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Increasing discharge from the Mackenzie River system to the Arctic Ocean

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Abstract:

The Mackenzie River, Canada's longest and largest river system, provides the greatest Western Hemisphere discharge to the Arctic Ocean. Recent reports of declining flows have prompted concern because (1) this influences Arctic Ocean salinity, stratification and polar ice; (2) a major tributary, the Peace River, has large hydroelectric projects, and further dams are proposed; and (3) the system includes the extensive and biodiverse Peace–Athabasca, Slave and Mackenzie deltas. To assess hydrological trends over the past century that could reflect climate change, we analysed historic patterns of river discharges. We expanded the data series by infilling for short gaps, calculating annual discharges from early summer-only records (typical $r^2 > 0.9$), coordinating data from sequential hydrometric gauges (requiring $r^2 > 0.8$) and advancing the data to 2013. For trend detection, Pearson correlation provided similar outcomes to non-parametric Kendall's τ and Spearman's ρ tests. There was no overall pattern for annual flows of the most southerly Athabasca River (1913–2013), while the adjacent, regulated Peace River displayed increasing flows (1916–2013, $p < 0.05$). These rivers combine to form the Slave River, which did not display an overall trend (1917–2013). The more northerly, free-flowing Liard River is the largest tributary and displayed increasing annual flows (1944–2013, $p < 0.01$, ~3.5% per decade) because of increasing winter, spring, and summer flows, and annual maximum and minimum flows also increased. Following from the tributary contributions, the Mackenzie River flows gradually increased (Fort Simpson 1939–2013, $p < 0.05$, ~1.5% per decade), but the interannual patterns for the Liard and other rivers were correlated with the Pacific Decadal Oscillation, complicating the pattern. This conclusion of increasing river flows to the Arctic Ocean contrasts with some prior reports, based on shorter time series. The observed flow increase is consistent with increasing discharges of the large Eurasian Arctic drainages, suggesting a common northern response to climate change. Analyses of historic trends are strengthened with lengthening records, and with the Pacific Decadal Oscillation influence, we recommend century-long records for northern rivers. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS empirical trend detection; flow seasonality; Liard River; Peace River

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INTRODUCTION

River flows integrate precipitation, evaporation and drainage over whole watersheds and thus provide diagnostic indicators of hydrological responses to land use development or climate change (Dai *et al*., 2009; Yip *et al*., 2012). Because of their economic, social and environmental values, and their usefulness as watershed sentinels, there is substantial interest in how river flows have changed over the past century, and by extension, how river flows and surface water supplies may change over the 21st century (Arnell, 1996).

There has been a general forecast that climate warming will accelerate the global water cycle, increasing precipitation and river flows (Pavelsky and Smith, 2006; Huntington, 2006). Conversely, warming weather would also increase evaporation, decreasing drainage (Shepherd *et al*., 2010). Also, most global river systems have been dammed and diverted for irrigation, industrial or municipal use, and this has often reduced instream flows (Locke *et al*., 2008). Landscape alterations such as forest clearing and the construction of roads and settlements also alter infiltration of rainfall or snowmelt and accelerate surface runoff, altering the magnitude, timing and quality of river flows (Peters *et al*., 2013). Thus, there are complex and opposing influences that complicate investigations of historic patterns in river flows.

Climate change is likely to be more severe at higher latitudes, and this would involve changes to temperatures and precipitation, which influence water balances and river flows (Déry and Wood, 2005; Rawlins *et al*., 2010; Shepherd *et al*., 2010). Boreal regions generally have reduced water demands for human uses, including agricultural irrigation, and the limited human development and landscape alterations, combined with the increased responsiveness of boreal and subpolar regions

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to climate change, should increase the utility of analysing river flows at higher latitudes (Yip *et al*., 2012).

The Mackenzie River of western Canada is the largest northern river in the Western Hemisphere and drains extensive mountain, foothills, boreal and taiga regions. Worldwide, it ranks 13th relative to drainage area (~1.79 M km^2), fifth in length (Peace, Slave, Mackenzie sequence – 5472 km) and 14th in average annual flow (325 km^3/year). It is the fourth largest system contributing to the Arctic Ocean, behind Russia's Yenisey, Lena and Ob Rivers.

The river system originates from the east slope of the Rocky Mountains of Alberta and British Columbia, and the Mackenzie Mountains of the Yukon, and flows northerly, receiving further inflows from Saskatchewan and Canada's three territories, before flowing into the Beaufort Sea of the Arctic Ocean (Figure 1). The river system drains three of the ten largest lakes of North America (Great Bear, Great Slave and Lake Athabasca) and flows through three globally significant delta systems, the Peace–Athabasca, Slave and Mackenzie deltas, with each providing extensive ecohydrological complexity and supporting rich biodiversity.

