Recent hydrological response of glaciers in the Canadian Rockies to changing climate and glacier configuration

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Abstract. Mountain snow and ice greatly influence the hydrological cycle of alpine regions by regulating both the quantity and seasonal variations of water availability downstream. This study considers the combined impacts of climate and glacier changes due to recession on the hydrology and water balance of two high-elevation basins in the Canadian Rockies. A distributed, physically based, uncalibrated glacier hydrology model developed in the Cold Regions Hydrological Modelling platform (CRHM) was used to simulate the glacier mass balance and basin hydrology of Peyto and Athabasca Glacier basins in Alberta. Bias-corrected reanalysis data were used to drive the model. The model calculates the water balance of glacierized basins, influenced by the surface energy and mass balance, and considering redistribution of snow by wind and avalanches. It was set up using hydrological response units based on elevation bands, surface slope and aspect, as well as changing land cover. Aerial photos, satellite images and Digital Elevation Models (DEM) were assimilated to represent the changing configurations of glacier area and the exposure of ice and firn. Observations of glacier mass balance, snow and glacier ice surface elevation changes at glacier and alpine tundra meteorological stations and streamflow discharge at the glacier outlets were used to evaluate the model performance. Model results indicated that both basins have undergone continuous glacier loss over the last three to five decades, leading to a 6-31% reduction in glacierized area, a 78-109% increase in ice exposure, and changes to the elevation and slope of the glacier surfaces. Air temperatures are increasing, mainly due to increasing winter maximum and summer minimum daily temperatures. Annual precipitation is not changing much, but rainfall ratios have increased. Basin hydrology was simulated over two periods, 1965-1975 and 2008-2018, using observed glacier configurations. The results show that changes in both climate and glacier configuration caused changes in melt rates and runoff, and a shift of peak flows from August to July. Glacier melt contributions increased/decreased from 27-61% to 43-59% of annual discharges. Recent discharges were 3-19% higher than in the 1960s and 1970s. The results suggest that increased exposure of glacier ice and lower surface elevation due to glacier thinning were less influential than climate warming in increasing streamflow. Streamflow from these glaciers continues to increase.

1 Introduction

Mountain streamflow profoundly affects the quantity, quality and seasonal variation of downstream water availability, particularly in arid and semiarid regions of western North America (Marks et al., 2008). Glaciers contribute significantly to streamflow during warm and dry periods and in doing so moderate inter-annual variability and contribute to flow water during extreme warm and dry periods (Comeau et al., 2009; Fountain and Tangborn, 1985; Hopkinson and Young, 1998). North American mountain glaciers began to retreat after the Little Ice Age ended in the early 1800s (Barry, 2006; Riedel *et al.*, 2015). In recent decades, Western Canada has experienced a warming climate, with changes in precipitation regimes and decline in snow cover (DeBeer et al., 2016). As a result, glaciers in the region are retreating more rapidly than in the past (DeBeer et al., 2016; Schiefer et al., 2007; Tennant et al., 2012) and glacier meltwater is being added to headwaters discharge and groundwater storage (Castellazzi et al., 2019).

Marshall *et al.* (2011) projected glacier volumes of the Canadian Rockies (eastern slopes) for the next century. Their projected values are alarming, as they indicate a further ~85% loss of glacier volume by 2100 and an order of magnitude decrease in glacier contribution to streamflow in Alberta from 1.1 km^3 per year at present to 0.1 km^3 per year at the end of this century. Similarly, Clarke *et al.* (2015) projected a 75% loss of glacier mass in western Canada by the end of the 21st Century compared to 2005.

It has been proposed that as the climate warms, flow originating from glaciers will increase for a certain time due to increased melt rates, then decline as the glacier-covered area decreases (Moore *et al.*, 2009). The duration and timing of this change from increasing to decreasing flow, however, will be regionally dependent on basin elevation and/or glacier coverage of the basin (Casassa *et al.*, 2009). Stahl and Moore (2006) observed that late summer streamflow from British Columbia glacierized mountain basins has been declining, which suggests that most source glaciers have already completed the phase of increased flow due to rising temperatures and increasing melt rates and now contribute less streamflow as their areas decline. Chernos et al. (2020) projected a rise in glacier discharge in Athabasca River Basin in Alberta until the mid-21st century and then reduced discharge. Similarly, Neupane et al., (2017) modelled the upper Athabasca River basin and assessed the effects of changes in temperature and precipitation on simulated future discharge for the 2080-2099 period. They projected a reduction in water availability in the basin during the summer months.

Therefore, there are changes in both climate and glacier configuration occurring in Western Canada. Glacier mass loss is associated with a reduction in glacier-covered area, an increase in ice exposure and changes to the elevation and slope of the glacier surface. However, it is yet to be fully understood how the changes in glacier configuration and climate impact the streamflow jointly and individually. The integrated impacts of climate change on mountain streamflow are complex and can sometimes changes in hydrological processes can have compensating effects on streamflow generation (Fang and Pomeroy, 2020; Harder et al., 2015). Therefore, the impacts from climate change and glacier change on hydrology need to be diagnosed both separately and together. This study investigates the individual and combined impacts of changing climate and receding glaciers on the headwater hydrology of two well instrumented glacierized basins on the eastern slopes of the Canadian Rockies using a cold regions glacier hydrological model, CRHM-glacier (Cold Regions Hydrological Model – Glacier), forced by bias-corrected reanalysis data.

2 Study basins, data, methods

2.1 Study basins

Two alpine glacier basins in the Canadian Rockies, Alberta, Canada (Figure 1) were chosen for this research, Peyto Glacier Research Basin (PGRB, 22.43 km^2) in Banff National Park and Athabasca Glacier Research Basin (AGRB, 29.3 km^2) in Jasper National Park. The details of these basins are provided by Pradhananga and Pomeroy (2021) and Pradhananga et al. (2021). Both glaciers are instrumented with on-ice meteorological stations on the lower ice tongues of the glacier and off-ice meteorological stations on moraine below the tongue and their outlet streams are gauged at the outlets of their current proglacial lakes. Both glaciers have been losing mass continuously since the mid-1970s (Demuth and Keller, 2006; Intsiful and Ambinakudige, 2021; Kehrl et al., 2014; Reynolds and Young, 1997; Tennant and Menounos, 2013). Clarke et al. (2015) projected that AGRB will lose half of its glacier coverage by 2050. Kehrl *et al.* (2014) estimated that Peyto Glacier may lose about 85% of its present-day mass by 2100.

2.2 Meteorological forcing datasets

Bias-corrected ERA-40 (Uppala et al., 2005) and ERA-Interim reanalysis data (Dee et al., 2011) representing surface levels for air temperature, vapour pressure, wind speed, precipitation, incoming short- and longwave radiation were used to force the CRHM-glacier model. The ERA-40 was available for the period of 1957-2002 and ERA-Interim for the period of 1979-2019 with an overlapping period of 1979-2002. These ERA global reanalysis were first bias corrected to *in situ* observational datasets from meteorological stations near to the glaciers (Athabasca Moraine Station for AGRB and Peyto Main Station for PGRB, Figure 1). A monthly quantile mapping approach (Gudmundsson, 2016) with monthly bias correction factors were used for the bias correction of ERA-40 and ERA-Interim.

For PGRB, ERA-Interim data were bias-corrected to Peyto Main Station observations from 2013-2018 and ERA-40 data were bias-corrected to the archived observations from the station for the common overlap period of 1992-2001 (Munro, 2011), as described by Pradhananga et al. (2021). For AGRB, ERA-Interim data were bias-corrected to 2014-2018 observations at the Athabasca Moraine Station. The bias corrections were transferred to ERA-Interim 1979-2002, the overlapping period of ERA-40 and ERA-Interim, ERA-40 was bias-corrected to that. These bias corrections were transferred to ERA-40 for 1965-1975, similar to Krogh and Pomeroy (2018) as no *in situ* meteorological observations were available for the period before 2014 from AGRB.

