Analysis of streamflow response to variability of climate in northwestern North America

Ming-ko Woo[1*], Robin Thorne[1],

[1] *School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario L8S4K1, CANADA*
**Corresponding author, e-mail: woo@mcmaster.ca*

ABSTRACT
Variability of climate is expected to affect interannual streamflow fluctuations. Snowmelt discharge is particularly important in northern latitudes and in northwestern North America, the Pacific Decadal Oscillation which is strong in the cold season, may exert influence on interannual variations in spring high flows. However, the rivers of Alaska, Yukon, Northwest Territories, British Columbia and Alberta have variable response to this climate signal. An analysis of the flow of some rivers in this region indicates that rivers draining the Pacific coast may be positively correlated with PDO and some rivers in the interior may correlate negatively. Not all river flows have significant correlation with the PDO, as non-climatic factors such as location, topography and storage can modify the climatic effects. Furthermore, interdecadal fluctuations may be erroneously interpreted as trends. Caution must be exercised when using short records to detect long-term trends in streamflow.

KEYWORDS
Arctic environments; thirtieth anniversary; conference paper; paper template; electronic files

1. INTRODUCTION

Climatic variability has been found to affect variations in surface air temperature and precipitation. Frey and 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 North America similarly influences the temperature and precipitation regimes of the region. The Arctic Oscillation and the PDO are expected to have teleconnection with river discharge of the Hudson Bay drainage in Canada (Déry and Wood, 2004) and with the flows of southeastern Alaskan rivers (Neal *et al*. 2004). In the temperate and subarctic latitudes of northwestern 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.

The spring season in northern areas is especially important in terms of water supply and hazards as many of their rivers receive large influx of water from snowmelt. The PDO signals are notably stronger in the cold season than in the summer, and would likely induce year to year variations in spring discharge. There has also been a growing interest in streamflow trends (Burn et al., 2004; Peterson et al., 2002; Zhang et al., 2001), 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 and the climate variability signal on a regional scale and assesses the role of inter-decadal streamflow variability in flow trend identification.

2. NORtHWESTERN NORTH AMERICA

Northwestern North America encompasses Alaska, Yukon and Northwest Territories, British Columbia and Alberta. Western Cordillera, with chains of lofty mountains, plateaus and valleys, dominate 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 climates zones exist in the region, including cold temperate, subarctic and arctic climates in maritime and continental settings. 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 and Woo 1982).

3. 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 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. We included only those stations with streamflow record that cover 1965-2005 and with less than five years of missing data. PDO indices are obtained from http://jisao.washington.edu/pdo/PDO.latest. 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. Similarly, streamflow series were correlated with time for linear trend analysis. Spatial patterns of the correlation coefficients were then mapped with solid (positive) and dashed (negative correlation) isolines.

4. PDO AND STREAMFLOW CORRELATIONS

Positive or warm PDO corresponds with period of high temperature and low precipitation in the winter. As examples, the weather stations at Fairbanks (64°48'N,147°51'W) and Talkeetna (62°19'N,150°5'W) in Alaska, yield positive correlation between their winter air temperature and PDO, but the winter precipitation of Fairbanks correlates negatively with PDO. This confirms that positive PDO values are associated with warm and dry winters.

Figure 1 maps the spatial pattern of locations where monthly streamflow is correlated with the winter PDO, for the spring season. As the timing of spring runoff differs among different environments in northwestern North America, three separate maps are provided, for the months of April, May and June (Woo and Thorne 2002). One prominent feature is a lack of significant correlation for many parts of the region. 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).