The Mackenzie River Basin includes three major tributaries (Figure 1). The most southerly Athabasca River originates from Rocky Mountain snowmelt and rainfall runoff and then flows through a vast boreal region that includes the extensive Athabasca oil sands deposits (Peters *et al*., 2013; Rood *et al*., 2015). The adjacent Peace River watershed has had extensive forest harvesting, and the 186-m-high W.A.C. Bennett Dam was completed in 1968, forming Williston Reservoir, the world's seventh largest reservoir by volume (Chao *et al*., 2008). This dam and reservoir and the subsequent Peace Canyon Dam have altered river and sediment flows, and two further hydroelectric dams downstream are under consideration, Site C in British Columbia and Dunvegan in Alberta. The Athabasca and Peace rivers join near Lake Athabasca (Rasouli *et al*., 2013) to form the Slave River that flows northwards into Great Slave Lake. A proposed

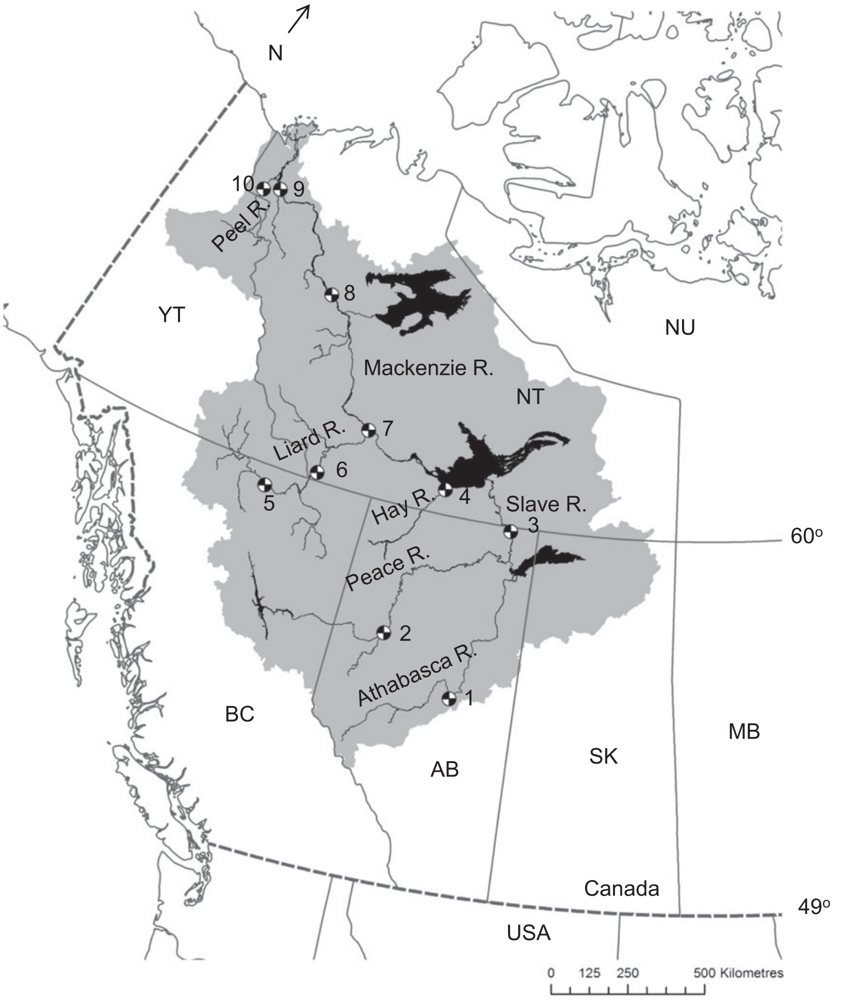

Figure 1. Map of the Mackenzie River Basin, showing the study rivers and primary hydrometric gauges, with numbers corresponding to Table II

hydroelectric project on the Slave River appears less likely, but smaller hydroelectric projects are likely on tributaries in the Northwest Territories (WWF, 2009).

The Mackenzie River commences with the outflow from Great Slave Lake, and subsequently, the Liard River is the largest tributary, contributing about one-third of the flow of the Mackenzie River. The Liard River is free flowing, and the watershed is relatively pristine, and thus, the Liard River represents an especially useful river system to detect boreal and subpolar impacts from climate change, without confounding effects from land use changes or river regulation (Burn *et al.*, 2004b). Downstream from the Liard, the Mackenzie River gradient is consistently gradual, and no dams are currently anticipated, but the valley corridor has been proposed for pipelines and powerlines to developing Arctic Ocean ports (WWF, 2009).

A number of prior studies have investigated historic trends in flows within the Mackenzie River Basin (Table I). These analyses have consistently used the Water Survey of Canada's HYDAT stream flow database, and the prior studies generally considered common data intervals for various tributaries, thus limiting those analyses to intervals of three or four decades. These prior studies generally found no significant change or declining flows over the study intervals, which often commenced in the 1960s (Table I).

Complicating trend analyses, North American river flows are naturally highly variable across years and also display some correlation with climate patterns and especially the Pacific (multi) Decadal Oscillation (PDO) (Mantua and Hare, 2002; Rood *et al.*, 2005; Whitfield *et al.*, 2010). Longer records become increasingly confident in detecting progressive trends that are superimposed on the stochastic variation and the cyclic oscillation (Yip *et al.*, 2012; Whitfield *et al.*, 2010). Consequently, we sought to lengthen the record intervals for the Mackenzie Basin rivers by selecting gauges with the longest records and extending these data sets by estimating annual flows from early, seasonal flow data

Table I. Analyses of historic patterns of discharges (Q) of rivers (upstream to downstream) in the Mackenzie River Basin

