Hydro-climatic drivers of mid-winter break-up of river ice in western Canada and Alaska

B. W. Newton, T. D. Prowse and L. P. de Rham

ABSTRACT

The mid-winter break-up of a competent river ice cover can cause ice jamming and flooding, which can have profound impacts on the structure and strength of the ice cover. This research identifies 52 mid-winter break-up events in western Canada (1950–2008) and Alaska (1950–2014) and evaluates the hydro-climatic drivers including temperature and precipitation. The identified mid-winter break-up events are primarily located in the temperate zone, defined as the region between 400 and 1,000 winter (December–February) freezing degree-days. Further delineation by terrestrial biome revealed considerable variability in hydro-climatic triggers, particularly the role of freeze-thaw days ($T_{max} > 0\,^{\circ}C$ and $T_{min} < 0\,^{\circ}C$) in Tundra and Boreal Forest/Taiga biomes and short-term (3-day) warming events in Temperate Coniferous Forests and Temperate Grasslands, Savannas, and Shrublands. The classification of 5-day sequences of mid-tropospheric circulation indicates that a persistent trough of low-pressure over Alaska and the North Pacific is the dominant pattern preceding mid-winter break-ups. Furthermore, the trough is stronger for events in British Columbia and Alberta compared with Alaska and the Yukon. The results of this research improve our understanding of the hydro-climatic conditions that generate mid-winter break-up events in western Canada and Alaska and will aid in the prediction and risk management of such events.

Key words | mid-winter, rain on snow, river ice break-up, warm spells

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INTRODUCTION

The break-up of river ice is responsible for some of the most extreme flooding in cold regions (Beltaos & Prowse 2001; Prowse & Beltaos 2002; Jasek 2003; de Rham *et al.* 2008), and can have severe impacts on geophysical, socio-economic, and biological systems (e.g. Van der Vinne *et al.* 1991; Doyle 1992; Prowse & Culp 2003; Lind *et al.* 2014). Of particular concern is the mid-winter break-up of a competent ice cover, which is often unexpected and can cause localized flooding that can be difficult to manage, especially following the return of freezing temperatures (Beltaos 2002). Furthermore, the refreezing of river ice can increase the thickness and strength of the ice cover (Beltaos 2002), and exacerbate spring break-up conditions (Beltaos 1997, 1999, 2008; Janowicz 2010).

The formation, growth, and break-up of river ice are important components of the hydrologic cycle in cold regions. There is a strong correlation between air temperature and the timing of river ice freeze- and break-up (Bonsal & Prowse 2003; Bieniek *et al.* 2011). Therefore, the duration and extent of the river ice season can be estimated using the timing of the 0 °C isotherm, which generally increases with increasing latitude (Bennett & Prowse 2010).

River ice break-up is influenced by both thermodynamic and hydrodynamic processes (Beltaos & Prowse 2001; Beltaos 2003). In a purely thermal break-up, thermodynamic processes dominate and resisting forces, including the strength of the ice cover and attachment to riverbanks, diminish without a substantial increase in driving forces

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(Beltaos 1997). Thermal break-up often occurs when spring temperatures are mild and the combination of slow snowmelt and little or no rainfall produce low runoff (Gray & Prowse 1993; Beltaos 2003). Conversely, a purely mechanical break-up occurs when driving forces, caused by rising discharge and stage, increase to the point where they exceed maximum resisting forces (Beltaos 1997), often resulting in high flood stage (de Rham *et al.* 2008). Mechanical break-up is often associated with a large, rapid spring discharge pulse driven by high-intensity snowmelt, and in some cases heavy rainfall (Gray & Prowse 1993; Beltaos 2003).

The decay of an intact river ice cover is controlled by numerous energy inputs. These include: short- and long-wave radiation; latent heat of vaporization; sensible heat exchange, which is a function of the difference between air and ice surface temperatures; heat transfer from precipitation (Prowse & Marsh 1989; Hicks *et al.* 2008) and warm water flowing under the ice cover providing heat to the base of the ice (Gray & Prowse 1993). Decay commences as energy inputs increase the temperature of the ice cover; once it becomes 0 °C isothermal, the ice cover begins to melt (Gray & Prowse 1993; Hicks *et al.* 2008). Initial melt occurs at ice crystal boundaries, causing the ice cover to fragment (Beltaos 2003). The mechanical strength of the ice cover decreases (Prowse *et al.* 1990b) and it separates from the shoreline and consequently, the ability for a spring flood wave to proceed downstream without jamming increases (Gray & Prowse 1993). Thermodynamic processes play an important role during spring as temperatures rise and the angle of solar declination increases. When the spring freshet is anomalously early, the river ice cover lacks thermal or radiative deterioration (Beltaos 2002) and the spring flood wave reaches an area with a hydraulically strong, intact ice cover that may still be attached to the bed and banks (Prowse *et al.* 1990a). These conditions can result in dynamic break-up events accompanied by ice jamming and extreme water levels (de Rham *et al.* 2008).

