Analysis of cold season streamflow response to variability of climate in north-western North America

Ming-ko Woo and Robin Thorne

ABSTRACT

Previous studies have correlated interannual streamflow fluctuations with changes in the climate. We note that decadal shifts in climate forcing can impart a stronger signal on streamflow than does the long-term climatic trend. In north-western North America, the Pacific Decadal Oscillation (PDO), which is strong in the cold season, may exert influence on interannual variations in spring high flows. In the 20th century, several major shifts in the PDO have been recognized. However, the rivers of Alaska, Yukon, Northwest Territories, British Columbia and Alberta have variable response to such climate signals. An analysis of the flow of rivers in this region indicates that a number of rivers draining the Pacific coast are positively correlated with PDO and some rivers in the interior correlate negatively. Not all river flows correlate with the PDO because factors such as location, topography and storage can overwhelm the climatic influence. Given these considerations, the interpretation of long-term trends in streamflow should take account of the interdecadal climatic shifts and basin characteristics that affect flow generation.

Key words | climate variability, north-western North America, Pacific decadal oscillation, streamflow trend, streamflow variability

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INTRODUCTION

Low frequency variability modes in the climate have been found to affect variations in surface air temperature and precipitation. Frey & Smith (2003), for example, noted that the Arctic Oscillation is important in driving the observed temperature and precipitation trends in western Siberia. The Pacific Decadal Oscillation (PDO) in the North Pacific similarly influences the temperature and precipitation regimes of north-western North America. The Arctic Oscillation and the PDO are reported to have teleconnection with river discharge of the Hudson Bay drainage in Canada (Déry & Wood 2004) and with the flows of south-eastern Alaskan rivers (Neal *et al.* 2002). In the temperate and subarctic latitudes of north-western North America, variations of streamflow have important implications on the environment, ecology and economic activities, including floods and droughts, aquatic habitats and salmon migration, hydropower generation and irrigation.

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The PDO signals are notably stronger in the cold season than in the summer, and would likely induce variations in winter and spring discharge, depending on location. There has also been a growing interest in streamflow trends (Zhang *et al.* 2001; Peterson *et al.* 2002; Burn *et al.* 2004), largely driven by climate warming concerns, but the short record length of most northern rivers may render it difficult to distinguish long-term trends from medium-term variability. The present study examines the linkage between discharge during cold months and the climate variability signal on a regional scale. It also assesses the role of interdecadal streamflow variability in flow trend identification. Summer flows are excluded from this study as streamflow in the non-cold season is largely influenced by factors other than the interdecadal oscillation, though Shabbar & Skinner (2004) noted that the summer drought pattern in Canada may be related to anomalies in the global sea surface temperature pattern in the preceding winter season.

NORTH-WESTERN NORTH AMERICA

North-western North America encompasses Alaska, Yukon and Northwest Territories, British Columbia and Alberta. The Western Cordillera with chains of lofty mountains, plateaus and valleys dominates the region. The mountains present a barrier to the eastward passage of the Pacific air and often prevent the outbreak of cold Arctic air to the Pacific coast. East of the Cordillera lie the Interior Plains and the Canadian Shield. Several climate zones exist in the region, including cold temperate, subarctic and Arctic climates in maritime and continental settings. Hare & Thomas (1979) subdivided the region climatically into Pacific, Cordillera, Prairies, Boreal and Arctic (Figure 1). Most river flow exhibits a nival regime in which spring melt generates high flows that are orders of magnitude larger than the winter discharge, and the spring freshet is followed by a decline in flow but the recession flow is revived occasionally by summer rainstorms. Rivers along the Pacific coast have a mixed response to rainfall and snowmelt that vary in proportion depending on fluctuations of the freezing altitude (Waylen & Woo 1982).