River station	Interval	Change in Q: ↑, ↑, or ~; increase, decrease or no trend[a]	Author(s)
Peace			
Peace point	1972–1999	~	Woo and Thorne, 2003
19 stations	1966–2010	~	Bawden *et al.*, 2014
Peace River	1916–1930; 1958–2013	↑**	This study
Slave			
Fitzgerald	1916–1930; 1952–1967; 1972–2012[b]	~	This study
Liard			
Mouth	1972–1999	Apr↑t, Dec↑*	Woo and Thorne, 2003
5 stations	1961–2000	Feb, Mar, Apr, Dec↑t	Burn *et al.*, 2004a
7 stations	1960–1999	↑t Mar, Apr, May, Dec ↑t Jun, Aug ↑t	Burn *et al.*, 2004b
Fort Liard	1966–1980; 1983–2009	~	Rayne and Forest, 2010
Fort Liard	1944–2013[b]	↑** Jan through Jun, Sep, Oct, Dec↑* or **	This study
Mackenzie			
Reference stations	1967–1996	~	Zhang *et al.*, 2001
Reference stations	1967–1996	~	Yue and Wang, 2002
Arctic Red River	1972–1999	~	Woo and Thorne, 2003
21 stations	1960–2000	39%↑t Mar, Apr 41 to 50%↑t	Abdul Aziz and Burn, 2006
Arctic Red River	1948–2004[b]	~	Dai *et al.*, 2009
Fort Simpson	1939–1948; 1951–1961; 1964–2013	↑**	This study
Arctic Red River	1965–2014[b]	↑t	This study

Changes relate to average annual Q or monthly Q as indicated by month abbreviations. A similar listing for the Athabasca River was provided in Rood *et al.* (2015).

[a] t (trend), *, ** = $p < 0.1$, $p < 0.05$, $p < 0.01$.

[b] Data extended through coordination with other gauges.

and through the coordination of data from sequential or associated hydrometric gauges (Rood *et al*., 2005; 2016).

At the onset of our study, we expected that annual flows would have declined over the past century since (1) flow declines have been observed along other rivers that originate in adjacent but more southerly headwaters in the east slope of the Rocky Mountains (Rood *et al*., 2005) and (2) some prior analyses had concluded that recent flows had been declining within the Mackenzie River Basin (Table I; Rood *et al*., 2015). We further anticipated that there could be seasonal changes and particularly flow declines in the summer, as had been observed for the adjacent, more southerly rivers that drain the Rocky Mountains (Rood *et al*., 2008).

METHODS

River discharges (Q) were obtained from the Water Survey of Canada's HYDAT database (http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm), with validated records extending to 2012, 2013 or 2014 (Table II). Following our consideration of available records, we selected the gauging stations with the longest and most continuous data series. We subsequently assessed the data gaps, and in some cases, lapses of only a single or few days were responsible for the missing monthly and subsequent annual Q values. In such cases, we interpolated the missing daily value(s) by averaging the discharges of the flanking days and then calculated the monthly and annual Q (Q_{annual}) for that year.

Some yearly records had longer data gaps, and in these cases, we estimated Q_{annual} through linear regression of the Q_{annual} for the years with complete data sets *versus* the averages of the available monthly Q for the incomplete years. We did not estimate missing monthly Q values, and the analyses of monthly and seasonal Q are based on the direct, archived data. In the early years of gauging, manual records were maintained, and these were limited to the warmer season, typically from April through

Table II. Rivers and stations investigated relative to historic discharges (Q) in the Mackenzie River Basin, with numbers corresponding with map locations (Figure 1)

	River (station)	Latitude (N) longitude (W)	Gauged drainage area (km^2)	Mean Q (m^3/s)	Period of record	Analysed record (years[a])
1	Athabasca (Athabasca) 07BE001	54°43′19″ 113°17′16″	74 600	422	1913–1930; 1938–1951[b]; 1952–2013	78
2	Peace (Peace River) 07HA001	56°14′41″ 117°18′51″	194 000	1845	1916–1931; 1953–1959[b]; 1960–2013	67
3	Slave (Fitzgerald) 07NB001	59°52′20″ 111°35′0″	606 000	3371	1920–1921[b]; 1953–1967[b]; 1972–2012	72
4	Hay (Hay River) 07OB001	60°44′34″ 115°51′34″	51 700	110	1964–2014	51
5	Liard (Lower Crossing) 10BE001	59°24′45″ 126°05′50″	104 000	1148	1947–1965[b]; 1966–2014	67
6	Liard (Fort Liard) 10ED001	60°14′29″ 123°28′31″	222 000	1968	1944–1959[b]; 1960–2013[c]	69
7	Mackenzie (Fort Simpson) 10GC001	61°52′6″ 121°21′32″	1 301 435	6875	1939–1964[b]; 1965–2013[b]	75
8	Mackenzie (Norman Wells) 10KA001	65°16′19″ 126°51′0″	1 590 000	8514	1943–2013[b]	65
9	Mackenzie (Arctic Red River) 10LC014	67°27′21″; 133°45′11″	1 679 100	9187	1965–1972[c]; 1973–2014	50
10	Peel (Fort McPherson) 10MC002	67°15′32″; 134°53′19″	70 600	692	1975–2014	39

[a] Years for Q_{annual} analysis, records varied for some other measures.
[b] Incomplete record.
[c] Data extended through correspondence with other gauges.

October. This interval provides by far the period of greatest flow, while the natural winter flows of all of the study rivers were proportionally lower and also fairly consistent. Consequently, the linear correspondences between warm season flows (May through September or October) and Q_{annual} were very high, and correspondences (coefficients of determination, r^2) of the mean Q of these 5 or 6 months and Q_{annual} generally exceeded 0.95 (Figure 2).

Our analyses also considered Q data from multiple hydrometric gauges from individual rivers. For the Athabasca, Peace and Liard rivers, we spliced data from multiple-gauge sites to fill in some missing years from the location that was selected as the primary location. We applied linear regression analysis, using Q_{annual} data for the period(s) of data overlap and required a correspondence $(r^2) > 0.8$ for inclusion in the data series that was analysed for historic patterns.

