Response to referees' comments on "Diagnosis of future changes in hydrology for a Canadian Rocky Mountain headwater basin" by Xing Fang and John W. Pomeroy

<u>1. Point to point response to review:</u>

Response to referee #1's comments:

<u>General comments</u>

The manuscript presents a climate change study for a small Canadian Rocky Mountain headwater basin. As process understanding has to be developed at the local scale, such regional/local studies are of a high value. The study is presented in a concise way and contributes well to current discussions. Small changes could improve the readability of the paper (see detailed comments).

However, I would strongly recommend to add a discussion on the uncertainty of the hydrological modelling results. The results chapter is full of numbers, partly with a high number of positions after the decimal point suggesting a high accuracy. Depending on the model design and the catchment characteristics, some results of hydrological modelling are more reliable than others. If, e.g., a model does not represent hydrophobic effects and if they play an important role in a catchment, then the model may simulate overall runoff with a satisfying efficiency but the calculated portion of Hortonian overland flow calculated by the model will be less reliable in this case. Thus, for readers not familiar with CRHM, a discussion on the strengths and especially weaknesses of the model concepts and the resulting reliability of the model results would be very valuable.

Response to general comments: Thanks to referee #1 for general comments about the manuscript. We added a discussion on the strengths and weakness of model in Discussion section. We also revised the manuscript to improve its structure, readability and flow.

The comments in detail:

<u>Detailed comment 1:</u> The paper contains numerous abbreviations (WRF, MCRB, CRHM, CTRL, PGW, QDM, WY,…). A list of abbreviations would improve the readability.

Response 1: Yes, we added an appendix to include a list of abbreviations to improve the readability.

<u>Detailed comment 2:</u> In the entire paper: please do not use "alpine" and "treeline" as single words, but always in combination with ecozone: "alpine ecozone", "treeline ecozone". This would improve the grammatical correctness of the sentences and the readability.

Response 2: Yes, we added ecozone after "alpine" and "treeline" in the revised manuscript.

Detailed comment 3: I am no native speaker, but to my feeling sometimes articles are missing, e.g.

Page 2, line 18: of the world,

Page 2, line 23: two of the most

Page 3, line 29: in the eastern slopes

Page 5, line 5/6: the complex mountain terrain

Page 9, line 23: had a very comparable … value (or had … values)

Page 11, line 28: the entire basin

Page 13, line 16: by a combination

Page 14, line 15: a large elevational gradient

Page 14, line 18: these changes were result of the interaction

Response 3: Yes, we added these missing articles in the revised manuscript.

Detailed comment 4: Page 3, line 19 and page 4, line 20: A model does not permit convective precipitation processes (they are permitted by the atmospheric conditions), but it permits the representation/simulation/consideration of convective precipitation processes. Please adapt the formulation.

Response 4: Yes, we adapted the formulation suggested by the referee.

Detailed comment 5: Page 3, line 20/21: I would delete "to combine …. from CRHM to" as this is also said by "using a dynamically… model" (line 23-24).

Response 5: Yes, we removed the redundant words and rewrote the objectives as: "The objectives of this paper are to use CRHM driven by WRF to: (1) evaluate the ability to simulate snowpack and streamflow regimes in a Canadian Rockies headwater basin without calibration; (2) diagnose the detailed changes in hydrology due to impending climate change for this headwater basin. By relying on physically based, uncalibrated simulations and dynamical downscaling, it is hoped that the approach introduces a highly robust method for evaluating the impacts of climate change on mountain hydrology."

Detailed comment 6: Page 5, line 29: I would include a citation (e.g. Pomeroy et al., 2007) at the first appearance of the model.

Response 6: Yes, we added Pomeroy et al., 2007 at the first appearance of the model.

Detailed comment 7: Page 6, line 1: Please explain dynamic networks of HRUs (in the models I have worked with, HRUs are defined for a catchment and remain the same during the whole simulation).

Response 7: Yes, HRUs in this model also remain the same throughout the whole simulation, so we deleted "dynamic networks of" to be clearer and reduce confusion.

Detailed comment 8: Page 6, line 12: please give some short information on the June 2013 flood.

Response 8: Yes, we added some brief information for the June 2013 flood: "…the updated model was evaluated in the June 2013 flood when approximately 250 mm precipitation fell at MCRB during 17-24 June 2013 (Fang and Pomeroy, 2016; Pomeroy et al., 2016).".

Detailed comment 9: Page 6, line 26 to 28: Most of the content of this sentence is repeated in the next sentence, please streamline this text.

Response 9: Yes, we combined two sentences to improve the readability and rewrote it as: "Near-surface hourly air temperature, relative humidity, wind speed, precipitation, and shortwave irradiance from observations, uncorrected WRF CTRL outputs, and bias corrected WRF CTRL outputs were compared for the Centennial Ridge, Fisera Ridge, Vista View, Upper Clearing and Upper Forest stations in MCRB, and the comparisons are shown in the quantile-quantile (Q-Q) plots (Fig. 3).".

Detailed comment 10: Page 6/7, line 31/1: "do not appear to be linear distribution" does not sound to be formulated correctly (linearly distributed).

Response 10: Yes, we changed it to "…do not appear to be linearly distributed.".

Detailed comment 11: Page 7: line 6/7: I would suggest to shorten the sentence, for example in this way: "… for the uncorrected WRF outputs, with two exceptions: Values of RMSD…"

Response 11: Yes, we shortened the sentence as suggested by the referee.

Detailed comment 12: Page 8, line 22: unit is missing: 112 mm

Response 12: Yes, we added the missing unit.

Detailed comment 13: Page 8, line 26/27: "Sublimation is the total of blowing snow, surface snowpack and forest canopy interception sublimation." This sentence is either grammatically circular (sublimation is sublimation) or – if the last word does not belong to "blowing snow" - physically incorrect as the blowing of snow means a reduction of snow at the windward site, but by snow transport, not by sublimation in its physical sense.

Response 13: Yes, we changed the wording to make more grammatically sound: "Sublimation is the total flux of snow sublimated from surface snowpack and during blowing snow and forest canopy interception processes…".

Detailed comment 14: Page 9/10, line 31-32/1 and page 14, line 21: Regarding the uncertainty associated with hydrological modelling in general and climate projections, I would recommend to give only one position after the decimal point. Doing so means that you partly loose the differences between the CTRL and PGW values – but that means that they seem to be smaller than the uncertainty.

Response 14: Yes, we accepted the suggestion and made changes.

"…melt rate was slightly higher for alpine ecozone (i.e. from 1.9 mm day-1 in CTRL to 2.0 mm day-1 in PGW) and remained unchanged for forests ecozones (i.e. 0.6 mm day-1 at upper forest and 0.5 mm day-1 at lower forest in both CTRL and PGW).".

"…snowmelt rates declined by 1.1 mm day-1 for treeline ecozones and by 0.9 to 1.6 mm day-1 for forest clearings ecozones, but increased by 0.1 mm day-1 for alpine ecozone,…"

Detailed comment 15: Page 10, line 23-25: Please explain why the centre of flow volume shifts to an earlier period in PGW, but the peak basin discharge remains unchanged.

Response 15: The centre of flow volume measures the 50% of water year flow volume; its shifting to an earlier period in PGW is caused by a combination of earlier snowpack deletion and snowmelt runoff occurrence in springtime and higher evapotranspiration and consequently lower flow in summertime in PGW. For the peak basin discharge, its timing remains unchanged in PGW, while it is at lower value in PGW. The peak basin discharge is balanced by runoff in all ecozones and is primarily influenced by alpine and treeline ecozones at MCRB. While there is no change in peak runoff date for alpine, forest circular clearing north-facing ecozones, peak runoff occurs four days earlier in treeline ecozone but delays by one day to 9 days in other ecozones. This is a complex streamflow generation system with interplay of hydrological fluxes and states from many processes, and in this case, the changes in peak runoff date in all ecozones happens to result in no change in peak basin discharge date.

Detailed comment 16: Page 10, line 32: Please consistently use two positions after the decimal point for the discharge values.

Response 16: Yes, for consistency, we used two positions after the decimal point for the discharge values.

Detailed comment 17: Page 11, line 26 and page 11, line 28: "close" instead of "closed"

Response 17: Yes, we changed to "close to".

Detailed comment 18: Page 12, line 3: "September" instead of "Septmeber"

Response 18: Yes, we used the corrected word "September".

Detailed comment 19: Page 12, line 28: sublimation losses from blowing snow –> see comment above

Response 19: Yes, we changed wording to "…even though sublimation losses from blowing snow in the alpine ecozone and intercepted snow in the forested ecozones also decreased." to improve clarity.

Detailed comment 20: Figure 2c: Can you please explain the relative humidity values up to 300%?

Response 20: Yes, the values of RH up to 300% are the converted values based on uncorrected WRF air temperature, specific humidity, and specific pressure outputs, and we showed the values of RH up to 300% to indicate the errors in these uncorrected WRF outputs. We added some clarification for the values of RH up to 300% in the Section 3.1 of revised manuscript.

Detailed comment 21: Figure 2e/g: The dotted line for "best linear fit" is misunderstanding. It is just the best linear fit for the lower values. For the whole data set, a best linear fit would look different. I would delete this line.

Response 21: Yes, we deleted the "best linear fit" line in all plots.

Detailed comment 22: Figure 4: I would recommend to show the simulation line in light blue instead of dark blue to get a stronger contrast to the black observation line.

Response 22: Yes, we changed the simulation line to light blue for better contrast.

Detailed comment 23: Figure 11 and 12: The differences between the ecozones would appear clearer if you would use a uniform scaling of the y-axis.

Response 23: We tried to have a uniform scaling of the y-axis for both Figs. 11 and 12, but the figures turned out showing the differences among the ecozones, but they are not great to show the differences between CTRL and PGW for some ecozones, particularly when their values are small, e.g. Fig. 11c, d, g, and Fig. 12c, d, e, f, g. We included the changed figures with the uniform scaling of the y-axis below, so we think the original Figs 11 and 12 are probably better ones and will keep the original ones.

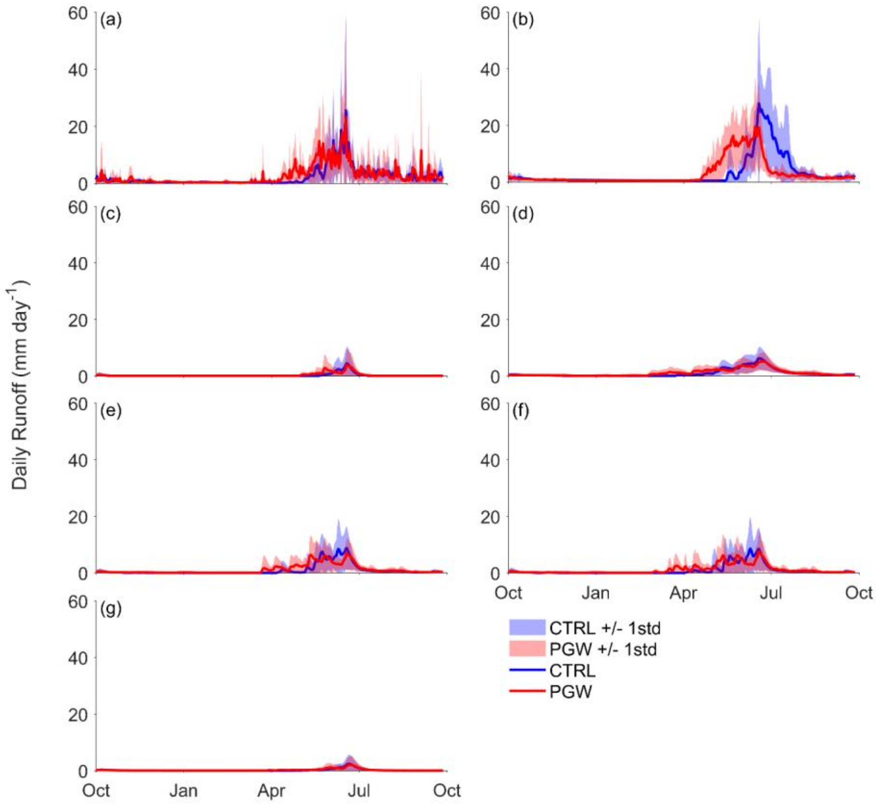

Figure 11. Simulated annual mean daily runoff for WRF CTRL and PGW. (a) Alpine, (b) treeline, (c) upper forest, (d) forest clearing blocks, (e) forest circular clearing north-facing, (f) forest circular clearing south-facing, and (g) lower forest ecozones. Line represents the annual mean and the shadow represents the standard deviation of the eight-water year runoff.

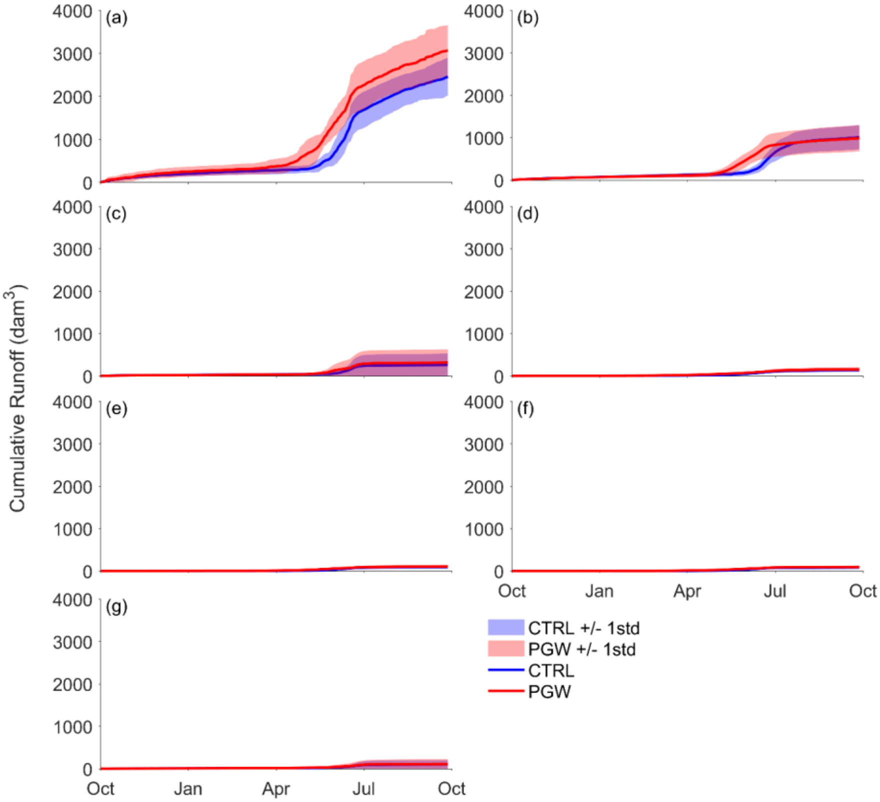

Figure 12. Simulated annual mean cumulative runoff for WRF CTRL and PGW. (a) Alpine, (b) treeline, (c) upper forest, (d) forest clearing blocks, (e) forest circular clearing north-facing, (f) forest circular clearing south-facing, and (g) lower forest ecozones. Line represents the annual mean and the shadow represents the standard deviation of the eight-water year runoff.

Response to referee #2's comments:

General comments

I do mostly agree with referee #1. The paper is a very valuable contribution to the understanding of climate change effects on the hydrology of small high mountain catchments. Its strength are the modelling tools that were used to provide a physically and process based analysis, and the clear and well-structured text of the paper. Very well done. Likewise, I am no native speaker, but there is an issue with the use of articles all through the text. See my supplement. I would also suggest to always add "ecozone" after its name. Other things that would improve the overall value of the paper:

- a brief explanation of how the ecozones were derived

- some more words about the generation of the PGW simulation (particularly extending "The climate perturbation was derived from 19-model ensemble mean change from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) under a "business as usual" forcing scenario: representative concentration pathway 8.5 (RCP8.5; van Vuuren et al., 2011).")

- a map of the HRUs

Everything else: see supplementary comments.

Congratulations, a very nice paper, very interesting, and fun to read. Good work!

Response to general comments: Thanks to referee #2 for general comments about the manuscript. We added a brief explanation of the ecozones generation along with a map of the HRUs, because they are connected: ecozone were derived from the same landcover type of the HRUs. We also added a few more words for PGW simulation. Last, we added some missing articles as suggested in the detailed supplementary comments, and we also added "ecozone" after its name. We also revised the manuscript to improve its structure, readability and flow.

Supplementary comments

Supplementary comment 1:

Page 1

- 6: skip comma

- 9: „Rocky Mountains"

- 16: „during a current period (…) and a future period (…)"

- 17: what does „PGW" stand for (comes on page 3)?

- 22: „as well as a shorter snow season“: repetition; „in the alpine“

Response 1: We keep the comma for readability although the comma can be skipped. The sentence would be quite long when skipping comma.
Yes, we changed to use "…Canadian Rockies".
Yes, we added the missing articles "a".
Yes, we used "…a current period (2005-2013) and a future pseudo global warming period (PGW, 2091-2099)" to replace "…current period (CTRL, 2005-2013) and future period (PGW, 2091-2099). Also, an appendix for abbrevations is added, which is suggested by the referee #1.
We rephrased to "The alpine snow season will be shortened by almost one and half month, but at some lower elevations there will be large decreases in peak snowpack (~45%) in addition to a shorter snow season."; this is to convey the message "besides a shorter snow season, large decreases in peak snowpack occurred at some lower elevations".