2.3 CRHM-glacier model

The CRHM-glacier model (Pradhananga and Pomeroy, 2021), developed in the Cold Regions Hydrological Modelling Platform (Pomeroy *et al.*, 2007) was applied in this study to evaluate the impacts of changes in climate and in glacier configuration on the hydrology of glacierized basins. CRHM-glacier is a physically based, flexible, multi-physics hydrological model (Pradhananga and Pomeroy, 2021). It downscales and distributes meteorological variables (shortwave and longwave radiation, air temperature, relative humidity, wind speed, precipitation and its phase) to differing slopes, aspects, elevations and groundcovers defined by hydrological response units (HRU), using in-built algorithms and macros (Ellis et al., 2010; Harder and Pomeroy, 2013). The HRUs used to discretize these basins are presented in Pradhananga and Pomeroy (2021). CRHM-glacier simulates the hydrology of both glacier and non-glacier areas in a basin. It redistributes snow by coupling the blowing snow transport and sublimation processes with snow avalanching. The implementation used here does not calculate ice flow. Melt energies for snow and icemelt are calculated separately, based on *Snobal* and energy budget glacier melt modules, respectively to calculate snow, firn and ice mass balances (Pradhananga and Pomeroy, 2021). Meltwater routing is through three glacier reservoirs (snow, firn, and ice) modified to the de Woul *et al*. (2006) approach. Once water leaves the glacier, rain and meltwater are routed further into the soil surface, subsurface and groundwater using well developed alpine routing routines (Fang *et al.*, 2013). The model includes calculation of actual evapotranspiration using the Penman-Monteith method, and soil moisture and groundwater dynamics based on infiltration to frozen and unfrozen soils, and use of saturated and unsaturated hydraulic conductivities to calculate flow velocities in porous media. The model is uncalibrated, with parameters selected primarily from local observations, and its operation has been verified against observed albedo, mass balance, melt rate and streamflow at PGRB and ABRB (Pradhananga and Pomeroy, 2021).

2.4 Modelling scenarios

CRHM-glacier was run to simulate the hydrological responses of the two glacier research basins to four experimental scenarios. Observed glacier configurations, “past” corresponding to the late 1960s to early 1980s and “present” to the early 2010s, were set as initial conditions for two modelling scenarios in each basin. Initializing the model with observed glacier configurations, and restricting simulation periods to one decade, compensated for the lack of ice flow dynamics in the model scenarios.

Glacier configuration maps for the two periods were prepared according to the availability of suitable DEM and landcover information. These maps were used to delineate accumulation (snow or firn-covered) and ablation (ice-exposed) areas and DEMs were used to determine their elevations, slopes and aspects. The glacier area was taken as the sum of the snow, firn and the ice exposed areas. The accumulation area ratio (AAR) of the glaciers was calculated as the ratio of snow/firn-covered area to the total glacier area.

A topographic map of Peyto Glacier from 1966 (Sedgwick and Henoch, 1975) was used to prepare the past glacier configuration scenario. Both the 1966 DEM (10 m resolution) and the 1966 landcover map were developed from this topographic map, which was produced from aerial photographs taken in August 1966. The 2014 DEM was prepared at 10 m resolution from aerial photographs taken during July and September 2014 by Parks Canada over Banff National Park and made available for this study. The landcover map for the present basin was prepared based upon a Landsat image from 2014. Bolch *et al.* (2010) found only 1.7% deviation between aerial photograph and satellite imagery approaches for delineating glacier area and snow/firn/ice coverage. For AGRB, two DEMs, each at 20 m horizontal resolution, from 1983 and 2011, were used, and Landsat images from 1984 (Landsat 5) and 2014 (Landsat 8) were used to prepare past and present landcover maps.

The models were then run for two climate periods, past (1965-1975) and present (2008-2018). A novel approach was used in that past and present climate forced both past and present glacier configurations to diagnose how past glaciers would respond to the present-day climate and present-day glaciers to the past climate. Therefore, there was a combination of four model simulation scenarios, A-D using two separate decades of climate forcing from past and present periods, with past and present glacier configurations:

A: Past Climate, Past Glacier

B: Past Climate, Present Glacier

C: Present Climate, Present Glacier

D: Present Climate, Present Glacier

Based on these four experimental scenarios (A-D), five comparisons (C1-C5, Table 1) were employed to diagnose the impacts of climate and glacier changes on streamflow. C1 represents realistic conditions of both climate and glacier configuration; it compares A and D, i.e., past climate – past glacier with present climate – present glacier. The other comparisons are falsified modeling experiments to segregate the impacts of changing climate and glacier configurations. C2 and C5 consider only changes in the glacier configuration, while keeping the climate fixed in either the past or present. C3 and C4 compare the impacts from changing the climate while keeping the glacier configuration constant, as either the past or present glacier. Simulated runoff from these model outputs was examined to diagnose the hydrological response to both glacier change and climate change.

Statistical tests, the Student's t-test and the Wilcoxon Signed-Rank test (Wilcoxon, 1945) in the R environment (R Core Team, 2017) were applied to test the significance of the changes between the results obtained from the model scenarios. The Wilcoxon Signed-Rank test and Student's t-test were used for two paired samples using *wilcox.test* and *t.test* functions in R. These tests were used to assess whether one population of model output metrics is statistically distinguishable from the other. All tests were conducted at the 5% level of significance.

3 Results

3.1 Change in climate

Air temperature and precipitation over PGRB and AGRB were analyzed for the two decades – 1965-1975 (past) and 2008-2018 (present). Daily mean (Tmean), maximum (Tmax), and minimum (Tmin) temperature (Figure 2 and Table ST2-ST4) and monthly precipitation (Figure 3 and Table ST1), averaged and aggregated over the two climatic periods, were compared using C1.

Except for the summer maximum at AGRB, annual and seasonal average temperatures generally increased in the present decade compared to the past. Annual Tmax increased by 1 ^{o}C at AGRB and by 1.5 ^{o}C at PGRB. Analysis for monthly time periods also shows that air temperatures have increased at both glaciers. The greatest increases in the monthly Tmax were in January, when they rose by 5.1 ^{o}C at AGRB and 4.8 ^{o}C at PGRB. Monthly Tmin at AGRB increased by 3.6 ^{o}C in January and by 1 ^{o}C in July, and that at PGRB increased by 3.5 ^{o}C in January and 1.9 ^{o}C in July. Annual Tmean at AGRB increased by 0.5 ^{o}C, and that at PGRB increased by 1 ^{o}C. Temperature differences over time that were found to be significantly different from zero are more consistently evident at PGRB than at AGRB.

Annual precipitation increased slightly (15.2 mm at AGRB and 71.7 mm at PGRB) in the present decade compared to the past (Figure 3 and Table ST1), but these differences are not statistically significant. Winter (Dec-Feb) precipitation decreased at both basins, by 49.5 mm at AGRB and by 35.2 mm at PGRB. But precipitation in the other seasons (spring, summer and fall) increased by 13.1 mm, 38.5 mm and 13.1 mm respectively at AGRB and by 29.7 mm, 50.2 mm and 27.0 mm respectively at PGRB. The increases in summer precipitation at both basins and decrease in winter precipitation at AGRB were statistically significant (Table ST1).

There was an increase in rainfall ratio, for the present climate and present glacier configuration, compared to the past climate and past glacier configuration in both research basins (Figure 4), from 0.182 to 0.215 at AGRB and from 0.233 to 0.276 at PGRB (Table 2). The average annual rainfall ratios increased with reductions in glacier area and surface elevation; at ABRB from 0.182 to 0.184 for the past climate and from 0.213 to 215 for the present climate; and at PGRB from 0.233 to 0.248 for the past climate and from 0.263 to 0.276 for the present climate (Table 2). However, rainfall ratios increased mainly due to changes in climate over time. The average annual rainfall ratio for the past glacier configuration increased from 0.182 to 0.213 at AGRB and from 0.233 to 0.263 at PGRB; and for the present glacier configuration, the ratio increased from 0.184 to 0.215 at AGRB and from 0.248 to 0.276 at PGRB.

