Reviewer 1: Kristian Förster

P1L17: Here, I would recommend to provide the annual runoff in mm per year too, since it helps to compare the values with other studies.

Response: This is a good suggestion, the values in m/yr have been added to the abstract and the conclusions in the final draft.

P1L23: Please provide an explanation for the abbreviation CTD. In the current version of the manuscript, it becomes only clear on page 5.

Response: A correction for this abbreviation has been added to the final draft.

P3L9: What do you mean by "large uplift rates"? Please be more specific.

Response: We are referring to the regional uplift rates for Glacier Bay and southeast Alaska from isostatic rebound caused by glacial wastage since the little ice age. See Larsen et al. (2005) for more information. For clarity, in Section 1, ¶6 we changed large to *rapid* and added *from isostatic rebound* to the final draft.

Larsen, C.F., Motyka, R.J., Freymueller, J.T., Echelmeyer, K.A. and Ivins, E.R., 2005. Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat. *Earth and Planetary Science Letters*, *237*(3-4), pp.548-560.

P3L16: Here, you explain that the model output is available as daily output. What is the internal time step of the (energy balance) model? P4L25pp.: Here you could provide some more details on the time step of the model. Since it is an energy balance model, I would expect sub-daily time steps (even though the output is daily).

Response: The internal timestep of the model is 3 hrly and the results have been aggregated to daily and monthly for the climatological analysis. A sentence about the timestep information has been added to the model Section 3.1, ¶3.

P5L15p.: ET is computed by SnowModel? Was there any attempt to compare the results with the MODIS data – at least for reasons of plausibility, given that there is a mismatch in scales between MODIS and SnowModel?

Response: ET of the land surface is not calculated by SnowModel. When snow is present in the grid cell, sublimation of the snowpack is calculated by the energy balance sub-model (EnBal) and sublimation of blowing snow is calculated by the snow transport sub-model (SnowTran-3D), see Liston et al. (2006) for a review of all of the model physics and subroutines. It should be noted that the snow transport model is not recommended for model resolutions above 100m, and since our model resolution is 250m, SnowTran3-D was not utilized for the simulations.

However, obviously ET does make up a portion of the water balance and we therefore use the MODIS ET dataset to supplement the results of our SnowModel simulations. Hill et al. (2015) estimated the ET component of annual runoff for the entire Gulf of Alaska region to be ~17%. Beamer et al. (2016) estimate ET for the Gulf of Alaska region to be 10-15% less than Hill et al. (2015) results. Since much of the GBNPP domain is glaciated or covered in snow for many months of the year, the authors decided to simply estimate ET values from the MODIS ET dataset for the historic simulation time period and spatially subset by watershed or grouped watershed. See section 3.2.3 for more information, as well as the section below in our responses regarding another ET question by Reviewer1. We find that the MODIS based ET values range from 5%-13% of annual runoff in the GBNPP watersheds and we've added a table with this information below. The authors decided to add this table (new Table 4) to the manuscript to clarify the ET process and results.

Watershed Name	Historic MODIS ET (m/yr)	Percentage of Annual Precipitation (%)	Adjusted Annual Runoff (m/yr)
GBNPP	0.3	9	3.1
North	0.3	9	2.8
West	0.2	5	4.1
West-Arm	0.2	5	3.2
East-Arm	0.3	9	3.3
Tarr	0.2	3	2.7
Carroll	0.2	8	2.7
Dundas	0.4	9	2.7

Beamer, J.P., Hill, D.F., Arendt, A. and Liston, G.E., 2016. High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed. *Water Resources Research*, *52*(5), pp.3888-3909.

Hill, D.F., Bruhis, N., Calos, S.E., Arendt, A. and Beamer, J., 2015. Spatial and temporal variability of freshwater discharge into the Gulf of Alaska. *Journal of Geophysical Research: Oceans*, *120*(2), pp.634-646.

P5L27: A new subsection 3.3.1 is introduced in section 3.3 but there is not any other subsection (e.g., 3.3.2 etc.). I was wondering if it is worth to merge the sections 3.3 and 3.3.1?

Response: This is a good idea, and we merged these two sections in the final draft.

P6L19: The term "forecast" is used throughout the manuscript to describe the scenario data and the corresponding results. I am not sure if this term is correct in this context. I would suggest using "projection" instead since this term acknowledges additional uncertainty involved in climate scenarios which arise from uncertain greenhouse gas emissions (i.e. external forcing that is not exactly known). For instance, in a recent paper we also used the term projection to highlight this type of forcing (Hanzer et al., 2018). In contrast, according to Kirtman et al. (2013), the term forecast refers to initialized climate model runs (e.g., seasonal to decadal predictions, see their Box 1.1, or http://glossary.ametsoc.org/wiki/Climate_prediction).

Response: The difference in these terms is important, and the authors agree that the term 'projection', as defined by Reviewer1 above, is more in line with the intention of the use of 'forecast' in the original manuscript. We are not attempting to make a climate prediction (as defined in the provided weblink) of what will happen in the future in Glacier Bay. We are modeling one of the potential scenarios that may occur in the hydrology of the region that would accompany the RCP8.5 emissions scenario. For these reasons, the authors have chosen to change the term 'forecast scenario' to 'projection scenario', in every instance, throughout the manuscript. These changes are added to the final draft.

P6L30: Here, I would suggest to add some thoughts why you have selected RCP8.5 only. It is clear that running impact models for numerous RCPs is expensive in terms of computational costs. However, you could argue that you are interested in a worst-case.

Response: See Section 3.5.1, ¶2 for text added as an explanation for why we chose the RCP8.5 scenario. The modified paragraph is below, added text is italic.

"Although future climate simulations *from SNAP* exist for numerous RCP (representative concentration pathway) scenarios, in this study we restrict ourselves to the RCP 8.5 scenario and to the 5-model mean. *The other RCP scenarios (RCP 2.5, RCP 4.5, RCP 6.0) represent concentrations of greenhouse gases (GHGs) in the atmosphere that peak earlier in the 21st Century or at lower levels of GHGs than the RCP 8.5 scenario. Keep in mind that the choice of the RCP 8.5 scenario is not an attempt to evaluate the likelihood of the future GHG concentrations. Rather, we use the RCP 8.5 scenario for the projection scenario because we are interested in the hydrologic changes that might occur in the worst-case scenario.*"

P7L14: Does it mean that you did not apply SnowModel to future periods, e.g. by forcing the model with modified MERRA data (scaling of meteorological forcing)? From your explanations, you compared the historic run from SnowModel with the future simulation of Beamer et al. (2017) in terms of long-term averages on runoff. If I understood this correctly, this would suggest a simple approach that contradicts the first line of your abstract (". . . is

used to estimate current and future runoff into Glacier Bay.”). I would encourage the authors to provide more details on the setup of future scenarios.

Response: In section 3.5.3 Future Climatologies, we discuss creating the projection scenario climatologies. First, a review of the process. Beamer et al. (2017) conducted a SnowModel historic and forecast simulation for the larger Gulf of Alaska study area. The authors subset the GBNPP study area results from the more spatially extensive Gulf of Alaska simulations. These SnowModel simulations were forced with CFSR for the historic and projection scenarios, for the entire model space (at the lower 1km resolution) and complete model timeframe (3hrly). Climatologies were created by temporal averaging and spatial aggregation into the GBNPP watersheds or grouped watersheds.

