Journal of Hydrology 371 (2009) 108–119

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation

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ARTICLE INFO

Article history:
Received 5 May 2008
Received in revised form 19 February 2009
Accepted 14 March 2009

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Phillip Arkin, Associate Editor

Keywords:
Yukon River
Pacific Decadal Oscillation
Streamflow trends
Permafrost thaw

SUMMARY

Streamflow characteristics in the Yukon River Basin of Alaska and Canada have changed from 1944 to 2005, and some of the change can be attributed to the two most recent modes of the Pacific Decadal Oscillation (PDO). Seasonal, monthly, and annual stream discharge data from 21 stations in the Yukon River Basin were analyzed for trends over the entire period of record, generally spanning 4–6 decades, and examined for differences between the two most recent modes of the PDO: cold-PDO (1944–1975) and warm-PDO (1976–2005) subsets. Between 1944 and 2005, average winter and April flow increased at 15 sites. Observed winter flow increases during the cold-PDO phase were generally limited to sites in the Upper Yukon River Basin. Positive trends in winter flow during the warm-PDO phase broadened to include stations in the Middle and Lower Yukon River drainage basins. Increases in winter streamflow most likely result from groundwater input enhanced by permafrost thawing that promotes infiltration and deeper subsurface flow paths. Increased April flow may be attributed to a combination of greater baseflow (from groundwater increases), earlier spring snowmelt and runoff, and increased winter precipitation, depending on location. Calculated deviations from long-term mean monthly discharges indicate below-average flow in the winter months during the cold PDO and above-average flow in the winter months during the warm PDO. Although not as strong a signal, results also support the reverse response during the summer months: above-average flow during the cold PDO and below-average flow during the warm PDO. Changes in the summer flows are likely an indirect consequence of the PDO, resulting from earlier spring snowmelt runoff and also perhaps increased summer infiltration and storage in a deeper active layer.

Annual discharge has remained relatively unchanged in the Yukon River Basin, but a few glacier-fed rivers demonstrate positive trends, which can be attributed to enhanced glacier melting. A positive trend in annual flow during the warm PDO near the mouth of the Yukon River suggests that small increases in flow throughout the Yukon River Basin have resulted in an additive effect manifested in the downstream-most streamflow station.

Many of the identified changes in streamflow patterns in the Yukon River Basin show a correlation to the PDO regime shift. This work highlights the importance of considering proximate climate forcings as well as global climate change when assessing hydrologic changes in the Arctic.

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Introduction

The Yukon River Basin (Fig. 1), located in northwestern Canada and central Alaska, is the fourth largest basin in North America with a drainage area of 857,300 km^2 and an average annual discharge of 6400 m^3/s (Brabets et al., 2000). The basin represents one of the largest and most diverse ecosystems in North America. Salmon, which are a staple of the subsistence lifestyle of rural villages, travel the entire length of the river (approximately 2800 km) to spawn. Villages and towns obtain water for drinking from the river and associated aquifers (Brabets et al., 2000). The Yukon River is also fundamental to the Bering Sea ecosystem, providing most of the freshwater runoff, sediments, and dissolved solutes in the eastern part of the sea (Lisitsysn, 1969). Thus, processes that influence the Yukon River and its major tributaries in turn influence the Bering Sea.

Global surface temperatures have increased at a rate of 0.13 °C ± 0.03 °C per decade for the past 50 years, a rate nearly double that of the past 100 years (www.ncdc.noaa.gov). Recent climate warming is particularly evident in high-latitude regions such as the Yukon River Basin (Hinzman et al., 2005). Permafrost is thawing (Osterkamp, 2007), and glaciers are retreating (BESIS, 1997). How changes to the hydrologic system related to climate variability in

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0022-1694/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2009.03.018

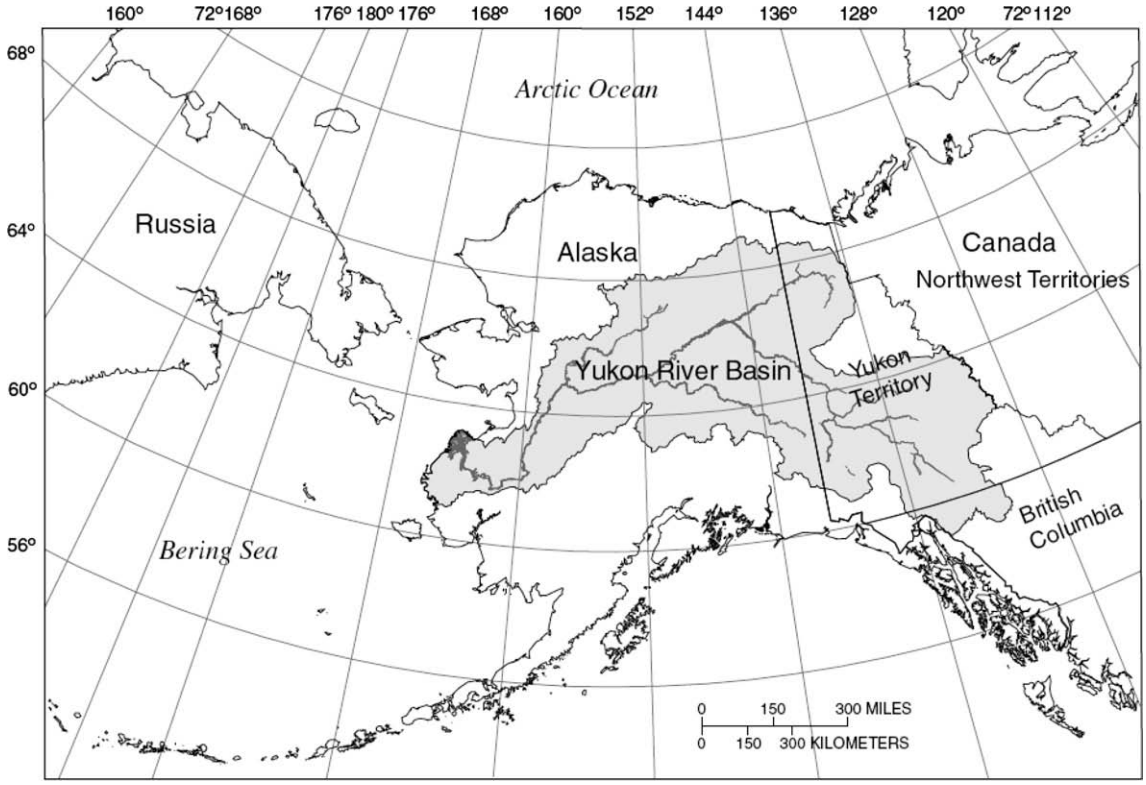

Fig. 1. Location of Yukon River Basin.

the interior and arctic regions of Alaska and western Canada ultimately influence the amount and timing of flow in the main stem of the Yukon River and its tributaries is of interest from both a water resource management perspective and ecologic sustainability perspective. The timing of river ice breakup is strongly influenced by spring temperatures. Ice breakup dates on the Yukon River at Dawson, Yukon Territory (YT) and the Tanana River at Nenana, Alaska (AK) are occurring earlier in the year (data from the Yukon Department of Environment and the Arctic Environmental Information Data Center, respectively; Fig. 2). Earlier ice breakup is likely in response to higher spring temperatures. Walvoord and Striegl (2007) report an upward trend of 0.7–0.9% per year in