3.2 Change in glacier configuration

Figure 5 compares the configuration of both glaciers between two periods and shows changes in accumulation and ablation areas. During the period 1966-2014, the area of Peyto Glacier shrank from 14.4 km^2 to 9.9 km^2 (31%) and its AAR dropped from 0.75 to 0.35, exposing more ice in 2014, more than double the area exposed in 1966. The exposed ice area increased from 3.6 km^2 to 6.4 km^2 (78%), whereas the snow/firn area decreased from 10.8 km^2 to 3.5 km^2. Though to a lesser degree than Peyto Glacier, the area of Athabasca Glacier also decreased from 18 km^2 to 16.9 km^2 (6%), and its AAR decreased from 0.76 to 0.47. The exposed ice area of Athabasca increased from 4.3 km^2 to 9.0 km^2 (109%), and the snow/firn area decreased from 13.6 km^2 to 7.9 km^2. The firn line moved to a higher elevation in both glaciers, and glacier surfaces have become steeper from the past to present period. The other change in the two glacier configurations was in elevation; the mean glacier surface elevation Peyto Glacier decreased from 2628 m to 2615 m, whilst that of Athabasca Glacier increased from 2799 m to 2826 m.

3.3 Change in glacier mass balance

Seasonal and annual mass balance for AGRB and PGRB from the four model scenarios, A-D, are presented in Figure 6. The results from the statistical analysis are presented in Table ST7. Except for the change in winter mass balance between A and D (C1), the mass balance changes are not statistically significant at AGRB. There were significant changes in winter and annual mass balances between past and present climates and glaciers at PGRB (C1). Mean annual winter accumulation decreased from an average of 586 mm [1965-1975] to 324 mm [2008-2018], resulting in negative mean annual mass balances, from -271 mm in the past climate to -733 mm in the present climate (Table ST7). These changes are more due to the change in climate than the change in glacier configuration. Summer ablation increased significantly from past to present climate for both past and present glacier configurations (C3 and C4). The changes are not statistically significant in model runs for C2 and C5. However, the past glacier configurations resulted in greater winter snow accumulations in both basins for both past and present climates.

3.4 Change in runoff and runoff generation processes

Figure 7 shows runoff and volumetric melt components of runoff from AGRB and PGRB for A and D scenarios (C1). Snowmelt runoff dominated both the basins, in comparison to rainfall runoff, icemelt runoff, and firnmelt runoff. The present climate and present glacier configurations (D) produced more runoff than the past climate and past glacier configurations (A). There was a 19% increase significant at α = 5% (p=0.005) in mean annual runoff, from 1581 mm to 1888 mm (19%) at PGRB (Table ST5). This was mainly due to an increased contribution from icemelt, from 265 mm to 667 mm. There was a decrease in mean annual snowmelt and firnmelt, but the changes in these and the other fluxes were not statistically significant. For AGRB, the increase in runoff from 1320 mm to 1365 mm (3%) was not significant at α = 5% (p=0.578, Table ST5), though there was a significant increase in rainfall from 175 mm to 262 mm. AGRB experienced increased snowmelt and firnmelt but decreased icemelt.

Monthly averaged runoff from the four model scenarios is presented in Figure 8. The glaciers in AGRB and PGRB produced more runoff in the recent period (D) than in the past (A). Both past and present glaciers produced more runoff in the present than in the past climate. However, the past glaciers generated more streamflow compared to the present glaciers with both present and past climates. As the climate shifted there was a shift in peak from August in the past (A) to July in the present (D) at PGRB.

Significant changes in runoff, firnmelt and snowmelt occurred for PGRB, suggesting that the increase in runoff over time (C3 and C4) was due to an increase in firnmelt and icemelt (Table ST5). The large loss of firn coverage from past to present at PGRB resulted in a decrease of firnmelt by 65% (from 414 mm to 146 mm), when the past glacier configuration was replaced by the present one, with the climate for both glacier configurations held constant at the present climate (C5). In the case of AGRB, only increases in rainfall in the C3 and C4 and in snowmelt in C4 were significant. More rainfall occurred with both past and present glacier configurations.

4 Discussion

The glacio-hydrological model, CRHM, was used to simulate headwater hydrology of two glacierized mountain basins with four scenarios by combining the climate and glacier configurations of two periods, mid-20th century and early 21st century. These scenarios were used to diagnose the hydrological responses to changes in glacier and climate, individually and jointly presenting how glaciers in the past would respond to present day climate and glaciers today to past climate.

Changes in glacier configurations included changes in glacier extent, glacier surface elevation and slope, and change in AAR, which also changed the albedo feedback of glacier surface. Compared to the past, present glacier areas have declined, elevations have decreased, surface slopes have become steeper, AARs have become smaller, exposing more ice and thus reducing the glacier albedos. Air temperatures increased from past to present, the changes were more often significant at PGRB than at AGRB.

Though there was not much change in the total precipitation, rainfall ratios increased in the present compared to past due to changes in both climate and glacier configuration and this caused reduced snowfall at both basins. The differences for the same climate were due to the change in glacier configurations, for instance the present glacier configurations feature a smaller glacier surface at a lower surface height than do past configurations; both factors contribute to increased rainfall ratios. Increases in the rainfall ratio in these basins are consistent with other studies, for example, in western Canada by DeBeer et al., (2016) and in Europe by Hynčica and Huth (2019). In the case of glacier mass balance, the present climate and present glacier were responsible for making the winter mass balance less positive. Compared to the present glacier configuration, the past glacier gained more mass during winter.

Snowmelt dominated basin runoff, providing 52-70% and 52-53% of all runoff for PGRB and AGRB, respectively. At PGRB, rainfall-runoff provided 19-20% of basin runoff, which exceeded icemelt and firnmelt contributions, except for icemelt in the current climate and glacier configuration. The sum of firnmelt and icemelt contributions at PGRB increased from 27% in the past to 43% in the present (C1). At AGRB, rainfall-runoff provided 13-19% of basin runoff and was smaller than either firnmelt or icemelt contributions. Firnmelt was smaller than both snowmelt and icemelt. The sum of firnmelt and icemelt contributions at AGRB decreased from 61% in the past to 59% in the present. Basin runoff increased 19% at PGRB but only 3% at AGRB from past to present climate and present glacier configuration (C1). This increase was due to increases in rainfall (statistically significant), snowmelt and firnmelt at AGRB, whereas it was due to increase in rainfall and a 152% increase in icemelt (statistically significant) at PGRB (Table ST5). Snowmelt declined 12% at PGRB. Basin runoff increased due to the warming climate for both past and present glaciers (C3 and C4), whereas it decreased with decreasing glacier configurations for both the past and present climates (C2 and C5).

There was a reduction in peak monthly flows from both basins as the glacier area declined over time with the climate held constant (Figure 8). However, with the climate changing and the glacier configuration held constant, peak monthly flows increased over time. The combination of moving from past to present climate and changing glacier configuration shifted peak monthly flows forward by a month at PGRB, but the impact of changing climate was greater than that of the changing glacier configuration. The shift in PGRB's peak monthly flow from August to July is in line with the future prediction by Kienzle *et al.* (2012) for the Cline River watershed that spring runoff and peak streamflow would shift 18 – 26 days advance in the 21st century (2020 – 2080) compared to the baseline period (1961-1989).

In general, there was increased runoff in the present compared with the past for both basins, particularly from PGRB. This shows that these glaciers in Alberta, in the cold, high elevation headwaters on the northeastern slopes of the Canadian Rockies are still in the initial phase of warming-induced increased runoff, in contrast to most glaciers in British Columbia, including the more temperate southwestern slopes of the Canadian Rockies (Stahl and Moore, 2006) and western Canada, in general (DeBeer et al., 2016). However, this is similar to the results of Chernos et al. (2020), who projected glacier contributions to streamflow to increase till the middle of the twenty-first century (2040) and to decrease then after for the Athabasca River. Moore et al. (2009) also noted increasing trends of runoff in glacierized basins in relatively colder northwest British Columbia and southwest Yukon. Casassa et al. (2009) generalized that high elevation basins and/or basins with high glacierization were experiencing increasing runoff trends around the world.