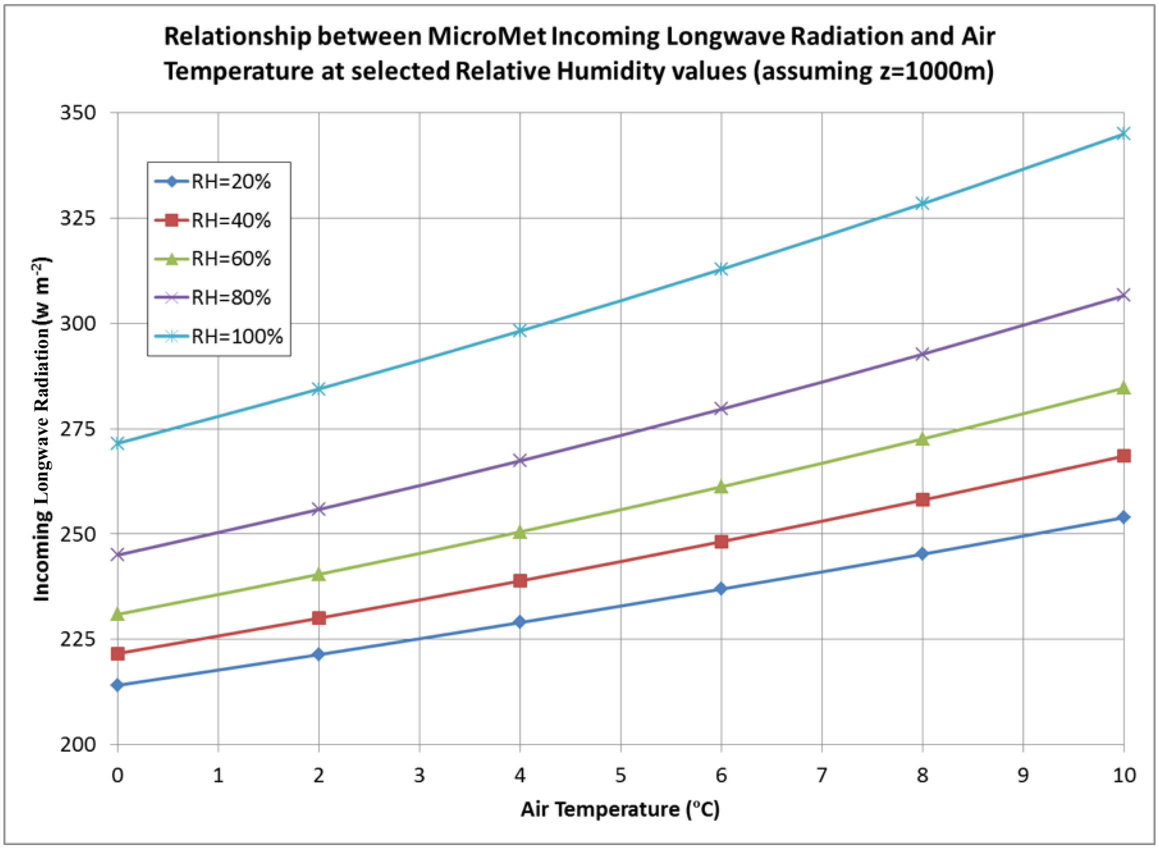
Next, a full SnowModel historic simulation for the GBNPP study area was conducted at the higher spatial resolution of 250m, forced by the MERRA reanalysis product. Climatologies were then created by temporal averaging and spatial aggregation by watershed or grouped watershed. At this point, we have spatially and temporally averaged climatologies for each watershed or grouped watershed (1. CFSR-based historical climatologies, 2. CFSR-based projection scenario climatologies, 3. MERRA-based historical climatologies). We created a scaling factor from the CFSR historic and projection scenarios to apply to the MERRA historic climatologies. After the application of these scaling factors we have the MERRA-based projection scenario climatologies by watershed or grouped watershed.

This study presents projection scenario results as 30-year climatologies. We do not present results related to the frequency characteristics of the runoff. As such, we are not presenting results on frequency distributions, or peak flows, etc. For long-term characteristics of runoff, however, we believe that our approach is appropriate because changes in runoff are driven by long-term changes in precipitation and temperature, which vary relatively slowly in space, and these changes are preserved in the scaling from CFSR-based historical climatologies to CFSR-based projection scenario climatologies.

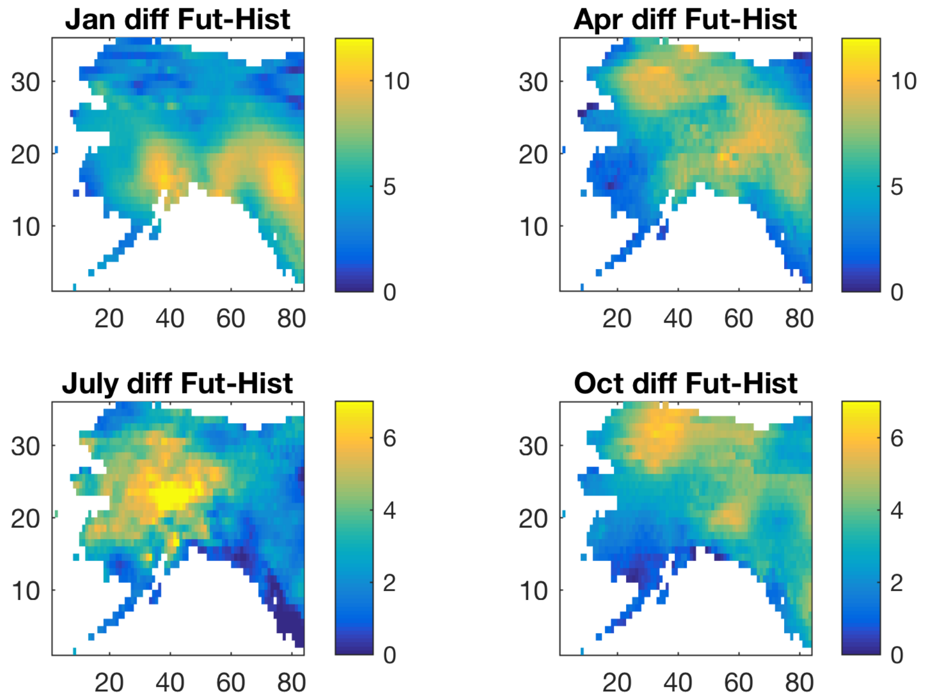
P12L32p.: I was wondering why only temperature and precipitation have been considered, given that SnowModel requires additional meteorological quantities?

Response: This is a decision based in part on the fact that only temperature and precipitation anomalies from SNAP for the RCP scenarios are available for the AK region. While MicroMet inputs include relative humidity, wind speed, wind direction, shortwave and longwave radiation, and surface pressure, those have not been modified in the projected scenario. In order to investigate the impacts of leaving out any potential changes in other variables, such as humidity, the authors considered the changes in relative humidity for their Gulf of Alaska results and the results from this additional analysis are below.

First, it's important to understand that MicroMet will modify the radiation balance through temperature increases. See the figure below, where its obvious that longwave radiation changes substantially with both Temperature and Relative Humidity. Since we already have a good idea of the expected increases in Temperature from SNAP (from the ΔTemp analysis discussed in our Results Section 4), the question becomes how different might relative humidity values be in the projection scenario?



To answer this question, we turned to the VEMAP project (https://daac.ornl.gov/VEMAP/guides/VEMAP_Alaska.html) which provides low resolution downscaled monthly grids of many variables including relative humidity. These grids come from two climate models, and we looked at the results from one (HadCM2). The results provided were for the GHG+A1 scenario, sometimes referred to IS92a. This scenario is quite comparable to the SRESA2 scenario which, in turn, falls between the RCP6.0 and RCP8.5 projection scenarios. We computed climatologies of relative humidity for the periods 1966-1996 and 2070-2100 for four months of the year (Jan, Apr, Jul, Oct). The figure below shows the differences in relative humidity between the two climatological periods (Future – Historical).



In the figure above, we see that Relative Humidity is projected to increase throughout the Alaska region, including the Glacier Bay region in the lower, right portion of the figure. In July and October, the increases are typically less than five percent. In January, the increases throughout Alaska are in the range of 5-10 percent. The first figure above, which shows longwave radiation as a function of temperature and RH, suggests that the ~4 deg C temperature increases that are predicted by RCP 8.5 produce a change in longwave of about 25 watts per square meter. An increase in RH of about 5-10 percent appears to produce a smaller (~10 watts per square meter) change in longwave. So, while it would be conceptually preferable to adjust all weather forcing variables, it appears that the expected changes in temperature dominate. This fact is what led us to adopt the future SNAP climatologies for Temperature and Precipitation as a good 'leading order' study of the effects of changing climate with the RCP8.5 projection scenario.

Additionally, the focus of this manuscript and scientific questions is not changes in climate variability, weather extremes, or high runoff events, but rather longer-term, climatological averages. The authors think it's not within the scope of this project to create our own statistically downscaled, projection scenario weather variables (RH, shortwave and longwave radiation). Since we are primarily focused on the climatological averages of the model output, we find the choice of perturbing the temperature and precipitation inputs for the projection scenario to be adequate, and aligned with the methods summarized in Beamer et al. (2017).

P12L36: The validation could be done in a quantitative way too. The only linkage between your results and oceanographic data is provided on page 12, lines 7 to 8 (by comparing Figure 7a with Figure 9). Since the model calibration is done for another region (indeed, in which your region is included), I would expect a closer look on this dataset, since it is the only dataset available for assessing model accuracy.

Response: The authors decided to use the oceanographic dataset primarily in a qualitative way because the of the complex, understudied open boundary of the bay system, where water (fresh and salt) moves freely in and out of the boundary into Icy Strait, the Cross Sound, and eventually the Pacific Ocean. Critically, freshwater fluxes are not measured or analyzed at the mouth of Glacier Bay, and to the best of the authors' current knowledge, a dataset that includes these fluxes entering and exiting the system does not exist. Thus, we are not able to explicitly determine what component of FWV is sourced by freshwater runoff as opposed to fluxes of highly stratified water at the bay's inlet. Therefore, we've chosen to focus on the change in freshwater volumes from month to month within the bay, instead of quantifying total bay freshwater volume at any given time. Given the sharp temporal gradients in freshwater runoff, the oceanographic dataset is presented to qualitatively assess whether the FWV signal shows a strong temporal gradient that is synchronous with freshwater runoff predicted by the model.

