Spatial and temporal characteristics in streamflow-related hydroclimatic variables over western Canada. Part 2: future projections

H. C. L. O'Neil, T. D. Prowse, B. R. Bonsal and Y. B. Dibike

ABSTRACT

Much of the freshwater in western Canada originates in the Rocky Mountains as snowpack. Temperature and precipitation patterns throughout the region control the amount of snow accumulated and stored throughout the winter, and the intensity and timing of melt during the spring freshet. Therefore, changes in temperature, precipitation, snow depth, and snowmelt over western Canada are examined through comparison of output from the current and future periods of a series of regional climate models for the time periods 1971–2000 and 2041–2070. Temporal and spatial analyses of these hydroclimatic variables indicate that minimum temperature is likely to increase more than maximum temperature, particularly during the cold season, possibly contributing to earlier spring melt. Precipitation is projected to increase, particularly in the north. In the coldest months of the year snow depth is expected to increase in northern areas and decrease across the rest of study area. Snowmelt results indicate increases in mid-winter melt events and an earlier onset of the spring freshet. This study provides a summary of potential future climate using key hydroclimatic variables across western Canada with regard to the effects these changes may have on streamflow and the spring freshet, and thus water resources, throughout the study area.

Key words | climate, hydrology, snow accumulation, snowmelt, spatial analysis, western Canada

H. C. L. O'Neil (corresponding author)
T. D. Prowse
Y. B. Dibike
Water and Climate Impacts Research Centre, Environment Canada,
University of Victoria,
3800 Finnerty Rd,
Victoria,
British Columbia,
Canada,
V8P5C2
E-mail: *hcl.oneil@gmail.com*

B. R. Bonsal
National Hydrology Research Centre, Environment Canada,
Saskatoon,
Saskatchewan,
Canada

INTRODUCTION

Climate change and variability result in a variety of impacts on the hydrologic regime of a watershed. Numerous changes have already been linked to increasing air temperatures, including melting of ice, snow cover reductions, increasing atmospheric water-vapour content and the resulting changes in precipitation patterns, and changes to runoff and soil moisture (Bates *et al.* 2008). Understanding how such changes in climate affect hydroclimatic conditions in critical water-supply regions is essential for effective water-resource planning. Therefore, examining the linkages between hydrologic and climatic variables, such as air temperature, precipitation, snow depth, and snowmelt, can provide more information about observed trends in streamflow.

A large portion of the river flow to the Canadian Arctic originates in the mid-latitudes, particularly from alpine snowpacks of the Northern Rocky Mountains, which includes the headwaters of some of the largest river systems in North America, including the Mackenzie, Saskatchewan and Columbia rivers. Freshwater flow from the Mackenzie River to the Arctic is an important factor for the freshwater budget of the Arctic Ocean, which affects ocean convection in the sub-Arctic seas, and thus thermohaline circulation (Holland *et al.* 2007; Min *et al.* 2008). The Saskatchewan and Columbia rivers provide streamflow that is essential for water-resource use, particularly in dry, prairie regions. These are predominantly nival river regimes, and mountain snowpack serves as a natural precipitation reservoir in the cold season. Therefore, any climate-related changes that affect snow accumulation quantity or the volume and timing of melt can have resource implications downstream.

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Headwaters for these major watersheds are in close proximity, therefore the spatial distribution of snow accumulation and melt determines whether melt contributes to the Mackenzie, Saskatchewan or Columbia rivers. Any north-south or east-west shifts in climate, including temperature and precipitation, can have major effects on where the snowfall and snowmelt occur, and thus what water resources are available in each region.

Instrumental observations and paleo-reconstructions have been used to analyze hydroclimatic trends in the historical period, however, global climate models (GCMs) and regional climate models (RCMs) provide information with respect to possible future scenarios. GCM and RCM analyses in a great deal of previous research often focus on large scale continental or hemispheric changes, or individual drainage basins (e.g., Šeparović *et al.* 2013). This approach provides information on individual watersheds as well as large scale national or continental projections, but does not focus on potential hydroclimatic changes that may alter the spatial distribution of precipitation between the major drainage basins of western Canada, and therefore regional water availability in these river systems. Evaluation of hydroclimatic trends and variability within sub-basins of large watersheds as well as between major drainage areas is necessary to determine 'water rich' and 'water poor' regions in addition to directional shifts in precipitation and snowfall patterns.

This study is part of the Climatic Redistribution of Western Canadian Water Resources (CROCWR) project, which was designed to quantify past, current, and potential future changes to water distribution in Canada. The analysis includes several individual studies that focus on evaluation of a series of hydroclimatic variables including atmospheric circulation patterns, hydroclimatic variables affecting streamflow, and streamflow (Prowse *et al.* 2013; Newton *et al.* 2014a, 2014b; Bawden *et al.* 2015; O'Neil *et al.* 2016). Water resources are essential for hydroelectricity generation, agricultural production, municipal and industrial use, ecological integrity, and fisheries and wildlife management. Therefore, results from the CROCWR study will be invaluable to water resource managers and policy makers.

This research investigates temporal and spatial variations in future projections of hydroclimatic conditions across western Canada, with emphasis on evaluating spatial redistribution of water across the study area. This involves meeting two primary objectives: (1) assess projected changes at annual and monthly timescales for hydroclimatic variables affecting river flows in western Canada using a series of RCMs (temperature, precipitation, snow depth, snowmelt) for the time periods 1970–2000 and 2041–2070; and (2) assess spatial variation of future projections for the above hydroclimatic variables across the region. The variables chosen for study were selected for their strong influence on streamflow, particularly the spring freshet.

Study area

The study area for this project covers western Canada, from the west coast of British Columbia to western Manitoba and from the Canada–United States border to the Mackenzie River Delta in the northernmost reaches of continental Canada (Figure 1(a)). This includes the Saskatchewan, Mackenzie, Fraser, and Columbia River Basins, as well as several small basins that drain British Columbia to the Pacific. A companion study (Bawden *et al.* 2015) has identified a series of hydrometric stations that correspond to distinct hydroclimatic regions within the study area. The identified region is based on drainage areas of 35 hydrometric stations, but these are amalgamated into eight study regions for the analysis presented in this study.

