Atmospheric drivers of winter above-freezing temperatures and associated rainfall in western Canada

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Abstract

Winter thaw episodes, especially when accompanied by rain, can significantly deplete the winter snowpack, which is a critical water storage component in the mountainous headwater regions of the major river basins of western Canada. Here we identify the characteristic synoptic-scale mid-tropospheric atmospheric circulation regimes that tend to foster such extreme hydrologic events using self-organizing map analysis of meteorological reanalysis data from 1949-2012. Daily winter 500 hPa geopotential height fields over the Pacific Ocean and western Canada are classified into 12 dominant synoptic types, for which conditional probabilities of above-freezing temperatures and rainfall are then calculated and mapped using daily high-resolution gridded data. Results show that above-freezing surface air temperatures and rain events in winter are commonly associated with the occurrence of a ridge of high pressure over western Canada, which induces southwesterly advection of relatively warm, moist maritime air masses into the continental interior, and that the intensity and spatial footprint of the surface climate response is related to the strength and position of the ridge. Conversely, the development of a ridge of high pressure over the Pacific Ocean and adjacent trough of low pressure over western Canada, which favours northwesterly to westerly mid-tropospheric flow over the continental interior in winter, tends to suppress the occurrence of above-freezing temperatures and rain. The synoptic type most strongly associated with winter thaw and rain events underwent a statistically significant step-change increase in mean frequency in 1977, accompanied by a corresponding step-change decrease in the frequency of the dominant synoptic type depicting westerly (zonal) circulation, coinciding with a well-documented shift to a positive phase of the Pacific Decadal Oscillation.

Introduction

The availability of freshwater in western Canada is strongly dependent upon winter snowpack, particularly in the mountain headwater regions of major river basins (Barnett *et al.,* 2005; Stewart, 2009). Spring freshet, typically the largest hydrologic event in cold regions, is dominated by snowmelt at lower elevations, while the high-elevation snowpack continues to contribute to streamflow throughout the summer. A deficit of water during critical periods threatens numerous biophysical and socio-economic systems, including agricultural productivity (Pentney and Ohrn, 2008), hydroelectricity generation (Filion, 2000; Roberts *et al.,* 2006), and aquatic ecosystems (Wrona *et al.,* 2006; Burn *et al.,* 2008; Wrona *et al.,* 2016). Furthermore, a lack of adequate winter snow accumulation or anomalously early melt can intensify summer drought conditions (Bonsal *et al.,* 2011; Hanesiak *et al.,* 2011). Recent climate change has affected the magnitude of winter snow accumulation and timing of melt, raising concerns over diminishing water security (Walker and Sydneysmith, 2008; Sauchyn and Kulshreshtha, 2008) and the potential for extreme hydrologic events (Bates *et al.*, 2008), such as mid-winter river ice break-up (Beltaos, 2002; Newton *et al.*, 2017) and flooding (Anderson and Larson, 1996; Marks *et al.,* 1998; McCabe *et al.*, 2007). There is thus a growing need to understand the complex drivers of climatic and hydrologic variability to effectively inform water resource management (McGregor, 2017).

The magnitude of snow accumulation is a function of hydroclimate throughout the winter season. The onset of snow accumulation and melt are strongly associated with air temperatures falling below and rising above freezing (Bonsal and Prowse, 2003; Brown and Mote, 2009), while end-of-season snow water equivalent (SWE) is related to the amount and phase of cold season precipitation and any winter melt events. There is considerable hydroclimatic variability across western Canada, both spatially and temporally (Whitfield and Cannon, 2000; Zhang *et al.*, 2000; Edwards *et al.*, 2008; Shabbar *et al.*, 2011; Vincent *et al.*, 2015; Edwards *et al.*, 2017). In addition to this variability, snow accumulation has decreased and snowmelt has occurred earlier in western Canada over recent decades. For example, O'Neil *et al.* (2017a) quantify snow accumulation and timing of melt in major river basins in western Canada using high-resolution gridded climate data, from 1950-2010, and a temperature-index snow accumulation and melt model and find widespread declines in both snow accumulation and melt. Kang *et al.* (2016) find that snowpack in the Fraser River basin declined between 1949 and 2006, with the snowmelt-driven freshet occurring 10 days earlier. Najafi *et al.* (2017) report declines in spring (1 April) SWE in the upper Peace, Fraser, and upper Columbia river basins. Similarly, declines in spring snow cover extent are detected (Déry and Brown, 2007; Brown and Mote, 2009; Choi *et al.*, 2010; Hernández-Henríquez *et al.*, 2015) with the most vulnerable regions being the Western Cordillera (Brown and Mote, 2009; Choi *et al.*, 2010) at low- to mid-elevations (Brown and Mote, 2009; Hernández-Henríquez *et al.*, 2015). The integrity of the snowpack is vulnerable to extreme winter weather. In particular, anomalously cold or warm conditions and precipitation phase can affect the structure of the snowpack and are linked to the generation of hydrologic extremes (e.g. Doyle and Costerton, 1993). In relation to this, Newton (2018) find that the frequency and magnitude of winter (DJFM) above-freezing temperatures and rainfall increased in western Canada from 1946-2012, particularly during January and March.

Large-scale atmospheric circulation is responsible for the movement and distribution of water and energy (Trenberth and Stepaniak, 2003), and directly impacts the climatic variability in western Canada. Specifically, the mid-troposphere is characterized by a series of mid-latitude troughs and ridges resulting in meridional flow, or, in the absence of troughs and ridges, zonal flow (Holton, 1979). These patterns of airflow direct the movement of surface high- and low-pressure systems and the movement of warm or cold, moist or dry air masses.

Numerous studies evaluate links between atmospheric circulation patterns and surface climate and hydrology. A mid-tropospheric ridge of high pressure centred over western Canada is linked to above-average temperatures and below-average precipitation while a ridge of high pressure centred over the Pacific Ocean and adjacent trough over the continent is associated with below-average temperatures and above-average precipitation in western Canada (Romolo *et al.*, 2006a,b; Newton *et al.*, 2014a; Bonsal *et al.*, 2017; Bonsal and Cuell, 2017). Romolo *et al.* (2006a) determine that winter snow accumulation in the Peace River Basin increased with a higher frequency of zonal flow or a trough of low pressure over western Canada, in contrast to conditions when high pressure persisted over western Canada. In the same region, Romolo *et al.* (2006b) find that a mid-tropospheric ridge of high pressure over western Canada is linked to the onset of spring snowmelt. Newton *et al.* (2014a) determine that a strong ridge of high pressure in the mid-troposphere, whether centred over the Pacific Ocean or western Canada, exhibits strong persistence, often occurring over multiple consecutive days.

The persistent meridional flow associated with high-amplitude ridges and troughs is linked to extreme weather in North America (Francis and Vavrus, 2012; Petoukhov *et al.*, 2013; Screen and Simmonds, 2014). Newton *et al.* (2017) find that a persistent ridge of high pressure over western Canada is a contributing driver to numerous mid-winter river ice break-up events. Fitzharris (1987) describe patterns of surface high- and low-pressure systems as they relate to major avalanche winters in southwestern British Columbia and determine that persistent cold Arctic outbreaks followed by warm, Pacific frontal systems are conducive to major avalanche activity, highlighting the sequencing of large-scale circulation for the generation of extreme events. Hydrological responses may not be linear functions of climatic variability, but rather nonlinear functions or the product of a threshold exceedance (Ali *et al.*, 2015; McGregor, 2017; Scaife and Band, 2017), emphasizing the importance of understanding links between persistence and extreme weather and hydrologic phenomena.