Winter temperatures rising above freezing and/or rain-on-snow can trigger a mid-winter break-up (Prowse *et al.* 1990b; Beltaos & Prowse 2001; Beltaos 2002; Beltaos *et al.* 2003). Mid-winter break-ups lack the thermal decay processes that occur during spring and therefore, the ice cover is typically strong and intact and break-up is mechanical (Beltaos 2002, 2003). Unlike the spring break-up event, which clears the fragmented ice, mid-winter break-up refreezes, and the resulting ice cover is thicker and rougher, with a greater hydraulic strength (Beltaos 2002, 2003). Notably, if the mid-winter melt is large enough to substantially reduce the volume of water equivalent in the surrounding snowpack, the potential for high hydrodynamic forces during the spring melt is decreased (Beltaos 2008).

Numerous variables influence the magnitude of the mid-winter break-up, including hydrologic parameters such as freeze-up stage, ice thickness, and discharge, and hydro-climatic factors, including air temperature and snow depth and density. For example, an equivalent warm spell later in the season can elicit a different hydrologic response compared with warming earlier in the season (Doyle & Costerton 1993). Rainfall can also be an important factor, as even modest amounts of rainfall can generate runoff. Melting snow and ice requires heat energy from the surrounding environment. Rain on snow events contribute sensible heat due to the relative warmth of the liquid water; however, the energy release through latent heat of fusion as the rain freezes in the snowpack is far greater than the energy from sensible heat (Gray & Prowse 1993). Consequently, rainfall will generate more energy on a cold snowpack compared with an isothermal snowpack.

Mid-winter break-ups are common in temperate and maritime regions of North America, and typically occur during January and February (Beltaos 2002; Prowse *et al.* 2002; Carr & Vuyovich 2014). Evidence indicates the frequency of mid-winter break-ups is increasing in some regions, and occurring in regions that have not previously reported mid-winter events. For example, Prowse *et al.* (2002) reported an increase in mid-winter (January–February) warming events near the northern boundaries of a defined temperate region in North America, with the greatest increases occurring in western Canada and United States. Huntington *et al.* (2003) reported an increase in mid-winter break-up on the Picataquis River in Maine, primarily attributed to winter rainfall. Beltaos (2002) determined that higher proportions of precipitation falling as rain, resulting from an increased frequency of mild winter days, contributed to higher streamflow and consequently, mid-winter break-up on the Saint John River in Maine and New Brunswick. Carr & Vuyovich (2014) detected an increasing trend on the Fox and Grand Rivers, but a decreasing trend on the Kankakee River, all located in the Midwest United States. Recently, Janowicz (2010) described the first mid-winter break-up event in the Yukon, occurring on the Klondike River in 2002. Additionally, research has indicated an increase in January snowmelt in southwestern Canada (Linton 2014) and an increase in the frequency and duration of winter (January–March) warm spells in western Canada (Shabbar & Bonsal 2003).

The aim of this research is to compile a database of mid-winter break-up events on rivers in western Canada and Alaska and evaluate the climatic drivers of these events. Specifically, the date of mid-winter break-up events are identified and corresponding daily temperature and precipitation records from the nearest climate station and/or gridded data are extracted and compared with two threshold criteria given in Prowse *et al.* (2002) and Carr & Vuyovich (2014) to determine if those thresholds are sufficient triggers of mid-winter break-up events across western Canada and Alaska, given the biogeographic and topographic variability of the study region. Additionally, sequences of dominant daily mid-tropospheric circulation patterns are identified to determine the role of atmospheric trajectory and persistence in generating mid-winter break-up events. Understanding the hydro-climatic conditions conducive to mid-winter break-up is essential for the prediction of such events and the mitigation of impacts including flooding and damage to infrastructure and property. Additionally, it will aid in determining whether the hydro-climatic triggers of mid-winter break-up have been increasing or will increase in the future.

STUDY AREA

Western Canada–British Columbia (BC), Alberta, Saskatchewan, Manitoba, Yukon, Northwest Territories (NWT), and Nunavut–and Alaska encompass a wide range of physiographic and hydro-climatic regions. For the purposes of this research, the study region is represented by four broad terrestrial biomes (Olson *et al.* 2001; WWF 2016). Temperate Coniferous Forests covers the southern two thirds of BC and portions of western Alberta. This region is characterized by moist, mild winters, except for leeward mountain slopes, which are drier, and subalpine regions, which are cold and snowy. The southern half of the Prairie Provinces, extending from the Alberta foothills through Manitoba, is located in the Temperate Grasslands, Savannas, and Shrublands region, and is known for cold winters, low precipitation, and frequent droughts.