P22L9 (Figure 7): Why do you plot ET derived by MODIS only, given that your model accounts for ET too? If ET computations are available for the model too, you could plot ET for the future scenarios as well. In my opinion, analyzing changes in ET would be an interesting asset to describe the hydrological change.

Response: In Figure 7 and Appendix A we plot monthly ET values derived from MODIS because SnowModel calculates sublimation of the snowpack when solving the energy balance equations but does not calculate ET from the land surface when no snowpack is present. See previous answer on ET for more details. This is why Beamer et al. (2017) added the SoilBal sub-model to their analysis of the Gulf of Alaska SnowModel simulations. Many other previous studies using SnowModel from the Arctic, Patagonia, Greenland, and Alaska do not calculate ET using an additional sub-model, and this manuscript is no different. (Mernild et al., 2012; 2013; 2014; 2017a)

Our intention in plotting the MODIS derived ET values on the runoff plots (Figure 7 and Appendix A) is to give the reader an estimation of how much the monthly runoff would be altered if ET were included. See the explanation in section 3.2.3 for more details. We temporally average (14-year), and spatially aggregate the MODIS ET values for each watershed/grouped watershed. We do not subtract these monthly values from the partitioned climatologies (snowmelt, glacier melt, rain runoff) because the model does not resolve which of these sources would be the appropriate origin of the ET-based water. Even more importantly, in the projection scenario, we have no land cover evolution beyond a simple estimation of glacier area change. If glaciers continue to recede, as they have over the last several hundred years and are projected to change in the future in Glacier Bay, these changes will continue to alter the landscape, in both landcover species and landcover type designations. These landcover changes would inevitably cause changes to ET in the future. We admittedly make no attempt to quantify or characterize these types of landcover changes, nor the subsequent ET changes, because it is outside the scope of our current project and analysis.

To clarify the ET results, the authors will be adding this table in the final draft of the estimated monthly ET values from MODIS by watershed and we include the percentage of annual runoff and the adjusted annual runoff values. We have also added the adjusted runoff values in the abstract and conclusion paragraphs for clarity. Note: these are historic values because we do not estimate ET for the projection scenario.

Watershed Name	Historic MODIS ET (m/yr)	Percentage of Annual Precipitation (%)	Adjusted Annual Runoff (m/yr)
GBNPP	0.3	9	3.1
North	0.3	9	2.8
West	0.2	5	4.1
West-Arm	0.2	5	3.2
East-Arm	0.3	9	3.3
Tarr	0.2	3	2.7
Carroll	0.2	8	2.7
Dundas	0.4	9	2.7

Mernild, S.H. and Liston, G.E.: Greenland freshwater runoff. Part II: Distribution and trends, 1960-2010, *Journal of Climate*, *25*(17), pp.6015-6035, DOI: 10.1175/JCLI-D-11-00592.1, 2012.

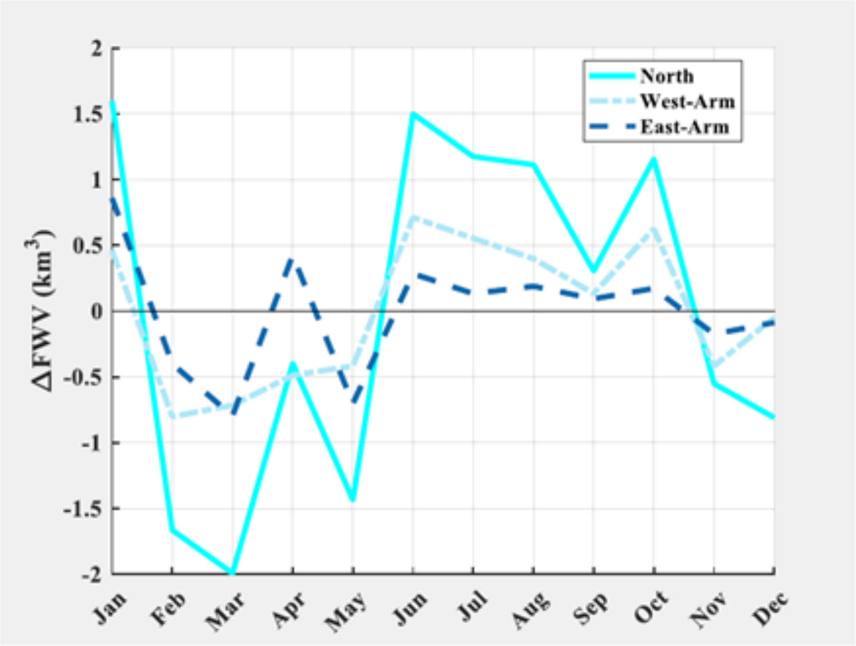
Mernild, S.H., Lipscomb, W.H., Bahr, D.B., Radić, V., Zemp, M.: Global glacier changes: a revised assessment of committed mass losses and sampling uncertainties, The Cryosphere 7, 1565–1577, DOI: 10.5194/tc-7-1565-2013, 2013.

Mernild, S.H., Liston, G.E. and Hiemstra, C.A.: Northern hemisphere glacier and ice cap surface mass balance and contribution to sea level rise, *Journal of Climate*, *27*(15), pp.6051-6073, DOI: 10.1175/JCLI-D-13-00669.1, 2014.

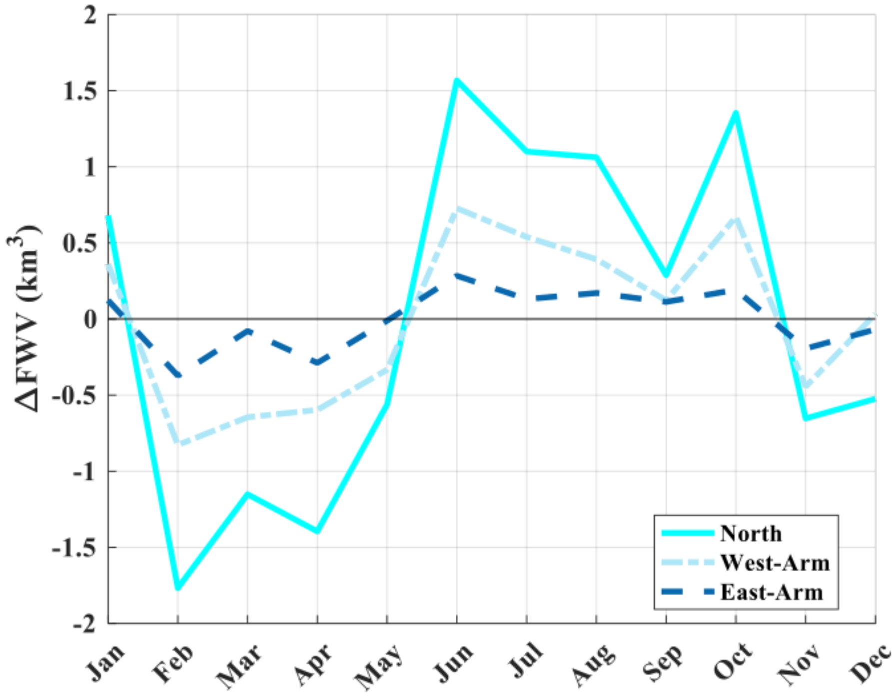
Mernild, S.H., Liston, G.E., Hiemstra, C.A., Malmros, J.K., Yde, J.C. and McPhee, J.: The Andes Cordillera. Part I: snow distribution, properties, and trends (1979–2014), *International Journal of Climatology*, *37*(4), pp.1680-1698, DOI: 10.1002/joc.4804, 2017a.

P23L10 (Figure 9): Why do we see a maximum in delta FWV in January? I would at least expect a brief discussion on that maximum in the text.

Response: This is a good question, and we decided to look at these specific months (Jan and Dec) in our analysis below. For clarity, the January value ΔFWV_jan in Figure 9 is equal to FWV_jan – FWV_dec. In assessing the certainty in this signal, it is important to consider: (1) Winter is vastly under-sampled as compared to other seasons, and (2) there can be great variability between monthly FWC from year to year. The authors realized that because of these two factors, some months were excluded in the FWV extrapolation for all months. After incorporating these excluded months into the analysis, we made changes to Figure 9 that is more representative of all months in the entire dataset. See the old and new versions of Figure 9 below. Some of undersampled winter monthly FWV values have changed slightly, the more highly-sampled summer monthly FWV values remain largely intact, and the ΔFWV_jan value is dampened in the final Figure 9. In the revised figure, it is evident that the strongest signals in monthly changes in freshwater occur in the summer (May to October). Although the figure does suggest that there is an increase in FWV from December to January, it must be weighed in the context of the uncertainties described herein.



Old Figure 9



New Figure 9

P27 (Table 3): It would be helpful for the readers to have a separate column for each existing column which provides the runoff in mm too. In your text, you already highlight the benefit of using specific runoff for reasons of comparison.

Response: A new column has been added to Table 3 in the final draft with the specific runoff in meters for the historic and projection scenarios.

P7L17: There is no Sect. 3.4.1.