Following the data extensions, we plotted the Q_{annual} time series for the rivers and produced plots of the Q_{annual} values for pairs of rivers, to reveal the extent of coordination and to detect outlier values. These plots demonstrated correspondences for the different rivers (Table III), and these were increased for related rivers such as for the Athabasca or Peace and the subsequent Slave River and for the Slave or Liard and the subsequent Mackenzie River. The comparisons revealed the 1950 Mackenzie River Q data as anomalous, and those values were omitted from the subsequent Q_{annual} and seasonal Q analyses.

Table III. Correspondences (r^2) of mean annual discharges (Q_{annual}) for major rivers or locations within the Mackenzie River Basin, with significant ($p < 0.05$) values in bold font

	Peace	Slave	Liard	Mackenzie (Ft. Simpson)	Mackenzie (Arctic Red River)
Athabasca	**0.144**	**0.252**	0.001	0.001	0.003
Peace		**0.588**	**0.121**	**0.260**	**0.149**
Slave			**0.104**	**0.432**	**0.231**
Liard				**0.539**	**0.543**
Mackenzie (Ft. Simpson)					**0.717**

We thus investigated historic trends in the composite Q_{annual} series, as well as analyses of monthly Q and average Q for 3-month groupings corresponding to the climatic seasons: winter = December, January, February, and so on. For extreme values, we assessed the maximum and minimum mean daily Q over the records. We considered the calendar year rather than the water year because October flows extend the flow recession after the June peak, and aquatic and riparian organisms display activity and life cycle patterns that extend from the summer into autumn (Rood *et al*., 2008; Locke *et al*., 2008). Because October through December flows of these northern rivers were low, there would be little difference in analyses based on chronological *versus* water years.

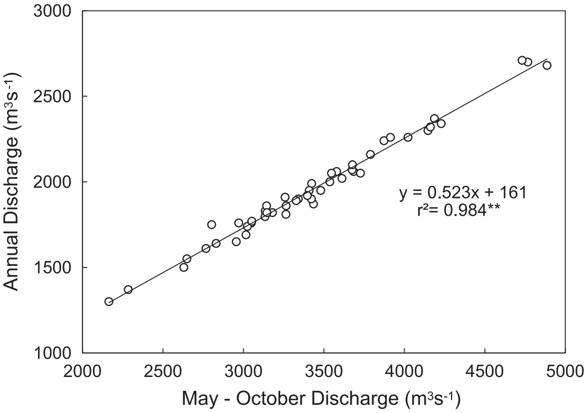

Figure 2. Mean annual discharge (Q_{annual}) *versus* mean May through October discharge of the Liard River. The linear regression was used to estimate Q_{annual} from seasonal Q data that had been collected during the early years of hydrometric gauging

To detect historic trends, we used SPSS19 (IBM, Armonk, NY) to undertake linear regression and Pearson correlation analysis, a parametric approach, in addition to the non-parametric, rank-order Kendall's τ and Spearman's ρ tests (Rood *et al*., 2005). For figures, we provide the linear regression lines and equations for data series with statistically significant outcomes ($p < 0.05$).

To consider the possible influence from correlation across sequential years due to factors such as carry over snowpack or groundwater, we investigated autocorrelation within the Q_{annual} time series, undertook trend free pre-whitening (TFPW, Abdul Aziz and Burn, 2006) and then repeated the correlation analyses. This possible confounding influence is generally reduced with longer time series and even with our short series for the Liard River, the 1-year lag autocorrelation provided only a statistical trend (Box-Ljung value 3.47, $p = 0.062$), and the correlations were minimally altered with TFPW (Pearson r: 0.383, $p = 0.001$ *vs.* with TFPW: 0.369, $p = 0.002$; Kendall's τ: 0.289, $p = 0.000$ *vs.* with TFPW: 0.264, $p = 0.001$). Thus, the outcomes were similar, and we present those without TFPW to retain statistical power (Bayazit and Önöz, 2007).

RESULTS

The Athabasca River hydrometric record commenced in 1913 (Table II) to provide the earliest and most complete flow record for any Northern Hemisphere river that drains to the Arctic Ocean. The record displays extensive interannual variation but no overall trend in annual discharge (Table IV). There was an apparent decline after 1960 (Figure 3) that we and others have previously reported, partly corresponding to a phase transition in the PDO (Rood *et al*., 2015). A multi-year data gap exists during the North American Great Depression, which coincided with a drought interval. We have previously filled in the record gaps at 'Athabasca' based on the closely correlated upstream 'Entrance' hydrometric gauge to derive an almost continuous record from 1913 to 2012 that did not display any overall trend (Rood *et al*., 2015), similar to our present analysis.

The headwaters of the Peace River are in British Columbia, and gauging commenced a century ago at the Alberta town of Peace River (Table II), which is below the major mountain inflows. Annual mean flows increased significantly over the period of record (Table IV, Figure 3), and there was also substantial interannual variation, with low and high flows occurring even in sequential years such as in 1995 and 1996 (Figure 3). Because of the massive W.A.C. Bennett Dam and Williston Reservoir, flows have been regulated after 1968, altering the seasonal flow regime and hindering analyses of possible influences from climate change on flow seasonality or extremes.

The Athabasca and Peace rivers join to produce the Slave River, with the Fitzgerald gauge near the 60°N parallel (Figure 1). Gauging here was only undertaken for two early years, 1921 and 1922, and resumed three decades later. Regression analysis including these two early years would indicate a pattern of decline (Pearson's $r = 0.292$, $p = 0.01$; Kendall's $\tau = 0.193$, $p = 0.02$), but the records from the contributing Athabasca and Peace rivers show that 1921 and 1922 were unusually high flow years. Probable flows for prior and subsequent years along the Slave River were estimated through linear regression with the combined flows of the Peace River and Athabasca River (doubled for the Athabasca to reflect the gauge location upstream from substantial inflows; $Q_{\text{Slave}} = (Q_{\text{Peace}} + 2Q_{\text{Athabasca}}) \times 0.851 + 1081$; $r^2 = 0.541$; $p < 0.001$). This extended the Slave River record (with the '×'s plotted, Figure 3), and with these derived values, there was no significant pattern in annual discharge over the interval from 1916 to 2013 (Table IV).