The Boreal Forests/Taiga region spans northern BC, Alberta, Saskatchewan, and Manitoba, southern Nunavut, most of the NWT, southern Yukon, and central Alaska. Boreal Forests/Taiga are characterized by long, cold winters and low precipitation, primarily falling as snow. Much of this region is underlain by sporadic (10–50%) to extensive (50–90%) discontinuous permafrost (Brown *et al.* 1998). Similarly, the Tundra region is known for long, cold, dry winters. This region extends from central Yukon to the southwestern coast of Alaska as well as the north Arctic coast of Alaska, Yukon, NWT, and much of Nunavut. Additionally, a narrow portion of northern BC and the Alaska panhandle is classified as Tundra, due to the steep mountainous environment that extends through southwestern Yukon and southeastern Alaska and contains some of the highest peaks in North America. Permafrost in this region ranges from sporadic discontinuous in southern Alaska/Yukon to continuous along the north coast (Brown *et al.* 1998).

Permafrost limits the hydrological connectivity within a basin as runoff is confined to the surface and seasonally thawed active layer (Woo 1986; Woo *et al.* 2008). Rainfall runoff response rates are typically high and surface ponding is common during the spring melt period (Woo 1986). Permafrost zones are generally poorly drained and wetlands are common (Olson *et al.* 2001); however, runoff response depends on soil, topography, and vegetation (Carey & Woo 2001). The winter season is characterized by negligible energy fluxes due to the high latitude environment; consequently, high temperature gradients exist between the subsurface and overlying atmosphere (Woo 1986). Cold season warming or rainfall events can affect the temperature regime of the subsurface as water refreezes to the base of the snowpack, releasing latent heat (Westermann *et al.* 2011). These ice lenses can impact runoff from subsequent rainfall or snowmelt events (Kane 1980).

Patterns of atmospheric circulation have been shown to affect winter surface climate in western Canada and Alaska. Temperature and precipitation in this region are strongly influenced by warm, moist air masses originating over the Pacific Ocean and outbreaks of cold, dry Arctic air masses. The mountainous topography of BC and Alberta is subject to orographic effects as moist air is forced to rise and precipitate, resulting in heavy snow and rainfall on the windward slopes. The leeward slopes receive less precipitation and frequently spawn Chinook winds – dry, adiabatically warmed air descending the mountains that cause a rapid, short-term increase in temperatures and, consequently, snowpack sublimation and melt (Goulding 1978). In southwestern Canada anomalously warm winter days are associated with a mid-tropospheric trough of low pressure over Alaska and the North Pacific and adjacent ridge of high pressure over western Canada (Newton *et al.* 2014). Conversely, a ridge of high pressure over the North Pacific is associated with anomalously cold, wet winter days (Newton *et al.* 2014). In Alaska, temperature and precipitation are strongly influenced by the strength and position of the Aleutian Low. For example, an Aleutian Low to the west of the Aleutian Islands is associated with anomalously warm temperatures in central, western, and northern Alaska, but anomalously cold temperatures in the Alaska panhandle (Cassano *et al.* 2011). A low-pressure system located in the Gulf of Alaska is associated with anomalously cold temperatures over most of Alaska, but anomalously warm temperatures over the panhandle (Cassano *et al.* 2011).

DATA AND METHODS

Mid-winter break-up onset and peak water level are identified through the meticulous inspection of pen-recorder charts from 1950 to ~1996 and digital stage records from ~1996 to 2008 obtained from Water Survey of Canada (WSC) for 90 unregulated rivers in BC, Alberta, Saskatchewan, Manitoba, NWT, Yukon, and Nunavut using the criteria described in Beltaos (1990). The timing of freeze- and break-up are determined through evaluation of stage records and annotation of the WSC 'B' dates on daily discharge records, where 'B' indicates the presence of ice, but does not specify ice cover extent or thickness. Stage decreases as the river begins to freeze, and following the formation of a full ice cover the river stage stabilizes and remains relatively low. Mid-winter break-up events were identified as a 'spike' in stage over a short period of time.

Mid-winter break-up events in Alaska are identified using the Cold Regions Research and Engineering Laboratory (CRREL) Ice Jam Database (CRREL 2015). The ice jam database is a comprehensive record of freeze- and break-up ice jam events. The precise location of the ice jam is given, which, in many cases, is between hydrometric gauging stations, whereas the Canadian events are only detected at hydrometric stations. As this database includes only those break-up events that result in an ice jam, it may exclude minor mid-winter break-up events.

Following Prowse *et al.* (2002), a temperate region for western Canada and Alaska is defined. The temperate region represents an area where a solid, sufficiently thick (~30–50 cm) ice cover is expected to form, but that is also subject to mid-winter (January–February) warm spells. The temperate region is represented by the region bounded by 400 and 1,000 accumulated mean winter (December–February) freezing degree-days (FDD) calculated using data from 210 climate stations in Canada and 660 stations in the United States. As river ice phenology is a function of temperature, accumulated FDD is commonly used to model ice growth on lakes and rivers (Michel 1971). This study employs high-resolution ($0.25 \times 0.25^\circ$) gridded twice-daily winter (December–February) reanalysis temperature data from the European Centre for Medium Range Weather Forecast (ERA-Interim) for 1979–2014 (Dee *et al.* 2011) to delineate the temperate region in western Canada and Alaska. Comparisons were made between ERA-Interim and reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay *et al.* 1996) and a high-resolution (10×10 km) gridded dataset using the ANUSPLIN thin-plate spline interpolation method of climate station data in Canada (McKenney *et al.* 2011). The resulting temperate region was similar between datasets; however, the NCEP/NCAR Reanalysis data were too coarse and the ANUSPLIN dataset is only available for Canada. The ERA-Interim data were deemed most appropriate for this research.

