Comment on hess-2021-349

Referee comments on "Recent hydrological response of glaciers in the Canadian Rockies to changing climate and glacier configuration" by Dhiraj Pradhananga and John W. Pomeroy, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-349-RC2, 2021

Referee #1

Response: We thank the reviewer for the time spent in reviewing the manuscript and making very helpful comments and suggestions. We have improved the manuscript and provided our responses to the reviewer's comments in this document.

Pradhananga and Pomeroy discuss a clearly important topic in a well-written but oddly unbalanced paper: less than 3 pages of the text discuss the results in 11 figures and 11 tables. Figures 2 and 8 and Tables 2 and 4 largely just repeat information given fully in the text. The Sentinel images in Figure 7 are interesting, but never discussed, and all of the relevant information has already been shown in Figure 6. It is useful to have the statistics in Tables 5 to 11 available, but they might be better presented in a supplement (considering, for example, that S2 and S5 mass balance changes are dismissed in a single sentence of the text). Having stripped out the redundancy, it is unfortunate that the J. Hydrol. submission by the same authors is not yet available to check whether this is a rather thin slicing of material for two papers; the authors will have to convince us otherwise in response.

Response: Text has been added and repeat information has been removed to address this imbalance. Figure 2, 7 and 8 have been removed; Tables 1, 2, and 4 have been removed. Figure 6 is now discussed in detail. Tables 5-11 are now moved to the Supplement. They are now described accordingly. The J. Hydrol submission is in review and it can be accessed through this link (https://t.ly/jABt). The J. Hydrol paper describes the CRHM-glacier model development and its validation in the basins, whereas this HESS manuscript uses the model to diagnose the hydrological responses to changes in glacier and climate.

page 2, line 4
"and contribute to flow" would help the reader keep track of where this sentence is going.

Response: Edited.

page 2, line 22
A strict reading of this sentence would be incorrect: Moore et al. (2009), discussing glacier change in western North America, did not make any postulates about future stream flow in the Himalayas.

Response: Edited and removed the details on the Himalayas.

page 4, line 15
“proglacial lakes”

Response: Edited

page 5, line 15
The locations of the in situ meteorological measurements could be quite well indicated on Figure 1, avoiding this out of sequence reference to Figure 7.

Response: Figure 1 has been updated to show the locations of the in-situ meteorological stations, and cross-reference has also been directed to Figure 1.

Section 2.4

More information is required on the bias correction. Is this simply a removal of the average bias over the period of overlap with observations (the text would imply so) or a monthly quantile mapping as used between ERA-40 and ERA-Interim? Were all of the required variables for running CRHM-glacier included in the observations? The periods of the reanalyses (ERA-40 1957-2002 and ERA-Interim 1979-2019) would be useful information for understanding some of the choices made here. For AGRB, I think that ERA-Interim was bias-corrected to 2014-2018 observations, the bias corrections were transferred to 1979-2002 ERA-Interim, ERA-40 was bias corrected to that, and those bias corrections were transferred to 1965-1975 ERA-40 – but I am guessing.

Response: Thank you for your constructive suggestion. The text is revised to clarify and elaborate on the meteorological forcing datasets and how these were used in bias correction. Monthly quantile mapping was applied for the bias corrections using the qmap package in R (Gudmundsson, 2016) for both ERA-40 and ERA-Interim. This is now explicitly explained with additional text. The published datasets for PGRB (Pradhananga et al., 2021) have also been mentioned. The data availability of ERA-40 and ERA-Interim has been added. The bias-corrected meteorological variables against the observation were of air temperature, relative humidity, wind speed, precipitation, incoming shortwave and longwave radiations, which were used for forcing the CRHM-glacier model. Yes, the bias correction of ERA-40 was exactly the same way as you have mentioned. We have now rephrased the text for clarity.

page 7, line 26
The decline in glacier mass is not directly relevant here; it is the decline in glacier area that leads to reduction in peak flows.

Response: Edited to glacier area.

page 7, line 31
“but the impact”

Response: Replaced ‘however’ by ‘but’.

page 8, line 2
Delete “resulted”

Response: Deleted.

Figure 1
Elevation would be an attractive addition to the location map.

Response: Elevation has been added and location of the main stations in both basins have also been added.

Is there a particular reason for the different presentation of averages as box plots for temperature in Figure 3 and bar charts for precipitation in Figure 4?

Response: Both figures are now presented in box plots, bar charts for precipitation have been replaced by box plots and the cumulative precipitation plots have been removed.