The warmer temperatures and increased rainfall ratio in the present climate led to increased glacier runoff from both basins. However, the reduced glacier extent in the present glacier configuration resulted in decreased runoff from both basins, counteracting the direct impacts of climate change on the basins. In summary, the outputs show that changes in both climate and basin configurations were causing changes in the melt rate and runoff. Compared to the past climate and past glacier configuration, present climate and present glacier configuration provided more runoff in both basins, although there were significant losses of glacier area over the last five decades.

5 Conclusions

This study investigated the influence of snow and glaciers on headwater hydrology in two mountain basins in the Canadian Rockies, where a warming climate and glacier retreat continue to cause concern about changes in high mountain hydrology.

There was an increase in air temperature, mainly in daily maximum and winter minimum temperatures. Total precipitation has not increased, but the rainfall ratio has increased with the shift in climate. Both present climate and present glacier caused an increase in rainfall ratio compared to past climate and past glacier. Decreases in winter precipitation were balanced by increased precipitation in the other seasons, some of which fell as rainfall. Both mass balance observations and analysis of satellite imagery show that the glaciers are losing mass and area, and that the exposure of ice at the glacier surfaces has increased. The fractional glacier retreat is lower at AGRB (6%) than at PGRB (31%), whereas the fractional change in the exposure of ice is higher at AGRB (109%) than at PGRB (78%). The retreat of the glaciers has led to reductions in glacierized areas and changes in elevation and slope of the glacier surfaces. The decreases in AAR over time as the glacier changed configuration have caused increases in both proportional and areal ice exposure.

The study used a novel approach to apply present climate forcings to drive hydrological modelling using past glacier configurations and past climate forcings to drive modelling using present glacier configuration, so that the impacts of changes in glacier configuration and climate on glacier hydrology could be explicitly separated. The modelling results presented here show that glacier retreat and ablation are due to the joint effect of warming climate and an increase in ice exposure, which increased both seasonal melt and runoff. The sum of firnmelt and icemelt contributions to annual discharges increased at PGRB from 27 to 43%, and decreased at AGRB from 61%

to 59%. Increased streamflow discharge (3-19%) was due to climate warming and is limited somewhat by glacier retreat. Model results indicated that streamflow from the glaciers is still increasing in the present climate (2008-2018) from the past climate (1965-1975) despite reductions in glacier area and volume. Such a modelling approach is important for diagnosing the hydrological responses from a glacierized basin in the context of climate change and variability. The results suggest that increased exposure of glacier ice and lower surface elevation due to glacier thinning were less influential than climate warming in increasing streamflow.

Author contribution

DP and JWP conceptualized the research. DP did the analysis and prepared the manuscript. JWP instrumented the research basins, guided research methods and edited and revised the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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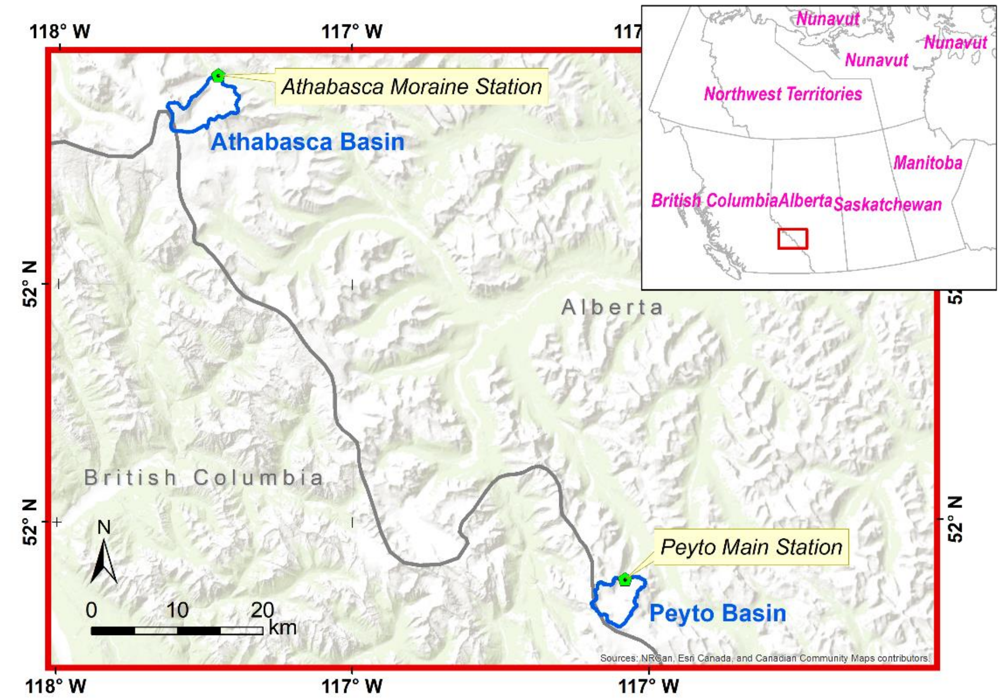

Figure 1: Location map of Peyto and Athabasca glacier research basins. Gray line is the border between two provinces, blue polygons are basin boundaries, and green circles are meteorological stations.

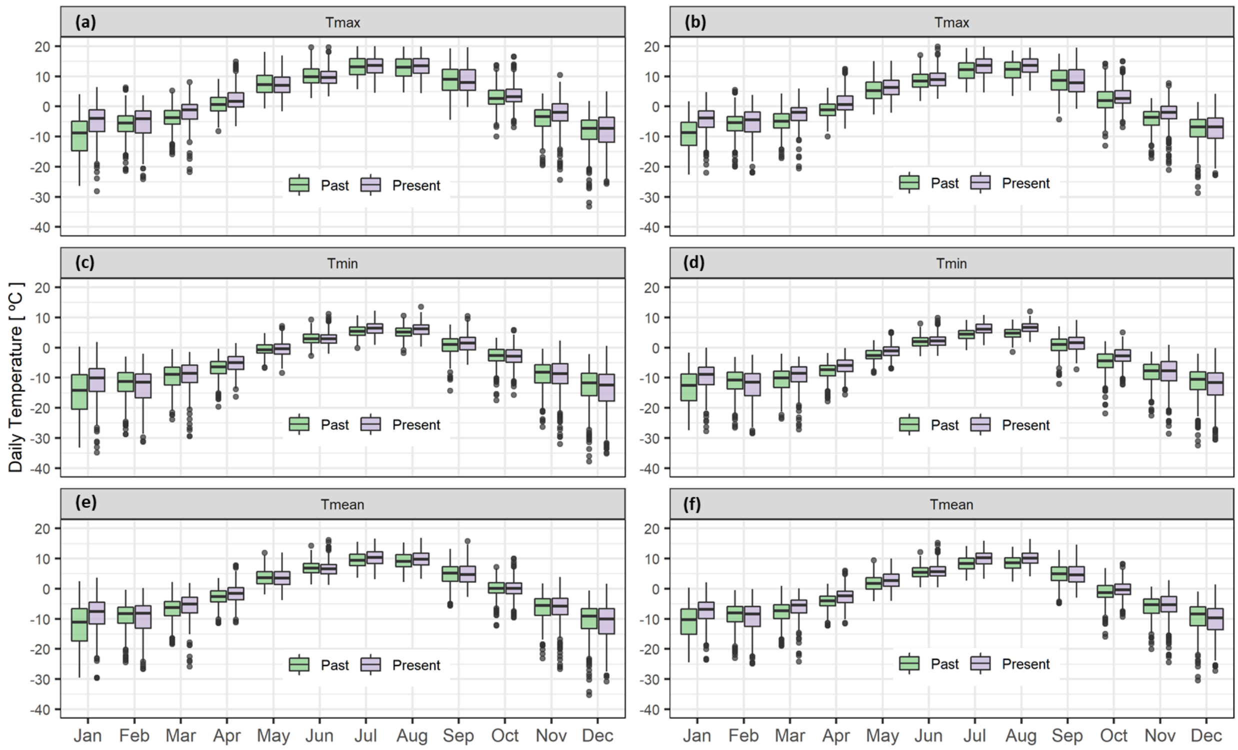

Figure 2: Monthly means of daily maximum (a, b), minimum (c, d) and mean (e, f) temperature comparison between two periods: past (1965-1975) and present (2008-2018). (a, c, and d) AGRB (b, d, f) PGRB.