Variability of climate in western Canada is linked to large-scale teleconnection patterns that act on interannual and interdecadal time scales, including El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Pacific North American Pattern (PNA). The PNA is a metric of 500 hPa anomalies in the Northern Hemisphere (Wallace and Gutzler, 1981). Winters dominated by positive PNA are associated with a higher frequency of a ridge of high pressure over western North America, below average snow accumulation, and anomalously early snowmelt (Romolo *et al.* 2006a; Pederson *et al.* 2013). The surface climate responses to positive and negative phases of ENSO and the PDO are a function of the influence of these teleconnections on the frequency of dominant atmospheric circulation patterns (Romolo *et al.*, 2006a,b; Stahl *et al.*, 2006; Newton *et al.*, 2014a). El Niño (negative Southern Oscillation Index; SOI) and positive phases of the PDO are associated with above-average winter temperatures and below-average precipitation in western Canada, while La Niña (positive SOI) and negative phases of the PDO are associated with below-average temperatures and above-average precipitation (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Bonsal *et al.*, 2001). Recently, Newton *et al.* (2014a) describe an increase in the frequency of a ridge of high pressure over western Canada during El Niño and positive phases of the PDO, particularly when these two teleconnection patterns coincide. Conversely, a ridge of high pressure over the Pacific Ocean and adjacent trough of low pressure over western Canada, as well as zonal flow over western North America, occur with a higher frequency during La Niña and negative phases of the PDO (Newton *et al.*, 2014a).

Although several studies have examined relationships between surface climate and mid-tropospheric circulation patterns or atmospheric/oceanic teleconnections, none have assessed the role of atmospheric circulation on the frequency and magnitude of winter above-freezing temperatures and rainfall. Given the high risk posed by diminishing snowpack for water security in western Canada and the potential for the generation of hydrologic extremes, it is valuable to improve our understanding of large-scale atmospheric drivers of winter climate variability. Therefore, this research identifies the synoptic-scale mid-tropospheric circulation patterns associated with temperature and precipitation patterns conducive to snowmelt or degradation of the snowpack during the winter season in western Canada. Specifically, dominant atmospheric circulation patterns in the mid-troposphere are identified and conditional probabilities of above-freezing temperatures and associated rainfall are calculated.

Study Area

This research focuses on major river basins in western Canada, spanning varied hydroclimatic and physiographic regions including the Western Cordillera, boreal forest, and Prairies (Figure 1). The Liard River flows from alpine headwaters through boreal regions in northeastern British Columbia and southeastern Yukon Territory and is a major tributary of the Mackenzie River. Similarly, the Peace and Athabasca rivers flow from mountain headwaters, across the Parkland and Boreal forest regions to the Peace-Athabasca Delta, and are also tributaries of the Mackenzie River. The Saskatchewan River flows east from the Rocky Mountain headwaters and across the Prairies, ultimately contributing to the Nelson River and draining into Hudson Bay. The Stikine, Nass, and Skeena rivers are located on the north coast of British Columbia and drain into the Pacific Ocean. The Fraser and Columbia rivers originate on the western slopes of the Rocky Mountains and eastern slopes of the Columbia Mountains and drain into the Pacific Ocean. These rivers are snowmelt-dominated, with peak flows occurring in late spring or early summer, coinciding with snowmelt. Summer streamflow is a function of high-elevation snowmelt, rainfall and glacier melt. Flows decrease in the autumn and remain low throughout the winter, with many rivers developing an ice cover.

The winter climate of western Canada is strongly influenced by warm, moist air masses originating over the Pacific Ocean and cold, dry air masses originating over the Arctic Ocean and northern Canada. Precipitation is highest along the coast and decreases with increasing distance from the Pacific Ocean. The convergence of moist Pacific and cold Arctic air masses can result in heavy, dense snowfall, particularly near coastal British Columbia (Geng *et al.,* 2012). Atmospheric rivers, originating over the sub-tropical Pacific Ocean, are infrequent, but have the potential to deliver a concentrated band of moisture and heat over western Canada (Roberge *et al.,* 2009). The windward slopes of mountain regions receive higher precipitation as moist air masses are forced to rise and release moisture, while leeward regions such as the Fraser Plateau and the Prairies receive lower precipitation. Chinook winds, dry adiabatically warmed air masses that descend the leeward side of mountains, frequently occur to the east of the Rocky Mountains, particularly in southern Alberta (Longley, 1967; Goulding, 1978).

Data and Methods

Daily winter (DJFM) geopotential height (GPH) data at 500 hPa, between 30°N and 70°N and 100°W and 170°W, from 1949-2012, obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay *et al.*, 1996), are classified into a set of dominant patterns using the Self-Organizing Maps (SOM) Toolbox for Matlab (Vesanto *et al.,* 2000). This synoptic domain captures atmospheric flow pathways from the Pacific and Arctic Oceans as well as circulation features over western North America. SOM is public domain software, available from the Laboratory of Computer and Information Science Adaptive Informatics Research Centre at Aalto University in Espoo, Finland (http://www.cis.hut.fi/research/som-research/). SOM is a statistical tool in the field of artificial neural networks that clusters data and arranges them onto a topologically ordered array such that spatial and temporal relationships between daily patterns are preserved (Kohonen, 2001). Daily atmospheric circulation patterns are not discrete and the evolution of atmospheric states is captured through SOM classification. Maximum variance exists in the opposite corners of the array while neighbouring patterns are most similar. Thus, SOM presents an advantage over alternative methods of classification, such as Principal Components Analysis (Hewitson and Crane, 2002; Reusch *et al.,* 2005; Jiang *et al.,* 2012). The organizational capabilities of SOM give rise to a visual representation of atmospheric states that facilitates analyses among synoptic types and with surface climate variables. A comprehensive description of SOM is found in Kohonen (2001) and SOM applications to synoptic circulation classification can be found in Hewitson and Crane (2002), Reusch *et al.* (2005), Reusch (2010), Sheridan and Lee (2011), and Newton *et al.* (2014a,b).

A number of metrics are used to statistically describe the relationships among and temporal evolution of atmospheric states. The frequency of each synoptic type is calculated for each winter season and trends are evaluated using the Mann-Kendall non-parametric test (MK; Mann, 1945; Kendall, 1975), using the $p < 0.05$ significance level and noting trends at the $p < 0.10$ level. The direction and magnitude of the trends is calculated using Sen's method for slope estimation, which is a robust method for non-parametric data and is largely unaffected by outliers (Sen, 1968). Synoptic type frequencies are evaluated for change points to determine if there is an abrupt shift in the time series. Three statistics are selected to evaluate change points: mean, standard deviation, and slope. For the distribution of each synoptic type, the point at which the statistical metric changes most abruptly is identified using change point analysis in the Matlab programming platform. The time series for each synoptic type is then divided into two segments based on the change point identified for each metric and compared using the two-sample non-parametric Kolmogorov-Smirnov (KS) test to evaluate whether the two series are from the same continuous distribution.