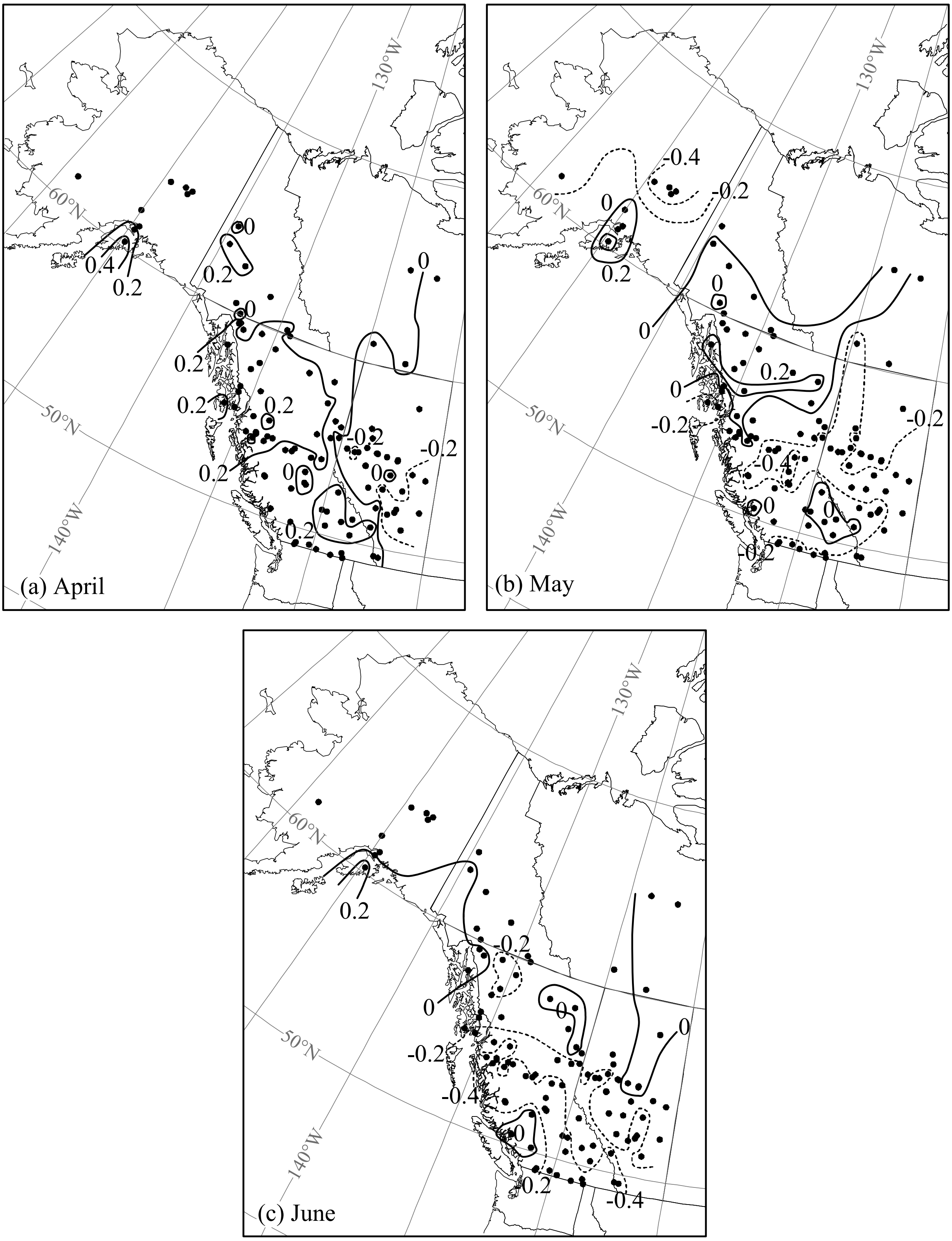

Figure 9 Spatial patterns of correlation (r-values) between mean flows of (a) April, (b) May and (c) June, and Oct-to-Mar PDO. Dots indicate location of stations that provide data for this study. Solid or dashed isolines indicate positive or negative correlation, respectively.

Areas of significant correlation are disbursed 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 to 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, 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.

