Observed trends in the river ice regimes of northwest Canada

J. Richard Janowicz

ABSTRACT

Yukon air temperature trends have been observed to change over the last several decades with an increase in annual, summer and winter air temperatures, while changes in precipitation have not been consistent. An assessment of freeze-up and break-up dates indicates that the ice cover season is becoming shorter with delays in freeze-up and advances in break-up timing. Mid-winter break-up events and associated flooding have been observed for the first time. Break-up water level trends suggest that break-up severity is increasing. These changes cannot be definitely attributed to climate change as there is some evidence suggesting that teleconnections may be a factor. The observed changes have significant implications pertaining to public safety, and economic impacts on property and infrastructure, transportation networks and hydroelectric operations. Ice jams and associated backwater and surges also affect aquatic ecosystems through impacts on biological and chemical processes.

Key words | break-up, climate warming, ice jam, Mann–Kendall, river ice, trend analysis

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INTRODUCTION

River ice is an important component of both socio-economic and environmental features of cold regions. Accentuated in remote, sparsely populated areas, frozen rivers are frequently used for transportation purposes for the construction of ice bridges and as transportation networks. In northern North America river ice is frequently relied upon to act as a platform for fishing and trapping purposes. Freeze-up and break-up processes often produce ice jams which may result in flooding with significant implications for public safety, and economic impacts associated with damage to property and infrastructure, road and rail networks and hydroelectric operations. Ice jams and subsequent backwater and surges also affect aquatic ecosystems through impacts on biological and chemical processes.

A warming climate is affecting the hydrologic response in cold regions. There have been a number of studies carried out in northern regions of North America on the impact of climate change on hydrologic response (Kite 1993; Burn 1994; Whitfield & Taylor 1998; Spence 2002; Hinzman *et al.* 2005), while there has only been limited work to date on the impact of climate change specific to Yukon hydrology. Whitfield (2001) found the hydrologic response to be generally characterized with higher year-round flows. Janowicz (2001) found significant increases in mean annual flood to occur from predominantly glacierized systems in western Yukon. Zhang *et al.* (2001) and Yue *et al.* (2003) found winter low flows in northern British Columbia and Yukon to have increased significantly. Similar results were found by Walvoord & Striegl (2007) for the Yukon River basin and by Janowicz (2008), who assessed streamflow characteristics related to Yukon permafrost distribution.

Climate warming is also affecting the ice regimes of cold regions. In subarctic regions break-up is typically a spring event, with the timing generally a function of latitude. In southern and maritime regions which are prone to freezing conditions, break-up is more typically a mid-winter event. The length of the ice cover season has shortened, with later occurrence of freeze-up and earlier break-up

doi: 10.2166/nh.2010.145

events (Prowse & Beltaos 2002; Beltaos & Burrell 2003). Beltaos & Prowse (2009) provide a summary of trends in ice phenology of northern rivers. More information on freeze-up dates is available for Europe and Asia than North America. The most significant regional trend was observed in Russia and Ukraine where freeze-up of the Danube, Don, Dnieper and lower Volga rivers was delayed by two to three weeks (Ginzburg *et al.* 1992). White *et al.* (2007) summarize the findings of studies carried out in Alaska and Maine. Their summary indicates that freeze-up of two Maine rivers was delayed by approximately 30 days per century. Winter ice cover is becoming thinner as a result of increased winter temperatures, reducing downward freezing of the water column and less frazil ice generation. Increased winter discharge may also contribute to a thinner ice cover through the transport of frazil ice from the bottom of the ice cover. In some cases greater snow cover is accentuating the development of thinner ice covers through its insulating effect (Michel 1971). In some situations snow cover can promote ice growth by its effect on ice cover buoyancy and associated surface flooding and subsequent refreezing to form "snow" ice (Beltaos & Prowse 2009). The duration and severity of break-up events are also being affected. Break-up severity is a function of ice cover strength and integrity balanced by hydrometeorological conditions which control streamflow discharge and water level. At the lower range of severity, a thermal break-up occurs when the ice cover has deteoriated sufficiently by radiation from above and erosion from below to allow it to break up with little increase in discharge. In contract, a mechanical break-up occurs when streamflow discharge and water level increase rapidly, causing the ice cover to break its bond with channel banks while it is still strong and competent. Such events occur when a colder-than-normal period is followed by the rapid melt of a greater-than-normal snowpack and subsequent runoff.