Table IV. Correlation coefficients and probabilities for mean annual discharges *versus* years for rivers in the Mackenzie River Basin (Table II), with the parametric Pearson, and non-parametric Kendall's τ b and Spearman's ρ tests

River	Pearson's r, p	Spearman's ρ, p	Kendall's τ, p
Athabasca	−0.073, 0.53	−0.095, 0.41	−0.082, 0.29
Peace	**0.292**, **0.01**	**0.286**, **0.01**	**0.193**, **0.02**
Slave	−0.041, 0.73	−0.079, 0.33	−0.129, 0.28
Hay	0.138, 0.34	0.186, 0.19	0.132, 0.17
Liard (Ft. Liard)	**0.383**, **0.01**	**0.402**, **0.01**	**0.289**, **0.01**
Mackenzie (Ft. Simpson)	**0.276**, **0.02**	**0.298**, **0.01**	**0.212**, **0.01**
Mackenzie (Arctic Red River)	0.222, 0.12	*0.238*, *0.10*	*0.168*, *0.09*
Peel	−0.084, 0.61	−0.060, 0.71	−0.040, 0.74

A negative correlation indicates decline and trends ($p < 0.1$, *italics*) or significant ($p < 0.05$, **bold**) patterns are indicated.

The dammed Peace River provides a larger flow contribution to the Slave River than the free-flowing Athabasca River, and this regulation alters the monthly, seasonal and extreme Slave River flows, excluding the investigation of possible patterns of these flow characteristics associated with climate change. The Slave River flows northward into the massive Great Slave Lake, and the outflow is designated as the commencement of the Mackenzie River.

Initially flowing westward, the Mackenzie River is joined by its largest tributary, the free-flowing Liard River (Figure 1). Hydrometric records commenced later for the more northerly rivers and only in 1944 for the Liard River (Figure 3). From 1944 to 2013, there was substantial interannual variation that was superimposed on progressive increase in the mean annual flow (Table IV, Figure 3). That increase was about 0.35% per year, or around 3.5% per decade.

Because the Liard is free flowing, its historic pattern should reveal patterns in seasonality associated with climate change. There were significant increases in winter, spring and summer flows, while the autumn flows displayed no significant pattern (Figure 4). For contribution to the overall annual flow increase, summer flows were largest and most influential, followed by the increase in spring flows. Winter flows were consistently lower, but the increase in winter flows may have been proportionally greater, although this analysis is limited by the shorter winter record (Figure 4). There was general consistency in the patterns in seasonal flows between the two Liard River gauges, but the mountain watershed displayed increasing summer flows, which were apparently not reflected in the contributions from the downstream boreal region (Figure 4). This indicates some differentiation in the influences of climate change across the watershed, similar to that observed for the Athabasca River (Rood *et al*., 2015).

The increase in winter flows was confirmed by analyses of monthly means, with significant increases in December, January and February (Table V). Monthly flows also increased in the spring months of March through May. Of the summer season months, only June flows were significantly increased, although the regression coefficients suggested increases in July and August. There was apparently some differentiation within the autumn season,