This study area incorporates a variety of climatic regions, including prairie, mountain and northern permafrost areas. Most areas between 55° and 65° north contain discontinuous permafrost, while areas north of 65° are continuous permafrost (Natural Resources Canada (NRCan) 1995). Much of the study area exists within the alpine region, above 1,000 m, with the remainder at lower elevations in the boreal plains or prairies (Figure 1(b)). The Mackenzie River basin is one of the largest river systems in the world, with a drainage area of 1,800,000 km^2 (Burn 2008). The basin covers several climatic regions, including cold temperate, mountain, sub-arctic, and arctic zones (Woo & Thorne 2003). The Liard River basin, Peace River basin, Athabasca River basin, and Great Slave-Upper Mackenzie region are all contained within the Mackenzie basin. The Peel River converges with the Mackenzie River near the delta to create the Peel River-Lower Mackenzie region.

The Saskatchewan River Basin has a drainage area of approximately 364,000 km^2, and includes the North and

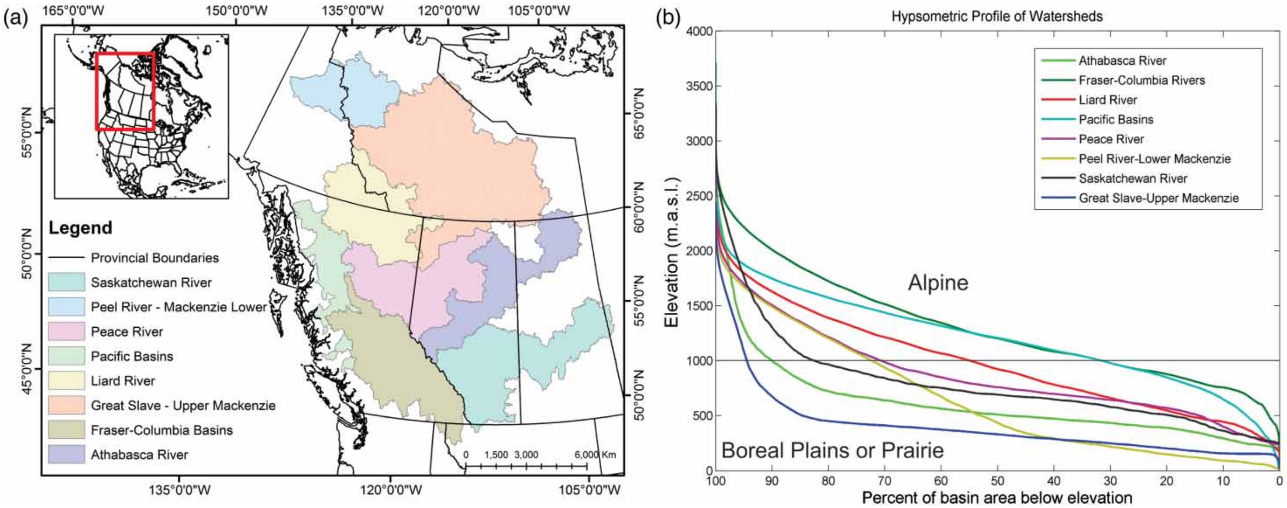

Figure 1 | (a) CROCWR study area with study regions identified by colour; and (b) hypsometric curves of each study region with the horizontal line at 1,000 m indicating what percentage of each region is alpine.

South Saskatchewan Rivers which are fed by the Red Deer and Bow Rivers (Cohen 1991). Headwaters originate as glacier and snow melt in the Rocky Mountains and flow east through the prairie grasslands, where very little runoff is contributed to the streamflow. The Fraser River covers a drainage area of approximately 217,000 km^2, and receives flow from snowmelt in spring, glacier melt in summer, and some rainfall throughout the year (Thorne & Woo 2011). The Columbia River basin has a total drainage area of approximately 696,000 km^2 and covers parts of seven western states as well as part of British Columbia, and a large portion of the flow is obtained from the Northern Rocky Mountains (Payne *et al.* 2004; Pederson *et al.* 2011a). The smaller basins draining to the Pacific (Pacific Drainage Region) consist of several rivers with small watershed areas that drain the Coast Mountains of British Columbia. The landscape in this area consists of steep-sided fjords and valleys with mountain peaks up to 2,265 m above sea level and alpine ice fields and glaciers occurring at high elevations (McCuaig & Roberts 2002).

DATA AND METHODS

Analysis of future climate scenarios was based on the outputs of six RCMs from the North American Regional Climate Change Assessment Program (Mearns *et al.* 2007). The models used in this study are: CRCM-CGCM3, CRCM-CCSM, RCM3-GFDL, RCM3-CGCM3, WRFG-CGCM3, and WRFG-CCSM and all climate model simulation results correspond to the A2 emissions scenario (Nakicenovic & Swart 2000). The A2 emissions scenario assumes a continuation of twentieth century energy policies throughout the twenty first century, and results include increased greenhouse gases and strong warming trends (Carter *et al.* 2007). The models all cover the 1971–2000 for the current time period and 2041–2070 for the future (Mearns *et al.* 2009). The spatial resolution of the RCMs is 50 × 50 km, with results recorded at 3-hour intervals. This research utilized an ensemble mean approach to compensate for model bias (Sain & Furrer 2010).

These six models were chosen because they provided the appropriate spatial and temporal coverage, as well as the required variables of maximum and minimum daily air temperature, precipitation, snow depth (in snow water equivalent, SWE), and snowmelt. These variables were chosen for study due to their strong influence on streamflow, particularly the spring freshet. However, the datasets were not always complete. The current period of all CCSM-driven models ends in December 1999 instead of December 2000, providing 29 years of data instead of the expected 30 years and the WRFG-CGCM3 future time period was missing every fifth year of data for SWE and snowmelt. The RCM3-CGCM3 and RCM3-GFDL models were missing all snowmelt data, so results for this variable contain only four models instead of six.

Analysis was completed on a monthly basis to identify month-to-month variation in the selected hydroclimatic variables. Though data was analyzed monthly, results were discussed on a cold/warm season basis. The cold season includes November through April with the warm season covering May to October. The cold season covers the majority of the snow accumulation period through spring breakup across much of the study area. The warm season includes the end of breakup in the north through the dry summer months to the beginning of freeze-up. The seasons vary across the study area due to variations in elevation as well as the large range of latitudes; however, the seasonal definitions were chosen to represent the cold and warm halves of the year as well as the hydrologic seasons as they exist throughout the majority of the study area and to allow comparison with companion studies (i.e., Newton *et al.* 2014a, 2014b; Bawden *et al.* 2015; O'Neil *et al*. 2016).