This paper attempts to provide a summary of climate warming impacts on the river ice regimes of the Yukon Territory.

CLIMATE TRENDS

While there is as yet no definitive evidence to prove that climate variability in northern Canada is anthropogenic, air temperature and precipitation in Yukon Territory have fluctuated significantly over the last century. There is some recent data that suggests the fluctuations could be outside the natural range of variability. Dawson City in central Yukon experienced the warmest winter in its 110 year record in 2003 (Janowicz 2003). Some trends have been observed in the last several decades. Tables 1 and 2 provide a summary of annual, winter and summer temperature and precipitation trends of long-term Meteorological Service of Canada stations in Yukon Territory. The Mann–Kendall z statistics indicate that many of the trends are statistically significant (Mann 1945; Kendall 1975).

Table 1 | Historical Yukon and northwest Canada air temperature trends

		Mann–Kendall z statistic		Mann–Kendall z statistic		Mann–Kendall z statistic	
Station name	**Record period**	**Years record**	**Summer**	**Years record**	**Winter**	**Years record**	**Annual**
Whitehorse	1942–2006	62	−0.58	60	1.88^{*}	59	1.63
Dawson	1907–2006	93	0.68	96	2.36^{**}	91	1.75^{*}
Mayo	1925–2006	79	4.61^{****}	76	1.70^{*}	76	2.72^{***}
Watson Lake	1938–2006	65	−0.09	64	1.25	62	0.95
Beaver Creek	1969–2005	31	3.04^{***}	29	1.69^{*}	28	3.20^{***}
Burwash Landing	1966–2006	37	2.60^{***}	36	2.30^{**}	35	2.16^{**}
Fort McPherson	1986–2006	19	0.00	16	−0.27	16	0.23
Inuvik	1957–2005	47	2.30^{**}	44	3.62^{****}	43	3.75^{****}
Old crow	1951–2005	34	3.38^{****}	26	2.47^{**}	26	2.51^{**}
Shingle point	1957–1992	30	1.11	22	2.14^{**}	22	1.07

Level of significance: *0.10; ** 0.05; *** 0.01; **** 0.001.

Table 2 | Historical Yukon and northwest Canada precipitation trends

		Mann–Kendall *z* statistic		**Mann–Kendall *z* statistic**		**Mann–Kendall *z* statistic**	
Station name	**Record period**	**Years record**	**Summer**	**Years record**	**Winter**	**Years record**	**Annual**
Whitehorse	1942–2006	63	0.77	61	−2.30**	60	−0.01
Dawson	1907–2006	92	1.46	95	−1.70*	90	0.12
Mayo	1925–2006	79	2.76***	76	0.37	76	2.27**
Watson Lake	1938–2006	65	1.77*	65	−2.92***	64	−0.51
Beaver Creek	1969–2005	31	0.97	30	−0.71	27	0.21
Burwash Landing	1966–2006	37	0.50	36	−2.14**	35	−1.48
Fort McPherson	1986–2006	19	0.56	17	0.62	17	−0.45
Inuvik	1957–2005	46	−0.59	43	−2.98***	43	−1.42
Old Crow	1951–2005	30	1.57	24	2.41**	23	3.27***
Shingle Point	1957–1992	26	1.17	27	3.00***	23	2.99***

Level of significance: *0.10; ** 0.05; *** 0.01; **** 0.001.

Annual, winter and summer temperatures have generally increased in all regions, with greater increases observed in central and northern regions. Annual precipitation trends are not consistent. Winter precipitation has generally increased in northern regions and decreased in southern regions. Summer precipitation has generally increased slightly throughout, with greater increases in southeast and central areas.

Observed temperature trends are within the range of projections developed by a Canadian Climate Centre global climate model (GCMIII), which is based on a 100% increase of CO_2 in the atmosphere (Intergovernmental Panel on Climate Change 2006). Observed precipitation trends are somewhat outside the range of developed projections which suggest that annual precipitation will increase in all Yukon regions by 5–15%. There is also some evidence suggesting the trends may be associated with teleconnections between large-scale oceanic and atmospheric processes such as El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Barlow *et al.* 2001). Over the last century, the PDO appears to have shifted between positive and negative phases every 20–30 years (Cayen 1996). A positive PDO is generally associated with lower-than-normal precipitation and higher-than-normal air temperatures and a negative PDO is associated with higher-than-normal precipitation and lower-than-normal air temperatures. Inspection of the PDO index shows a major shift to have occurred in the 1970s, coinciding with the significant temperature increases observed in northern Canada during this time period.