Temperature and precipitation data are obtained from the climate station nearest to the hydrometric station (Canada) or location of the ice jam (Alaska). In several cases the nearest climate station is located outside the watershed, or could not adequately describe the hydroclimatic conditions leading up to the mid-winter break-up, and high-resolution gridded climate data from ERA-Interim are used to supplement the station data. Precipitation phase and volume are of particular concern, as point source data are not necessarily characteristic of the entire watershed, particularly for large watersheds with varying topography (Carr & Vuyovich 2014). Temperature data are used to calculate FDD prior to and following the mid-winter break-up event and any identified event not bounded by sufficient ice growth is rejected.

Although it is known that anomalously warm temperatures and/or rain-on-snow trigger the mid-winter break-up of an ice cover, few studies have quantified temperature or rainfall thresholds related to these break-up events. Two such studies, Prowse *et al.* (2002) and Carr & Vuyovich (2014) used a temperature-index approach, along with hydrometric records, to define break-up events. Specifically, Prowse *et al.* (2002) defined a minimum of 25 melting degree-days (MDD) over a 7-day period to initiate a mid-winter break-up. Carr & Vuyovich (2014) do not distinguish threshold differences between spring and mid-winter break-up events, except that an ice cover reforms following mid-winter break-up events. They found that mechanical break-up events were attributed to an MDD of 8–19 or 2.8–7.6 mm of rainfall over a 5-day period, where a thermal break-up was attributed to an MDD of 22–31 over a 5-day period. Note that the rivers evaluated by Carr & Vuyovich (2014) fall within the temperate region defined by Prowse *et al.* (2002). This research compares 7- and 5-day MDD and 5-day rainfall for each event to determine if the criteria used by Prowse *et al.* (2002) and Carr & Vuyovich (2014) is adequate to pick up the majority of events in western Canada and Alaska.

Mid-winter break-up events are often preceded by several days of anomalous winter weather. Therefore, a multi-day synoptic classification, based on a series of daily atmospheric circulation patterns (Compagnucci *et al.* 2001; Philipp 2009) rather than a daily classification, is more appropriate. The sequencing of atmospheric circulation patterns provides an enhanced understanding of the persistence and trajectory of atmospheric states and has been used to evaluate extreme temperature and hydrologic events (e.g. Jacobeit *et al.* 2006; Peña *et al.* 2015).

The method of self-organizing maps (SOM) is used to classify 5-day sequences of 500 hPa geopotential heights, obtained from NCEP/NCAR (Kalnay *et al.* 1996), to identify dominant atmospheric circulation patterns preceding the mid-winter break-up events. SOM uses competitive and cooperative learning to cluster and organize data vectors (Vesanto *et al.* 2000; Kohonen 2001) and has been successful in classifying daily synoptic-scale atmospheric circulation patterns (e.g. Cassano *et al.* 2011; Newton *et al.* 2014). Sequences of 5 days were considered suitable for this research as it is long enough to indicate the spatial and temporal structure of atmospheric states, but short enough that variability is minimized. For each identified mid-winter break-up event, the corresponding daily temperature and precipitation data are examined to determine the timing of the warm spell and/or rainfall that contributed to the break-up event. In most cases, the last day of the 5-day sequence is the same as the onset of the mid-winter break-up event. However, for some mid-winter break-up events the 5-day sequence was selected to be the day prior to the break-up. In these cases, the warm spell or rainfall ended the day prior to the break-up event date, and generally occurred in larger river basins where upstream warming or rainfall triggered the break-up event. For events in Alaska, the CRREL Ice Jam Database report was reviewed to ensure adequate match between weather conditions and timing of break-up.

RESULTS AND DISCUSSION

In western Canada, 15 of the 90 WSC hydrometric stations had at least one mid-winter break-up event between 1950 and 2008, and many of these rivers experienced multiple events. Additionally, six mid-winter break-up events were found in Alaska between 1950 and 2015. A total of 52 mid-winter break-up events occurred over the study period and are summarized in Table 1. The sizes of the drainage basins vary considerably, and there does not seem to be any discernable pattern between basin size, frequency, or timing of events.