<u>Supplementary comment 2:</u>

Page 3

- 3: „Empirical snow modelling methods … have great difficulty“: reformulate, because it is not the method having a difficulty but we ourselves in interpreting its results with respect to a certain research question

Response 2: Yes, we rephrased to "Empirical snowmelt modelling methods that use temperature-index techniques are inappropriate in cold mountain regions…".

<u>Supplementary comment 3:</u>

Page 4

- 32: correct „gird“ to „grid“

Response 3: Yes, we made correction.

<u>Supplementary comment 4:</u>

Page 5

- 9: „**the** systematic bias“

- 19: „to force **the** hydrological simulations“

Response 4: Yes, we made the changes as suggested.

<u>Supplementary comment 5:</u>

Page 6

- 15: „for **the** current period"

- 16: „for **the** future period"

- 17 and 18: „in **the** CTRL period"

- 20: „calculated by **the** equations"

Response 5: Yes, we made the changes as suggested.

Supplementary comment 6:

Page 7

- 1: better „linearly distributed" than „linear distribution"

- 16/17: „the simulation had large differences with the observations": find better formulation

- 29: „suggesting that **the** model had some"

Response 6: Yes, we made the changes as suggested.

Supplementary comment 7:

Page 8

- 22: „112 **mm"**

- 30: „**the** entire basin"

- in general: always add „**ecozone**" to its name (everywhere)

Response 7: Yes, we made the changes as suggested.

Supplementary comment 8:

Page 10

- 10: „for **the** basin"

- 27: explain „**dam3**"

- 32: delete „Whilst", or connect sentence with previous one („… in May, whilst monthly …")

Response 8: Yes, we added the missing article "the".
dam3 stands for cubic decametre, equal to 1000m3. It is one of the SI units, and according to journal's

house standards, units do not need to be defined in text.
Yes, we changed it to "…in May. In contrast, monthly…".

Supplementary comment 9:

Page 11:

- 1: „and had **a** very similar low value"

- 7: „onset of **the** spring freshet"

- 9: delete „While", or connect sentence with previous one („… (Fig. 11a), while the largest …")

- 11: „ranging **from** 0.3 mm"

- 13: „from **the** forest clearing"

- 19: „and **the** entire basin"

Response 9: Yes, we made the changes as suggested.

Supplementary comment 10:

Page 12

- 11: „these … simulations **require**" (not „requires", it is plural)

- 9-13: evtl. add Warscher et al. 2019, same (and very recent) discussion

- 18: „in **the** Rocky Mountain**s** region" … and probably better skip „in this region"

- 19: „**One** study suggests …"

- 20: „while other**s** reported"

- 23: „gradient**s**"

- 27: „in **the** PGW period"

- 30: you may even add „for other sites with different climates"

- 31: „of **the** snowcover"

Response 10: Yes, we made the changes as suggested and added Warscher et al. 2019 to the discussion.

Supplementary comment 11:

Page 13

- 5: „in **the** PGW period"

- 12: „for **the** upper forest ecozone"

- 31/32: evtl. add Strasser et al. 2019

Response 11: Yes, we made the changes as suggested and added Strasser et al. 2019 to the discussion.

Supplementary comment 12:

Page 14

- 2: „for **a** more comprehensive"

- 15: „large elevational gradient**s**" or „**a** large elevational gradient"

Response 12: Yes, we made the changes as suggested.

Supplementary comment 13:

Fig 1

- „Hydrometeorological Stations" should be „Hydrometeorological Station" (Singular)

- „WRF Grid" should be „WRF Grid centroid", and the latter should be explained in the caption. The „and" before it should be removed

Response 13: Yes, we made the changes as suggested.

Supplementary comment 14:

Fig. 2

- caption: „… that **the** best linear fit is **a** straight line …"

Response 14: In the new Fig. 3, we removed the best linear fit as suggested by the referee #1.

Supplementary comment 15:

Fig. 3

- caption: Comparison without **-s** (better singular). Add what belongs to where in the caption.

Response 15: Yes, we changed it to "Comparison of the…".

Supplementary comment 16:

Fig. 5

- caption: „Note that **the** total water year precipitation is presented **here,** and **the** average water year value is presented for **the** other variables.“

Response 16: We made change: "…Note that the accumulation over the water year is used for precipitation, and the average value over the water year is presented for the other variables.".

Supplementary comment 17:

Fig. 6

- caption: „… (FCCSF) **and** lower forest …“

Response 17: Yes, we made the change as suggested.

Supplementary comment 18:

Fig. 7

- caption: better „mean annual“; „**The** line …“

Response 18: Yes, we made the change as suggested.

Supplementary comment 19:

Fig. 9

- caption: „**The** line …“

Response 19: Yes, we made the change as suggested.

Supplementary comment 20:

Fig. 10

- caption: „for **the** eight- water year **period** between …“

Response 20: Yes, we made the change as suggested. Now "Figure 11. Change between WRF CTRL and PGW periods in the simulated mean Marmot Creek monthly streamflow discharges during March to October for the eight-water years."

Supplementary comment 21:

Fig. 11

- caption: „The line …“

Response 21: Yes, we made the change as suggested.

Supplementary comment 22:

Fig. 12

- caption: „The line …“

Response 22: Yes, we made the change as suggested.

Supplementary comment 23:

Fig. 13

- caption: „**Mean rainfall ration and runoff** … ecozones and **the entire** Marmot Creek basin“

Response 23: Yes, we made the change as suggested.

Supplementary comment 24:

Table 4

- caption: better „mean daily“

Response 24: The evaluation is for the time-series of daily mean streamflow value (i.e. daily discharge) from the simulation. We think daily mean is better one to use.

2. A list of relevant changes made in the manuscript:

The following lists the relevant changes in addition to changes made based on reviewers' comments and suggestions.

- Slight change in title to "**Diagnosis of future changes in hydrology for a Canadian Rockies headwater basin**"
- Moved brief introduction of CRHM to **1. Introduction** section from **2.3 Hydrological model and simulations** section. This is to introduce CRHM to readers early on, rather than in method section.
- Edited **4. Discussion** section to improve readability, flow and make arguments better.
- Revised figures in **Supplement**: deleted the "best linear fit" line in all quantile-quantile plots.
- Other edits in English throughout the revised manuscript to improve its readability.

The revised manuscript with marked-up changes is shown in the next.

Diagnosis of future changes in hydrology for a Canadian Rockies~~y~~ ~~Mountain~~ headwater basin

Xing Fang and John W. Pomeroy

[1]Centre for Hydrology, University of Saskatchewan, Saskatoon, S7N 1K2, Canada

Correspondence to: Xing Fang (xing.fang@usask.ca)

Abstract. Climate change is anticipated to ~~have~~ impact~~s on~~ the hydrology~~water resources~~ of the Saskatchewan River, which originates~~s~~ in the Canadian Rockies~~y Mountains~~ mountain range. To better understand the climate change impacts in the mountain headwaters of this basin, a physically based hydrological model was developed for this basin using the Cold Regions Hydrological Modelling platform (CRHM) for Marmot Creek Research Basin (~9.4 km^2), located in the Front Ranges of the Canadian Rockies~~y Mountains~~. Marmot Creek is composed of ecozones ranging from montane forests to alpine tundra and alpine exposed rock and includes both large and small clearcuts. The model included blowing and intercepted snow redistribution, sublimation, energy-balance snowmelt, slope and canopy effects on melt, Penman-Monteith evapotranspiration, infiltration to frozen and unfrozen soils, hillslope hydrology, streamflow routing and groundwater components and was parameterised without calibration from streamflow. Near-surface outputs from the 4-km Weather Research and Forecasting (WRF) model were bias~~-~~corrected using the quantile delta mapping method with respect to meteorological data from five stations located from low elevation montane forests to alpine ridgetops~~mountaintop~~ and running over~~during~~ October 2005-September 2013. The bias corrected WRF outputs during a current~~current~~ period (~~CTRL,~~ 2005-2013) and a future pseudo global warming~~future~~ period (PGW, 2091-2099) were used to drive model simulations to assess changes in Marmot Creek's hydrology. Under a "business as usual" forcing scenario: representative concentration pathway 8.5 (RCP8.5) in PGW, the basin will warm~~s~~ up by 4.7 °C and receive~~s~~ 16% more precipitation, which will lead~~s~~ to a 40 mm decline in seasonal peak snowpack, 84 mm decrease in snowmelt volume, 0.2 mm day^{-1} slower melt rate, and 49 days shorter snowcover duration. The alpine snow season will be shortened by almost one and half month, but at some lower elevations there will be~~are~~ large decreases in peak snowpack (~45%) in addition to~~as well as~~ a shorter snow season. Declines in the ~~Losses of~~ peak snowpack will be much greater in clearcuts than under mature forest canopies. In alpine and treeline ecozones, blowing snow transport and sublimation will be suppressed by higher threshold wind speeds for transport, in forest ecozones~~canopies,~~ sublimation losses from intercepted snow will decrease due to faster unloading and drip, and throughout the basin~~for all ecozones~~, evapotranspiration will increase due to a longer snow-free season~~s~~ and more rainfall. Runoff will begin earlier in all ecozones, but, as result of variability in surface and subsurface hydrology, forested and alpine ecozones will generate the greatest~~larger~~ runoff volumetric increases~~es~~, ranging from 12% to 25%, whereas the treeline ecozone will have~~has~~ a small (2%) decrease in runoff volume due to decreased melt volumes from smaller snowdrifts. The shift in timing in streamflow will be~~is~~ notable, with 236% higher flows in spring months and 12% lower flows in summer and 13% higher flows in early fall. Overall, Marmot

Creek’s basin annual streamflow discharge will increase by 18% with PGW, without a change in its streamflow generation efficiency, despite itsthe basin shifting from primarily snowmelt runoff towards rainfall-dominated runoff generation.

1 Introduction

The eastern slopes of the Canadian Rockiesy Mountains form the headwaters of the Saskatchewan River Basin (SRB) and are a vital source of water supply to downstream users in the three Prairie Provinces of Canada. These high mountain headwaters occupy onlyabout 12.6% of the SRB’s total drainage area but provide about 87% of streamflow, which is used downstream, for total water yield for domestic, agricultureal, communities and industrieyial users in the SRB (Redmond, 1964). Climate in this region has been experiencing changes since the last century (Whitfield, 2014; DeBeer et al., 2016). Western Canada has experienced Aa significant warming of 0.5 °C to 1.5 °C has occurred in from western Canada over the period 1900 to-1998, with the greatest increases found forin winter daily minimum temperatures (Zhang et al., 2000). The regional wWarming of has been exceeded in the eastern slopes of the Canadian Rockiesy Mountains is greater than the regional average, with mean temperatures increasing by 2.6 °C and winter minimum temperatures increasing by 3.6 °C at middle elevations in Marmot Creek Research Basin (MCRB) since the early 1960s (Harder et al., 2015). With the warming air temperatures, the rainfall ratio (ratio of rainfall to total precipitation) is increasing as the fraction of precipitation as snowfall declines (Lapp et al., 2005; Shook and Pomeroy, 2012). In mountains of western North America this leads to decreases in the seasonal snowpack (Mote et al., 2005; Brown and Robinson, 2011) and consequently earlier spring runoff (Stewart et al., 2004). In contrast to ubiquitous warming temperatures, trends in precipitation volume are mixed for Canadian Rockiesy Mountains, withas some studies showing increasing trends of about 14% in annual precipitation over the period 1948-2012 (Vincent et al., 2015) and other studies finding do neitherot find trends nor change (Valeo et al., 2007; Harder et al., 2015). With furtherthe anticipated climate change expected ins in the future climate for this region (IPCC, 2013), understanding the impacts of projected climate change on the hydrological cycle in mountain headwater basins is important for evidence-based future water management ofin the SRB in the future.

Winter snow accumulation provides the greatest source of streamflow runoff in many mountain regions of the world (Grant and Kahan, 1974; Serreze et al., 1999), as snowmelt is the most important annual hydrological event (Gray and Male, 1981). Melt from the seasonal snowpack is the main contributor toof streamflow in the eastern slopes of the Canadian Rockiesy Mountains (Kienzle et al., 2012; Pomeroy et al., 2012; Fang et al., 2013). Streamflow generation in mountain regions is highly variable and is controlled by many biophysical and hydrometeorological factors (Hunsaker et al., 2012; Zhang and Wei, 2014). Elevation affects both air temperature and precipitation; two of the most important drivers of snowpack variability in mountains (Lundquist and Cayan, 2007; Marks et al., 2013). Topographic features, such as slope/aspect and ecosystem features such as forest structure are other important factors contributing to the heterogeneity of radiation, atmospheric energy and wind flow in mountain environments (Föhn and Meister, 1983; Bernhardt et al., 2009; Marsh et al., 2012; Musselman and Pomeroy, 2017; MacDonald et al., 2018), and result in the high spatial variability of snow accumulation, melt patterns, evapotranspiration, and runoff in complex mountain terrain (Pomeroy et al., 20045; MacDonald et al., 2010; Ellis et al., 2013; Revuelto et al., 2014; Knowles et al., 2015; DeBeer and Pomeroy, 2017).

Many studies have examined the impacts of climate change on snow accumulation, redistribution, snowmelt, evapotranspiration, soil moisture storage, and streamflow in mountain drainage basinsalpine watersheds through the simulations of hydrological models driven by future climate scenarios generated by downscaling of climate model outputs or perturbations of current meteorological observations (Kienzle et al., 2012; López-Moreno et al., 2014; Rasouli et al., 2015; Jepsen et al., 2016; Weber et al., 2016; Meißl et al., 2017). Physically based hydrological models are effective ways to analyse the hydrological response to climate change, as they can capture the complex hydrological processes governing streamflow generation and can be extrapolated beyond the hydrometeorological conditions under which they were developed for mountain watersheds. Empirical snowmelt modelling methods that use temperature-index techniques for temperate zone arehave great difficulty inappropriate in cold mountain regions (Swanson, 1998) and generally do not perform well because of their lack of physical basis, need for calibration from sparse snowmelt observations, and neglect of sublimation contributions to ablation (Walter et al., 2005; Pomeroy et al., 2005; 2013). The Cold Regions Hydrological Modelling platform (CRHM; Pomeroy et al., 2007; 2016) offers a full suite of streamflow generation processes that commonly operate in the for Canadian Rockiesy Mountains, such as (i.e. wind redistribution of alpine snow, snow avalanching on steep alpine slopes, canopy snow and rain interception, sublimation, drip and unloading from forest canopies, infiltration to frozen and unfrozen soils, overland and detention flow, hillslope sub-surface water redistribution, and evapotranspiration from forests, clearings and alpine tundra). CRHM is an object-oriented, modular and flexible platform for assembling physically based hydrological models. With CRHM, the user constructs a purpose-built model from a selection of possible basin spatial configurations, spatial resolutions and physical process modules of varying degrees of physical complexity. Basin discretization is performed via hydrological response units (HRUs) whose number and nature are selected based on the variability of basin attributes and the level of physical complexity chosen for the model. The user, in light of hydrological understanding, parameter availability, basin complexity, meteorological data availability and the objective flux or state for prediction, selects physical complexity. A full description of CRHM is provided by Pomeroy et al. (2007). Physically based algorithms in CRHM have been developed from field process studies (Pomeroy et al., 2009; DeBeer and Pomeroy, 2010; Ellis et al., 2010; MacDonald et al., 2010; Harder and Pomeroy, 2013) and have been extensively evaluated using model falsification and multivariate evaluation in mountain headwater basins where models created using CRHM can be run successfully without calibration from streamflow (Fang et al., 2013; Pomeroy et al., 2013; Rasouli et al., 2015; Fang and Pomeroy, 2016; Pomeroy et al., 2016).

A recent application of the Weather Research and Forecasting (WRF) model provides 4 km simulation outputs for both current climate and a future climate scenario using dynamical downscaling from reanalysis data for large portions of western North America with perturbations from an ensemble of Regional Climate Model (RCM) projections called "pseudo global warming" (PGW) as discussed by Liu et al. (2017) and Li et al. (2019). This remarkably high resolution WRF application permits the representation of convective precipitation processes, resolves mountain topography and so can capture variations in near-surface meteorology due to mesoscale orography such as found in mountains. The objectives of this paper are to use CRHM driven by WRF to ~~combine the climate predictions from WRF with the hydrological predictions from CRHM to~~: (1) evaluate the ability to simulate snowpack and streamflow regimes in a Canadian Rockies~~y Mountain~~ headwater basin without calibration~~, using a dynamically downscaled atmospheric model (WRF) coupled to a physically based cold regions hydrology model (CRHM)~~; (2) diagnose the detailed changes in hydrology due to impending climate change for this headwater basin ~~using cold regions hydrology simulations driven by dynamically downscaled current and future climate outputs~~. By relying on physically based, uncalibrated simulations and dynamical downscaling, it is hoped that the approach introduces a highly robust method for evaluating the impacts of climate change on mountain hydrology.