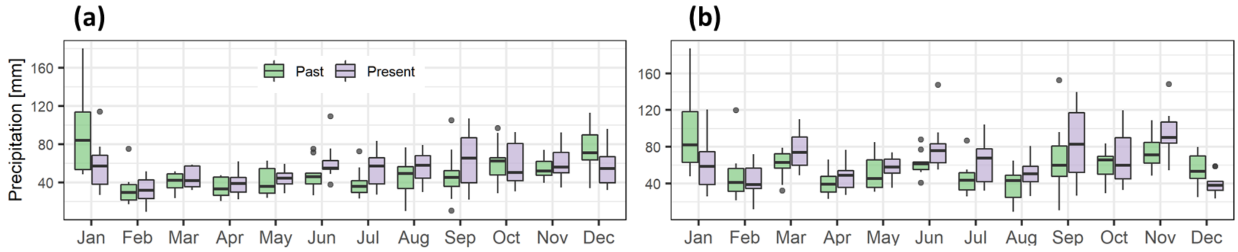

Figure 3: Monthly mean precipitation averaged over the two periods: past (1965-1975) and present (2008-2018). (a) AGRB (b) PGRB.

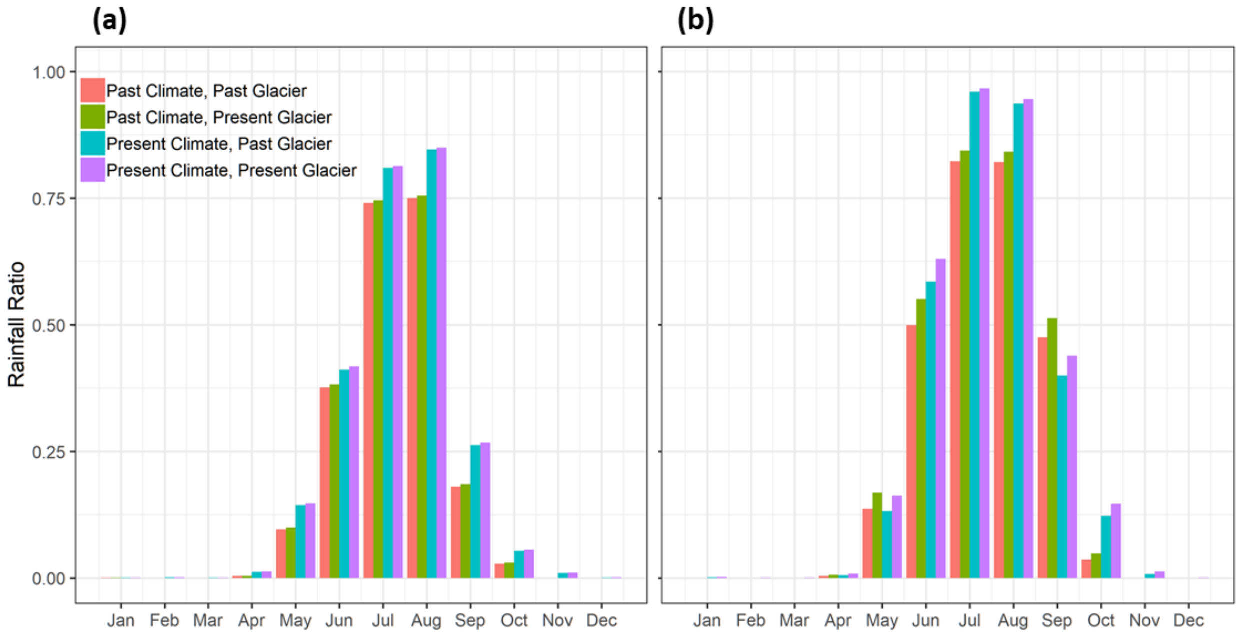

Figure 4: Mean-monthly rainfall ratios simulated for the four model run scenarios, A-D combining past and present climate and glacier. (a) AGRB, (b) PGRB.

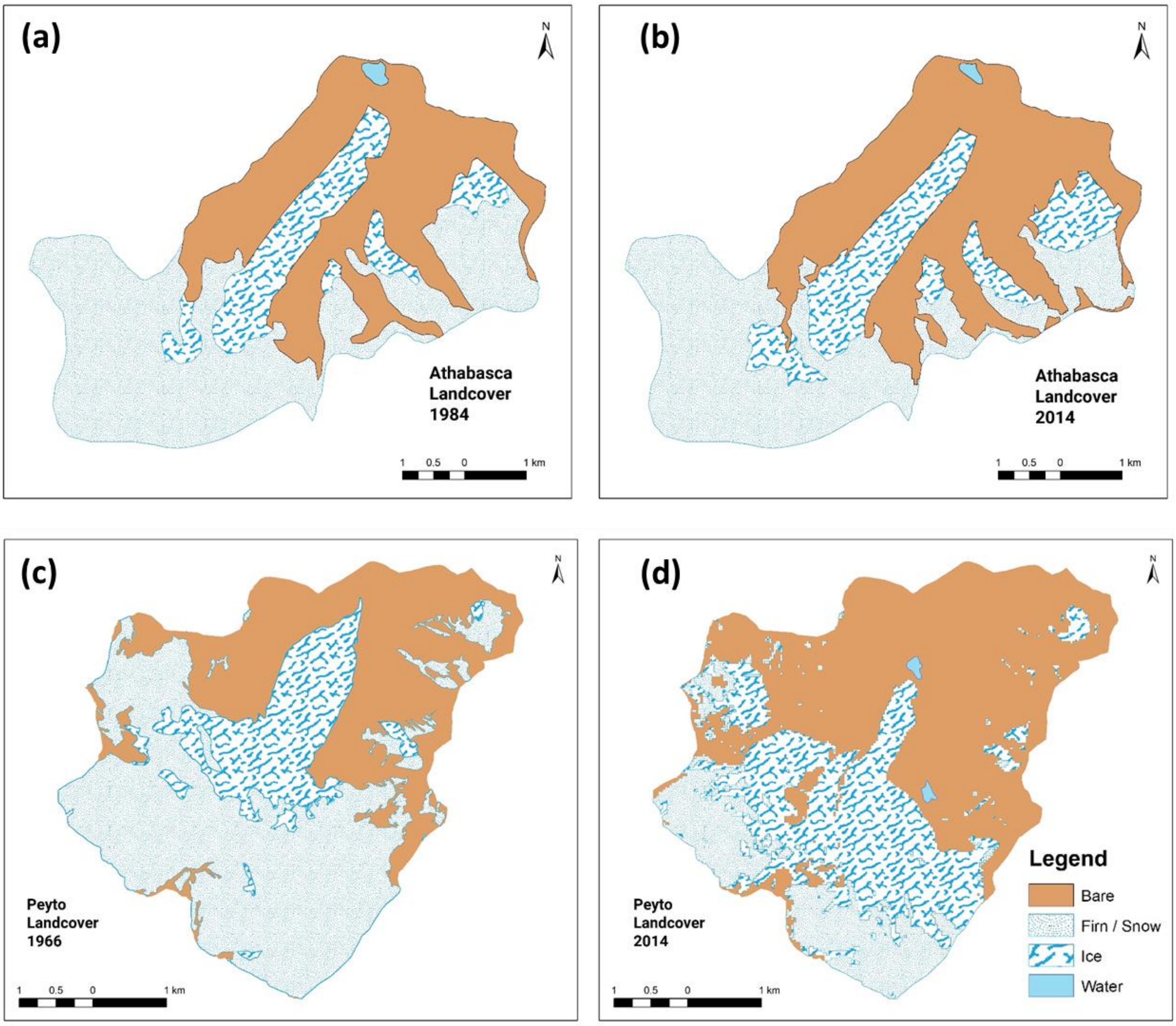

Figure 5: Change in landcover between the glaciers in past and present. (a) and (b) are AGRB in 1984 and 2014, respectively; (c) and (d) are PGRB in 1966 and 2014, respectively.

