Responses to the Editor and Reviewers

We thank the Reviewers and the Editor for their constructive comments, which helped us to improve the manuscript. We provide our detailed responses (in bold italic) to all the comments submitted by the editor and each referee along with the information on how the paper is revised as per the anonymous referees' suggestions.

Editor:

Based on the referee comments and suggestions, the manuscript needs major revision to bring it up to the standards required for publication, but I do believe the paper has the potential to make a new and important contribution. Your responses indicate a willingness to accept most of their advice. There were a few overarching concerns and issues that should be addressed. First is that the paper needs to clearly demonstrate what is novel and unique. There should be emphasis on how this relates to other regions, what insights are transferable, and how this advances our understanding and prediction of hydrological change in cold, mountainous regions under a warming climate. It should be made clear how this study differs and builds upon the earlier work here by the lead author (stated in the introduction), and also where this work is leading towards (i.e. the second paper to look at extremes).

Thank you for handling our manuscript and allowing us to revise it as per the reviewers' suggestions. The revised manuscript was restructured considerably to address the reviewers' comments and overarching concerns you mentioned above. Most of the sections in the manuscript are re-written to better highlight the novel aspects of our work. The revised discussion and conclusion sections now provide information on the transferability and importance of our findings to other mid-latitude, mountainous basins with strong maritime influences. In our revised Results section, we have provided a more comprehensive analysis of future-projected hydrological changes to i) estimate specific processes that contribute most to the increase in runoff variability and to ii) explain why the signal of increased future runoff is so much more evident in the Coast Mountains region. The later utilizes a multivariate linear regression analysis to identify the key driver(s) that control changes in runoff mean under projected climate change. Furthermore, in the revision process, we have emphasized how the methodology and the research focus of the present work differ from the earlier study of Islam et al. (2017). Specifically, we have highlighted the methodological improvements of the present study over Islam et al. (2017) by including further details of modifications applied to the new downscaling and bias correction scheme and the utility of the snowmelt detection algorithm.

Regarding your point "where this work is leading towards", we have now mentioned explicitly in the introduction section that the present paper is the first of two papers analyzing the same set of hydroclimatic simulations. The present effort deals with features of the transition from seasonal snow to a hybrid snowmelt/rainfall runoff regime, with special attention to the changes in snowmelt dynamics and daily runoff variability. A forthcoming paper (in preparation) addresses the consequences of these changes for river discharge at the main outlet to the FRB at Hope, BC, including a formal flood frequency (extreme value) analysis for the 21st century.

A concern is the fact that land cover change is not explicitly dealt with or addressed, as noted by reviewer #1. Indeed, when applying models of today under future climates, “turning handles”, and getting results, it is questionable how meaningful or useful the results really are. It may be premature to say that land cover change and deglaciation constitute a second order forcing – these could potentially have a major influence and unanticipated consequences. In this region, under all plausible future climate scenarios, we expect rapid deglaciation in the headwaters and widespread forest impacts across the basin due to changing fire regime and other disturbances. How this will affect runoff responses and land–atmosphere interactions is not fully understood. Although it may be beyond the scope of this study to include scenarios of land cover change, this is a major limitation of the study and needs to be properly considered and addressed in the discussion.

We agree that the land cover changes are not explicitly addressed in our initial manuscript. In the revised discussion section, we have included a detailed discussion focusing on the potential impact of land use and glaciers on hydrological simulations along with clarification that the present effort deals solely with projected hydrological changes under strong greenhouse gas forcing. Once the primary hydrologic response to this forcing 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) will be warranted.

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 have distinguished projected changes in the FRB that are fairly universal from those that are case-specific. We have revised the discussion section in our revised manuscript to highlight this point.

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 that there are many 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 anticipated in the CMIP5 future projections (Payne & Magnusdottir, 2015; Radic et al., 2015; Warner et al., 2015; Warner & Mass, 2017). While small, mountainous catchments on the Norwegian coast are also strongly influenced by atmospheric rivers, they have 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. In the revised manuscript and Supplemental Material, we have now included results (Figure 3, Table 2, and Supplementary Figure 5) 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 albedo and other surface properties as ice and 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 second-order forcings 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) will be warranted.

In our revised manuscript, we have included further detail in the discussion section to address these issues.

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 has better highlighted the novel aspects of this work. In our revised Results and Discussion sections, we have provided a more comprehensive 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 analyses 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 Mountains, Interior Plateau and Rocky Mountains subregions of the FRB (Figure 3). 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 phases (rainfall and snowfall) and temperature (Table 2 and Supplementary Figure 5). The model, which explains 50-90% of the total variance in runoff over a large portion of the basin, allows us to estimate the contributions of these drivers to the simulated runoff variability at individual gridcells.

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 temperature, oxygen content, and also a solid knowledge of salmonid biology, which is not our area of expertise. We have, however, initiated a study to estimate the impacts of changing water temperatures on salmon migration and populations in the Fraser River, which will be reported in a future publication.

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 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, and a robust snowmelt detection algorithm. Our determination of snowmelt-dominant categories (SDCs) and their future change, carried out at fine spatial scales 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. We have revised the methodology section accordingly.

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. In the revised manuscript and Supplemental Material, we have included new results 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 have highlighted the methodological improvements of BCCAQ2 downscaling and bias correction over that of BCSD, along with the utility of the snowmelt detection algorithm we employed. Specifically, we emphasize that

future-projected changes in daily flow variability and runoff extremes cannot be accurately examined using BCSD-downscaled driving data. 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).

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.

<u>Specific comments:</u>

a. p.5 l.3-4: While the authors state that it "[...] is important to evaluate such regime transitions on regional scales while characterizing snowmelt and rainfall driven flows independently", they never clearly state why this is important and how they will use this analysis.

a. The FRB exhibits substantial spatial variation of air temperature and precipitation due to its complex topography and maritime influences. The hydrologic response therefore varies considerably across the basin differentiating its flows mainly into snow-dominant or hybrid (rain and snow) regimes. These distinct flow regimes are expected to change under future climate change with hybrid or rainfall-dominant flow regimes becoming more prevalent. Such changes will most probably accelerate the onset of spring snowmelt and will modulate the magnitude of summer flood events in snowmelt-dominant flow regimes and will increase winter flows and flood events in rainfall-dominant flow regimes. Therefore the quantification of flow regime transitioning is particularly important for the FRB that could have implications for reginal adaptation measures and water resources management in the region.

To quantify such changes, we have used the snowmelt pulse detection technique to characterize snowmelt and rainfall driven flows independently. This technique separates snowmelt-dominant flows from rainfall-dominant flows using the maximum cumulative departure within the defined time window (Supplementary Fig. 1). In our revised manuscript, we have included a further discussion of flow regime transitioning in the discussion and conclusion sections. We have also further clarified the snowmelt pulse detection technique in Section 2.5 of the revised manuscript.

b. Section 2: This section should reference their earlier work (Islam et al., 2017) more directly, as much of the model setup is the same, in particular the setup of the hydrological model. As is, the section is rather uneven. It goes into great detail regarding the resolution of the ANUSPLIN dataset ("having a spatial resolution of about 9.26 km in the meridional direction and one that varies proportionally to the cosine of latitude in the zonal direction.") but says nothing about the VIC calibration or setup. Incidentally - is the ANUSPLIN dataset simply a 5 arcmin resolution (1/12_)?

b. We have revised Section 2 to make it more informative about the VIC model setup and calibration and removing unnecessary details about the ANUSPLIN data. Yes, the ANUSPLIN data are of 5 arcmin resolution.

c. Section 2.2: In addition to the strengths, the authors should also address the shortcomings of the downscaling techniques that they use, especially since they look at variability in daily time series. For example, Gutmann et al. (2014) noted that BCCA overestimates wet day fraction and underestimates extreme events. Perhaps the combination with BCCI fixes this, but that would be good to discuss.

c. BCCAQ2 does, in fact, reduce the magnitude of biases in BCCA, as pointed out in the Werner & Cannon (2016) reference given in our Sec. 2.2 (p. 8). More specifically, as reported in a recent paper by Li et al. (2018), "BCCAQ avoids these issues by separating the downscaling and bias correction operations: BCCA, which includes a quantile mapping step at the GCM scale and subsequently generates realistic fine-scale spatial variability, precedes the application of second quantile mapping at each grid point to further correct quantile distributions at the fine scale. Furthermore, the quantile mapping algorithm that is used explicitly preserves the climate change signal additively for temperature and multiplicatively for precipitation of the underlying climate model projections (Cannon et al. 2015)." According to Werner & Cannon (2016), BCCAQ "really shone for use with modelling hydrologic extremes. In this context, it exceeded all other methods." Further, as modified via BCCAQ2, it is especially suited to climate change applications, as featured in Cannon et al. (2015). That said, any bias correction method is only as good as the target data set used, and in this respect, the known biases of ANUSPLIN (e.g., the low precipitation bias at high elevations) are of course transmitted to the downscaled model results via BCCAQ2. This is a point we have now made explicitly in Sec. 2.2 of the revised manuscript, and added additional references as necessary.

d. p.9 l.1: Wu et al. (2011) does not describe a routing scheme, but simply provides routing networks at different spatial resolutions. From the sentence that follows it appears that the authors have used the Lohmann routing scheme. This should be clarified.

d. Thanks for pointing this out. We have now revised these sentences and have clearly stated that the Lohmann et al. (1996, 1998a, b) routing scheme was used to extract runoff at basin outlets.

e. Section 2.3: The authors do not provide sufficient detail about the VIC setup. It is fine to refer to their earlier paper, but it would be good to mention model resolution, a two-line summary of the source of the parameters, etc. That would be more useful than the long list of references to previous uses of the VIC model (p. 9 second paragraph).

e. In our revised manuscript, we have now included paragraphs under section 2.3 describing the VIC model resolution, parameters, and it calibration and validation for the FRB.

f. p.11 l.1-2: "Peak runoff during the cold season was computed between 1 October and 1 March when the 3-day running mean daily air temperature exceeds 0 C at each gridcell." Why the extra condition based on air temperature?

f. Using the extra condition based on air temperature helps to identify the end of the cold season more precisely in each year. The last day of the cold season therefore depends on the temperature criterion. A 3-day running mean is used to avoid extreme events when daily mean temperature exceeds 0°C for a given day within the cold season. In our revised manuscript, we have clarified this point under section 2.4.1.

g. Section 2.4.2: This section needs to be streamlined. The equations are unnecessary, since most of us know how to calculate a mean and variance for a data set.

g. In our revised manuscript, we have removed these equations and have explicitly defined all the symbols.

h. In the results section I found the narrative hard to follow in part because of the way in which the authors use abbreviations to refer to the different sub-basins. Sentences such as "The advance in the timing of the annual peak flow in these sub-basins is slightly less than for the FRB as a whole (_20 days for UF, _18 days for QU, _25 days for TN and _35 days for CH) [...]" are difficult to read. The numbers may be more effectively presented in a Table, which allows the text to focus on some particular insight that can be derived from this.

h. As per the Reviewer's suggestion, we have deleted this parenthesized portion in the revised manuscript, and have included these numbers in Table 1.

i. Figures were generally of good quality.

i. Thank you.

Reviewer # 3

We thank the Reviewer for the careful review of our manuscript and useful suggestions to further improve the analysis.

1. My first assessment was similar to that of the previous reviewers: what has been modelled for the Fraser River has been modelled and reported many times before: changes in mean flow, regime, snow-rain ratio, etc. Abstract and conclusion provide little new information and the international reader doesn't know what knowledge gain to transfer to other regions. In this context we should remember that HESS has the same requirements for special issue papers as for regular contributions. Manuscripts submitted as type 'research articles' should 'clearly advance our understanding', ms type 'cutting edge-case study' needs to provide all data to serve others as testbed e.g. for models (from the HESS website). The current manuscript is perhaps in-between.

1. We agree that there are many studies reporting changes in mean flow and snow- to rain-dominated regime changes in the FRB. However, most of these studies have examined future hydroclimatic changes on monthly and annual time scales focusing on the spring and summer seasons. 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 require the use of a large model ensemble, an effective downscaling and bias-correction method (BCCAQ2), and a robust snowmelt detection algorithm. Furthermore, our determination of snowmelt-dominant categories carried out at fine spatial scales, is an original contribution in a hydroclimatic modelling context for any basin worldwide to study projected runoff regime transitions. 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 all the Reviewers' comments to better emphasize the novel methodology and key research results of this study in the revised manuscript.

Regarding the Reviewer's comment on "what knowledge gain to transfer to other regions", we agree that, in the original submission, we did not pay sufficient attention to what this particular regional study can teach us about other similar regions in the world. As mentioned in our response to the other reviewers, the specific physical setting of the FRB can teach us a great deal about hydroclimatic change in a mid-latitude, mountainous basin with strong maritime influences. In our revised manuscript, we have distinguished projected changes in the FRB that are fairly universal from those that are case-specific.

2. A symptomatic indicator is the start of Section 5 "..overall question...how...precipitation phase and variability will modulate the FRB's runoff variability and flow regimes". Instead of this case study view, the science question should be how cold climate hydrology transitions to temperate climate hydrology - the FRM just happens to be considered the case that is used for illustration. However, with the running model at hand and gauging from the responses given already there is potential to focus on a particular process or phenomenon that is not yet well understood and is still specific to cold regions transitioning to temperate climate.

2. Thank you for providing this comment on the scientific focus of our study. While our geographic region of focus is the FRB, we have made clear in the revised manuscript that the overall context of the work is indeed just the type of hydrologic transition that the Reviewer

identifies. We agree with the Reviewer that the application of the CMIP5-VIC ensemble over the FRB specifically permits us to make a detailed analysis of the processes responsible for this transition.

3. Some of the analyses on the variability and pulses etc. that are presented here stand out and may provide a nice starting point. They are the ones that could be made the sole focus, analysed more specifically and quantitatively to make this an original contribution specifically dealing with features of the transition from seasonal snow to more rainfall-runoff dominated flow dynamics. It would have been very interesting, for example, to see the analysis on the daily to weekly variability expanded more systematically to scale and quantities - e.g. will this cause more floods? The rather abstract mm values could be interpreted within exceedance probabilities or so to make sense of them. This should not only be discussed as a by-product but analysed and demonstrated. Such a focus would require a thorough analysis and discussion of how the downscaling and bias-correction affect the results - are they able to reproduce and project daily to weekly joint warm and moist events in winter such as for example the atmospheric rivers that are mentioned? I am a little skeptic how an analogues procedure will still be concurrent with the climate model projection trends at daily scale then. But this could be analysed.

3. The Reviewer should be made aware that the present work is the first of two papers analyzing the same set of CMIP5-VIC simulations. This point is now mentioned explicitly in the introduction section of the revised manuscript. The present paper deals with features of the transition from seasonal snow to a hybrid snowmelt/rainfall runoff regime, with special attention to the changes in snowmelt dynamics and daily runoff variability. Our upcoming paper (Curry et al., in preparation) addresses the point raised by the Reviewer, namely the consequences of these changes for river discharge at the main outlet to the FRB at Hope, BC, including a formal flood frequency (extreme value) analysis for the 21st century. The methodological question raised by the Reviewer "how the downscaling and bias-correction affect the extreme value analysis" is also addressed in this forthcoming work.