High-resolution (1/16-degree), gridded daily winter (DJFM) minimum and maximum air temperature (°C) and precipitation (mm) data for western Canada, from 1949 to 2012, are used to evaluate surface climate variables associated with synoptic types. The dataset was developed using a thin-plate spline interpolation of climate station data, using ClimateWNA (western North America) climatology (Wang *et al.*, 2012) as a covariate (Werner *et al.*, 2019). Daily maximum and minimum temperatures are averaged to estimate mean daily temperature. This method of calculating mean daily temperature produces similar results compared with other methods, including using mean hourly temperature (Weiss and Hays 2005). Days when the mean daily temperature is above freezing (T_{mean} > 0°C) are identified and accumulated melting degree-days (MDD) are calculated as the sum of mean daily temperatures above freezing throughout the winter season. Rainfall is identified using a temperature-index precipitation phase equation, whereby precipitation of at least 0.2 mm falling on days when the mean daily temperature is equal to or above 1°C is considered rain, and below 1°C is snow, as used in previous studies (USACE, 1956; Rohrer, 1989; L'hôte *et al.,* 2005; Yuter *et al.,* 2006; Lundquist *et al.,* 2008; Kienzle, 2008). The greatest uncertainty for precipitation phase determination exists between 0°C and 2°C (Feiccabrino *et al.,* 2012) and at temperatures nearing 0°C precipitation may be mixed rain and snow, slush, graupel, or hail; however, these precipitation types may be associated with sufficient heat energy to generate snowmelt (USACE, 1956).

Relationships between atmospheric circulation patterns and the frequency of above-freezing temperatures and rainfall are calculated as conditional probabilities for identified synoptic types using the formulas,

$$P(AO_i|ST_i) = \frac{P(ST_i \cap AO_i)}{P(ST_i)} \qquad (1)$$

$$P(R_i|ST_i) = \frac{P(ST_i \cap R_i)}{P(ST_i)} \qquad (2)$$

where ST_i is the total number of days classified as a particular synoptic type, $A0_i$ and R_i are the subset of days within that synoptic type that are above-freezing and rainfall occurs, respectively. Therefore, the probabilities of above-freezing temperatures or rainfall for a given condition (synoptic type) are determined. Probabilities are expressed as percentages and are mapped to corresponding synoptic types.

Results

Mid-tropospheric circulation

Daily winter 500 hPa GPH are classified into 12 types on a topologically organized 3 × 4 array using SOM, which is large enough to identify dominant atmospheric circulation patterns and small enough to capture differences between patterns (Figure 2). The synoptic types are numbered according to the position on the array. Atmospheric flow direction in the mid-troposphere is roughly parallel to the contour lines and directs surface high- and low-pressure systems (Holton, 1979). Types 1 and 4 in the top left corner of the SOM array are characterized by a strong ridge of high pressure extending over the Pacific Ocean and Alaska and adjacent trough of low pressure over western Canada, indicative of northerly meridional advection of cold Arctic air over western Canada. Conversely, a ridge of high pressure over western Canada (Types 7-12) directs warm Pacific air masses toward coastal BC and blocks the movement of cold, Arctic air masses from entering the region. These circulation types are linked to anomalously warm, dry surface climate, where the magnitude of the surface climate response is related to the strength and position of the ridge (Bonsal *et al.*, 2001; Stahl *et al.*, 2006; Newton *et al*., 2014a). Zonal flow patterns (Types 2, 3, 5, and 6) indicate a lack of surface high- and low-pressure systems and unobstructed airflow from the Pacific Ocean over the study region. Zonal flow during the winter season is associated with above-average precipitation and below-average temperatures (Romolo *et al.*, 2006a,b; Newton *et al.*, 2014a).

Synoptic type frequency, persistence, and trajectory describe the evolution and dominant states of atmospheric circulation. Synoptic types in the four corners of the SOM array, Types 1, 3, 10, and 12, occur with the greatest frequency (Figure 3a), while intermediate types, particularly in the centre of the SOM array (Types 5 and 8) are infrequent transition patterns, facilitating the shift from one dominant atmospheric state to another. Types characterized by a strong ridge of high pressure, 1, 10, and 12, are the most persistent, with an average persistence of 76%, 70%, and 73%, respectively (Figure 3b). Type 1 persists for an average of four days, but has persisted for up to 34 consecutive days. Similarly, Types 10 and 12 persist for an average of three and four days and up to 19 days and 28 days, respectively. Extreme weather phenomena are linked to persistent atmospheric circulation patterns, particularly those characterized by strong meridional flow, such as Types 1, 10, and 12 (Francis and Vavrus, 2012; Petoukhov *et al.*, 2013; Screen and Simmonds 2014). Zonal flow (Type 3) is also highly persistent (average of 67%), occurring for an average of three days, and persisting for up to 14 consecutive days. Trajectory (Figure 3c) indicates preferred shifts from one synoptic type to neighbouring patterns, where the length of the arrow is proportional to the frequency of shifts from one pattern to another. It is evident that the preferred trajectory follows the outer patterns along the array with approximately equal frequency in either direction.

Significant decreases in frequency are seen in Type 1 ($p < 0.05$) and Type 3 ($p < 0.10$), while Type 10 has significantly increased ($p < 0.05$) over the study period (Figure 4). These trends indicate a decrease in both high-pressure ridging over the Pacific Ocean and zonal flow, and an increase in ridging over British Columbia. Interannual variability of synoptic type frequency is high, particularly for the four dominant patterns, Types 1, 3, 10, and 12 (Figure 4). For example, the frequency of Type 1 ranges from 0 to 36% of winter days, while Type 12 ranges from 0 to 50%. High-frequency peaks exceeding two standard deviations above the mean frequency are evident in the time series of each synoptic type. These peaks are more apparent in the synoptic types on the left side of the SOM array (Types 1-6) during the first half of the study period (1949-1980) and on the right side of the SOM array (Types 7-12) during the second half (1981-2012). The high-frequency peaks in Types 10 and 12 coincide with previously identified El Niño and/or positive PDO (Type 10: 2010, Type 12: 1983, 1986, 1995, 1998), while high-frequency peaks in Type 1 (1950, 1957) coincide with La Niña and/or negative PDO (Bonsal *et al.* 2001; Shabbar and Bonsal 2004). This is consistent with Bonsal *et al.* (2001) and Newton *et al.* (2014a) who find that a ridge of high pressure over western Canada dominates winters categorized by positive phases of the PDO and negative phases of the SOI (El Niño), particularly when positive PDO and El Niño occurred simultaneously, and a ridge of high pressure over the Pacific Ocean and adjacent trough over western Canada occurred with a greater frequency during negative phases of the PDO and La Niña.