Watershed delineations for each of the eight study regions were created based on a series of latitude-longitude points which correspond to hydrometric stations from Environment Canada's HYDAT database. ArcHydro was used to delineate the contributing areas for each hydrometric station. ArcHydro is an object-oriented model that is capable of establishing a topological network that includes flow direction, connectivity and upstream/downstream relationships of stream segments using a digital elevation model, a stream network, and points to distinguish watershed outlets (Fürst & Hörhan 2009).

Each data point (50×50 km pixel) received a unique spatial identifier, and was analyzed individually for temporal changes in each variable, and then results were mapped over the study area. Each model contains a future and current time period, so the potential future change was determined using a delta method (Future – Current = Change). Monthly or annual values for precipitation and temperature were calculated as cumulative and average values over each period, respectively. Due to snow depth being provided as an instantaneous measure, the April 1st SWE was used in the annual analysis and end of month SWE was used for monthly values, while snowmelt was accumulated over each analysis period. The change in average values for both annual and monthly results was mapped for visual interpretation. The projected changes were then averaged by study region to obtain zonal means of change for each month and each variable.

RESULTS AND DISCUSSION

Maximum and minimum temperature

Average annual maximum daily temperature (Tmax) and minimum daily temperature (Tmin) generally ranges from -15 to 15 °C (Figures 2(a), 2(b) and 3(a), 3(b)). The difference between the 30-year means of the current and future time periods shows an expected Tmax increase of 1.5 to 2.5 °C (Figure 2(c)) and a Tmin increase of 2.5 to 3 °C (Figure 3(c)) across the study area.

Monthly Tmax and Tmin for both the current and future periods are given in Figure 4(a), 4(b), 4(d) and 4(e). Projected changes show expected increases of 1.5 to 5 °C during the cold season for both Tmax and Tmin, and lesser increases of 1 to 2.5 °C through the warm season (Figure 4(c) and 4(f)). The projections show the greatest increases are likely to occur more in non-coastal regions and northern latitudes, especially the Peel River-Lower Mackenzie, Upper Mackenzie, Peace, and Athabasca regions, with less warming predicted in the southwest. This is consistent with other recent studies which also show the cold season is likely to experience greater temperature increases than the warm season with a north-south gradient (e.g., de Elía *et al.* 2013; Šeparović *et al.* 2013).

Precipitation

Annual precipitation ranges from 250 mm to over 1,200 mm per year (Figure 5(a) and 5(b)). The difference between the 30-year means of the current and future time periods indicates that annual precipitation is expected to increase across the study area by as much as 100 mm (Figure 5(c)). The greatest increases of 100 mm occur in the western half of the study area, with increases of 20–70 mm expected through the remainder.

Precipitation varies greatly throughout the year; most study regions receive the greatest quantities of precipitation during the warm season, though coastal areas receive the

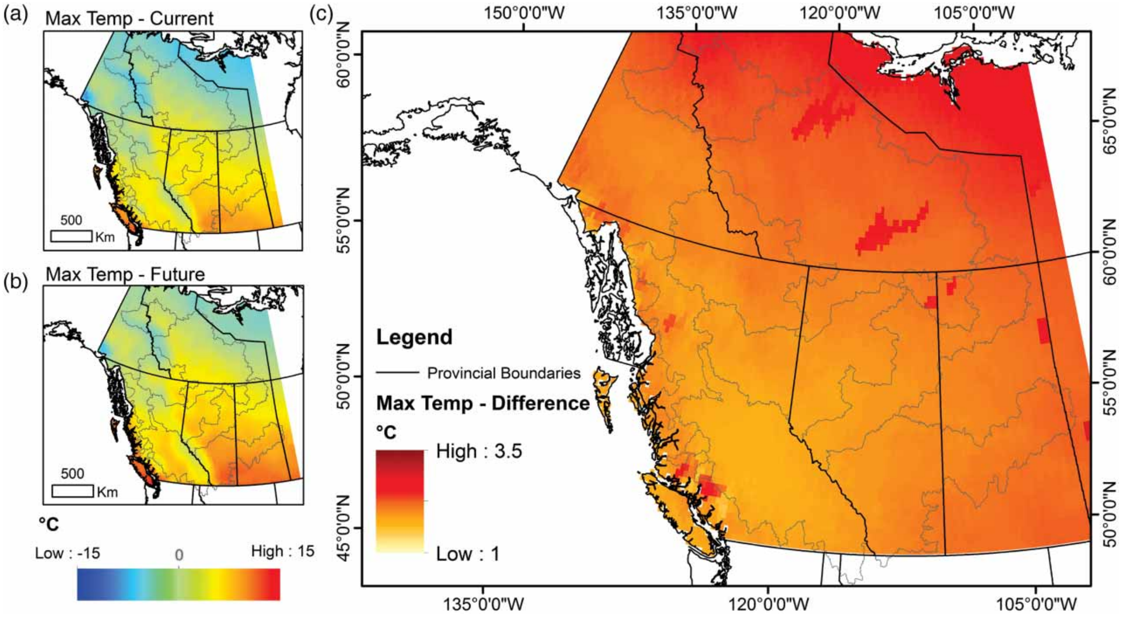

Figure 2 | Multi-model mean of Tmax for (a) the current and (b) future time periods, and (c) the expected difference.