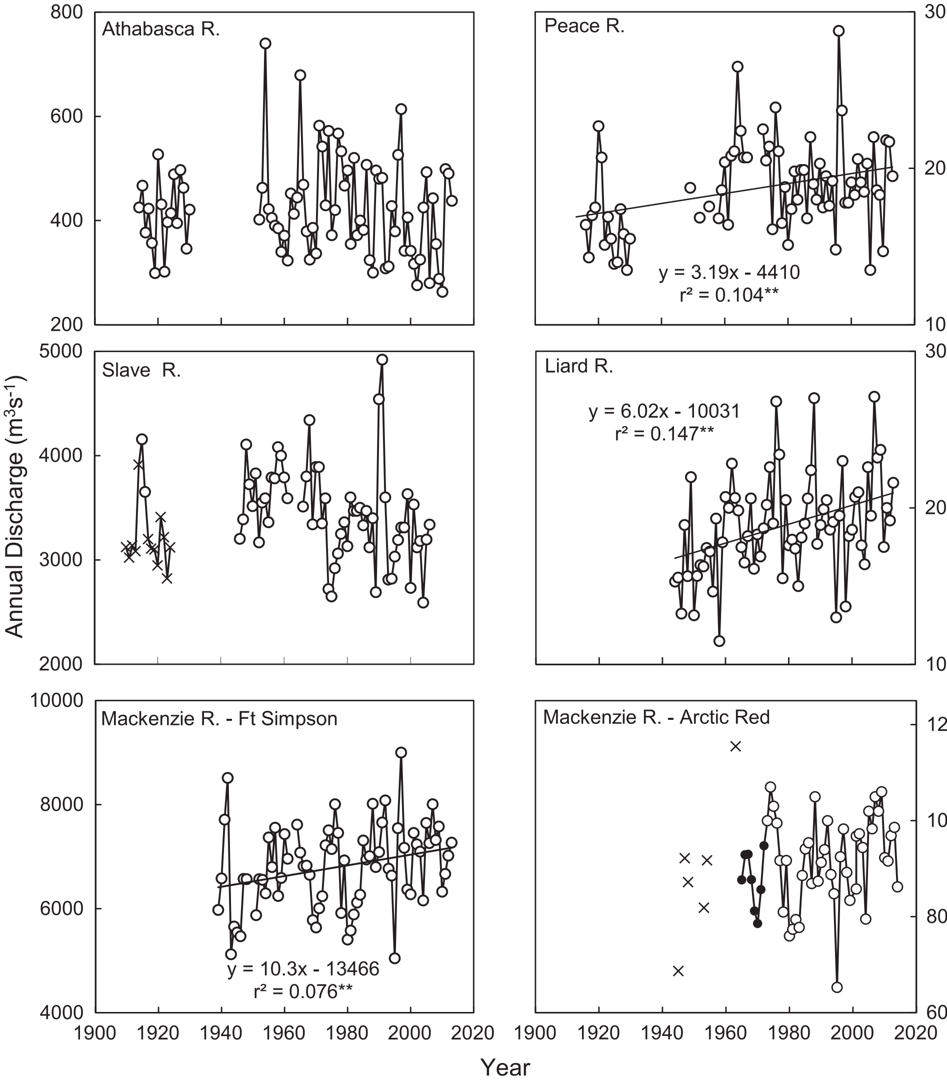

Figure 3. Mean annual discharges (Q_{annual}) of six major rivers in the Mackenzie River Basin. For the Peace River and Slave River downstream, the W.A. C. Bennett Dam was completed in 1968, and flows were reduced over the next 3 years of reservoir filling and that interval is excluded from the trend analysis. For the Slave River and Mackenzie River at the Arctic Red gauge, 'Xs' in the early record indicate values that were derived through regression with inflows from the two contributing tributaries. The dark symbols indicate values derived from the upstream record. Note different *y*-axis scales for each river

with significant increases in September and October followed by a tendency for decline in November. The record also revealed progressive increases in the annual peak flows and in the annual minimum flows (Figure 5). Thus, the annual, seasonal, monthly and extreme flows all indicated increases over the past seven decades for the Liard River.

Below the Liard, river gauging along the Mackenzie River commenced in 1938 at Fort Simpson, and there has subsequently been irregular gauging at various other locations. The Fort Simpson gauge reflects flows from about three-quarters of the Mackenzie River Basin (Table II), with warm season gauging from 1939 through 1959 and generally year-round monitoring thereafter. There was 85.1% correspondence between $Q_{\mathrm{Jun\text{-}Sep}}$ and Q_{annual}, enabling a fairly confident Q_{annual} record from 1939 to 2013 (Figure 3). Within this interval, the annual flows of the Mackenzie displayed substantial interannual variation, similar to that observed for the contributing tributaries (Figure 3). The Mackenzie River record also displayed progressive increase over the past 74 years (Table IV), consistent with the observed increases of the free-flowing and largest tributary, the Liard and of the Peace River, which has headwater drainages adjacent to the headwater of the Liard River.

Downstream from Fort Simpson, a hydrometric gauge was installed at Norman Wells in 1945 but only irregular warm season monitoring followed until 1966. Further downstream, the Arctic Red River gauge records commenced in 1972 and 83.8% correspondence between

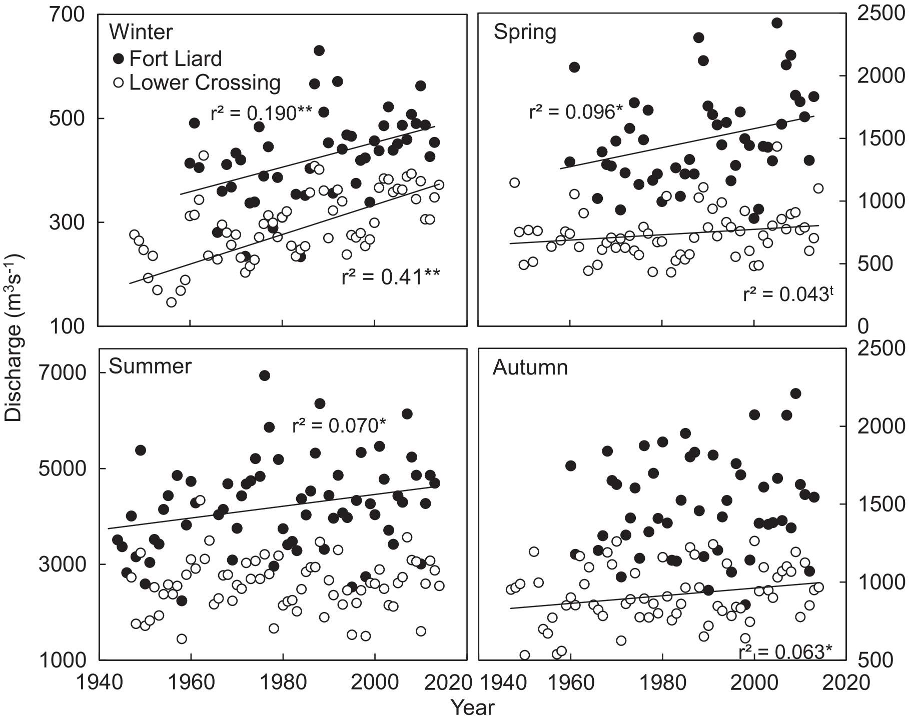

Figure 4. Mean discharges (Q) for the climatic seasons (spring = March, April, May, and so on) for the intervals of record of the Liard River at the Fort Liard and Lower Crossing gauging stations

Q_{annual} for the Norman Wells and Artic Red River gauges enabled splicing to develop a composite record from 1965 to 2014 (Figure 3). This record displayed a similar pattern to that of the upstream Fort Simpson gauge (72% correspondence, Table III) and with the shorter interval the pattern provided a statistical trend (i.e. $p < 0.1$, Table IV). Provisional record extension was based on estimations from the irregular, warm season records at Norman Wells, as plotted in Figure 3. This further supports a progressive increase in the Mackenzie River flows but is less confident because the correspondences between different combinations of warm season monthly flows and Q_{annual} were between 65% and 70%.