As discussed in our response to the other reviewers, in the revised manuscript we have conducted additional analysis to address the issue raised by the Reviewer, namely "features of the transition from seasonal snow to more rainfall-runoff dominated flow dynamics". The new analysis has allowed us to determine the rate of change of runoff variability and mean with respect to the amount of warming in the Coast Mountains, Interior Plateau and Rocky Mountains subregions of the FRB (Figure 3). We also employed a multivariate linear regression model to decompose the cold season runoff monthly variability into separate contributions from rainfall, snowfall and air temperature (Table 2 and Supplementary Figure 5). This procedure allows us to estimate the contribution of these drivers to the simulated runoff variability at individual gridcells. These additional analyses, combined with existing results in the paper addressing changes in snow dominant categories and daily runoff variability, both heighten the impact of the present work and provide a foundation for our forthcoming work on streamflow extremes in the FRB.

4. Another option may indeed be to focus on key features of river flow variability that are important for salmon.

4. As discussed in the Response to Reviewer #2, point 1, the question of impacts on the salmon population is beyond the scope of this study.

5. In any case, a clear focus and message will be required that will make readers remember more than 'again a general shift from snow to more rain dominated regime in winter'. The necessary revisions may be too substantial to be considered the same paper, but it could perhaps be resubmitted with a more focused title and content to the same Special Issue.

5. As mentioned in the response to Reviewers 1 & 2, the Conclusion of our revised manuscript now provides a clear take-home message that better highlights the novel aspects of our work. The additional analysis we have conducted not only provides readers with a clearer notion of the mechanisms behind hydrologic change in the FRB, but also points out commonalities with other mid-latitude basins that are likely susceptible to the same climatic drivers.

Minor comments:

6. Figure 7 - good start of this and illustrative, but is the absolute amount of the variability (scale) really so relevant? For readers who don't know the river.

The units for all three panels in Figure 7 (Figure 8 in the revised manuscript) are kept identical to maintain consistent and comparable results. The values in panel b and c are daily and 7-day standard deviations. Use of the same units allows readers to clearly see changes in variability, which would be obscured using the Coefficient of Variation (CV) with a changing mean.

7. Figure 6 - right panels should perhaps use another color scheme. I found the same to be confusing.

In our revised manuscript, we have changed the color scheme for all three right panels in Figure 6 (Figure 5 in the revised manuscript).

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Quantifying projected changes in runoff variability and flow regimes of the Fraser River Basin, British Columbia

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Abstract. In response to ongoing and future-projected global warming, mid-latitude, nival river basins are expected to transition from a snowmelt-dominated flow regime to a nival-pluvial regime with an earlier spring freshet of reduced magnitude. There is, however, a rich variation in responses that depends on factors such as the topographic complexity of the basin and the strength of maritime influences. We illustrate the potential effects of a strong maritime influence by studying future changes in cold season flow variability in the Fraser River Basin (FRB) of British Columbia, a large extratropical watershed extending from the Rocky Mountains to the Pacific Coast. We use a process-based hydrological model driven by an ensemble of 21 statistically downscaled simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) following the Representative Concentration Pathway (RCP) 8.5.

Warming under RCP8.5 leads to reduced winter snowfall, shortening the average snow accumulation season by about one-third. Despite this, large increases in cold season rainfall lead to unprecedented cold season peak flows and increased overall runoff variability in the VIC simulations. Multivariate linear regression analysis further reveals a rainfall increase in the cold season as a

dominant climatic driver in the Coast Mountains contributing 60% to mean runoff change in the 2080s. At the main outlet to the basin, cold season runoff increases by 70% by the 2080s and its interannual variability more than doubles compared to the 1990s, suggesting substantial challenges for operational flow forecasting in the region. Furthermore, the application of a snowmelt pulse detection algorithm classifies the entire FRB as a snow-dominated runoff regime in the 1990s with 45% of the basin area transitioning to primarily rain-dominated in the 2080s. While these projections are consistent with the anticipated transition from nival to nival/pluvial in the FRB, the marked increase in cold season runoff is likely linked to more frequent landfalling atmospheric rivers in the region projected in the CMIP5 models, providing insights for other maritime-influenced extratropical basins.Canada's Fraser River Basin (FRB), the largest watershed in the province of British Columbia, supplies vital freshwater resources and is the world's most productive salmon river system. We evaluate projected changes in the FRB's runoff variability and regime transitions using the Variable Infiltration Capacity (VIC) hydrological model. The VIC model is driven by an ensemble of 21 statistically downscaled simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5), for a 150-year time period (1950-2099) over which greenhouse gas concentrations follow the CMIP5 Representative Concentration Pathway (RCP) 8.5. Using mean and standard deviation (variability) metrics, we emphasize projected hydroclimatological changes in the cold season (October to March) over different sub-basins and geoclimatic regions of the FRB.

Warming consistent with the RCP8.5 scenario would lead to increased precipitation input to the basin with higher interannual variability and considerably reduced winter snowfall shortening the average snow accumulation season by about 38%. Such changes in temperature and precipitation will

~~increase cold season runoff variability leading to higher cold season peak flows. In the lower Fraser River, cold season runoff will increase by 70% and its interannual variability will double compared to the 1990s, presenting substantial challenges for operational flow forecasting by the end of this century. Cold season peak flows will increase substantially, particularly in the Coast Mountains, where the peak flow magnitudes will rise by 60%. These projected changes are consistent with a basin-wide transition from a snow-melt driven flow regime to one that more closely resembles a rainfall driven regime. This study provides key information relating to projected hydroclimate variability across the FRB, describes potential impacts on its water resources, and assesses the implications for future extreme hydrological events.~~

Keywords: Climate change, hydrological modelling, runoff, snow, ~~Fraser River~~ mid-latitude basin, Fraser River Basin

1 Introduction

Climate change will continue to modify the hydrology of mid-latitude, mountainous river basins especially those with strong maritime influences. The hydrologic response to increasing temperature and changing precipitation phase will be quite distinct in these basins depending mostly on their topographic features and intensifying maritime influences. One such basin is the ~~The~~ Fraser River Basin (FRB) in the province of British Columbia, Canada, one of ~~is one of~~ the largest ~~watershed~~watershedss draining the western Cordillera of North America (Benke and Cushing, 2005). Extending from the Pacific coast to the continental interior, i~~I~~t spans 240,000 km^2 of diverse ~~landscapes including~~landscapes including dry interior plateaus bounded by the Rocky Mountains to the east and the maritime influenced Coast Mountains ~~to the~~ in the west. Its elevation ~~-~~ranges from sea level to 3954 m at its tallest peak, Mt. Robson in the Rocky Mountains (Benke and Cushing, 2005). Descending at Fraser Pass near Blackrock Mountain, the Fraser River runs 1400 km before draining into the Strait of Georgia and Salish Sea at Vancouver, British Columbia (BC) (Schnorbus et al., 2010). ~~The FRB's rich diversity and abundance of natural resources yield economic opportunities and prosperity related to agriculture, fishing, forestry, mining, hydropower production, tourism and recreation (Benke and Cushing, 2005). As an extensive freshwater aquatic ecosystem, it remains the most important salmonid-producing river system in North America, sustaining the largest migrations of Pacific Ocean sockeye salmon in the world (Labelle, 2009; Eliason et al., 2011). The Fraser River also forms the aquatic habitat of North America's largest wild population of white sturgeon now listed as an endangered species due to its declining populations (Scott and Crossman, 1973; McAdam et al., 2005; Hildebrand et al., 2016).~~

Over the past 60 years, mean annual surface air temperature in the FRB has risen by 1.4°C modifying the FRB's natural water cycle (Kang et al., 2014). Impacts of this warming include reductions in snow accumulation~~s~~ (Danard and Murty, 1994), decline<u>s</u> in the contribution of snow to runoff generation (Kang et al., 2014) and earlier melt-driven runoff with subsequent reductions in summer flows (Kang et al., 2016). The corresponding changes in mean flow (Danard and Murty, 1994; Morrison et al., 2002; Ferrari et al., 2007; Kang et al., 2014, 2016) have been accompanied by considerable amplification in the interannual variability~~ of the flow~~ over recent decades across many streams and rivers in the FRB (Déry et al., 2012).

<u>Over land</u>~~In general~~, the dominant climatic drivers of water availability are precipitation, temperature, and evapotranspiration with the relative importance of each varying by geographic location. Projected warming will likely result in considerable changes in mean evapotranspiration and precipitation (Collins et al., 2013). Along with mean precipitation, its variability is also expected to increase on daily to interannual timescales over almost all global land areas in response to global warming (Pendergrass et al., 2017).~~–~~ In the FRB, further warming will continue to modify the partitioning of precipitation phase~~, decreasing the overall snow to rain ratio (Islam et al., 2017)~~. <u>The hydrologic response to warming will be influenced by two possibly confounding factors, the change of snow to rain ratio and the very substantial increase in atmospheric moisture supply (atmospheric rivers) to the North American west coast as anticipated in the future projections (Payne and Magnusdottir, 2015; Radic et al., 2015; Warner et al., 2015; Warner and Mass, 2017).</u> Such changes, along with expected increases in precipitation variability, will alter the magnitude and timing of seasonal flows in

the FRB and may increase the potential for flooding ~~(Curry et al., 2018, in preparation)~~, thus threatening the natural, ecological and social systems within the basin.

Recent studies such as ~~Recent studies such as~~ Shrestha et al. (2012), Kang et al. (2014, 2016), and Islam et al. (2017) have evaluated observed and projected changes in runoff~~the~~ timing and magnitud~~e~~e ~~of summer runoff~~ in the~~focusing on~~ FRB under changing climate. Using the mean climatological hydrographs, they found advances of spring freshets and reduced summer peak flows in the FRB's major tributaries. In contrast, little attention has been focused on the detection of changes in flow variability and low flow season (fall-winter) magnitudes. Assessing how the FRB's flows~~s~~ variability will change in the future~~,~~, requires rigorous scientific attention. This includes the use of advanced downscaling methods and simulation tools along with improved future climate projections. To understand future changes in the peak flow mechanisms and its predictability, it is crucial to quantify projected changes in ~~FRB runoff~~flow variability on daily and interannual timescales induced by changes in the proportionality of snowfall to rainfall and snowmelt-driven runoff timing.

Changes in air temperatures, precipitation and resulting runoff will also modify the characteristics of FRB flow regimes. Currently, the hydrologic response in the FRB varies considerably across the basin due to its complex topography and maritime influences that differentiate its flows mainly into snow-dominant or hybrid (rain and snow) regimes (Wade et al., 2001). These distinct flow regimes are expected to change under future climate change with hybrid or rainfall-dominant flow regimes becoming more prevalent. The detailed quantification of such flow regime transitioning is not well appreciated in the current literature, which is especially important for the FRB that could have implications for reginal adaptation measures and water resources management in the region.

The principal goals of this study are therefore: 1) to investigate how projected climatic change affects the mean state and daily time scale variability of FRB flows, 2) to illustrate the potential effects of a strong maritime influence on cold season flows that is punctuated by frequent, intensifying atmospheric rivers, and ~~2~~3) to evaluate the likelihood of transitions from snowmelt-dominant to hybrid snowmelt-rainfall or rainfall-dominant flow regimes in a spatially explicit manner across the basin.~~-~~ The latter is achieved via the use of a snowmelt pulse detection technique to distinguish between distinct runoff regimes, applied within a semi-distributed, macroscale hydrological model driven by 21 downscaled simulations of future climate from Global Climate Models (GCMs). This approach provides insight into the location and timing of these transitions, while the use of many different GCM-driven hydrological simulations allows a concomitant estimate of the associated uncertainties. The present work is the first of two papers analysing the same set of ~~CMIP5 VIC~~hydroclimatic simulations over the FRB. The present~~is~~ effort deals with features of the transition from seasonal snow to a hybrid snowmelt/rainfall runoff regime, with special attention to the changes in snowmelt dynamics and daily runoff variability. A~~Our~~ forth~~up~~coming paper (~~Curry et al., ~~in preparation) addresses the consequences of these changes for river discharge at the main outlet to the FRB at Hope, BC, including a formal flood frequency (extreme value) analysis for the 21^{st} ~~-~~century.

2. Domain, Modelling Framework, and Methodology

2.1 Study ~~domain~~Domain

Our primary focus ~~was~~ is on the Fraser River main stem at Hope, BC (Lower Fraser, LF) since it integrates flows from about 94% of the FRB area, and is the location of the longest instrumental streamflow record for the basin's main stem. We also consider~~ed~~ four mountainous sub-basins (the Upper Fraser (UF), Quesnel (QU), Chilko (CH) and Thompson-Nicola (TN) Rivers; Fig. 1a, Table 1), along with three geo~~-~~climatic regions~~ within the FRB~~ (the Interior Plateau, the Rocky Mountains, and the Coast Mountains; Moore, 1991, Fig. 1b). These regions represent the range of distinctive physiographic and hydro~~-~~climatic conditions found within the FRB. The FRB exhibits snowmelt-dominant flows in ~~the Interior Plateau and Rocky Mountains~~all sub~~-~~regions in late spring and early summer in the current climate. In addition~~However~~, several catchments in the Coast Mountains and in the ~~Lower Mainland~~LF exhibit a secondary runoff peak owing to Pacific synoptic~~frontal~~ ~~rain~~storms often associated with atmospheric rivers in October-December. ~~Together, these regions represent the range of distinctive physiographic and hydro-climatic conditions found within the FRB.~~

2.2 Climate Models, Observational Data, and Statistical Downscaling

We used statistically downscaled climate simulations from 21 GCMs (Supplementary Table 1) submitted to the Coupled Models Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). A single realization was used from each GCM, driven by historical greenhouse gas and aerosol forcing up to 2005 and Representative Concentration Pathway 8.5 (RCP 8.5) forcing subsequently. GCM-simulated daily precipitation and daily maximum and minimum surface air temperature for the period

1950-2099, downscaled to 10-km spatial resolution, were obtained from the Pacific Climate Impacts Consortium (PCIC, 2017). Downscaling is necessary to apply the coarse-scale GCM results (ranging from 1.1° to 3.7° in longitude and 0.9° to 2.8° in latitude; Supplementary Table 1) at the finer scale of the hydrologic model, which is configured at 0.25° horizontal resolution in both latitude and longitude. The downscaling process also corrects GCM biases in air temperature and precipitation relative to the ANUSPLIN station-based daily gridded climate dataset (Hopkinson et al., 2011; NRCan, 2014). ANUSPLIN refers to the gridding technique, which is based on the Australian National University spline interpolation method (Hutchinson et al., 2009)as the downscaling target (described below). This dataset contains gridded daily maximum and minimum air temperature (°C), and total daily precipitation (mm) data for the Canadian landmass having at a spatial resolution of 0.0833° (~about 109.26 km × 10 km, depending on latitude) in the meridional direction and one that varies proportionally to the cosine of latitude in the zonal direction. The CMIP5 projections were initially downscaled from the native GCM resolutions to the resolution of ANUSPLIN for the bias correction step.Daily wind speed grids are interpolated from coarse-scale (2.5° latitude × 2.5° longitude) daily wind speeds at a 10-m height above ground from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis

PCIC performed the dDownscaling was performed with the Bias Correction/Constructed Analogue Quantile Mapping method, version 2.0 (BCCAQ2), a hybrid approach that combines the bias corrected constructed analogues (BCCA; Maurer et al., 2010) and bias corrected climate imprint (BCCI; Hunter and Meentemeyer, 2005) techniques. BCCA bias-corrects the large-scale daily GCM temperature and precipitation using quantile mapping to a target gridded observational product (here, ANUSPLIN), aggregated to the GCM grid-scale and then integrates spatial information by regressing each daily large-scale temperature or precipitation field on a collection of fine-scale historical analogues selected from ANUSPLIN. Using this relationship, fine-scale patterns are generated from the target dataset. In parallel, BCCI applies quantile mapping to daily GCM outputs that have been interpolated to the high-resolution grid based on “climate imprints” derived from long-term ANUSPLIN climatologies (Hunter and Meentemeyer, 2005). BCCA produces results that may be subject to insufficient temporal variability whereas BCCI can contain artifacts due to spatial smoothing. In BCCAQ, daily values within a given month from BCCI are reordered according to their corresponding ranks in BCCA, improving the spatiotemporal variability (Werner and Cannon, 2016). BCCAQ2 further refines BCCAQ by ~~reducing the magnitude biases by the~~ substitution of quantile delta mapping instead of regular quantile mapping in BCCI to preserve the magnitude of projected changes over all quantiles from the GCM in the downscaled output (Cannon et al., 2015; Li et al., 2018). The performance of the ~~This method generates realistic fine-scale spatial variability and preserves the climate change signal for temperature and precipitation of the underlying climate model projections (Cannon et al. 2015, Li et al., 2018).~~

~~The CMIP5 projections were initially downscaled from the native GCM resolutions to the 0.0833° resolution of ANUSPLIN, then averaged to a resolution of 0.25° to match the VIC model grid. However, it should be noted that a~~Abias correction method depends mainly on the ~~, however,~~target dataset used for corrections.~~, and i~~In this respect, the known biases of ANUSPLIN (e.g., the low precipitation bias ~2-5 mm day^{-1} at high elevations~~,~~ compared to other datasets; Islam et al., 2017) are transmitted to the downscaled model results via BCCAQ2.