2 Methods

2.1 Study site

The study was conducted in the Marmot Creek Research Basin (MCRB) (50.95°N, 115.15°W) in the Kananaskis Valley, Alberta, Canada, located in the eastern slopes of the Canadian Rockies (Fig. 1). MCRB is a small headwater basin (9.4 km^2) of the Kananaskis River which contributes to the Bow River ~~Basin~~and ultimately the Saskatchewan River Basin ~~and flows into the Kananaskis River~~. MCRB is composed of three upper sub-basins: Cabin Creek (2.35 km^2), Middle Creek (2.94 km^2), and Twin Creek (2.79 km^2), which converge into the ~~c~~Confluence ~~s~~Sub-basin above the main stream gauge (1.32 km^2). MCRB~~The basin~~ elevation ranges from 1590 m a.s.l. (above sea level) at the main gauged~~Marmot Creek~~ outlet to 2829 m at the summit of Mount Allan. Much~~ost~~ of MCRB is covered by needleleaf forest; Engelmann spruce (*Picea engelmanni*) and subalpine fir (*Abies lasiocarpa*) are dominant in the upper part of basin (1710 to 2277 m). The lower elevation (1590 to 2015 m) forests are mainly Engelmann spruce and lodgepole pine (*Pinus contorta* var. Latifolia) with aspen woodland near the basin outlet (Kirby and Ogilvy, 1969). Alpine larch (*Larix lyallii*) and short tundra shrubs, tree islands, dwarf trees and krummholz are found around the treeline at approximately 2016 to 2379 m. Exposed rock surfaces and talus predominate in the high alpine part of basin (1956 to 2829 m). Forest management experiments conducted in the 1970s and 1980s left large ~~clearcut~~clearcuts ~~blocks~~ (1838 to 2062 m) in the Cabin Creek sub-basin and numerous small circular clearings (1762 to 2209 m) in the Twin Creek sub-basin (Golding and Swanson, 1986). Physiographic descriptions of these ecozones are shown in Table 1. ~~These ecozones were derived from the same landcover types of HRUs at MCRB shown in Fig. 2, and generation of these HRUs is described by Fang et al. (2013). The s~~Surficial soils are poorly developed mountain soils consisting principally of glaciofluvial, surficial till and postglacial colluvium deposits (Beke, 1969). Relatively impermeable bedrock is found near the surface at the higher elevations and headwater areas, whilst the rest of basin is covered by a deep layer of coarse and permeable soil allowing for rapid rainfall infiltration to subsurface layers overlying relatively impermeable shale (Jeffrey, 1965). The ecozones defined by vegetation, soils, bedrock, slope, aspect and hydrography form the landcover types that contribute to defining the HRUs by which CRHM discretizes the basin, and are shown in Fig. 2. Fang et al. (2013) describe the generation of these HRUs in MCRB in detail.

Continental air masses control the weather in the region, which has long and cold winters and cool and wet springs with a late spring/early summer precipitation maximum that can fall as rainfall or snowfall. Westerly warm and dry Chinook (~~foehn~~föhn) winds lead to brief periods with air temperatures well above 0 °C during the winter months. Annual precipitation ranges from 600 mm at lower elevations to more than 1100 mm at the higher elevations, of which approximately 70 to 75% occurs as snowfall;~~- with~~ the percentage increasing with elevation (Storr, 1967). Mean monthly air temperatures range from 14 °C observed at 1850 m in July to -10 °C observed at 2450 m in January.

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2.2 WRF model

2.2.1 Model overview

The Weather Research and Forecasting (WRF) model Version 3.4.1 wa~~i~~s used in this modelling experiment~~paper~~. This version of WRF ~~permits the s~~simulates~~ion of~~ convective weather systems at sub-synoptic scales and deals with mesoscale orography at a 4 ~~-~~km horizontal grid spacing for large portions of North America. Two 13-year experiments were conducted, consisting of a control (CTRL) simulation and a pseudo global warming (PGW) simulation. The CTRL simulation is retrospective for 2000-2013 period with initial and boundary conditions from 6-hour 0.703° ERA-Interim reanalysis data (Dee et al., 2011). The PGW simulation is a 13-year (i.e. 2000-2013) simulation forced with the 6-hour ERA-Interim reanalysis data plus a climate perturbation. The climate perturbation was derived from 19-model ensemble mean change from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) under a "business as usual" forcing scenario: representative concentration pathway 8.5 (RCP8.5; van Vuuren et al., 2011). The PGW simulation is equivalent to a future climate scenario for the 2086-2099 period. The perturbation for the WRF PGW simulation using the 19-model ensemble mean can reduce uncertainties in climate projections from Global ~~c~~Climate ~~m~~Models (GCMs) due to~~because of~~ inter-GCM~~model~~ variability ~~among GCMs~~ (Li et al., 2019)~~ and The perturbation for the WRF PGW is different from monthly perturbed climate that is based on differences in monthly 30-year means between current and future climate in 11 RCM outputs described in Rasouli et al. (2019)~~. A detailed description of the WRF model setup is provided by Li et al. (2019). For MCRB, the 4 km hourly WRF outputs from both CTRL and PGW simulations were extracted f~~o~~rom the WRF g~~i~~rid shown in Fig. 1. The extracted variables include near-surface air temperature, vapour pressure, wind speed, precipitation, and shortwave irradiance; relative humidity is required by CRHM and was estimated with conversion equations using air temperature and vapour pressure (Tetens, 1930).

2.2.2 Bias correction

Although the 4 ~~-~~km WRF model allows direct use of microphysics and resolves mesoscale convection to~~, which~~ provide~~s~~ a considerable level of spatial detail, it still produced~~s~~ biases in the near-surface meteorology for MCRB. The biases were~~is~~ caused by the complex mountain terrain in MCRB and other factors. M~~, and m~~any of the topographic features such as alpine ridges, wind exposed and wind sheltered slopes, and valley bottoms influence the distribution of near-surface meteorological conditions at scales smaller than 4 km (Vionnet et al., 2015). To produce a more reliable driving meteorology dataset, ~~Thus,~~ the ~~extracted~~ 4-km WRF outputs were bias-corrected using the quantile delta mapping (QDM) algorithm against data from five meteorological stations in MCRB (Cannon et al., 2015). The QDM algorithm correct~~s~~s the systematic bias in quantiles of WRF outputs with respect to the observations and preserves model projected relative changes in quantiles. First, the QDM algorithm was used to ~~first~~ extract~~s~~ the climate change signal from projected future quantiles and then was used to detrend~~s~~ the series before reintroducing the trends in projected future quantiles. A transfer function that transform~~es~~d the cumulative distributions of the model outputs to match the cumulative distributions of observed data wa~~i~~s employed~~used~~ in the QDM algorithm to correct both historical and projected model outputs. More details of QDM are provided by Cannon et al. (2015). Observations of air temperature, relative humidity, wind speed, precipitation, and shortwave irradiance from the Centennial Ridge, Fisera Ridge, Vista View, Upper Clearing and Upper Forest hydrometeorological stations were used to correct WRF model outputs using~~in~~ the QDM algorithm. These stations are shown in Fig. 1 and are described in several publications (DeBeer and Pomeroy, 2010; Ellis et al., 2010; MacDonald et al., 2010; Pomeroy et al., 2012). This bias correction downscaled the WRF grid ~~with respect~~ to the locations of these stations to~~and~~ create~~d~~ a sub-grid WRF "virtual station" surface meteorology ~~at these stations that are treated as~~that was ~~virtual stations~~ used to force CRHM~~the hydrological~~ simulations. ~~For the WRF CTRL outputs, t~~The bias correction was performed for eight water years (i.e. 1 October to 30 September) from 2005 to 2013 that~~; this is the~~ had overlap ~~ofping period for~~ WRF CTRL outputs and MCRB observations ~~in MCRB~~. The WRF PGW outputs were similarly bias corrected by preserving the model projected relative changes in quantiles, resulting in eight water years of corrected WRF PGW outputs from 1 October 2091 to 30 September 2099. Statistical indexes used to assess WRF CTRL outputs included~~were~~ the root mean square difference (RMSD) calculated as in Fang et al. (2013) and the mean absolute difference (MAD) computed as follows:

$$MAD = \frac{1}{n}\sum|x_s - x_o|, \quad (1)$$

where n is number of samples, and x_s and x_o are the observed and modelled values, respectively.

2.3 Hydrological model and simulations

~~The Cold Regions Hydrological Modelling platform (~~CRHM (~~,~~ Pomeroy et al., 2007) was used to create a hydrological model for MCRB. ~~CRHM is an object-oriented, modular and flexible platform for assembling physically based hydrological models. With CRHM, the user constructs a purpose-built model from a selection of possible basin spatial configurations, spatial resolutions and physical process modules of varying degrees of physical complexity. Basin discretization is performed via dynamic networks of hydrological response units (HRUs) whose number and nature are selected based on the variability of basin attributes and the level of physical complexity chosen for the model. Physical complexity is selected by the user in light of hydrological understanding, parameter availability, basin complexity, meteorological data availability and the objective flux or state for prediction. A full description of CRHM is provided by Pomeroy et al. (2007).~~ For MCRB, a set of physically based modules was assembled to simulate the dominant hydrological processes by Pomeroy et al. (2012) and Fang et al. (2013), including wind redistribution of alpine snow, snow interception, sublimation, drip and unloading from forest canopies, sub-canopy radiation energetics, slope/aspect effects on radiation and wind flow, infiltration to frozen and unfrozen soils, overland flow, hillslope sub-surface water flow and storage, and evapotranspiration from forests, clearings and alpine tundra. Recent updates were made to the evaporation and hillslope modules for better representation of runoff, including detention flow, on hillslopes and evapotranspiration from vegetation with seasonal variations in leaf area index and height, and the updated model was evaluated in the June 2013 flood when approximately 250 mm precipitation fell at MCRB during 17-24 June 2013 (Fang and Pomeroy, 2016; Pomeroy et al., 2016).

Hydrological model simulations were conducted driven bywith the bias-corrected WRF near-surface meteorological variables: air temperature, relative humidity, wind speed, precipitation, and shortwave irradiance for CTRL and PGW periods, respectively. Simulations in both periods covered eight water years: CTRL for the current period (i.e. 1 October 2005 to 30 September 2013) and PGW for the future period (i.e. 1 October 2091 to 30 September 2099). Model simulations of snow accumulation, spring snowmelt, and streamflow in the CTRL period were evaluated against the observations of snow accumulation, snowmelt, and streamflow in MCRB. Statistical indexes used to evaluate the model simulations in the CTRL period were the Nash Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and other indexes , root mean square difference (RMSD), normalised RMSD (NRMSD), and model bias (MB) calculated as perby the equations shown in Fang et al. (2013). Then, water balance variables and radiation fluxes for all ecozones in MCRB shown in Table 1 and basin streamflow from model simulations in CTRL and PGW periods were compared and used to diagnose the changes in hydrology for all ecozones and for the whole MCRB.

3 Results

3.1 WRF CTRL outputs

Near-surface hourly air temperature, relative humidity, wind speed, precipitation, and shortwave irradiance from observations, uncorrected WRF CTRL outputs, and bias corrected WRF CTRL outputs were compared for the Centennial Ridge, Fisera Ridge, Vista View, Upper Clearing and Upper Forest stations in MCRB, and. the comparisons are shown in Figure 2 shows the quantile-quantile (Q-Q) plots (Fig. 3).of air temperature, relative humidity, wind speed, precipitation, and shortwave irradiance for the well-exposed Fisera Ridge station from observations, WRF CTRL outputs, and bias corrected WRF CTRL outputs. The points in the Q-Q plots of observations and bias corrected WRF outputs shown in Fig. 32b, 32d, 32f, 32h, and 32j are linearly distributed on the 1:1 line, while the points in the Q-Q plots of observations and uncorrected WRF outputs shown in Fig. 23a, 32c, 32e, 32g, and 32i do not appear to be linearly distributedion. This suggests that the near-surface meteorological variables from observations and bias-corrected WRF CTRL outputs form the same distribution. The Q-Q plots for other stations show the same results and are provided as Supplement. Table 2 shows MAD and RMSD indexes for accessing the WRF CTRL outputs compared to observations. The uncorrected WRF CTRL relative humidity was converted using air temperature, specific humidity and specific pressure of air outputs and had values higher than 100% (Fig. 3c), indicating errors in these uncorrected WRF CTRL outputs. ~~Values of t~~The MAD for the bias-corrected WRF outputs were zero and were smaller than those for the uncorrected WRF outputs, suggesting there is no difference in the statistical distributions of observations and bias-corrected WRF CTRL outputs. ~~Values of t~~The RMSD for the bias-corrected WRF outputs were lower than those for the uncorrected WRF outputs, with two exceptions:~~except for wind speed for Centennial Ridge station and precipitation for Fisera Ridge station.~~ ~~values of the~~ ~~Values of~~ RMSD were 4.88 m s^{-1} and 0.6 mm for bias-corrected WRF wind speeds for the Centennial Ridge station and bias-corrected WRF precipitation for the Fisera Ridge station, respectively, and were slightly higher than the RMSD of 4.61 m s^{-1} and 0.56 mm for the original WRF wind speed and precipitation. Despite that, the bias correction generally improved WRF outputs and reduced the ~~mean d~~difference from ~~compared to~~ the observations.

3.2 Hydrological model evaluations

Without changing any model parameters from previously published runs made using locally observed meteorological forcing, CRHM simulations of the snow water equivalent accumulation (SWE) using bias-corrected WRF CTRL near-surface outputs were compared to observed SWE for the sheltered, mid-elevation Upper Forest and Upper Clearing sites (Fig. ~~3~~4a-b) and for the wind-blown, high-elevation Fisera Ridge site (Fig. ~~3~~4c-f) for 2007-2013. The results demonstrate that the model forced with the bias-corrected WRF outputs was able to simulate SWE for both forest and alpine environments, with an exception~~s~~ in ~~for~~ the Upper Forest site during season of 2007/2008. In addition, Table 3 shows that there were large differences between the simulations ~~had large differences with~~and the observations for both forest and alpine sites during the season of 2011/2012, with RMSD ranging from 52.3 to 297.5 mm for spruce forest and lower alpine south-facing slope and MB ranging from -0.65 to -0.35 for spruce forest and larch forest treeline, respectively. For all six seasons, model simulations captured the general seasonal patterns of snow accumulation and ablation for these forest and alpine sites, with MB values of all seasons ranging from -0.43 for the forest clearing to 0.17 for the alpine ridge top (Table 3). All season RMSD ranged from 46.5 mm for the mature spruce forest to 260.1 mm for the larch forest treeline, while the NRMSD ranged from 0.39 for upper alpine south slope to 0.84 for the mature spruce forest.

Further model evaluation was conducted using the CRHM~~-~~simulated streamflow driven by bias-corrected WRF CTL outputs and the observed outlet streamflow discharge measured by the Water Survey of Canada (WSC) gauge (05BF016) for 2005-2013 (Fig. 5~~4~~). Again, no parameters were changed for these model runs from previously published CRHM simulations of Marmot Creek that were driven by observed meteorology. The WSC gauged streamflow from 1 May to 30 September during 2006-2012 and for part of 2013 before the flood. Streamflow during 2013 flood was estimated by the University of Saskatchewan Centre for Hydrology (CH) using the best available information but with great uncertainty (Harder et al., 2015). After the flood, a streamflow gauge established near the same outlet by CH continued measurements for the remainder of 2013. The seasonal NSE values ranged from -0.33 in 2009 to 0.72 in 2012, and the overall eight-season NSE was 0.4 (Table 4), suggesting the model had some predictability for the temporal evolution of daily basin discharge in these eight seasons.

The eight-season RMSD, NRMSD and MB listed in Table 4 were 0.212 $m^3 s^{-1}$, 0.79 and 0.001 for the predicted daily basin discharge, respectively, indicating relatively small differences between the simulated and observed Marmot Creek streamflow.

3.3 Changes in WRF meteorology due to climate change

The WRF near-surface meteorological variables that had been bias-corrected with respect to MCRB stations were compared for eight water years (WY) between CTRL (i.e. 1 October 2005 to 30 September 2013) and PGW (i.e. 1 October 2091 to 30 September 2099). Figure 56 shows the comparisons of mean WY air temperature, relative humidity, wind speed and shortwave irradiance and cumulative WY precipitation at the Centennial Ridge, Fisera Ridge, Vista View, Upper Clearing and Upper Forest stations. There were consistent increases in mean WY air temperatures in PGW for all MCRB stations compared to those in CTRL. Compared to the eight-WY mMean temperatures in CTRL which ranged from -1.8 °C at Centennial Ridge to 1.4 °C at Vista View, however, those in PGW ranged from 2.9 °C at Centennial Ridge to 6.1 °C at Vista View and so were about 4.7 °C warmer for all stations (Fig. 56a). The mean WY rrelative humidity decreased slightly within PGW compared to that in CTRL, with the eight-WY mean humidity declining by 1.8% for all stations (Fig. 65b), whilst the mean WY wind speed remained unchanged between CTRL and PGW (Fig. 65c). There were slight increases in the mean WY shortwave irradiance in PGW compared to CTRL, withand the eight-WY mean shortwave irradiance increasinged by 2.8 W m^{-2} at both Centennial Ridge (i.e. from 141.4 to 144.2 W m^{-2}) and Fisera Ridge (i.e. from 152.4 to 155.2 W m^{-2}) and increasinged by 2.1 W m^{-2} at Upper Clearing (i.e. from 140.7 to 142.8 W m^{-2}) (Fig. 65d). There was much more precipitation within PGW, and annual WY precipitation was 1287 and 882 mm over eight-WY in with PGW at Fisera Ridge and Upper Clearing, respectively, about 147 and 150 mm more or 13% and 20% increasessd compared to the those in CTRL period at Fisera Ridge and Upper Clearing (Fig. 65e).