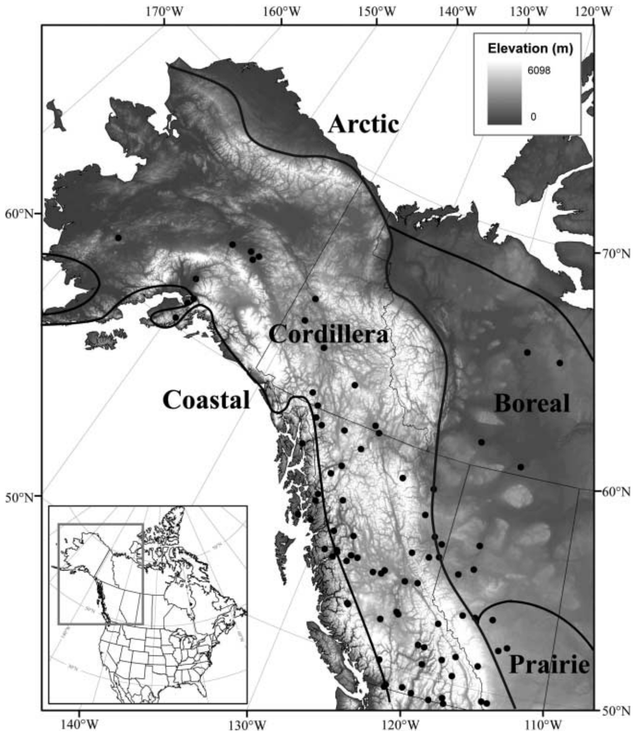

Figure 1 | Topography and climatic regions in north-western North America. Dots indicate location of gauging stations.

DATA SOURCES AND ANALYSIS

This study uses climate station and hydrometric data for Canada and Alaska. The northern region has a sparse data network. Many stations do not extend back beyond 1960 and the number of stations has also declined since the 1990s (Shiklomanov *et al.* 2002). Air temperature and precipitation are provided by Environment Canada and by the Alaskan Climate Center at University of Alaska Fairbanks (http://climate.gi.alaska.edu). Canadian streamflow data are taken from HYDAT and Alaskan data are obtained from http://nwis.waterdata.usgs.gov. Table 1 lists those stations with streamflow records that covered 1965–2005 and with less than five years of missing data. PDO indices are obtained from http://jisao.washington.edu/pdo/PDO. This study used the average PDO values of October–March for each year. Streamflow and climate data were correlated with PDO using non-parametric Spearman correlation. Comparable results were obtained using the Mann–Kendall test and these are not reported here. Similarly, streamflow series were correlated with time for linear trend analysis using stations from Table 1 but with at least 35 years of data from 1960 to 1999. Although the number of stations decreased, this period was selected to ensure enough data before and after a major shift in the atmospheric general circulation that occurred during the mid-1970s. Spatial patterns of the correlation coefficients were then mapped with solid (positive) and dashed (negative correlation) isolines. To test for significant shifts in the PDO and streamflow data series, the Pettitt (1979) test was applied.

PDO AND STREAMFLOW CORRELATIONS

The PDO is a pattern of Pacific climate variability, similar to the El Niño pattern, but shifts phases (positive or negative) on an interdecadal timescale of about 20–30 years. For the winter period over north-western North America,

Table 1 | Hydrometric stations used in this study that covered 1965–2005 and with less than five years of missing data

