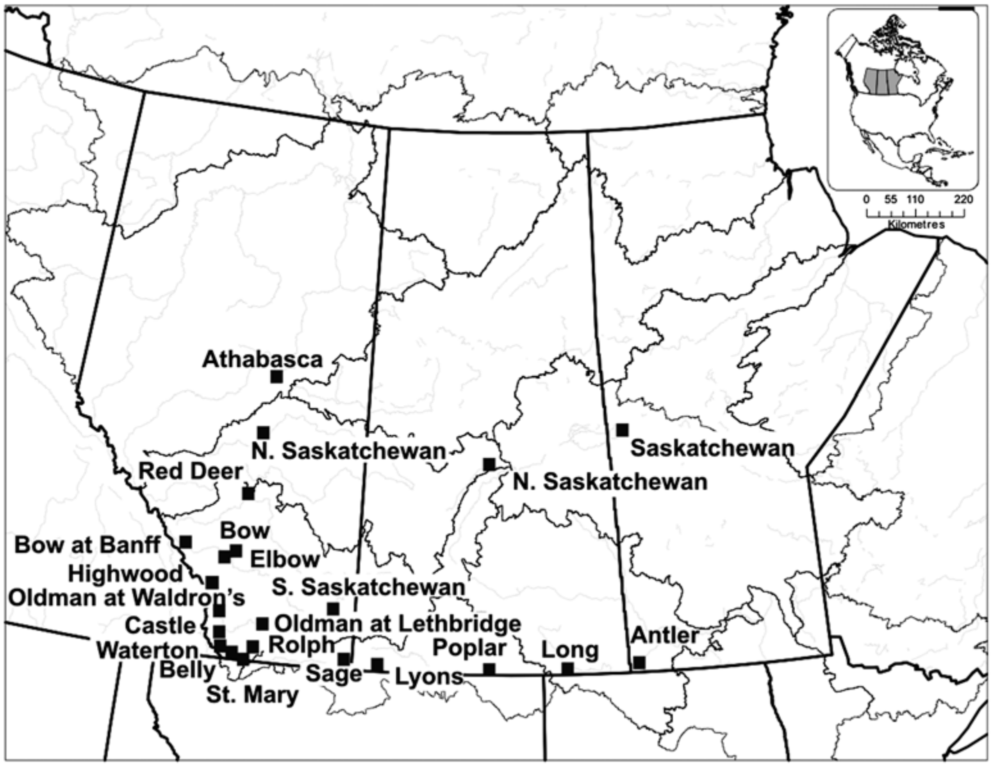

Figure 5. The nine naturally flowing and 11 regulated long continuous streamflow records used in the analysis of the effect of the Pacific Decadal Oscillation (PDO) on the probability of two successive years of low or high flows.