3.4 Changes in water balance variables

The simulated annual water balance variables for all ecozones were compared for eight WY bbetween the CTRL (i.e. 1 October 2005 to 30 September 2013) and PGW (i.e. 1 October 2091 to 30 September 2099)periods. Compared to CTRL, rainfall increased and snowfall decreased withinPGW for all ecozones (Fig. 76a-b). The increase in the annual rainfall ranged from 201 mm atin the lower forest ecozone to 328 mm in theat alpine ecozone, whilst the decrease in the annual snowfall ranged from 63 mm in theat lower forest ecozone to 168 mm in theat alpine ecozone. AveragedOn average for over the whole basin, the eight WY annual rainfall rose by 268 mm and annualthat of snowfall declined by 112 mm, and there was a 156 mm or 16% increase in total precipitation within PGW (Table 5). Actual evapotranspiration is the sum of evaporation from soil, intercepteforest canopy d rain interception, and and open water, and transpiration from plants; this increased within PGW for all ecozones because of more rainfall (Fig. 67c). The increase in annual actual evapotranspiration over eight WY ranged from 59 mm at alpine ecozone to 179 mm at upper forest ecozone, with 124 mm increase for the whole basin shown in Table 5. Sublimation is the total flux of snow sublimated of blowing snow,from surface snowpack and during blowing snow and forest canopy interception sublimationprocesses and declined within PGW for all ecozones as a result of decreased snowfall and the impact of warmer air temperatures in limiting blowing snow occurrence and increasing unloading of intercepted snow from forest canopies; the decrease in annual sublimation ranged from 6 mm at the forest circular clearing north-facing ecozone to 58 mm at the alpine ecozone (Fig. 76d), with a reduction of 40 mm for the entire basin (Table 5). For the sheltered and sparsely vegetated forest clearing ecozones, neither blowing snow nor forest interception processes occur, so there was only change in surface snowpack sublimation for these ecozones. For the alpine and treeline ecozones, blowing snow is a very important process in controlling seasonal snow accumulation and; the alpine ecozone is the a source area for of blowing snow (i.e. negative value for blowing snow transport) whilst the treeline ecozone accumulatesreceives blowing snow which accumulates in deep snowdrifts (i.e. positive value for blowing snow transport). Fig. 76e shows that blowing snow transport was suppressed withinin PGW, resulting in a smallerlower annual blowing snow transport loss from the alpine ecozone of 24 mm and a smallerlower annual blowing snow transport gain to the treeline ecozone of 53 mm. Blowing snow does not occur in ecozones below the treeline in MCRB and so , where no changes in blowing snow transport occurred in subalpine ecozones in blowing snow transport. Annual surface runoff increased by 250 mm withinin PGW for the alpine ecozone (Fig. 76f), and bywith 87 mm more for the entire basin (Table 5). In other, subnon-alpine, ecozones, flow predominantly occurred in the subsurface and did not show change in the surface runoff between CTRL and with PGW. Annual subsurface flow from alpine and treeline ecozones decreased with PGW by 61 and 24 mm, respectively, with PGW. Although there were increases in annual subsurface flow withinin PGW for other ecozones, ranging from 8 mm from theat lower forest ecozone to 56 mm fromat the forest circular clearing north-facing ecozone (Fig. 76g), on average overfor the whole the basin, there was a 12 mm reduction in annual subsurface flow withinin PGW (Table 5). In contrast, Ggroundwater flow stayed relatively constant withbetween CTRL and PGW for all ecozones (Fig. 67h). There were increases in annual total subsurface storage in soil and groundwater withinin PGW for some ecozones, ranging from 9 mm inat the upper forest ecozone to 27 mm inat the forest circular clearing south-facing ecozone, whilst the total subsurface storage dropped by from 2 mm at the lower forest ecozone to 40 mm at the forest clearing blocks ecozone withunder PGW (Fig. 67i). Annual suSubsurface storage for the entire basin declined by 12 mm, from 416 mm underin CTRL (i.e. 45% saturation) to 404 mm withinin PGW (i.e. 43% saturation) as shown in for the entire basin (Table 5).

3.5 Changes in snow regime

The simulated snowpack accumulation (SWE) for all ecozones and the entire basin was compared betwfor eight WY between CTRL (i.e. 1 October 2005 to 30 September 2013) and PGW (i.e. 1 October 2091 to 30 September 2099) periods. Figure 78 illustrates the annual time-series of SWE for CTRL and PGW simulations and demonstrates the impacts of PGW on seasonal SWE by PGW climate for different ecozones. For all ecozones, the peak SWE occurred earlier and was much lower withinin PGW compared to CTRL, with declines in peak SWEcreases ranging from 7 mm at the upper forest ecozone, to 166 mm at the treeline ecozone. In the alpine ecozone, the cold mid-winter snowpack in the cold mid-winter was not impacted by PGW climate and had a similar to very comparable and even higher levelsvalue before by early April compared to the that in CTRL, but shortlyaf after alpinethat SWE ablated rapidly and disappeared 26 days earlier – by about 26 days, in with PGW. For subalpineother ecozones, the seasonal snowpack declined underwent substantially declines and decreased throughout the season within PGW., and t The date of seasonal snowpack depletion advanced from early August to late June with PGW at the treeline ecozone and from mid-June to late May in the other ecozones. For eight WY, tThe mean snowmelt rate was estimated by dividing mean annual annual peak SWE by the number of days from peak SWE to snowpack disappearaenceepletion and with PGW was lower for the treeline and forest clearings ecozones in PGW, decliningwith decreases ranging by from 0.9 mm day^{-1} inat the forest clearing blocks ecozone (i.e. from 1.4 mm day^{-1} in CTRL to 0.5 mm day^{-1} in PGW) to 1.6 mm day^{-1} inat the forest circular clearing north-facing ecozone (i.e. from 2.9 mm day^{-1} in CTRL to 1.3 mm day^{-1} in PGW). Whilst the melt rate was slightly higher for alpine ecozone (i.e. from 1.9 mm day^{-1} in CTRL to 2.0 mm day^{-1} in PGW) and remained unchanged for forests ecozones, (i.e. 0.6 mm day^{-1} at upper forest and 0.5 with increases ranging from 0.01 mm day^{-1} at upper forest (i.e. from 0.63 mm day^{-1} in CTRL to 0.64 mm day^{-1} in PGW) to 0.04 mm day^{-1} at both alpine (i.e. from 1.95 mm day^{-1} in CTRL to 1.99 mm day^{-1} in PGW) and lower forest in both CTRL and PGW) (i.e. from 0.46 mm day^{-1} in CTRL to 0.50 mm day^{-1} in PGW). For the entire basin, there was a very small decline in the melt rate from 1.3 mm day^{-1} in CTRL to 1.1 mm day^{-1} in PGW (Table 5).

Changes in the seasonal total snowmelt, peak SWE, snowcover duration and radiation fluxes to snowcover from eight WY were also compared between CTRL and PGW. Figure 98a shows that cumulative snowmelt volume decreased within PGW for all ecozones, and for the eight WY mean seasonaltotal snowmelt at the, treeline ecozone declined the mostsuffered highest decrease by (215 mm), with the decreaseslines elsewhere ranging from 32 mm at upper forest to 113 mm at alpine ecozone. The pPeak SWE declinedof seasonal snowpack reduced for all ecozones within PGW, with the largest and decrease in the mean value of eight WY peak SWE was highest in at the treeline ecozone by (149 mm) and the lowest at the upper and lower forests ecozones by (11 mm), as shown in (Fig. 89b). The duration of seasonal snowcoverpack declined became shorter for all ecozones iwithn PGW, with the eight WY mean snowcover duration shortened, ranging from by 31 days at the forest circular clearing north-facing ecozone to 49 days at the treeline ecozone (Fig. 98c). Table 5 shows that the for the basin-wide, eight WY mean snowmelt volume, peak SWE and duration of seasonal snowcoverpack decreased by 84 mm, 40 mm and 49 days, respectively. The seasonalannual net radiation to snowcover increased slightly within PGW for all ecozones, ranging from an additional 2 W m^{-2} at lower forest to 4 W m^{-2} at other ecozones (Fig. 89f). The increases in the net radiation to snowcover wereas due to because of higher annual longwave irradiance to snowcover in with PGW for all ecozones, ranging from an additional 10 W m^{-2} tohigher at the lower forest ecozone to 17 W m^{-2} higher atto the treeline and forest clearings ecozones (Fig. 89e), whilst the annual seasonal solar irradiance to snowcover declinedreduced fo for all ecozones with PGW, with declines ranging from 2 W m^{-2} less at the upper forest ecozone to 17 W m^{-2} less at the forest clearing blocks ecozone (Fig. 98d). BFor the entire basin-wide, in PGW, annual seasonal solar irradiance to snowcover decreased by 11 W m^{-2} and longwave irradiance to snowcover decreased by 11 W m^{-2} and increased by 14 W m^{-2}, respectively, resulting in an increase of with 4 W m^{-2} increase in annual net radiation to snowcover with PGW (Table 5).

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3.6 Changes in streamflow

Simulated daily streamflow discharge was compared ~~for the eight WY~~ between CTRL ~~(i.e. 1 October 2005 to 30 September 2013)~~ and PGW ~~(i.e. 1 October 2091 to 30 September 2099)~~ in~~.~~ Fig~~ure~~ 10~~9~~a, which shows the annual time-series of Marmot Creek ~~basin~~ discharge for CTRL and PGW periods. The results suggest ~~and illustrates th~~that ~~the~~ basin discharge will remain~~as~~ very similar ~~between CTRL and PGW~~ over winter through~~before~~ mid-March~~, suggesting the discharge was not greatly impacted by PGW climate in the winter months~~. However, the average onset of spring freshet advanced forward~~by~~ 45 days, from 8 May for CTRL to 24 March with~~for~~ PGW, with the centre of flow volume occurring 12 days earlier, from 22 June for CTRL to 10 June with~~for~~ PGW. The peak basin discharge was 1.13 m^3 s^{-1} and 1.01 m^3 s^{-1} in CTRL and with PGW, respectively, both on 21 June. ~~Compared to CTRL, the d~~Daily streamflow discharge ~~declined~~during ~~in~~ the recession ~~limb~~ after~~between t~~ the date of peak discharge ~~date~~ through to~~and~~ late August, declined with PGW compared to the CTRL period, ~~for PGW period~~ because of higher evaporation losses within~~in~~ PGW ~~shown in~~ (Fig. 7~~6~~c). Despite the lower peak and faster recession, ~~T~~the cumulative annual discharge volume increased with PGW by 18% from 3973 dam^3 in CTRL to 4683 dam^3 within~~in~~ PGW (Fig. 10~~9~~b). ~~In addition, simulated monthly streamflow discharge was compared for the eight WY between CTRL and PGW for March to October, and~~ The change in ~~the~~ monthly discharge was calculated by subtracting the monthly discharge within~~in~~ PGW from~~by~~ that in the CTRL period. Figure 11~~0~~ shows noticeable increases in monthly discharge ~~in~~ with PGW for ~~months of~~ March to May and September, with PGW increases ranging from 0.02 m^3 s^{-1} in March to 0.27 m^3 s^{-1} in May compared to CTRL monthly discharges ~~in CTRL~~ of 0.01 m^3 s^{-1} in March and 0.13 m^3 s^{-1} in May. In contrast~~.,~~ ~~W~~~~whilst~~ monthly discharge within~~in~~ PGW declined notably in June and July by 0.03 m^3 s^{-1} and 0.09~~6~~ m^3 s^{-1} from ~~from monthly discharge in~~ CTRL values of 0.69 m^3 s^{-1} ~~in June~~ and 0.29 m^3 s^{-1} ~~in July~~, respectively. Monthly discharge in PGW decreased by only 0.01 m^3 s^{-1} in August from the CTRL~~compared to that~~ value of 0.13 m^3 s^{-1} ~~in CTRL~~ and was ~~had a very~~ similar~~ly~~ low value~~s~~ ~~of~~ (0.06 m^3 s^{-1}~~)~~ ~~to that in CTRL~~ in October. Monthly ~~For percentage change, m~~fractional chang~~increas~~es in ~~onthly~~ discharge within~~in~~ PGW ranged from a 573% increase in April to a 33% decrease in July; seasonal fractional ~~increas~~changes in discharge ranged from a ~~, and on the seasonal basis, streamflow was~~ 236% increase~~higher~~ in spring ~~months~~ (~~i.e.~~ March to May), a 12% decline~~lower~~ in summer (~~i.e.~~ June to August) and a 13% increase~~higher~~ in ~~early~~ fall (~~i.e.~~ September to October).

The simulated daily runoff fluxes (surface, sub-surface and groundwater runoff) and annual runoff volumes were ~~also~~ plotted for all ecozones in MCRB~~armot Creek~~ to examine ~~their~~ changes between CTRL and PGW. Figures 12~~1~~-123 consistently show minimal change in winter months and an advance in the onset of the spring freshet for all ecozones with PGW. The annual peak runoff from the alpine ecozone decreased from 25.6 mm day^{-1} in CTRL to 23.2 mm day^{-1} within~~in~~ PGW, both occurring on 20 June (Fig. 1~~1~~2a)~~.,~~ ~~W~~whil~~st~~e the greatest~~largest~~ decline in annual peak runoff occurred from the treeline ecozone, from 27.8 mm day^{-1} in CTRL to 19.5 mm day^{-1} within~~in~~ PGW, on 21 June and 17 June, respectively (Fig. 12~~1~~b). There were moderate declines in annual peak runoff within~~in~~ PGW from other ecozones, ranging from 0.3 mm day^{-1} less at the lower forest ecozone to 2.0 mm day^{-1} less at the forest circular clearing north-facing ecozone. The change in ~~, with no change to the~~ dates of annual peak runoff with PGW ranged from no change at the forest clearing north-facing ecozone to ~~that occurring~~ 9 days later at the forest clearing south-facing ecozone (Figs. 12~~1~~c-g). There were moderate increases in ~~the~~ annual runoff volumes from the forest clearing and lower forest ecozones within~~in~~ PGW, ranging from 12 dam^3 increase from~~at~~ the lower forest ecozone to a 17 dam^3 increase from~~at~~ the forest clearing blocks ecozone~~s~~ (Figs. 13~~2~~d-g). The annual runoff volume from the upper forest ecozone increased from 258 dam^3 in CTRL to 316 dam^3 within~~in~~ PGW (Fig. 13~~2~~c). The ~~For~~ alpine and treeline ecozones are the~~,~~ primary sources for Marmot Creek ~~basin~~ discharge; here~~,~~ the annual runoff volume increased 25%~~substantially,~~ ~~from the alpine ecozone~~ from 2457 dam^3 in CTRL to 3065 dam^3 within~~in~~ PGW, from the alpine ecozone, ~~(i.e. about 25% increase)~~ but decreased 2% ~~from the treeline ecozone~~ from 1007 dam^3 in CTRL to 986 dam^3 within~~in~~ PGW from the treeline ecozone ~~(i.e. about 2% decline)~~ (Figs. 1~~2~~3a-b).

The relationship between rainfall ratio (RR) and runoff efficiency (RE) was~~ere~~ examined for all ecozones and the Marmot Creek ~~entire~~ basin for~~in~~ CTRL and PGW periods. The ~~A~~ RR~~rainfall ratio~~ is ~~defined as~~the cumulative ~~total~~ rainfall divided by cumulative ~~total~~ precipitation over~~for~~ a WY~~water year~~, and RE~~a runoff efficiency~~ is the cumulative~~defined as total~~ runoff (surface, subsurface and groundwater runoff) divided by cumulative ~~total~~ precipitation for a WY~~water year~~. A RR > 0.5 indicates a rainfall-dominated precipitation regime, and a RR < 0.5 indicates a snowfall-dominated precipitation regime. The RE describes how well the basin or ecozone converts~~the fraction of~~ precipitation volumes to ~~that is transformed to~~ runoff volumes ~~by different ecozones in the basin~~ and it normally varies between 1 and 0. Figure 1~~3~~4 illustrates the changes between CTRL and PGW in mean ~~values of~~ RR and RE values for ~~all~~ ecozones and the ~~whole~~ basin ~~between CTRL and PGW~~. The ~~mean~~ RR in CTRL was 0.43 for the alpine ecozone, meaning it is snowfall-dominated, and ~~that~~ for treeline ecozone wa~~i~~s 0.51, close~~d~~ to an equal snowfall and rainfall precipitation regime. For other ecozones, the ~~mean~~ RR in CTRL were between 0.6 and 0.62, indicating rainfall dominance ~~in CTRL~~. With PGW~~In contrast~~, the ~~mean~~ RR increased ~~in PGW and~~ to range~~d~~ from 0.61 at the alpine ecozone to 0.76 at the lower forest ecozone. F~~, and f~~or the ~~entire~~ basin, the ~~mean~~ RR rose from 0.52 in CTRL (i.e. close~~d~~ to equal snowfall and rainfall) to 0.68 within~~in~~ PGW (i.e. rainfall-dominated). The ~~mean~~ RE stayed relatively unchanged for the forest ecozones, ranging from 0.1 for lower forest ecozone to 0.11 for upper forest ecozone in both CTRL and PGW periods. For the forest clearing ecozones, ~~mean~~ RE values dropped by 0.02. The ~~mean~~ RE changed substantially ~~had large changes~~ in the alpine and treeline ecozones; ~~it~~ dropping~~ed~~ from 1.04 in CTRL to 0.91 within~~in~~ PGW for the treeline ecozone but increasing~~ed~~ from 0.62 in CTRL to 0.69 in PGW for the alpine ecozone. The value near 1 in CTRL for treelines ecozones refers to melt of late lying snow patches. For the entire basin, the RE ~~mean SGE~~ increased by only 0.01 with PGW, from 0.44 in CTRL to 0.45 in PGW despite the basin shifting towards domination by rainfall-runoff.