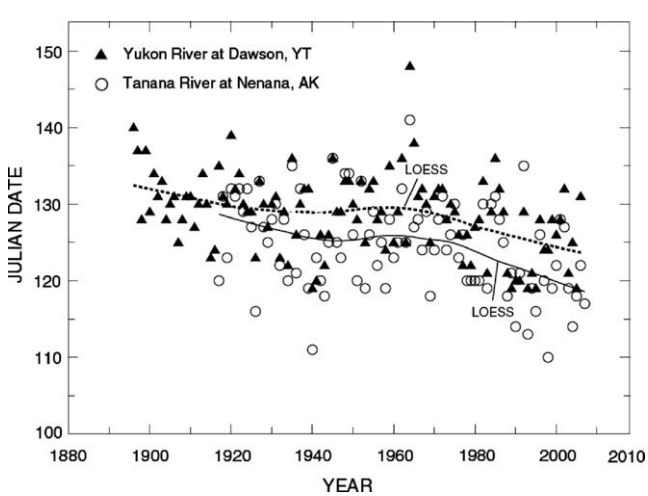

Fig. 2. Breakup dates for Yukon River at Dawson, YT and Tanana River at Nenana, AK.

groundwater contribution to total streamflow in the Yukon River Basin that they attribute to permafrost thawing associated with an overall warming trend evidenced in the Arctic in recent decades (Serreze et al., 2000). Relative change in streamflow components affects the proportions of inorganic and organic carbon and nitrogen exports and total carbon exports to the Bering Sea. Although it is likely that warming has had an effect on streamflow in the Yukon River Basin, the study described here further considers the importance of proximate climate variability, specifically the Pacific Decadal Oscillation (PDO), on streamflow changes in the Yukon.

The PDO represents a pattern of Pacific climate variability with regional climate signatures similar to those associated with the El Niño/Southern Oscillation (ENSO) although not as extreme (Zhang et al., 1997). PDO regimes typically persist for 2–3 decades while ENSO phases last from 6 to 18 months. The warm phase, indicated by positive polarity in the PDO index, is associated with anomalously cool Central-North-Pacific sea-surface temperatures (SSTs) and warm SSTs in the eastern tropical Pacific. The cold phase, indicated by negative polarity in the PDO index, occurs when the SSTs are reversed. The change in location of cold and warm water ocean masses alters the path of the jet stream responsible for storm delivery. In northwestern North America, this generally translates as below-average October – March precipitation and above-average October – March temperatures during the warm-PDO phase relative to the cold-PDO phase (Mantua et al., 1997). The climate system over the North Pacific altered its basic state abruptly in the summer of 1976 resulting in a phase shift from a cold- to a warm-PDO (Fig. 3) with air temperature changes most pronounced in continental regions of Alaska as compared to maritime regions (Hartmann and Wendler, 2005). Long-term precipitation records in the Yukon River Basin are relatively sparse. Hartmann and Wendler (2005) report no statistically significant change in annual precipitation between the most recent cold and warm-PDO phases (1951–1975 and 1977–2001, respectively) in the interior of Alaska,

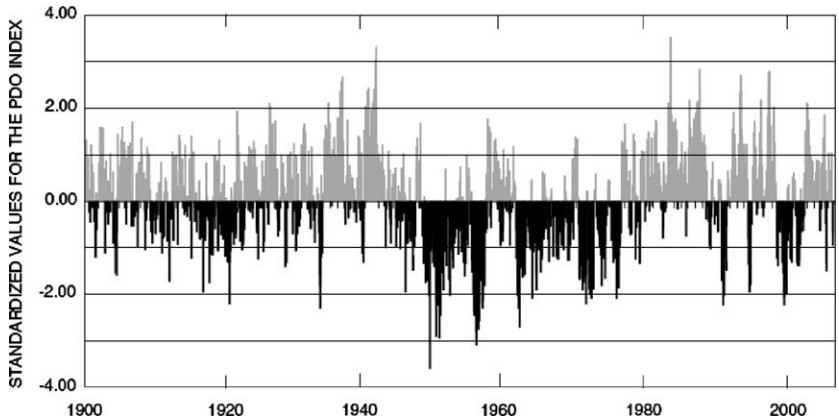

Fig. 3. Time series of the monthly values of the PDO index from 1900 to 2005. Grey indicates positive or warm phase. Black indicates negative or cold phase.

which encompasses the majority of the Yukon River Basin. However, they do report changes in annual precipitation in adjacent regions of Alaska as the climate shifted phase from the cold to the warm PDO, mainly as a result of changes in winter precipitation. Annual precipitation increased (+15%; $p < 0.10$) for western Alaska and decreased (−16%; $p < 0.10$) in arctic Alaska. These regions cover parts of the Yukon River Basin. Hartmann and Wendler (2005) also report a statistically significant increase in winter snowfall (+20%; $p < 0.10$) for interior Alaska between the cold and warm PDO. Thus, the observed precipitation response to the PDO is somewhat mixed across the Yukon River Basin. In contrast, air temperatures, particularly during the winter and spring, throughout all parts of Alaska have experienced an increase concurrent with the PDO phase shift. Hartmann and Wendler (2005) identified the greatest difference in mean seasonal air temperatures, +3.7 °C from cold to warm PDO ($p < 0.01$), during the winter months in the interior of Alaska. Yet, the PDO index has not consistently remained positive since 1976. For example, the winters of 1989/1990, 1998/1999, and 1999/2000 occurred during the warm regime of the PDO and yet are among the coldest winters in Alaska, corresponding with negative PDO indices. The PDO index also became negative in 1999 but rebounded to a positive index in 2002 that continued through 2005. Additional time is required to determine if the phase of the PDO has in fact switched back to a predominately negative phase.

Climate variability associated with the PDO has been shown to affect streamflow timing in the high-latitudes of North America. Stewart et al. (2005) examined trends towards earlier snowmelt and spring runoff in western North America that could be partially explained by temperature and precipitation patterns influenced by the PDO, although a general springtime warming trend spanning the PDO phases was also found to play an important role. Similar results were noted by Burn (2008) with reference to streamflow patterns in the headwaters of the MacKenzie River in northern Canada. Neal et al. (2002) demonstrated patterns in greater winter flow and lower summer flow associated with the warm-PDO phase, and converse patterns for the cold-PDO phase in southeastern Alaska. Neal et al. proposed that higher temperatures during the warm-PDO winter resulted in more precipitation falling as rain (vs. snow) and immediately draining to streams thus generating above-average winter flows. In contrast, lower temperatures during the cold-PDO winters resulted in more storage of winter precipitation as snow, which generated greater summer flows upon snowmelt. Neal et al. found no significant change in annual discharge resulting from climate variability associated with the PDO in southeastern Alaska.

In this paper, trends in monthly, seasonal, and annual discharge derived from streamflow records are examined from the beginning of systematic streamflow measurement in 1944 to 2005 in the Yukon River Basin. Included with this analysis is a discussion of the effect of the 1976 climate regime shift (PDO) on streamflow timing. The PDO is not the only climate feature that influences the atmosphere–ocean system in this area of Alaska. ENSO, the Arctic Oscillation (AO), and other climate patterns also may influence streamflow but are not discussed in this paper.

Data and site description

Daily mean streamflow data for 21 gauging stations in the Yukon River Basin were used in the analysis. Nine of the 21 streamflow gauging stations are located in Alaska (USGS National Water Information System accessed at URL http://www.waterdata.usgs.gov/nwis), and 12 streamflow gauging stations are located in the Yukon Basin in Canada (Water Survey of Canada accessed at URL http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=main_e.cfm) (Table 1, Fig. 4). Basin size ranges from 2430 km^2 to 831,000 km^2 and the period of record varies: some stations have been in existence only since 1976, the start of the warm-PDO phase, while others have record beginning as early as 1944.