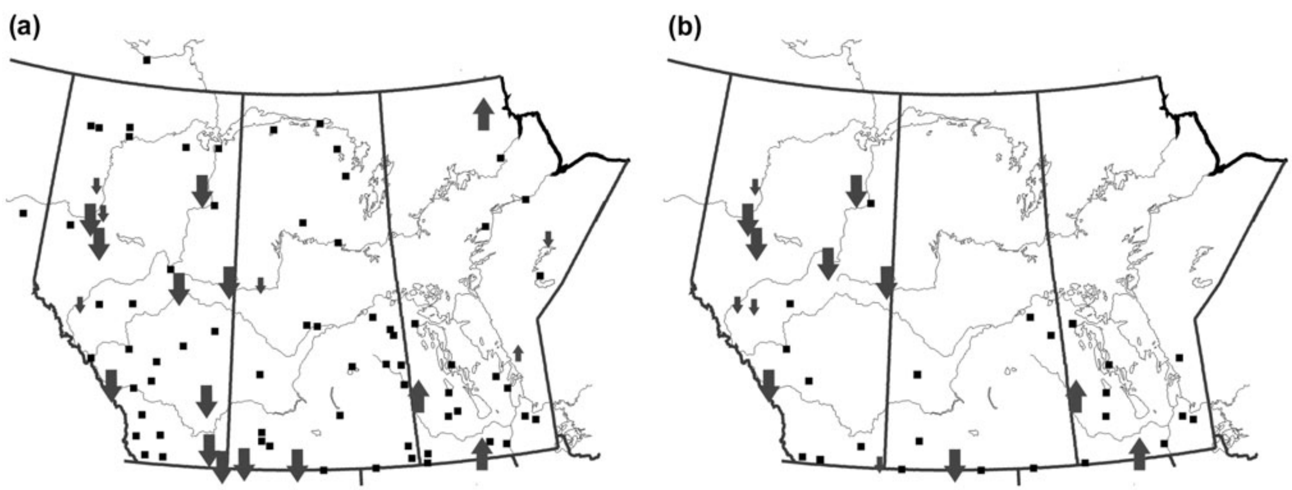

Figure 6. Geographic pattern of trends in 86 naturally flowing mean daily streamflow records, annualized over January–December from the Canadian Prairie Provinces as assessed by a modified Mann-Kendall test. A down (up) arrow denotes a decreasing (increasing) trend. A large arrow denotes significance at the $p \leq 0.05$ level, a small arrow denotes significance at the $0.05 < p \leq 0.1$ level and a square denotes no trend. (a) Full variable period of record analyzed. (b) 1962–2010 analyzed.

Correlation between streamflow and climate indices

The strong impacts of the extra-tropical oceanic PDO and the extra-tropical atmospheric PNA are shown on the calendar year mean daily discharge of naturally flowing Prairie streams with 49% and 40% of the gauges respectively having a significant permutation *t*-test ($p \leq 0.10$) (Figure 7a and 7b). There are negative relationships between the PDO and the PNA and streamflow throughout the Prairies, i.e. more discharge during negative PDO and PNA years, and decreased flow during