Response: Section 3.4.1 has been removed in the final draft.

P10L: Figure 9 does not show any trends. Why do you plot the delta in FWV instead of FWV?

Response: The word *trends* in Section 4.6, ¶1 has been changed to *seasonal timing of changes in freshwater*, which is a more precise wording of the sentence.

P11L12: Please correct the reference to the figure (there is no Fig. 9a).

Response: This mistake has been removed in the final draft.

Reviewer 2: Anonymous

My main concerns are the following: i) the link between modelling results and CTD observations is weak, lacks description and a convincing discussion. ii) the calibration of the modelling chain lacks description and convincing results. iii) an uncertainty discussion of the modelling results is missing. iv) the structure of the ms is at some locations mixing methods, data description and results v) due to the concerns above the conclusions are vague, speculative and lack conviction.

Major concerns: 1. The linkage between FWV and FWC would require a thorough discussion of the mixing of freshwater into ocean water. Numerous paper exist on this topic but this ms fails to review the literature and discuss this complex topic in a convincing manner.

Response: The manuscript originally contained a more detailed explanation of oceanographic processes, with a more thorough discussion of freshwater mixing. However, it is not within the scope of this manuscript to review in great detail the theoretical extent of these oceanographic processes, nor is it especially relevant to the readers of The Cryosphere. Instead, we added a paragraph in Section 1 in the manuscript that focuses on the bioecological effects of stratification in Glacier Bay specifically, in order to address this comment and to keep the focus on the study area. The paragraph added to the intro section in the final draft of the manuscript is below in italics.

Long-term shifts in terrestrial freshwater storage and runoff can have significant implications for oceanographic stratification and circulation that moderate biogeochemical and ecological activity within Glacier Bay. Since Glacier Bay is a highly understudied, relatively remote national park, the complete freshwater budget for the bay cannot be quantified due to the lack of available data. However, seasonal trends in modeled freshwater runoff can be qualitatively compared with seasonal trends in broadscale oceanographic salinity records from 1993 to present collected by the U.S. National Park Service's Southeast Alaska Inventory & Monitoring Network (SEAN). This SEAN dataset served as the basis of the analysis performed by Etherington et al. (2007), which found positive correlations between phytoplankton biomass and stratification levels. The competing forces of macro-tidal flushing and strong stratification within the glacially-carved estuary generates temporally and spatially shifting trends in upwelling and nutrient availability (Etherington et al., 2007). Thus, accurate estimation of projection scenario runoff into Glacier Bay plays a paramount role in constraining future changes in water and nutrient circulation.

2. The description of the calibration is weak: if the authors claim to make realistic projections of future FWV into the ocean, I would expect a thorough discussion of the efficiency regarding snow melt, ice melt and rain runoff of the model; the necessity of multi dataset calibrations for hydrologic modelling under climate scenarios have been discussed in the literature.

Response: This comment from Reviewer 2 about the calibration description is warranted, and in the light of other reviewer's comments, the authors added a paragraph in Section 3.4 to clarify our calibration decisions and process. It should be noted that one of the primary reasons the authors chose to use the historical oceanographic dataset is because long-term observational datasets of stream flow and weather conditions within the boundary of Glacier Bay National Park do not exist. This is also why we chose to calibrate the model with observations and records from the nearby Mendenhall Glacier, as further explained in more detail in the new paragraph in Section 3.4. The paragraph added to the calibration section in the final draft of the manuscript is below in italics.

Recent studies (Beamer et al., 2016; Lader et al., 2016) have investigated the accuracy and biases of the MERRA reanalysis product in coastal Alaska compared to other reanalysis products such as ERA-Interim (Dee et al., 2011), CFSR (Saha et al., 2010), NCEP-NCAR (Kalnay et al, 1996), NARR (Mesinger et al., 2006), and others. Many SnowModel parameters were tested by doing a sensitivity analysis for each reanalysis product, including monthly precipitation adjustment factors, snow/rain temperature thresholds, snow and ice albedo factors, and more (see Beamer et al. (2016) their Table 2). For each of 4 reanalysis products, they calibrated model parameters based on observations of streamflow (Q) and glacier mass balance (B). The MERRA simulation Coefficient of Determination scores (r2) for glacier mass balance (B) and stream discharge (Q) for the Beamer et al. (2016) study were 0.80 and 0.95, respectively, and the Nash Sutcliffe Efficiency (NSE) scores were 0.67 and 0.91, respectively. While Beamer et al. (2016) identified the CFSR product as the 'best overall' for the GOA region, they found that MERRA was superior at the Mendenhall Glacier observational station, which is the closest calibration point (< 25 km) to GBNPP. For these reasons, in this study we rely on the model calibration of Beamer et al. (2016; their section 3.4) and we adopt their calibration parameters for SnowModel from their Table 2 and Table A1.

Long-term glacial mass balance programs and long-term streamflow gauge datasets do not exist within the GBNPP study area, thus constraining our ability to conduct additional calibration efforts. While the Mendenhall Glacier observation station is close in proximity to Glacier Bay, the glacier has receeded and thinned significantly since the early 1900's, glacial wastage is a significant component of annual streamflow (17%), and glacial meltwater contributes heavily to streamflow in the summer (50%; Motyka et al., 2003). As a result of these similarities in geography and hydrology, we rely on the calibration process, parameters, and best-performing reanalysis product (MERRA) from Beamer et al. (2016) for our study.

3. The uncertainty of the results are not discussed; are the projected changes significant? What is the uncertainty of the future scenarios?

Response: Please see the response to another comment from this Reviewer below about uncertainty and the variability of the historical simulations. Here, the Reviewer raises an important point, and included below is an analysis of the variability of the historical simulation results for the all watersheds in GBNPP. This table includes historical annual variability (+/- $\boldsymbol{\sigma}$ standard deviation in the table below) for the GBNPP study area and various grouped watersheds for the modeled output for runoff, snow precipitation, and SWE. This table includes the monthly climatological average (36-year) of the variable, the standard deviation of the 36-year monthly values of the variable, and the percentage of the climatological average represented by the +/- one standard deviation. The annual variability in the historical runoff averages 9% of the annual runoff when averaged over the entire GBNPP domain. The standard deviation can be calculated annually or monthly, by grouped or individual watershed, or over the entire domain for every variable. The reasoning for not including variability (***σ***) in every monthly figure is to cut down on visual clutter and also because the variability differs by a few percentage points from watershed to watershed.

Table: Historical variability (standard deviation of 36-year climatology; ***σ* (m)**) for annual runoff, annual snow precipitation, and annual snow water equivalence (SWE) spatially aggregated for each grouped and individual watershed.

	Annual Runoff			**Annual Snow Precipitation**			**Annual SWE**		
Watershed	**(m)**	***σ* (m)**	**(%)**	**(m)**	***σ* (m)**	**(%)**	**(m)**	***σ* (m)**	**(%)**
GBNPP	3.4	+/- **0.3**	9	2.0	+/- **0.3**	15	1.1	+/- **0.2**	18
North	3.1	+/- **0.3**	10	1.9	+/- **0.3**	16	1.1	+/- **0.2**	18
West	4.3	+/- **0.4**	9	2.1	+/- **0.3**	13	1.2	+/- **0.2**	17
West-Arm	3.4	+/- **0.4**	12	3.3	+/- **0.5**	15	1.9	+/- **0.3**	16
East Arm	3.6	+/- **0.4**	11	1.8	+/- **0.3**	17	1.0	+/- **0.2**	20

Additionally, Reviewer 2 asks about the uncertainty of the forecast scenario results. First, because of this comment and the comments of another reviewer, the authors chose to adopt the language of ‘projection scenario’, instead of ‘forecast’ scenario for the final draft of the manuscript. Adopting the term ‘projection’ is more in line with the original intent of the manuscript. As Reviewer 1 notes, “I would suggest using “projection” instead since this term acknowledges additional uncertainty involved in climate scenarios which arise from uncertain greenhouse gas emissions.” We highlight our response to Reviewer 1 here: *We are not attempting to make a climate prediction (as defined in the provided weblink;* ***http://glossary.ametsoc.org/wiki/Climate_prediction****) of what will happen in the future in Glacier Bay. We are modeling one of the potential scenarios that may occur in the hydrology of the region that would accompany the RCP8.5 emissions scenario. For these reasons, the authors have chosen to change the term ‘forecast scenario’ to ‘projection scenario’, in every instance, throughout the manuscript. These changes are added to the final draft.* The authors have also added text in Section 3.5.1 to make this point clear in the final draft of the manuscript.

