Responses to Reviewers

We are thankful to anonymous Reviewer #1 and #2 for their comprehensive comments on our manuscript. Here we provide a general overview of our responses (in bold italic) to the major comments submitted by each referee.

Reviewer # 1:

In this study, the authors examined the influence of future climate scenarios on streamflow in the Fraser River basin in British Columbia, Canada. They used statistically downscaled output from 21 GCMs for the RCP 8.5 emissions scenario, using one realization from each GCM. The authors used the VIC hydrologic model, which has been applied in previous studies to look at the effects of climate and land-cover change on streamflow. Key results are that the basin will transition from a snow-dominated regime to a more rain-dominated regime, and that flow variability will increase in winter, with an increase in the magnitude of cold-season peak flows.

Thank you kindly for reviewing this manuscript.

1. Overall, the study appears to have been conducted in a competent manner using up to-date approaches for generating the future climate scenarios. I expect that the results will be of great interest to the agencies involved in managing water-related resources and hazards in the Fraser basin. However, the manuscript reads like a regional case study, and I struggled to discern how this work contributes novel and significant knowledge in the context of the international readership of HESS.

1. We appreciate the careful review of our manuscript, and thank the Reviewer for his/her perceptive comments. While a majority of HESS papers are in fact regionally focused, we agree that we have not paid sufficient attention to what this particular "regional case study" can teach us about other similar regions in the world. In fact, as we discuss below, the somewhat unusual physical setting of the FRB can teach us a great deal about hydroclimatic change in a mid-latitude mountainous basin with strong maritime influences. Furthermore, as our manuscript is targeted for the HESS special issue on "Understanding and prediction earth system and hydrological changes in cold regions," in our revised manuscript we better distinguish projected changes in the FRB that are fairly universal from those that are case-specific.

2. The shift from snow-to rain-dominated regimes in mountainous mid-latitude catchments has been identified in dozens, if not hundreds, of earlier climate-impact studies published in the international literature.

2. We agree with the Reviewer that there are many different studies reporting snow- to rain-dominated regime changes. However, the FRB does in fact differ in important ways from other mountainous mid-latitude catchments. While it is indeed a mid-latitude nival basin, it extends from the Pacific coast to the continental interior, meaning that it is also maritime-influenced. Specifically, the hydrologic response to warming in the FRB is influenced by two possibly confounding factors: first, the change of phase from snow to rain; and second, the very significant increase in atmospheric moisture supply (atmospheric rivers) to the North

American west coast as projected in the CMIP5 future projections (Payne & Magnusdottir, 2015; Radic et al., 2015; Warner et al., 2015; Warner & Mass, 2017). It is the latter feature that is somewhat unusual compared to other large, mid-latitude mountainous basins worldwide. For example, while small, mountainous catchments on the Norwegian coast are also strongly influenced by atmospheric rivers, they are also characterized as hybrid pluvial-nival regimes at present, and lack the extensive interior snowpack that exists in the FRB headwaters of the Canadian Rockies. An important research question that we aim to address is whether this interior snowpack will increase or decrease in response to these large-scale changes, because the exact, geographic and seasonal change in moisture supply needs to be included as part of the modelling chain. We feel that these are questions that can only be addressed in the region we selected using our carefully designed modelling framework. In the revised manuscript and Supplemental Material, we have now included results that make the "added value" of our simulation strategy for answering these types of questions much more evident.

3. Based on descriptions of the model set-up in earlier work by the authors, I infer that land cover was held constant through the simulations. In reality, however, land-cover will evolve, particularly in response to widespread forest disturbance related to the Mountain Pine Beetle outbreak that began in the 1990s, and the salvage logging that followed. In addition, glacier retreat will undoubtedly influence the hydrology of some of the mountainous headwaters. An important question is the extent to which these land-cover changes would amplify or diminish the effects of climatic change.