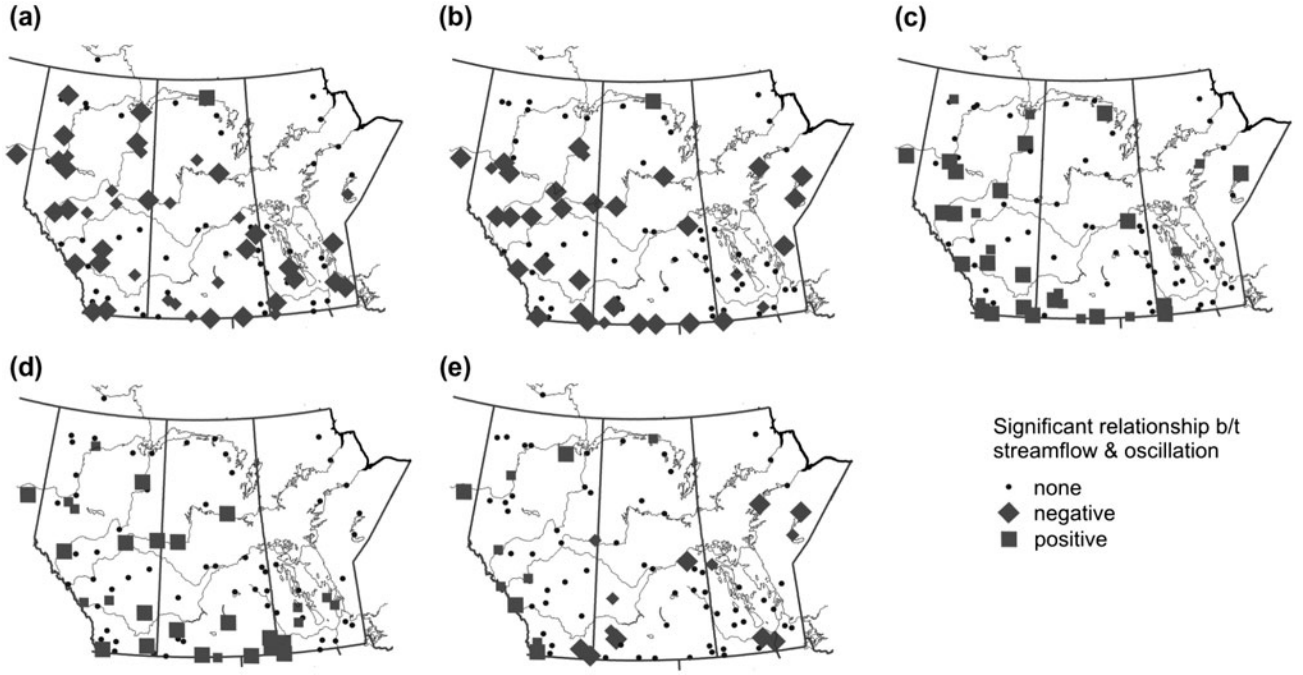

Figure 7. (a) Impacts of the Pacific Decadal Oscillation (PDO) on the 86 Prairie naturally flowing mean daily discharges. (b) Impacts of the Pacific North American mode (PNA) on the mean daily discharges. (c) Impacts of the North Pacific Index (NPI) on the mean daily discharges. (d) Impacts of the Southern Ocean Index (SOI) on the mean daily discharges. (e) Impacts of the Arctic Oscillation (AO) on the mean daily discharges. All assessed by permutation *t*-tests: a large symbol denotes significance at the $p \leq 0.05$ level; a small symbol denotes significance at the $0.05 < p \leq 0.1$ level.

positive PDO and PNA years, except for the far north where the relationship becomes weaker. The impact is clearest in Alberta (57% and 49% respectively of the gauges are significant), next clearest in Saskatchewan (48% and 33%), and weakest in Manitoba (36% and 32%). For the PDO, $f = 0.49$, and the binomial distribution (Equation 1) specifies a field significance of $p < 0.05$. Therefore, the PDO's effect is real. As well, the effect of the PNA has a field significance of $p = 0.05$, and hence the PNA's effect is also real.

The impacts of the extra-tropical atmospheric NPI and the tropical atmospheric SOI are also shown on the calendar year mean daily discharge of naturally flowing Prairie streams, with 37% and 34% respectively of the gauges having a significant permutation *t*-test ($p \leq 0.10$) (Figure 7c and 7d). There is a positive relationship between the NPI and the SOI and streamflow throughout the Prairie Provinces, i.e. more discharge during high NPI and La Niña years, and decreased flow during low NPI and El Niño years. Again, the impact is clearest in Alberta (51% and 37% respectively of the gauges), then in Saskatchewan (30% and 37%), and weakest in Manitoba (23% and 27%). Both the effects of the NPI and the SOI have a field significance of $p = 0.05$, and therefore, their effects are real.

The weaker impact of the polar atmospheric AO is shown on the calendar year mean daily discharge of naturally flowing Prairie streams, with only 27% of the gauges having a significant permutation *t*-test ($p \leq 0.10$) (Figure 7e). The pattern in the precipitation correlation plot is different from those of the other Pacific-based climate oscillations, with negative correlations in the central Prairies and positive correlations in the southern Rocky Mountains of Alberta, southern Saskatchewan and Manitoba, and northern Saskatchewan and northern Manitoba. In Alberta, 32% of the gauges show its impact, in Saskatchewan 19% of the gauges, and in Manitoba 27%. The binomial distribution specifies a field significance of $p = 0.05$, and the AO's effect is real.

The results from the composite analyses restricted to the 1972–2010 and 1962–2010 calendar year streamflows are comparable to those of the full records. For 1972–2010, 38% of the gauges showed the impact of the PDO, 25% the impact of the PNA, 14% the impact of the NPI, 25% the impact of the SOI and 18% the impact of the AO. For 1962–2010, 64% of the gauges showed the impact of the PDO, 50% the impact of the PNA, 28% the impact of the NPI, 47% the impact of the SOI and 28% the impact of the AO. The analyses using the water year were again comparable to those using the