Streamflow records were extended for two stations, the Porcupine River near Fort Yukon (site 14) and the Yukon River at Pilot Station (site 21), using the maintenance of variance-extension (MOVE) technique described by Helsel and Hirsch (1992). A statistical relation was developed between concurrent discharge measurements made on the Porcupine River near Fort Yukon and from a station located on the Porcupine River at the Alaska – Canada border. Using the relationship between discharge values, the streamflow record for the Porcupine River near Fort Yukon was extended to encompass years of record (1980–2005) that were only recorded from the Porcupine River at the international border. Similarly, a statistical relation was developed between flow at the Yukon River at Pilot Station and flows at the Yukon River at Ruby and the Yukon River at Kaltag to extend the Yukon River at Pilot Station record from 1956 to 1975.

The Yukon River Basin can be characterized into three distinct areas based on drainage area, physiographic, and permafrost characteristics: Upper, Middle, and Lower Yukon drainage basins (Fig. 4). The Upper Yukon is primarily in Canada, includes high mountainous areas, and is generally underlain by discontinuous permafrost and sporadic masses of permafrost. Runoff in the Upper Yukon is derived primarily from snowmelt and rainfall. Thirteen streamflow stations used in our analysis are in this area with four sites located on the main stem of the Yukon River: at Whitehorse (site 2), Carmacks (site 6), above the White River (site 9), and Eagle (site 13). Stations located on the main tributaries in this area include the Teslin (site 5), Pelly (site 8), White (site 10), and Stewart

Table 1
Streamflow gauging stations used in analysis and basin characteristics.

Map ID	Name	Period of record	Watershed area, km[b]	Lake area, %	Glacier area, %	Annual precipitation, cm	Annual snowfall, cm	Permafrost coverage in watershed
Upper Yukon								
1	Atlin River near Atlin, BC	1950–2005	6810	9	4	30	191	Sporadic
2	Yukon River at Whitehorse, YT	1944–2005	19,400	8	5	38	183	Sporadic
3	Takhini River near Whitehorse, YT	1948–2005	6990	4	3	36	163	Sporadic
4	Swift River near Swift River, BC	1956–2005	3320	1	0	46	406	Sporadic
5	Teslin River near Teslin, YT	1944–1995	30,300	3	0	33	198	Sporadic
6	Yukon River at Carmacks, YT	1951–1996	81,800	4	1	30	178	Sporadic
7	Ross River at Ross River, YT	1960–2005	7250	3	0	30	381	Discontinuous
8	Pelly River at Pelly Crossing, YT	1952–2005	49,000	2	0	51	251	Discontinuous
9	Yukon River above White River near Dawson, YT	1956–2005	150,000	4	1	25	216	Discontinuous and sporadic
10	White River at Alaska Highway near Koidern, YT	1975–2005	6240	0	28	56	198	Discontinuous
11	Stewart River at mouth near Dawson, YT	1965–2005	51,000	1	0	30	254	Discontinuous
12	Klondike River above Bonanza Creek near Dawson, YT	1965–2005	7800	0	0	41	206	Discontinuous
13	Yukon River at Eagle, AK	1950–2005	294,000	1	3	30	140	Discontinuous and sporadic
Middle Yukon								
14	Porcupine River near Fort Yukon, AK[a]	1964–2005	76,400	2	0	25	114	Continuous
15	Yukon River near Stevens Village, AK	1976–2005	508,000	3	2	38	114	Mixed
16	Salcha River near Salchaket, AK	1948–2005	5620	0	0	38	229	Discontinuous
17	Chena River near Two Rivers, AK	1967–2005	2430	0	0	41	254	Discontinuous
18	Tanana River at Nenana, AK	1962–2005	66,300	4	6	41	178	Discontinuous
Lower Yukon								
19	Yukon River at Ruby, AK	1956–1977	671,000	4	1	38	152	Mixed
20	Koyukuk River at Hughes, AK	1960–1982	47,700	1	0	41	191	Continuous
21	Yukon River at Pilot Station, AK[b]	1956–2005	831,000	4	1	41	152	Mixed

[a] Record extended from 1980 to 2005.
[b] Record extended from 1956 to 1975.

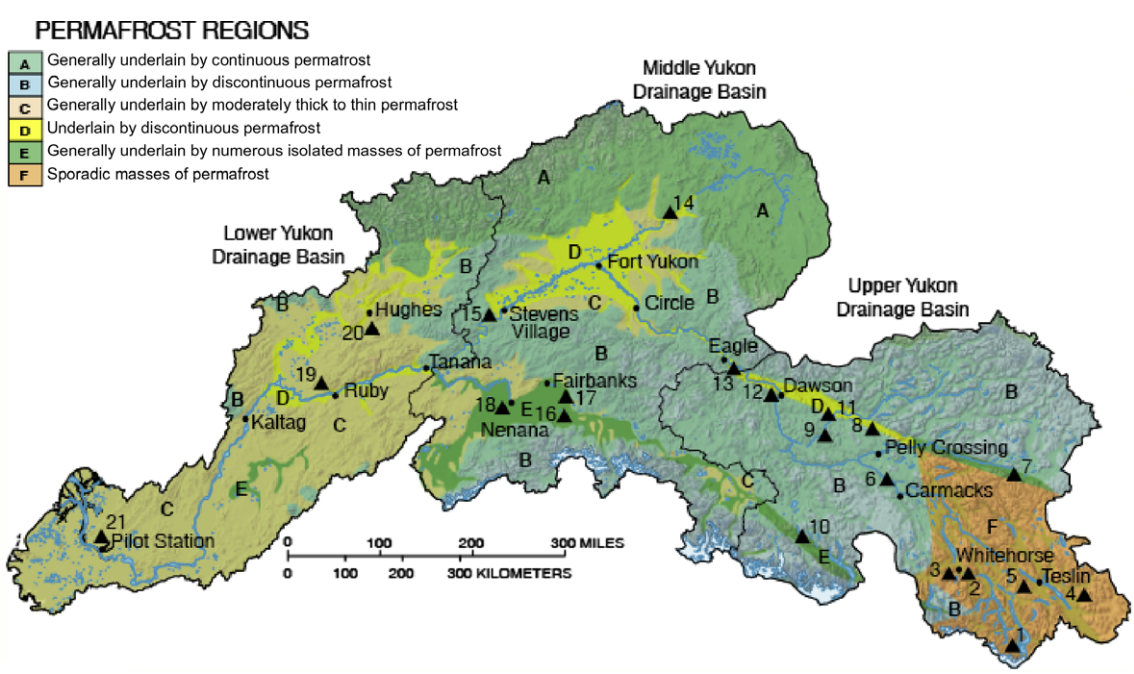

Fig. 4. Location of stream gauging stations, major drainage basins, and permafrost regions of the Yukon River Basin (permafrost regions from Ferrians, 1965; Brown et al., 1997), map IDs listed in Table 1.

(site 11) Rivers. The White River is one of the two large glacier-fed rivers in the Yukon River Basin. (The other is the Tanana River discussed below). The Pelly, Stewart, and Teslin Rivers are large clear-water (low suspended sediment) streams. The remaining five sites are the Swift River (site 4) (tributary to the Teslin River), the Ross River (site 7) (tributary to the Pelly River), and the Takhini (site 3), Atlin (site 1), and Klondike (site 12) Rivers (small tributaries to the Yukon River).