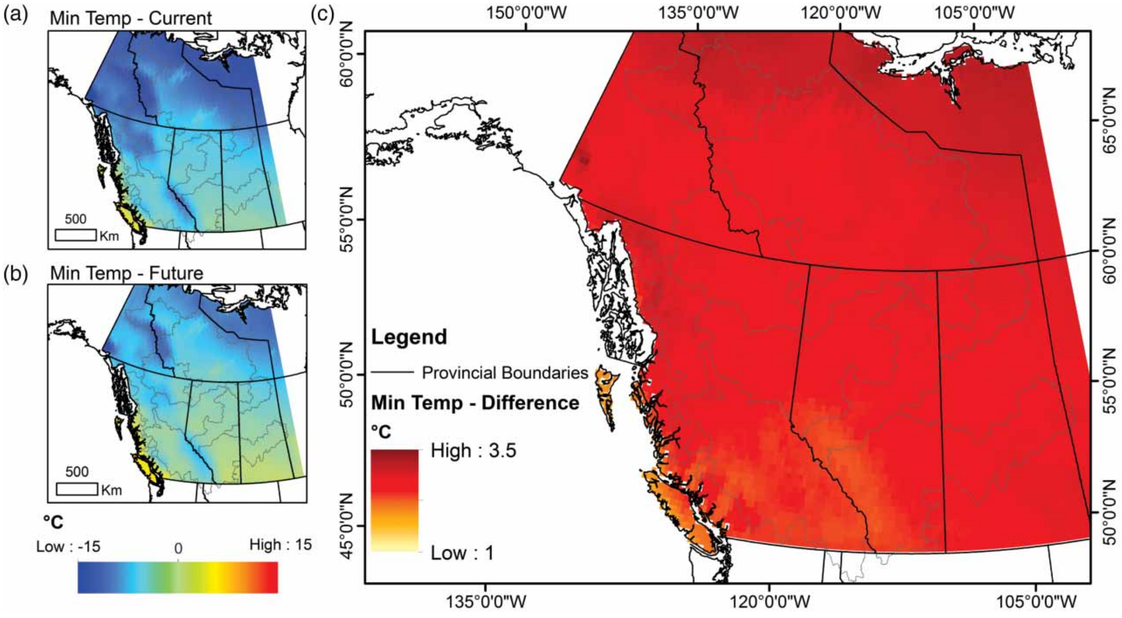

Figure 3 | Multi-model mean of Tmin for (a) the current and (b) future time periods, and (c) the expected difference.

most during the cold season (Figure 6(a) and 6(b)). The regional averages show that differences between the current and future periods are likely to be mostly positive throughout the year in all study regions (Figure 6(c)). The changes range from values slightly above zero to over 25 mm each month.

Overall, more spatial variation is expected in precipitation scenarios than for Tmax and Tmin, due to the high spatial variability of precipitation patterns. Both the cold and warm season show some projected increases to precipitation, with the greatest increases expected in coastal regions during the cold season. Decreases are

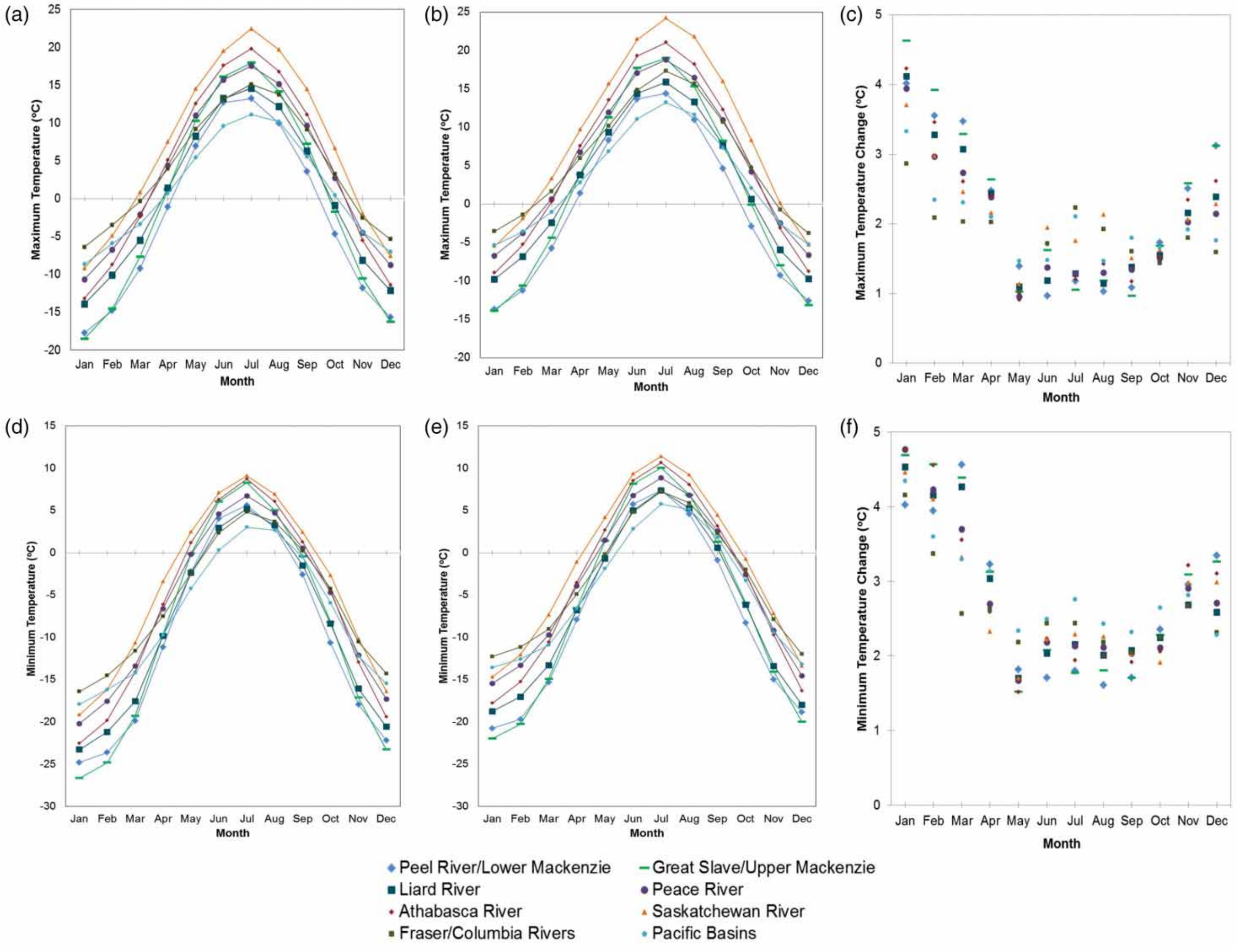

Figure 4 | (a) Daily average Tmax for the current period; (b) daily average Tmax for the future period; (c) change in Tmax; (d) daily average Tmin for the current period; (e) daily average Tmin for the future period; (f) change in Tmin. All results shown are monthly and are spatially averaged for each study region.

also expected in many months, though the regional averages do not always reflect the variations within each region. Projections for the warm season indicate a continuation of the northward shift in precipitation discussed in O'Neil *et al.* (2016), with the Liard, Peace, and Upper Mackenzie expected to receive 5 to 13 mm increases and the Rocky Mountains projected to experience decreases, especially in the Fraser-Columbia basin which shows a regional average decrease of 1 to 3 mm. However, decreased precipitation across the Rocky Mountains will affect the headwaters of the Saskatchewan and Athabasca basins, not just the Fraser-Columbia region. This is consistent with results from other studies that show precipitation in the future is expected to increase at northern latitudes, and continue to decrease in dry, interior regions (e.g., Adam *et al.* 2009; Šeparović *et al.* 2013; Schnorbus *et al.* 2014).