4 Discussion

~~The dynamical downscaling 4 km WRF near-surface meteorology outputs were bias corrected using quantile delta mapping method with respect to station data during October 2005-Septemeber 2013 at MCRB and then were used to force hydrological model simulations in CTRL (i.e. 1 October 2005 to 30 September 2013) and PGW (i.e. 1 October 2091 to 30 September 2099) periods. The aim is to diagnose the changes in hydrology for this small mountain headwater basin of South Saskatchewan~~

~~River at end of the 21st century.~~ The ~~R~~results suggest~~how~~ that the bias-corrected 4-km resolution WRF CTRL near-surface meteorological variables were comparable to detailed station observations of a well-instrumented mountain basin, and the hydrological~~CRHM~~ simulations driven by these variables~~ bias corrected WRF CTRL near-surface meteorology~~ could make~~achieved~~ acceptable~~reasonable~~ predictions of~~for~~ seasonal snow accumulation, melt, and streamflow~~ at MCRB~~, that compared well to ~~when comparing to the~~ field observations~~measurements~~. WRF can be run at ~~simulations can be conducted for~~ higher resolutions than ~~below~~ 4-km, which may provides even more realistic precipitation patterns, especially for extreme events (Tao et al., 2016; Li et al., 2017). However, these higher-resolution WRF simulations require~~s~~ more greater computational capacity~~s and are still under experiment and evaluation stage~~, and the so the 4 km ~~and 5 km~~ WRF simulations are currently considered ~~one of~~ the best options to assess future climate change for large region (Liu et al., 2017; Prein et al., 2017; Warscher et al., 2019).

For the business-as-usual scenario (RCP8.5) with PGW, ~~Results show that the~~ MCRB on average warmed up by 4.7 °C~~ for the high-end scenario (i.e. RCP8.5) in the PGW period~~, and this degree of warming ~~degree~~ is comparable to other findings for this region by the end of the 21st century (Nogués-Bravo et al., 2007; Kienzle et al., 2012). As air warms, the water holding capacity of atmosphere increases based on the Clausius-Clapeyron equation, resulting in 13 to 20 % greater~~more~~ precipitation ~~for different elevations~~ to~~at~~ MCRB in the projected PGW period. Th~~i~~es combination of a warm~~er~~ing and wetter future climate ~~directly affects water availability in the Rocky Mountains region but sometimes~~ produce~~s~~s complex hydrological~~streamflow~~ responses~~ in this region~~. ~~SomeOne study suggests declines in the river flows in the 21st century for the central Rocky Mountain region corresponding to reducing annual precipitation (Rood et al., 2005), while others reported decreases in annual streamflow despite projected increases in precipitation (Tanzeeba and Gan, 2012). These complex streamflow responses are associated with variable influences of surface and subsurface hydrology on streamflow, especially in mountain headwater basins.~~ MCRB is composed of ~~a number of~~ landcovers that vary with elevation~~span a large elevational gradient (i.e. ecozone in this study)~~ (ecozones), for which there ~~and there are~~are different dominant hydrological processes in each ecozone, leading to variable hydrological responses to the warming climate. A~~Results demonstrate that a~~nnual precipitation shifted towards more rainfall and less snowfall for all ecozones, with larger changes to alpine and treeline ecozones, and MCRB shifted from a balance of ~~closed to equal~~ snowfall and rainfall ~~basin~~ towards rainfall-domination with~~ed in~~ the PGW~~ period~~. As result of decreased snowfall, the seasonal snowpack dropped substantially~~collapsed~~ for all ecozones within~~in~~ the PGW~~ period~~, even though sublimation losses from ~~both fluxes of snow sublimated during sublimation losses from~~ blowing snow ~~process for~~in the alpine ecozone and intercepted snow in the forested ecozones ~~from during canopy interception process for forest~~ also decreased. The ~~T~~treeline ecozone, developed large snow drifts and so sustained~~had~~ the highest seasonal snow accumulation in MCRB and suffered the greatest~~most~~ loss due to ~~because of combination of red~~reduced snowfall and diminished ~~supressed~~ blowing snow transport. These results are ~~fairly intuitive and~~ consistent with modelling results for warmer climates ~~previous findings~~ in other mountain basins where the model has a detailed representation of snow processes (López-Moreno et al., 2013; Pomeroy et al., 2015; Marty et al., 2017). In contrast to the ubiquitous slower snowmelt rates predicted by Musselman et al. (2017), snowmelt~~Melt~~ rates ~~of the snowcover examined in this study~~ exhibited~~show~~ a mixed responses to the projected PGW, with climate: lower melt rates for the treeline and forest clearings ecozones, and slightly higher melt rates for the alpine ecozone, and unchanged melt rates for the forest ecozones, and a slightly lowersmall declined melt rates overfor the whole basin. These melt rate responses are due to perplexing because of the complex interaction amongst changes inof precipitation, air temperature, albedo decay, and radiation fluxes to snowcover within PGW climate. This finding is somewhat different from slower melt rates under warmer climate reported by Musselman et al. (2017). On the other hand, all ecozones at MCRB experiencedubiquitously experienced earlier depletion of the seasonal snowpack and a shorter snowcover duration with in the projected PGW climate; as a result, the onset of snowmelt runoff and timing of Marmot Creekbasin streamflow shifted earlier towards earlier spring. Results also show decreases in the basin Marmot Creek streamflow declined during summertime within the PGW period because of higher evaporation loss, and earlier consequently water availability from the basin shifted earlier. The shift in snowmelt runoff, snowcover depletion and decline in summer discharge have been found se are common findings of streamflow response in the projected future climate for many snow-dominated mountain basins (Stewart et al., 2004; Barnett et al., 2005; Kienzle et al., 2012; Jepsen et al., 2016) and suggests that the water management offor mountain basins will would be severely impacted by that (Rood et al., 2005; Chen et al., 2006; Bongio et al., 2016). The results here suggest an overall increase in discharge volume, which contrasts with earlier studies One study suggestings declines in Canadian Rockies streamflowthe river flows in the 21st century for the central Rocky Mountain region corresponding to reducing annual precipitation (Rood et al., 2005;), while others reported decreases in annual streamflow despite projected increases in precipitation (Tanzeeba and Gan, 2012). However, earlier studies used much coarser climate models to inform hydrological predictions and model outputs were not verified against current high altitude observations.T

It is interesting to note the variability of runoff response from different ecozones inat MCRB to the projected PGW climate. Despite an earlier onset of runoff for all ecozones, the annual runoff volume increased only very moderately for the forest clearings and lower forest ecozones and increased moderately for the upper forest ecozone within PGW. climate, as iIncreases in precipitation, particularly rainfall, with PGW were almost completely consumed by increases in evaporation from for these densely vegetated ecozones. At higher elevations where most runoff is produced, the Alpine and treeline ecozones compose about 45% of MCRB, and their runoff response to PGW climate impose dominant influence on basin streamflow change. Rresults show the opposingite responses between alpine and treeline ecozones. For alpine ecozone, annual runoff volume increased with PGW; this is caused by a combination of limited available subsurface storage, and increases in rainfall that overwhelmed the increased in evaporation loss. Increases in , ultimately resulting in higher flow in alpine ecozone primarily from surface runoff more than compensated for the despite the slightly reduced subsurface runoff from this ecozone with PGW. In contrast, the annual runoff volume decreased for the treeline ecozone, this is caused by the following factors: a large reduction in seasonal snow accumulation due to decreasedlined snowfall and supressed blowing snow transport, decreased runoff from reduceddeclined snowmelt, higher evaporation in the longer snow-free period that more than compensated forexhausted increased rainfall, andwith more available subsurface storage, subsequently leading to less flow from subsurface runoff. However, the Ddecline in runoff from the treeline ecozone was compensated for by an increase in runoff from the alpine ecozone, which contributeds to an overall increase in annual basin streamflow discharge ofby 18% for aabout 16% increase in precipitation within the PGW period. The Aalpine and treeline ecozones compose about 45% of MCRB and receive more than half of the basin's annual precipitation, and so their runoff response to PGW climate impose dominantes influence on changes in basin streamflow change. Interestingly, MCRB has shown was reported for its hydrological resilience to past changes in from historic climate, forest disturbance, and extreme events (Harder et al., 2015); it also exhibits somewhat resilience to the projected future climate in respect to its from the perspective of basin RE. That is, despite theat basin shiftinged towards rainfall-runoff dominance with PGWted, the basin RE values areremained almost unchanged between current and future climates.

The hydrological model set up in CRHM provided a physically and process based analysis of climate change effects on the hydrological changes at MCRB by including the relevant hydrological processes for streamflow generation. These processes were that are parameterised from local research results without calibration from streamflow (Pomeroy et al., 2009; Ellis et al., 2010; MacDonald et al., 2010; Harder and Pomeroy, 2013; Fang et al., 2013; Pomeroy et al., 2016; DeBeer and Pomeroy, 2017). This is athe strength of the CRHM mmodelling approach in this study. However, the CRHM model does have some weaknesses in simulating groundwater systems and groundwater-surface interactions in the hillslope module given the insufficient information available to describe and fully parameterise all of the processes that may influence this system (Fang et al., 2013). The parameterisation in the hillslope module assumes surface tension in the pore spaces is the dominant factor, while in mountain basins,are coarse-textured and unconsolidated materials overwith underlying bedrock or impeding layers could be found in subsurface and groundwater layers. This may, resulting in preferential flow regimes influencingthat controls the groundwater-surface interactions in ways that are incompletely understood and described in this model (Sidle et al., 2000; McClymont et al., 2011). There is an ongoing effort in CRHM to improve the parameterisation for groundwater-surface interactions. Thus, some caution should be taken when interpreting the results of changes in groundwater storage and flow.

In this study, the assessment of future changes in hydrology at MCRB held landcover and soil properties static between CTRL and PGW periods. Cautions should therefore be takenused when in interpreting this study's results, as landcover and soil properties could also change in the warmer climate (Rasouli et al., 2019). Modelling studies in the southern Rocky Mountains, USA and the Eastern European Alps examinecalculatedemonstrate future changes in basin hydrology and water availability by coupling climate change and landcover disturbance and suggest that the feedbacks of landcover disturbance within athe warmer climate should be considered when assessing future impacts on mountain basin hydrology (Buma and Livneh, 2015; McDowell et al., 2016; Bennett et al., 2018; Strasser et al., 2019). However, landcover changes such as forest expansion into the alpine ecozone under a warmer climate areis less likely uncertain in the Canadian Rockies than elsewherey Mountain because of the of landscape limitations imposed by the geological, microclimate and geomorphologicalic processes on tree establishment above current treelines (Macias-Fauria and Johnson, 2013). In the For Canadian Rockiesy Mountain, greatermore collaboration amongstbetween hydrologistsy, ecologistsy, micrometeorologists and soil scientistsce is warranted to examine the regional changes in vegetation and soil for the future climate and to come up with more meaningful scenarios of landcover and soil disturbance under changing climate for a more comprehensive assessment of future mountain hydrology.

5 Conclusions

A physically based hydrological model was set up using the CRHM platform and was forced by bias-corrected 4-km WRF near-surface meteorology outputs in CTRL (i.e. 1 October 2005 to 30 September 2013) and PGW (i.e. 1 October 2091 to 30 September 2099) periods to assess the future changes in hydrology at Marmot Creek Research Basin. Model simulations using the bias-corrected WRF outputs over the~~in~~ CTRL period provided~~achieved~~ reasonable predictions for snow accumulation and melt for forest and alpine sites compared to the field observations~~, with MB ranging from -0.43 for forest clearing to 0.17 for alpine ridge top~~. Model streamflow simulations were~~as~~ also evaluated against observed ~~daily basin~~ streamflow discharge, which showed adequate~~s~~ ~~some~~ predictability~~ for basin discharge, with values of 0.4 and 0.001 for NSE and MB indexes, respectively~~. Compared to CTRL period, Marmot Creek on average warmed up by 4.7 °C and received 16% more precipitation for the business-as-usual~~the high-end~~ climate warming scenario~~ (i.e. RCP8.5) in PGW period~~; as a result, the rainfall ratio rose above 0.5~~ for Marmot Creek~~, with a 268 mm increase in rainfall and 112 mm decrease in snowfall. However, changes in basin hydrology were more complex than those~~ese~~ in precipitation, as the basin is composed of seven ecozones ranging from forest to alpine tundra, and spanning a large elevational gradient. Under climate change, a~~On average in PGW period, a~~ll ecozones developed ~~experienced~~ lower ~~seasonal~~ snowpacks, with decreases in peak SWE ranging from 11 mm for the upper and lower forests ecozones to 149 mm for the treeline ecozone, shorter snowcover duration ranging~~ed~~ from 31 days for the forest circular clearing north-facing ecozone to 49 days for the treeline ecozone, and total seasonal snowmelt volume decreasing~~ed~~ from 32 mm for the upper forest ecozone to 215 mm for the treeline ecozone. These changes were impacted by ~~in PGW were result of the interaction from~~ several cold regions hydrological processes, including~~:~~ suppressed~~ion of~~ blowing snow transport and sublimation for alpine and treeline ecozones and reduced sublimation from smaller canopy snow interception for forest ecozones. With climate change, ~~S~~snowmelt rates ~~under climate change~~ declined by 1.1 mm day^{-1} for treeline ecozones and by 0.9 to 1.6 mm day^{-1} for forest clearings ecozones, but ~~and~~ increased by 0.~~04~~1 mm day^{-1} for alpine ecozone, and ~~by 0.01 to 0.04 mm day^{-1}~~ remained unchanged for forest ecozones showing that slower snowmelt is not ubiquitous with warming. Additionally, evaporation losses~~ on average~~ increased with climate change~~in PGW f~~ from 59 mm for the alpine ecozone to 179 mm for the upper forest ecozone, with a 124 mm greater evaporation loss for the whole basin. Runoff~~Streamflow~~ responses to ~~the projected PGW~~ climate change were even more variable in the different Marmot Creek ecozones. Runoff began earlier for all ecozones with climate change~~in PGW period~~, and forested and alpine ecozones generated ~~larger~~ annual runoff volumes that were~~,~~ from 12% to 25% larger, whereas runoff from the treeline ecozone declined~~had a small (~~ by 2%~~) in annual runoff volume~~. For the whole basin, the declining runoff from the~~at~~ treeline ecozone was more than compensated by higher runoff from~~at~~ the other ecozones, resulting in an 18% increase in ~~higher annual~~ basin streamflow discharge with climate change~~in PGW period~~. Given the 16% increase in precipitation, the runoff efficiency for Marmot Creek is virtually unchanged under climate changefor the projected PGW climate despite the hydrological shift from snowmelt-runoff towards rainfall-dominated runoff.

Appendix A: Abbreviation list

a.s.l.	above sea level
CH	Centre for Hydrology
CMIP5	Coupled Model Intercomparison Project fifth phase
CRHM	Cold Regions Hydrological Modelling platform
CTRL	control from WRF
GCMs	Global climate models
HRUs	hydrological response units
IPCC	Intergovernmental Panel on Climate Change
MAD	mean absolute difference
MB	model bias
MCRB	Marmot Creek Research Basin
NRMSD	normalised RMSD
NSE	Nash Sutcliffe efficiency
PGW	pseudo global warming from WRF
Q-Q	quantile-quantile
QDM	quantile delta mapping
RCM	Regional Climate Model
RCP8.5	representative concentration pathway 8.5
RE	runoff efficiency
RMSD	root mean square difference
RR	rainfall ratio
SRB	Saskatchewan River Basin
SWE	snow water equivalent
WRF	Weather Research and Forecasting
WSC	Water Survey of Canada
WY	water years

Data availability. The dataset is available upon request through the Changing Cold Regions Network (CCRN) database (http: //www.ccrnetwork.ca/outputs/data/; CCRN, 2018) and the corresponding author of the paper (xing.fang@usask.ca).

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Author contribution. XF and JP designed the study. JP instrumented the research basin and developed the model. XF performed the WRF bias correction, model simulations, and analyses. XF and JP prepared and edited the manuscript~~ with contributions from JP in the manuscript outline and editing, results analysis and discussion~~.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue “Understanding and predicting Earth system and hydrological change in cold regions”. It is not associated with a conference.