The Middle Yukon drainage basin includes the Porcupine and Tanana Rivers and the Yukon Flats, a large wetland area near Fort Yukon (Fig. 4). The climate in the Porcupine River Basin is most representative of arctic Alaska, whereas the Tanana River Basin to the south reflects the climate of interior Alaska. The Porcupine River Basin has flat to gently rolling topography, has no glaciers, is underlain by continuous permafrost, and supports minimal groundwater discharge to streamflow (~8% of the total annual flow) (Walvoord and Striegl, 2007). In contrast, the Tanana River Basin consists of a variety of physiographic regions, some with glaciers (Brabets et al., 2000), and is generally underlain by discontinuous permafrost. The coarse subsurface material and steep hydraulic gradients support substantial groundwater discharge to streamflow (over a quarter of the annual flow in the Tanana River) (Walvoord and Striegl, 2007). Glacial meltwater is another substantial component of flow in the Tanana River, draining the north side of the Alaska Range. Stream gauges are located on both the Porcupine and the Tanana Rivers (sites 14 and 18, respectively) in addition to one site on the main stem of the Yukon River near Stevens Village (site 15) and two tributaries to the Tanana River: the Salcha and Chena Rivers (sites 16 and 17).

The Lower Yukon drainage basin is generally a low-relief area with the exception of the mountainous area in the upper part of the Koyukuk River Basin. Two stations are located on the main stem of the Yukon River; at Ruby (site 19) and at Pilot Station (site 21). One site is located on the Koyukuk River (site 20), another large basin underlain by continuous permafrost and more reflective of the arctic Alaskan climate, similar to the Porcupine River Basin.

Of the 21 streamflow records analyzed, 7 are from stations located along the main stem of the Yukon River. In the Upper Yukon, sites 2, 6, and 9 are located upstream of any major direct glacial inputs. There are glaciers are in the headwaters of the Yukon River Basin, but runoff flows into large lakes that moderate flows and trap most of the fine-grained sediment. The Yukon River at Eagle, AK (site 13) reflects inflow from the glacier-fed White River (site 10). In the Middle Yukon, the Yukon River near Stevens Village, AK (site 15) receives inflow from the flat-lying permafrost-dominated Porcupine River Basin (site 14), reflective of an arctic basin. In the Lower Yukon, the Yukon River at Ruby (site 19) is influenced by the large glacier-fed Tanana River (site 18). The site furthest downstream on the Yukon River, at Pilot Station, AK (site 21), integrates all of the above basins plus the second largest permafrost-dominated arctic basin, the Koyukuk River Basin (site 20).

Methods

Based on a typical hydrograph of streams in the Yukon River Basin (Fig. 5), the following flow statistics were examined: (1) the average annual discharge, (2) the average winter flow from January 1 to March 31, which represents the period when streams are ice covered, terrestrial surface layers are frozen, and groundwater is assumed to be the major input to the Yukon River (Walvoord and Striegl, 2007), (3) average monthly discharges during the open water (ice-free) period of streams and rivers in the Yukon that extends from April to September, and (4) the average flow from October 1 to December 31, which represents the fall recession period when surface runoff decreases and river ice formation begins. Glacier-fed rivers have much different runoff patterns than non glacier-fed rivers even though their basins may contain as little as 5% glacier ice (Glass, 1999). Glacier-fed rivers have a rather broad, almost Gaussian, streamflow distribution pattern with increased flow from mid spring to early fall depending on location. Snowmelt-dominated rivers have a sharp peak in late spring that tails off throughout the summer and into the fall.

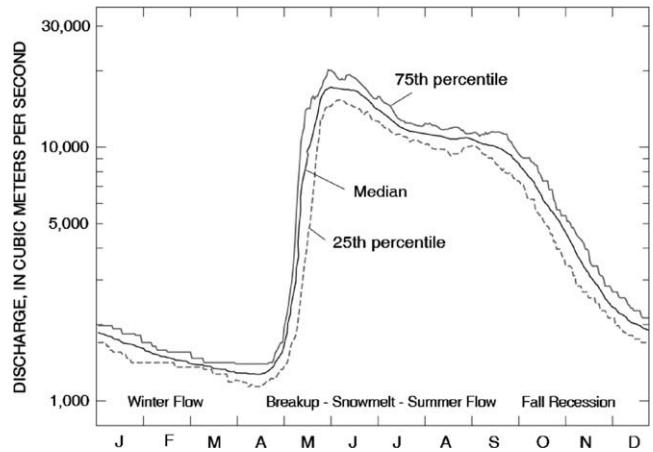

Fig. 5. Flow regimes of the Yukon River at Pilot Station, Alaska (site 21), based on records from 1977–2005.

To test for trends, the non-parametric Mann-Kendall test (Helsel and Hirsch, 1992) was used. Cohn and Lins (2005) discussed the use of statistical significance and the difficulty in assessing p values, because they depend on subjective assumptions about the underlying stochastic process. In utilizing the Mann-Kendall test, two criteria were used to determine a statistically significant trend. First, if $p > 0.10$, it was assumed no trend existed. Second, the 95% confidence intervals for the slope were computed. If the confidence intervals included zero, it was assumed no trend existed. No trend analysis was done for the Koyukuk River (site 20) in the warm-PDO phase or for the Chena River (site 17) in the cold-PDO phase because there were only 6 and 8 years of record, respectively, for these two periods.

The trends in streamflow records were visually inspected using locally-weighted regression (LOESS) lines (Cleveland and Devlin, 1988). Linear regression lines for the entire period of record, the cold-PDO phase, and the warm-PDO phase, were plotted as a verification of the LOESS line. Deviations from long-term means also were plotted as another tool to visually detect trends. Flow data for the cold and warm-PDO phases were analyzed using the Wilcoxon Rank-Sum test (Helsel and Hirsch, 1992), which does not require normally-distributed data, to determine whether average discharges from the cold-PDO phase were statistically different than average discharges from the warm-PDO phase. The two groups were considered different for $p < 0.10$. For the purposes of this study, the cold-PDO phase was considered to include the years from 1944 through the end of 1975, and the warm-PDO phase was considered to include the years from 1976 to 2005.

A technique developed by McCabe and Wolock (2002) to analyze flow characteristics in the conterminous United States related to climatic step change was applied here to determine if changes in flow characteristics in the Yukon River Basin reflected step-like behavior and could in some part be explained by the PDO shift. McCabe and Wolock (2002) presented two approaches to evaluate the temporal changes in streamflow statistics. The first approach determines standardized departures by subtracting the respective long-term (period of record) mean from the respective flow statistic and dividing by the standard deviation. The second approach involves a multiple trend analysis in which the period of record is varied. Following these approaches, standardized departures were calculated for each flow statistic of interest for each site in the Yukon River Basin. The average standardized departure for each flow statistic was then computed. Multiple trends were computed for all sites by varying the beginning and ending date analyzed. Trend tests were computed for all possible periods of at least 10 years in length from 1944 to 2005.

Results

Streamflow trends over the entire period of record

The trend analysis for the streamflow record available at each site for the years between 1944 and 2005 indicates that most sites have experienced statistically significant increases in winter flow (January 1 to March 31) and average April flow. During the winter, surface-water runoff is unlikely due to frozen surface conditions, thus the increase is presumed to be due to increased groundwater discharge to the stream. A few sites show positive trends in the average flow for May and the fall recession (October 1–December 31) (Table 2).