Figure 5
It is worth noting that the differences in rainfall ratios between past and present glaciers with the same climate are purely due to differences in the areas over which ratios are calculated; no climate feedbacks are included in this study.

The differences for the same climate (for example, present climate) are due to the change in glacier configurations, present glacier configurations (lower elevation of a smaller glacier surface) resulted in increased rainfall ratios. However, rainfall ratios also varied due to differences between two climate periods, past and present, notably the increase in rainfall ratios in the present climate compared to the past climate. Therefore, both warming climate and lowering/shrinking of the glacier surface have increased the rainfall ratios, so that there is more rainfall on the glaciers now than in the past.

Figure 10 shows increased runoff compared with the past for both basins, particularly Peyto. Does this suggest a disagreement or regional difference between modelling and interpretation of observations across the divide in BC by Stahl and Moore (2006)?

This study shows that runoff from the basins is still increasing, and that these glaciers are yet to leave the initial phase of warming-induced increased runoff. This is true for both modelling and observations at Peyto and Athabasca glaciers. This differs from the results found in more temperate glaciated regions of Western Canada (Stahl and Moore, 2006). It should also be noted that the results in this study are from the glacier-covered headwaters at the outlets of proglacial lakes and do not include the influence of warmer and drier non-glacial environments downstream, where the influence of glacier melt runoff is greatly reduced (Comeau et al., 2009). The results of this study are consistent with those of Chernos et al. (2020) in the same region, who projected glacier contributions in the upper Athabasca River Basin to streamflow to increase till middle of the twenty-first century (2040) and to decrease afterwards. Moore et al. (2009) also noted increased flows from glacier-fed streams in colder regions such as northwest British Columbia and southwest Yukon. These discussions are now added in Section 4, Discussion.

Eleanor Bash (Referee # 2)

We thank Eleanor Bash for the time spent in reviewing the manuscript and making very helpful comments and suggestions. We have improved the manuscript and provided our responses to her comments in this document.

The manuscript uses a hydrological model, CRHM, to simulate runoff in two glaciated catchments. The authors create a suite of scenarios by combining the climate and glacier coverage of two periods (mid-20th century and early 21st century). The approach of comparing static and dynamic climate/glacier coverage is not entirely new, but the authors' model scenarios present an interesting perspective by including both backward and forward comparisons of these configurations. While the modelling scenarios have the potential to provide new insights, the manuscript is generally unfocused, and I think the main contributions are lost in the text.

Response: Thank you for your review and helpful feedback. We have now revised the text to make the manuscript more focused. The sequence of the subsections has been revised and a discussion section has been added as suggested.

Major comments:

Overall, the manuscript needs better structure to guide readers to the salient points. The introduction fails to clearly highlight the knowledge gaps the authors are trying to fill. Given the wealth of modelling studies about glacier retreat and runoff, I think the contribution of their analysis is more nuanced than you suggest. The model you use does not model glacier behaviour, I believe, it uses glacier landcover classes to model runoff response. The clearest statement of what this paper contributes is P4L22-23.

Response: The manuscript has been restructured. As suggested, now the text in the manuscript has been revised to more focus on diagnosing the hydrological response to changes in glacier and climate. The introduction has been updated with the recent literature, and it has been restructured.

A more thorough review of recent literature on glacier runoff, hydrological contributions, and glacier retreat in Western Canada specifically needs to be included with particular attention to the gaps the authors hope to fill. I would suggest including these references and removing those that are outdated or pertaining to other regions:

Neupane, R. P., Adamowski, J. F., White, J. D., & Kumar, S. (2018). Future streamflow simulation in a snow-dominated Rocky Mountain headwater catchment. Hydrology Research, 49(4), 1172-1190.

Castellazzi, P., Burgess, D., Rivera, A., Huang, J., Longuevergne, L., & Demuth, M. N. (2019). Glacial melt and potential impacts on water resources in the Canadian Rocky Mountains. Water Resources Research, 55.

DeBeer, C. M., Wheater, H. S., Carey, S. K., & Chun, K. P. (2016). Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis. Hydrology and Earth System Sciences, 20(4), 1573-1598.

Chernos, R. J. MacDonald, M. W. Nemeth & J. R. Craig (2020). Current and future projections of glacier contribution to streamflow in the upper Athabasca River Basin, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 45:4,324-344.

Intsiful, A., Ambinakudige, S. (2021). Glacier Cover Change Assessment of the Columbia Icefield in the Canadian Rocky Mountains, Canada (1985–2018). Geosciences, 11, 19.