SETTING

Yukon Territory is situated in northwestern Canada, bounded by Alaska and the Northwest Territories to the west and east, respectively, and the 60th parallel of latitude and the Arctic Ocean to the south and north, respectively. The climate is characterized as subarctic in the south and arctic in the north, with some maritime influence from the Gulf of Alaska in the southwest regions (Wahl *et al.* 1987). Annual mean daily air temperatures range from −1°C in the south to −10°C in the north. Annual precipitation amounts are significant in the Coast and Saint Elias Mountains with amounts up to 2,000 mm. Precipitation throughout much of the Territory ranges from 300–600 mm, with annual amounts declining to approximately 150 mm on the Arctic coast. Much of the Yukon is underlain by permafrost subdivided into continuous, discontinuous and sporadic zones, representing 30, 45 and 25% of the Yukon, respectively (NRC 1995). There are four distinct hydrologic response types exhibited by Yukon streams (Figure 1). The Western hydrologic zone is comprised of the Saint Elias and Coast Mountains which experiences the highest mean annual precipitation and temperature in the Territory, and subsequently has the greatest mean annual runoff. Streamflow response is

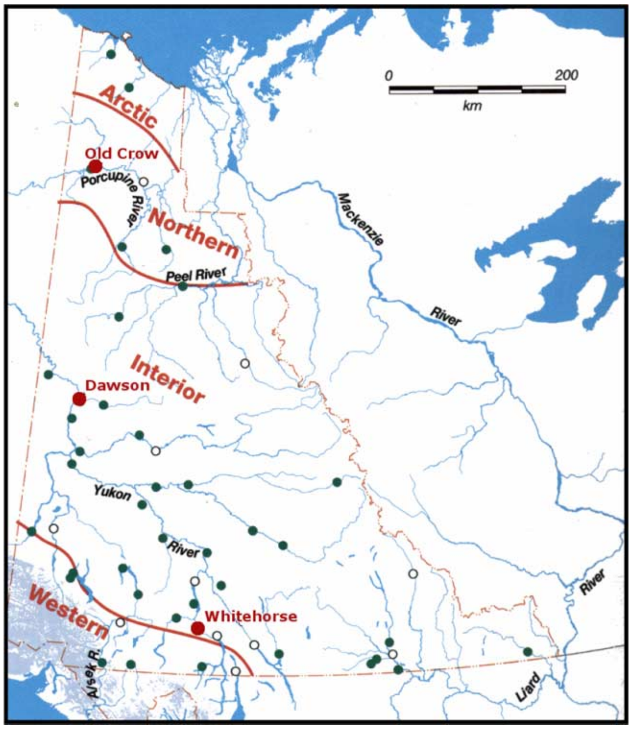

Figure 1 | Location plan and hydrologic zones.

characterized by a rapid increase in discharge in the late spring in response to snowmelt at lower elevations, and increases to the annual peak flow later in the summer in response to higher elevation snow and glacier melt. Hydrologic response from the remaining three zones is closely tied to, and coincides in location and extent, to the three permafrost zones: continuous, discontinuous and sporadic (Janowicz 2004). Streamflow response in the Interior hydrologic zone is characterized by a rapid increase in discharge in the spring due to snowmelt, with peak flows generally occurring in June. Streamflow response in the Northern hydrologic zone is largely controlled by the underlying permafrost. Peak flows generally occur in June, and are greater relative to areas with less permafrost due to shorter pathways to the stream channel as a result of limited infiltration rates. The controlling influence of the underlying permafrost on hydrologic response is extreme in the Arctic hydrologic zone. Peak flows generally occur in June and exhibit very quick response times because of the shallow active layer. Secondary peak flows in all zones occur during the summer months as a result of rainfall. Occasionally smaller systems will have the dominant peak resulting from rainfall. Annual minimum discharge occurs in March or April, coinciding in timing with minimum annual groundwater inputs. Annual minimum flows decrease moving northward due to lesser groundwater contributions to winter streamflow. Many smaller streams within the continuous permafrost zone are completely dominated by underlying permafrost and have no observed flow during the latter part of the winter.