Negative trends for June and July flows were observed at a number of stations in the Upper and Middle Yukon drainage basins. No trends in average annual discharge were noted with the exception of increases in the Atlin and Tanana Rives, fed by glaciers and perennial snowfields, and a decrease in the Porcupine River.

PDO influence on streamflow

Computed seasonal and monthly average discharge values for sixteen sites were used to compare effects of the PDO on the timing of flow. Based on the Wilcoxon Rank-Sum test, 15 of the 16 sites show increased average winter flow and average April flow for the warm-PDO phase compared to the cold-PDO phase (Table 3).

Table 2
Statistically significant streamflow trends for the period of record at sites in the Yukon River Basin.

Site	Map ID	Annual	WF	April	May	June	July	August	September	FR	Years of record
Upper Yukon											
Atlin River	1	+		+	+		+	+	+		55
Yukon River at Whitehorse	2		+	+		–	–				61
Takhini River	3							–			57
Swift River	4			+							49
Teslin River	5		+								51
Yukon River at Carmacks	6		+	+	+						45
Ross River	7		+	+		–	–				45
Pelly River	8		+	+							53
Yukon River abv White River	9		+	+			–				49
White River at Alaska Hwy	10		+								30
Stewart River	11		+	+	+						40
Klondike River	12		+	+						+	40
Yukon River at Eagle	13		+	+	+					+	55
Middle Yukon											
Porcupine River	14	–	+	+		–					41
Yukon River near Stevens Village	15		–								29
Salcha River	16		+	+	–	–					57
Chena River	17		+	+							38
Tanana River	18	+	+	+						+	43
Lower Yukon											
Yukon River at Ruby	19										21
Koyukuk Rivers at Hughes	20										22
Yukon River at Pilot Station	21		+	+					+	+	49

+, Indicates positive trend ($p < 0.10$); –, indicates negative trend ($p < 0.10$); blank, no trend; annual, average annual discharge; WF, average winter flow; and FR, fall recession.

Table 3
Statistically significant differences ($p < 0.10$) between streamflow values for the cold and warm phases of the PDO at sites in the Yukon River Basin based on the Wilcoxon Rank-Sum test.

Site	Map ID	Annual	WF	WF (%)	April	April (%)	May	June	July	August	September	FR
Upper Yukon												
Atlin River	1	+	+	7	+	12	+	+	+	+		+
Yukon River at Whitehorse	2		+	43	+	55	+					
Takhini River	3		+	11	+	10						
Swift River	4				+	26						
Teslin River	5		+	14								
Yukon River at Carmacks	6		+	21	+	32						
Ross River	7		+	25	+	42		–				+
Pelly River	8		+	16	+	20		–				
Yukon River abv White River	9		+	12	+	23		–				
Stewart River	11		+	3	+	18						
Klondike River	12		+	18	+	48						
Yukon River at Eagle	13		+	21	+	32	+					+
Middle Yukon												
Porcupine River	14		+	31	+	30						
Salcha River	16		+	22	+	63	–	–				+
Tanana River	18		+	13	+	27						+
Lower Yukon												
Yukon River at Pilot Station	21		+	22	+	47						+

+, Indicates warm-PDO greater than cold-PDO flow value; –, indicates warm-PDO lower than cold-PDO flow value; annual, average annual discharge; WF, average winter flow; %, percent change between flow values computed for the cold and warm-PDO phases; and FR, fall recession.

The increase in winter flow between the cold and warm-PDO phases ranges from 3% (Stewart River) to 43% (Yukon River at Whitehorse). Observed increases in average April flow range from 10% (Takhini River) to 63% (Salcha River). Three sites show positive differences in May, and four sites indicate negative differences (less flow) in June. Six sites indicate a positive difference in the fall recession.

Results of the Wilcoxon Rank-Sum test are considered to be an indication that at least part of the observed changes in streamflow is related to changes in climate associated with the PDO. To further examine this association, seasonal, monthly, and annual flows in each PDO phase were analyzed individually for trends. Trends detected separately within the cold and the warm-PDO phases signify an overlying trend spanning PDO phases that could be attributed to a climatic change occurring over a longer timescale than that associated with the PDO. Standardized departures and multiple flow trend analyses (using the Mann–Kendall test) were analyzed following the techniques developed by McCabe and Wolock (2002) to identify step changes and determine if these step changes coincided with the PDO shift.

Most streamflow trends for the cold-PDO phase are detected at stations in the Upper Yukon (Table 4). Positive cold-PDO trends in the Upper Yukon River Basin are most common for average winter flow and average April flow. However, much fewer positive trends in winter and average April flow are noted when the record is limited to the cold phase (Table 4) compared to the entire period of record (Table 2). And, contrary to other sites with a measureable (positive) trend, the Ross River in the Upper Yukon records a neg-

Table 4
Trends for the cold-PDO phase at sites in the Yukon River Basin.

Site	Map ID	Annual	WF	April	May	June	July	August	September	FR
Upper Yukon										
Atlin River	1			+						
Yukon River at Whitehorse	2		+	+	–	–	–			
Takhini River	3									
Swift River	4									
Teslin River	5				–		+	+		
Yukon River at Carmacks	6		+	+						
Ross River	7		–		+					–
Pelly River	8									
Yukon River abv White River	9			+						
Stewart River	11				+					
Klondike River	12									
Yukon River at Eagle	13	+	+	+		+	+	+	+	+
Middle Yukon										
Porcupine River	14									
Salcha River	16									
Tanana River	18					–				–
Lower Yukon										
Yukon River at Ruby	19									
Koyukuk Rivers at Hughes	20	–								
Yukon River at Pilot Station	21									

+, Indicates positive trend ($p < 0.10$); –, indicates negative trend ($p < 0.10$); blank, no trend; annual, average annual discharge; WF, average winter flow; and FR, fall recession.

Table 5
Trends for the warm-PDO phase at sites in the Yukon River Basin.

Site	Map ID	Ave	WF	April	May	June	July	August	September	FR
Upper Yukon										
Atlin River	1									
Yukon River at Whitehorse	2									
Takhini River	3							–		
Swift River	4									
Teslin River	5									
Yukon River at Carmacks	6									
Ross River	7						–			
Pelly River	8			+						
Yukon River abv White River	9									
White River at Alaska Hwy	10		+	+	+			–		+
Stewart River	11		+	+					+	
Klondike River	12	+	+						+	
Yukon River at Eagle	13		–				–			
Middle Yukon										
Porcupine River	14	–	+	+						
Yukon River near Stevens Village	15		–				–			
Salcha River	16									
Chena River	17		+					+		
Tanana River	18	+								
Lower Yukon										
Yukon River at Pilot Station	21	+		+	+				+	

+, Indicates positive trend ($p < 0.10$); –, indicates negative trend ($p < 0.10$); blank indicates no trend; annual, average annual discharge; WF, average winter flow; and FR, fall recession.

ative trend in winter flow during the cold PDO. Comparison of average April flow with average winter flow values during the cold PDO for the four sites in the upper main stem of the Yukon River (Whitehorse, Carmacks, above White River, and Eagle) shows little disparity indicating that baseflow (groundwater fed) conditions dominated into April. The Yukon River at Eagle, AK, which represents runoff from the upper third of the entire Yukon River Basin, shows positive trends in the cold-PDO phase with respect to annual flow and all the seasonal and monthly average flows examined with the exception of May flow. In the Middle and Lower Yukon drainage basins, negative trends in streamflow averages during the cold-PDO phase are noted only at two sites, the Tanana River (June flow and fall recession) and the Koyukuk River (annual discharge) (Table 4). No increases in annual, seasonal, or monthly average flows are detected in the Middle and Lower Yukon drainage basins during the cold PDO.