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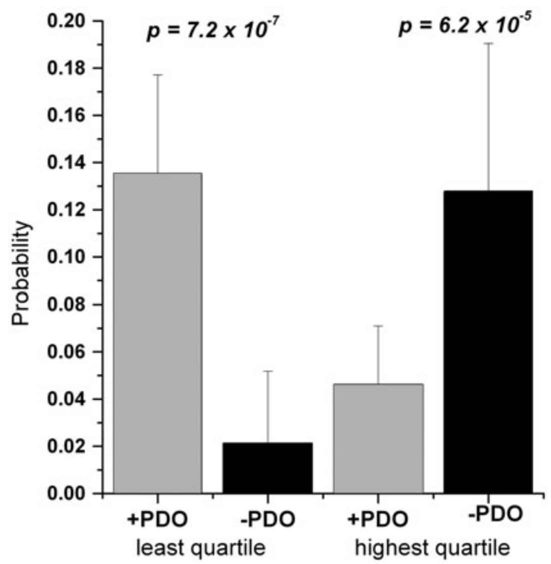

Figure 8. Mean probabilities and standard deviations of two successive years of least quartile and highest quartile flows composited according to Pacific Decadal Oscillation (PDO) phase with standard deviations for the 22 long Prairie records. Also shown are the *p*-values from the paired permutation *t*-tests determining the significance of the mean Prairie-wide difference between the probability of two successive years of least (highest) quartile flow in a given river during the positive PDO phase versus the probability of two successive years of least (highest) quartile flow in the same river during the negative PDO phase.

calendar year and the impacts of the PDO, PNA, NPI and SOI remained field significant across the Prairies. The analyses based on the different definitions of strong climate events, using 1.0, 0.9, 0.8 and 0.5 standard deviations and all years when the climate oscillation was negative versus all years when it was positive, were also comparable to those using the 0.75 threshold, for both the calendar and water year records. The impacts of the PDO, PNA, NPI and SOI remained field significant across the Prairies in all but a few cases. The impacts of AO were field significant a third of the time.

The effect of PDO phase on the probability of two years of successive least (or highest) quartile flows of Prairie streamflows confirms the PDO's impact, with sustained higher flows during the negative phase and sustained lower flows during the positive phase, using calendar year records (Table 3). The mean probability of two years of successive least quartile flows is 0.135 during the positive phase of the PDO; this probability drops to 0.022 during the negative phase of the PDO. This difference is significant according to a paired permutation *t*-test (p = 7.2 x 10^{-7}) (Figure 8). Conversely, the mean probability of two years of successive highest quartile flows is 0.046 during the positive phase of the PDO; this probability increases to 0.128 during the negative phase. Again, this difference is significant according to a paired permutation *t*-test (p = 6.2 x 10^{-5}) (Figure 8). This pattern in the least quartile flows is seen in 21 of the 22 examined discharge records; the Red Deer River at Red Deer is the exception. This pattern in the highest quartile flows is seen at 18 of the 22 examined discharge records; the Bow River at Banff, the Athabasca River at Athabasca, and Sage and Lyons Creeks are the exceptions. Analysis of corresponding naturalized flows for the Alberta regulated gauges (St. Jacques et al. 2010) also confirmed this pattern of successive higher flows during the negative PDO phase and successive lower flows during the positive PDO phase.

Discussion

There are declines in mean daily flow in the naturally flowing streams throughout Alberta and southwest Saskatchewan, no significant trends in the central region and increased flows in Manitoba in both the far north and south in both the geographically extensive and the temporally restricted record sets (Figure 6). Composite analyses based upon permutation *t*-tests show that the PDO, PNA, NPI and SOI have a clear impact on Prairie mean daily discharge, with higher discharges occurring during negative PDO, negative PNA, high NPI and La Niña years, and lower flows during the positive PDO, positive PNA, low NPI and SOI years throughout most of the Prairie Provinces (Figure 7a–d). Composite analyses also show the weaker effect of the AO (Figure 7e).