Acknowledgements. The authors would like to gratefully acknowledge ~~the~~ funding assistance provided from the Canada First Research Excellence Fund’s Global Water Futures programme, Alberta Government departments of Environment and Parks, and Agriculture and Forestry;~~,~~ Alberta Innovates;~~,~~ ~~the IP3 Cold Regions Hydrology Network of the Canadian Foundation for Climate and Atmospheric Sciences, and~~ the Natural Sciences and Engineering Research Council of Canada’s Discovery Grants and Changing Cold Regions Network, the University of Saskatchewan Global Institute for Water Security, and the Canada Research Chairs programme. Logistical assistance was received from the Biogeoscience Institute, University of Calgary and the Nakiska Ski Area. Streamflow data from the Water Survey of Canada is gratefully acknowledged. ~~Field work~~Fieldwork by many graduate students and technicians in and collaborators with the Centre for Hydrology ~~and research officers Michael Solohub, May Guan and Angus Duncan~~ were~~as~~ essential in accurate data collection in adverse conditions. Comments of the editor and two anonymous reviewers were greatly appreciated.~~Dr. Kabir Rasouli is acknowledged for providing source to download WRF .nc files used to extract outputs for this study.~~

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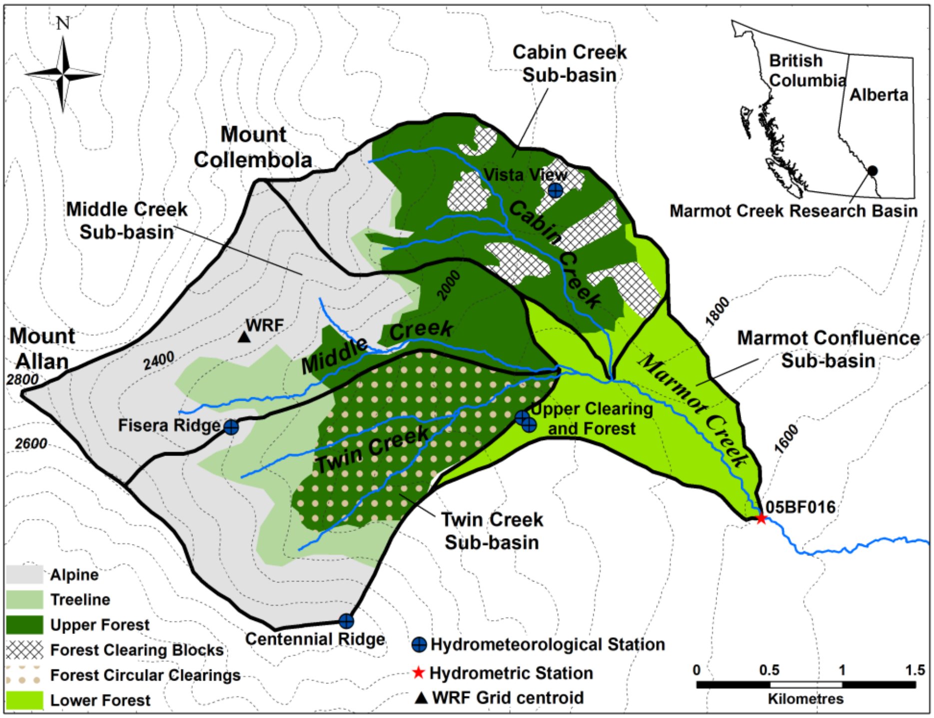

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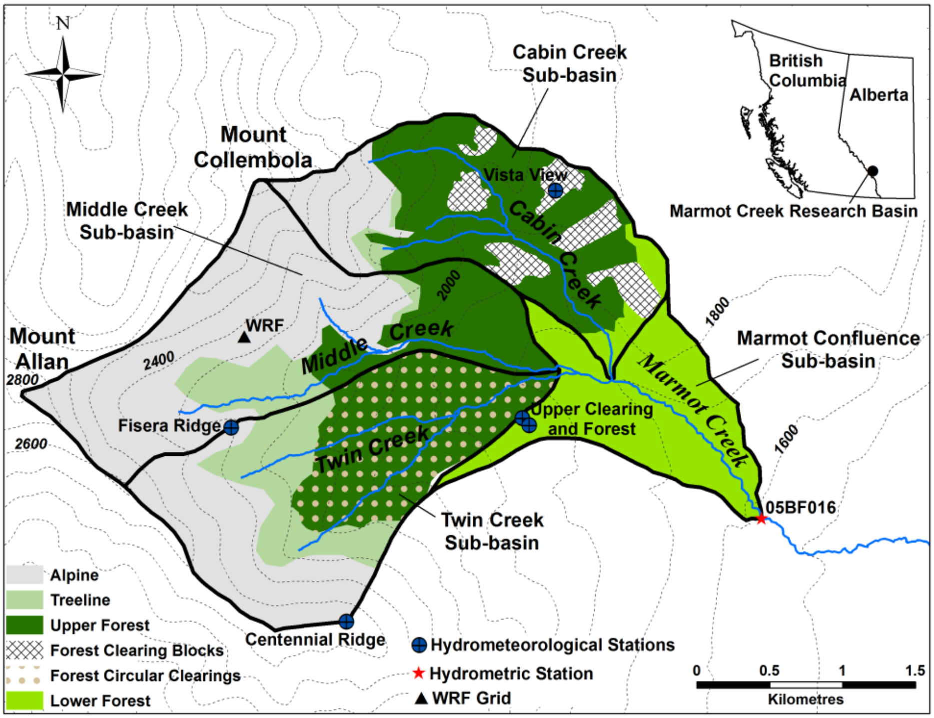

Figure 1. Location and contour map of the Marmot Creek Research Basin (MCRB), showing hydrometeorological stations, hydrometric station, ~~and~~ WRF grid centroid, and ecozones of the MCRB: alpine, treeline, upper forest, forest clearing blocks, forest circular clearings, and lower forest. Note that WRF grid centroid represents the centre of the 4-km WRF grid, and the size and areas of circular clearings in Twin Creek are meant to represent a honeycomb pattern and are not to scale.

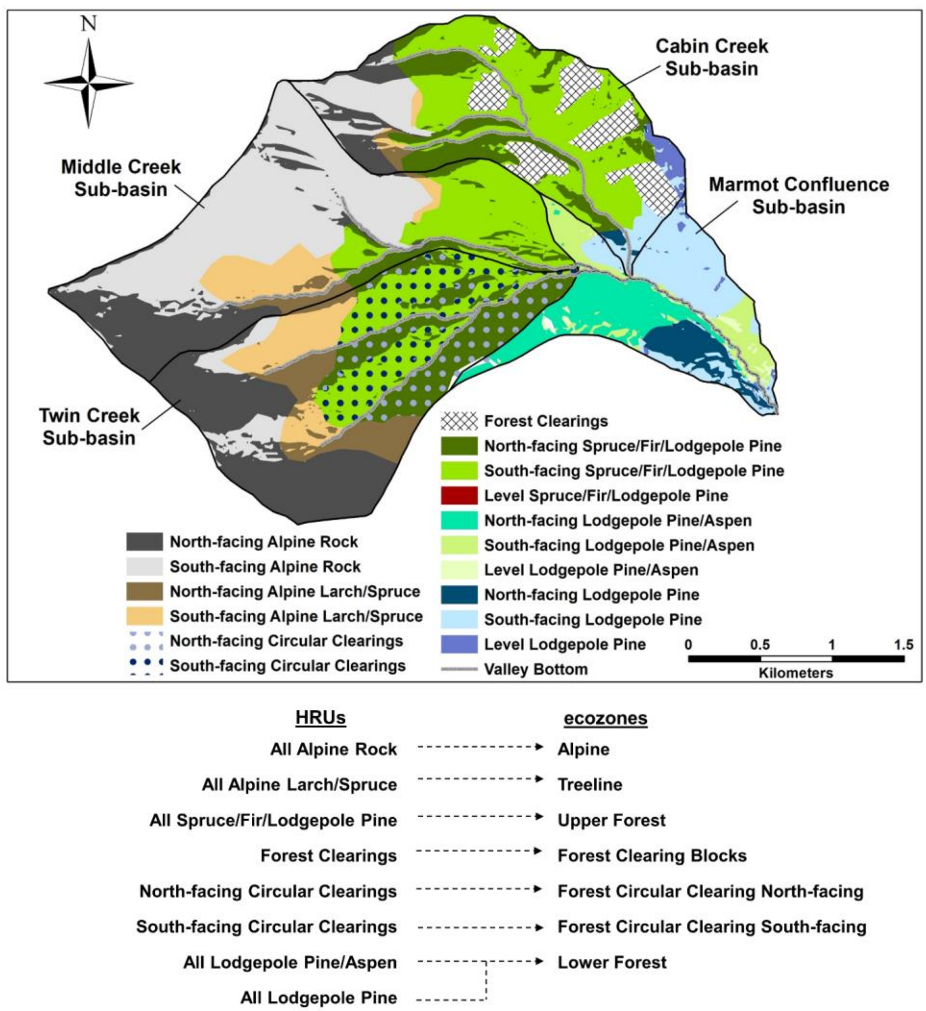

Figure 2. HRUs map and ecozones ~~generation at~~of Marmot Creek Research Basin. Note that the size and areas of circular clearings in Twin Creek are not to scale.

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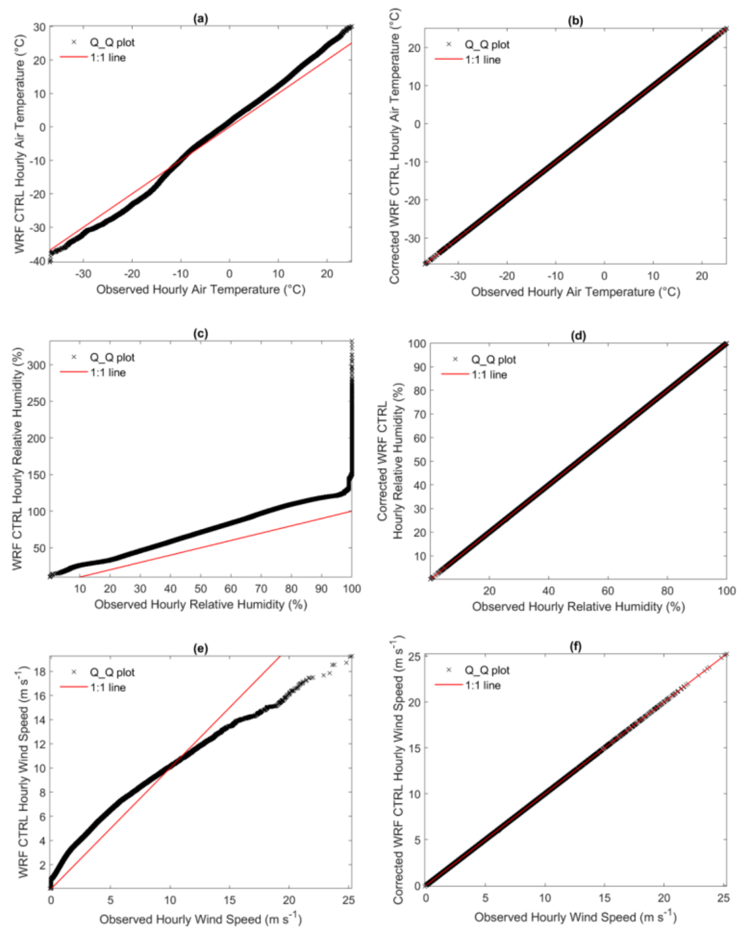
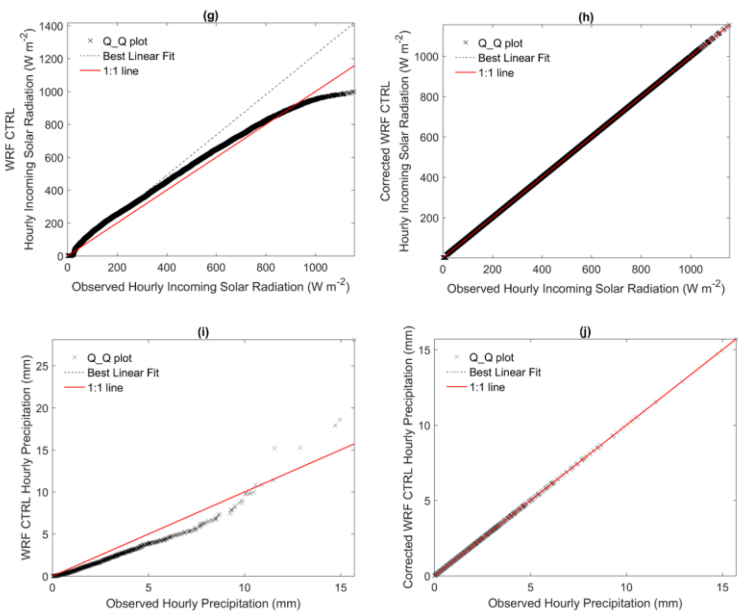


Figure ~~2~~3. Quantile-quantile plots of observations and WRF CTRL outputs for the Fisera Ridge station in MCRB: (a) WRF CTRL and observed air temperature, (b) corrected WRF CTRL and observed air temperature, (c) WRF CTRL and observed relative humidity (d) corrected WRF CTRL and observed relative humidity, (e) WRF CTRL and observed wind speed (f) corrected WRF CTRL and observed wind speed, (g) WRF CTRL and observed incoming solar radiation (h) corrected WRF CTRL and observed incoming solar radiation, (i) WRF CTRL and observed precipitation (j) corrected WRF CTRL and observed precipitation.~~ Note that best linear fit is straight line connecting the first and third quartiles.~~



(g)
WRF CTRL
Hourly Incoming Solar Radiation (W m-2)
Observed Hourly Incoming Solar Radiation (W m-2)
Q_Q plot
Best Linear Fit
1:1 line
(h)
Corrected WRF CTRL
Hourly Incoming Solar Radiation (W m-2)
Observed Hourly Incoming Solar Radiation (W m-2)
Q_Q plot
Best Linear Fit
1:1 line
(i)
WRF CTRL Hourly Precipitation (mm)
Observed Hourly Precipitation (mm)
Q_Q plot
Best Linear Fit
1:1 line
(j)
Corrected WRF CTRL Hourly Precipitation (mm)
Observed Hourly Precipitation (mm)
Q_Q plot
Best Linear Fit
1:1 line

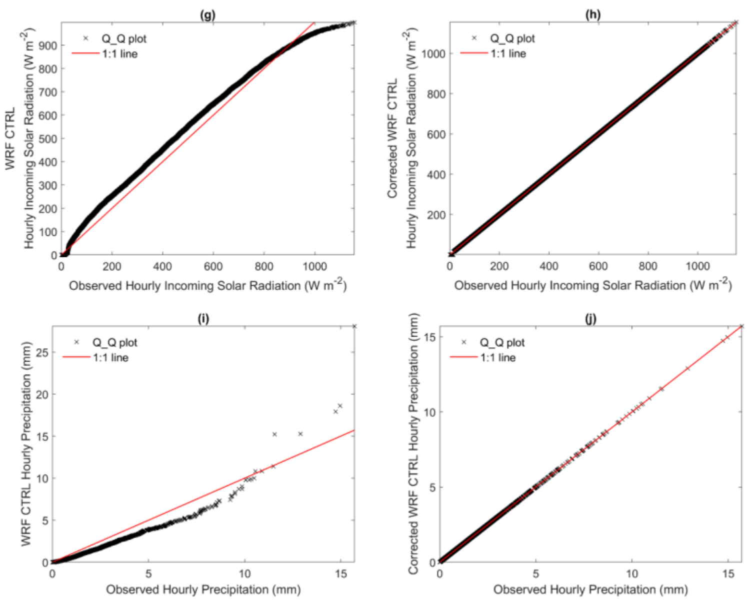


Figure 32. Continued.

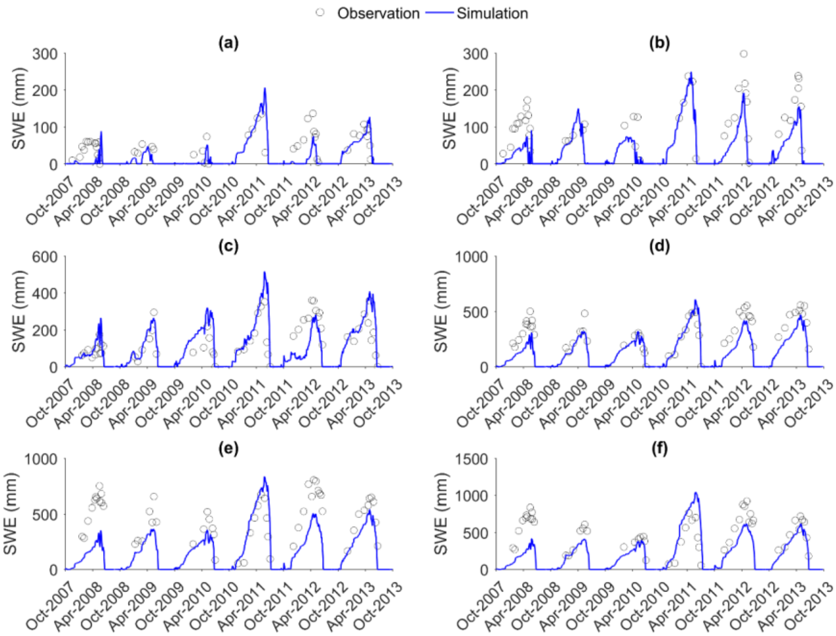
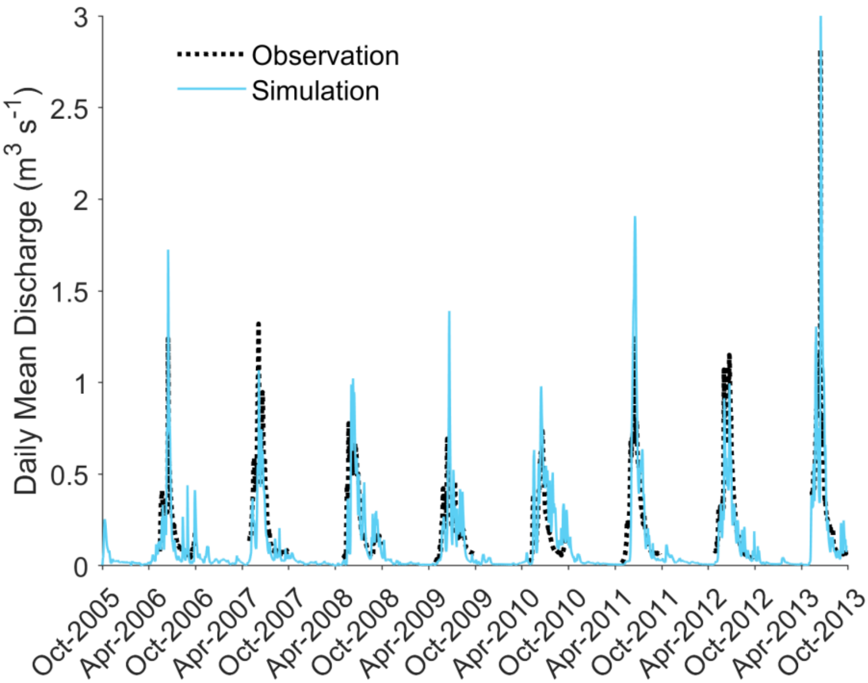


Figure 34. Comparisons of the observed and simulated snow accumulation (SWE) for 2007-2013 at the sheltered, mid-elevation Upper Forest/Clearing and the wind-blown, high-elevation Fisera Ridge sites in MCRB. (a) Mature spruce forest, (b) forest clearing, (c) ridge top, (d) upper alpine south-facing slope, (e) lower upper alpine south-facing slope, and (f) larch forest treeline.