Station name	Lat. (°N)	Long. (°E)	Basin area (km²)	Station name	Lat. (°N)	Long. (°E)	Basin area (km²)
Adams (08LD001)	50.56	−119.39	3080	Little Susitna (15290000)	61.42	−149.13	160
Ashnola (08NL004)	49.12	−119.59	1050	Mcgregor (08KB003)	54.14	−121.40	4780
Athabasca (07AD002)	53.25	−117.34	9780	Mcleod (07AF002)	53.28	−116.37	2560
Atlin (09AA006)	59.36	−133.49	6810	Mendenhall (15052500)	58.25	−134.34	220
Atnarko (08FB006)	52.21	−126.00	2430	Morice (08ED002)	54.07	−127.25	1900
Baker (08KE016)	52.58	−122.31	1550	Muskwa (10CD001)	58.47	−122.40	20,300
Battle (05FA001)	52.39	−113.35	1830	Nass (08DB001)	55.16	−129.05	18,500
Beatton (07FC001)	56.17	−120.42	15,600	Nautley (08JB003)	54.06	−124.36	6030
Beaverlodge (07GD001)	55.11	−119.27	1610	North Thompson (08LB047)	51.36	−119.55	4450
Bella Coola (08FB007)	52.25	−126.09	3720	Notikewin (07HC001)	56.55	−117.37	4680
Birch (07KE001)	58.19	−113.03	9860	Old Tom (15085100)	55.23	−132.24	15
Blindman (05CC001)	52.21	−113.47	1790	Oldman (05AA023)	49.49	−114.11	1446
Blueberry (07FC003)	56.41	−121.13	1750	Parsnip (07EE007)	55.41	−122.54	4900
Bow (05BB001)	51.10	−115.34	2210	Pelly (09BC001)	62.50	−136.34	49,000
Bulkley (08EE004)	54.38	−126.54	7350	Pembina (07BB002)	53.36	−115.00	4420
Camsell (10JA002)	65.36	−117.45	32,100	Pine (07CA005)	54.49	−112.46	1450
Chena (15493000)	64.54	−146.21	2427	Pine (07FB001)	55.43	−121.12	12,100
Chilko (08MA001)	52.04	−123.32	6940	Power (15216000)	60.35	−145.37	53
Chilliwack (08MH001)	49.06	−121.57	1230	Quesnel (08KH006)	52.50	−122.13	11,500
Clearwater (08LA001)	51.39	−120.04	10,200	Ram (05DC006)	52.23	−115.25	1860
Columbia (08NB005)	51.29	−117.10	9710	Ross (09BA001)	61.59	−132.24	7250
Coppermine (10PB001)	65.24	−114.00	19,200	Salcha (15484000)	64.28	−146.55	5620
Cottonwood (10AC005)	59.07	−129.49	888	Salmo (08NE074)	49.02	−117.17	1230
Driftwood (07BK007)	55.15	−114.13	2100	Salmon (08KC001)	54.05	−122.40	4230
Duncan (08NH119)	50.38	−117.03	1330	Sand (06AB001)	54.28	−111.11	4910
East Prairie (07BF001)	55.25	−116.20	1460	Saulteaux (07BK005)	55.09	−114.14	2600
Elk (08NK016)	49.52	−114.53	1870	Ship (15276000)	61.13	−149.38	234
Exchamsiks (08EG012)	54.22	−129.19	370	Sikanni Chief (10CB001)	57.24	−122.42	2160
Fish (15072000)	55.23	−131.11	83	Similkameen (08NL007)	49.27	−120.31	1850
Frances (10AB001)	60.28	−129.07	12,800	Simonette (07GF001)	55.08	−118.10	5050
Fraser (08KA007)	52.59	−119.00	1710	Skeena (08EF001)	54.38	−128.26	42,300
Freeman (07AH001)	54.22	−114.54	1660	Slocan (08NJ013)	49.27	−117.34	3320
Goathorn (08EE008)	54.39	−127.07	126	Smoky (07GJ001)	55.43	−117.37	50,300
Granby (08NN002)	49.02	−118.26	2050	Stellako (08JB002)	54.00	−125.00	3600
Harding (15022000)	56.12	−131.38	175	Stewart (09DD003)	63.17	−139.15	51,000
Harrison (08MG013)	49.18	−121.49	7870	Stikine (08CE001)	57.54	−131.09	29,300
Hay (07OB001)	60.44	−115.51	47,900	Stuart (08JE001)	54.25	−124.17	14,200
Heart (07HA003)	56.03	−117.07	1960	Sturgeon (05EA001)	53.47	−113.13	3350
Homathko (08GD004)	50.59	−124.55	5720	Surprise (08DA005)	56.61	−129.29	221
Illecillewaet (08ND013)	51.00	−118.05	1150	Susitna (15292000)	62.46	−149.41	15,954
Iosegun (07GG003)	54.44	−117.09	1950	Swan (07BJ001)	55.19	−115.24	1900

(continued)

Table 1 | (*continued*)