Although there is no overall field significance to the trends in the extensive record set, for this pattern to be due to chance, there would be no geographical pattern in the trends, and no geographical consistency of trend sign. Therefore, the individual regional patterns could be emerging and real, particularly the drying trends in southern Alberta and southwest Saskatchewan, which are consistent with global warming scenarios. The non-parametric MK test is a relatively low-powered test (Yue et al. 2002). To provide climatological context for these trend results, Zhang et al. (2000) showed with an MK based analysis of Adjusted Historical Canadian Climate Data that the Prairie Provinces have become significantly warmer over the past century, as well as wetter (significantly wetter in the Rocky Mountains, in the far north and in eastern Manitoba).

The declining trends in both the geographically extensive and the temporally restricted record sets should be interpreted with care in Alberta and southwestern Saskatchewan as this area's streamflow is strongly affected by the PDO (Figures 4a and 7a). The 50–60-year low frequency cycle of the PDO can potentially generate a declining linear trend in short instrumental streamflow records. Many western North American instrumental streamflow records begin in the 1950s or 1960s (a period

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of negative PDO, hence high prairie streamflow), or omit the 1930s and 1940s (periods of positive PDO, hence low prairie streamflow). Therefore, any trend line fit between this initial high flow period followed by this subsequent low flow period shows a declining trend. If this influence of the PDO is not taken into account in an analysis of prairie instrumental hydroclimatic records, this could produce detected declines that could be attributed to climate change, while they are actually confounding effects of the sampling period and the PDO phase changes (Chen and Grasby 2009). Very few western streamflow trend analyses have considered the issue of PDO phase (but see Rood et al. 2005; Luce and Holden 2009; St. Jacques et al. 2010). One solution is to weight more heavily the only seven continuous naturally-flowing records in the Prairie Provinces that span at least a PDO cycle and a half (~75 years). The six declining gauge records in the southwest Prairies are among the longest streamflow records, with five beginning in the 1910s or 1930s, and spanning more than one PDO cycle; therefore, the declines are less likely to be due to PDO phase. Zhang, Harvey et al. (2001), using the MK test on prewhitened data, found similar declining annual mean streamflow at naturally flowing gauges in the southwest Prairies over an earlier period of record. Rood, Samuelson et al. 2005, Rood et al. (2008) and St. Jacques et al. (2010) also detected declining trends in southern Albertan naturally flowing stream gauge records. Hence, the streamflow declines in the southwestern Prairies are likely real.

In the central Prairie region, annual naturally flowing hydrological series show no significant trends. Previous studies by Gan (1998) and Burn et al. (2008) also showed little significant change in annual or warm-season discharge in Saskatchewan. Since Zhang et al. (2000) showed that Saskatchewan's climate has become significantly warmer over the past century, as well as wetter, the streamflow analysis suggests that either increased evaporation from higher temperatures is balanced by increased precipitation throughout much of the province, or that emerging trends in the short hydrological time series are still below the threshold of detection of the weak MK test. However, Burn and Hesch (2006) found no increase in potential and pan evaporation, and even decreases, with increased temperatures. In response to a warming climate, Burn et al. (2008) and Rood et al. (2008) detected seasonal shifts towards earlier peak flow from snowmelt across the prairies, particularly in western Alberta.

Southern Manitoba exhibits increasing mean daily flow in both the geographically extensive and the temporally restricted record sets, similar to emerging trends in adjacent North Dakota (pers. comm. R.W. Dudley, United States Geological Survey). It is uncertain whether this is due to climatological changes and/or to landscape changes, i.e. increased drainage of wetlands. Zhang et al. (2000) showed significantly increased annual precipitation for much of Manitoba over the period 1950–1998, which is in accord with projected precipitation increases (Barrow 2010). Immediately to the north of the Prairie Provinces, rivers in the Northwest Territories are showing increases in annual discharge and winter baseflow due to hydrological cycle changes and possible decaying permafrost from anthropogenic global warming (Smith et al. 2007; St. Jacques and Sauchyn 2009). This could be the same scenario in northern Manitoba, where sporadic permafrost is present, and there has been a significant 37.1% increase in winter baseflow in the Seal River (estimated by January–March average daily flow) over the 56 years of record as detected by the modified MK test ($p < 0.05$).