Observation
Simulation
Daily Mean Discharge (m3 s-1)
3
2.5
2
1.5
1
0.5
0
Oct-2005
Apr-2006
Oct-2006
Apr-2007
Oct-2007
Apr-2008
Oct-2008
Apr-2009
Oct-2009
Apr-2010
Oct-2010
Apr-2011
Oct-2011
Apr-2012
Oct-2012
Apr-2013
Oct-2013

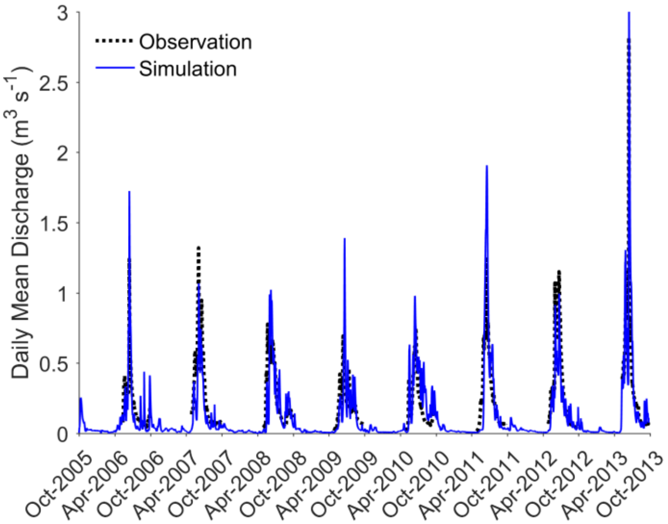


Figure 45. Comparisons of the observed and simulated daily streamflow at the basin outlet overfor 2005-2013 for Marmot Creek.

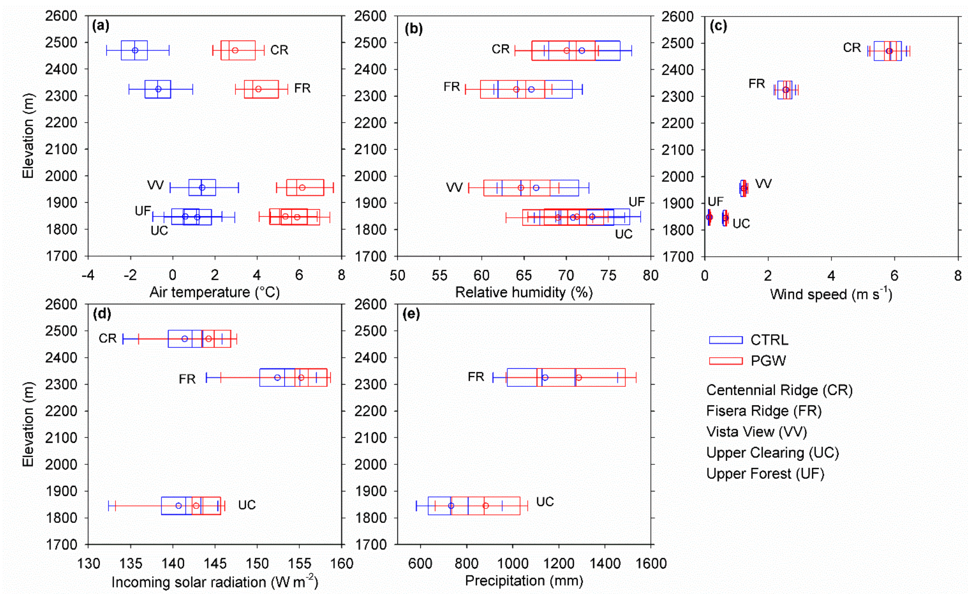


Figure 56. Boxplots of the bias corrected WRF CTRL and PGW near-surface meteorology for MCRB station sites. (a) Aair temperature, (b) relative humidity, (c) wind speed, (d) incoming solar irradiancection, and (e) precipitation. Note that the accumulation over thetotal water year is used for precipitation is presented here, and the average value over the water year value is presented for the other variables. The Vvertical line within the box = median value of the eight-water year data, box = interquartile range (Q1: 25% to Q3: 75%) of the eight-water year data, whiskers = minimum and maximum, circle = mean value of the eight-water year data.

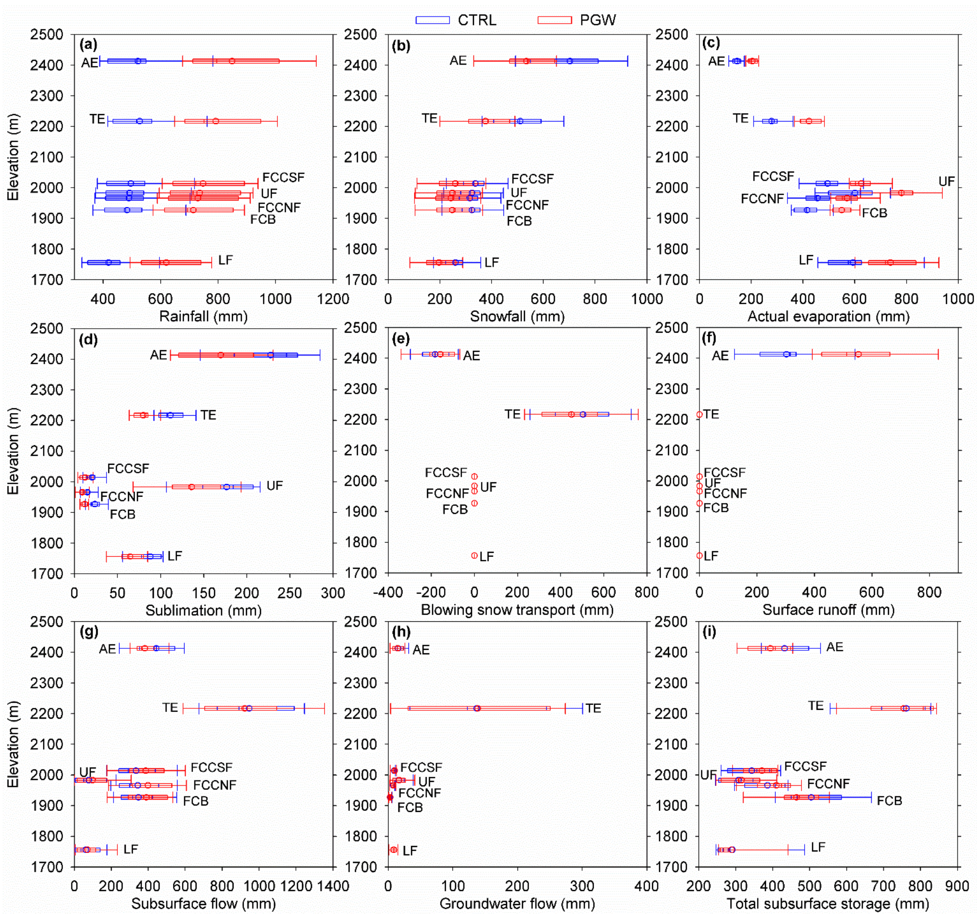


Figure ~~6~~7. Boxplots of the simulated annual water balance variables for WRF CTRL and PGW for alpine (AE), treeline (TE), upper forest (UF), forest clearing blocks (FCB), forest circular clearing north-facing (FCCNF), forest circular clearing south-facing (FCCSF)~~,~~ and lower forest (LF) ecozones. (a) Rainfall, (b) snowfall, (c) actual evaporation, (d) sublimation, (e) blowing snow transport, (f) surface runoff, (g) subsurface flow, (h) groundwater flow, and (i) storage change. The ~~V~~vertical lines within the box = median value of the eight-water year data, box = interquartile range (Q1: 25% to Q3: 75%) of the eight-water year data, whiskers = minimum and maximum, circle = mean value of the eight-water year data.

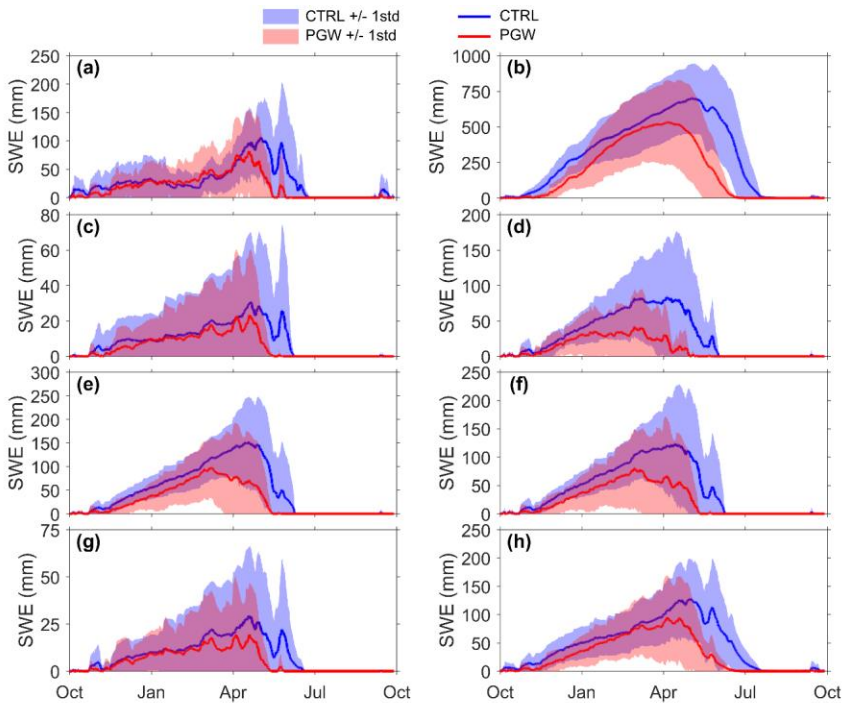


Figure 8~~7~~. Simulated ~~annual~~ mean annual snow accumulation (SWE) for WRF CTRL and PGW. (a) Alpine, (b) treeline, (c) upper forest, (d) forest clearing blocks, (e) forest circular clearing north-facing, (f) forest circular clearing south-facing, (g) lower forest ecozones, and (h) MCRB~~armot Creek basin~~. The ~~L~~line represents the ~~annual~~ mean and the shadow represents the standard deviation of the eight-water year SWE.

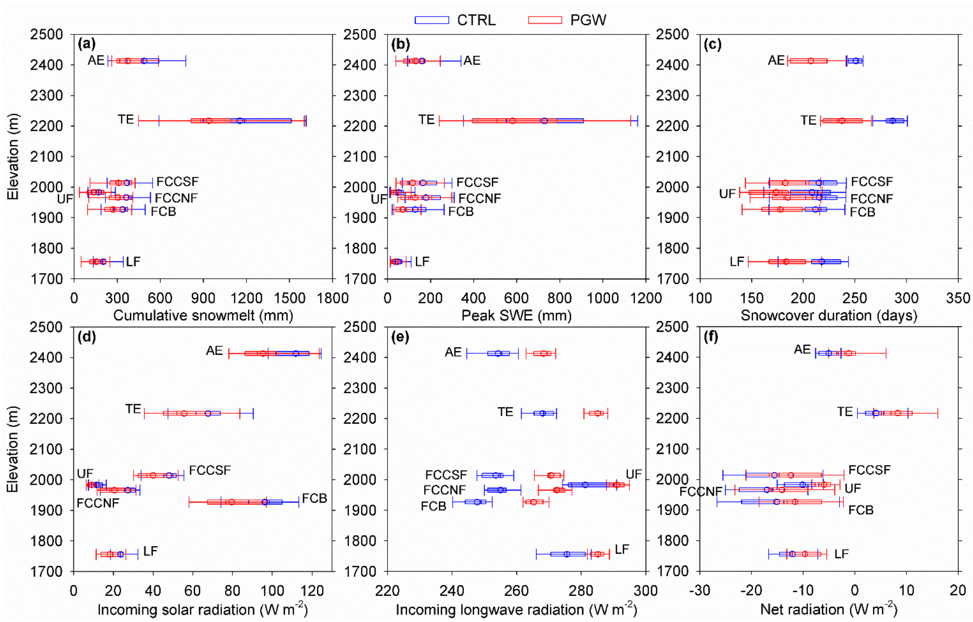


Figure 89. Boxplots of the simulated water year (a) cumulative snowmelt, (b) peak snow accumulation (SWE), (c) snowcover duration, (d) incoming solar radiation to snow, (e) incoming longwave irradiancetion to snow, and (f) net radiation to snow for WRF CTRL and PGW for alpine (AE), treeline (TE), upper forest (UF), forest clearing blocks (FCB), forest circular clearing north-facing (FCCNF), forest circular clearing south-facing (FCCSF), lower forest (LF) ecozones. The Vvertical lines within the box = median value of the eight-water year data, box = interquartile range (Q1: 25% to Q3: 75%) of the eight-water year data, whiskers = minimum and maximum, circle = mean value of the eight-water year data.

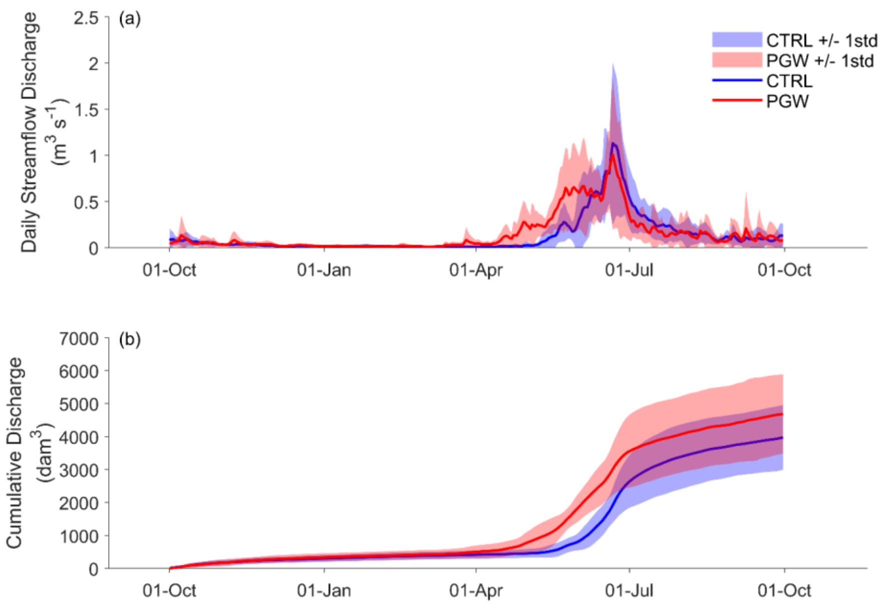


Figure 10~~9~~. Simulated ~~annual~~ mean annual (a) Marmot Creek daily streamflow discharge and (b) cumulative discharge for the WRF CTRL and PGW periods. The ~~L~~lines~~s~~ represents the ~~annual~~ mean and the shadow~~s~~ represents the standard deviation of the streamflow discharges over the eight-water year ~~streamflow discharges~~.