SWE

April 1st SWE ranges from 20–200 mm SWE across the study area in both the current and future periods (Figure 7(a) and 7(b)). The difference between the current and future periods shows that the south is anticipated to decrease by 5 to 20 mm SWE while the north is expected to increase by 5 to 20 mm SWE (Figure 7(c)). The greatest changes are projected in mountainous regions, where snow depth is generally largest.

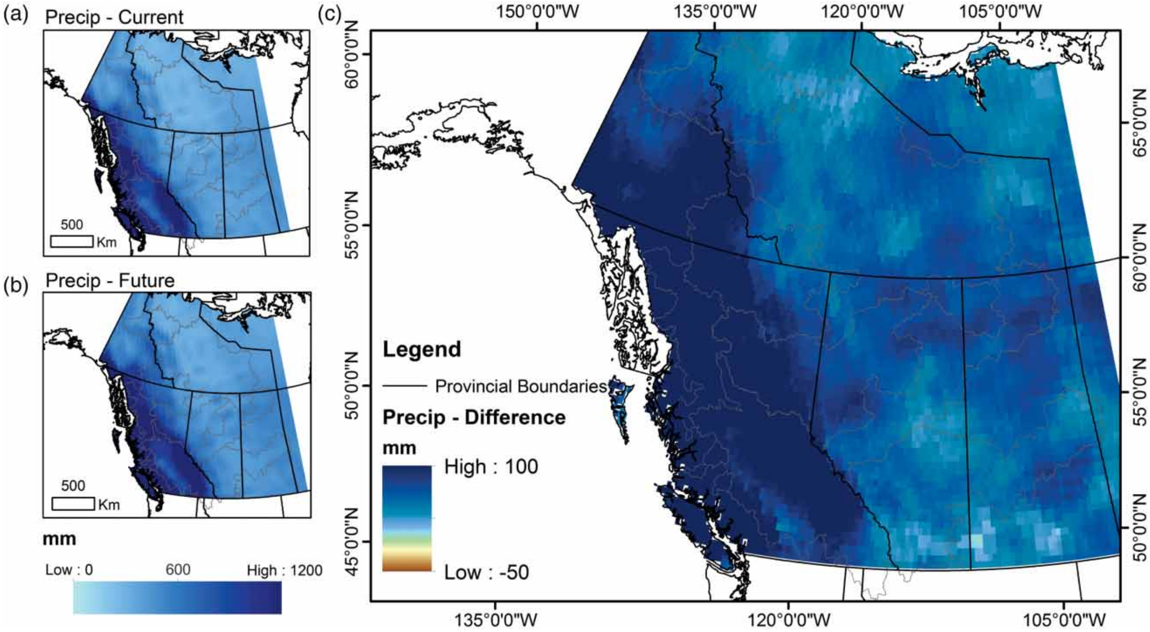

Figure 5 | Multi-model mean of mean annual precipitation for (a) the current and (b) future time periods, and (c) the expected difference.

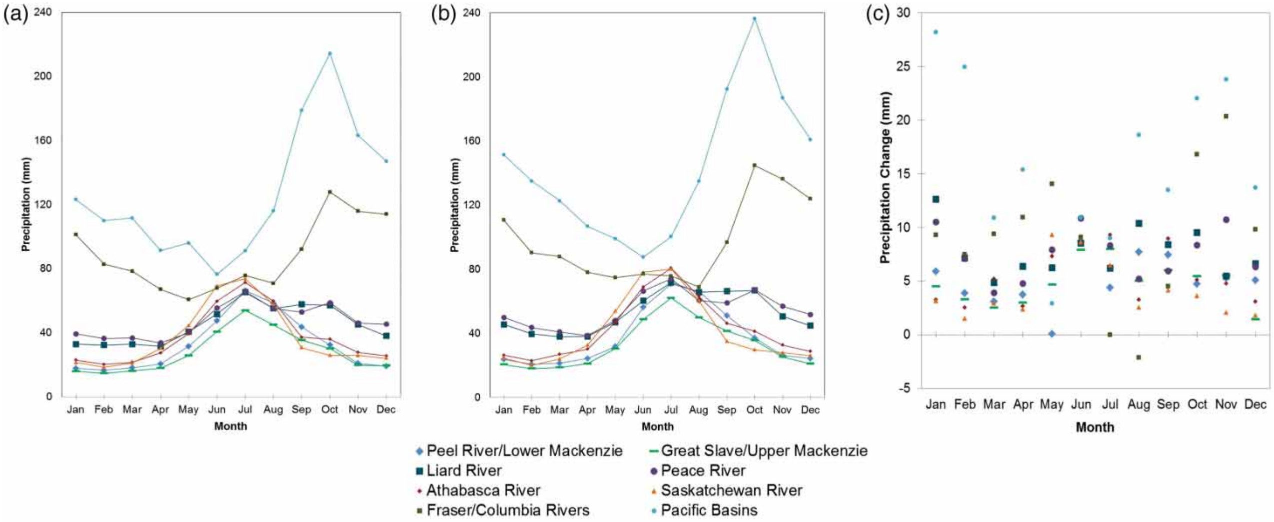

Figure 6 | Precipitation during each month in (a) the current and (b) future periods spatially averaged for each study region. (c) Spatially averaged regional change in monthly precipitation between the current and future periods.

SWE varies greatly depending on location and time of year, and is mostly expected to decrease in the future. Peak values range from 50 mm SWE in the Saskatchewan to over 500 mm SWE in the Pacific region (Figure 8(a) and 8(b)). Increases up to 20 mm SWE are expected during the cold season at northern latitudes, particularly the Peel River-Lower Mackenzie, Liard, and Upper Mackenzie. However, SWE across the remainder of the study area is projected to decrease during all months of the year (Figure 8(c)).