Station name	Lat. (°N)	Long. (°E)	Basin area (km^2)	Station name	Lat. (°N)	Long. (°E)	Basin area (km^2)
Iron (05FB002)	52.42	−111.18	3500	Swift (09AE003)	59.56	−131.46	3320
Iskut (08CG001)	56.44	−131.40	9350	Takhini (09AC001)	60.51	−135.44	6990
Kenai (15258000)	60.29	−149.48	1642	Talkeetna (15292700)	62.20	−150.01	5170
Kiskatinaw (07FD001)	55.57	−120.34	3570	Tanana (15515500)	64.33	−149.05	66,304
Kispiox (08EB004)	55.26	−127.43	1880	Toad (10BE004)	58.51	−125.23	2570
Kitimat (08FF001)	54.03	−128.40	1990	Trout (10FA002)	61.08	−119.51	9270
Klondike (09EA003)	64.21	−139.24	7800	Tutshi (09AA013)	59.57	−134.20	992
Kneehills (05CE002)	51.28	−112.58	2429	Tuya (08CD001)	58.04	−130.49	3600
Kuskokwim (15304000)	61.52	−158.06	80,549	Wapiti (07GE001)	55.04	−118.48	11,300
Liard (10AA001)	60.03	−128.54	33,400	Waskahigan (07GG001)	54.45	−117.12	1040
Lillooet (08MG005)	50.21	−122.48	2160	West Prairie (07BF002)	55.27	−116.29	1160
Little Chena (15511000)	64.53	−147.14	963	West Road (08KG001)	53.18	−122.53	12,400
Little Red Deer (05CB001)	52.01	−114.08	2578	Wheaton (09AA012)	60.08	−134.53	875
Little Smoky (07GG002)	54.44	−117.10	3010	Zymoetz (08EF005)	54.29	−128.20	2980

a positive (warm) PDO phase corresponds with a period of high temperature and low precipitation, whereas a negative (cold) PDO phase has the opposite effect. As examples, 55 years of records from the weather stations at Fairbanks (64°48′N,147°51′W) and Talkeetna (62°19′N,150°5′W) in Alaska yield positive correlations between their winter air temperature and PDO ($r = 0.76$ for Fairbanks and $r = 0.81$ for Talkeetna), but the winter precipitation of Fairbanks correlates negatively with PDO ($r = -0.44$). This confirms that positive PDO values are associated with warm and dry winters. The physical linkage between low frequency climate variability and discharge is not entirely straightforward. Figure 2 is a conceptualization of the influence of climatic circulation regime on streamflow. Sea level pressure response to atmospheric circulation affects the regional temperature and precipitation patterns. However, topographic considerations such as altitude, aspect or distance to large water bodies modify temperature and precipitation distribution on a local scale. On the catchment level, basin characteristics (such as geology, landform and vegetation) affect the partitioning of the water balance components, water storage and release, and runoff delivery. All these considerations have notable effects on the magnitude and timing of discharge, as shown in the study area.

Figure 3 maps the spatial pattern of locations (based on the stations listed in Table 1) where monthly streamflow is correlated with the October–March PDO for the winter and spring seasons. As the timing of spring runoff differs among different environments in north-western North America, separate maps are provided for January–June (Woo & Thorne 2003*a*,*b*). While generalized regional patterns of high correlation may be discerned from these

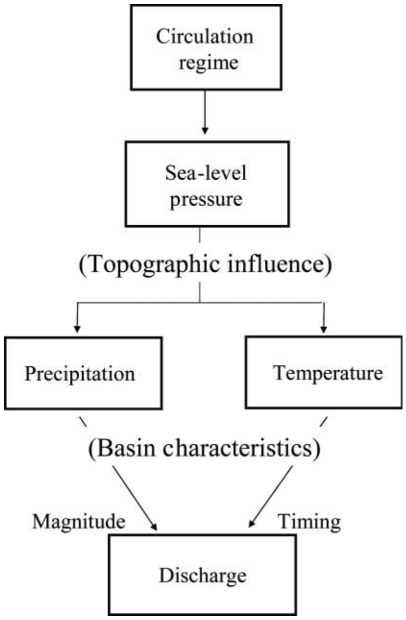

Figure 2 | Conceptualization of physical linkage between low frequency climatic variability and discharge.