A number of sites show positive trends for winter flow and April flow in the warm-PDO phase, although two negative trends in winter flow were also detected (Table 5). Positive trends in April flows are noted at sites in all three major Yukon drainage basins. In the Upper Yukon, average April flows are generally greater than the average winter flow values during the warm PDO, indicating that April flows generally include some surface-water runoff from snowmelt in addition to groundwater-dominated baseflow. In the Middle and Lower Yukon, average April flows are approximately equal to the average winter discharge values, indicating that flow during the month of April is mainly comprised of baseflow, similar to conditions during the months of January through March. For some sites in the Middle and Lower Yukon, positive trends in winter flow over the entire period of record may have been identified as a result of the strong positive trend during the warm phase and the step increase from the cold to the warm PDO. The record from the Chena River provides a good example of such a case (Fig. 6A). Negative trends are detected in July and August average flows during the warm PDO at several sites, particularly in the Upper Yukon. A negative trend in average annual flow during the warm PDO is noted for the Porcupine River (Fig. 6B). In contrast, the average annual flow for the Tanana River increased during the warm-PDO phase (Fig. 6C). Similar positive trends in annual flow during the warm PDO are found for the Klondike River and for the Yukon River at Pilot Station, AK, the latter of which represents an integration of hydrologic processes throughout the Yukon River Basin.

The mean standardized departures for winter flow and April flow for all sites are shown in Fig. 7A and B, respectively. The departures indicate a shift around 1976 from primarily negative to primarily positive rather than a trend spanning the entire period of record and are a good verification of the results from the Wilcoxon Rank-Sum test. A linear regression analysis between the standardized departures and the PDO index values for these two flow statistics indicate significance at the 5% level and moderate correlations for the winter flow ($r = 0.37$) and April ($r = 0.40$) periods (Figs. 7C and D), providing support for the effect of the PDO on these changes in streamflow. The latter approach resolves the issue of PDO interannual variability in determining the strength of the relationship between the PDO and seasonal/monthly flow.

Deviations from the long-term monthly average discharge from stations located along the main stem of the Yukon River from Carmacks, YT, to Pilot Station, AK consistently indicate below-average flow in winter months for the cold PDO and above-average flow in winter months for the warm PDO (Fig. 8). Although less pronounced, results also illustrate a reversal in the summer months, showing above-average flow for the cold PDO and below-average flow in the warm PDO.

To further examine if the changes in streamflow patterns are abrupt and coincide with the 1976 PDO shift as opposed to following a gradual trend spanning PDO phases, a multiple trend analysis

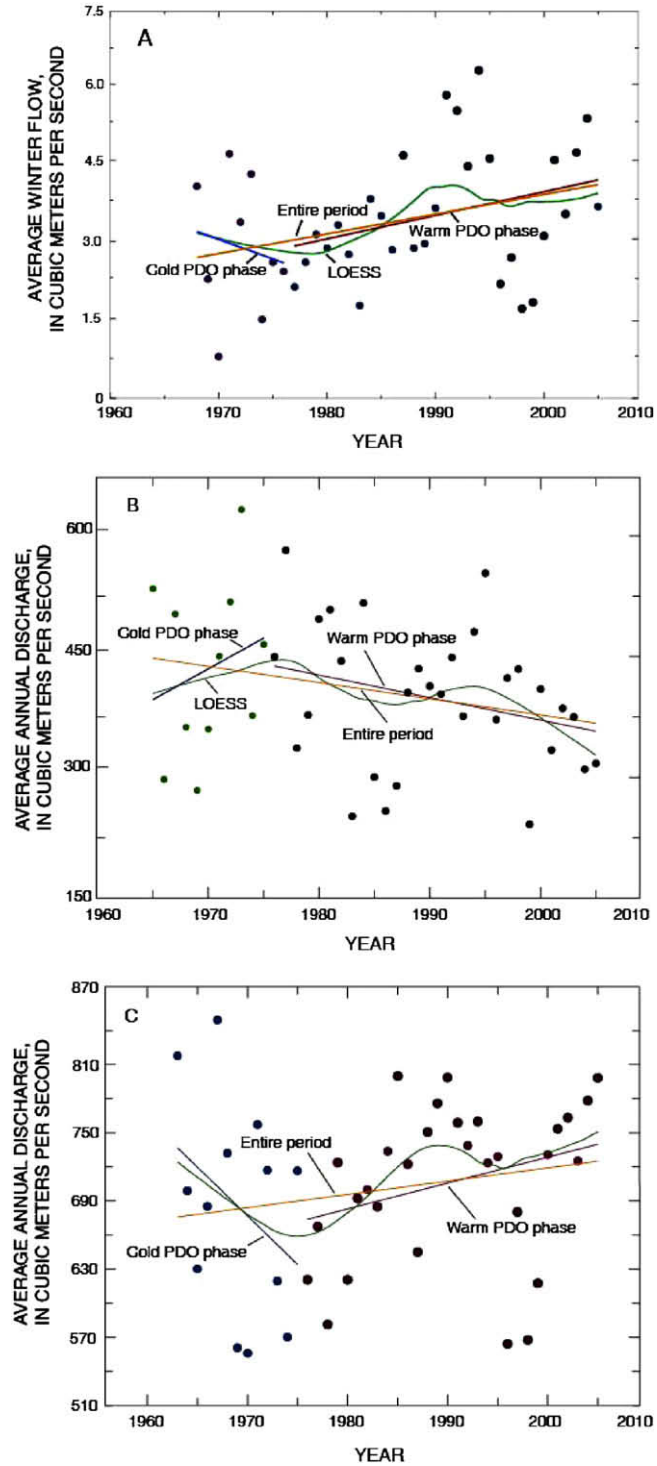

Fig. 6. Winter flow trends for (A) the Chena River near Fairbanks, Alaska, 1967–2005, average annual discharge for (B) the Porcupine River near Fort Yukon, Alaska, 1966–2005, and (C) the Tanana River at Nenana, Alaska, 1964–2005. Linear regression lines are shown for the cold-PDO phase, the warm-PDO phase, and the entire period of record. LOESS line if for entire period of record.

was computed by varying the beginning and ending date considered. The number of sites with significant ($p < 0.10$) positive or negative trends for each time period was tabulated. Table 6 provides selected results from the multiple trends test showing the interval over which the most negative and positive trends were detected for each of the average discharge statistics examined. For all statistics with significant trends, the highest number of stations