Lastly, the annual variability of the modeling results can be quantified, and the table above shows the historical variability (standard deviation) of runoff, snow precipitation, and SWE. However, there are many ways uncertainty affects the modeling results that are difficult to characterize and unrelated to annual variability. For example, spatially explicit modeling at 250m resolution is a simplification of a hydrologic system and environment that, in reality, operates at infinitely smaller scales. There are also environmental processes imperfectly described my model physics or imperfect model parameterizations that increase the uncertainty of the results. Additionally, a weather reanalysis product is used to force the model in the absence of long-term, in-situ weather station data, and there are errors and biases associated with reanalysis data assimilation and interpolation processes. The RCP 8.5 projection scenario then adds more layers of uncertainty, due to GCM model resolution and physics, and the associated likelihood of greenhouse gas concentrations in the future. Fully quantifying each of these uncertainties is not the aim of this study, and we acknowledge that this is an important limitation of the current study. We simultaneously think that since no long-term weather station records, stream flow gauges, or glacier mass balance programs exist within the study area, our physically-based, spatially explicit modeling approach is a valuable inquiry into the hydrology of Glacier Bay. It advances the current knowledge of a system that is not well characterized or measured, and it advances our understanding beyond the current literature.

We are not attempting to make a prediction of the likelihood of future hydrologic conditions, only describe the historical and projection scenario climatologies of these conditions. To address these concerns, we changed the language throughout the manuscript from ‘forecast’ to ‘projection scenario’ to clarify future scenario results, and we’ve added multiple clarifying sentences about the purpose and aims of the study (Abstract, sentence 3; Section 1, para 8; Section 3.5.1, para 2).

Specific comments: 1) Title: what is hydrologic diversity? This term is never mentioned in the ms accordingly it seems misleading to use it in the title. I would be helpful to have a title that reflects the content of the ms.

Response: Another reviewer commented on the ambiguity of this term in the title too. The title has been changed to *Seasonal Components of Freshwater Runoff in Glacier Bay, Alaska: Diverse Spatial Patterns and Temporal Change.*

2) Abstract: An introductory sentence explaining the problematic and the purpose of the ms is missing;

Response: The authors are comfortable leaving the abstract summarization of the research questions and problems primarily intact. Some of the language in the abstract has been changed to clarify the original intent of the manuscript. Additionally, the authors have added a single introductory sentence (in italics below) explaining the purpose of the manuscript.

The purpose of this study is to characterize the recent historical components of freshwater runoff to Glacier Bay and quantify the potential hydrological changes that accompany the worst-case climate scenario during the final decades of the 21st century.

L16 why “wide variety”, the same “variety” exist in any glaciated catchment;

Response: To address this comment about a ‘wide variety’ vs ‘variety’, the authors removed ‘wide’ from the final version of the abstract.

L24: this sentence is redundant, as it does not contain any conclusive information about the study:

Response: After further review, the authors agree that this sentence is redundant, and the sentence has been clarified in the final version to reduce repeated ideas.

3) Introduction: Nice description of the study site; however, a description of the linkage between fresh water inflow in an ocean bay and the subsequent impacts on marine life is missing; also a review of the literature of intruding freshwater into water bodies would be helpful.

Response: The authors are attempting to balance the length of the manuscript and the scope of the ideas covered in the intro section. As previously mentioned, we added a paragraph in Section 1 to address some of the missing linkages between freshwater inflow and impacts on marine life.

pg3, L 15: “the goals are different”: it would be helpful to outline the goals;

Response: To address this comment about the last paragraph in Section 1, and other related comments from other Reviewers, the authors added two sentences in this paragraph in the final draft to clarify the goals of the study.

L20: the results present do not convincingly present changes in the coastal runoff (see major concerns).

Response: The text in this line of the manuscript originally read ‘*The results of this study will add to the understanding developed by Etherington et al. (2007) and will provide constrained estimates of how much the coastal runoff in GBNPP will change in the future*.’ After acknowledging the comments from this and other reviewers, the authors have changed this sentence to more accurately reflect the original intent of the manuscript.

The sentence now reads, ‘*These results will add to the understanding developed by Etherington et al. (2007) and will provide constrained estimates of potential changes in runoff in GBNPP under the RCP 8.5 projection scenario*.’ This change in language is important, and the scrutiny of this sentence by the Reviewers makes sense. We are not attempting to make a climate prediction or define the likelihood of what will occur hydrologically in the future. We are saying that if the greenhouse gas concentrations associated with the worst-case scenario RCP 8.5 come to pass, the hydrology (runoff, precipitation, SWE, etc.) will be affected in the specific ways that are outlined in our results and discussion sections. This difference is important to note and we have made an effort to clarify this throughout the paper.

4) Methods1: pf4, L 8: model chain? Only two models are used, one for the reanalysis of the forcing data and the SnowModel.

Response: It is true that SnowModel and MicroMet are the only two models used for this study. Therefore, the words 'model chain', and every reference thereafter, were removed from the manuscript.

5) Methods2: I think the clarity of the ms would improve if methods and data were two separate chapter;

Response: The methods and datasets have been presented in the same section of the publication because the input datasets are closely linked to the modeling process. The authors think the article benefits from the inclusion of these two parts in the same chapter, and it is quite common for articles in The Cryosphere to present data and methods together. However, as noted by Reviewer 3, some of our methods were first presented alongside results in various results paragraphs. The authors have removed all of the text about methods from the results and placed them into the methods sections for clarity.

6) Methods 3: 3.4. describes in a very rudimentary way model calibration; r2 and NSE values are provided. Since the authors claim to provide an "added understanding" and "constrained estimates of how coastal runoff will change in the future" I would expect a thorough discussion on the efficiency of their modelling in regard to runoff, snow melt and ice melt contribution during the calibration period. If the calibration is not presented adequately, how can one trust in the results of future runoff?

Response: This comment makes sense, and the original version of the calibration description was lacking in clarity and length. As previously mentioned, we added description and details about the calibration decisions to Section 3.4 in the final draft.

7) Results: pg7,8: here results and methods to calculate the results are in the same chapter; I think a clear separation between methods and results would be helpful;

Response: This comment is similar to other Reviewer comments about the results section occasionally mixing descriptions of the methods into the text. We have made an effort to move all of these discussions about methods to the previous section whenever necessary in the final draft.

Additionally, the authors want to clarify that the descriptions of the results through Eq. 2, Eq. 3, and Eq. 4 are not equivalent to descriptions of methods. We are attempting to clarify exactly what is represented in the results figures, so that readers can easily understand what is meant by a changes in metrics like temperature, precipitation, and snowfall equivalent to total precipitation. These metrics, and changes in their values from a historical period to a projection scenario, are not methods for producing modeling results. They are metrics that describe the results produced by the simulations. There could be many ways to describe model output in terms of temperature, precipitation, and snowfall, and we are making an effort to be very clear about how we are presenting these changes in the results section. For these reasons, the authors think the descriptions of these equations belong in the results section and not in the methods section.

8) Figures 1, 2 and 5 (in total 8 maps) all show specific aspects of the study site; this information could be combined and presented in one or perhaps 2 large panels.

Response: Since Figure 5 is a visualization of the results of changes in glacier coverage between the historical period and the projection scenario, the authors think Figure 5 needs to remain on its own as a depiction of glaciers in the study area.

The nested watersheds study design, depicted in Figure 2, is complex to visualize in the same map. We are presenting a study design that includes different watershed scales, the entire study area as a group (GBNPP), the grouped watersheds that flow into Glacier Bay and the Pacific Ocean, the grouped watersheds in separate arms of Glacier Bay, and the individual watersheds that lie within these other areas. Visualizing these on the same map is likely to be difficult to interpret by readers and presenting them in separate panels, side-by-side was an important decision by the authors to clearly depict the study design. Additionally, due to another Reviewer's comment, we decided to add labels for Glacier Bay, the Pacific Ocean, and Icy Strait in Figure 2.

As for Figure 1, the authors think that it is necessary to show the larger region of interest, as well as the digital elevation model/bathymetry and intend to keep Figure 1 intact.

9) Figure 3: I do not understand why contour plots are used here; bars indicating the exact value of T and P change would be more helpful.

Response: Color heatmaps are one of the best ways to convey hundreds of values, along multiple axes through the use of a color gradient. The authors chose to use the heatmap to visualize these changes in temperature and precipitation because it efficiently and intuitively communicates 104 different values in a compact and clear package. Since this is a 3 panel figure, the authors think that displaying 312 bars or points representing these changes or 312 numbers in a large table would not clearly or succinctly communicate the changes in these 3 variables over time.

10) Figures 4, 6, 7, 8, 9 and 10: it would be helpful to add an uncertainty to each point; e.g. stdev from the mean over the 30 yrs (but this would only account for climatic availability); I recommend checking recent literature on this topic.

Response: We've chosen not to include the variability at each point for the modeling results in these figures because we want to simplify the visualization of the results. However, the authors have done some additional analysis to show the reviewers the standard deviation from the mean for some of the historical climatologies in runoff, snow precipitation, and SWE. See Table above for all of the grouped and aggregated watersheds and the authors' response to an earlier comment about uncertainty and variability.

Reviewer 3: Janet Curran

Title: Can you find a term other than "hydrologic diversity" that better brings the topics of changes in runoff volume, seasonality, and drivers to mind? Hydrologic regime diversity. . .? Freshwater runoff . . .? Not sure I have the perfect term, might take a phrase to say it.