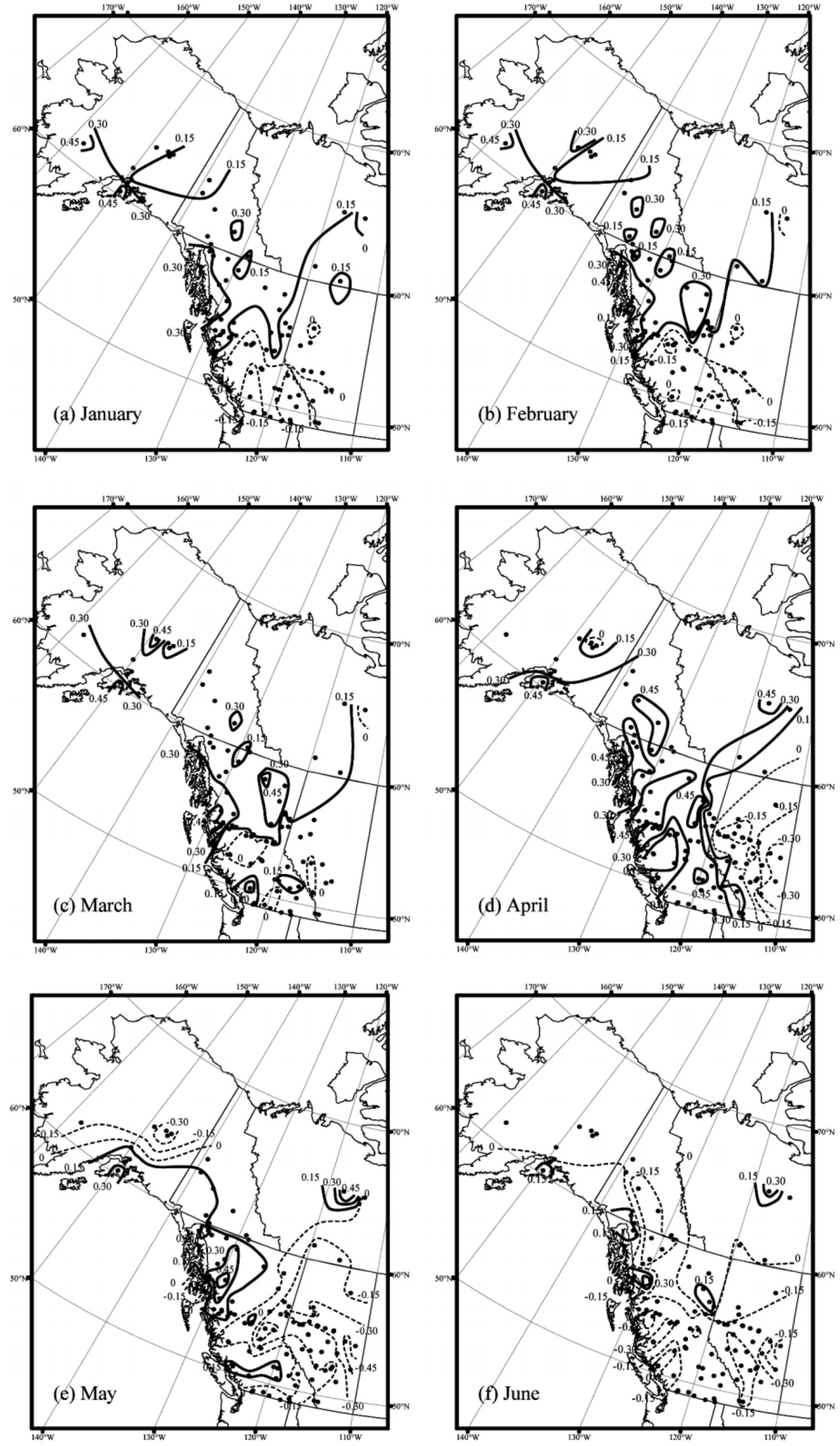

Figure 3 | Spatial patterns of correlation (*r* values) between mean flows of January–June (a)–(f), and October–March PDO. Dots indicate location of stations that provide data for this study. Solid or dashed isolines indicate positive or negative correlation, respectively. Correlation is significant at 5% where $|r| \geq 0.30$.