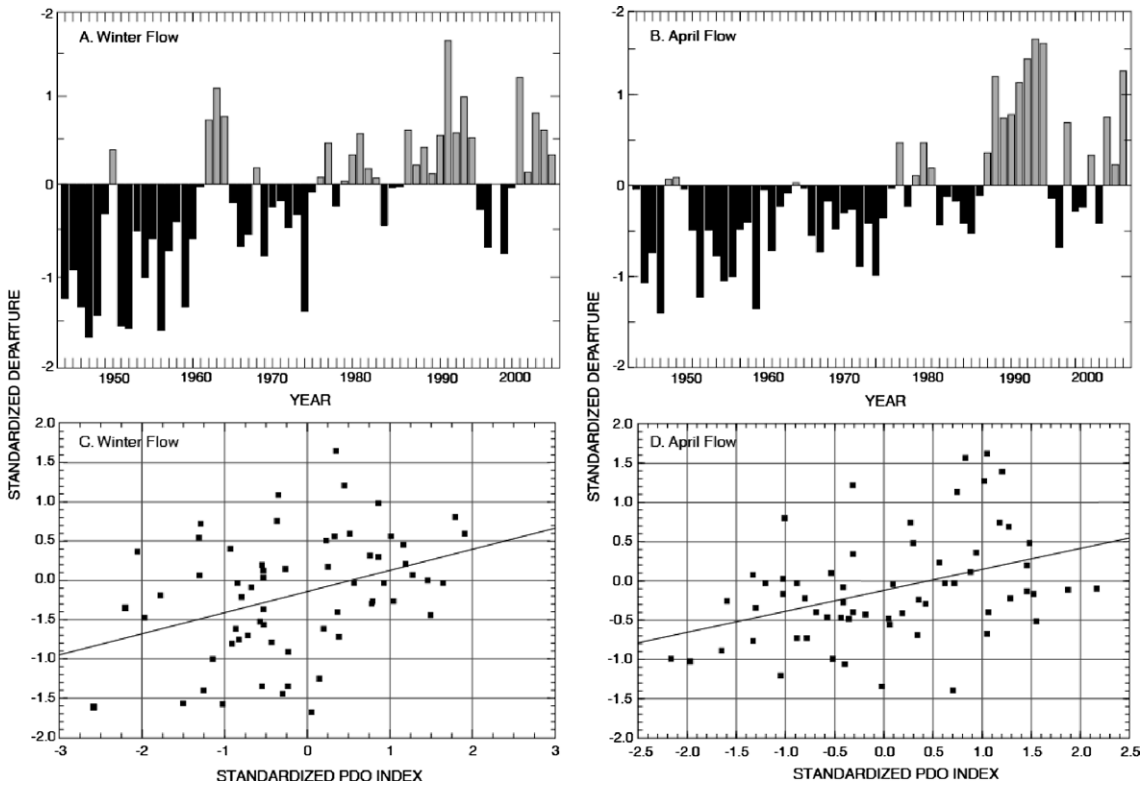

Fig. 7. Mean standardized departures of winter flow and April flow (A and B) and standardized departures (C and D) versus standardized PDO index for 21 sites in the Yukon River Basin, 1944–2005.

with detected trends corresponds to intervals beginning with or ending with the PDO shift from cold to warm. Results of the multiple trend tests indicate relatively few negative trends in May, August and September and few positive trends in the June through the fall period. For flow records beginning in the early 1960s and ending in 1976, there are negative trends for winter, April, June, July, fall recession, and annual flow and a positive trend for average May discharge. The positive trend for May discharge ends in 1976, probably due to the shift to earlier spring melt and earlier ice breakup. A number of stations have positive trends beginning in 1976 and ending in the mid 1990s for annual, winter, and April flow. In the mid 1990s, the PDO did shift back to a cold phase for a few years (Fig. 3), which may explain the break in identified flow increases.

Discussion

Hartmann and Wendler (2005) noted increased snowfall in the interior of Alaska, increased annual precipitation in western Alaska, decreased annual precipitation in arctic Alaska, and increased air temperature (mainly during winter months) throughout Alaska associated with the PDO shift in 1976. The effects of increased snow and air temperature are the two primary factors that promote permafrost thawing (Osterkamp, 2007). Permafrost thawing in the Yukon River Basin throughout the 20th century (Osterkamp, 2007; Lachenbruch and Marshall, 1986) has likely resulted in increased recharge areas, infiltration rates, and subsurface water storage, which in turn has enhanced groundwater discharge to streamflow, evident during baseflow conditions that predominate during the winter months. Thus, the increases in average winter flow observed at nearly all sites in the Yukon River Basin from the cold to the warm PDO are consistent with net permafrost thawing and resultant groundwater flow enhancement. Deviations from the long-term record of mean streamflow reveal below-average winter flow during the cold PDO and above-average summer flow during the warm PDO. Although results support a PDO influence on increases in winter flow, positive trends in winter flow are observed at some sites within the cold and the warm-PDO phases alone and also spanning both phases. Positive trends in winter flow during the cold-PDO phase are limited to the Upper Yukon, although it should be noted that fewer sites in the Middle and Lower Yukon were investigated. Increases in winter flow during the warm-PDO phase and spanning both PDO phases (the entire period of record) extend to the Middle and Lower Yukon drainage basins. The results suggest that permafrost thawing that has led to increases in winter flow has been progressing in the Upper Yukon over the period of available streamflow records and was enhanced by the PDO shift to a warm phase in 1976 leading to observable increases in groundwater discharge to streams further downstream in the Yukon River Basin.

April, a transition month between baseflow-dominated flow and snowmelt runoff-dominated flow at many sites in the Yukon, also yields statistically significant increases in streamflow from the cold to the warm PDO and positive trends in flow during the warm-PDO phase in the Upper Yukon. These increases may be attributed to increased groundwater discharge to streamflow (as seen in the winter, discussed above), earlier spring snowmelt runoff, and greater snow accumulation during the winter months in the interior of Alaska that is then available for melt runoff in April. Increased flows in May from the cold to the warm-PDO phase at a few sites in the Upper Yukon may also be attributed to an earlier snowmelt period and/or greater winter precipitation.

A likely consequence of the earlier spring snowmelt is reduced streamflow in the summer months, which is borne out in the results of our analysis. Negative trends in June, July, and August average flows, particularly in the Upper Yukon, over the entire period of