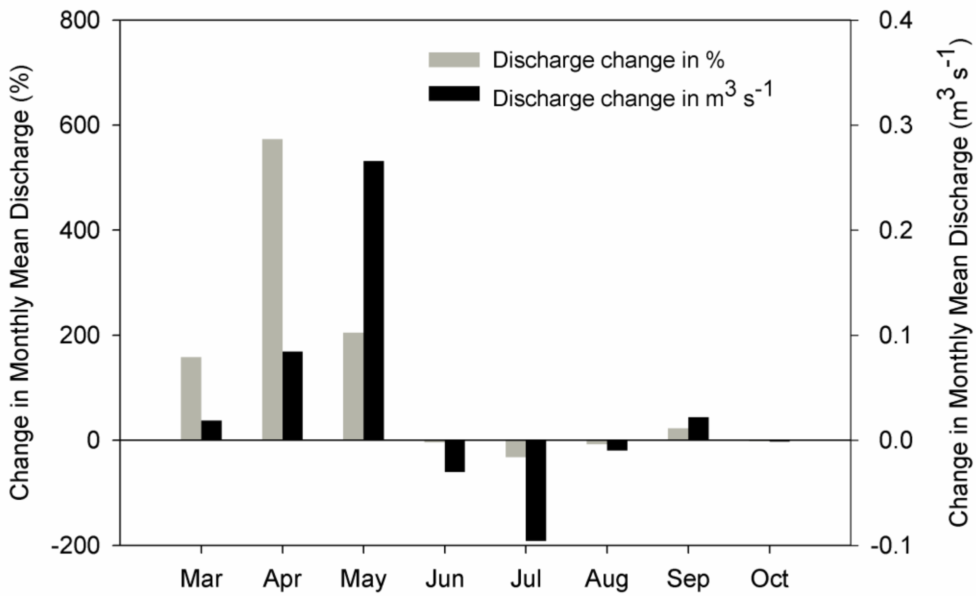


Figure 1~~0~~1. Change between WRF CTRL and PGW periods in the simulated mean Marmot Creek monthly streamflow discharges during March to October for the eight-water years~~ period between WRF CTRL and PGW~~.

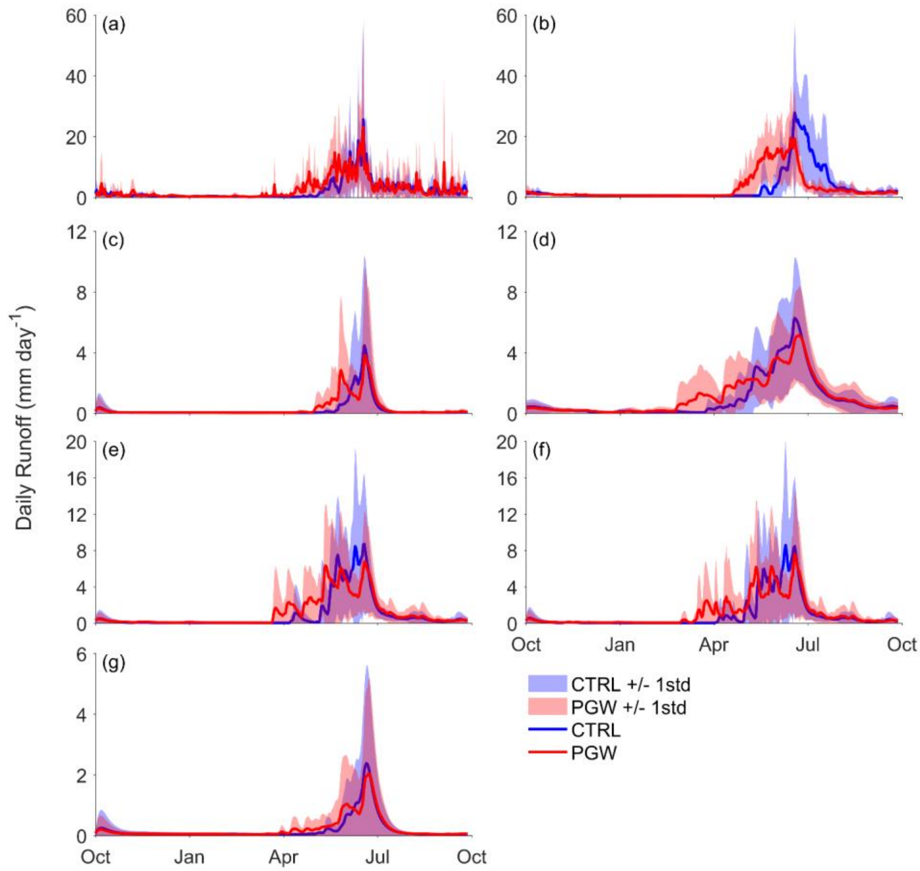


Figure 1~~1~~2. Simulated~~ annual~~ mean annual daily runoff for WRF CTRL and PGW. (a) Alpine, (b) treeline, (c) upper forest, (d) forest clearing blocks, (e) forest circular clearing north-facing, (f) forest circular clearing south-facing, and (g) lower forest ecozones. The ~~L~~lines represents the ~~annual~~ mean and the shadows represents the standard deviation of runoff over the eight-water year~~ runoffs~~.

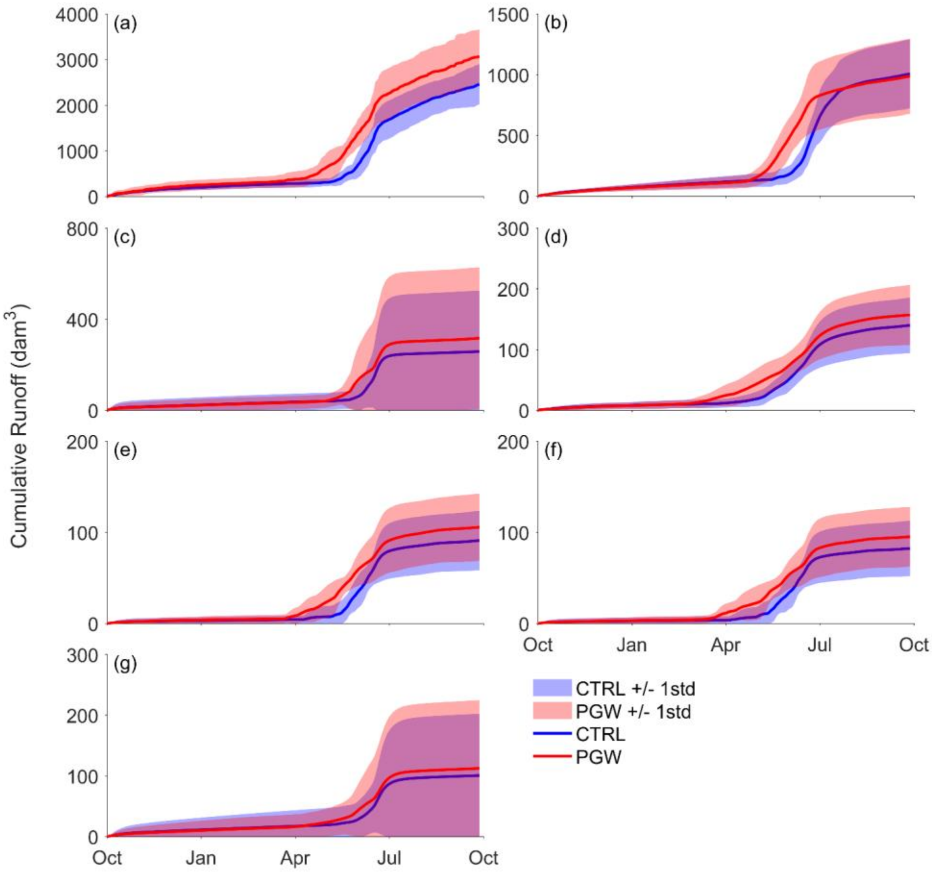


Figure 13~~2~~. Simulated ~~annual~~ mean annual cumulative runoff for WRF CTRL and PGW. (a) Alpine, (b) treeline, (c) upper forest, (d) forest clearing blocks, (e) forest circular clearing north-facing, (f) forest circular clearing south-facing, and (g) lower forest ecozones. The ~~L~~line represents the ~~annual~~ mean and the shadow represents the standard deviation of the eight-water year runoff.

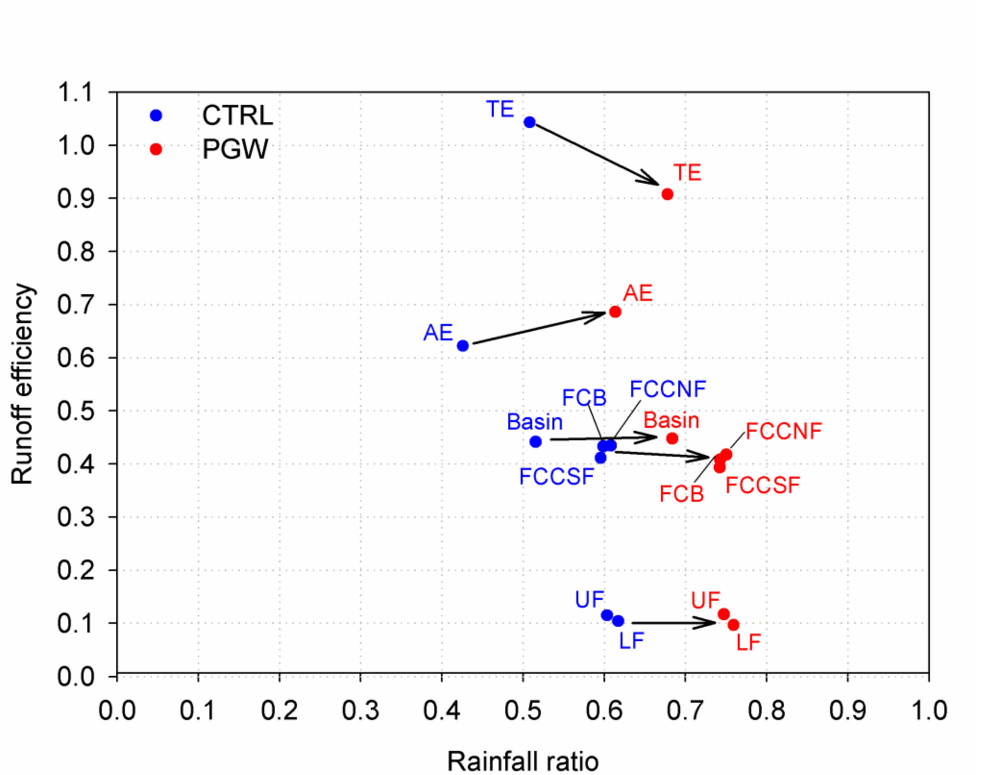


Figure 134. Scatter plots of the mMean rainfall ratio and runoff efficiency for WRF CTRL and PGW for alpine (AE), treeline (TE), upper forest (UF), forest clearing blocks (FCB), forest circular clearing north-facing (FCCNF), forest circular clearing south-facing (FCCSF), lower forest (LF) ecozones and the entire Marmot Creek basin.

Table 1. Area and mean elevation, aspect, and slope for ecozones at the Marmot Creek Research Basin. Note that the aspect is in degree clockwise from North.

Ecozone	Area (km^2)	Elevation (m a.s.l.)	Aspect (°)	Slope (°)
Alpine	3.23	2413	110	30
Treeline	0.93	2217	91	22
Upper Forest	2.75	1983	108	20
Forest Clearing Blocks	0.40	1927	140	11
Forest Circular Clearing North-facing	0.26	1966	34	17
Forest Circular Clearing South-facing	0.24	2014	113	21
Lower Forest	1.42	1756	113	14

Table 2. Comparison of observations and WRF outputs for MCRB stations, with mean absolute difference (MAD) and root mean square difference (RMSD). Values are for bias corrected WRF outputs; values inside parentheses are for WRF outputs without bias correction.

	MAD					RMSD				
	Centennial Ridge	Fisera Ridge	Vista View	Upper Clearing	Upper Forest	Centennial Ridge	Fisera Ridge	Vista View	Upper Clearing	Upper Forest
Air temperature (°C)	0.00	0.00	0.00	0.00	0.00	3.46	3.29	2.90	3.19	3.17
	(2.35)	(1.24)	(0.83)	(0.59)	(0.025)	(4.67)	(4.01)	(3.28)	(3.37)	(3.38)
Relative humidity (%)	0.00	0.00	0.00	0.00	0.00	17.54	18.37	18.38	18.72	17.75
	(20.79)	(26.74)	(26.21)	(21.82)	(19.57)	(33.14)	(37.17)	(36.29)	(33.94)	(32.81)
Wind speed (m s^{-1})	0.00	0.00	0.00	0.00	0.00	4.88	2.73	0.86	0.66	0.18
	(1.97)	(1.30)	(2.62)	(3.20)	(3.71)	(4.61)	(2.95)	(3.41)	(3.93)	(4.38)
Incoming solar radiation (W m^{-2})	0.00	0.00		0.00		108.16	121.22		125.08	
	(28.14)	(17.18)		(28.87)		(123.33)	(123.16)		(132.34)	
Precipitation (mm)		0.00		0.00			0.60		0.43	
		(0.053)		(0.006)			(0.56)		(0.45)	

Table 3. Evaluation of simulated snow accumulation using the root mean square difference (RMSD, mm SWE), normalised RMSD (NRMSD) and model bias (MB) at the Upper Forest/Clearing and Fisera Ridge sites, Marmot Creek Research Basin.

	Upper Forest/Clearing		Fisera Ridge			
	Spruce Forest	Forest Clearing	Ridge Top	Upper South-facing Slope	Lower South-facing Slope	Larch Forest
RMSD						
2007/2008	41.0	76.6	60.3	170.1	358.8	386.2
2008/2009	32.2	40.4	37.4	75.5	171.0	154.3
2009/2010	22.4	65.8	110.2	33.1	129.1	96.7
2010/2011	78.3	33.3	148.7	81.2	193.3	332.3
2011/2012	52.3	78.4	124.7	152.9	297.5	237.9
2012/2013	40.0	58.6	107.8	141.2	142.0	103.9
All seasons	46.5	66.1	106.5	126.9	244.8	260.1
NRMSD						
2007/2008	1.05	0.77	0.66	0.50	0.64	0.62
2008/2009	0.80	0.50	0.29	0.28	0.43	0.38
2009/2010	0.82	0.79	1.10	0.17	0.39	0.27
2010/2011	0.85	0.22	0.89	0.28	0.53	0.83
2011/2012	0.78	0.54	0.49	0.39	0.49	0.36
2012/2013	0.58	0.39	0.61	0.33	0.30	0.21
All seasons	0.84	0.55	0.68	0.39	0.52	0.51
MB						
2007/2008	-0.89	-0.71	0.36	-0.48	-0.62	-0.59
2008/2009	-0.78	-0.26	0.16	-0.22	-0.37	-0.28
2009/2010	-0.65	-0.67	0.98	-0.02	-0.36	-0.26
2010/2011	0.42	0.06	0.55	0.13	0.43	0.68
2011/2012	-0.65	-0.50	-0.46	-0.38	-0.47	-0.35
2012/2013	0.25	-0.32	0.40	-0.32	-0.28	-0.16
All seasons	-0.31	-0.43	0.17	-0.27	-0.33	-0.22

Table 4. Evaluation of simulated daily mean streamflow discharge for Marmot Creek using Nash-Sutcliffe efficiency (NSE), root mean square difference (RMSD, $m^3 s^{-1}$), normalised RMSD (NRMSD) and model bias (MB).

	NSE	RMSD	NRMSD	MB
2006	0.44	0.146	0.76	0.01
2007	0.64	0.175	0.58	-0.36
2008	0.31	0.183	0.68	-0.01
2009	-0.33	0.180	0.91	0.000
2010	0.32	0.156	0.76	0.44
2011	0.20	0.252	0.89	0.15
2012	0.72	0.173	0.55	-0.27
2013	0.30	0.364	0.96	0.18
All seasons	0.40	0.212	0.79	0.001

Table 5. Simulated basin-scale mean annual air temperature ~~(°C)~~, relative humidity ~~(%)~~, wind speed ~~(m s^{-1})~~, mean annual water balance fluxes ~~(mm)~~, mean annual radiation fluxes to snowcover ~~(W m^{-2})~~, mean seasonal cumulative snowmelt ~~(mm)~~, peak snow accumulation ~~(mm)~~, snowcover duration ~~(days)~~ and melt rate ~~(mm day^{-1})~~ for WRF CTRL and PGW.

	CTRL	PGW	Change: PGW - CTRL
Air Temperature (°C)	0.2	4.9	4.7
Relative Humidity (%)	69.2	67.4	-1.8
Wind Speed (m s^{-1})	2.76	2.80	0.04
Rainfall (mm ~~/~~yr^{-1})	493	761	268
Snowfall (mm yr^{-1}~~/yr~~)	464	352	-112
Total Precipitation (mm yr^{-1}~~/yr~~)	957	1113	156
Actual Evaporation (mm yr^{-1}~~/yr~~)	394	518	124
Sublimation (mm yr^{-1}~~/yr~~)	158	118	-40
Blowing Snow Transport (mm yr^{-1}~~/yr~~)	-12	-10	2
Surface Runoff (mm yr^{-1}~~/yr~~)	106	193	87
Subsurface Flow (mm yr^{-1}~~/yr~~)	317	305	-12
Groundwater Flow (mm yr^{-1}~~/yr~~)	26	26	0
Total Subsurface Storage (mm)	416	404	-12
~~Incoming S~~Solar Irrad~~Radi~~ia~~n~~n~~tion~~ce (W m^{-2})	69	58	-11
~~Incoming~~ Longwave Irradiance (W m^{-2})~~Radiation~~	263	277	14
Net Radiation (W m^{-2})	-7	-3	4
Cumulative Snowmelt Volume (mm)	401	317	-84
Peak Snow Accumulation (mm SWE)	160	119	-40
Snowcover Duration (days yr^{-1}~~/yr~~)	287	238	-49
~~Melt Rate~~Melt Rate (mm day^{-1})	1.3	1.1	-0.2