Types 3 and 10 have a change point in 1977 for all three metrics, and the KS test shows that for both Type 3 and Type 10, the two distributions, 1949-1976 and 1977-2012 are significantly different ($p < 0.05$). Despite the appearance of a change in frequency and variability of Type 12, the analysis failed to detect a change point that divided the time series into two significantly different distributions. The mean frequency of Type 3 is higher from 1949-1976 compared with 1977-2012, presenting an alternate to the linear increase detected by the MK test (Figure 4). Conversely, the mean frequency of the 1949-1976 time series of Type 10 is lower than 1977-2012 (Figure 4). Additionally, the average seasonal persistence of synoptic types, measured as the percentage of days each winter when that type occurs for consecutive days, is evaluated for trend and change points. A significant increasing trend and a step-change increase in 1977 in the mean persistence are detected for Type 10 (Figure 5). These step-changes coincide with a documented shift from a predominantly negative to positive phase of the PDO (Mantua *et al.*, 1977; Mantua and Hare, 2002), which is associated with anomalous surface climate and streamflow in western Canada, including links between positive phases of the PDO and positive winter temperature anomalies (Bonsal *et al.*, 2001), lower precipitation, particularly in coastal regions (Fleming and Whitfield, 2010), and lower streamflow (Mantua *et al.*, 1997; Déry and Wood, 2005), with opposite hydroclimatic impacts during negative phases of the PDO.

Surface above-freezing air temperature and associated rainfall

The frequency of days when the mean daily temperature is above freezing for each synoptic type is calculated as a percentage of the total distribution at each grid point (conditional probability). The position of each pattern of above-freezing surface air temperatures corresponds to the synoptic type in the same position on the SOM array (Figure 6). The frequency of above-freezing temperatures increases gradually from the upper left corner (Type 1) to the lower right corner (Type 12) of the array. The frequency is high across much of the study region during days when there is a ridge of high pressure over western Canada, and the strength of the surface climate response is dependent on the strength and position of the ridge (Types 9-12). For example, the frequency of above-freezing temperatures associated with Type 12 approaches 100% along the coastal region, 50% in the low-elevation regions of the Fraser and Columbia basins and the upper Saskatchewan basin, and 40% in portions of the upper Peace and upper Athabasca basins. Above-freezing temperatures associated with Types 8, 9, and 11 are similar to Type 12, albeit with a lower frequency. Conversely, Type 1 in the opposite corner of the array is associated with very few days when the mean daily temperature is above freezing, with up to 60% of winter days in near-shore coastal areas and up to 20% of winter days in the Fraser, Columbia, and north-coastal basins above freezing. Type 3 exhibits a low frequency of above-freezing temperatures, primarily seen in the southern half of the study region. These patterns of above-freezing temperatures are consistent with negative temperature anomalies associated with a ridge of high pressure over the Pacific Ocean and adjacent trough of low pressure over western Canada, directing the flow of cold, dry air masses from the Arctic to western Canada and westerly zonal flow from the Pacific Ocean over the study region, and the positive temperature anomalies associated with a ridge of high pressure over western Canada (Bonsal *et al.*, 2001; Romolo *et al.*, 2006b; Newton *et al.*, 2014a).

The conditional probability of all winter precipitation is calculated for the given synoptic types (Figure 7) to provide a reference precipitation total with which to compare rainfall probabilities. In general, winter precipitation is low east of the Rocky Mountains and high along the coast, particularly during days when there is a ridge of high pressure over western Canada (Types 7-12). Precipitation is slightly higher in this region during days when there is a ridge of high pressure over the Pacific Ocean and adjacent trough over western Canada. Synoptic types located on the top row of the SOM array (Types 1, 4, 7, and 10) are associated with low precipitation compared with those types along the bottom row (Types 3, 6, 9, and 12). Specifically, Type 1 is associated with low precipitation across the study region with slightly higher precipitation along the coast while Type 10 is related to higher precipitation along the coast, but very low precipitation inland. Type 10 is characterized by a strong ridge of high pressure and a ridge axis centred near the coast, which effectively blocks moisture inflow to the study region. Days with zonal flow (Type 3) see higher precipitation along the coast and the Rocky Mountains with low-to-moderate precipitation in the remainder of the study region. Type 12, a ridge of high pressure over western Canada, is associated with high precipitation along the coast and minimal precipitation east of the Rocky Mountains.

The percentage of winter days when rainfall occurs for each grid point is calculated for each synoptic type (Figure 8). A very low frequency of rainfall, confined to the southern coastal region of the study area, is associated with Types 1, 2 and 3. A moderate to high frequency of rainfall (> 50%) is seen along the coast and low (< 30%), but widespread rainfall is found in the Columbia, Fraser, upper Peace, and north coastal basins during days classified as Type 12. Similar spatial patterns of rainfall frequency, at a smaller magnitude, are associated with Types 9 and 11. These synoptic types are characterized by a ridge of high pressure over western Canada, which effectively blocks the advection of moisture into the study region, particularly east of the Rocky Mountains; however, these types are associated with a high frequency of above-freezing temperatures, increasing the likelihood of precipitation falling as rain. Type 10 is also characterized by a blocking ridge of high pressure over western Canada, with a ridge axis centred near the coast, and is associated with lower rainfall across the study region compared with Types 9, 11 and 12. Types 5 and 8 are infrequent transition patterns, but are associated with a low (< 20%) frequency of rainfall across the Saskatchewan and Athabasca river basins. Zonal flow (Type 3) is associated with a very low frequency of rainfall, except along the coast. Zonal flow is conducive to moisture advection from the Pacific Ocean over the study region; however, it is also associated with a relatively low frequency of above-freezing temperatures. Thus, the precipitation seen with Type 3 falls primarily as snow.

High frequency, persistent circulation

The topological organization of the SOM array, where neighbouring patterns exhibit similar characteristics, enables the grouping of synoptic types into regimes to facilitate analysis of synoptic regime persistence. Individual synoptic types exhibit persistence (Figure 3b), but the calculations of persistence of a single type fails to detect instances of longer-term persistence punctuated by short (1-2 day) shifts to a neighbouring pattern. Additionally, synoptic type trajectories (Figure 3c) demonstrate the preferred shifts from one type to a neighbouring pattern, suggesting that when a particular type occurs with a high frequency throughout the season, a shift to a neighbouring pattern is far more likely than a shift to distant pattern. For example, when Type 10, in the top right corner (Figure 2) occurs with a high frequency, neighbouring patterns (Types 7,8,9, 11, and 12) also tend to occur with an above average frequency, while distant patterns (Types 1-6) tend to occur with an average or below average frequency.

On the left side of the SOM array, Types 1 and 4, characterized by a ridge of high pressure over the Pacific Ocean and adjacent trough over western Canada, and Types 2, 3, 5 and 6, depicting zonal flow over the study region elicit a similar surface climate response with respect to the frequency of above-freezing temperatures and rainfall. Additionally, neither of these two flow types on their own dominate a winter season, and there is a tendency for these two flow types to co-occur with an above-average to high frequency; therefore, they are grouped into a single regime (LS). The regime on the right side (RS) consists of Types 7-12, which are characterized by a ridge of high pressure over western Canada, of various strengths and ridge axis positions.