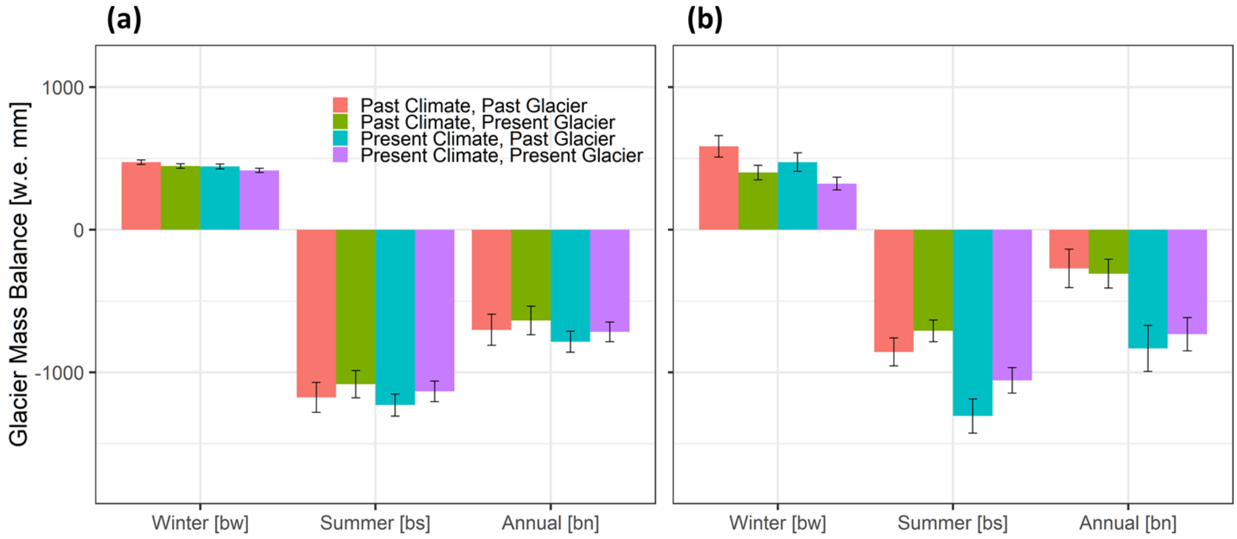

Figure 6: Glacier mass balance – winter, summer and annual, from the four model scenarios, A-D combining past and present climate and glacier. Error bars show the annual variability, defined as the standard error between years. (a) AGRB and (b) PGRB.

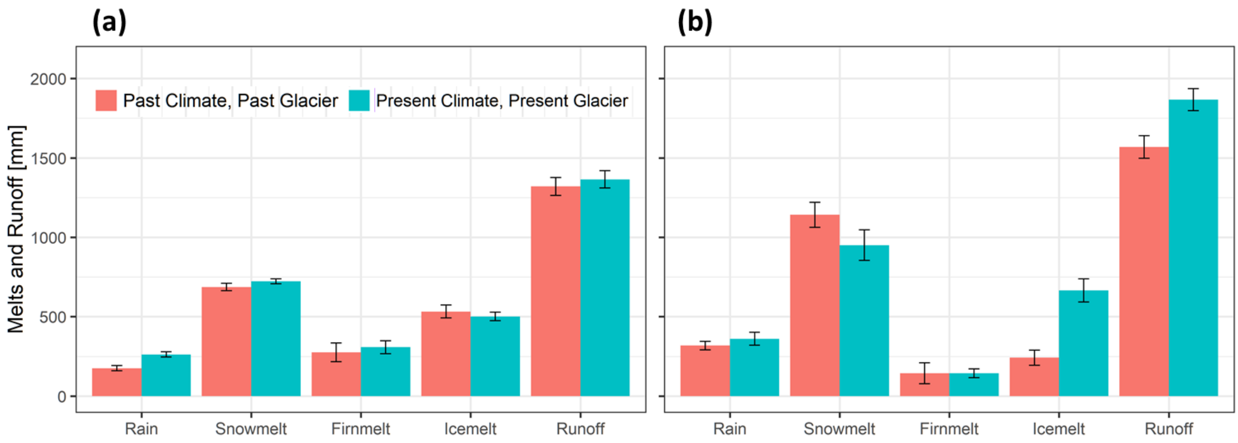

Figure 7: Mean annual melt, rainfall-runoff and basin runoff for the past and present glacier configuration and climate scenarios. Error bars show the annual variability, defined as the standard error between years. (a) AGRB (b) PGRB.

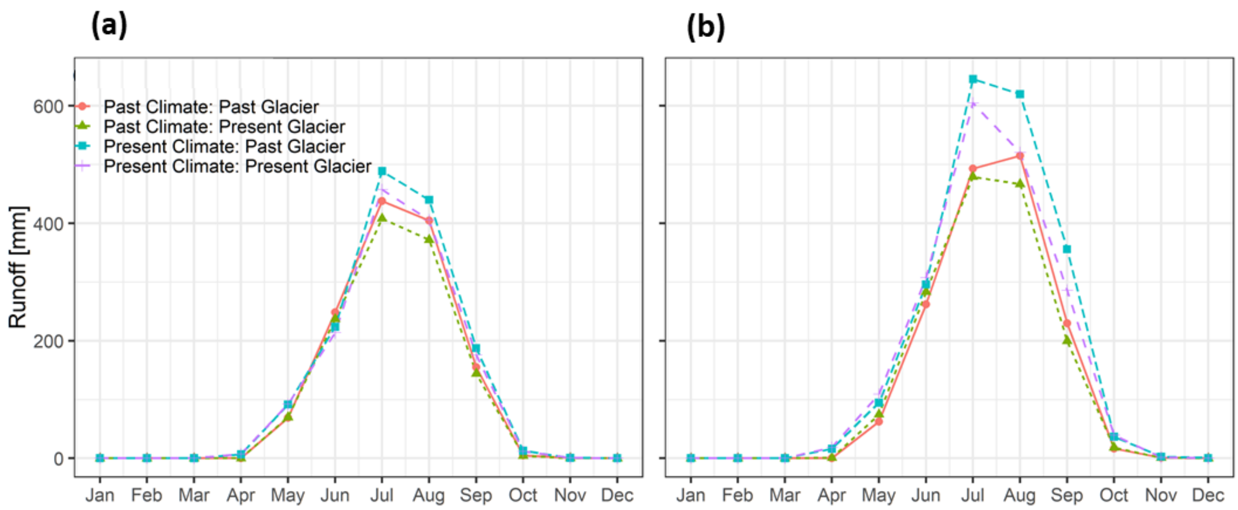

Figure 8: Monthly averaged runoff simulated using the past and present glacier and climate scenarios. (a) AGRB (b) PGRB.

Table 1: Comparison of model outputs.

Comparison #	Comparison of model scenarios		
C1	Past Climate-Past Glacier [A]	*VERSUS*	Present Climate-Present Glacier [D]
C2	Past Climate-Past Glacier [A]	*VERSUS*	Past Climate-Present Glacier [B]
C3	Past Climate-Past Glacier [A]	*VERSUS*	Present Climate-Past Glacier [C]
C4	Past Climate-Present Glacier [B]	*VERSUS*	Present Climate-Present Glacier [D]
C5	Present Climate-Past Glacier [C]	*VERSUS*	Present Climate-Present Glacier [D]

Table 2: Average annual rainfall ratio for the four model scenarios.

Model scenarios	AGRB	PGRB
Past Climate, Past Glacier [A]	0.182	0.233
Past Climate, Present Glacier [B]	0.184	0.248
Present Climate, Past Glacier [C]	0.213	0.263
Present Climate, Present Glacier [D]	0.215	0.276

Supplementary Tables

Table ST1: Changes in precipitation for annual, seasonal and monthly time periods [Comparison C1]. Highlighted bold numbers are significant at 95% confidence level.