Response: This comment is similar to another reviewer's comment about the term 'hydrologic diversity' being undefined and potentially ambiguous. The authors will change the final version to *Seasonal Components of Freshwater Runoff in Glacier Bay, Alaska: Diverse Spatial Patterns and Temporal Change*.

Abstract, L 24-25: "a variety of changes" is vague. What is meant here?

Response: The authors have clarified the meaning of this sentence in the final draft, which reads, "The hydrographs of individual watersheds display a diversity of changes between the historical period and project scenario simulations, depending upon…"

P6, L15-17: The closest calibration point isn't always the most appropriate. Can you also say that the Mendenhall basin is the most similar?

Response: See the new added paragraph in the calibration Section 3.4 that addresses this comment and the comment below simultaneously.

Recent studies (Beamer et al., 2016; Lader et al., 2016) have investigated the accuracy and biases of the MERRA reanalysis product in coastal Alaska compared to other reanalysis products such as ERA-Interim (Dee et al., 2011), CFSR (Saha et al., 2010), NCEP-NCAR (Kalnay et al, 1996), NARR (Mesinger et al., 2006), and others. Many SnowModel parameters were tested by doing a sensitivity analysis for each reanalysis product, including monthly precipitation adjustment factors, snow/rain temperature thresholds, snow and ice albedo factors, and more (see Beamer et al. (2016) their Table 2). For each of 4 reanalysis products, they calibrated model parameters based on observations of streamflow (Q) and glacier mass balance (B). The MERRA simulation Coefficient of Determination scores (r2) for glacier mass balance (B) and stream discharge (Q) for the Beamer et al. (2016) study were 0.80 and 0.95, respectively, and the Nash Sutcliffe Efficiency (NSE) scores were 0.67 and 0.91, respectively. While Beamer et al. (2016) identified the CFSR product as the 'best overall' for the GOA region, they found that MERRA was superior at the Mendenhall Glacier observational station, which is the closest calibration point (< 25 km) to GBNPP. For these reasons, in this study we rely on the model calibration of Beamer et al. (2016; their section 3.4) and we adopt their calibration parameters for SnowModel from their Table 2 and Table A1.

Long-term glacial mass balance programs and long-term streamflow gauge datasets do not exist within the GBNPP study area, thus constraining our ability to conduct additional calibration *efforts. While the Mendenhall Glacier observation station is close in proximity to Glacier Bay, the glacier has receeded and thinned significantly since the early 1900's, glacial wastage is a significant component of annual streamflow (17%), and glacial meltwater contributes heavily to streamflow in the summer (50%; Motyka et al., 2003). As a result of these similarities in geography and hydrology, we rely on the calibration process, parameters, and best-performing reanalysis product (MERRA) from Beamer et al. (2016) for our study.*

Motyka, R.J., O'Neel, S., Connor, C.L. and Echelmeyer, K.A.: Twentieth century thinning of Mendenhall Glacier, Alaska, and its relationship to climate, lake calving, and glacier run-off. Global and Planetary Change, 35(1-2), pp.93-112, DOI: blah, 2003.

P6, L17-18: These metrics are for the Beamer et al. (2016) study, correct? Since this "calibration" section oddly refers to the calibration of a prior study, I suggest phrasing this clearly so the skimming reader doesn't assume these metrics are for your study.

Response: These metrics are from the Beamer et al. (2016) study. This paragraph in Section 3.4 has been re-written to clear up any vague phrasing that may exist for the final draft. The authors have also added some additional explanation of the calibration process for clarity due to the comments of at least one other Reviewer on the calibration process. See new, additional calibration paragraph above.

P8, L1: This sounds like a justification for a higher-than-expected result, but the wording isn't clear. Does the RCP8.5 scenario establish a minimum of 3 degrees change?

Response: The RCP8.5 scenario, and corresponding SNAP temperature and precipitation anomalies, do not establish a minimum or baseline of 3 degrees change. The statement in the text is simply a description of the lower range of temperature changes that are found within each watershed group between the historical and projection scenario modeling results. In Section 4.1 we changed the end of this sentence to avoid confusion.

P10, L3: Is the 3.40 m/yr value actually for "runoff", not "precipitation" as stated? That would be more consistent with the value in the next line.

Response: In this case, for all watersheds in the GBNPP domain, the annual average historical precip value is 3.4m and the annual average historical runoff value is 3.4m. This is different within each grouped watershed. Remember, the authors are reporting the runoff value calculated by SnowModel, which includes all the water made available at each grid cell from precip (snow & rain) + glacier melt processes. ET is not subtracted from these runoff values, just simply plotted on the same graph for context (from Figure 7 and Appendix B). We also do not estimate long-term changes in the groundwater or glacial wastage (ΔStorage) within the 36-year historic and 30-year projection scenarios. For a further discussion of ET calculations and estimations, please refer to the responses to Reviewer 1.

Let’s look more in depth at some of these runoff and precipitation values. See the table below for additional information. When PRECIP < RUNOFF like in the West watershed below, there is likely glacier ice melt occurring over the time period that is supplementing the freshwater flows in the basin. When the snowpack disappears from a glacier grid cell, the energy balance model melts the glacier ice and adds to water to the runoff variable. When PRECIP > RUNOFF, like the West-Arm and Tarr watersheds below, there is likely SWE left over at the end of the the year, on glacier surfaces and at the highest elevations, that gets zeroed out at the end of the water year in the SnowModel simulations. This is because SnowModel does not include glacier dynamics, and there will be net accumulation of snowpack above the equilibrium line. When running multi-year simulations, SnowModel offers the option to zero out all the grid cells that still contain SWE on the last day of the water year, in order to not carry over SWE into the next water year. In this study, we chose to zero out the SWE in this manner at the end of every water year, and this method is the recommended/default method for SnowModel users when running multi-year simulations in regions with glacier coverage. In watersheds like the West-Arm and Tarr, where there is 54%-68% glacier coverage, the amount of snow precipitation and leftover SWE is likely to be a substantial portion of the overall precipitation, and that is reflected in the Runoff and Precip values for these watersheds. However, we have not conducted the spatial or temporal end-of-water-year SWE analysis for all years and all watersheds because it is not directly related to the aims and scope of this study.

When PRECIP ~ RUNOFF, like in the GBNPP aggregated watershed, there is a balance between these glacial melt processes and leftover SWE at the end of the time period.

Watershed	Historical PRECIP (m)	Historical RUNOFF (m)
GBNPP	3.4	3.4
North	3.3	3.1
West	3.8	4.3
West-Arm	4.4	3.4
East-Arm	3.3	3.6
Tarr	6.1	2.9
Carroll	2.4	2.9
Dundas	2.4	3.1

P12, 13-14: This statement about a non-stationary system is inconsistent with the presentation of Figure 10 on P10, L20-22, which notes little significant change with one basin

as an exception. The trend for the excepted basin isn't very convincing ($p > 0.05$, short and discontinuous dataset, a bit noisy), making the comments on P12 seem overstated.

Response: Based on the current Figure 10, your observation and comment is warranted. This is an overstatement in this context. The sentence was originally written for a different figure showing more significant trends in the grouped GBNPP watershed overall, but we had previously decided to remove that figure and the previous results. We will adjust the wording accordingly, by taking out the reference to non-stationarity, and the authors have also decided to remove Figure 10, because the presence of this figure is not adding any additional, necessary information to the manuscript. We've adjusted the language in Section 4.6, paragraph 2.

Appendix B: Interestingly, the forecast runoff hydrographs, which admirably show the relative contributions of runoff processes, produce a few seasonalities that aren't apparent for individual streams in my present work characterizing historical hydrographs. The composite GBNPP and North basins appear to have a snowmelt-dominated spring peak and a larger rainfall-dominated fall peak, a reversal of the typical relative magnitudes for a bimodal glacierized basin hydrograph. Can this be explained by an increase in spatial distribution of future rainfall-dominated areas within the composite basin or any other observations from the modeling?

Response: This is an excellent question, and one that would require more in depth spatial analysis of the modeling results to answer quantitatively. At first glance, your suspicion about the increase in spatial distribution of future rainfall dominated areas within the composite basin contributing to the larger rainfall dominated fall peak makes sense in the context of the temperature and precipitation results. Looking at Figure 3 may shed some light on this question. We can see the largest increases in temperatures, the largest increase in precipitation, and the most significant decreases in snowfall occur for most watersheds during the months between Oct and Dec (appearing as a blob of darker colors during those months). However, to calculate the exact spatial extent (area in km^2) of the increase in rainfall-dominated areas would require additional spatial analysis of the results during both the historic and projection scenarios. Since a close look at Figure 3 contains some of the answers to your questions, the authors are comfortable keeping the Appendix A explanation in the manuscript and figure caption without changes.