Response: These recent examples of literature from Western Canada are included as suggested and we have removed the literature that is less relevant either because it is old or from other regions. We have now developed a discussion section that compares the results from this study with regional results and that of other regions.

There is a lot of repeated information in section 2. Introduce study sites, then model, data, and modelling scenarios. The statistical tests you use need more description, since you place a lot of emphasis on them in your results. In addition, the scenarios are laid out in a confusing manor with a description of data in the middle. P5L4 refers to A-D but this has not been described in text. Figure 2 should be update dot include the S1-S5 scenarios. The terms modelling approach, scenario, and scheme seem to be used interchangeably, once they have labels (A-D, S1-5) stick to those.

Response: The repeated information has been deleted. The introduction paragraph in Section 2 has been removed, and the text in the subsection is now updated. A description of the statistical tests has been added in Section 2.4. The sequence is restructured accordingly, and section head is also rephrased as follows:
2. Study basins, data and methods
2.1 Study basins
2.2 Meteorological forcing datasets
2.3 CRHM-glacier model
2.4 Modelling scenarios

Model scenarios were presented in Figure 2. Now, that figure has been removed and these are described in Section 2.4, Model scenarios. The text has also been revised for consistency.

Section 3 does not focus enough on the modelling experiments. A full page is devoted to describing the climate data and glacier retreat which is described in other papers in great detail. Instead these could be briefly mentioned, with more text devoted to describing the outcomes of all 5 modelling scenarios. The combination of results and discussion leaves the most important outcomes lost in a lot of text. I suggest separating these to interpret the results and bring the reader back to the research gaps identified early on. As it is written, I was left wondering what the new contributions were other than the scenario approach.

Section 3.1 and Section 3.2 have been reduced by half and the outcomes of the five modelling scenarios are discussed to a much greater degree. Discussion has been separated from results and

includes a comparative analysis with early conceptions of the hydrological impact of glacier loss and contrasting with other regional examples.

Specific comments:

P1 L13 glacier changes

Response: Edited.

L13-14 Climate trends in Arctic are not relevant for your work, up to date climate trends for W Can.

Response: They are replaced by climate trends for western Canada.

L21 dependent on what?

Response: it is dependent on basin elevation and glacier coverage of the basin. The sentence is now elaborated upon with additional text.

L24 compensation by precipitation is not in contrast to the findings of Moore 2009, it is an additional hydrological variable that will affect stream flows and glacier runoff

Response: Agreed. And as suggested earlier, we have now removed the whole paragraph.

L31 the previous paragraph you suggest this may not be a real phenomenon

Response: We have now restructured the introduction to remove inconsistencies.

P2 L3 – I think you mean link, not establish?

Response: Yes, but now they are removed with restructuring the section.

L6 it is no surprise that pdo and enso are linked with winter mass balance, but did this study link them with net mass balance as you suggested in L3?

Response: This sentence is now removed.

L23 introduce the study sites before using these acronyms

Response: This is corrected. The Section 2.1 (study sites) has been introduced before model introduction (Section 2.3).

P4 L5 this study doesn't validate the model, rather you are using the model to draw conclusions about these two basins

Response: Yes. The paragraph has been removed.

P5 L30 the decade is a sufficient identifier or consider using "recent"

Response: Rephrased and removed 'present'.

P6 L4 what maximum does this refer to? the absolute maximum, or a period of maximum?

Response: a period of maximum.

L6 these are more than a few exceptions

Response: These details are now removed to reduce climate section as you have suggested above.

L16 what statistical analysis this needs to be in the methods

Response: Details of the statistical analysis are added in section 2.4, Model scenarios.

L23-25 this isn't your results

Response: They have been removed as these details have already been included in Section 2.2, Study sites.

L28 if you intend to discuss to AAR, include some relevant information in your introduction or methods – how did you measure the change in AAR? Is this from the model? In general, I find myself confused about where the results in 3.2 are derived from, are AAR, slope, snowline, etc. output in CRHM or do these come from satellite and DEM?

Response: These are from the satellite images and DEM. The approach to measure them is now detailed in the methodology.

P7 L13 what does a decrease in mean annual snowmelt mean? Is there less melt or less snow to begin with?

Response: This is the snowmelt volumetric contribution to runoff generated from the model.

L26 be precise in language, you are not accounting for mass change, only area change

Response: Edited.

L31 this is the most interesting finding you are reporting but it reads like an afterthought. Lead the paragraph with this and then justify it

Response: Thank you. The paragraph has been restructured to emphasize this.