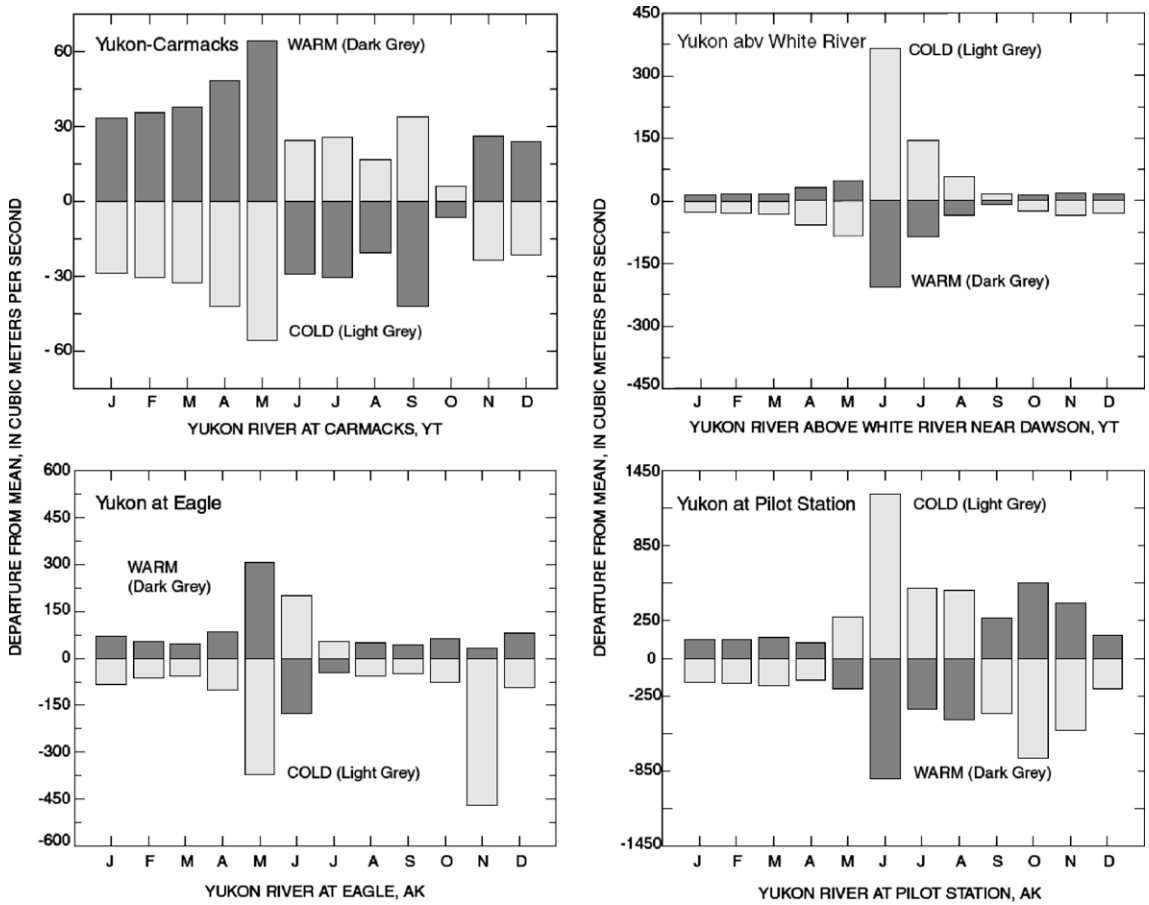

Fig. 8. Deviations from long-term means in monthly discharge for the period of record for four streamflow stations along the Yukon River. Dark grey bars represent the deviation during the warm-PDO phase, and light grey bars represent deviations during the cold-PDO phase.

Table 6
Results of multiple trend tests.

Flow statistic	Stations with detected trends	Beginning year	Ending year	Remarks
Negative trends				
Annual	6 of 14	1961	1976	End Cold PDO
Winter flow	4 of 14	1963	1976	End Cold PDO
April	3 of 15	1964	1976	End Cold PDO
May	None			
June	5 of 14	1963	1976	End Cold PDO
July	6 of 14	1962	1976	End Cold PDO
August	None			
September	None			
Fall recession	5 of 14	1963	1976	End Cold PDO
Positive trends				
Annual	7 of 18	1976	1993	Start Warm PDO
Winter flow	6 of 19	1976	1996	Start Warm PDO
April	12 of 20	1976	1995	Start Warm PDO
May	7 of 15	1964	1977	End Cold PDO
June	None			
July	None			
August	None			
September	None			
Fall recession	None			

"End Cold PDO": ending year corresponds to PDO shift from cold to warm.
"Start Warm PDO": beginning year corresponds to PDO shift from cold to warm.

record and during the warm PDO alone are likely a result of earlier spring snow melting and runoff which depletes the water supply left to be discharged in the summer. Deviations from the long-term records of streamflow means generally reveal above-average summer flow during the cold PDO and below-average summer flow during the warm PDO. Summer streamflow trends are likely connected to the PDO, but only as an indirect result of earlier spring runoff and perhaps also as a result of increased infiltration and soil

water storage within a deeper active layer. A deepening active layer created by permafrost thaw is associated with warmer air and soil temperatures during the warm PDO. The resulting deeper (and longer) flowpaths between the point of infiltration and discharge to the stream create a longer soil water residence time and a lag in streamflow derived from soil water infiltrated during the summer months. This lag in stream discharge of water infiltrated during the summer could also help explain increases in streamflow during the fall recession period between the cold and warm-PDO phases observed at several sites in the Yukon Basin.

Increases in annual discharge for the Atlin River and the Tanana River are likely the result of intensified melting of glacial ice due to higher air temperatures (Folland et al., 2001). The positive trends in annual flow during the warm PDO at the Yukon River at Pilot Station site and at the Klondike River site are perhaps reflections of increases in annual precipitation in the interior of Alaska (as noted by Hartmann and Wendler (2005)) and in the adjacent parts of the Yukon Territory, although observed precipitation increases in interior Alaska were not statistically significant as reported by Hartmann and Wendler (2005). Although positive trends in annual flow were not noted in most major tributaries and the Yukon River at upstream stations, the Yukon River at Pilot Station location incorporates the additive effect of small increases within the entire basin resulting in a stronger positive signal. Similar findings were noted by Peterson et al. (2002) on an even larger scale. They found compelling evidence for an increase in annual discharge to the Arctic Ocean from the six largest Eurasian rivers only when the discharges from these six were summed.

Decreases in annual discharge for the Porcupine River, which drains the northernmost watershed in the Yukon River Basin, may be attributed to reduced precipitation in the arctic portion of Alaska following the 1976 PDO shift as noted by Hartmann and Wendler (2005). The Porcupine River Basin is underlain by continuous permafrost and supports relatively little groundwater discharge to the Porcupine River (Walvoord and Striegl, 2007). Accordingly, less precipitation (and thus surface runoff) during the warm-PDO phase may not be balanced by increases in groundwater from permafrost thawing, thus resulting in a decline in annual flow.

Conclusions

Streamflow patterns in the Yukon River Basin have changed over the past 5–6 decades. Although annual discharge has remained fairly constant with a few exceptions, streamflow timing has changed. Analysis of historical streamflow records indicates increases in average winter and April flows at sites throughout the Yukon River Basin. Generally, these increases have been offset by decreasing flows in June–August, although negative trends in summer flow are much less pronounced than positive trends in winter and early spring flows. This study suggests a relationship between changes in seasonal streamflow patterns and the climatic shift in the Pacific Decadal Oscillation. This proximate relationship may be superimposed on a warming trend that spans phases of the PDO simultaneously impacting hydrologic processes in the Yukon. In the upper one third of the Yukon River Basin, permafrost has been progressively thawing since the beginning of data collection, and winter flow has increased as a result of enhanced groundwater discharging to large streams that are not completely frozen during the winter. When the PDO shifted to the positive or warm phase, air temperatures increased and permafrost thaw likely progressed, resulting in greater baseflow throughout most of the basin. Net glacier mass has likely been reduced following the pervasive temperature increase associated with PDO shift in 1976, resulting in greater annual discharge in the Tanana River, a glacier-fed tributary to the Yukon River. The PDO shift produced decreased precipitation in arctic regions of the Yukon River Basin, which may be responsible for the observed decline in annual flow in the Porcupine River.

A number of streamflow statistics considered here were noted to have step changes coincident with the shift of the PDO. The identification of an abrupt change in streamflow timing rather than a gradual trend is important. The interpretation of a gradual trend is that the trend is likely to continue into the future, whereas the interpretation of a step change associated with a decadal climate pattern is that the change is transient and reversible. While the results of this study support an important connection between streamflow timing and the PDO, positive trends in winter and April flow that span PDO phases suggest that a change in climate occurring over a longer timescale than the PDO also plays a role in influencing hydrologic processes in the Yukon River Basin. This analysis demonstrates the importance of a proximate climate forcing overprinted on global climate trends in generating streamflow changes in the Yukon River Basin.

Acknowledgments

We thank USGS colleagues, G. Hodgkins, H. Lins, G. McCabe, and NOAA colleague L. Rundquist for providing thoughtful comments that were used to improve the manuscript.

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