By better representing historical daily variability and also the antecedent drivers of daily streamflow extremes, BCCAQ2 represents an advance over the Bias Correction and Spatial Downscaling (BCSD) method used in Islam et al. (2017). While BCSD reflects historical intra-month variability via stochastic sampling, BCCAQ2 preserves climate model skill in simulating daily variability, where and when it exists.

2.3 Variable Infiltration Capacity (VIC) Model and Simulation Strategy

We used t~~T~~he semi-distributed macroscale Variable Infiltration Capacity (VIC) model (Liang et al., 1994, 1996) ~~was used~~ to simulate hydrological processes in the FRB. The VIC model has been extensively used for climate change research over various river basins (e.g. ~~due to its process-based structure that allows the model to respond to changing air temperature and precipitation in a more physically realistic way than empirically-based or lumped models. It has been commonly applied to assess water resources, land atmosphere interactions and hydrological responses over various river basins globally (e.g., Nijssen et al., 2001a, b; Haddeland et al., 2007;~~ Adam et al., 2009; Cuo et al., 2009; Hidalgo et al., 2009; Elsner et al., 2010; Gao et al., 2010; Wen et al., 2011; ~~,~~ Schnorbus et al., 2011; Zhou et al., 2016~~). It is also used to evaluate climate change driven hydrologic responses in the basins having snowmelt-dominant runoff (Christensen and Lettenmaier, 2007; Hidalgo et al., 2009; Cherkauer and Sinha, 2010; Schnorbus et al., 2011; Islam et al., 2017~~) including the FRB~~. It has been successfully implemented, calibrated and evaluated for the FRB as reported in Shrestha et al. (2012),~~ (~~-~~Shrestha et al., 2012; Kang et al., ~~(~~2014, 2016;~~), Islam et al. (2017) and~~ Islam et al., 2017; Islam and Déry, ~~(~~2017). It conserves

~~The VIC model conserves~~ surface water and energy balances for large-scale watersheds such as the FRB (Cherkauer et al., 2003). ~~In addition to the daily meteorological forcings mentioned in Sec. 2.2, the model also requires a number of static gridded fields to characterize soil type, vegetation type, and elevation.~~ VIC simulates the sub-grid variability by dividing each 0.25° × 0.25° grid cell into several elevation bands (Nijssen et al., 2001~~a~~), each of which is further subdivided into a number of tiles that represent different land surface types, producing a matrix delineated by topography and land surface type. Energy and water balances and snow are determined for each tile separately (Gao et al., 2009). The VIC model is coupled ~~(offline)~~ to a routing scheme (Lohmann et al., 1996, 1998a, b) ~~adapted from Wu et al. (2011)~~ that approximates the ~~known~~ runoff from gridcells using a known channel network (Wu et al., 2011) ~~runoff from gridcells (accumulated from tiles within grid boxes)~~. Streamflow produced in this way is extracted at outlet points of specific sub-basins of interest (Lohmann et al., 1996, 1998a, b).

After the CMIP5 projections ~~were~~were bias-corrected and downscaled to the ANUSPLIN grid, the resulting fields were averaged to a resolution of 0.25° × 0.25° to match the VIC model grid. In addition to the daily meteorological forcings mentioned in Sec. 2.2, VIC also requires daily wind forcing and a number of static gridded fields (as reported in Kang et al., 2014) to characterize soil type, vegetation type, and elevation. The wind fields ~~are~~were obtained by interpolating ~~interpolated to the VIC grid from~~ coarse-scale (2.5° × 2.5°) daily wind speeds at 10-m height above ground from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al., 1996) to the VIC grid.

Calibration and validation of the VIC model for this study was conducted through retrospective hydrologic simulations from 1979 to 2006 using ANUSPLIN re-gridded to the ~~the VIC grid directly~~0.25°

~~model~~ horizontal resolution of VIC. The model was run in water balance mode using a daily time step, 3 soil layers and –10 elevation bands in each gridcell. Model parameters were calibrated based on an optimization process that minimizes the difference between observed and simulated hydrographs using the Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970). The daily NSE values for the entire FRB and its sub-basins range between 0.64 to 0.90 in the calibration time period revealing reliable application of the VIC model (see Table 2 in Islam et al., 2017). Figure 2 describes the full experimental setup while further details of the VIC model implementation and application to the FRB are described in Islam et al. (2017) and Islam and Déry (2017).

-The calibrated VIC model was integrated at a daily time step from 1950 to 2099 using statistically ~~-~~downscaled daily precipitation, maximum and minimum air temperature from each of the 21 downscaled CMIP5 GCM simulations (using historical and RCP 8.5 forcing) at 0.25° horizontal resolution. ~~Three 30-year periods were analysed in detail: the 1990s (1980 to 2009), 2050s (2040 to 2069) and 2080s (2070 to 2099). Relative changes were computed using the 1990s as a base period.~~ We initialized e~~E~~ach simulation ~~was initialized~~ by running VIC for five years using the 1950 meteorological forcings to allow the model to spin-up. 30-year time periods were analysed in detail: the 1990s (1980 to 2009), 2050s (2040 to 2069) and 2080s (2070 to 2099) and changes relative to the 1990s were described.

2.4 Analysis Methods

2.4.1 Analysed Variables

Our ~~The~~ analysis focuse~~d~~s primarily on VIC-simulated daily values of total runoff computed as the sum of baseflow and surface runoff at each model gridcell (~~as~~ VIC does not simulate sub-surface flows between gridcells). At the basin~~'s~~ outlet, routed streamflow ~~was~~ is converted to areal runoff by division of ~~ding it by~~ the corresponding basin ~~or sub-basin~~ area and then converting ~~it~~ to precipitation equivalent units. To support our results of projected changes in runoff, we evaluate several other variables such as total precipitation, ~~(~~snowfall, ~~and~~ rainfall, ~~)~~ ~~and~~ air temperature, ~~forcings~~ and VIC-~~-~~simulated snow water equivalent (SWE) and snowmel~~t~~t ~~were also evaluated~~. ~~Snowfall and rainfall variables were extracted from VIC output.~~ VIC uses~~s~~ specified air temperature thresholds to determine precipitation phase. In the current implementation, total precipitation ~~was~~ is classified as~~partitioned into~~ 100% rainfall for temperature above 1.5°C, 100% snowfall for temperatures below -0.5°C and is partitioned as a mixture of rainfall and snowfall for temperatures between these two thresholds.

We perform analyses ~~Analyses were performed u~~using the water year, defined here as 1 October to 30 September of the following calendar year. ~~We defined~~T~~t~~he cold season is defined as the period from 1 October to 31 March, except for the cold season peak flow analysis, where the end of the cold season is taken to be the day when the 3-day running mean daily air temperature first exceeds 0°C at each gridcell between 1 and 31 March. Using the additional condition based on air temperature helps to identify the end of the cold season more precisely in each year. The last day of the cold season therefore depends on the~~–~~ air temperature criterion. A 3-day running mean avoids events when daily mean temperature suddenly exceeds 0°C for only a single day within the cold season. The snow accumulation season comprises days of the cold season when daily SWE accumulation~~s~~, the difference between daily snow accumulation and snow melt, exceeds~~is >~~ 1 mm.

2.4.2 Mean and Variability Calculations

Considering each model realization as a valid approximation to the real climate, we use ~~we characterize~~ the multi-model ensemble (MME) results~~–~~ summarised with ~~by~~~~through~~ four statistics: the temporal mean and standard deviation of each model, and the multi-model mean and inter-model standard deviation. Specifically, for a daily variable *x* and model *i*, the mean climatology $\bar{x}_i$ and the interannual standard deviation $\bar{S}_i$ ~~was~~is calculated for ~~each model~~ each 30-year analysis period (i.e. 1990s, 2050s, and 2080s). The MME ~~as:~~

$$\bar{x}_i = \frac{1}{T}\sum_{t=1}^{T} x_{it} \qquad (1)$$

where x is the variable of interest, i indicates ensemble member and t represents time. The interannual standard deviation S_i for each model was calculated as:

$$S_i = [\frac{1}{T-1}\sum_{t=1}^{T}(x_{it} - \bar{x}_i)^2]^{\frac{1}{2}} \qquad (2)$$

Using Eqs. (1) and (2), the MME mean climatology $\bar{x}$ and MME mean meanss of these quantities, $\bar{x}$ and $\bar{S}$ MME standard deviation , $\bar{S}$ wereareas then estimatedthen calculated as:

$$\bar{x} = \frac{1}{I}\sum_{i=1}^{I}\bar{x}_i \qquad (3)$$

$$\bar{S} = \frac{1}{I}\sum_{i=1}^{I} S_i \qquad (4), \text{ and.}$$

where I = 21 is the number of simulations. tThe inter-model spread in $\bar{x}$ and $\bar{S}$ was , S_{MME} S_{MME}, is characterizestimated by thea 5-95% models rangeconfidence interval in $\bar{x}_i$. AEquation (2) was used to calculate annual (or cold season) variability within each 30-year time period was calculated by evaluating the interannual standard deviation for each day of the water year in the 1990s, 2050s and 2080s time periods. Equations (3) and (4) were used for both the MME mean and the MME mean interannual

The effect of transient warming within the 2050s and 2080s periods in the RCP8.5 scenario was is removed by subtracting the least squares linear trend from each time series before calculating its variability. Variability in 7-day runoff was is also computed using a 7-day running mean of the window from daily runoff time series.

In an attempt to better understand the contributions of future air temperature and precipitation change to runoff change in the simulations, we use a multivariate linear regression (MLR) analysis, following a similar approach by Kapnick and Delworth (2013). We decompose the cold season runoff ROF into separate contributions from rainfall Rn, snowfall Sn, mean air temperature T and residual E on a monthly basis as follows:

$$\frac{\Delta ROF_{n,m}}{ROF_{m,1990s}} = a\frac{\Delta Rn}{ROF_{m,1990s}} + b\frac{\Delta Sn}{ROF_{m,1990s}} + c\frac{\Delta T}{ROF_{m,1990s}} + E \qquad (1)$$

where a, b and c are regression coefficients corresponding to the rainfall, snowfall and mean air temperature, $m = 1, \ldots, 6$ denotes the cold season month (Oct-Mar), and $n = 2070, \ldots, 2099$ represents the water year. $ROF_{m,1990s}$ represents the multi-year mean runoff for each month in the 1990s time period. The regression model is fitted for each gridcell and model independently using detrended monthly anomalies from 2070-2099. Spatial averages over the FRB and geoclimatic regions only use gridcells for which the MLR is statistically significant with a p-value < 0.05. The relative contribution of each variable to future runoff change is obtained by normalizing the area average of each term in Eq. (1) by the corresponding area-averaged ΔROF. We only consider the lag-0 correlation between the driving and response variables considering that monthly time resolution is sufficient to encompass any lags at the local grid scale.

~~The 5% and 95% lower and upper bounds for 90% confidence intervals of the MME mean were calculated using the standard deviation among ensemble members where the degrees of freedom are the ensemble members (I-1). A t-test statistic (p < 0.05) was used to test the significance of the linear regression slopes.~~

2.5 Snowmelt Pulse Detection

Apart from the analysis of changes in cold season flow variability, we estimate the flow regime transitions that are usually induced by snowpack reduction under increasing summer temperatures. We investigate transitions to new hydrological regimes in the FRB using th~~We used ~~the Snowmelt Pulse (SP) detection technique (Cayan et al., 2001; Fritze et al., 2011)~~ to investigate the potential for transitions to new hydrological regimes in the basins of interest~~. This technique separates snowmelt-dominant flows from rainfall-dominant flows using the maximum cumulative flow departure from mean flow within the defined time window. The SP date, which is defined as the day when the cumulative departure from that water year's mean flow is most negative, provides a way for determining the time at which increased ablation in a snowmelt-dominant basin initiates the transition from low winter base flows to high spring flow (freshet) conditions. While accumulation of flow departures ~~commenced ~~for each water year commences on 1 October, we only consider~~ed~~ those SPs occurring between 1 March (water-day 151; ~~(~~152 for leap years~~)~~) and 15 June (water-day 238; ~~(~~239 for leap years~~)~~), the present-day freshet period, so as to exclude runoff pulses induced by rainfall events~~ outside the (present-day) freshet period~~. Runoff is r~~R~~ainfall-dominant ~~runoff is indicated We also ignored SPs~~ when the ratio of the area of positive cumulative flow departure (indicating rainfall events) to the area of negative departure between water-days 151 and 238 ~~was~~ is greater or equal to unity.~~, as this also indicates rainfall-dominant runoff.~~

A~~s a~~n illustration of the robustness of~~, we applied~~ the algorithm to different river flow regimes using ~~daily observed~~historical data is shown in Supplementary Fig. 1.~~ acquired from the Water Survey of Canada's Hydrometric Dataset (HYDAT; Water Survey of Canada, 2018). As an example, we show the cumulative departures from annual mean flow for two distinct flow regimes, i.e. Capilano River Above Intake (Fig. 3a) and Fraser River at Hope (Fig. 3b) for selected years in the 1914-2010 period.~~ The application of the algorithm reveals the presence of a SP in the snowmelt-dominant system~~Fraser River at Hope~~ in all selected years, while for the rainfall-dominant system~~Capilano River, an example of a rainfall-dominant system~~, SPs are quite rare.

To explore potential regime changes in the FRB, we evaluate~~d~~ and compare~~d~~ the fraction of years for which SPs a~~we~~re recorded within each analysis period (1990s, 2050s, 2080s) at~~, for~~ each 0.25° gridcell and for all CMIP5-VIC simulations (with sample size of 21 CMIP-VIC simulations × 30 years = 630 years). In each simulation, each gridcell ~~was~~ is classified into one of four snow-dominant categories (SDCs) as defined by Fritze et al. (2011): SDC1 (clearly rain-dominant: SP occurrence in < 30% of water years); SDC2 (mostly rain-dominant, SP occurrence ≥ 30% but < 50%); SDC3 (mostly snowmelt-dominant, SP occurrence ≥ 50% but < 70%); and SDC4 (clearly snowmelt-dominant, SP occurrence ≥ 70%). This allowed spatial comparison~~s~~ of regime projections for the 2050s and 2080s

~~and spatial distributions of gridcells in each SDC relative~~ with the regime characteristics of ~~to those from~~ the 1990s ~~base period~~. Finally, the SDC results a~~we~~re aggregated by geoclimatic region.