The two synoptic regimes occur with nearly equal average frequency over the study period. The average winter frequencies of the LS and RS regimes are 50.2% and 49.8%, respectively; however, as evidenced by the interannual variability of individual synoptic types (Figure 4), there are numerous years when one of these regimes is dominant and highly persistent. For example, in 1983, synoptic types in the RS regime (Types 7-12) occur 91.7% of winter days and persist up to 80 consecutive days. Similarly, in 2009, synoptic types in the LS regime occur 82.6% of winter days (56 days of the zonal flow type and 44 days of a ridge of high pressure over the Pacific Ocean) and persist up to 68 consecutive days. The two synoptic type regimes are evaluated for change-points in mean frequency and persistence using the metrics applied to individual synoptic types. For the LS regime, a step change decrease in the mean frequency occurs in 1977 (Figure 9a) and in 1978 for persistence (Figure 10a). Conversely, a step change increase in the mean frequency (Figure 9b) and persistence (Figure 10b) occurs in 1977 for the RS regime. This indicates a broad shift in dominant mid-tropospheric circulation regimes favouring a persistent ridge of high pressure over western Canada in the second half of the study period.

To capture the surface climate response to the two synoptic regimes over western Canada, composite winter accumulated MDD and total rainfall anomalies are calculated for winters when each regime is dominant. The winter frequencies for each regime are ranked, and the top 20% for each regime were selected (Table 1). The average accumulated MDD and rainfall of winters in the top 20% of each regime are calculated and subtracted from the mean accumulated MDD and rainfall for the total time series to determine anomalies. Several years with strong El Niño events appear in the top 20% of the RS distribution, including 1983, 1992 and 1998 (Bonsal *et al.* 2001; Shabbar and Bonsal 2004; Newton *et al.* 2014a), which also coincide with the warm, or positive phase of the PDO (Bonsal *et al.* 2001; Newton *et al.* 2014a), indicating a strong influence of these teleconnections on atmospheric circulation persistence. Similarly, 1950, 1962, and 2009 are in the top 20% of the LS distribution, La Niña and negative PDO index. Composites of accumulated MDD and rainfall are calculated for the top 20% for the LS and RS regimes and the mean accumulated MDD and rainfall are subtracted to calculate anomalies for each variable at each grid point.

Results reveal negative accumulated MDD anomalies in the LS regime and positive anomalies in the RS regime (Figure 11). In particular, winters dominated by Types 7-12 (RS) are characterized by accumulated MDD that are up to 140 MDD above normal along the coast and low-elevation river valleys in the Fraser and Columbia river basins, and up to 50 MDD above normal in the upper Saskatchewan, and 25 MDD above normal in the upper Athabasca and upper Peace river basins. Similarly, rainfall is higher than normal when the RS regime dominates mid-tropospheric circulation (Figure 12). Winter rainfall anomalies of up to 100 mm fall in the north-coastal, upper Peace, Fraser, and Columbia river basins, except for coastal areas of these watersheds, with higher rainfall at lower elevations.

Discussion and Conclusions

This research advances understanding of the atmospheric drivers of above-freezing winter temperatures and associated rainfall in major river basins in western Canada. The majority of annual streamflow in these rivers originates as winter snowpack and the loss of seasonal snowpack threatens water security and has the potential to generate hydrologic extremes (Sauchyn and Kulshreshtha, 2008; Walker and Sydneysmith, 2008). Daily winter (DJFM) mid-tropospheric GPH data are classified using SOM to identify dominant circulation patterns and conditional probabilities of above-freezing temperatures and rainfall are calculated for all synoptic types. Patterns on the right half of the array depict varying strengths and locations of a ridge of high pressure over western Canada, while patterns in the upper left corner are characterized by a ridge of high pressure over the Pacific Ocean and trough over western Canada, and patterns in the lower left corner are indicative of zonal flow. This facilitates the grouping of synoptic types into two regimes to evaluate broader regime frequency and persistence.

A ridge of high pressure over western Canada is associated with a high frequency of above-freezing temperatures across the study region and the magnitude of the surface response is related to the strength and position of the ridge. Additionally, the greatest and most spatially widespread frequency of rainfall is associated with a ridge of high pressure over western Canada; however, rainfall is largely confined to the coastal, upper Peace, Fraser, and Columbia river basins, suggesting that these river basins are at the greatest risk of winter rainfall or rain-on-snow, which can contribute both rain and snowmelt volume to runoff (USACE, 1956; Colbeck, 1975; Male and Gray, 1981).

This research relies upon a temperature-index rainfall determination where precipitation falling on days when the mean daily temperature is equal to or above 1°C is considered rain. A rain-snow separation threshold greater than 1°C may improve precipitation phase determination in the region east of the Rocky Mountains (e.g. Kienzle, 2008); however, results of this research indicate that the probability of rainfall is very low for this region and would not substantially change by applying multiple region-dependent rain-snow thresholds. Two of the synoptic types with the strongest high-pressure ridging are seen in Type 10, in the upper right corner of the SOM array, and Type 12 in the lower right corner. These two types are frequent, persistent, and elicit a strong surface climate response, suggesting that these types could produce a high volume of winter runoff.

A ridge of high pressure over the Pacific Ocean and adjacent trough of low pressure over western Canada (Types 1 and 4) is associated with a low frequency of above-freezing temperatures and rainfall. This surface response is unsurprising given that this type of circulation directs cold, Arctic air over western Canada and is associated with negative surface air temperature anomalies in the study region (Romolo *et al.*, 2006b; Newton *et al.*, 2014a). Similarly, zonal flow (Types 2, 3, 5 and 6) is associated with a low frequency of above-freezing temperatures and rainfall, but a high probability of precipitation. This is consistent with previous research that identifies negative temperature anomalies and positive precipitation anomalies with zonal flow (Romolo *et al.,* 2006a,b; Newton *et al.,* 2014a). Given the relatively low frequency of above-freezing temperatures, precipitation during days with mid-tropospheric zonal flow is likely falling as snow; however, projections of increasing winter temperatures (e.g., O’Neil *et al.,* 2017b; Dibike *et al.,* 2017), suggests that zonal flow has the potential to generate more frequent winter rainfall in the future.

The frequency of Type 1, a strong ridge of high pressure over the Pacific Ocean and trough of low pressure over western Canada, significantly decreased over the study period, indicating a decrease of circulation conducive to the suppression of above-freezing temperatures and associated rainfall. Similarly, the frequency of Type 3, characterized by zonal flow, significantly decreased over the study period; however, step-change analysis reveals a step-change decrease in 1977 resulting in a lower mean frequency. A significantly increasing trend and step-change increase in 1977 are detected in the mean frequency of Type 10. Additionally, the persistence of Type 10 has a step-change increase in 1977. An increase in the frequency of Type 10 and corresponding surface response, combined with a decrease in Type 1 and Type 3, is consistent with trends in above-freezing temperatures and rainfall reported by Newton (2018) and decreasing snowpack and earlier snowmelt found in western Canada (O'Neil *et al.*, 2017a), the Fraser River Basin (Kang *et al.*, 2014, 2016), the Peace River Basin (Romolo *et al.*, 2006a,b), and the upper Peace, Fraser, and upper Columbia river basins (Najafi *et al.*, 2017).