Table V. Analyses of historic mean monthly discharges (Q_{month}) over the periods of record for the Liard River (Ft. Liard, 1944–2013 for some warm season months, shorter intervals through winter), with significant patterns ($p < 0.05$) in bold font

Month	Pearson's r, p	Kendall's τ, p
January	**0.45**, **0.01**	**0.35**, **0.01**
February	**0.46**, **0.01**	**0.39**, **0.01**
March	**0.42**, **0.01**	**0.32**, **0.01**
April	**0.47**, **0.01**	**0.35**, **0.01**
May	**0.24**, **0.05**	**0.17**, **0.05**
June	**0.31**, **0.01**	**0.21**, **0.01**
July	0.14, 0.29	0.11, 0.22
August	0.17, 0.18	0.14, 0.11
September	**0.40**, **0.01**	**0.28**, **0.01**
October	**0.37**, **0.02**	**0.26**, **0.01**
November	−0.20, 0.16	−0.07, 0.44
December	**0.39**, **0.01**	**0.29**, **0.01**
Annual	**0.38**, **0.01**	**0.29**, **0.01**

Positive coefficients indicated increasing values.

The Arctic Red River gauge is situated upstream from the channel distributaries of the Mackenzie Delta. The final major tributary, the Peel River, inflows downstream from that gauge into the delta. The continuous record for the Peel River at Fort McPherson only commenced in 1975, and no trend emerges with this short and variable time series (Table IV). As the most northerly tributary, it

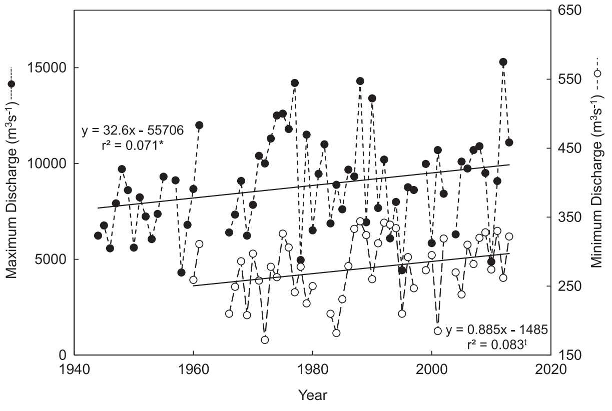

Figure 5. Annual maximum and minimum mean daily discharges ($Q_{\max}$, $Q_{\min}$) of the Liard River for the periods of hydrometric record

could be instructive to follow the Peel River flows as this hydrometric record increases

The regulation of the Peace River influences downstream flows of the Slave River and subsequently the Mackenzie River. While this complicates analyses of seasonal and monthly flows of the Mackenzie River, the averaged daily hydrograph patterns of the Mackenzie River at Fort Simpson displayed very similar changes to those of the Liard River (Figure 6). This is illustrated with comparisons of averaged flows from 1966 to 1975, the earliest decade with year-round gauging, *versus* the recent decade of 2004 to 2013 (Figure 6).

For both rivers, the major changes included an advancement of the spring peak and subsequently increased flows through the spring and into early summer (Figures 4 and 6). Thereafter, the recession limbs of the hydrographs were almost identical in the early *versus* recent decades. Winter flows of the Liard displayed slight increase, while the greater increase in winter flows of the Mackenzie River would reflect flow augmentation from the Peace River, following hydroelectric power generation through the winter.

Our final analysis explored the possible correlation between river flows and the PDO, and for comparison, we present the free-flowing Liard River (Figure 7). The two patterns displayed some similar rises and falls, but the Q_{annual} generally lagged, and a 2-year offset provide the strongest apparent correspondence (Figure 7). With this offset, there were intervals with strong association such as with the parallel fall and rise sequences from 1983 to 1993 ($r^2 = 0.775$, $p < 0.01$) and from 2002 to 2011 ($r^2 = 0.814$, $p < 0.01$), or the longer interval from 1975 to 2011 ($r^2 = 0.405$, $p < 0.01$). There was a major change in the PDO in the interval from 1971 to 1983, and this represents a transition in the PDO phase (Mantua and Hare, 2002). Thus, the annual discharge of the Liard River displayed a pattern with two overlapping components: a progressive increase over the past three-quarter century, combined with variation that was correlated with the PDO.