Additionally, the freezing line altitude (FLA) analysis (see Figure 11) includes a ΔFLA from historic to projection scenario for the winter (+234 m) and summer (+1341 m) months. We did not include the spring (+910 m) and fall (+775 m) ΔFLA values in the figure due to simplicity's sake. These increases in the FLA during spring and fall would represent a large corresponding increase in the spatial distribution of the rainfall dominated areas in the RCP8.5 projection scenario, and makes sense with the changes in temperatures found in Figure 3.

Introduction: Trim and keep focused on the study by omitting details about GOA (especially in 1st and 2nd paragraph), minimizing drama (P2, L6-7), and considering moving setting

information to the Study Area section if it's actually needed (the long discussion of tidal mixing and stratification and the Etherington et al. study made me think this was the study focus on first read). It's all interesting, but it's not until the penultimate paragraph (P3, L37-39) that the problem is hinted at and not until the final paragraph (P3, L13) that the actual work of the study is introduced, and the reader can finally start understanding the direction of the manuscript.

Response: The discussion of the GOA in the intro paragraphs 1 & 2 are important to give the readers of the Cryosphere the geographical context within which the Glacier Bay region exists. However, some of the details and general statements about the region can be trimmed to keep the focus on Glacier Bay.

In Section 1, para 2, the word 'dramatic' will be changed to 'considerable'. Also the authors are comfortable taking out the end of the following sentence, which will now read 'Indeed, the coastal mountain ranges of Alaska have recently sustained rapid rates of deglaciation (Arendt et al., 2002; Arendt et al., 2009; Gardner et al., 2013; O'Neel et al., 2015).' Drama was not the intent with the previous sentence and wording, and these changes remove any question or potential of dramatic language.

Reviewers have requested both more information (Reviewer 1) about oceanographic processes (stratification, mixing, etc.) and less information about these processes (Reviewer 3). The authors are attempting to balance all the requests, while simultaneously keeping the original flow and intent of the article. In this case, we choose to keep the remaining paragraph structure of the intro intact.

P2, L31 and P3, L3-4: The number of references to particular places within Glacier Bay suggests Figure 2 could be presented earlier.

Response: This is a good suggestion. Figure 2 will now be referenced in this paragraph.

Study Area, paragraphs 1 and 2: Clearly define study area (all watersheds within GBNPP, which includes all the lands of GBNPP and some areas outside it?). The multiple nested, paired watersheds are a nice study design but are hard to keep track of. Suggest moving the parts of paragraph 2 that aren't obvious from the figure or table (P3, L29-30) into paragraph 1. Consider using a defining characteristics for the names or adding a column to Table 1 to associate basin names with a defining characteristic. It would be helpful to know "North" is the full Glacier Bay basin and that the choice of the three named basins allows comparison of basins having. . .(a range of elevation? a range of glacier characteristics?), for example.

Response: The authors have added text in this paragraph to clarify the study area boundary decisions in Section 2. In this section, para 1 describes the entire GBNPP study area, and para 2 describes the 4 grouped watersheds, and paragraph 3 describes the individual watersheds. The authors think this is an appropriate structure for the paragraphs, and some additional text has been added to these paragraphs to clarify.

P7, L23-24: This is one of the clearest statements of the goals/outcome of the study. Could use this earlier.

Response: This is a good suggestion from Reviewer 3. This sentence has been altered slightly and added to the last paragraph of the Section 1, in order to more clearly state the outcome of the present study.

P9, L11-12: Delete information repeated from methods.

Response: This is another good suggestion that makes the manuscript more concise. The first sentence in Section 4.3 summarizes paragraphs found in the methods section and has been removed from the final draft.

P9, L25-35: Many details of computations, and the discussion of the omission of routing, seem like methods. Consider moving to Section 3.1 or elsewhere in Methods.

Response: Again, this comment from Reviewer 3 makes sense for the flow of the paper and for keeping a clear delineation between methods and results. This paragraph has been moved to the methods section and removed from this results paragraph in the final draft.

P10 and 11, Section 5, first and second paragraphs: Most of the main points are made in the first paragraph; suggest combining the two and reducing detail. Consider moving computation of FLAs to methods.

Response: The authors think the detail in this paragraph is a warranted discussion of the FLA analysis and the landscape dependencies of seasonal snow patterns. However, there are a few sentences in this section that have been appropriately moved to the methods section in accordance with this suggestion.

P12, L5-6: Nice explanation of why CTD dataset was included, could use this earlier.

Response: This is an important point, and the authors have restated this in Section 1, para 7.

P11, L11-12 and L20: Check figure number. I assume you mean figure 11a and b, respectively.

Responses: Good catch, yes, this was previously Figure 9 and was changed in the final stages of drafting.

References: References are used appropriately. I did not check to make sure all are used, or that all references cited are included. The recommended citation for USGS reports includes the report series title and report number. For Curran et al. (2003) that's Water-Resources Investigations Report (or WRIR, if preferred) 03-4188 and for Wiley and Curran (2003) it's Water-Resources Investigations Report 03-4114.

Response: These two citations have been changed to include the Water Resources Investigations Report.

Fig. 1: Labeling Alaska and Canada (a) and Glacier Bay (b and c) would help reader comprehension.

Response: Agreed, the labeling of Glacier Bay is a missing piece of these maps and they will be added to the final figures. As for labeling Alaska and Canada, the authors want to keep the maps as simple as possible, without clutter, and do not think it is necessary to know exactly where the international boundary lies, since we have no other non-physical geographical locations (cities/towns, boundaries, roads, etc.) labeled.

Fig. 2: Label Glacier Bay. The Alaska/Canada boundary is referenced in the text but not shown here.

Response: Again, the authors think it's worth mentioning the boundary in the text but it is not a necessary part of the maps. Glacier Bay has been labeled in the final draft figure.

Fig. 5 : Shading of forecast glaciers is distractingly similar to ocean. The title "Glacier Change" doesn't match the legend items, which include two glacier positions and the GBNPP boundary.

Response: For the final draft, the legend title 'Glacier Change' has been removed completely from the legend of the figure. The authors agree that the color palette for the forecast glaciers needs to be different for reader comprehension, and the final draft of the figure has a different color palette.

Fig. 6: Suggest being consistent with the x-axis scale used for other monthly plots (use Jan-Dec, not Sept-Aug)

Response: The reason the SWE climatologies are presented in water year format, from Sept-Aug, instead of presenting them in the previously used calendar year format is because the progression of snow water equivalence is simpler, and possibly more intuitive to visualize and understand when the winter is not split in two parts. Often, but not always, when SWE climatologies are presented in the literature they span the water year and not the calendar year. For these reasons, the authors think the SWE climatology is easiest to understand in its current format.

Fig. 7 caption, last sentence for (a): Check for typo in “the modeled for runoff climatology”

Response: This typo has was changed in the final draft.

Tables 1 and 3, and Appendix A and B: Suggest some structure to convey basin/sub-basin relationship and the various pairings of nested basins (a line or spacing, for example). At a minimum, keep the same order in the Appendices as is used for the tables.

Response: The authors have divided the tables into groupings, and the order of the Tables and Appendices are kept the same in all instances.

Appendices: These plots are useful results and would lend themselves well to being reduced in size. Consider rearranging to fit each Appendix on 1 page with a single legend for each and including in the text.

Response: The authors are open to including the appendices in the main text, and to reducing them in size, instead of including these sets of figures as appendices. This decision can be ultimately be left up to the editors discretion at the Cryosphere.

Seasonal Components of Freshwater Runoff in Glacier Bay, Alaska: Diverse Spatial Patterns and Temporal Change

Deleted: Hydrologic Diversity

Ryan L. Crumley[1], David F. Hill[2], Jordan P. Beamer[3], Elizabeth Holzenthal[2]

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Abstract. A high spatial resolution (250 m), distributed snow evolution and ablation model, SnowModel, is used to estimate current and future scenario freshwater runoff into Glacier Bay, Alaska; a fjord estuary that makes up part of Glacier Bay National Park and Preserve. The watersheds of Glacier Bay contain significant glacier cover (tidewater and land-terminating) and strong spatial gradients in topography, land cover, and precipitation. The physical complexity and variability of the region produces a variety of hydrological regimes, including rainfall, snowmelt, and ice-melt dominated responses. The purpose of this study is to characterize the recent historical components of freshwater runoff to Glacier Bay and quantify the potential hydrological changes that accompany the worst-case climate scenario during the final decades of the 21st century. The historical (1979-2015) mean annual runoff into Glacier Bay proper is found to be 24.5 km^3 yr^{-1}, or equivalent to a specific runoff of 3.1 m yr^{-1}, with a peak in July, due to the overall dominance of snowmelt processes that are largely supplemented by ice-melt. Future scenarios (2070-2099) of climate and glacier cover are used to estimate changes in the hydrologic response of Glacier Bay. Under the representative concentration pathway (RCP) 8.5 projection scenario, the mean of five climate models produces a mean annual runoff of 27.5 km^3 yr^{-1} or 3.5 m yr^{-1}, representing a 13% increase from historical conditions. When spatially aggregated over the entire bay region, the projection scenario seasonal hydrograph is flatter with weaker summer flows and higher winter flows. The peak flows shift to late-summer and early-fall and rain runoff becomes the dominant overall process. The timing and magnitudes of modeled historical runoff are supported by a freshwater content analysis from a 24-year oceanographic Conductivity-Temperature-Depth (CTD) dataset from the U.S. National Park Service's Southeast Alaska Inventory and Monitoring Network (SEAN). The hydrographs of individual watersheds display a diversity of changes between the historical period and projection scenario simulations, depending upon total glacier coverage, elevation distribution, landscape characteristics, and seasonal changes to the freezing line altitude.