Seasons	AGRB					PGRB				
	p-value Wilcox test	p-value t-test	Past (mm)	Present (mm)	Difference (mm)	p-value Wilcox test	p-value t-test	Past (mm)	Present (mm)	Difference (mm)
Annual	0.912	0.683	611.4	626.6	15.2	0.143	0.121	697.0	768.7	71.7
Winter	0.043	0.037	**254.5**	**205.0**	**-49.5**	0.436	0.223	272.2	237.0	-35.2
Spring	0.089	0.191	115.0	128.1	13.1	0.064	0.057	152.4	182.1	29.7
Summer	0.052	0.020	**132.9**	**171.4**	**38.5**	0.009	0.006	**146.2**	**196.4**	**50.2**
Fall	0.481	0.468	109.0	122.1	13.1	0.218	0.260	126.2	153.2	27
January	0.123	0.056	92.9	58.2	-34.7	0.089	0.060	94.6	60.7	-33.9
February	0.821	0.882	32.5	31.5	-1	1.000	0.613	48.8	43.4	-5.4
March	0.436	0.313	40.1	45.1	5	0.165	0.069	61.2	77.2	16
April	0.496	0.356	34.6	39.6	5	0.280	0.259	40.7	48.3	7.6
May	0.436	0.571	40.4	43.5	3.1	0.393	0.420	50.6	56.5	5.9
June	0.043	0.095	**47.1**	**61.0**	**13.9**	0.029	0.076	**61.9**	**80.0**	**18.1**
July	0.054	0.055	39.0	55.0	16	0.089	0.064	45.1	63.6	18.5
August	0.353	0.319	46.7	55.4	8.7	0.123	0.103	39.2	52.8	13.6
September	0.280	0.227	48.0	63.6	-15.6	0.315	0.288	66.2	85.5	19.3
October	0.739	0.814	60.9	58.5	-2.4	0.529	0.497	60.0	67.7	7.7
November	0.579	0.462	53.9	58.8	4.9	0.063	0.067	73.7	93.7	20
December	0.082	0.086	75.3	56.5	-18.8	0.035	0.032	**55.1**	**39.3**	**-15.8**

Table ST2: Changes in daily maximum temperature for annual, seasonal and monthly periods [Comparison C1]. Highlighted bold numbers are significant at 95% confidence level.

Seasons	AGRB					PGRB				
	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)
Annual	0.002	0.002	**2.1**	**3.1**	**1**	0.000	0.000	**1.3**	**2.8**	**1.5**
Winter	0.009	0.009	**-7.2**	**-5.3**	**1.9**	0.001	0.001	**-0.2**	**1.7**	**1.9**
Spring	0.052	0.044	**1.5**	**2.6**	**1.1**	0.043	0.016	**11**	**12.1**	**1.1**
Summer	0.796	0.979	12.3	12.3	0	0.315	0.358	5.3	5.9	-0.6
Fall	0.436	0.529	5.9	6.3	0.4	0.007	0.005	**-6.8**	**-5**	**1.8**
January	0.000	0.001	**-10.1**	**-5.0**	**5.1**	0.000	0.000	**-9.4**	**-4.6**	**4.8**
February	0.579	0.668	-6.0	-5.4	0.6	0.579	0.740	-5.9	-5.5	-0.4
March	0.075	0.023	**-3.9**	**-1.9**	**2**	0.015	0.008	**-5.0**	**-2.7**	**2.3**
April	0.063	0.054	0.7	2.2	1.5	0.003	0.002	**-1.1**	**1.2**	**2.3**
May	0.684	0.878	7.5	7.4	-0.1	0.165	0.110	5.4	6.5	1.1
June	0.631	0.546	10.3	9.9	-0.4	0.393	0.405	8.7	9.2	0.5
July	0.739	0.723	13.3	13.5	0.2	0.015	0.012	**12.0**	**13.4**	**1.4**
August	0.631	0.771	13.1	13.3	0.2	0.123	0.070	12.2	13.4	1.2
September	0.912	0.986	8.9	8.9	0	0.853	0.809	8.5	8.8	0.3
October	0.218	0.230	3.0	3.7	0.7	0.105	0.157	2.2	3.1	0.9
November	0.105	0.081	-4.2	-2.6	1.6	0.029	0.032	**-4.3**	**-2.5**	**1.8**
December	1.000	0.870	-8.4	-8.2	0.2	0.912	0.980	-7.6	-7.6	0

Table ST3: Changes daily minimum temperature for annual, seasonal and monthly periods [Comparison C1]. Highlighted bold numbers are significant at 95% confidence level.

Seasons	AGRB					PGRB				
	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)
Annual	0.190	0.081	-4.5	-4.0	0.5	0.000	0.001	**-4.9**	**-3.8**	**1.1**
Winter	0.971	0.671	-12.3	-12	0.3	0.853	0.673	-11.2	-10.9	0.3
Spring	0.089	0.077	-5.7	-4.9	0.8	0.001	0.001	**-7.0**	**-5.5**	**1.5**
Summer	0.043	0.023	**4.5**	**5.2**	**0.7**	0.000	0.000	**3.7**	**5.0**	**1.3**
Fall	0.247	0.384	-1.1	-0.7	0.4	0.009	0.008	**-2.0**	**-0.6**	**1.4**
January	0.007	0.012	**-15.0**	**-11.4**	**3.6**	0.001	0.003	**-13.3**	**-9.8**	**3.5**
February	0.796	0.517	-12.1	-13.1	-1	0.739	0.382	-11.5	-12.8	-1.3
March	0.684	0.490	-9.8	-9.2	0.6	0.089	0.067	-10.8	-9.3	1.5
April	0.029	0.018	**-6.9**	**-5.3**	**1.6**	0.015	0.008	**-7.9**	**-6.2**	**1.7**
May	1.000	0.699	-0.5	-0.3	0.2	0.004	0.004	**-2.4**	**-1.0**	**1.4**
June	0.853	0.734	2.9	3.1	0.2	0.739	0.516	1.9	2.2	0.3
July	0.043	0.023	**5.4**	**6.4**	**1**	0.000	0.000	**4.3**	**6.2**	**1.9**
August	0.019	0.020	**5.1**	**6.1**	**1**	0.000	0.000	**4.8**	**6.6**	**1.8**
September	0.280	0.169	0.7	1.6	0.9	0.190	0.182	0.8	1.6	0.8
October	0.853	0.937	-2.9	-2.9	0	0.004	0.004	**-4.7**	**-2.8**	**1.9**
November	0.631	0.807	-9.2	-9.4	-0.2	0.739	0.985	-8.5	-8.5	0
December	0.280	0.393	-12.7	-13.9	-1.2	0.190	0.251	-11.4	-12.7	-1.3

Table ST4: Changes daily mean temperature in annual, seasonal and monthly periods [Comparison C1]. Highlighted bold numbers are significant at 95% confidence level.

Seasons	AGRB					PGRB				
	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)	p-value Wilcox test	p-value t-test	Past (ºC)	Present (ºC)	Difference (ºC)
Annual	0.105	0.089	-1.1	-0.6	0.5	0.001	0.001	**-1.6**	**-0.6**	**1**
Winter	0.481	0.336	-9.7	-9	0.7	0.529	0.342	-8.9	-8.4	0.5
Spring	0.165	0.119	-2	-1.2	0.8	0.003	0.003	**-3.4**	**-2**	**1.4**
Summer	0.393	0.392	8.7	9	0.3	0.003	0.002	**7.6**	**8.7**	**1.1**
Fall	0.529	0.799	2.4	2.6	0.2	0.28	0.23	1.7	2.4	0.7
January	0.004	0.006	**-12.5**	**-8.6**	**3.9**	0.000	0.001	**-11.3**	**-7.6**	**3.7**
February	0.912	0.704	-9.1	-9.7	-0.6	0.796	0.537	-8.7	-9.6	-0.9
March	0.353	0.234	-6.8	-5.8	1	0.075	0.058	-7.9	-6.3	1.6
April	0.063	0.054	-2.9	-1.6	1.3	0.007	0.007	**-4.3**	**-2.6**	**1.7**
May	0.579	0.943	3.8	3.8	0	0.105	0.044	**1.8**	**3.0**	**1.2**
June	0.912	0.754	7.0	6.8	-0.2	0.436	0.507	5.7	6.0	0.3
July	0.190	0.214	9.7	10.3	0.6	0.002	0.001	**8.4**	**10.1**	**1.7**
August	0.631	0.373	9.3	9.8	0.5	0.019	0.010	**8.6**	**10.1**	**1.5**
September	0.739	0.727	4.8	5.1	0.3	0.631	0.727	4.7	5.0	0.3
October	0.853	0.991	0.1	0.1	0	0.052	0.089	-1.2	-0.2	1
November	0.853	0.870	-6.5	-6.4	0.1	0.971	0.632	-6.2	-5.8	0.4
December	0.436	0.499	-10.4	-11.2	-0.8	0.247	0.285	-9.4	-10.5	-1.1

Table ST5: Results of Student's t-test for changes in annual mean values of water fluxes. Highlighted bold numbers are significant at the 95% confidence level. The comparisons are defined in Table 1.