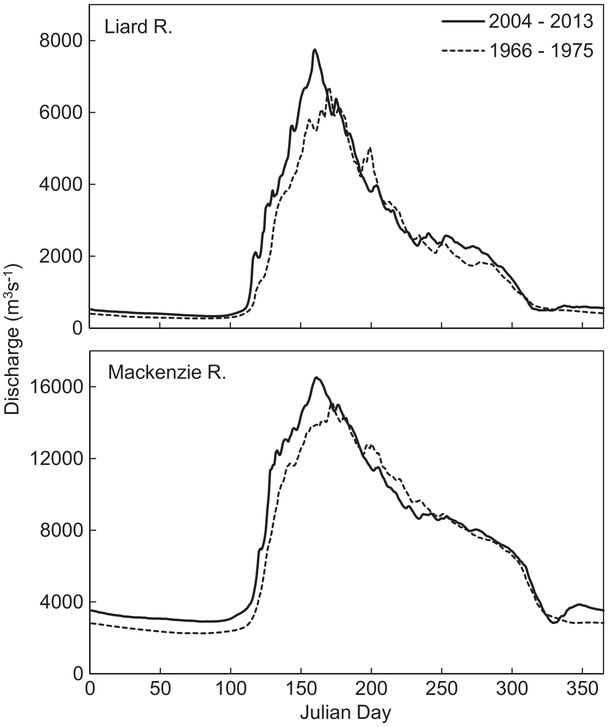

Figure 6. Hydrographs of the free flowing Liard River at Fort Liard (top) and Mackenzie River at Fort Simpson (bottom), showing mean daily values averaged for earlier (1966–1975) and recent (2004–2013) decades

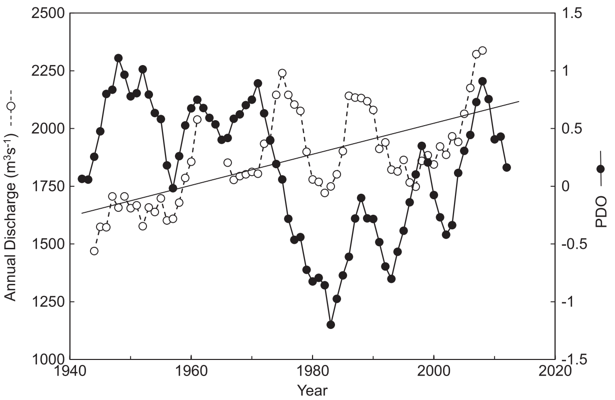

Figure 7. Moving 5-point averages for mean annual discharges (Q_{annual}) of the Liard River and for the Pacific Decadal Oscillation (PDO) index. The PDO is inverted (i.e. × −1) to coordinate the patterns and is offset 2 years earlier to account for the apparent lag prior to the Q response. The plotted line represents the Q_{annual} linear regression ($r^2 = 0.403$, $p < 0.01$)

DISCUSSION

The study outcomes lead to the confident rejection of our primary prediction, that there would have been declining flows of these Arctic drainages. That prediction was based on two lines of evidence: reports of declining flows in prior studies (Table I) and the decline in flows over the past century for the adjacent rivers to the south, which also drain the east slope of the Rocky Mountains (Rood *et al*., 2005).

Previous reports investigated shorter intervals of three or four recent decades, and this period would have been confounded by the PDO phase transition around the 1970s. To absorb the influence from climate oscillation, it is useful to assess intervals of at least two oscillations, or around eight decades (Rood *et al*., 2016; Whitfield *et al*., 2010). Our current study reaches this criterion for the southerly rivers, but the record for the northern tributaries and the overall Mackenzie River would benefit from a longer hydrological record. With or without influences from climate oscillation, trend analyses for river flows become progressively more confident with longer duration.

Our observed differences in the historic patterns between the more northerly and more southerly rivers in the Mackenzie Basin suggest a latitudinal transition in the hydroclimatic response to climate change. Rivers even further south, draining the central Rocky Mountains towards Hudson Bay, have displayed declining flows over the past century (Rood *et al*., 2005). The Athabasca River that represents the most southerly Arctic Ocean drainage has not displayed a significant pattern over the past century, but there was correlation with PDO (Rood *et al*., 2015). In this present study, we have determined that the more northerly Peace and Liard Rivers that provide major contributions within the Mackenzie River Basin displayed increasing flows (Figure 3). This indicates a transition in the influence of climate change on water cycle patterns, which may reflect changing precipitation. While winter snow and associated snowpacks have probably been decreasing in the central Rocky Mountain region, the increased spring flows of the Liard and Mackenzie Rivers would suggest increased snowmelt, which provides the major contribution to early spring flows (Burn, 2008). This interpretation would be consistent with the observed changes in the seasonal flow patterns (Figure 6) and our conclusion of differing river flow responses from central *versus* northern Rocky Mountain regions (Rood *et al*., 2005; 2016). However, warming conditions in the Arctic regions are also leading to permafrost thawing that can influence wetland drainage, infiltration and groundwater flows, thus providing other hydrological alterations that could contribute to the changing flows of these northern rivers (St. Jacques and Sauchyn, 2009; Connon *et al*., 2014).

Also related to the broader spatial patterning, our conclusion of increasing flows of the largest Western Hemisphere river system draining to the Arctic Ocean provides a pattern that is apparently consistent with the observations for the largest Arctic drainages in the Eastern Hemisphere (McClelland *et al*., 2006; Pavelsky and Smith, 2006; Shiklomanov and Lammers, 2009). This suggests a common hydroclimatic response to climate change through the most northern regions of North America and Eurasia.

Finally, relative to the management implications, the conclusion that major Arctic drainages in western Canada have displayed increasing flows might indicate that flows could further increase, at least over the next half century (Shepherd *et al*., 2010). This would influence environmental conditions and has economic implications for continuing and expanded hydroelectric power generation. The Peace River currently supports two major hydroelectric dams, W.A.C. Bennett and Peace Canyon, and a third, ‘Site C’, was recently approved. We might anticipate consideration for further hydroelectric development for the large and largely undeveloped northern rivers, as a possible strategy to increase renewable power generation to limit climate change. If so, comprehensive assessments of prospective future projects will rely on a better understanding of the probable future flow patterns of the prospective rivers, including the various tributaries of the Mackenzie River Basin.

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