YUKON RIVER ICE REGIME TRENDS

Freeze-up timing

On a territorial scale freeze-up generally progresses from north to south, tied closely to the stream cross-section energy balance. On a regional scale stream channel characteristics contribute significantly to freeze-up. Within the same region, wide shallow streams will freeze before deeper larger flow streams because of the difference in surface area to volume flux (Beltaos & Prowse 2009). Within the same stream ice cover is likely to occur within tight meanders or other constrictions which act as a lodgement point for growing ice pans, with the ice front progressing upstream from this point. In the study of freeze-up on the Yukon River (Janowicz 1982, 1983), the initial lodgement of a 700 km reach of river was observed to occur at the same location within a confined meander in two consecutive years, though meteorological conditions immediately preceding freeze-up initiation varied considerably (Gerard *et al.* 1984). Freeze-up observations were sporadically made in Yukon Territory since the 1890s primarily for river transportation reasons. Fountain & Vaughn (1984) provide a summary of observations taken on the Yukon River from Whitehorse to Alakanuk near the mouth. The data was initially collected by the transportation shipping companies, with the Atmospheric Environment Service taking over this role in later years. This practice was discontinued in the mid-1990s. Figure 2 provides a graphical summary of the observations. Freeze-up of the Yukon River at Whitehorse has been delayed by approximately 30 days since 1902.

Break-up timing

Because of the river transportation history there is an excellent record of break-up dates for the Yukon River

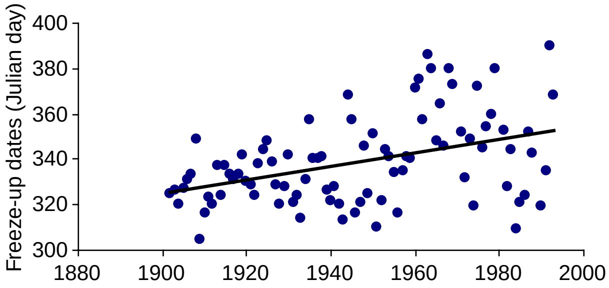

Figure 2 | Yukon River at Whitehorse freeze-up dates (1902–1993).

at Dawson. Break-up heralded the end of winter isolation for Dawson, which would be followed by the arrival of the first steamship from outside in about two weeks. A lottery to predict the exact minute of break-up has been held in Dawson since 1896 and continues today. Over the period of record, break-up at Dawson has ranged from 28 April to 29 May, with a mean date of 9 May. Jasek (1999) carried out an assessment of the data to 1998 and observed that the break-up date advanced 5 days per century. The last two decades have seen an unprecedented advancement of the break-up date. Prior to 1989, only two April break-ups have been observed (≤julian day 120 (leap year 121)), while after 1989, six April break-ups have been observed. Figure 3 provides a statistically significant graphical representation of the data.

A similar trend is noted for the Porcupine River at Old Crow, though the record begins in 1961. The break-up date ranges from 2 May to 30 May, with an overall mean of 16 May. The mean break-up date has advanced from 18 May during the first 20 years of record to 14 May in the last 20 years. Figure 4 provides a graphical representation of the data.

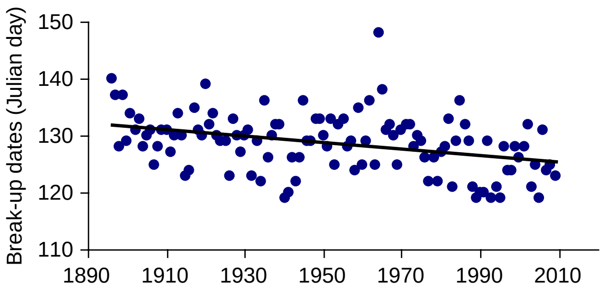

Figure 3 | Yukon River at Dawson break-up dates (1896–2009).

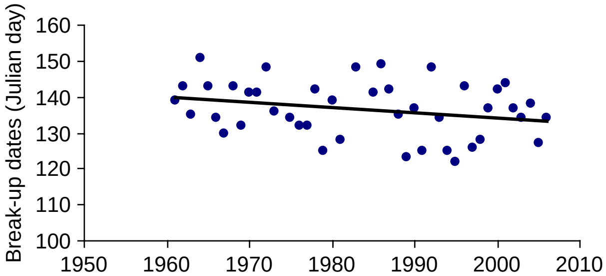

Figure 4 | Porcupine River at Old Crow break-up dates (1961–2009).