Overall, this study expands on Islam et al. (2017) who used 12 driving GCMs and only considered projections up to the 2050s to quantify changes in the FRB's mean runoff. Here we evaluate projected changes in runoff variability and flow regimes by the end of this century utilizing a set of 21 CMIP5 GCMs downscaled and bias-corrected using an advanced BBCAQ2 method and an efficient snowmelt pulse detection algorithm.

3 Results

We ~~examine~~ first examine the projected changes in the mean and interannual variability of precipitation over the different geographic regions of the FRB~~FRB~~. Next, we explore the consequences of these changes for runoff means and variability at various temporal and spatial scales and estimate the contribution~~.~~ of key drivers that control changes in runoff mean. This is followed by a discussion of changing flow regimes over the FRB at regional and sub-basin scales.

3.1 Projected Changes in Precipitation and Snow-to-Rain Ratio

The MME mean precipitation, spatially ~~-~~averaged over the FRB~~'s gridcells~~, ~~increases~~ rises steadily over the simulation period, increasi~~reachi~~ng~~by~~ nearly 15% in the 2080s relative to the 1990s ~~base period both in annual mean and~~ in the cold season (Fig. 3~~4~~a~~, b~~). The changes are largest in the northern and eastern FRB (Supplementary Fig. 2~~1~~a, c) reaching up to 20% ~~in the cold season~~ (Supplementary Fig. 2~~1~~c). The MME mean precipitation interannual variability ~~over the FRB~~ increases by 15%~~continuously~~ with warming between 2 and 5 °C, then increases more sharply to over 25% as this level of warming is exceeded (after the 2060s) ~~when spatially-averaged over the whole FRB and its sub-regions~~ (Fig. 3~~4~~a~~, b~~). ~~The relationship between~~Thus cold season precipitation variability ~~and FRB mean temperature is almost~~increases approximately linearly at ~~with~~ a rate of ~~~change of about~~ 4% °C^{-1} towards the end of the 21st century compared to the 1990s, about double the rate of change of ~~. The rate of change of precipitation interannual variability is as large as the~~ MME mean precipitation. The larger increase in p~~P~~recipitation variability ~~increases more substantially in the cold season (Fig. 34ab) with increases of ~20%- to ~80% in the interior and northern FRB (Supplementary Fig. 21d). In the cold season, the increase in interannual variability is greater than that in~~compared with mean precipitation is seen throughout the simulation period for both the entire~~whole~~ FRB and its three geoclimatic regions. ~~Such increases in the precipitation variability under the projected air temperature increase suggest a somewhat more variable future climate at the end of this century~~~~However~~Nevertheless, the models' 5-95% ~~confidence intervals~~ tend to overlap (except in the Interior Plateau; Fig. 3a, right), reflecting the considerable spread amongst models.

The partitioning of MME mean total precipitation into rainfall and snowfall reveals substantial increases in daily rainfall towards the end of the 21st century across the Coast Mountains, Interior Plateau and Rocky Mountains (Fig. 4~~5~~a, c, e). The increase in rainfall emerges prominently in the Coast Mountains in the latter half of the 21st century, especially in the cold season. Simultaneously, snowfall decreases (Fig. 4~~5~~b) markedly in this region~~, which can be attributed to reduced frequency of future subfreezing air temperatures~~. S~~Decreases in s~~nowfall also ~~occur~~ decreases in the Interior Plateau and Rocky Mountains (Fig. 4~~5~~d, f), but to a lesser degree than the Coast Mountains~~is smaller~~ in~~where the~~

~~latter region,~~ ~~remain more resilient to snowfall declines~~ probably due to persistent cold ~~temperaturesconditions~~temperatures at the higher elevations that dominate in this region~~there~~ (Table 1).

Warming temperatures and reduced snowfall induce considerable changes in the snow accumulation and ablation seasons and in snowmelt (Fig. 5~~6~~). Day-to-day SWE accumulation declines while~~and~~ its seasonality shifts~~decline~~ ~~towards the end of~~over the 21st century, again with more prominent changes in the Coast Mountains relative to other regions (Fig. 5~~6~~a). The length of the snow accumulation season is ~~shortens by~~ about 38% shorter on average in the 2080s for all geoclimatic regions relative to the 1990s ~~base period~~ with a reduction from nearly 80 to 50 days ~~-~~in the Coast (Fig. 5~~6~~a) and Rocky Mountains (Fig. 5~~6~~e), and from 65 to 40 days in the Interior Plateau (Fig. 5~~6~~c). The magnitude and seasonality of snowmelt (Fig. 5~~6~~b, d, f), which is responsible for generating high flows typically in May or June, shows earlier snowmelt freshets in the future and ~~decreases in~~reduced snowmelt volume. Changes in the partitioning of precipitation between rainfall and snowfall greatly impact the seasonal SWE distribution, consistent with the findings of Islam et al. (2017). While snowmelt during the freshet ~~events~~ diminishes overall in the future ~~overall~~, unprecedented snowmelt events begin to appear during the cold season in the Coast Mountains (Fig. 5~~6~~b) ~~towards the end of the 21st century~~by the 2050s, like~~possib~~ly due to more frequent warming episodes or perhaps increases in rain-on-snow events.

3.2 Projected Changes in Runoff Mean, Variability and Seasonality

~~As with precipitation variability, the FRB's runoff variability changes systematically with warming both in the annual mean and in the cold season (Fig. 34bc, d). The~~C~~c~~hanges in ~~the~~ cold season runoff ~~variability~~ (Fig. 3b) in the FRB are~~is~~ driven by both ~~the~~ warming and increases in the~~precipitation~~ mean and ~~its~~ variability of precipitation (Fig. 3a). Consequently, the CMIP5-VIC simulations display larger increases in runoff variability than in mean runoff throughout the simulation period for the entire FRB, Interior Plateau and Rocky Mountains regions. ~~However, t~~This is not, however, the case in the ~~The rate of change of runoff variability and mean with respect to the amount of warming in the Coast Mountains, Interior Plateau and Rocky Mountains suggests that the change in~~ Coast~~al~~ Mountains, where the increase in mean runoff (55% by the 2080s) is substantially larger than that~~e change~~ in runoff variability (40%)~~, unlike in the other two regions~~. This finding helps to explain why the increase in future runoff is ~~so~~ much more evident in the Coast Mountains region (~~see ff.,~~ Fig. 6~~8~~).

The substantial increases in cold season runoff are summarized by sub-region and sub-basin in Table 1. Of these, Thompson-Nicola exhibits the largest relative change (+140%) from the 1990s to 2080s, although it is historically the driest of the sub-basins, while the runoff at Hope increases by 71% between the same epochs. With respect to annual runoff, only the Coast Mountains and the Chilko~~CH~~ sub-basin display substantial increases (but much smaller in relative terms than cold season increases), with little change elsewhere (Supplementary Table 2~~3~~). The same qualitative results hold for runoff variability as for means, both in the cold season and annually (Supplementary Table 2~~3~~). In addition, by the 2080s, the runoff mean and standard deviation more than double over 83% and 71% of the FRB, respectively~~In addition, an inspection of results at the grid scale reveals that, by the 2080s, there is a more than doubling in mean runoff over % of the FRB area, and in standard deviation over % of the FRB~~ (Supplementary Fig. 3~~4~~).~~The MME projected hydrograph for the Fraser River at Hope shows more runoff in the late winter and spring owing to the earlier onset of spring snowmelt, which advances by~~

nearly 25 days (consistent with Islam et al., (2017)) in the 2050s and 40 days in the 2080s relative to the 1990s (Fig. 67a). The magnitudes of the annual peak and post-peak flows are, however, progressively diminished in the future periods, with reduced discharge until early October. These changes imply earlier recession to progressively lower flows in summer when salmon are migrating up the Fraser River.

Daily mean runoff in the UF, QU, TN and CH sub-basins exhibits similar features of future change (Supplementary Fig. 32). The advance in the timing of the annual peak flow in these sub-basins is slightly less than for the FRB as a whole (Supplementary Table 2) (~20 days for UF, ~18 days for QU, ~25 days for TN and ~35 days for CH), presumably due to their higher mean elevations. CH features a later freshet (by ~35 days) in the base period compared to the other three sub-basins. This reflects the fact that its flow is partially controlled by the Coast Mountains with influence from the Pacific Ocean along with the presence of large lakes and extensive glaciers in the basin. While the CH sub-basin also features an advance of peak runoff in the future, it exhibits only slightly reduced peak flow magnitudes, unlike the other sub-basins and the FRB as a whole (Supplementary Fig. 32j and Fig. 67a).

In the Rocky Mountains and Interior Plateau along with the UF, QU, TN and LF sub-basins, annual runoff remains stable or increases slightly (Supplementary Table 23) but cold season runoff increases substantially (Table 1). In the Coast Mountains and the CH sub-basin, cold season runoff increases in the future owing to robust rainfall increases year-round. The drainage area mean cold season runoff for the Fraser River at Hope increases from 83±2 mm yr^{-1} in the 1990s to 142±10 mm yr^{-1}

in the 2080s (Table 1). The substantial increase in cold season runoff accompanies corresponding increases in interannual variability by the end of this century (Table 1).

The changes in daily runoff variability (interannual variability of each day of water year) are modest in summer with small decreases that are consistent with corresponding runoff decreases (Fig. 67b). In contrast, variability increases substantially in the cold season with greater increases in the 2080s than in the 2050s for the Fraser River at Hope (Fig. 67b). Similar changes also emerge in the UF, QU, TN and CH sub-basins exhibiting increasing cold season variability with magnitudes comparable to the LF (Supplementary Fig. 32). The changes in daily variability in 7-day moving windows of daily runoff are fairly large in the cold season (Fig. 67c) revealing increased day-to-day flow fluctuations along with an increase in the interannual variability of daily variability in the 2050s and 2080s.

The slope is significantly positive between changes in cold season variability and elevations in each gridcell in the Coast Mountains and Interior Plateau geoclimatic regions revealing increasing runoff variability with rising elevations (Supplementary Fig. 3). The Rocky Mountains exhibit strong negative elevation dependency of runoff variability with a 30% reduction in runoff variability with every 1 km increase in elevation during the 2080s.

The future evolution of the annual cycle of daily runoff seasonality shows that while the dominant snowmelt-generated peak flow shifts earlier by ~1 month, noticeable cold season runoff events emerge in winter and spring at the end of the 21st century (Fig. 968). This is most pronounced in the Coast Mountains where fall-winter runoff events rival the summer peak runoff in magnitude (Fig. 698a). The spatially-averaged runoff over the Coast Mountains further highlights the strong increase in cold season peak runoff in this region (Supplementary Fig. 47). This increase in cold season peak runoff magnitude is simulated across the CMIP5-VIC ensemble (Fig. 7c). Apart from the increase in cold season peak runoff magnitude and its annual variability (Supplementary Fig. 75a), the corresponding peak flow occurs somewhat later with warming in the Coast Mountains, moving from late November (~water_-day 50) to the beginning of December (~water_-day 60) at the end of the 21st century (Supplementary Fig. 4b7b). Overall, as the climate warms, the cold season peak runoff date occurs later in the water year, and thus peak runoff also occurs later. SuchThis increase in cold season peak runoff magnitudes isare simulated by mostacross the CMIP5-VIC simulations ensemble (Supplementary Fig. 4c). Compared to the Coast Mountains, the changes in cold season peak flow timings are much larger in the Interior Plateau and Rocky Mountains probably due to more frequent winter rainfall events on snowpacks (Fig. 4 c and e).

Considering the significant changes in cold season runoff mean and variability, we further employed a multivariate linear regression model to decompose the cold season runoff variability into separate contributions from precipitation and temperature on monthly basis. This procedure allows us to determine the contribution of each key driver to the simulated runoff variability at individual gridcells. Overall, the regression models appear to perform well over whole FRB revealing dominance of temperature driven runoff changes. The multilinear regression model explains 70-90% of the total variance in runoff over a large portion of the basin. The general patterns of runoff trends of the regression model (Figs. 9a) are very similar to that of the MME simulation trends (Figs. 9b). Precipitation contributes to increases in runoff mostly in the Coastal Mountains (Fig. 9c) and over parts of the Rocky Mountains. Contribution of temperature to runoff trends is much higher than precipitation over most of the northern FRB and mountains. For both temperature and precipitation, runoff increase is greatest over Rocky and Coast mountains revealing that precipitation plays a crucial role in runoff changes under future warming. The MME projected hydrograph (routed streamflow) for the Fraser River at Hope (Fig. 86a) shows more runoff (estimated using the VIC routing scheme) in the late winter and spring owing to the earlier onset of spring snowmelt, which advances by nearly 25 days in the 2050s (consistent with Islam et al., (2017)) and 40 days in the 2080s relative to the 1990s. The magnitudes of the annual peak and post-peak flows are, however, progressively diminished in the future periods, with reduced discharge until early October. These changes indicate earlier recession to progressively lower flows in summer when salmon are migrating up the Fraser River.

Daily mean hydrographs (routed streamflow) in the Upper Fraser, Quesnel, Thompson-Nicola and Chilko UF, QU, TN and CH sub-basins exhibits similar features of future change as those seen at Hope (Supplementary Fig. 43). The advance in the timing of the annual peak flow in these sub-basins is slightly less than for the FRB as a whole (Supplementary Table 12), presumably due to their higher mean elevations and lower cold season temperatures. The CHChilko features a later freshet by ~35 days in the base period compared to the other three sub-basins. This reflects the fact that its flow is partially controlled by the Coast Mountains with influence from the Pacific Ocean along with the presence of of large lakes and extensive glaciers in the basin. Possibly due to these storage buffersfactors, the CHChilko sub-basin exhibits less of an advance in peak runoff in the future and only slightly reduced peak flow magnitude, unlike the other sub-basins and the FRB as a whole (Supplementary Fig. 43j and Fig. 86a).

The changes in daily runoff variability (interannual variability of each day of the water year) are modest in summer with small decreases that are consistent with corresponding runoff decreases (Fig. 86b). In contrast, the variability increases substantially in the cold season with greater increases in the 2080s than in the 2050s for the Fraser River at Hope (Fig. 8~~6~~b). Similar changes also emerge in the Upper Fraser, Quesnel, Thompson-Nicola ~~UF, QU, TN~~ and Chilko~~H~~ sub-basins that exhibit~~ing~~ increasing cold season variability with magnitudes comparable to the ~~LF~~Fraser River at Hope (Supplementary Fig. 4~~3~~). The changes in daily variability in 7-day moving windows of daily runoff are fairly large in the cold season (Fig. 8~~6~~c) revealing increased day-to-day flow fluctuations along with an increase in the interannual variability of daily variability in the 2050s and 2080s.