This study is the most comprehensive, in terms of prairie-wide extent and numbers of gauges and climate oscillations examined, to demonstrate teleconnections between large-scale climate patterns and Prairie Province streamflow. Burn et al. (2008) in part undertook a similar study on small prairie streams and found that no such relationships existed. However, their seminal study included only a quarter of the streamflow gauges examined here, was based upon shorter streamflow and climate oscillation records, and used a lower threshold of climate oscillation events and a regular *t*-test with its normality assumptions that are inappropriate for small streams (Gobena and Gan 2006). A permutation *t*-test has greater statistical power than a parametric *t*-test when the distributions are non-normal (Manly 2007). Using the non-parametric Mann-Whitney test and data ending in 2001, Gobena and Gan (2006) found that western Canadian river discharge is higher during negative PDO, negative PNA and La Niña years, and lower in the positive phase years. However, their work was concentrated in British Columbia and southern Alberta mountain headwaters; they included only three gauge records each from Saskatchewan and Manitoba. Woo and Thorne (2003) demonstrated significant relationships between western Canadian annual and spring peak flows and the PNA and the SOI, using Spearman's r^2 and 1968–1998 data.

Any analysis of the Canadian Prairie hydroclimatology is limited by the available streamflow data. In this study, the Saskatchewan hydrometric records are the shortest, with a mean period of record of 48 years, followed by those from Manitoba (51 years) and Alberta (53 years). Because of this short length, only one low-frequency positive phase (1977–2007) of the PDO is well represented in the period of record. Therefore, very few mean daily discharges from negative PDO years are available for analysis in the shorter periods of record, which lessens the probability of detecting significantly different streamflows between the different phases. This

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also means that there are relatively few mean daily discharge records from negative PNA, high NPI and La Niña years in the short records, as negative PNA, high NPI and La Niña events are more likely to occur during the negative phase of the PDO (Figure 3, Table 2). Similarly, discharge data from negative AO years are under-represented post-1975, as the AO has had a positive bias during these most recent 35 years. This explains the increases in detection of impacts when the 1962–2010 analysis is compared to the 1972–2010 analysis. On the other hand, discharges from positive PDO, positive PNA, low NPI, El Niño and positive AO years are well represented in the hydrological record. One phase of a climate oscillation, but not the other, may consistently affect streamflow, e.g. the southward displacement of the winter sub-polar jet in a positive PDO event may result in low flows, but the more northward position of the jet in a negative PDO event may not in itself be sufficient to guarantee high flows. Permutation tests of discharges during strong positive PDO years against discharges from all other years gave similar results to those presented here from tests between positive PDO years versus negative PDO years, and similarly for positive PNA and low NPI years (results not shown). Furthermore, there are few moderately sized naturally flowing rivers in the southern region of the Prairie Provinces. This is a serious limitation as moderately sized rivers have large enough watersheds to average the patchily distributed precipitation events, and thus are more likely to reflect the impact of the atmosphere-ocean climate oscillations more strongly than small, erratic streams, which are more impacted by small-scale, local, stochastic processes.

Conclusions

Hydrologists assume that the probability of extreme high or low flows is independently and identically distributed from year to year (Franks and Kuczera 2002; Kiem et al. 2003). The application of this assumption to Prairie streamflows must be critically examined given this result that there is a definite asymmetry in the effect of PDO phase on the probability of two years of successive least (or highest) quartile flows. The higher probability of two years of successive least quartile flow during the positive phase of the PDO should be considered for the operation of reservoirs that typically have at most two years of storage. This is especially relevant given the multi-centennial tree-ring records reconstructed for the South and North Saskatchewan Rivers, which show periods of multi-decadal low flows in the past millennium (Axelson et al. 2009; Sauchyn et al. 2011; Lapp et al. 2013).

The results of this study have implications for water resource management: the recognition of significant natural modes of hydrological variability leads to a more rigorous interpretation of recent trends and fluctuations in raw water supply, and is a further indication that conventional methods of water supply forecasting are wrong to assume the stationarity of hydrological time series. It also underlines the importance of building and maintaining centennial-length continuous hydrological records in this region.

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