The presence of step-changes in synoptic-scale mid-tropospheric circulation pattern frequency and persistence is indicative of nonlinear changes in the atmospheric system. Additionally, step-changes can be problematic as they result in a rapid shift in average hydroclimatic conditions and may reduce the ability of a system to adapt. The timing of the step-changes seen in Types 3 and 10 indicate a relationship with the PDO. Newton *et al.* (2014a) reports linkages between the frequencies of several dominant mid-tropospheric circulation patterns and winters with a strong positive or negative average seasonal PDO index value. This suggests the existence of both linear and nonlinear atmospheric responses to fluctuations in the PDO and the potential for parallel responses in climatic and hydrologic systems. Given the decadal or multi-decadal nature of PDO regimes (Mantua *et al.*, 1997; Mantua and Hare, 2002), additional step-changes may be evident in longer historic and future time series. While the PDO is an important mode of atmospheric, climatic and hydrologic variability, the predictive skill of the PDO is currently insufficient to anticipate future regime shifts (Liu and Di Lorenzo, 2018). The surface climates associated with mid-tropospheric circulation patterns presented here represent the average conditions related to each synoptic type, but given the step-changes evident in Types 3 and 10, it is likely that there are corresponding, but spatially and/or temporally variable step-changes in temperature and precipitation. McGregor (2017) raises the possibility that thresholds in atmospheric states may be required to generate a climatic or hydrologic response, and results from this research suggest thresholds exist in certain atmospheric states. Further analysis is required to evaluate these thresholds and examine associated climate and hydrologic responses.

The SOM array is divided into two regimes, each populated with six individual synoptic types. Winters dominated by the regime depicting various strengths of a ridge of high pressure over western Canada, on the right side of the SOM array (RS), result in strong and widespread positive accumulated MDD and moderate to strong rainfall anomalies, particularly in watersheds in BC. Conversely, winters dominated by zonal flow or a trough of low pressure over western Canada, on the left side of the SOM array (LS), are associated with negative accumulated MDD and rainfall anomalies, suggesting that persistent and/or frequent LS-type regimes result in fewer days when the mean daily temperature is above freezing and when rainfall occurs. Large interannual variability and step-changes in dominant circulation regimes are evident in the time series of the LS and RS regime frequencies and persistence. These step-changes occur in 1977 except for RS persistence, which occurs in 1978. The step-changes signify broad shifts in seasonal mid-tropospheric circulation regimes from a regime dominated by persistent, frequent zonal flow and trough of low pressure over western Canada to a regime dominated by a ridge of high pressure over western Canada. Surface climate responses to these atmospheric drivers suggest that a shift in hydroclimatic conditions, namely toward higher winter accumulated MDD and rainfall, has likely occurred in tandem with these step-changes. Persistence of meridional atmospheric circulation is associated with extreme weather (e.g., Francis and Vavrus, 2012; Petoukhov *et al.*, 2013; Screen and Simmonds, 2014) and hydrologic phenomena (e.g., Newton *et al.*, 2017). An increase in the persistence of a ridge of high pressure over western Canada signifies an increased potential for the generation of snowmelt. RS-dominated winters are expected to have a higher probability of an extreme hydrologic event, given the contribution of both rainfall and snowmelt to runoff. RS-dominated winters are also expected to have a thinner snowpack, which decreases the available water during the spring freshet and may result in a lower freshet volume. Additionally, it increases the risk of low water supply during the warm season, threatening water supply for hydroelectricity generation (Filion, 2000; Roberts *et al.*, 2006), agricultural productivity (Pentney and Ohrn, 2008), and exacerbating summer drought conditions (Bonsal *et al.*, 2011; Hanesiak *et al.*, 2011).

This research enhances our knowledge of atmospheric circulation patterns conducive to snowmelt-generating above-freezing winter temperatures and rainfall in western Canada. Additionally, it provides new insight into winter hydroclimatic conditions, particularly as it relates to persistence of atmospheric regimes through the grouping of synoptic types into similar regimes. Previous studies evaluate trends in the frequency of synoptic types (e.g., Newton *et al.*, 2014a,b; Bonsal *et al.*, 2017; Bonsal and Cuell, 2017); however, this study uses a new approach to identify statistical step-changes in synoptic type frequency, which may be beneficial for the evaluation of thresholds related to system changes or the generation of extremes (e.g., McGregor, 2017). An important aspect not explored in this research is within-type climatic trends and variability, driven by air mass thermodynamic characteristics (e.g. Kassomenos and McGregor 2006; Cassano et al. 2007). The delineation of surface climate changes induced by trends in dominant atmospheric circulation regimes and those produced by changes to temperature and atmospheric moisture content within air masses will be instrumental to the understanding of historic and future climate change in western Canada. This research has provided valuable information regarding the role of atmospheric circulation, particularly that of persistence, in winter hydroclimatic variability; however, the potential for hydrologic extremes and large-scale threats to winter snowpack merits continued research.

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References

Ali, G., Tetzlaff, D., McDonnell, J.J., Soulsby, C., Carey, S., Laudon, H., McGuire, K., Buttle, J., Seibert, J., and Shanley, J. (2015). Comparison of threshold hydrologic response across northern catchments. *Hydrological Processes*, *29*, 3575-3591.

Anderson, E.A. and Larson, L. (1996) The role of snowmelt in the January 1996 floods in the northeastern United States. *Proceedings of the 53rd Eastern Snow Conference,* Williamsburg, Virginia, pp. 141–149.

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438, 303-309.

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P., (Eds.), (2008) *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*, IPCC Secretariat, Geneva, Switzerland.

Beltaos, S. (2002) Effects of climate on mid-winter ice jams. *Hydrological Processes*, 16, 789-804.

Bonsal, B.R. and Cuell, C. (2017) Hydro-climatic variability and extremes over the Athabasca River basin: Historical trends and projected future occurrence. *Canadian Water Resources Journal*, 42, 315-335.

Bonsal, B.R. and Prowse, T.D. (2003) Trends and variability in spring and autumn 0°C-isotherm dates over Canada. *Climatic Change*, 57, 341-358.

Bonsal, B.R., Shabbar, A., and Higuchi, K. (2001) Impacts of low frequency variability modes on Canadian winter temperature. *International Journal of Climatology*, 21, 95-108.

Bonsal, B.R., Wheaton, E.E., Chipanshi, A.C., Lin, C., Sauchyn, D.J., and Wen, L. (2011) Drought research in Canada: A review. *Atmosphere-Ocean*, 49, 303-319.

Bonsal, B.R., Cuell, C., Wheaton, E., Sauchyn, D.J., and Barrow, E. (2017) An assessment of historical and projected future hydro-climatic variability and extremes over southern watersheds in the Canadian Prairies. *International Journal of Climatology*, 37, 3934-3948.

Burn, D.H., Buttle, J.M., Caissie, D., MacCulloch, G., Spence, C., and Stahl, K. (2008) The processes, patterns and impacts of low flows across Canada. *Canadian Water Resources Journal*, 33, 107-124.

Cassano, J.J., Uotila, P., Lynch, A.H., and Cassano, E.N. (2007). Predicted changes in synoptic forcing of net precipitation in large Arctic river basins during the 21st century. *Journal of Geophysical Research: Biogeosciences*, 112, G04S49.

Colbeck, S.C. (1975) *Analysis of Hydrologic Response to Rain-on-Snow.* Cold Regions Research and Engineering Lab, Hanover NH. No. CRREL-RR-340.

Déry, S.J. and Wood, E.F. (2005) Decreasing river discharge in northern Canada. *Geophysical Research Letters,* 32, L10401.

Dibike, Y., Prowse, T., Bonsal, B., and O'Neil, H. (2017) Implications of future climate on water availability in the western Canadian river basins. *International Journal of Climatology*, 37, 3247-3263.