3.3 Key Climatic Controls of Runoff in the CMIP5-VIC Simulations

The MLR analysis (as described in section 2.4.2) ~~Considering the significant changes in cold season runoff mean and variability, we further employed a multivariate linear regression model to decompose the cold season runoff variability into separate contributions from precipitation and temperature on a monthly basis.~~~~air~~ ~~This procedure allows us to~~ determines the contribution of key climatic drivers such as ~~each~~rainfall, snowfall and mean air temperature ~~key driver~~ to the VIC simulated change in cold season mean runoff ~~variability~~ at each ~~individual~~ gridcells in the FRB. The response variables (rainfall, snowfall and temperature) used in the MLR equation, however, are almost certainly not independent given the direct effect of temperature on precipitation phase and snowmelt rate.

The regression model tends to overestimate the mean runoff change (Table 2) when compared with VIC simulations. O ~~O~~verall, however, the ~~regression~~ models appear to perform well ~~over whole FRB~~ by estimating general patterns of cold season runoff changes somewhat similar to that of the VIC simulated runoff changes over a large portion of the basin with explained variance ranges between ~~revealing dominance of temperature - driven runoff changes. The multilinear regression model explains 70~~50-

990% (Supplementary Fig. 5). While changes in snowfall contribute only 5 to 7% to the runoff changes, changes in both mean air temperature and rainfall are about equally influential for runoff change in the Interior Plateau and Rocky Mountains. In the Coast Mountains, the projected rainfall leads temperature and contributes 61% to the runoff change compared to a 32% contribution of temperature change (Table 2)% of the total variance in runoff over a large portion of the basin. The general patterns of runoff trends of the regression model (Figs. 9a) are very similar to that of the MME simulation trends (Figs. 9b). Precipitation contributes to increases in runoff mostly in the Coastal Mountains (Fig. 9c) and over parts of the Rocky Mountains. This analysis further confirms the increasing cold season moisture supply (Fig. 4) and associated runoff increase (Fig. 6) in the Coast Mountains.

Contribution of temperature to runoff trends is much higher than precipitation over most of the northern FRB and mountains. For both temperature and precipitation, runoff increase is greatest over the Rocky and Coast mMountains revealing that precipitation plays a crucial role in runoff changes under future warming.

3.43 Changes in Runoff Regimes

Potential Projectedfuture changes in FRB flow regimes are assessed using the SP detection algorithm described in Sec. 2.5. SPs occur in the VIC simulations in all years at nearly most of theall gridcells in the 1990s base period (Supplementary Fig. 106), resulting in an SDC4 flow regime classification throughout the basin except in the lower Fraser valleymain stem Fraser River downstream from Hope (Fig. 911). The frequency number of SPs decreases in future periods with the maximum change

~~occurring~~ in the Interior Plateau ~~(Fig. 10)~~, where the SP years decreases to ~~where frequency declines from 100% to only 43%~~43±7% ~~-~~ ~~snow-dominant~~ in the 2080s when compared to 100% SP years in the 1990s. Such decreases in SPs are more modest~~, a(Table 2). nd smaller decreases~~ in t~~T~~he Rocky (64±6%) and Coast Mountains (57±4%) ~~-decline to 64% and 57% snowmelt-dominant systems by the 2080s~~ (Table 3~~2~~).~~.~~ ~~The corresponding uncertainties in these declines are 7%, 6% and 4% for Interior Plateau, Rocky and Coast Mountains, respectively. In contrast with the spatially-averaged response of the geoclimatic regions, routed flow at the UF, QU, TN, CH and LF shows a weaker transition of flow regimes (Table 2 and Supplementary Fig. 65).~~

~~The spatial classification of SP changes (Fig. 11) shows most~~A majority of ~~the~~ gridcells in the Interior Plateau transitions~~ing~~ from snowmelt-dominant SDC4 to rainfall-dominant SDC1 (33% of gridcells) or SDC2 (26% ~~gridcells~~) by the end of this century. By contrast, ~~mountainous regions such as~~ the Rocky and Coast Mountains show resilience to regime transitions compared to lower elevation regions~~s~~ and remain mostly snowmelt-dominant SDC3 ~~(14% gridcells)~~ or SDC4 ~~(58% gridcells)~~ in the 2080s – see Table 3~~2~~ for details. In the Coast Mountains, the higher elevations resist regime transitioning compared to other elevations that have ~~the remainder of the areas having~~ robust transitions to rainfall-dominant SDC1 or SDC2 regimes. In contrast with the spatially-averaged response of the geoclimatic regions, routed flows at the outlets of the Upper Fraser, Quesnel, Thompson-Nicola, Chilko and Fraser River at Hope~~UF, QU, TN, CH and LF~~ show ~~shows~~ a weaker transition of flow regimes (Table 3~~2~~ and Supplementary Fig. ~~6~~7). This characteristic arises from~~In~~ the ~~the~~ VIC routing procedure, wherein ~~the~~ model gridcells contributing flows to the outlet ~~gauge~~ occupy mostly higher elevations and hence produce flow statistics with more SPs. This attenuation of the climate change signal at channel outlets is consistent with the recent findings of Chezik et al. (2017).

4 Discussion and Conclusion

Overall, projected changes in precipitation, SWE and runoff we derived using the CMIP5-VIC modelling chain are in good qualitative agreement with the results of Islam et al. (2017), who used a smaller MME, a different downscaling procedure, and only considered projections up to the 2050s. In this work, we took advantage of a larger MME, an effective downscaling and bias-correction method (BCCAQ2) with proven utility at the daily time scale and a robust snowmelt detection algorithm defining snowmelt-dominant categories (SDCs) to gain a fuller understanding of hydrologic regime change in the FRB throughout the 21st century.

Our results Our results have clarified The overall question driving this study is how future projected increases in air temperature and precipitation mean along with changes in precipitation phase and variability will modulate the FRB's runoff variability and flow regimes through the remainder of this century. suggest that under the projected warming, the changes in precipitation variability and phase, as simulated by CMIP5 models (Pendergrass et al., 2017), play a leading role in declining cold season snowpack accumulation and shifting spring snowmelt earlier in FRB. Thus However, the work raises some additional issues that we address below.To this end, we used VIC simulations, driven by statistically downscaled CMIP5 model projections, to analyse the magnitude, timing and variability of simulated runoff in different sub-basins and geoclimatic regions within the FRB. Furthermore, we used a SP detection algorithm to identify the transition of snowmelt-dominant to rainfall-dominant regimes.

~~4.1 Projected changes in and resulting runoff mean~~

~~Analysis of contemporary and future climate and hydrological simulations suggests that warming and changes in precipitation variability (Fig. 4) and phase (Fig. 5) will lead to a significant decline in cold season snowpack accumulation and shift spring snowmelt earlier (Fig. 6). The projected change in the runoff mean is sensitive to changes in both the mean and variability of precipitation in a warming climate. These findings are consistent with a recent study by Pendergrass et al. (2017) reporting a global increase of precipitation variability in CMIP5 models simulations on both interannual and daily timescales. p~~projected increases in the precipitation rain-to-snow fraction will have a strong impact on the severity of flooding, for example on mountainsides, with increased spring rainfall accelerating snowmelt runoff. ~~Despite advances in annual maximum runoff (Fig. 7a), the total annual runoff in most sub basins does not change substantially (Supplementary Table 2). The stability of total annual runoff implies that a projected increase in rainfall fraction and seasonality will induce considerable changes in runoff timing. The absolute magnitudes of both SWE change and snowmelt are higher in the Coast Mountains (Fig. 6) compared to the Rocky Mountains, likely because the latter region will continue to have cold continental winters with future mean temperatures well below 0°C. Changes in SWE magnitude and seasonality in all three geoclimatic regions shift runoff timing earlier in spring and summer (Fig. 7). Increased cold season precipitation implies more water input to the basin and thus more intense peak flows. In contrast, warmer temperatures reduce the cold season snow and shorten the snow accumulation season hence moderating the snowmelt-driven peak flows in summer.~~

Annual peak flows in the ~~FRB's~~ Coast Mountains having a strong maritime influence will shift earlier by around one month by the 2080s ~~(Table 1)~~ and more frequent cold season runoff events will rival spring freshet flows in magnitude by the end of the 21st century (Fig. , Fig. S57). The source of this enhanced cold season runoff is a topic of ongoing research, but is likely connected to the The variability of cold season peak flows, linked to rainfall events, will also increase in the Coast Mountains. Furthermore, future increase of rainfall events accelerating snowmelt, may also contribute to increasing runoff variability in cold seasons. increasedEnhanced frequency of landfalling atmospheric rivers simulated in the CMIP5 models (Warner et al., 2015) may also increase rainfall events in the Coast Mountains. aAlong the North American west coast ((Warner et al., 2015; Gao et al., 2015; Payne &and Magnusdottir, 2015; Radic et al., 2015; Warner et al., 2015; Warner and Mass, 2017). Under the projected warming, the precipitation phase as rainfall will be a key driver modulating Coast Mountains runoff intensity and frequency especially in the cold season. , the CMIP5 models simulate higher numbers of heavy rainfall events associated with atmospheric rivers in future time periods when compared to the historical frequency. These strong increases in atmospheric moisture transport result in higher rainfall amounts in the CMIP5 ensemble which, in turn, produce increased cold season runoff in the VIC simulations of the FRB. This ese future increases in cold season runoff and variability may increase the risk of extreme flooding in the Coast Mountains and in the lower Fraser Basin (Curry et al., 2018, in preparation), with associated implications for. The current water management strategies in these areas.

The FRB hydrologic response in mountainous regions varies considerably across the basin differentiating its flows mainly into snow-dominant or hybrid (rain and snow) regimes. The SP detection analysis suggests changes in the snow-dominant category arising more prominently across the Interior Plateau probably due to its lower mean elevation with smaller snowpack accumulation in winter and thus higher sensitivity to temperature increases during the cold season. Snowpack declines are most pronounced at temperatures near freezing that occur more often at Interior Plateau lower elevations during fall or spring. In higher mountainous regions with cold climates, flow regimes depend mainly on the moisture availability and elevation, with higher elevations having cooler air temperatures and thus longer periods of snow accumulation. Therefore the snowpack declines are less sensitive to temperature change in the Rocky Mountains. In the Coast Mountains, the flow regimes will remain rain-dominant at lower elevations owing to abundant rainfall associated with the region's maritime climate.

~~(flood planning, water storage, etc.), particularly on the southwest coast of BC, will need to be bolstered to cope with projected increases in cold season peak flow events and variability.~~

~~Future changes in the FRB's runoff peak flows will also impact salmon life cycles at the stream level. Studies have observed an inverse relationship between salmon spawning survival and higher flows due to the scouring mortality of spawns caused by high runoff in increased rainfall periods (Thorne and Ames 1987; Steen and Quinn 1999; Martins et al., 2012). The projected increase in rainfall and consequently higher flows could increase the scouring mortality of sockeye salmon causing population reductions. Furthermore, the considerable changes in future flows may substantially increase physiological stress during up-river salmon migrations into the FRB and thus further degrade their reproduction rates.~~

~~*4.2 Projected changes in runoff variability*~~

~~The analysis of the annual cycle of 7-day variability in daily runoff shows evidence of greater day-to-day fluctuations in Fraser River flows in the 2050s and 2080s relative to the 1990s base period (Fig.~~

67c). The peak day-to-day variability, occurring mainly in October, intensifies in the future along with a shift towards November. Such increases in the magnitude, variability and shifts in its timing come from projected changes in precipitation phases (Fig. 45) and increases in cold season snowmelt events (Fig. 56). The projected changes in day-to-day flow variability in the summer probably arise from changes in the magnitude and timing of the spring freshet. Accelerated and earlier snowmelt may result in flashier flows causing the increase for potential flooding or attenuated spring freshet with attendant drought potential in summer. Furthermore, grid-scale projected changes in runoff variability are strongly dependent on the elevation (Supplementary Fig. 73). Higher elevations in the Coast Mountains will experience greater changes in runoff variability compared to lower elevations of the Interior Plateau. The main factors controlling cold season runoff variability are the changes in temperature mean and precipitation means and variability. This suggests that precipitation variability will contribute to more intense cold season runoff variability (Fig. 4) in addition to any increase that may be due to higher temperatures.

4.43 Transitions between runoff regimes

The FRB exhibits substantial spatial variation of air temperature and precipitation due to its complex topography and maritime influences. The hydrologic response therefore varies considerably across the basin differentiating its flows mainly into snow-dominant or hybrid (rain and snow) regimes. Based on the results of the SP detection analysis, the FRB will transition to a less snowmelt-dominated regime in the 21st century. The Interior Plateau will transition from snow-dominant to increasingly rain-dominant regimes (Table 2 and Fig. 10). Changes in the snow-dominant category arise more prominently across the Interior Plateau owing to its lower mean elevation with smaller snowpack accumulation in winter and thus higher sensitivity to changes in air temperature during the cold season. Snowpack declines are most pronounced at temperatures near freezing that occur more often at Interior Plateau lower elevations during fall or spring.

In FRB mountainous regions, flow regimes depend mainly on the proximity to marine influences and elevation, with higher elevations having cooler air temperatures and thus longer periods of snow accumulation. Therefore the snowpack declines are less sensitive to temperature change in the Rocky Mountains with a possibility of experiencing increased snowfall due to higher moisture availability.

Future percentages of SP years for all sub-basins are considerably larger than the spatially-averaged values of the geoclimatic regions overlapping them (Table 2). The former, computed at basin outlets, are sensitive to the channel network and the routing model used to route these sub-basin flows. In the routing procedure, the model gridcells contributing flows to the outlet gauge occupy mostly higher elevations and hence produce flow statistics with more SPs. This attenuation of the climate change signal at channel outlets is consistent with the recent finding of Chezik et al. (2017) reporting river networks dampen local hydrologic signals of climate change since the regional characteristics of the channel network aggregate the upstream climate at different spatial scales.

Sensitivity of Results to Other Forcings: This study 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 (GHG) forcing and does not investigate the projected land cover change on regional hydrology. Influences of other forcings, such as land cover change and glacier growth or loss, are neglected, similar to otherut recent modelling studies offocusing projected climate change impactss in the FRB (Schnorbus et al., 2014, Shrestha et al., 2012 and Islam et al., 2017)-. Although climate change may influence future forest dynamics (e.g., Marlon et al., 2009; Gonzalez et al., 2010), we used static land cover in our simulations similar to out modelling studies focusing projected climate changes in the FRB (Schnorbus et al., 2014, Shrestha et al., 2012 and Islam et al., 2017) . wWe point out that any choice of land use-/-land cover scenario is arbitrary considering that all future changes are conditional on a given GHG scenario. In addition, it is arguably morewould be difficult to projeedict how forest composition and disturbance regimes, which are regional by nature, will change in the future compared to globally well-mixed GHG concentrations (although we acknowledge that we have not explored the full range of available RCPs either). Several previous studies have shown that the sensitivity of runoff to forest cover change depends on a basin's size and regional characteristics (Wei et al., 2013; Zhang et al., 2017). The forest cover change response generally decreases with increasing basin size, with large snow-dominated basins being more resilient. Limited support for this is found in the study of Schnorbus et al. (2010), who utilized VIC simulations to quantify the impacts of idealized scenarios of mountain pine beetle and associated salvage harvesting across different watersheds within the FRB. They found that despite a large upstream sensitivity to land cover changes, the overall, integrated change in discharge at Hope, BC was quite low. Focusing In the Willow River basin within the Interior Plateau of the FRB, Wei and Zhang (2010) found a ~20% increase in runoff even after an increase in clear-cut area fraction of up to 80%. Moreover, Havel et al. (2018) quantified the wildfire influence on streamflow in mountainous catchments and found that even large runoff changes generated by high burnt area fractions in small sub-catchments have a relatively small influence on cumulative runoff in the larger parent watershed. Hence, we suspect that thydrology in modest,sLimited support for this is found in the study of Schnorb,who idealized scenarios of pba,integrated dischargeThe sensitivity of runoff to forest cover change depends on the basin's size and its regional characteristics (Wei et al., (2013); Zhang et al., 2017). The forest cover change response decreases with increasing size of the large basins with large snow-dominated basin being more resilient. However the forest cover is more sensitive in water-limited watersheds than in energy-limited watersheds (Zhang et al., 2017). Focusing the Willow River basin within Interior Plateau, Wei and Zang, (2010) found ~20% increase in the runoff even after the increase in clear-cut area fraction up to 80%. Havel et al., (2018) quantified the wildfire influence on streamflow in mountainous catchments and found even large runoff changes generated by high burnt area fractions in small sub-catchments have a relatively small influence on cumulative runoff in the larger parent watershed.