WSC stations (Canada) and mid-winter break-up jams (Alaska) are shown in Figure 1, superimposed over terrestrial biomes (Olson *et al.* 2001). The four biomes in

Table 1 | Summary of mid-winter break-up events by Water Survey of Canada station (Canada) or location of ice jam (Alaska)

River name	Station ID[a]	Latitude (°)	Longitude (°)	Drainage area (km²)	Number of events	Dates of break-up[b]
Canada						
Athabasca River	07AE001	54.21	−116.06	19,600	2	12 Feb 1971, 21 Jan 1975
Blindman River	05CC001	52.35	−113.79	1,796	2	29 Jan 1998, 10 Mar 2005
Chilcotin River	08MB005	51.85	−122.65	19,200	2	14 Feb 1979, 3 Feb 2005
Coldwater River	08LG048	49.86	−120.91	316	13	24 Dec 1969, 21 Jan 1976, 26 Dec 1980, 20 Jan 1986, 11 Jan 1987, 25 Jan 1989, 28 Jan 1993, 5 Jan 1994, 31 Jan 1995, 4 Feb 1996, 28 Jan 2002, 24 Jan 2003, 24 Dec 2005
Elbow River	05BJ004	50.95	−114.57	791	1	16 Jan 1981
Fraser River	08KB001	54.01	−122.62	32,400	2	5 Jan 1962, 2 Mar 1963
Klondike River	09EA003	64.04	−139.41	7,810	1	15 Dec 2002
Little Smoky River	07GH002	55.46	−117.16	11,100	1	26 Feb, 1992
Oldman River	05AA023	49.81	−114.18	1,446	3	7 Mar 1979, 1 Jan 2000, 20 Jan 2005
Quesnel River	08KH006	52.84	−122.22	11,500	4	11 Jan 1971, 11 Feb 1982, 14 Jan 2007, 30 Jan 2008
Similkameen River (Hedley)	08NL038	49.38	−120.15	5,580	3	17 Jan 2001, 26 Dec 2005, 20 Jan 2007
Similkameen River (Princeton)	08NL007	49.46	−120.50	1,810	3	7 Jan 1970, 23 Jan 1987, 3 Jan 2007
Smoky River	07GJ001	55.72	−117.62	50,300	2	3 Dec 1956, 4 Jan 1958
Stikine River	08CF001	57.49	−131.75	36,000	1	24 Feb 1992
Wapiti River	07GE001	55.07	−118.80	11,300	6	26 Jan 1968, 2 Mar 1986, 29 Feb 1992, 16 Mar 1996, 12 Dec 1998, 5 Mar 2005
Alaska						
Kuskokwim River (Aniak)	15304000 +	61.59	−159.55	80,549[b]	1	13 Nov 2014
Kuskokwim River (Bethel)	15304300	60.79	−161.75	129,500	1	26 Nov 2010
Naknek River	15297890	58.69	−156.66	6,806	1	1 Mar 1963
Nushagak River	15302500	59.35	−157.47	25,486	1	19 Nov 2003
Tanana River	15481000	64.45	−147.07	44,651	1	19 Nov 2002
Wasilla Creek	15285000	61.64	−149.20	49	1	31 Dec 2010

[a] MWB date is the date of break-up initiation or the date of peak flow in the cases where initiation date was unavailable. For Alaska data, MWB is given as the date listed in the CRREL database.

[b] Station ID and estimated area from Crooked Creek.

western Canada and Alaska – Temperate Coniferous Forests; Boreal Forests/Taiga; Temperate Grasslands, Savannas, and Shrublands; and Tundra – reflect the biogeography of each region, and thus hydro-climatic characteristics of each watershed. These biomes are not indicative of basin topography, which influences airflow characteristics, precipitation distribution, and runoff response. However, categorizing mid-winter break-up events by terrestrial biome is a first step in improving our understanding of the triggers of mid-winter break-up events by considering variables that affect the hydro-climate of the region (e.g. Brooks *et al.* 2013).

The temperate zone, between 400 and 1,000 FDD, is consistent with Prowse *et al.* (2002); however, it extends