5. STREAMFLOW TREND VERSUS VARIABILITY

The conventional approach in trend analysis assumes that changes in streamflow during 1960-99 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 and Thorne, 2003) 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 reduction 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 historical record into a single time series for linear trend analysis, detailed scrutiny of most data series suggests periodic variations that cannot be ignored. 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. Mantua *et al*., 1997; Trenberth, 1990), including northwestern 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. In view of the distinct climatological shift in the mid 1970s, it is physically sound to divide the 1960-99 streamflow data into two sub-periods (i.e.1960-74 and 1975-99) and examine the flow changes within each period. An example of the spring (April to June) discharge of North Thompson River (51°36'N,119°54'W) in Figure 2 illustrates the break in its time series that may be linked to the shift in the climatic regime.

The spatial pattern of spring flow in 1960-74 shows declining runoff on the leeward side of the Cordillera and little change on the windward side (Fig. 3). The 1975-99 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 1970s reflects such changes in winter snow accumulation (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.

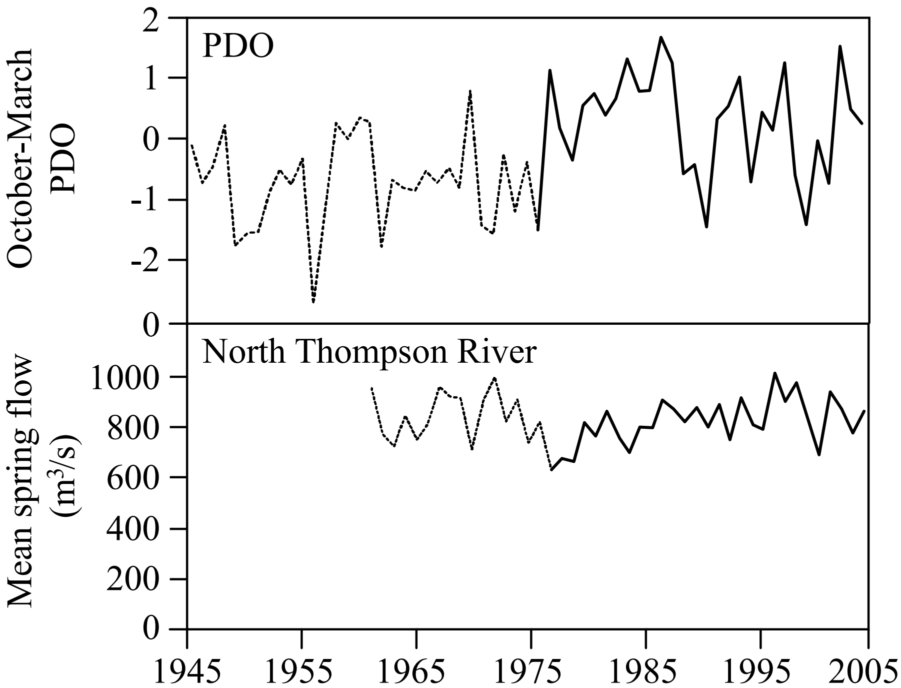

Figure 10 Time series of mean winter PDO (Oct-Mar) and mean spring flow (Apr-June) of North Thompson River, showing a shift in their regimes in the 1970s.