maps, parts of the region do not yield signification correlations between streamflow and PDO. Several factors can confound the relationship between streamflow and the climate. Topography can modify the climate variation signals (Moore *et al.* 2003) to complicate the pattern of streamflow response. The presence of lakes upstream of gauging stations (e.g. Camsell River in Northwest Territories at 65°35′N, 117°45′W) can buffer the flow response to the climatic variables. Glacierized basins may produce larger melt in the warm PDO years, but enhanced melt may be countered by the low winter precipitation during these years. Fleming *et al.* (2006) noted that hydroclimatic filtering effect of basin glacierization is important in determining local interannual flow fluctuations. These and other non-climatic considerations can effectively negate the influence of climatic factors on the variability of streamflow (Woo *et al.* 2006).

Areas of significant correlation are dispersed in two different zones. Coastal areas usually have winter rain at low altitudes and snow accumulation on high grounds so that both winter and spring high flows are possible. Rivers like the Kenai in Alaska (60°29′N, 149°48′W) show positive flow correlation with PDO for the months of January–April. The high correlation for the winter months may be attributed to more frequent occurrence of rainfall than snowfall to generate high winter runoff during warm PDO years. This interpretation is consistent with Neal *et al.*'s (2002) finding that warm-PDO winter flows are typically higher than the cold-PDO winter discharge. Positive correlation for the month of April indicates that warm PDO years bring forth higher discharge, possibly due to early melt of snow at high elevations.

Inland areas possess zones with significant negative correlation between PDO and streamflow in the snowmelt season. This arises because warm PDO years accumulate less snow so that the spring-melt discharge is reduced. The timing of spring runoff differs in different parts of the region. Thus, high negative correlation occurs in April and May for the interior Plains, in May for interior Alaska, and in June for interior British Columbia with high elevation zones. It is noted that the January–March air temperature of Prince George (53°9′N, 122°7′W) in interior British Columbia shows a significant positive correlation with winter PDO ($r = 0.59$), but this does not have a positive effect on streamflow. The flow is more responsive to winter precipitation which tends to be low during the warm PDO winters.

STREAMFLOW TREND VERSUS VARIABILITY

The timing and the magnitude of spring flows are strongly affected by warming in the cold season and by the amount of winter precipitation. The conventional approach in trend analysis assumes that changes in streamflow during 1960–1999 followed an approximately linear trend. Analysing the time series with this implicit assumption, the Spearman rank correlation suggests that spring flow in many rivers arrives earlier in recent years (e.g. in the Mackenzie Basin, see Woo & Thorne (2003*a*,*b*)) due to increased warming in April to advance the timing of snowmelt. The Pacific coastal rivers also show an increase in streamflow. Several mountain rivers in the Cordillera experience a flow increase in April that may be attributed to an early rise in the spring high flow, followed by a compensating decline in the recession flow.

While it is convenient to pool the entire length of the historical record into a single time series for linear trend analysis, detailed scrutiny of most data series suggests

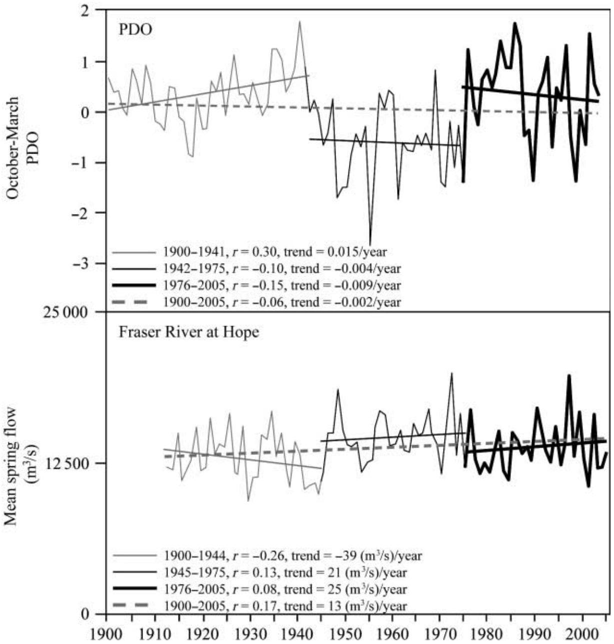

Figure 4 | Time series of mean winter PDO (October–March) and mean spring flow (April–June) of Fraser River, showing shifts in their regimes.