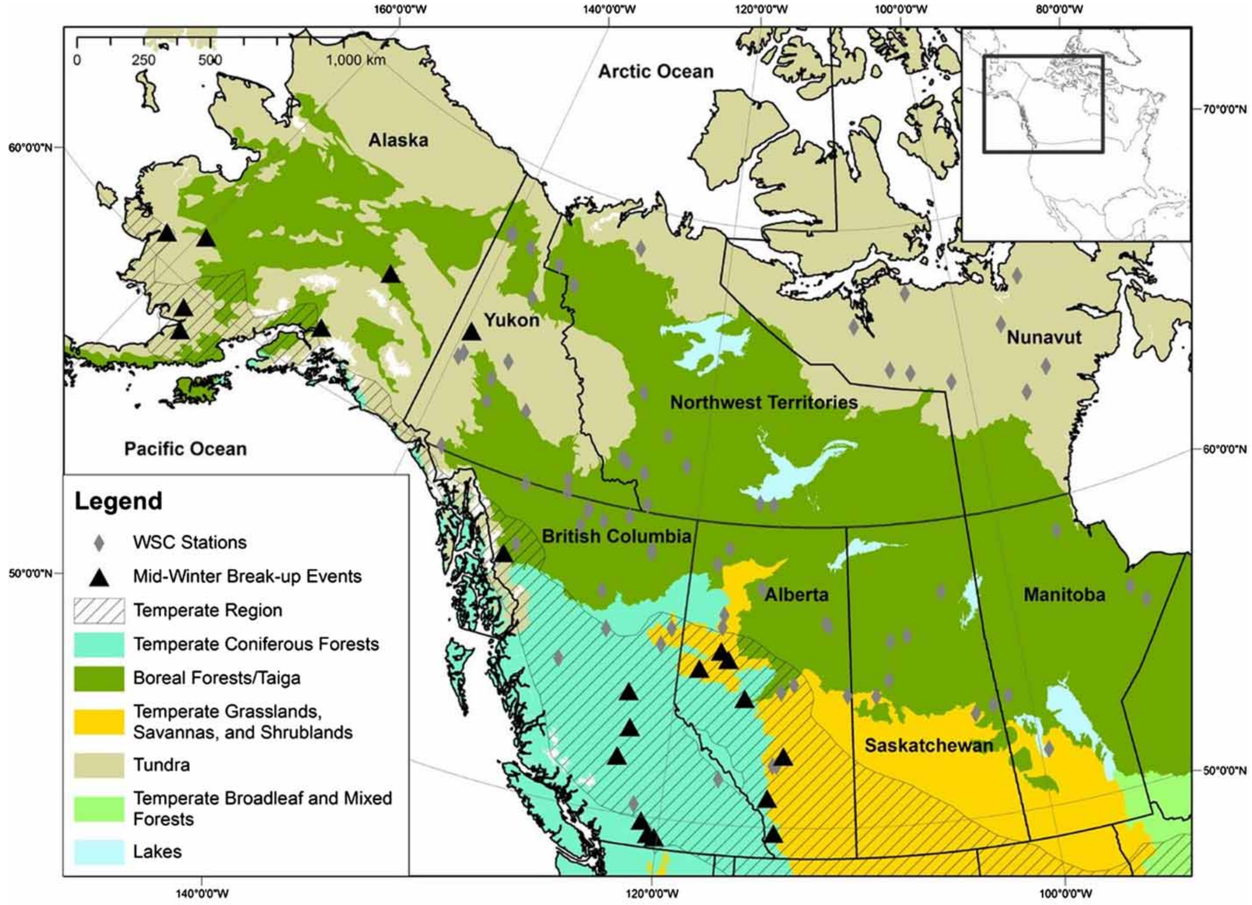

Figure 1 | Map of the study area indicating terrestrial biome regions and showing the locations of all Water Survey of Canada (WSC) stations evaluated for this research, and locations of identified mid-winter break-up events.

further south in BC and is extended north through coastal Alaska. As previously noted, the NCEP/NCAR Reanalysis and ANUSPLIN datasets produced similar temperate regions. Fifteen of the 21 mid-winter break-up sites are located within the temperate region, while two WSC stations are located just outside of the temperate zone, the Coldwater River and Similkameen River (Princeton), and four locations are north of the temperate zone: the Klondike River, Tanana River, Kuskokwim River (Aniak), and Wasilla Creek. The four events associated with these northern locations are also relatively recent, all occurring within the 21st century. Additionally, these four events occurred in late autumn-early winter (November–December).

The Coldwater River has the greatest number of mid-winter break-up events with a total of 13 from 1969 to 2005. The Coldwater River is a tributary to the Nicola River, a basin with not only numerous mid-winter break-up events, but also several premature spring break-ups that have caused severe flooding. Doyle (1988, 1992) describe severe break-up ice jam flooding events in January 1984 and February 1991, respectively. Both events were triggered by heavy rainfall and melting snow resulting in sequential ice jams and ice runs (Doyle 1992). Although these events occur during the winter season, the ice cover failed to reform following these break-up events; therefore, they are not classified as mid-winter break-ups for the purpose of this research.

Comparison with criteria used by Prowse *et al.* (2002) found that a minimum of 25 MDD over a 7-day period was a poor predictor of mid-winter break-up events, with only six of 52 events preceded by MDD of this magnitude (Table 2). A total of 32 events were preceded by the thresholds given by Carr & Vuyovich (2014): a minimum

Table 2 | Number of events that meet temperature and precipitation thresholds defined given by Prowse *et al.* (2002) and Carr & Vuyovich (2014)

	25 + MDD over 7 days (Prowse *et al.* 2002)	**8 + MDD or 2.8+ mm rain over 5 days (Carr & Vuyovich 2014)**
All events	6 (11%)	32 (60%)
Temperate Coniferous Forests	4 (12%)	20 (61%)
Boreal Forests	0 (0%)	1 (33%)
Temperate Grasslands	2 (18%)	8 (73%)
Tundra	0 (0%)	3 (60%)

of eight MDD or 2.8 mm of rain over a 5-day period. The classification of mid-winter break-up events by biomes reveals the regional variability in hydro-climatic triggers. In particular, the threshold of eight MDD or 2.8 mm of rainfall is a good predictor of mid-winter break-up events in Temperate Grasslands, but a poor predictor of mid-winter break-up events in Boreal Forests. Examination of mean and maximum temperatures preceding mid-winter break-up events revealed that above-freezing temperatures and/or rain on snow over as little as 3 days is sufficient to generate a mid-winter break-up in all hydro-climatic regions.