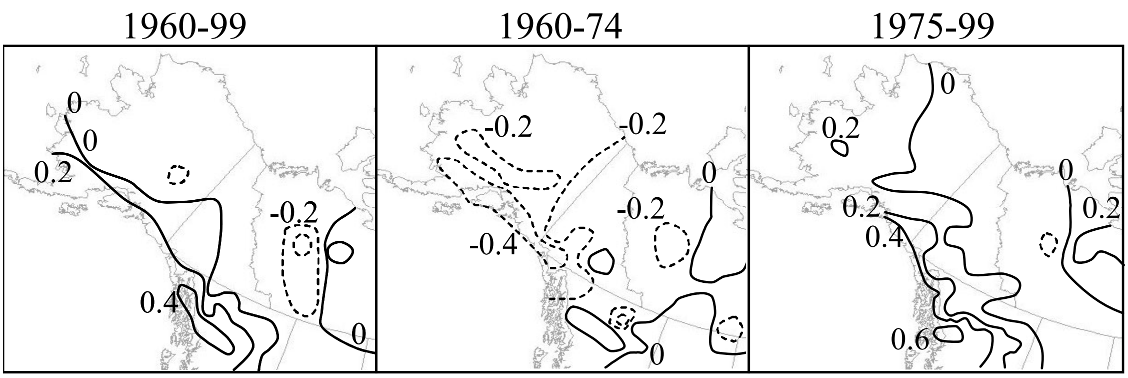

Figure 11 Trends in mean streamflow (discharge correlated against time) for 1960-1999, 1960-79 and 1980-99 periods for the spring season (April to June). Solid or dashed isolines of r-values indicate positive or negative correlation, respectively

6. CONCLUSIONS

Climatic factor is expected to play 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 northwestern 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 particular locations, particularly for areas with complex and rugged terrain.

In the past decades, there has been a prominent shift in the climatic regime in the North Pacific which affects northwestern 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 emerges if the entire 40-year (1960-99) time series rather than the climatologically driven regime segments are considered. Such a trend is 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.

ACKNOWLEDGEMENT
This study was funded by the Natural Sciences and Engineering Research Council of Canada through the Mackenzie GEWEX Study.

REFERENCES

Burn, D.H., Cunderlik, J.M. and Pietroniro, A. (2004) Hydrological trends and variability in the Liard River basin. *Hydrological Sciences Journal* **49**, 53-67

Déry, S.J. and Wood, E.F. (2004) Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. *Geophysical Research Letters* **31**, L18205, doi: 10.1029/2004GL020729

Fleming, S.W., Moore, R.D. and Clarke, G.K.C. (2006) Glacier-mediated streamflow teleconnections to the Arctic Oscillation. *International Journal of Climatology* **26**, 619-636

Frey, K.E. and Smith, L.C. (2003) Recent temperature and precipitation increases in West Siberian and their association with the Arctic Oscillation. *Polar Research* **22**, 287-300

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. (1997) A pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of American Meteorological Society* **78**, 1067-1079.

Moore, G.W.K., Alverson, K. and Holdsworth, G. (2003) The impact that elevation has on the ENSO signal in precipitation records from the Gulf of Alaska region. *Climatic Change* **59**: 101-121

Neal, E.G., Walter, M.T. and Coffeen, C. (2002) Linking the pacific decadal oscillation to seasonal stream discharge patterns in Southeast Alaska. *Journal of Hydrology* **263**, 188-197

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A. and Rahmstorf, R. (2002) Increasing River Discharge to the Arctic Ocean. *Science* **298**, 2171-2173

Shiklomanov, A.I., Lammers, R.B. and Vörösmarty, C.J. (2002) Widespread decline in hydrological monitoring threatens pan-Arctic research. *EOS* **83(2)**, 13-17

Trenberth, K.E. (1990) Recent observed interdecadal climate changes in the Northern Hemisphere. *Bulletin of American Meteorological Society* **71**, 988-993

Waylen, P. and Woo, M.K. (1982) Prediction of annual floods generated by mixed processes. *Water Resources Research* **18**, 1283-1286

Woo, M.K. and Thorne, R. (2002) Comment on "Detection of hydrologic trends and variability" by Burn, D.H. and Hag Elnur, M.A., 2002. Journal of Hydrology 255, 107-122. *Journal of Hydrology* **277**, 150-160

Woo, M.K. and Thorne, R. (2003) Streamflow in the Mackenzie Basin, Canada. *Arctic* **56**, 328-340

Woo, M.K., Thorne, R. and Szeto, K.K. (2006) Reinterpretation of streamflow trends based on shifts in large-scale atmospheric circulation. *Hydrological Processes* **20**, 3995-4003

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