The cold season months all show very similar patterns of change in SWE; the high elevation areas near the coast are expected to receive less snow in the future, with smaller

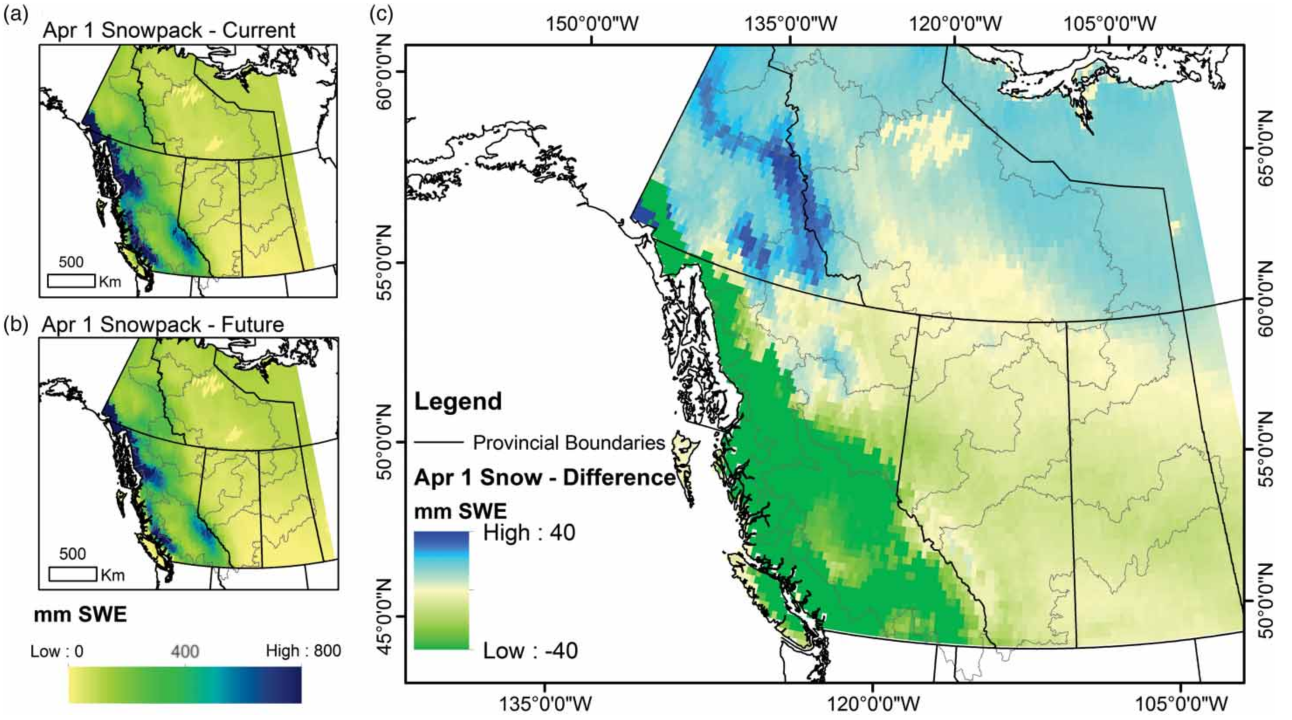

Figure 7 | Multi-model mean of April 1st SWE for (a) the current and (b) future time periods, and (c) the expected difference.

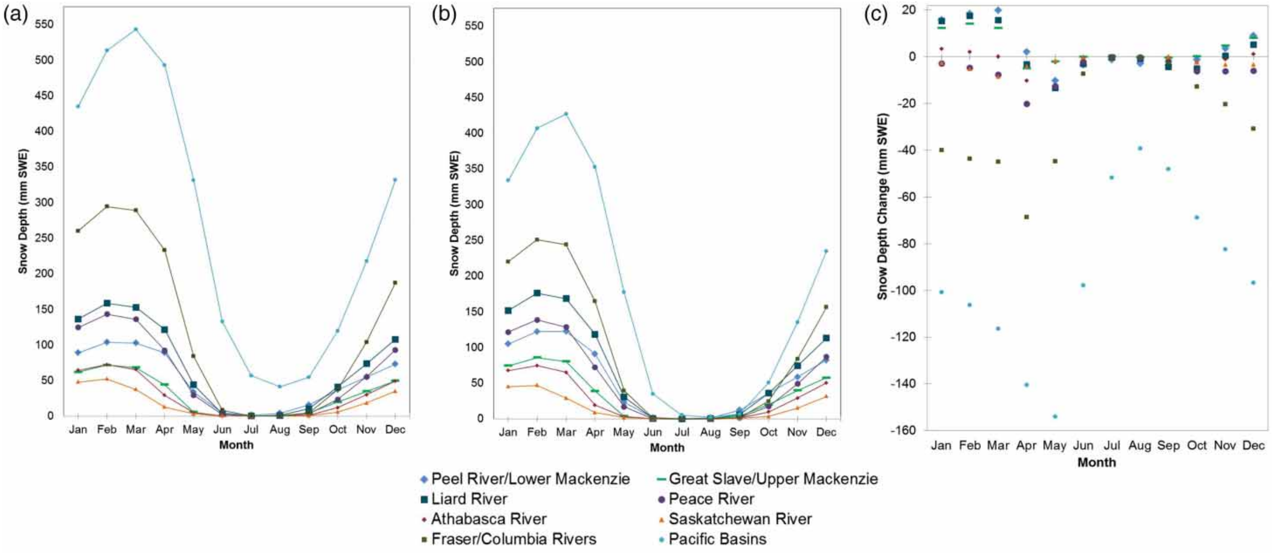

Figure 8 | SWE at the end of each month in (a) the current and (b) future periods spatially averaged for each study region. (c) Spatially averaged regional change in monthly SWE between the current and future periods.

decreases across the Prairies, and increases throughout the north. The expected increases in temperature throughout the north in these months allows for greater storage of water vapour in the air, leading to an increase in SWE at these higher latitudes (Davis *et al.* 1999; Hamlet *et al.* 2005). This pattern is consistent with other RCM and GCM studies of snow distribution in the northern hemisphere (e.g., Krasting *et al.* 2013).

Snowmelt

Total annual snowmelt ranges from 100–900 mm each year in both the current and future periods, with the greatest values located in the mountainous western half of the study area (Figure 9(a) and 9(b)). Snowmelt totals in the future are expected to be slightly lower in the west and slightly higher in the north and interior regions. The difference between the current and future periods shows decreases of 20 to 60 mm in the Fraser-Columbia and Pacific regions, with snowmelt increases of 10 to 30 mm expected in interior and northern regions (Figure 9(c)).

Snowmelt values are low throughout much of the year, with monthly totals of 0–40 mm, and then during April and May snowmelt peaks with values up to 225 mm during the spring freshet (Figure 10(a) and 10(b)). The projected changes in total monthly snowmelt show expected increases up to 20 mm during the cold season with decreases through the warm season in nearly all study regions (Figure 10(c)).