All of the mid-winter break-up events in the Tundra region were preceded by rainfall, although some 5-day rainfall totals were relatively small (<1 mm). However, rainfall was not a good predictive factor for events in the Boreal Forests region. The majority of the events in the Tundra, and all of the events in the Boreal Forest were associated with a relatively high 3-day sum of daily maximum temperatures (MDD_{max}) despite low 5-day MDD. The role of maximum daily temperature compared with minimum temperature is evident in the analysis of early and late spring break-up in Alaska (Bieniek *et al.* 2011). High-latitude regions experience a large diurnal temperature range, particularly during the winter season. Therefore, examining maximum daily temperature (MDD_{max}) and freeze-thaw days ($T_{min} < 0\,^{\circ}C$ and $T_{max} > 0\,^{\circ}C$; Zhang *et al.* 2011) may be more appropriate.

Sequences of 5 days leading up to, and in most cases including, the day of mid-winter break-up, are classified using SOM into three dominant sequence patterns (Figure 2). Note that a larger number of sequence patterns were tested, including six and four; however, these resulted in redundant sequences. Additionally, two sequence patterns and a

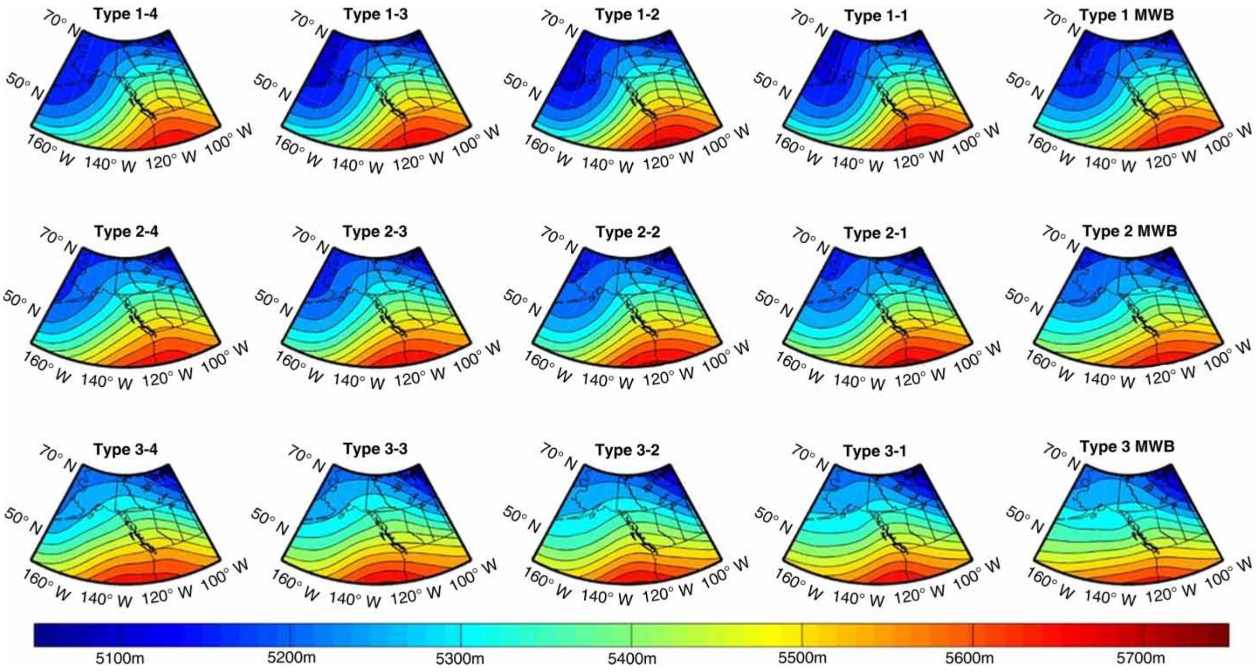

Figure 2 | Dominant 5-day sequences of daily 500 hPa geopotential heights leading up to mid-winter break-up (MWB), classified using self-organizing maps.

sequence comprised of averages using the entire dataset were tested, but did not provide adequate variability to describe all mid-winter break-ups given the spatial distribution of events. The three sequence patterns are somewhat similar, which highlights the role of warm, moist Pacific air masses in triggering mid-winter break-ups, which has previously been identified as a trigger for mid-winter break-up in southern BC (Doyle & Costerton 1993). Furthermore, similarities between days within each sequence emphasize the importance of synoptic pattern persistence on extreme events.