periodic variations that cannot be ignored. In terms of the climate, it is well established that a major shift in the atmospheric general circulation occurred during the mid-1970s that affected the climate of many regions of the world (e.g. Trenberth 1990; Mantua *et al.* 1997) including north-western North America. The regime shift has been attributed to a multidecadal oscillation in the North Pacific climate and is manifested in large scale indices, including the PDO. Other shifts have also been detected. Chevaz *et al.* (2003) noted an approximate 25-yr periodicity in the 20th century, with cool phases from about 1900–1925 and 1950–1975, and warm phases from about 1925–1950 and 1975 to the mid-1990s. These climatic shifts have apparent effects on decadal variations in streamflow. Coulibaly & Burn (2005) noted that, after 1950, there were strong streamflow–climate activities for many rivers in Canada. Neal *et al.* (2002) found a difference in the winter and summer flows of rivers in southeastern Alaska. During the cold-PDO (1947–1976) years, the winter flows were lower than those of the warm-PDO (1977–1998) years, and the reverse applied to the summer flows.

In view of the distinct climatological shifts, it is physically meaningful to divide the streamflow data into subsets to examine the flow changes within each period. An

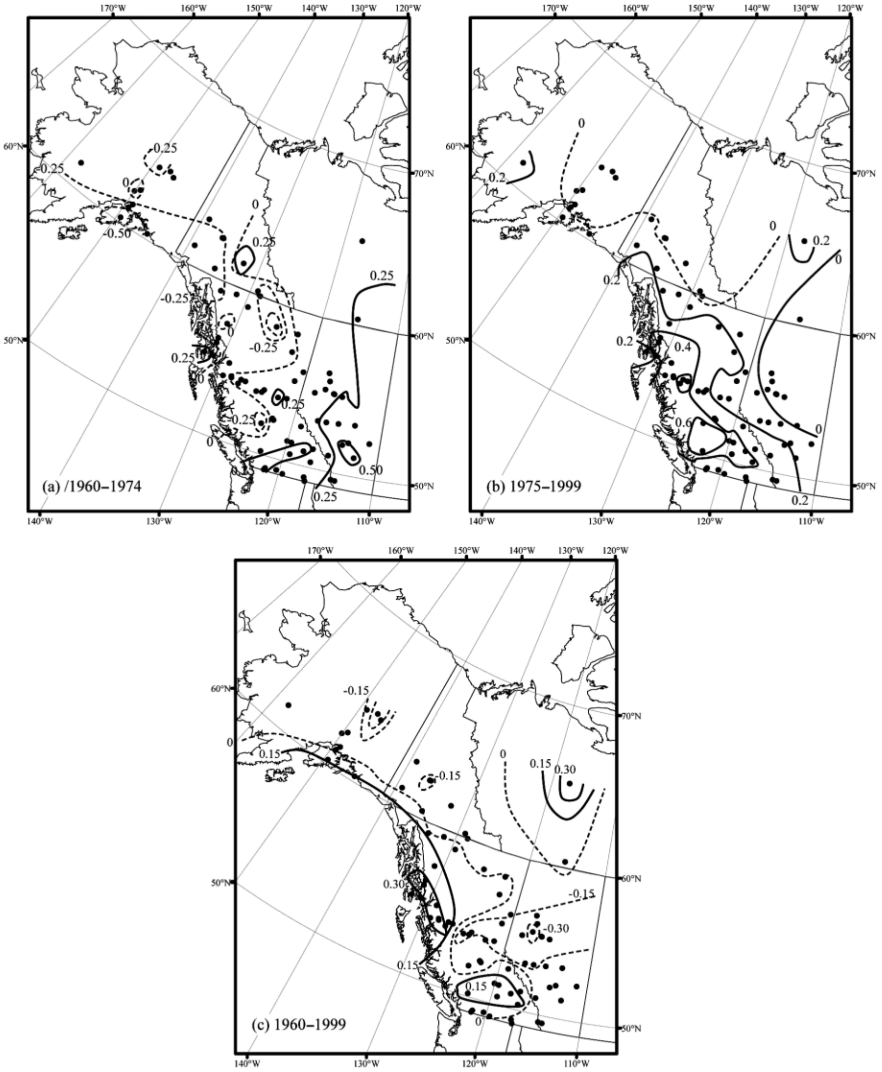

Figure 5 | Trends in mean streamflow (discharge correlated against time) for 1960–1999, 1960–1974 and 1975–1999 periods for the spring season (April–June). Solid or dashed isolines of r values indicate positive or negative correlation, respectively. Trend is statistically significant at 5% where $|r| \geq 0.3$ for the 1960–1999 series; where $|r| \geq 0.5$ for the 1960–1974 series; and where $|r| \geq 0.4$ for the 1975–1999 series.

example of the spring (April–June) discharge of Fraser River at Hope, B.C. (49.39°N and 121.45°W; basin area 217,000 km^2) in Figure 4 illustrates the breaks in its time series that may be linked to the shifts in the winter climate regime. Pettitt tests show that statistically significant breaks occurred in 1942 and 1976 for the winter (October–March) PDO, and in 1945 and 1976 for the Fraser River.

To spatially examine distinct breaks in the streamflow series over time, we analyzed streamflow data from 1960–1999. Although the number of stations decreased from the list of stations in Table 1, this period was selected to ensure enough data before and after the shift in the atmospheric general circulation that occurred during the mid-1970s. The trends in the streamflow time series were studied by considering the absence and then the presence of a shift in 1975. The spatial pattern of spring flow in 1960–1974 shows declining runoff on the leeward side of the Cordillera and little change on the windward side (Figure 5). The 1975–1999 pattern indicates increasing spring runoff on the windward aspect and a moderation of the runoff decline in the interior. A shift in the large-scale circulation regime has induced a strengthening of the onshore winter airflow. This enhanced flow interacts with the