Comparisons	Fluxes	AGRB				PGRB			
		p-value t-test	Mean 1 (mm)	Mean 2 (mm)	Difference (mm)	p-value t-test	Mean 1 (mm)	Mean 2 (mm)	Difference (mm)
C1	Snowfall	0.443	911	866	-45	0.121	1135	919	-216
	Rainfall	0.001	**175**	**262**	**87**	0.304	310	362	52
	Snowmelt	0.223	687	723	36	0.309	1105	974	-131
	Firnmelt	0.652	275	307	32	0.806	163	146	-17
	Icemelt	0.537	532	501	-31	0.000	**265**	**667**	**402**
	Runoff	0.578	1320	1365	45	0.005	**1581**	**1888**	**307**
C2	Snowfall	0.892	911	901	-10	0.591	1135	1060	-75
	Rainfall	0.983	175	175	0	0.923	310	313	3
	Snowmelt	0.432	687	661	-26	0.683	1105	1056	-49
	Firnmelt	0.930	275	267	-8	0.095	163	39	-124
	Icemelt	0.245	532	470	-62	0.225	265	364	99
	Runoff	0.279	1320	1236	-84	0.499	1581	1524	-57
C3	Snowfall	0.546	911	876	-35	0.292	1135	986	-149
	Rainfall	0.001	**175**	**262**	**87**	0.326	310	360	50
	Snowmelt	0.827	687	669	-18	0.613	1105	1041	-64
	Firnmelt	0.587	275	314	39	0.015	**163**	**414**	**251**
	Icemelt	0.460	532	571	39	0.003	**265**	**537**	**272**
	Runoff	0.125	1320	1452	132	0.000	**1581**	**2069**	**488**
C4	Snowfall	0.545	901	866	-35	0.287	1060	919	-141
	Rainfall	0.001	**175**	**262**	**87**	0.340	313	362	49
	Snowmelt	0.035	**661**	**723**	**62**	0.527	1056	974	-82
	Firnmelt	0.581	267	307	40	0.008	**39**	**146**	**107**
	Icemelt	0.454	470	501	31	0.006	**364**	**667**	**303**
	Runoff	0.101	1236	1365	129	0.001	**1524**	**1888**	**364**
C5	Snowfall	0.785	876	866	-10	0.606	986	919	-67
	Rainfall	0.986	262	262	0	0.974	360	362	2
	Snowmelt	0.504	669	723	54	0.621	1041	974	-67
	Firnmelt	0.908	314	307	-7	0.003	**414**	**146**	**-268**
	Icemelt	0.111	571	501	-70	0.192	537	667	130
	Runoff	0.295	1452	1365	-87	0.124	2069	1888	-181

Table ST6: Results of paired Student's t-test and Wilcox test for changes in monthly values of water fluxes. Highlighted bold numbers are significant at the 95% confidence level. The comparisons are defined in Table 1.

Comparisons	Fluxes	AGRB		PGRB	
		p-value t-test	p-value Wilcox test	p-value t-test	p-value Wilcox test
C1	Snowfall	0.424	0.986	**0.028**	**0.018**
	Rainfall	**0.000**	**0.000**	0.141	0.000
	Snowmelt	0.525	0.109	0.303	0.922
	Firnmelt	0.540	0.181	0.741	0.552
	Icemelt	0.437	0.859	**0.000**	**0.000**
	Runoff	0.500	0.059	**0.000**	**0.000**
C2	Snowfall	**0.000**	**0.000**	**0.000**	**0.000**
	Rainfall	**0.003**	**0.000**	0.100	**0.000**
	Snowmelt	**0.000**	**0.000**	**0.028**	0.262
	Firnmelt	**0.029**	**0.027**	**0.001**	**0.000**
	Icemelt	**0.000**	**0.000**	**0.000**	**0.000**
	Runoff	**0.000**	**0.000**	**0.023**	0.057
C3	Snowfall	0.538	0.839	0.138	0.113
	Rainfall	**0.000**	**0.000**	0.162	**0.001**
	Snowmelt	0.312	0.097	0.604	0.897
	Firnmelt	0.460	0.125	**0.003**	**0.002**
	Icemelt	0.336	0.072	**0.000**	**0.000**
	Runoff	0.061	**0.003**	**0.000**	**0.000**
C4	Snowfall	0.531	0.851	0.135	0.113
	Rainfall	**0.000**	**0.000**	0.170	**0.001**
	Snowmelt	0.265	**0.013**	0.496	0.613
	Firnmelt	0.453	0.160	**0.002**	**0.000**
	Icemelt	0.346	0.078	**0.000**	**0.000**
	Runoff	**0.048**	**0.004**	**0.000**	**0.000**
C5	Snowfall	**0.000**	**0.000**	**0.000**	**0.000**
	Rainfall	0.234	**0.000**	0.511	**0.000**
	Snowmelt	**0.000**	**0.003**	**0.006**	0.288
	Firnmelt	**0.035**	0.062	**0.000**	**0.000**
	Icemelt	**0.000**	**0.000**	**0.000**	**0.000**
	Runoff	**0.000**	**0.000**	**0.000**	**0.018**

Table ST7: Results of Student's t-test and Wilcox test for changes in glacier mass balances. Highlighted bold numbers are significant at 95% confidence level. The comparisons were made as per the Scenarios defined in Table 1.

Comparisons	Mass Balance	AGRB					PGRB				
		p-value Wilcox test	p-value t-test	Mean 1 (mm)	Mean 2 (mm)	Difference (mm)	p-value Wilcox test	p-value t-test	Mean 1 (mm)	Mean 2 (mm)	Difference (mm)
C1	**Winter**	0.029	0.019	**474**	**417**	**-57**	0.007	0.009	**586**	**324**	**-262**
	Summer	0.796	0.740	-1176	-1133	43	0.123	0.149	-857	-1056	-199
	Annual	0.579	0.910	-701	-716	-15	0.029	0.019	**-271**	**-733**	**-462**
C2	**Winter**	0.280	0.233	474	447	-27	0.043	0.059	586	401	-185
	Summer	0.247	0.522	-1176	-1083	93	0.123	0.249	-857	-709	148
	Annual	0.315	0.663	-701	-636	65	0.739	0.830	-271	-308	-37
C3	**Winter**	0.353	0.219	474	444	-30	0.315	0.278	586	474	-112
	Summer	0.481	0.686	-1176	-1229	-53	0.011	0.010	**-857**	**-1306**	**-449**
	Annual	0.529	0.534	-701	-785	-84	0.023	0.016	**-271**	**-832**	**-561**
C4	**Winter**	0.247	0.180	447	417	-30	0.315	0.266	401	324	-77
	Summer	0.481	0.683	-1083	-1133	-50	0.007	0.008	**-709**	**-1056**	**-347**
	Annual	0.529	0.519	-636	-716	-80	0.023	0.014	**-308**	**-733**	**-425**
C5	**Winter**	0.218	0.245	444	417	-27	0.089	0.075	474	324	-150
	Summer	0.218	0.374	-1229	-1133	96	0.105	0.114	-1306	-1056	250
	Annual	0.436	0.506	-785	-716	69	0.481	0.625	-832	-733	99