Snowmelt patterns are highly variable throughout the study area and throughout the year, though some patterns are visible. The southwest is likely to experience more instances of mid-winter melt, with January and February projected to experience greater snowmelt at low elevations and in coastal mountainous areas. Melt increases are located at greater elevations and more northern latitudes each month until April. These mid-winter melt events may contribute to decreased freshet volume in the spring due to less snow being present on the ground. The spring freshet is also expected to occur earlier in the year (Salathé 2005), with results for March and April showing many areas of increased snowmelt across the study area. Increased snowmelt is expected at lower latitudes in March, with April displaying increases at higher latitudes and decreases to lower latitudes. Snowmelt decreases occur throughout the warm season, particularly in May and June, mostly in higher elevation areas and at northern latitudes, likely due to less snow available for melt each year during these months. Snowmelt in late summer and throughout the fall is expected to decrease in the future, likely due to the reduced snowfall expected in these months.

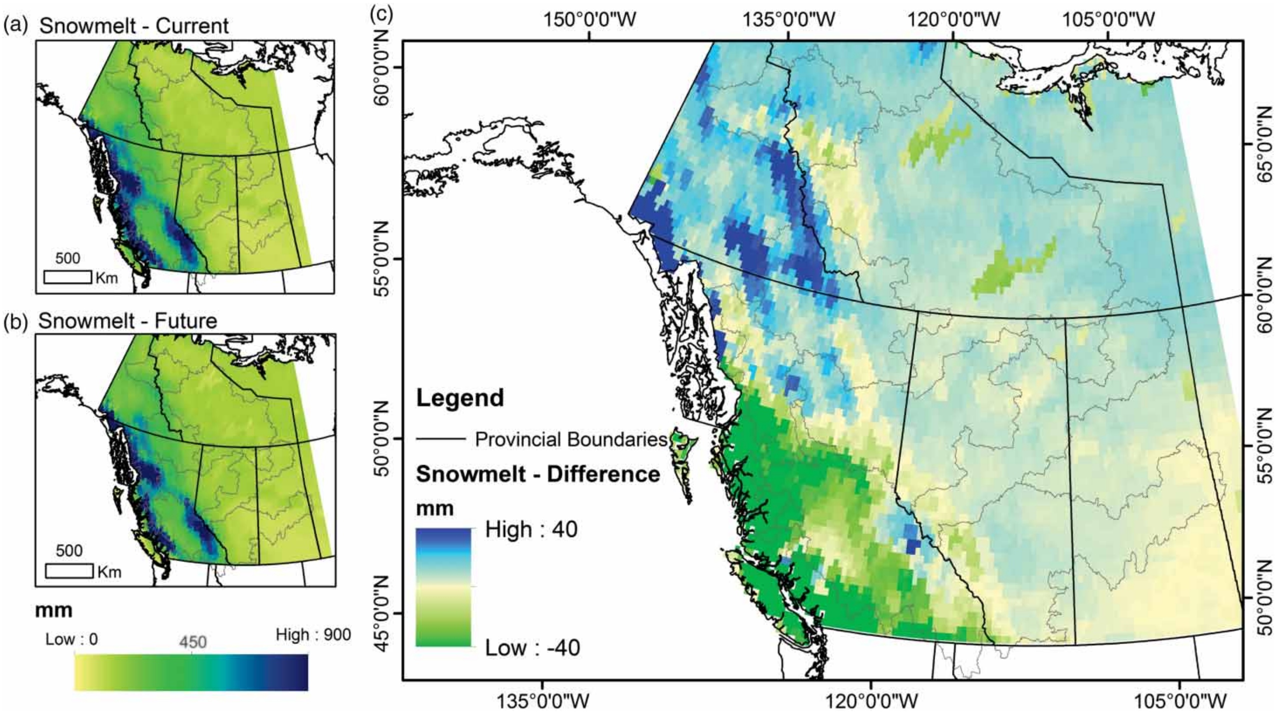

Figure 9 | Multi-model mean of annual snowmelt for (a) the current and (b) future time periods, and (c) the expected difference.

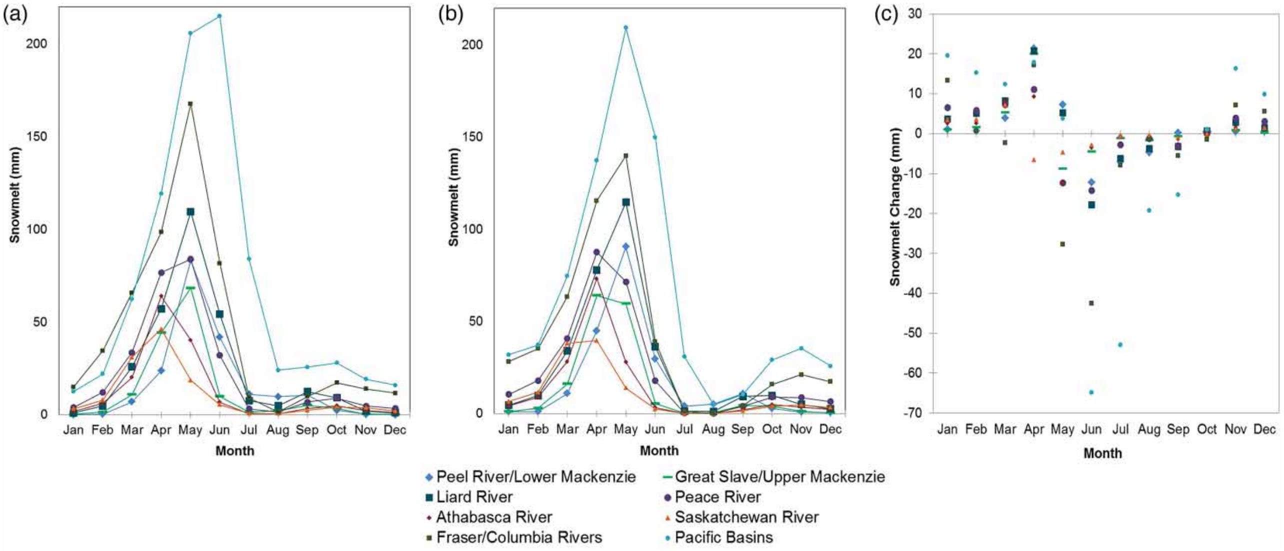

Figure 10 | Monthly snowmelt in (a) the current and (b) future periods spatially averaged for each study region. (c) Spatially averaged regional change in monthly snowmelt between the current and future periods.