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 dynamic properties as ice (e.g., they do not flow), they represent crudely simulated "glaciers" in model simulations that grow during the historical period in some locations, and subsequentlythat can ablate as melting outpaces deposition.

All of the historical CMIP5 driving data are essentially constrained to have the observed means and variability for the historical period in the statistical downscaling. The historical period variability therefore does not reflect large inter-model differences. Future variability does see the influence of inter-model differences and not just changes in variability due to forced climate change. The increase in the runoff variability may be therefore somewhat overestimated in our analysis. In addition to the downscaling methodology, the GCM dynamics, natural climate variability and hydrological modelling constitute additional sources of uncertainty in this study's projected hydrological changes. Furthermore, the hydrological model used in this study is integrated on a relatively coarse resolution (0.25°), which may not represent some aspects of the small-scale dynamics related to the FRB's complex topography. Nevertheless, considering the modest magnitude of the inter-model spread compared to the MME mean in the cold season, projected changes reported in this study are mainly induced by projected climate warming with increased precipitation variability. Such an increase in precipitation variability is also reported in Pendergrass et al. (2017) using CMIP5 MME precipitation without any downscaling method.

In summary, our work focuses onthe strong GHG () forcing into the late 21st century, with the presumption that an understanding of this response is a prerequisite for further investigations of additional forcings of interest.has been estimated, a follow-up future work will focus on the effects of land cover change and glacier retreat (with a hydrologic model including dynamic glaciers) will be merited.

5 Conclusion

Climate change is expected to induce considerable hydroclimatic alterations in mid-latitude river basins around the globe. The results presented in this study provide supportive information on key hydrological changes under projected warming and changes in precipitation phase by focusing on the Fraser River Basin, a large mid-latitude basin with mountainous terrain and a strong maritime influence.

Overall, future projected changes in precipitation, SWE and runoff are in good qualitative agreement with the results of Islam et al. (2017), who used a smaller MME and a different downscaling procedure. In this work, we take advantage of a larger MME with more realistic daily timescale variability, an effective downscaling and bias-correction method (BCCAQ2) with proven utility at the daily time scale and a robust snowmelt detection algorithm defining snowmelt-dominant categories (SDCs)to investigate future changes in runoff variability and seasonality.In such basins, quantification of projected changes in the input precipitation and associated runoff changes is quite challenging due to complex mountainous topography and varying intensity of maritime influences. Using the CMIP5 projections, and a hydrological model, this study clearly demonstrates that in the warmer climate, changes in rain to snow ratio (Fig. 4) play a crucial role in modulating cold season snow accumulation (Fig. 5) and runoff (Fig. 6). The contribution of rainfall to overall increases in the mean runoff is quite evident in the coastal regions where the marine influences strengthen with time and hence increasing rainfall substantially. The increasing strength and frequency of maritime influences are possibly linked to the projected significant increase in atmospheric rivers as simulated by the driving CMIP5 GCMs. Using the cold season runoff from the three geoclimatic regions with cold season precipitation input to those regions, the multivariate linear regression analysis (Table 2) further confirms rainfall as a dominant contributor to runoff increases in the Coast Mountains. Overall, our results suggest that in the mid-latitude basins with maritime influenced, the projected rainfall and runoff will rise much more rapidly. A larger fraction of the rainfall in these basins will become runoff producing rapidly rising cold season runoff.

Furthermore, our analysis of flow regime changes provides a new insight into expected regime transitioning in the snowfall-dominant basins with hybrid or rainfall-dominant flow regimes becoming more prevalent. In the mountainous basins, such changes are strongly coupled to projected changes in precipitation and air temperature along with the varying range of elevations. Compared to high elevation mountainous regions, regime transitioning will be more apparent in the low elevations where near-freezing temperatures prevail. In snowmelt-dominant flow regimes with higher elevations, such changes will most probably accelerate earlier onset of spring snowmelt and will decrease the magnitude of summer peak flow events.

While the results reported in this study are not precise representations of projected runoff changes due to several computational limitations and dataset uncertainties, they nevertheless provide valuable insight to the projected hydrological state of the mid-latitude mountainous basin and should be useful for planning and developing future water management resources including flood frequencies. ~~ersd,the~~

~~It should be noted, however, that all of the historical CMIP5 driving data are essentially constrained to have the observed means and variability for the historical period in the statistical downscaling. The historical period variability therefore does not reflect large inter-model differences. Future variability does see the influence of inter-model differences and not just changes in variability due to forced climate change. The increase in the runoff variability may be therefore somewhat overestimated in our analysis. Besides the downscaling methodology, the GCM dynamics, natural climate variability and hydrological modelling all form sources of uncertainty in this study's projected hydrological changes. Furthermore, the hydrological model used in this study is integrated on a relatively coarse resolution~~

~~(0.25°), which may not represent small-scale dynamics related to the FRB's complex topography.However, considering the lower inter-model spread compared to the MME mean in the cold season (Table 1), are mainly induced by projected climate change with increased precipitation variability. Such an increase in precipitation variability is also reported in other studies (see Pendergrass et al., 2017) using CMIP5 MME precipitation without any downscaling method.~~

~~Besides the downscaling methodology, the GCM dynamics, natural climate variability and hydrological modelling all form sources of uncertainty in this study's projected hydrological changes. Furthermore, the hydrological model used in this study is integrated on a relatively coarse resolution (0.25°), which may not represent small-scale dynamics related to the FRB's complex topography.~~

Acknowledgments

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) funded Canadian Sea Ice and Snow Evolution (CanSISE) Network, the Mountain Water Futures (MWF) initiative of the Global Water Futures (GWF) program and the Nechako Environmental Enhancement Fund (NEEF). Thanks to colleagues from the Pacific Climate Impacts Consortium for their assistance and contributions in the VIC model implementation. The authors thank Michael Allchin (UNBC) for plotting Fig. 1a and for providing useful comments. The authors acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP5, and thank the climate modelling groups for producing and making available their GCM output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. Thank to Stephen Sobie (PCIC) for clarification of the BCCAQ2 method. Thanks to the anonymous reviewers and the handling editor for constructive comments and suggestions that greatly improved this paper.

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Table 1: Characteristics of Water Survey of Canada (WSC) hydrometric stations and three geoclimatic regions within the FRB (Déry et al., 2012). The 30-year runoff mean and interannual variability (estimated by standard deviation) is calculated for each individual CMIP5-VIC simulation and all values are averaged to get the MME mean in the cold season. The inter-model spread in runoff mean and its interannual variability is indicated as uncertainty ranges (±) estimated by a 5-95% ~~confidence interval~~models range. The ~~L~~last column shows advances in the timing of the MME mean annual peak flow by 2080s.

Basin (Abbreviation) [WSC ID]	Gauged area [km^2]	Latitude [°N], Longitude [°W]	Mean elevation [m]	Cold season m~~M~~ean and interannual variability of Runoff [mm yr^{-1}]						Advance (days) by 2080s
				1990s (1980-2009)		2050s (2040-2069)		2080s (2070-2099)		
				Mean	Variability	Mean	Variability	Mean	Variability	
Rocky Mountains	-	-	1567	160 ± 3	25 ± 2	205 ± 12	51 ± 7	270 ± 22	65 ± 9	-
Interior Plateau	-	-	1101	58 ± 0	10 ± 1	78 ± 4	19 ± 2	102 ± 7	22 ± 2	-
Coast Mountains	-	-	1296	450 ± 10	90 ± 7	606 ± 23	139 ± 11	730 ± 34	158 ± 15	-
Upper Fraser (UF) [08KB001]	32400	54.01, 122.62	1308	76 ± 8	29 ± 4	107 ± 13	46 ± 7	133 ± 18	54 ± 9	20
Quesnel (QU) [08KH006]	11500	52.84, 122.22	1173	119 ± 3	24 ± 2	142 ± 8	42 ± 6	182 ± 16	52 ± 7	18
Thompson-Nicola (TN) [08LF051]	54900	50.35, 121.39	1747	47 ± 2	13 ± 1	74 ± 7	28 ± 5	113 ± 12	38 ± 4	25
Chilko (CH) [08MA001]	6940	52.07, 123.54	1756	95 ± 2	20 ± 2	119 ± 6	34 ± 5	151 ± 10	42 ± 4	35
Fraser at Hope (LF) [08MF005]	217000	49.38, 121.45	1330	83 ± 2	13 ±1	109 ± 6	26 ± 4	142 ± 10	33 ±4	25

Table 2: Decomposition of the key drivers affecting cold season runoff changes in the 2080s. Contributions are in % estimated using the multivariate linear regression (MLR, described in section 2.4.2) model using monthly time series from 21 CMIP5 simulations. R^2 provides the variance explained by all three variables. The gridcell averaged contributions are estimated only for statistically significant values at $p < 0.05$. Change in each variable is normalized by the total runoff change to estimate its contribution. The contributions listed in last three columns do not necessarily sum exactly 100% due to rounding off and/or masking of insignificant gridcells before taking area-averages.

Region	**Runoff Change 2080s (%)**		R^2	**Contribution to Runoff Change (%)**		
	VIC	**MLR**		**Rainfall**	**Snowfall**	**Mean Temperature**
Coast Mountains	121	146	0.70	61	8	32
Interior Plateau	114	140	0.42	44	4	46
Rocky Mountains	79	117	0.45	44	6	50
Fraser River Basin	107	133	0.45	47	8	46

Table ~~2~~3: CMIP5-VIC simulated projected change in snowmelt-dominant regimes. Values are in % calculated using the ratio of the sum of SPs years and the total number of years over all 21 CMIP5-VIC simulations. The uncertainty ranges (±) indicate inter-model spread in the MME mean values indicated by a 5-95% ~~confidence interval~~models range.

Region	Snowmelt-Dominant Regime (%)		
	1990s (1980-2009)	**2050s (2040-2069)**	**2080s (2070-2099)**
Coast Mountains~~Rocky Mountains~~	95±1~~100±0~~	74±3~~88±3~~	57±4~~64±6~~
Interior Plateau	100±0	73±5	43±7
Rocky Mountains	100±0	88±3	64±6
UF	95±9	95±9	93±9
QU	100±0	98±1	85±5
TN	100±0	98±1	80±8
CH	100±0	100±0	95±1
LF	100±0	98±1	81±7

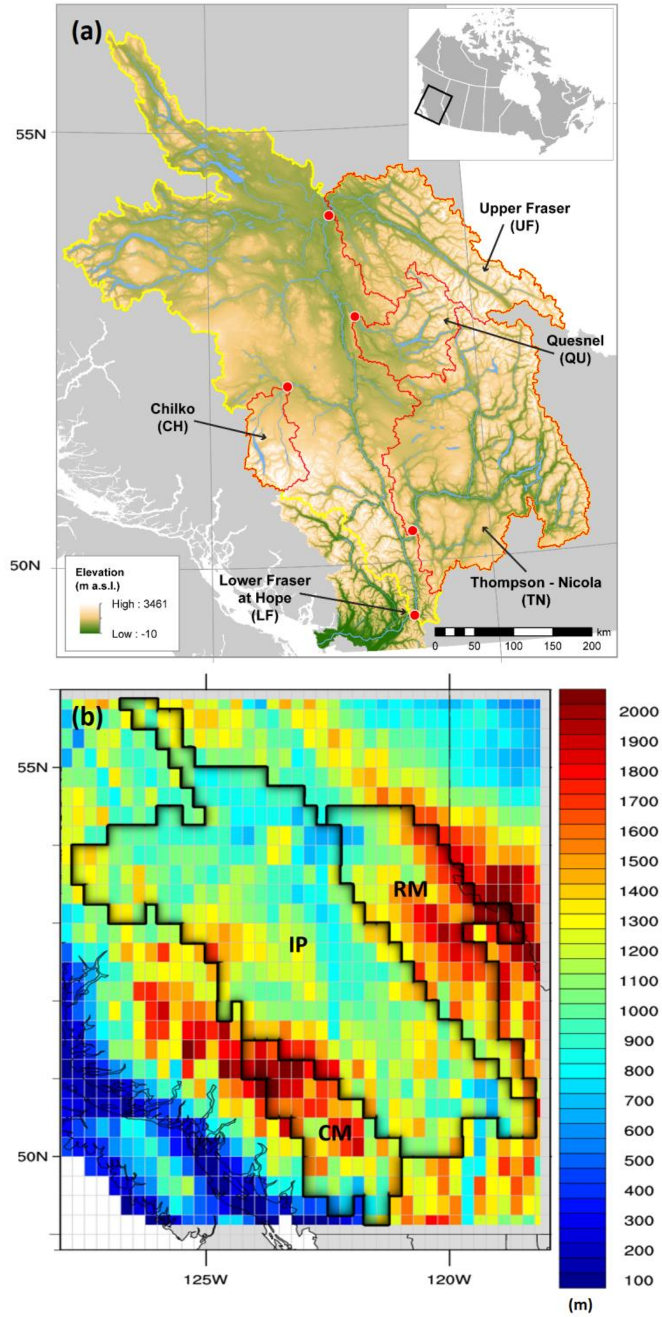

Figure 1: (a) Digital elevation map of the FRB with identification of sub-basins: Upper Fraser (UF), Quesnel (QU), Chilko (CH), Thompson–Nicola (TN), and Fraser at Hope (LF). (b) Elevation map highlighting the Fraser River Basin and three geoclimatic regions. RM, IP and CM represent the Rocky Mountains, Interior Plateau and Coast Mountains, respectively. Elevations are in meters and the horizontal grid resolution is that of the VIC hydrological model (0.25°).