2003 mid-winter Klondike River break-up

Dawson experienced the warmest winter of its 110 year record during 2002–3. An unusual period of warm weather and rain during December 2002 produced low elevation snowmelt resulting in an early winter break-up event and subsequent formation of an ice jam on the Klondike River. Though there was only minor flooding, the 3 km long jam resulted in unusually high water for the time of year. The jam subsequently refroze, creating “jumble” ice with thicknesses up to 3 m, which had major spring break-up implications on Klondike River water levels. During spring break-up at the end of April 2003, the lower Klondike valley experienced one of the most severe break-up floods on record, with a number of residences, businesses and the Klondike Highway affected.

Break-up severity

Numerous Yukon communities have historically experienced ice jam flooding, with the most severe floods having occurred at Dawson City on the Yukon River and Old Crow on the Porcupine River. Dawson City and Old Crow have experienced six and four major ice jam floods in the last century, respectively. Figure 5 provides a graphical summary of annual maximum ice-related water levels from 1896 to 2009. Data from 1896 to 1986 was compiled to provide design information for the construction of an engineered dyke after the 1979 flood of record (Klohn Leonoff 1987). Data prior to 1944 was obtained from archival sources and has confidence limits of ±0.5 to 0.75 m, depending on the original source (photographs and newspaper reports (Dawson City Museum and Historical Society 1981)). Peak water level data from 1945 to 1974 was

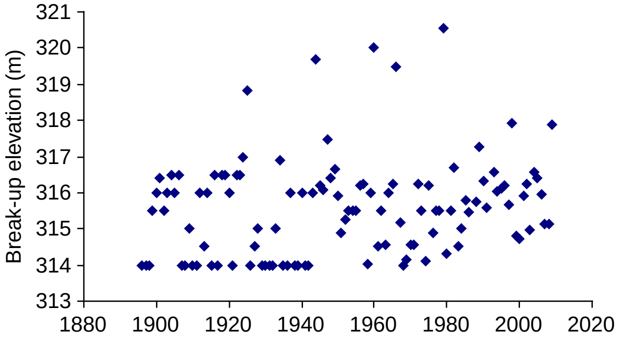

Figure 5 | Yukon River at Dawson annual maximum break-up elevations (1896–2009).

obtained from hydrometric observer field books, reducing the confidence limits to ± 0.15 to 0.25 m. Data from 1975 to 1986 was estimated from recorder chart records and have confidence limits of ± 0.15 to 0.75 m. Peak water levels from 1993 to present were obtained from surveyed high water marks, as were earlier extreme events (1925, 1944, 1979). There appears to be a trend of increasing elevations from the early 1970s to the present, possibly exhibiting the influence of climate warming. Though there is both considerable range and scatter, the trend of increasing elevations is evident at both low and high elevations.

A similar trend is not evident for the Porcupine River at Old Crow, possibly due to the paucity of data. Because of inherent problems associated with operating under ice conditions, the station was not normally operated during the break-up period. Because of these problems no ice-related water level data is available for these locations. Possibly the greatest flood of the 20th century occurred in 1991, inundating the community by over a metre. As a result of this event Yukon Water Resources began a formal forecasting and monitoring program for the community, and as such there is a reasonable peak ice-related water level record from 1992 to the present. A high water mark survey provided peak water levels for the 1989 and 1991 events. In the interests of implementing flood mitigation measures for the community, a study was carried out in 1992 to develop a stage frequency relationship (Janowicz 1992). Since the early hydrometric record is poor, societal and environmental information was used to reconstruct the higher peak ice-related water levels. Societal information consisted of archival information including photographs and descriptive reports, and resident recollections. Environmental information included high water marks produced by ice scars and deposition of material. Peak ice-related water levels for 1932, 1973 and 1983 were obtained in this fashion.

2009 break-up event

The 2009 spring break-up was unusual throughout Yukon. The winter had been colder than normal, producing thicker-than-normal ice cover. Ice measurements at Dawson yielded ice thickness values of 1.49 and 1.23 m. The winter snowpack was considerably heavier than normal with record levels at some locations. Spring air temperatures were lower than normal, followed by a rapid increase in the week prior to break-up, with record high temperatures at some locations. Numerous streams throughout Yukon broke up quickly, producing ice jams and subsequent flooding at several locations. The break-up water level on the Yukon River at Dawson was the seventh highest on record. Break-up was considerably more severe 150 km downstream at Eagle, Alaska, with the flood of record destroying much of the community.