3. While an investigation of land cover effects might be of interest, it is beyond the scope of the present effort, which deals solely with the impacts of projected changes in climate on the FRB's cold season runoff variability and flow regimes under strong greenhouse gas forcing. We point out that any choice of land use / land cover scenario is arbitrary considering that all future changes are conditional on a given scenario. In addition, it would be difficult to predict how forest composition and disturbance regimes will change in the future. We also suspect that the effect of glacier losses and ultimately the end of glacier wasting will not have a fundamental impact on future flow regimes at the scale of the FRB. In fact the hydrological model used in our study does store and ablate frozen water at high elevations in the form of piles of snow that grow over time under historical climate conditions. While those snow piles do not have quite the same surface properties as ice (e.g., they do not flow), they represent crude glaciers in model simulations that grow during the historical period in some locations, and subsequently ablate as melting outpaces deposition.

Most importantly, it is likely that both land cover change and glacier retreat constitute a second-order forcing compared to the dominant effect of the strong increase in greenhouse gas forcing under the RCP8.5 scenario. Once the primary hydrologic response to RCP8.5 has been estimated, a follow-up study focused on the effects of land cover change and glacier retreat (with a hydrologic model including dynamic glaciers) might be merited.

4. On balance, I am not fundamentally opposed to the publication of this work, but I believe the authors need to make a more convincing case that this study represents an internationally significant contribution to the literature and is not just a regional case study. The authors need to highlight what is novel about this work when considered within the broader context of the

international literature. I should note that I have not kept up with the climate-impacts literature for a few years, and I may not have the background to appreciate the novelty of this work without it being spelled out more explicitly.

4. We thank the Reviewer for this suggestion and reiterate that our revision will better highlight the novel aspects of this work. In our revised Results and Discussion sections, we have provided a more fulsome analysis of future-projected hydrological changes in the FRB (described in detail in our response to point 1 of Reviewer 2) that clearly sets our work apart from that on other mountainous mid-latitude catchments in the published literature.

Reviewer # 2:

This is a generally well-written paper that discusses changes in runoff variability and flow regimes in the Frasier River Basin under climate change. The authors analyze 21 downscaled CMIP5 simulations that have been used as input to a VIC model implementation at 0.25 resolution. While the paper is generally well-written, the study itself is mostly routine and is not sufficiently novel in its current form that I can recommend publication in HESS.

We thank the Reviewer for providing insightful comments and suggestions on our manuscript. The key issue touched on here regarding the novelty of our work is addressed in detail under point 2 below.

1. The paper is purely descriptive in its analysis. The authors describe the results from the model simulations, but make no real attempt to analyze and interpret them. For example, which specific processes contribute most to the increase in runoff variability? How does this increased variability affect the salmon population (the authors repeatedly make the point that the Frasier supports the largest migration of Pacific Ocean sockeye salmon in the world)?

1. Thank you for raising this issue. We agree with the referee's concerns and have placed additional emphasis on the analysis and explanation of model results throughout the Results and Discussion sections. In addition, we performed additional analysis to address the Reviewer's question, "which specific processes contribute most to the increase in runoff variability?" First, we examined the rate of change of runoff variability and mean with respect to the amount of warming in the Coast, Interior Plateau and Rocky Mountains subregions of the FRB. In the Coast Mountains, we found that the change in cold season mean runoff is significantly larger than the change in runoff variability, unlike in the other two regions. This finding helps to explain why the signal of increased future runoff is so much more evident in the Coast Mountains region. Second, we employed a multivariate linear regression model to decompose the cold season runoff monthly variability into separate contributions from precipitation and temperature. This procedure allows us to determine the contribution of each key driver to the simulated runoff variability at individual gridcells. Furthermore, the multilinear regression model explains 70-90% of the total variance in runoff over a large portion of the basin.

The question of impacts on the salmon population is beyond the scope of this study considering that such an impact assessment would involve an examination of water quantity, temperature, oxygen content, and also a solid knowledge of salmonid biology which is not our area of expertise. However, in our revised Discussion section, we do mention further possible links between hydrological changes in the FRB and salmon migration.

2. As is, the findings mostly have regional interest, as there is no new methodological development nor are any of the findings particularly surprising. Warming in climates with a large seasonal snow component will lead to larger flows in winter because of a shift from snowfall to rain, mid-season melt, and earlier melt, but this has been widely reported for similar basins in western North America and Europe. The field has progressed to where this may be extremely useful information for local water managers, but the study design and findings by themselves are not sufficient for publication in a scientific journal.