Sequence Type 1 is characterized by a series of 5 days with a strong trough of low-pressure over Alaska and the North Pacific and an adjacent ridge of high-pressure over western Canada, which is known to be associated with anomalously high temperatures in western Canada, and has been shown to exhibit high persistence (Newton *et al.* 2014). Sequence Type 2 is similar, but with a less pronounced trough and ridge and wider spacing between contours. The trough and ridge exhibited in Sequence Type 3 is subdued, and the break-up date (MWB) of this sequence is more indicative of zonal flow. There is a noticeable expansion of higher pressure and wider spacing of contours over Alaska compared with Sequence Types 1 and 2. Meridional mid-tropospheric flow, depicted by positive phase of the Pacific North American Pattern (PNA), is associated with a strong surface Aleutian Low (Wallace & Gutzler 1981), which has been shown to influence surface temperatures in Alaska (Cassano *et al.* 2011). Specifically, anomalously high temperatures in Fairbanks and Anchorage occur when a strong Aleutian Low was positioned over the Aleutian Islands. Additionally, Bieniek *et al.* (2011) found that a 500 hPa circulation pattern similar to the structure of the positive phase of the PNA was associated with earlier spring break-up in Alaska. The frequency of each sequence is given in Table 3, subdivided into north and south. What is most striking is the dominance of Sequence Type 3 preceding those events in Alaska and the Yukon, while events in BC and Alberta were primarily associated with Sequence Type 1.

Table 3 | Frequency of identified sequence types of daily 500 hPa geopotential heights given in Figure 2, for mid-winter break-up events in northern (Alaska-Yukon) and southern (BC-Alberta) regions

	Sequence 1	Sequence 2	Sequence 3
All	23 (44%)	12 (23%)	17 (33%)
Alaska-Yukon	1 (14%)	1 (14%)	5 (71%)
BC-Alberta	22 (49%)	11 (24%)	12 (27%)

Previous research has indicated that mid-winter break-up events can exacerbate spring break-up and ice jams (Beltaos 1997, 1999, 2008). Although this was not explicitly evaluated in this research, there is evidence that some of the mid-winter break-ups described here were associated with subsequent spring ice jams. Janowicz (2010) reported break-up flooding on the Klondike River in spring 2003 attributed to the mid-winter break-up ice jam that formed in December 2002. The CRREL database reported a severe spring break-up ice jam flood on the Tanana River at Salcha, Alaska, attributed to the ice jam that formed in November 2002 and remained in place throughout the winter (CRREL 2015). The spring ice jam flood persisted for several days and adversely affected numerous homes in the community.

CONCLUSIONS

This study identifies mid-winter break-up events in western Canada through the examination of pen-recorder and digital stage records from 90 WSC hydrometric stations from 1950 to 2008. A total of 15 stations were identified as having at least one mid-winter break-up, with several of those stations having multiple break-up events. Altogether, 46 events were identified across BC, Alberta, and the Yukon. Additionally, six mid-winter break-up events in Alaska were extracted from the CRREL Ice Jam Database. The hydro-climatic drivers of these events were examined, particularly in the context of two previous studies, Prowse *et al.* (2002) and Carr & Vuyovich (2014). The Prowse *et al.* (2002) study evaluated trends in mid-winter break-up events in a defined temperate region. Carr & Vuyovich (2014) documented a set of criteria accompanying a series of mechanical and thermal break-up events in the mid-western United States, and did not explicitly assess thresholds for mid-winter break-up, but noted that these events were defined as events followed by refreezing of the ice cover.

The majority of mid-winter break-up events fell within the temperate region, defined as the region between 400 and 1,000 winter (December–February) FDD. Prowse *et al.* (2002) describe the temperate region as having both the sufficient winter ice growth and frequent warm spells necessary to generate mid-winter break-ups. The mid-winter events were further classified by terrestrial biomes, which improved the evaluation of criteria preceding the mid-winter break-up events. Although the majority of mid-winter events in the Temperate Coniferous Forests and Temperate Grasslands regions were preceded by a minimum of eight MDD or 2.8 mm of rain over a 5-day period, a 3-day warm spell and/or rain on snow was found to be a sufficient trigger. The 5-day threshold given by Carr & Vuyovich (2014) was found to be a poor predictor of mid-winter events in the Tundra and Boreal Forest regions where diurnal temperature range is high. Alternatively, the 3-day sum of maximum daily temperatures, $\mathrm{MDD}_{\max}$, has emerged as an important trigger in both regions, while rainfall was only a factor in the Tundra region.

Classification of 5-day sequences of mid-tropospheric circulation patterns revealed that a persistent trough of low-pressure over Alaska and the North Pacific and ridge of high-pressure over western Canada was the most common pattern leading up to mid-winter break-up events, particularly in southern BC and Alberta. Mid-winter break-up events in Alaska and the Yukon were commonly preceded by a persistent subdued mid-tropospheric trough of low pressure over the North Pacific.

This research had increased our understanding of the hydro-climatic triggers of mid-winter break-up in western Canada and Alaska through the examination of temperature, precipitation, and atmospheric patterns preceding the identified break-up events. Although classification of mid-winter events using biomes has provided insight into the regional hydro-climatic triggers of mid-winter break-up, further research that includes additional parameters such as basin size, topography, and river slope would be invaluable to our understanding of the triggers of mid-winter break-up. Future research should focus on evaluating temporal trends and future projections of 3-day warm spells (mean daily temperature above freezing), freeze-thaw days, and rain on snow. Additionally, the contribution of mid-winter break-up to extreme spring break-up should be quantitatively evaluated.

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