<u>Figures and tables:</u>

F1 – this map needs more context. The border and the basin outlines are too similar, the red box has more visual weight than the important aspects of the map.
All figure captions need more detail.

Response: The basin polygons and province borders are now presented with blue and grey lines respectively. Elevation lines and location of the main stations are added in Figure 1 as suggested by Reviewer 1, details are also added in the figure caption.

F3 – give Each panel a letter label, move labels outside of graphs. Y-axis scales should be the same across all panels. These are monthly means of daily max/min/mean, not "seasonal daily"

Response: 'seasonal daily' has been replaced by 'monthly means of daily'. The graphs are updated. Both temperature and precipitation are now in boxplots. We have now added a letter label to each panel, and moved the labels outside the graph areas. Y-axis scales are now the same across all panels.

F4 – panel labels moved outside of graph boundaries, and A-D not A1, A2. Text the same size for all panels, colors consistent between panels, why say "past and present" in one and data period int eh other?

Response: Figure 4 is now replaced by box plots as suggested by reviewer 1. The other suggestions regarding text size, colour consistency, and indexes are addressed in the new graph.

F5 should be combined with F4 as it presents another set of precip data, clarify modelled output vs raw reanalysis data (in F4 I believe)

Response: These are bias-corrected reanalysis data (Figure 4). They are now specified in the text. Figure 5 presents modeled outputs for the four scenarios showing rainfall ratios. These are now detailed in the text.

F6 omit this figure and include snow/firn and ice in F7

Response: Figure 7 has been removed and the locations of the meteorological stations with basin boundaries are now added in Figure 1 as suggested by the reviewer#1. We are keeping Figure 6 as it conveys essential and new information on glacier extent changes and firn and ice coverage. It is also needed to interpret the model results. Therefore, Figure 6 has been now explained in detail about the snow/firn and ice areas changed between two time periods. The letter labels are also updated in F6, they are now consistent with the other figures.

F8 is not adding anything

Response: Figure 8 has been removed.

F10 This would be easier to interpret as 4 panels, both past climate scenarios and both present climate scenarios

Response: The comparisons are not only between two climates, but also between past and present glacier configurations; therefore, the runoff results are combined. Figure 10 has been now described in more detail in the result for clarity. We have also added details in the runoff results in the discussion section, which is now a separated as a different section from the results as suggested.

T1 this isn't adding anything, include information in text and omit table

Response: T1 has been removed. This information is now included in the text, mainly in Section 2.1, Study basins and in Section 3.2, Change in glacier configurations.

T5-10 this is supplementary information, these tests are not described or the results addressed in detail so the detailed tables are not warranted

Response: They have been now moved to the Supplement.

T11 highlight the cell rather than the text in the cell to draw the readers eye to the significant information, the more important values are the mass balance numbers, rather than the p-values

Response: Now the cells are highlighted instead of the text in the cells. And, the mass balance numbers are now highlighted instead of p-values.

References cited in this document:

Chernos, M., MacDonald, R. J., Nemeth, M. W. and Craig, J. R.: Current and future projections of glacier contribution to streamflow in the upper Athabasca River Basin, https://doi.org/10.1080/07011784.2020.1815587, 45(4), 324–344, doi:10.1080/07011784.2020.1815587, 2020.

Comeau, L. E. L., Pietroniro, A. and Demuth, M. N.: Glacier contribution to the North and South Saskatchewan Rivers, in Hydrological Processes, vol. 23, pp. 2640–2653., 2009.

Gudmundsson, L.: qmap: Statistical transformations for post-processing climate model output. R package version 1.0-4., R Packag. version 1.0-4, 2016.

Moore, R. D., Fleming, S. W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K. and Jakob, M.: Glacier change in western North America : influences on hydrology , geomorphic hazards and water quality, Hydrol. Process., 23, 42–61, doi:10.1002/hyp.7162, 2009.

Pradhananga, D., Pomeroy, J., Aubry-Wake, C., Munro, D. S., Shea, J., Demuth, M., Kirat, N. H., Menounos, B. and Mukherjee, K.: Hydrometeorological, glaciological and geospatial research data from the Peyto Glacier Research Basin in the Canadian Rockies, Earth Syst. Sci. Data, 13, 2875–2894, doi:10.5194/essd-13-2875-2021, 2021.

Stahl, K. and Moore, R. D.: Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada, Water Resour. Res., 42(W06201), 1–5, doi:10.1029/2006WR005022, 2006.