2. We thank the Reviewer for raising these points, which are similar to those raised by Reviewer #1. With regard to the comment, "the findings mostly have regional interest," we point out that, in fact, most papers in published in HESS have a regional focus. However, we agree that we did not pay sufficient attention to what our study of the FRB could teach us about other similar regions around the world. As mentioned in the response to Reviewer #1's point 2, we agree that we could better highlight the novel aspects of our work, and have made several changes to the revised manuscript to do just that. Previous studies that examined future hydroclimatic changes in the FRB were mostly focused on monthly and annual time scale differences in mean climatology and hydrographs. By contrast, there has been relatively little work quantifying cold season, daily time scale flow variability and regime transitions in the FRB. These research goals necessitate the use of a large model ensemble, an effective downscaling and bias-correction method (we used BCCAQ2 due to its proven utility at the daily time scale,) and a robust snowmelt detection algorithm. Our determination of snowmelt-dominant categories (SDCs) and their future change, carried out at fine spatial scale in Section 3.3, was not mentioned by either Reviewer. Yet, this is to our knowledge an original contribution in a hydroclimatic modelling context for any basin worldwide to study projected runoff regime transition. This study is therefore not a routine effort and represents a significant advance over what has appeared in the published literature. Nevertheless, we are strongly motivated by the Reviewer's comment to better emphasize the novel methodology and key research results of this study.

Regarding the Reviewer's comment that, "Warming in climates with a large seasonal snow component will lead to larger flows in winter because of a shift from snowfall to rain, mid-season melt, and earlier melt, …", we agree that most prior research bears this out. However, the situation is not so simple in the FRB, since there is evidence of a significant increase in atmospheric rivers impacting the North American west coast as projected in the CMIP5 models. This makes the FRB somewhat unusual compared to other mid-latitude mountainous basins isolated from maritime influences, and is an important reason why we chose this basin for our study, as discussed in more detail under Reviewer 1, point 2. In the revised manuscript and Supplemental Material, we have now included results (among them the change in the future SWE and snowcover distribution and their dependence on elevations) that make the added value of our simulation strategy for answering these types of questions much more evident.

3. The paper is not significantly different from an earlier paper by the same lead author in Journal of Hydrometeorology (doi:10.1175/JHM-D-16-0012.1), which discusses the same modeling chain and setup (some of the figures are near identical and should be attributed at the very least). That paper is based on a smaller model ensemble and focuses more on changes in the mean climate / hydrology rather than changes in variability. If the authors choose to focus on variability in this paper, then I would encourage them to analyze what this increase in variability actually means for the basin.

3. In fact, as mentioned above, both the methodology and the research focus of the present work differ significantly from the earlier study of Islam et al. (2017), although we acknowledge that these aspects were not sufficiently emphasized in the submitted manuscript. In the Methods section of the revised paper, we highlight the methodological improvements of BCCAQ2 downscaling and bias correction over that of BCSD, along with the utility of the

snowmelt detection algorithm we employ. Specifically, we emphasize that future-projected changes in daily flow variability and runoff extremes can only be examined using the chosen downscaling method, not BCSD. We also point out that Islam et al. (2017) examined projections only out to the 2050s using 12 CMIP5 models, while we use a 21-model CMIP5 ensemble and provide projections to 2100. The use of 21 models in this study allows us to better sample the uncertainty in driving GCMs. Indeed, the use of BCCAQ2 and the extended time horizon lead to new insights into projected changes in regional runoff and its variability that are not previously available in literature (e.g., the strongly increasing peak runoff in the Coast Mountains after ~2040). Finally, in our revised Discussion, we investigate the implications of the simulated increase in daily time scale variability in the FRB.

4. The manuscript lacks a clear conclusion section as the authors have a single combined discussion and conclusion without a clear take-home message. I would suggest splitting these components as it emphasizes the need to have a clear conclusion that adds to the existing body of knowledge and that is focused on findings that are of wider interest than the local changes in the Frasier River basin.

4. In our submitted manuscript, a separate Conclusions section has been created after the Discussion, to provide readers with a succinct and clear take home message.

Specific comments:

All specific comments will be addressed and incorporated in our revised manuscript.

References:

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