RESULTS AND DISCUSSION

Annual, winter and summer temperatures have generally increased in all regions, with greater increases observed in central and northern regions. Annual precipitation trends are not consistent. Winter precipitation has generally increased in northern regions and decreased in southern regions. Summer precipitation has generally increased slightly throughout, with greater increases in southeast and central areas. An assessment of freeze-up dates indicates that freeze-up of the Yukon River at Whitehorse has been delayed by 30 days since 1902. This is a greater delay in freeze-up timing than observations made by Ginzburg *et al.* (1992) for rivers in Russia, but similar to observations made by White *et al.* (2007) for more temperate rivers in Maine. Rannie (1983) observed a 12 day delay in freeze-up on the Red River in Manitoba. There is a relatively long record of break-up dates (1896–2009) for the Yukon River at Dawson. An assessment of this record indicates that there is a statistically significant trend in earlier break-up dates, with an advance of 5 days per century. This trend is consistent, but less than observations made on other northern rivers where break-up date advance was observed to be greater than 10 days per century for streams in Europe (Zachrisson 1989; Stonevicius *et al.* 2008) and southern North America (Rannie 1983; Beltaos 2002). Similar to the Yukon River at Dawson, White *et al.* (2007) observed the break-up date to advance 6 days per century in Alaska. A similar trend is noted for the Porcupine River at Old Crow, though the record is much shorter with observations beginning in 1961.

A plot of the annual maximum ice-related stage for the Yukon River at Dawson appears to exhibit a trend of increasing elevations from the early 1970s to the present. Though there is both considerable range and scatter, the trend of increasing elevations is evident in both the low and high elevation years. Intuitively less severe break-up events might be expected with climate warming. Warmer winters with less snowcover and an earlier melt should logically produce more thermal break-up events. Even with warmer winters, perhaps a lower snow cover is responsible for moderately thick ice as a result of less insulation. Though there is a reasonable amount of historical information on freeze-up and break-up timing, data pertaining to ice jam severity is less frequent, and what information is available is not consistent in terms of the trend. Beltaos (2004) observed a positive trend in peak break-up water level for the Southwest Miramichi River in Atlantic Canada for the 1962–1996 period. This trend was attributed to corresponding trends in air temperature and streamflow discharge prior to break-up. Prowse & Conly (1998) observed a lesser ice jam severity on the Peace River in northwestern Canada in recent decades. Though the system is no longer natural, with the addition of upstream regulation, less winter snowpack is also cited as a contributing factor to this trend. A mid-winter break-up event and associated ice jam occurred on the Klondike River at Dawson during the winter of 2002–3 resulting in flooding of the community. The mid-winter event was triggered by record high air temperatures and rainfall. Though the occurrence of such events are becoming more common in temperate regions (Beltaos 2002; Beltaos & Burrell 2003), this is the first recorded mid-winter event in Yukon. This event may be a direct result of climate warming. Winters have been warming steadily in much of the Yukon over the past few years and show every sign of continuing that trend. That could mean more mid-winter break-ups and greater spring floods in the future. The 2009 spring break-up was very unusual throughout Yukon and Alaska. The winter was colder than normal and winter snowpack was greater than normal throughout the region. Spring air temperatures were lower than normal, followed by a rapid rise to record high temperatures in some areas. These factors contributed to a dynamic event producing a relatively high break-up event at Dawson and the flood of record at Eagle, Alaska.

CONCLUSIONS

Yukon air temperatures have increased significantly in the last century. Precipitation is not as consistent with greater precipitation in some regions and less in others. The length of the ice cover period is becoming shorter with later freeze-up and earlier break-up dates. Mid-winter break-up events and associated flooding have been observed for the first time. Break-up water level trends on the Yukon River suggest that break-up severity is increasing. These changes cannot be definitely attributed to climate change as there is some evidence suggesting that teleconnections (PDO, ENSO) may be a factor. The observed changes have significant implications associated with public safety and economic impacts to property and infrastructure, transportation networks and hydro-electric operation. Ice jams and associated backwater and surges also affect aquatic ecosystems through impacts on biological and chemical processes.

ACKNOWLEDGEMENTS

The work carried out by Jessica Boucher in performing much of the climate data assessment and Robert Stillwell in compiling ice observation data, developing climate change projections and assistance with the graphics is greatly appreciated.

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First received 1 November 2009; accepted in revised form 28 May 2010. Available online September 2010