Hydrologic relevance

The variables analysed in this research are all individually important factors in the hydroclimate of a watershed and all have their own impacts on streamflow, but they also interact in numerous ways to produce changes to both small- and large-scale watersheds. Temperature is a primary controlling factor of whether or not precipitation occurs as rain or snow, and influences the intensity and timing of snowmelt. Therefore, the expected increases in daily temperature identified in this paper, as well as other recent studies (Christensen *et al.* 2007; Adam *et al.* 2009; Bonsal *et al.* 2012), will modify the proportion of rainfall to snowfall in the study area, a phenomenon which has already been documented for the current period (e.g., Screen & Simmonds 2012).

Temperature increases during the warm season will also contribute to less water being available for streamflow due to higher evaporation rates. Although predicted increases are lower in the warm season than the cold season, any decreases to streamflow in dry areas such as the Prairies could pose an issue for water availability. Warm season streamflow decreases have already been detected in dry, interior regions in the current period, particularly the Saskatchewan River basin (Rood *et al.* 2008; Bawden *et al.* 2015), and are expected to continue across the Rocky Mountains and Prairies, particularly the Peace and Athabasca basins (Kerkhoven & Gan 2011; Schnorbus *et al.* 2014).

Increased precipitation is expected in most regions, with slightly greater increases in northern regions (e.g., Christensen *et al.* 2007; Min *et al.* 2008; Adam *et al.* 2009), indicating a continuation of the northward shift identified during the current period (O'Neil *et al.* 2016). The predicted increases in warm season precipitation through the northern half of the study area may contribute to higher summer streamflow in these regions. Additionally, warm season precipitation in the south is expected to increase slightly over the Prairies, but decrease over mountainous headwater areas where most flow originates, particularly in the headwaters of the Saskatchewan and Athabasca Rivers. This may lead to a decrease in the available water resources for these important agricultural areas. The Prairie regions of western Canada already experience dry summers that have become drier in the current period, and results from this study, in addition to previous research, indicate that the dryness will likely intensify in the future with an increase in dry days and dry spells (e.g., Sushama *et al.* 2010) as well as longer, more frequent droughts (e.g., Bonsal *et al.* 2012). Model simulations for the 21st century consistently project precipitation increases at high latitudes and decreases through many mid-latitude regions (Bates *et al.* 2008). Outside these regions the results vary widely and projections become less consistent, leading to uncertainty in precipitation projections over many parts of the world. Hydrological projections are one of the largest sources of uncertainty when using future projections, due to the internal variability of the system, uncertainty in the amounts of future greenhouse gas and aerosol emissions that affect the hydrological system, and in some cases, relatively simple representation of a complex system within the model implementation (Bates *et al.* 2008).

Much of the streamflow across western Canada originates in the Rocky Mountains and is dependent upon winter snow accumulation and spring melt. These alpine areas are an essential water source for downstream users, and the expected widespread decreases to SWE in the southern half of the study area (Pederson *et al.* 2011b; Krasting *et al.* 2013) combined with projected temperature increases are likely to lead to an earlier spring freshet with decreased volume (Stewart *et al.* 2004), as well as decreased summer streamflow throughout western Canada in the future. The timing of the spring freshet is important, since it generally peaks in the spring and then snowmelt continues slowly throughout the summer, providing flow to much of western Canada during the driest times of the year. Projected changes to snow are the result of warming feedbacks on temperature through changes in albedo. The magnitude of this feedback varies greatly between models, creating some uncertainty in spring snowmelt projections (Bates *et al.* 2008). However, incorporating observed snowmelt rates into models may help reduce this uncertainty in future model predictions.

In addition to an earlier spring freshet, the results also predict increased mid-winter snowmelt at lower elevations in the western regions of the study area, likely as a result of the projected temperature increases. This may contribute to increases in winter streamflow, particularly in the Fraser-Columbia, Pacific, and Peace River basins. Greater winter streamflow in these areas has already been detected in the current period by Rood *et al.* (2008) and Bawden *et al.* (2015), and previous RCM analysis shows runoff in the Columbia and Peace Rivers may increase as much as 30 mm during the winter (Schnorbus *et al.* 2014). Increased instances of mid-winter melt deplete the snowpack throughout the cold season, leading to decreased snowpack available for streamflow during the spring freshet and warm season.

The changes and interactions between hydroclimatic variables within the study area indicate several potential changes in the future. Increased temperatures are likely to lead to a further shortening of the cold season, which will lead to the spring freshet occurring earlier in the year and freeze-up occurring later. The shortened cold season length, along with projected decreases in SWE and increased mid-winter melt events, are likely to lead to a decreased spring freshet volume and less snowmelt available to provide vital water resources to dry, interior regions during the warm season. Precipitation is predicted to shift more toward northern latitudes, with less precipitation occurring in headwaters of the driest parts of the study area, so summer streamflow is expected to be greater in northern watersheds while southern, interior watersheds will likely experience less streamflow during the warm season. Understanding streamflow patterns in the major watersheds of western Canada is important since these areas provide essential water resources for municipal and industrial use, hydroelectric generation, and agriculture. Information regarding future climate scenarios is key for preparation of future water management plans throughout the study area.

CONCLUSION

This study utilized a series of RCMs to analyze the potential changes to future climate in western Canada. This included spatial and temporal analysis of a series of hydroclimatic variables (maximum and minimum daily air temperature, precipitation, SWE, and snowmelt) for changes between the 1971–2000 and 2041–2070 time periods and spatial variation both over time as well as within the year. The greatest increases in Tmax and Tmin are expected to occur during the cold season, with Tmin increases expected to be greater than Tmax. Analysis of the historical period has revealed similar trends in temperature, so it appears likely that this trend will continue. Projected increases in temperature will likely contribute to later freeze-up, increased instances of mid-winter melt, earlier break-up and an earlier spring freshet. The shorter cold season combined with expected decreases to snow depth across much of the study area indicate a possible decreased spring freshet volume, particularly in the south. However, an overall increase in SWE is also predicted throughout the northern half of the study area in the future, indicating the possibility of increased spring freshet volume in those regions. Warm season results show some decreases in precipitation over alpine areas that serve as headwaters for several major watersheds, which is likely to increase summer dryness. The results indicate a continuation of the northward shift in moisture identified for the current period, with northern Canada becoming more 'water rich' and southern Canada becoming more 'water poor'. This indicates that water management across western Canada is likely to become even more difficult in the future, and updated water management plans will be necessary. Further research should include analysis of more recently produced models based on the Representative Concentration Pathways emissions scenarios.

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