Doyle, P.F. and Costerton R.W. (1993) *Predicting severe mid-winter breakups in southern British Columbia*. Regional Water Management, B.C. Environment, Kamloops, B.C., Canada.

Edwards, T.W.D., Birks, S.J., Luckman, B.H., and MacDonald, G.M. (2008) Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada. *Quaternary Research*, 70, 188-197.

Edwards, T.W.D., Hammarlund, D., Newton, B.W., Sjolte, J., Linderson, H., Sturm, C., St. Amour, N.A., Bailey, J.N.-L., and Nilsson, A.L. (2017) Seasonal variability in Northern Hemisphere atmospheric circulation during the Medieval Climate Anomaly and the Little Ice Age. *Quaternary Science Reviews,* 165, 102-110.

Feiccabrino, J., Lundberg, A., and Gustafsson, D. (2012) Improving surface-based precipitation phase determination through air mass boundary identification. *Hydrology Research,* 43, 179-191.

Filion, Y. (2000) Climate change: implications for Canadian water resources and hydropower production. *Canadian Water Resources Journal*, 25, 255-269.

Fitzharris, B.B. (1987) A climatology of major avalanche winters in western Canada. *Atmosphere-Ocean,* 25, 115-136.

Fleming, S.W. and Whitfield, P.H. (2010) Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. *Atmosphere-Ocean*, 48, 122-131.

Francis, J.A. and Vavrus, S.J. (2012) Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, 39, L06801.

Geng, Q., Mo, R., Brugman, M., Snyder, B., Goosen, J., and Pearce, G. (2012) Interaction of an intense Pacific low pressure system with a strong arctic outbreak over British Columbia: Forecast challenges of the early December 2007 storm. *Atmosphere-Ocean,* 50, 95-108.

Goulding, D.L. (1978) Calculated snowpack evaporation during Chinooks along the eastern slopes of the Rocky Mountains in Alberta. *Journal of Applied Meteorology*, 17, 1647-1651.

Hanesiak, J.M., Stewart, R.E., Bonsal, B.R., Harder, P., Lawford, R., Aider, R., Amiro, B.D., Atallah, E., Barr, A.G., Black, T.A., Bullock, P., Brimelow, J.C., Brown, R., Carmichael, H., Derksen, C., Flanagan, L.B., Gachon, P., Greene, H., Gyakum, J., Henson, W., Hogg, E.H., Kochtubajda, B., Leighton, H., Lin, C., Luo, Y., McCaughey, J.H., Meinert, A., Shabbar, A., Snelgrove, K., Szeto, K., Trishchenko, A., van der Kamp, G., Wang, S., Wen, L., Wheaton, E., Wielki, C., Yang, Y., Yirdaw, S., and Zha, T. (2011) Characterization and summary of the 1999–2005 Canadian Prairie drought. *Atmosphere-Ocean*, 49, 421-452.

Hewitson, B.C. and Crane, R.G. (2002) Self-organizing maps: Applications to synoptic climatology. *Climate Research*, 22, 13-26.

Holton, J.R. (1979) *An Introduction to Dynamic Meteorology*. Second edition. New York, NY: Academic Press, Inc.

Jiang, N., Cheung, K., Luo, K., Beggs, P. J., and Zhou, W. (2012) On two different objective procedures for classifying synoptic weather types over east Australia. *International Journal of Climatology*, 32, 1475-1494.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77, 437–471.

Kang, D.H., Shi, X., Gao, H., and Déry, S.J. (2014) On the changing contribution of snow to the hydrology of the Fraser River Basin, Canada. *Journal of Hydrometeorology,* 15, 1344-1365.

Kang, D.H., Gao, H., Shi, X., ul Islam, S., and Déry, S.J. (2016) Impacts of a rapidly declining mountain snowpack on streamflow timing in Canada’s Fraser River basin. *Scientific Reports*, 6, 19299.

Kassomenos, P.A. and McGregor, G.R. (2006) The interannual variability and trend of precipitable water over southern Greece. *Journal of Hydrometeorology*, *7*, 271-284.

Kendall, M.G. (1975) *Rank Correlation Measures*. London, UK: Charles Griffin

Kienzle, S.W. (2008) A new temperature based method to separate rain and snow. *Hydrological Processes*, 22, 5067-5085.

Kohonen, T. (2001) *Self-Organizing Maps*. New York, NY: Springer

L'hôte, Y., Chevallier, P., Coudrain, A., Lejeune, Y., and Etchevers, P. (2005) Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps. *Hydrological Sciences Journal*, 50, 989-997.

Liu, Z. and Di Lorenzo, E. (2018) Mechanisms and Predictability of Pacific Decadal Variability. *Current Climate Change Reports*, 4, 128-144.

Longley, R.W. (1967) The frequency of winter Chinooks in Alberta. *Atmosphere,* 5, 4-16.

Lundquist, J.D., Neiman, P.J., Martner, B., White, A.B., Gottas, D.J., and Ralph, F.M. (2008) Rain versus snow in the Sierra Nevada, California: Comparing Doppler profiling radar and surface observations of melting level. *Journal of Hydrometeorology*, 9, 194-211.

Male, D.H. and Gray, D.M. (1981) Snowcover ablation and runoff. In Gray, D.M. and Male, D.M. (Eds.), *Handbook of Snow: Principles, Processes, Management and Use,* (pp. 360-436), Toronto, ON: Pergamon Press

Mann, H.B. (1945) Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, 13, 245-259

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society,* 78, 1069-1079.

Mantua, N.J. and Hare, S.R. (2002) The Pacific decadal oscillation. *Journal of Oceanography*, 58, 35-44.

Marks, D., Kimball, J., Tingey, D., and Link, T. (1998) The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, 12, 1569-1587.

McCabe, G.J., Clark, M.P., and Hay, L.E. (2007) Rain-on-snow events in the western United States. *Bulletin of the American Meteorological Society,* 88, 319-328.

McGregor, G. (2017) Hydroclimatology, modes of climatic variability and stream flow, lake and groundwater level variability: A progress report. *Progress in Physical Geography*, 41, 496-512.

Newton B.W., Prowse T.D., and Bonsal B.R. (2014a) Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 1: Winter season. *Hydrological Processes*, 28, 4219-4234.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2014b) Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 2: Summer season. *Hydrological Processes*, 28, 4235-4249.

Newton, B.W., Prowse, T.D., and de Rham, L.P. (2017) Hydro-climatic drivers of mid-winter break-up of river ice in western Canada and Alaska. *Hydrology Research*, 48, 945-956.

Newton, B.W. (2018) An evaluation of winter hydroclimatic variables conducive to snowmelt and the generation of extreme hydrologic events in western Canada. PhD thesis University of Victoria, Victoria BC.

O'Neil, H.C.L., Prowse, T.D., Bonsal, B.R., and Dibike, Y.B. (2017a) Spatial and temporal characteristics in streamflow-related hydroclimatic variables over western Canada. Part 1: 1950–2010. *Hydrology Research*, 48, 915-931.

O'Neil, H.C.L., Prowse, T.D., Bonsal, B.R., and Dibike, Y.B. (2017b) Spatial and temporal characteristics in streamflow-related hydroclimatic variables over western Canada. Part 2: Future projections. *Hydrology Research*, 48, 932-944.