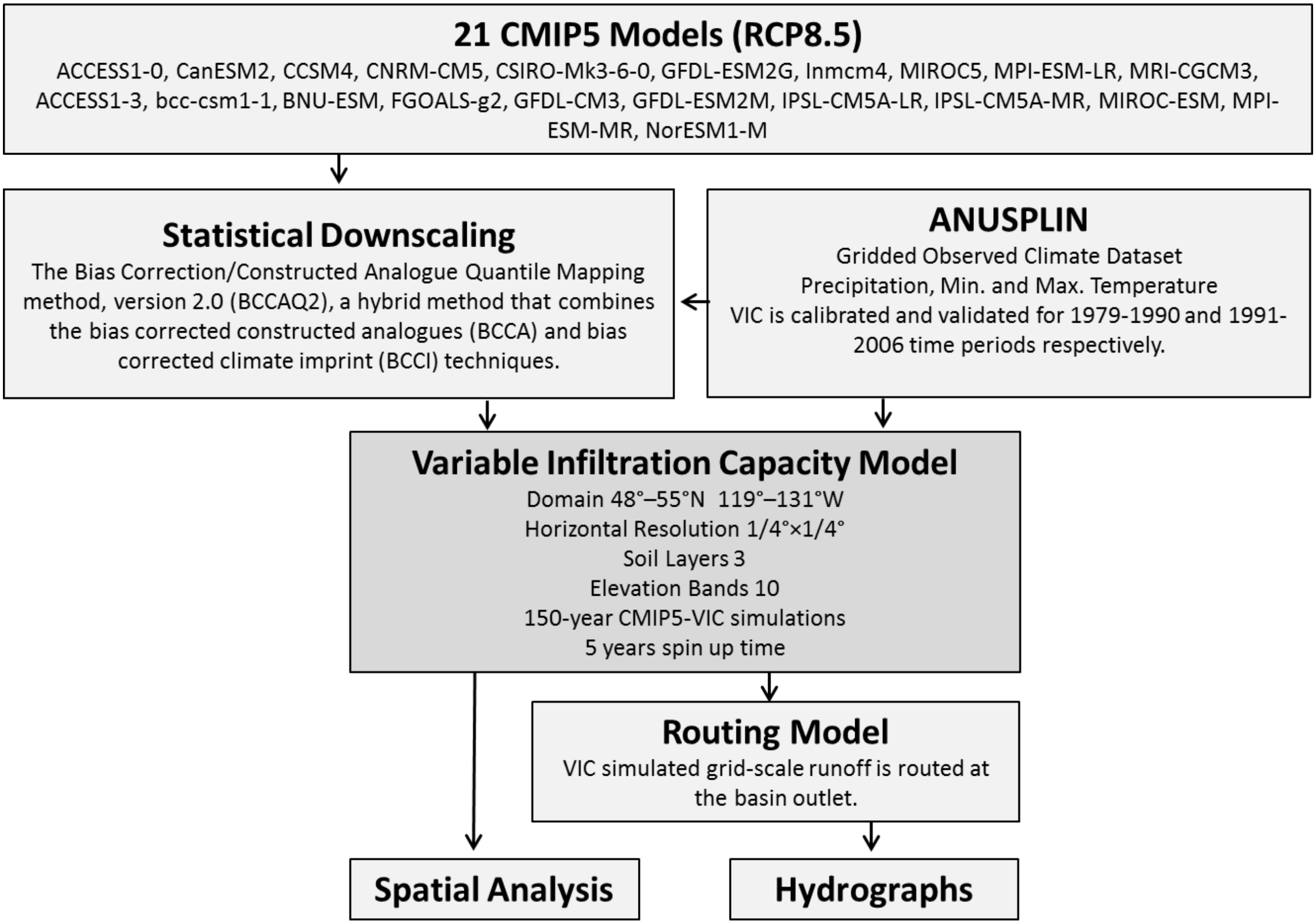

Figure 2: Block diagram of the VIC model experimental setup and analysis.

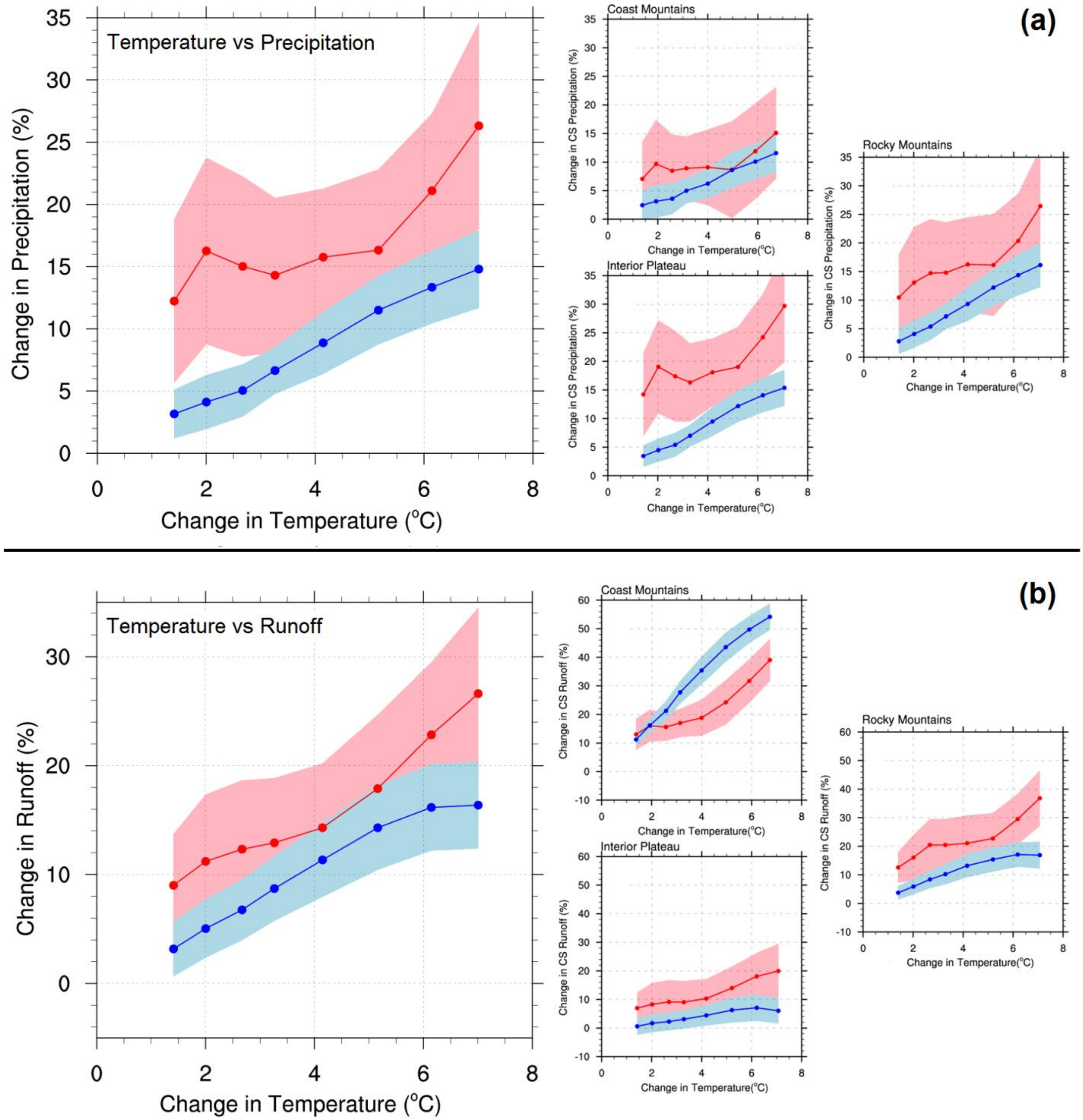

Figure ~~3~~4: Rate of change of mean and interannual variability with warming for ~~(a, b)~~ precipitation (a) and ~~(c, d)~~ runoff ~~d~~(b) during the cold season ~~(CS)~~. Changes in the mean (blue line) and interannual standard deviation (red line) ~~are~~ averaged over the FRB ~~and~~ are shown as a function of FRB cold season mean temperature change. Each marker indicates a 30-year period centred on consecutive decades between 2010 and 2080~~99~~ relative to the 1990s base period. Shading represents inter-model spread in 30-year means as indicated by a 5-95% ~~confidence interval~~models range.

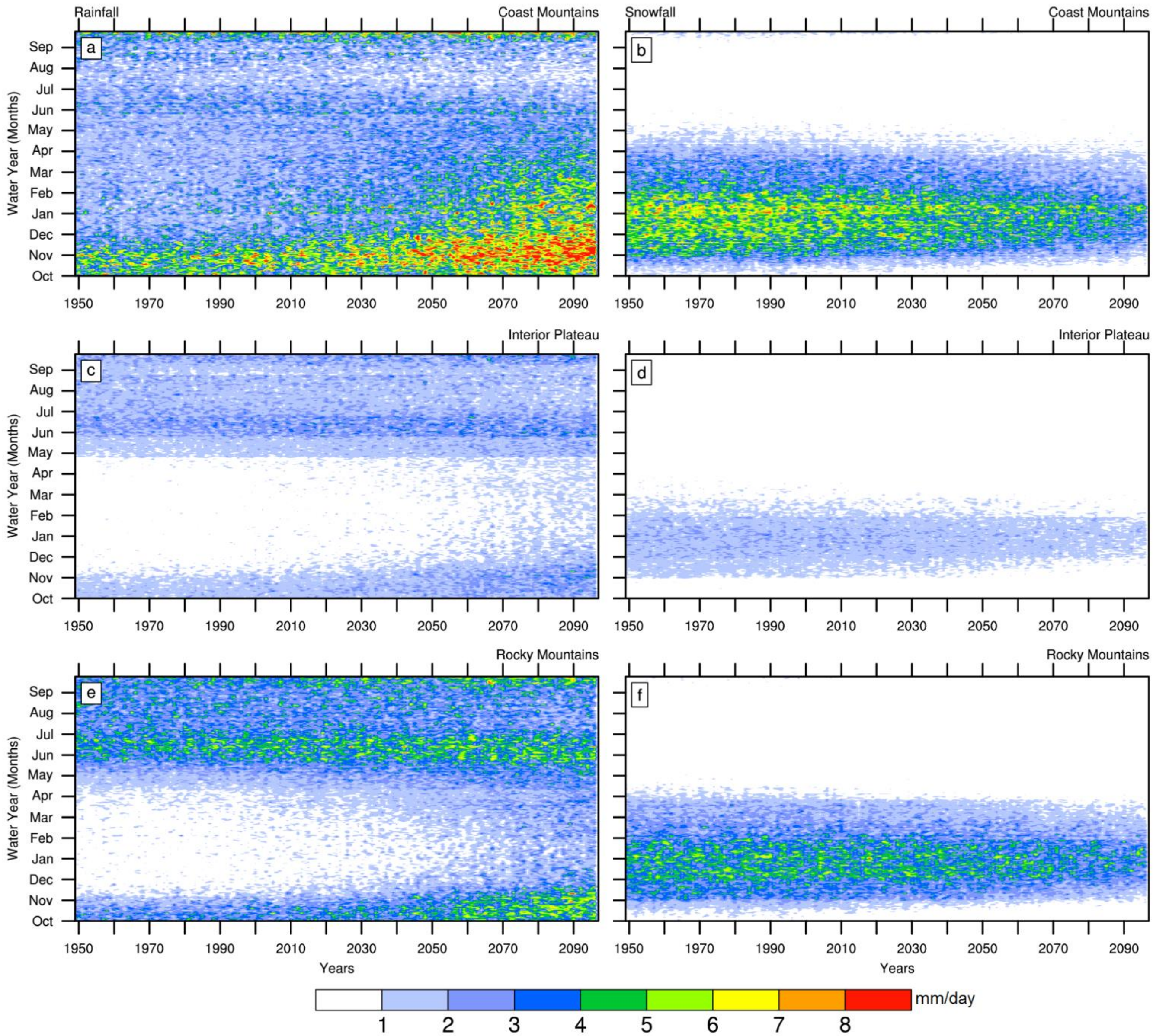

Figure 45: Partitioning of CMIP5 models MME mean total precipitation (mm day^{-1}) into daily (a, c, e) rainfall (a, c, e) and (b, d, f) snowfall (b, d, f) for the (a, b) Coast Mountains (a, b), (c, d) Interior Plateau (c, d) and (e, f) Rocky Mountains (e, f). Values are regional spatial averages over the three geoclimaticcally defined regions. Units are in mm day^{-1}.

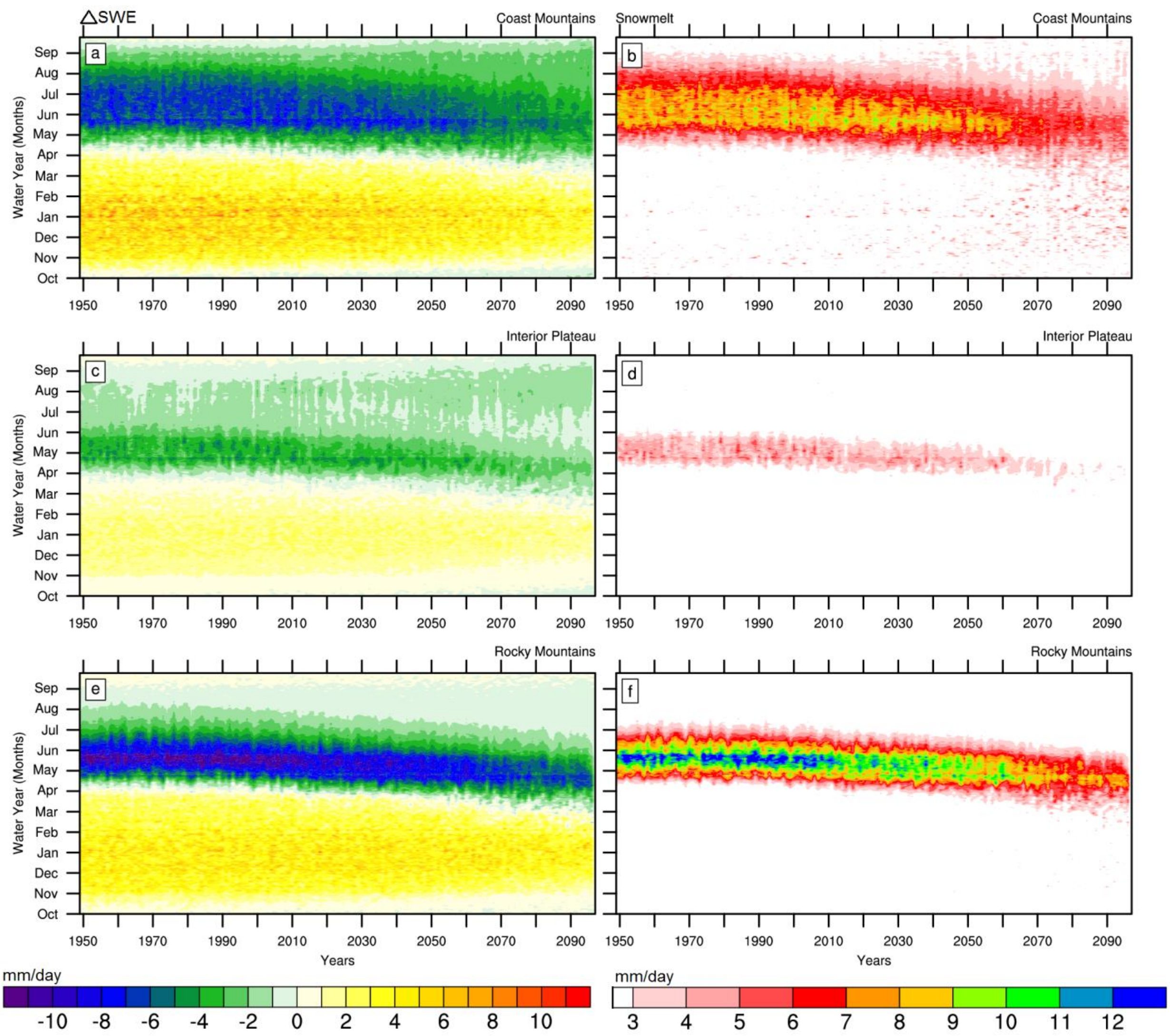

Figure 56: CMIP5-VIC simulated MME mean (a, c, e) ΔSWE (daily SWE rate) (a, c, e) and (b, d, f) snowmelt (b, d, f) for the (a, b) Coast Mountains (a, b), (c, d) Interior Plateau (c, d) and (e, f) Rocky Mountains (e, f). In panels (a), (c) and (e), values greater than 0 represent snow accumulation and while those below 0 are indicate snow ablation. Units are in mm day^{-1}.