formidable topographic barrier of the Cordillera to deposit greater snowfall on the windward side, accompanied by reduced winter precipitation in the leeward areas in the Mackenzie and Yukon river basins. The shift in spring runoff after the mid-1970s reflects such changes in winter snow accumulation (which is released by subsequent spring melt) in these respective areas. Given the possible link of streamflow with the regional climate forcing, a shift in streamflow should be viewed as an abrupt jump rather than as part of a linear trend.

This study does not refute the influence of climate change on streamflow. On the contrary, climate change can affect variability in the climate which may or may not be reflected in the flow pattern because of non-climatic factors related to the basin characteristics. We demonstrate the inadequacies of using linear trends to describe the flow response to a warming climate. Our concern with the interpretation of such a monotonic trend is based on several considerations: (1) there is insufficient physical basis to support a monotonic change in streamflow due to climate forcing; (2) the perceived presence of a linear trend may be a statistical artifact arising from fitting a line across several shifted segments in the historical record; and (3) extrapolation of the linear trend can lead to erroneous projection of future streamflow.

CONCLUSIONS

Changes in winter precipitation modify the magnitude of streamflow while changes in cold season temperature alter the timing of runoff. Thus, variation in the climate plays an important role in causing interannual variations in streamflow. There is evidence that the winter PDO is correlated with the spring discharge in parts of north-western North America. In the coastal zone, warm winters yield more rain than snow and the flow will increase. In inland areas, warm PDO years with low snow accumulation lead to reduced runoff. However, there are large parts of the region where the interannual variations in streamflow and climate are not significantly correlated. Local streamflow response to the regional climate forcing is complicated by such factors as terrain and basin storage. These considerations complicate the linkage between the variability of regional climate and streamflow in specific locations, particularly for areas of complex and rugged terrain.

In the past decades, there has been a prominent shift in the climatic regime in the North Pacific which affects north-western North America. Our analysis shows that the change in streamflow within each climatic regime is weak, but the change is large between the two regime periods. A trend would emerge if the entire 40-yr (1960–1999) time series rather than the climatologically driven regime segments are considered. Such a trend is only a statistical artifact of combining two sub-populations of streamflow, each responding to a different climatic forcing. This result offers a cautionary note against inadvertent interpretation of short-term regime shift as an indication of long term trend in hydrological data.

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