Pederson, G.T., Betancourt, J.L., and McCabe, G.J. (2013) Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, US. *Geophysical Research Letters*, 40, 1811-1816.

Pentney, A. and Ohrn, D. (2008) Navigating from history into the future: the water management plan for the South Saskatchewan River Basin in Alberta. *Canadian Water Resources Journal*, 33, 381-396.

Peters, D.L., Prowse, T.D., Pietroniro, A., and Leconte, R. (2006) Flood hydrology of the Peace-Athabasca Delta, northern Canada. *Hydrological Processes*, 20, 4073-4096.

Petoukhov, V., Rahmstorf, S., Petri, S., and Schellnhuber, H.J. (2013) Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the National Academy of Sciences*, 110, 5336-5341.

Reusch, D.B., Alley, R.B., and Hewitson, B.C. (2005) Relative performance of self-organizing maps and principal component analysis in pattern extraction from synthetic climatological data. *Polar Geography*, 29, 188-212.

Reusch, D.B. (2010) Nonlinear climatology and paleoclimatology: capturing patterns of variability and change with self-organizing maps. *Physics and Chemistry of the Earth, Parts A/B/C*, 35, 329-340.

Roberge, A., Gyakum, J.R., and Atallah, E.H. (2009) Analysis of intense poleward water vapor transports into high latitudes of western North America. *Weather and Forecasting*, 24, 1732-1747.

Roberts, E., Stewart, R.E., and Lin, C.A. (2006) A study of drought characteristics over the Canadian Prairies. *Atmosphere-Ocean*, 44, 331-345.

Rohrer, M. (1989, December). Determination of the transition air temperature from snow to rain and intensity of precipitation. In *WMO IAHS ETH International Workshop on Precipitation Measurement*, St. Moritz, Switzerland, pp. 475-482.

Romolo, L., Prowse, T.D., Blair, D., Bonsal, B.R., and Martz, L.W. (2006a) The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part I: Snow accumulation. *Hydrological Processes*, 20, 4097-4111.

Romolo, L., Prowse, T.D., Blair, D., Bonsal, B.R., Marsh, P., and Martz, L.W. (2006b) The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part II: Snow ablation. *Hydrological Processes*, 20, 4113-4129.

Sauchyn, D. and Kulshreshtha, S. (2008) Prairies. In Lemmen, D.S., Warren, F.J., Lacroix J., and Bush E. (Eds.), *From Impacts to Adaptation: Canada in a Changing Climate 2007*, (pp. 275-328), Ottawa, ON: Government of Canada

Scaife, C.I., and Band, L.E. (2017). Nonstationarity in threshold response of stormflow in southern Appalachian headwater catchments. *Water Resources Research*, *53*, 6579-6596.

Screen, J.A. and Simmonds, I. (2014) Amplified mid-latitude planetary waves favour particular regional weather extremes. *Nature Climate Change*, 4, 704-709.

Sen, P.K. (1968) Estimates of the regression coefficient based on Kendall’s tau. *Journal of the American Statistical Association*, 63, 1379–1389.

Shabbar, A. and Khandekar, M. (1996) The impact of El Niño-Southern Oscillation on the temperature field over Canada: Research note. *Atmosphere-Ocean*, 34, 401-416.

Shabbar, A., Bonsal, B., and Khandekar, M. (1997) Canadian precipitation patterns associated with the Southern Oscillation. *Journal of Climate*, 10, 3016-3027.

Shabbar, A. and Bonsal, B. (2004) Associations between low frequency variability modes and winter temperature extremes in Canada. *Atmosphere-Ocean*, 42, 127-140

Shabbar, A. (2006) The impact of El Niño-Southern Oscillation on the Canadian climate. *Advances in Geosciences*, 6, 149-153.

Shabbar, A., Bonsal, B.R., and Szeto, K. (2011) Atmospheric and oceanic variability associated with growing season droughts and pluvials on the Canadian Prairies. *Atmosphere-Ocean*, 49, 339-355.

Sheridan, S.C. and Lee, C.C. (2011) The self-organizing map in synoptic climatological research. *Progress in Physical Geography*, 35, 109-119.

Stahl, K., Moore, R.D., and McKendry, I.G. (2006) The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. *International Journal of Climatology*, 26, 541-560.

Stewart, I.T. (2009) Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, 23, 78-94.

Stewart, I.T., Cayan, D.R., and Dettinger, M.D. (2004) Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18, 1136-1155.

Trenberth, K.E. and Stepaniak, D.P. (2003) Covariability of components of poleward atmospheric energy transports on seasonal and interannual timescales. *Journal of Climate*, 16, 3691-3705.

U.S. Army Corps of Engineers (1956). *Snow Hydrology: Summary Report of the Snow Investigations,* North Pacific Division, Portland OR

Vesanto, J., Himberg, J., Alhoniemi, E., and Parhankangas, J. (2000) *SOM toolbox for Matlab 5*. Helsinki University of Technology. Rep. A57

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, E., Milewska, E.J., Wan, H., and Wang, X.L. (2015) Observed trends in Canada's climate and influence of low-frequency variability modes. *Journal of Climate,* 28, 4545-4560.

Walker, I.J. and Sydneysmith, R. (2008) British Columbia, In Lemmen, D. S., Warren, F. J., Lacroix J., and Bush E. (Eds.), *From Impacts to Adaptation: Canada in a Changing Climate, 2007,* (pp. 329-386), Ottawa, ON: Government of Canada

Wallace, J.M. and Gutzler, D.S. (1981) Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review*, 109, 784-812.

Wang, T., Hamann, A., Spittlehouse, D., and Murdock, T.N. (2012) ClimateWNA – High-resolution spatial climate data for western North America. *Journal of Applied Meteorology and Climatology,* 51, 16-29.

Weiss, A., and Hays, C.J. (2005). Calculating daily mean air temperatures by different methods: implications from a non-linear algorithm. *Agricultural and Forest Meteorology*, *128*, 57-65.

Werner, A.W., Schnorbus, M.S., Shrestha, R.R., Cannon, A.J., Dayon, G., Anslow, F., Zwiers, F.W. (2019) A long-term, temporally consistent, gridded daily meteorological dataset for northwest North America. *Scientific Data,* 6, 180299.

Whitfield, P.H. and Cannon, A.J. (2000) Recent variations in climate and hydrology in Canada. *Canadian Water Resources Journal*, 25, 19-65.

Wrona, F.J., Prowse, T.D., Reist, J.D., Hobbie, J.E., Lévesque, L.M., and Vincent, W.F. (2006) Climate change effects on aquatic biota, ecosystem structure and function. *AMBIO: A Journal of the Human Environment*, 35, 359-369.

Wrona, F.J., Johansson, M., Culp, J.M., Jenkins, A., Mård, J., Myers-Smith, I.H., Prowse, T.D., Vincent, W.F., and Wookey, P.A. (2016) Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences*, 121, 650-674

Yuter, S.E., Kingsmill, D.E., Nance, L.B., and Löffler-Mang, M. (2006) Observations of precipitation size and fall speed characteristics within coexisting rain and wet snow. *Journal of Applied Meteorology and Climatology*, 45, 1450-1464.

Zhang, X., Vincent, L.A., Hogg, W.D., and Niitsoo, A. (2000) Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*, 38, 395-429.