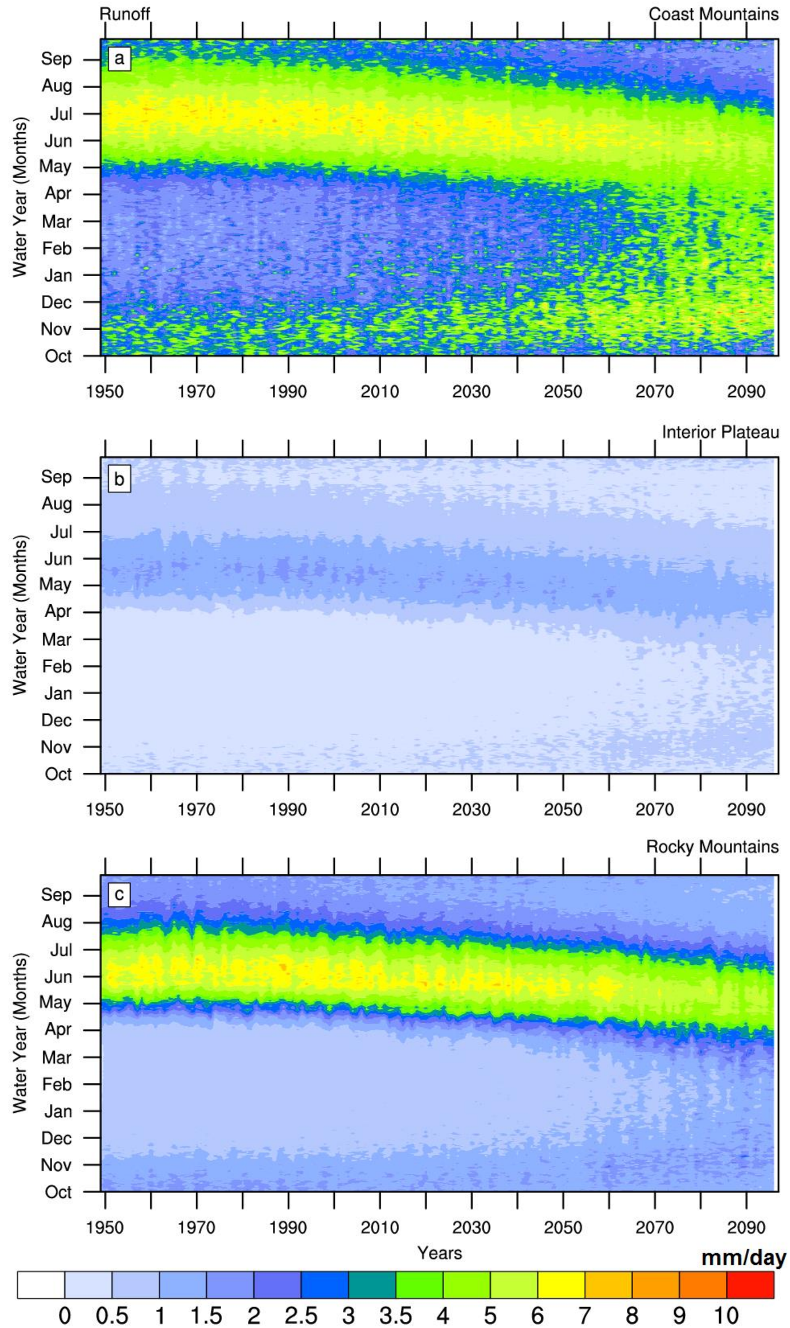

Figure 6: CMIP5-VIC simulated daily mean runoff for the Coast Mountains (a), Interior Plateau (b) and Rocky Mountains (c). Values are spatial averages over geoclimatic regions. Units are mm day^{-1}. Runoff units are an equivalent regional average rainfall rate rather than a discharge rate.

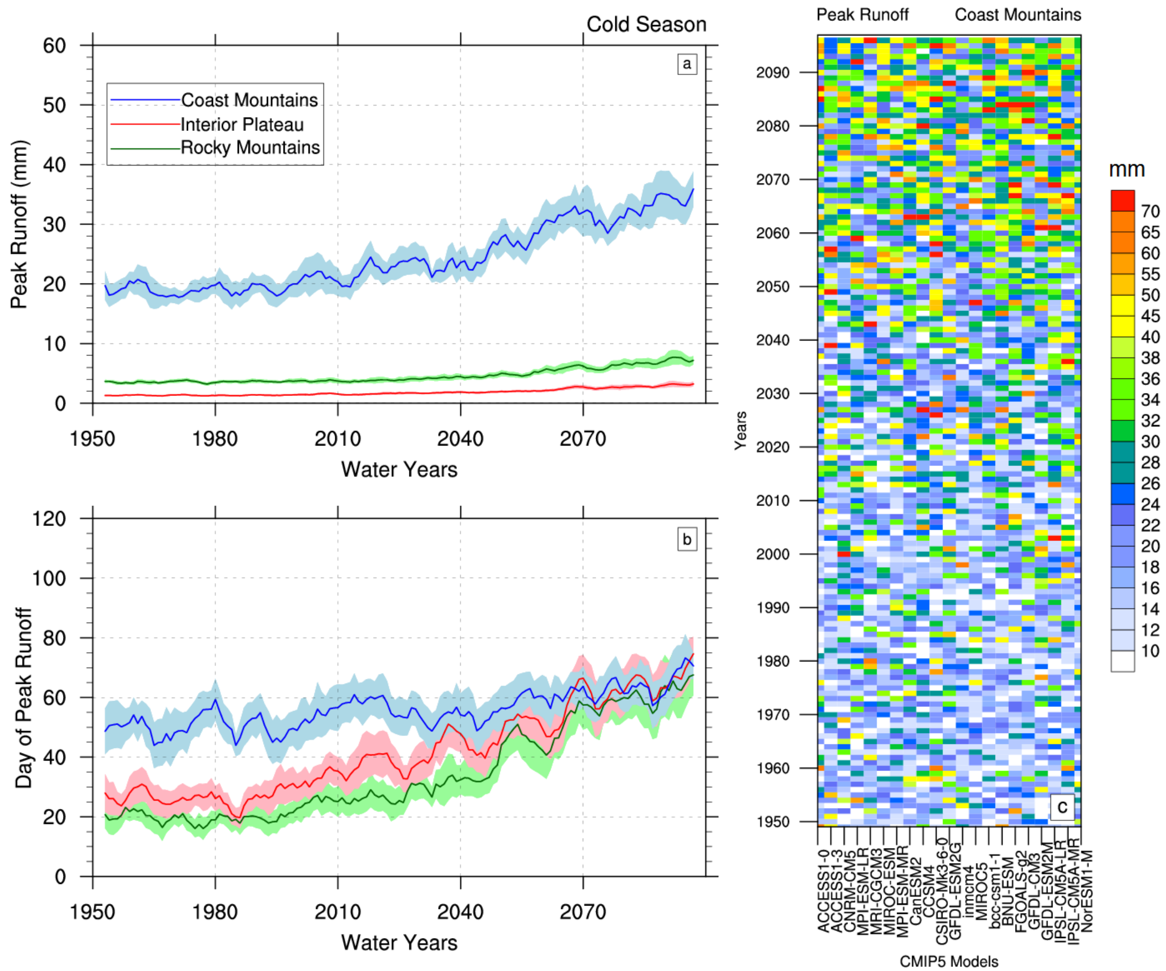

Figure 7: CMIP5-VIC simulated peak runoff (a) and corresponding day of the peak runoff (b) in the cold season of the water year for Coast Mountains, Interior Plateau and Rocky Mountains. Solid curves are for the MME mean and shading represents inter-model spread as represented by a 5-95% models range. A 5-year running mean is applied to smooth variations in all curves. Y-axis values in panel (b) represent days of water year where 0 corresponds to 1 October. Panel (c) displays cold season peak runoff simulated by individual CMIP5-VIC simulations for the Coast Mountains. Units are mm.

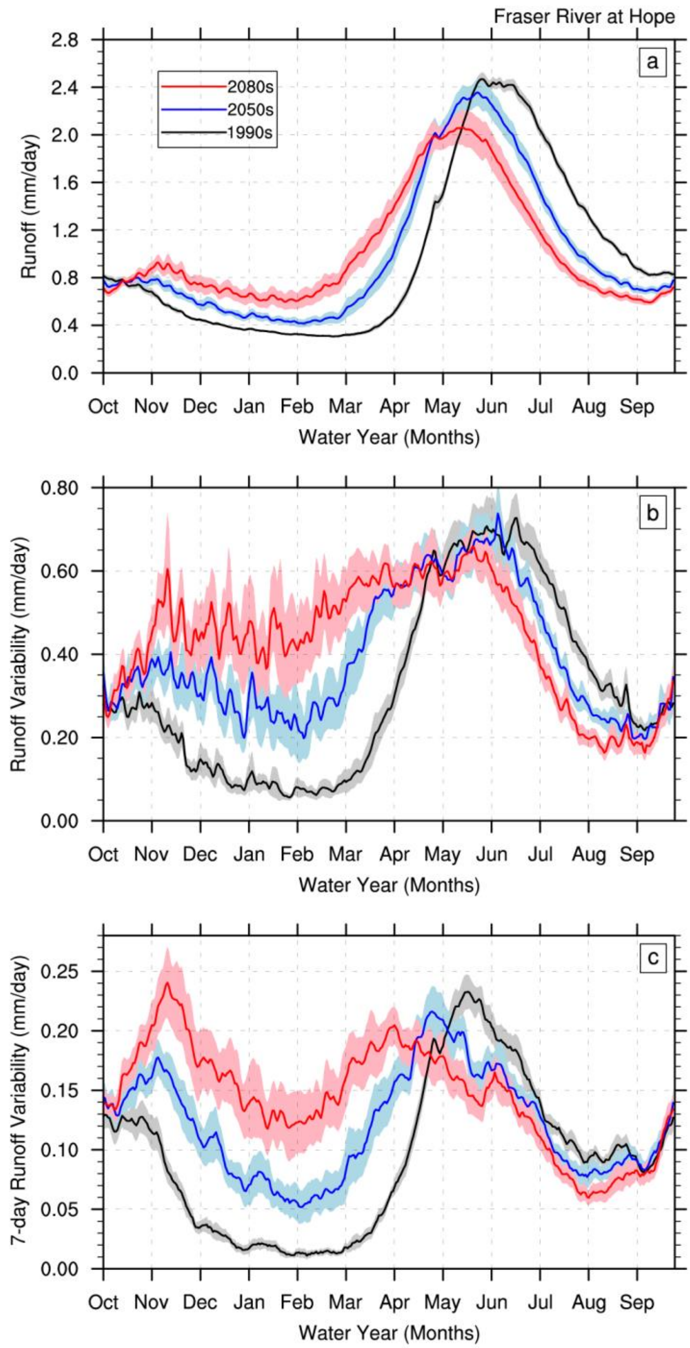

Figure 8: CMIP5-VIC simulated daily runoff (normalized discharge) ~~(a) ~~mean (a), ~~(b) ~~variability (b) and ~~(c) ~~7-day variability (c) for the Fraser River at Hope. Black, blue and red curves represent the MME mean for the 1990s, 2050s and 2080s, respectively. Shading represents inter-model spread as indicated by a 5-95% ~~confidence interval~~models range.

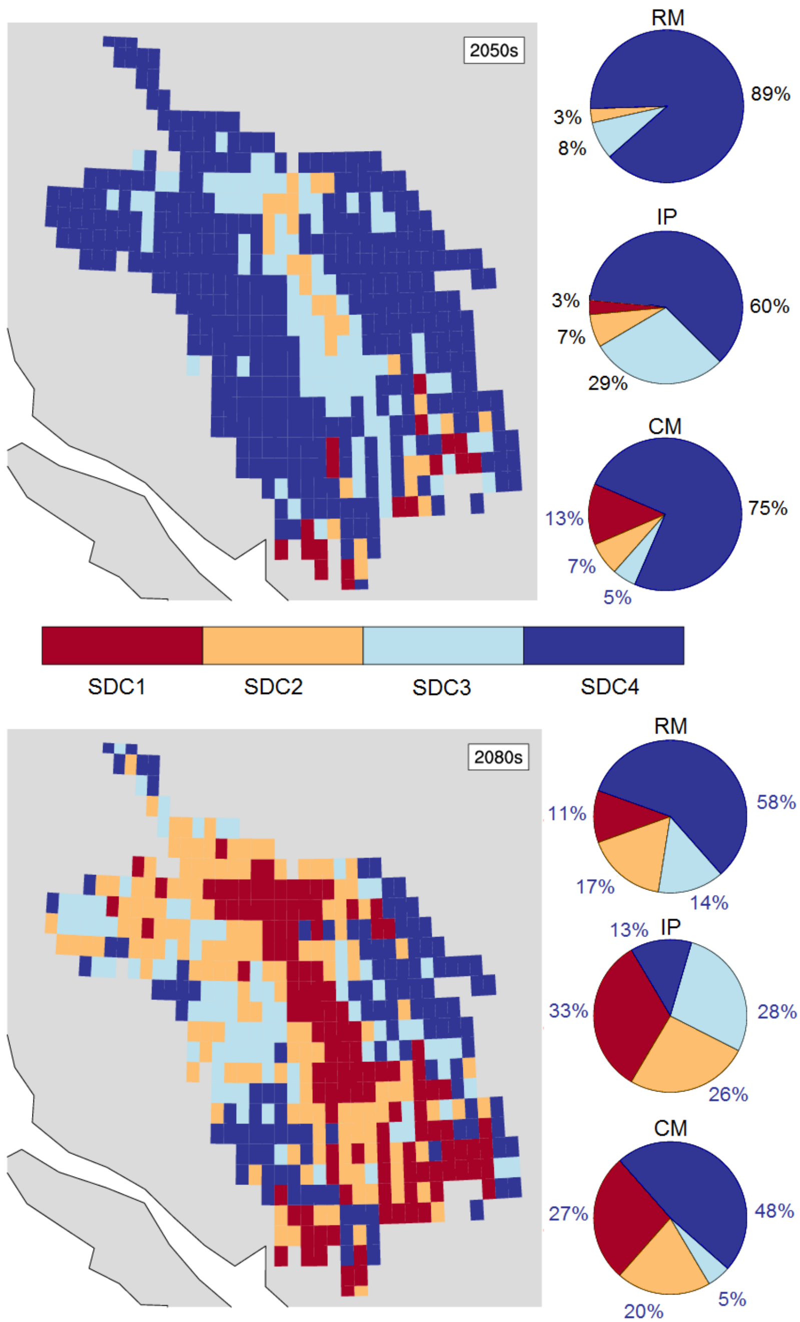

Figure 911: CMIP5-VIC simulated MME mean projected sSnowmelt-dominant Categories (SDC) in the 2050s and 2080s. SDCs are classified using the SP detection algorithm (described in section 2.5) and are based on changes (%) in the fraction of years with SP (see Sec. 2.5 for details). Pie charts show corresponding change in fraction of gridcells (%) in each SDC for the Rocky Mountains (RM), Interior Plateau (IP) and Coast Mountains (CM) geoclimatic regions.