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1 Introduction

South-central and southeastern Alaska (Figure 1a) are regions of physical, climatological, and hydrological extremes. Precipitation rates in excess of 8 m yr^{-1} water equivalent (w.eq; Beamer et al., 2016) fall on high mountain ranges (4000-6000 m) in close proximity to the ocean. The steep terrain drives strong orographic gradients in precipitation and creates compact drainage networks that rapidly deliver runoff to the coastline. Due to significant snowfall fractions for much of the year, and considerable glacier cover, the runoff to the coastline has significant contributions from rainfall, snowmelt, and ice-melt constituents. Glaciers cover 17% (Beamer et al., 2016) of the Gulf of Alaska (GOA) watershed and Neal et al. (2010) estimate that roughly half of the coastal runoff comes from glacier surfaces (ice-melt, snowmelt, and direct rainfall on glacier surfaces). The volume of water that is delivered to the coast is considerable. The GOA watershed, with an area of 420,300 km^2, has a runoff of approximately 760 km^3 yr^{-1}, and a specific runoff of 1.8 m yr^{-1} (Beamer et al., 2016). In contrast, the Mississippi River watershed has a runoff of

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approximately 610 km^3 yr^{-1} and a specific runoff of 0.19 m yr^{-1} (Dai et al., 2002). This runoff to the GOA is one of the important physical drivers of Alaska's nearshore oceanography and contributes to the Alaska Coastal Current (ACC; Weingartner et al., 2006), water column stratification (Carmack, 2007), and a variety of economically important fisheries (Fissel et al., 2014).

The hydrology of the GOA watershed is characterized by large seasonal variations in inputs (precipitation), outputs (runoff, evapotranspiration), and storage of water. Gravity Recovery and Climate Experiment (GRACE) satellite regional water storage data, for the period 2004-2013, show a mean annual accumulation of 295 km^3 yr^{-1} and a mean annual ablation of 355 km^3 yr^{-1} (Luthcke et al., 2013; Beamer et al., 2016) in the GOA watershed. The net decrease in regional water storage of 60 km^3 yr^{-1} indicates that the region is also undergoing consdierable change. Indeed, the coastal mountain ranges of Alaska have recently sustained rapid rates of deglaciation (Arendt et al., 2002; Arendt et al., 2009; Gardner et al., 2013; O'Neel et al., 2015.). The mass loss from the glaciers within the GOA region, derived from airborne altimetry, is 64 (+/-) 10 km^3 yr^{-1} (Larsen et al., 2015), which agrees well with the GRACE observations. Glacier volume loss (GVL) is a change in long-term water storage in a glacierized watershed, and represents an additional flux of water that would not be present if the glacier system was in equilibrium with its environment (Radiç and Hock, 2010). These additional fluxes can affect the physical and chemical oceanography in coastal Alaska's bays and fjords (Reisdorph and Mathis, 2014).

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Glacier cover changes in response to long-term changes in meteorological forcing, and Beamer et al. (2017) have estimated future hydrographs for the GOA in response to changes in precipitation, temperature, and glacier cover. They considered a variety of climate model outputs and representative concentration pathways (RCP). For the RCP 8.5 projection scenario, which corresponds to a scenario of comparatively high greenhouse gas concentrations in the atmosphere, they found that the overall runoff increased by 14%, but the runoff from glacier surfaces decreased by about 34%. Beamer et al. (2017) also found significant changes in the timing of the delivery of freshwater to the coast. In response to changes in temperature, precipitation, and glacier cover, summer flows were dramatically reduced, with strong increases in autumn and winter flows. The annual GOA hydrograph was estimated to change from one dominated by a summer a peak to one with two peaks; one due to spring snowmelt, the other due to autumn rains.

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Glacier Bay (Figure 1b-c) is a fjord estuary in southeast Alaska that makes up part of Glacier Bay National Park and Preserve. The bay itself is roughly Y shaped, with maximum depths of approximately 500 m in the upper west and east arms, and an overall volume of 162 km^3. In contrast, depths near the entrance sill are approximately 25 m. The tidal forcing of the bay is considerable, with a Great Diurnal Range (GT; difference between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW)) of 3.36 m (data from NOAA Station 9452634; Elfin Bay, AK). The large tidal range produces strong tidal mixing that tends to destratify the water column. This effect counteracts the large freshwater input to the bay that tends to stabilize the water column. The result is a complex pattern of spatial and temporal variability of water column properties. Etherington et al. (2007; their Figure 5) summarized 10 years of oceanographic measurements (CTD casts) made in Glacier Bay at a total of 24 stations (Figure 2a). They aggregated the CTD measurements by month and by region (West Arm, East Arm, Central Bay, and Lower Bay). The results showed that stratification was largest in the summer, due to the large runoff associated with ice-melt. Spatially, it was found that there was a strong up-bay gradient in stratification, with the weakest stratification found in the Lower Bay where shallow depths produced the strongest vertical mixing of the water column.

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Etherington et al. (2007) correlated various water column properties (stratification, chlorophyll *a*, etc.) against physical variables such as day length, wind speed, air temperature, etc., in order to develop a better understanding of the ecology of the bay. While their discussion considered the role played by freshwater inputs, the lack of observational data (stream gauging) and hydrological modeling studies of Glacier Bay left their hypotheses untested. Hill et al. (2009) applied the regression equations for flow exceedances (e.g., the discharge exceeded 50% of the time) and peak flows (e.g., the 10-year event) developed by the USGS (Curran et al., 2003; Wiley and Curran, 2003) to Glacier Bay in order to help constrain the likely range of flows into the Bay. Their results suggested that the 10-year return interval discharge into the bay was approximately 10,000 m^3 s^{-1} and that the 50% exceedance annual discharge was approximately 800 m^3 s^{-1}, however their study included a different contributing area, with watersheds on the southern side of Glacier Bay included.

As was the case with the GOA watershed as a whole, Glacier Bay is a region that continues to undergo dramatic change. Glaciers have retreated over 100 km since the end of the little ice age (LIA; Hall and Benson, 1995) and the volume of ice lost in the Glacier Bay region alone was enough to raise global sea levels by 0.8 cm (Larsen et al., 2005). This glacial retreat has led to rapid vegetation succession (Chapin et al., 1994) and to rapid uplift rates from isostatic rebound (30 mm yr^{-1}; Larsen et al., 2005) that produce falling relative sea levels. The GRACE data for the Glacier Bay region show a downward trend of 12 cm yr^{-1} w.eq., which is very close to the average decrease of 13.3 cm yr^{-1} obtained for the entire GOA watershed (Luthcke et al., 2013; Beamer et al., 2016).

Long-term shifts in terrestrial freshwater storage and runoff can have significant implications for oceanographic stratification and circulation that moderate biogeochemical and ecological activity within Glacier Bay. Since Glacier Bay is a highly understudied, relatively remote national park, the complete freshwater budget for the bay cannot be quantified due to the lack of available data. However, seasonal trends in modeled freshwater runoff can be qualitatively compared with seasonal trends in broadscale oceanographic salinity records from 1993 to present collected by the U.S. National Park Service's Southeast Alaska Inventory & Monitoring Network (SEAN). This SEAN dataset served as the basis of the analysis performed by Etherington et al. (2007), which found positive correlations between phytoplankton biomass and stratification levels. The competing forces of macro-tidal flushing and strong stratification within the glacially-carved estuary generates temporally and spatially shifting trends in upwelling and nutrient availability (Etherington et al., 2007). Thus, accurate estimation of projection scenario runoff into Glacier Bay plays a paramount role in constraining future changes in water and nutrient circulation.

This paper presents the results of a hydrological modeling study of Glacier Bay. We understand it to be the first high-resolution (sub-km), process-based study of the water cycle in the region. Recall that the results of Hill et al. (2009) were statistical and only provided a few representative flow values. Here, the goals are very different. We use an energy-balance model to evolve the snowpack and melt glacier ice after the seasonal snowpack has disappeared. Also, our model results are output on a 3-hourly time step, aggregated to daily, and then used to provide a variety of derived products (monthly averages, seasonal and annual climatologies, etc.). Glacier Bay is a high-gradient landscape (rapid spatial changes in terrain, precipitation, e.g.) and we anticipate considerable spatial variability in both present hydrographs as well as projection scenario hydrographs. The results of this study are used to characterize historical and projection scenario climatologies of runoff and thereby quantify seasonal changes in the delivery of freshwater to Glacier Bay. Using this observational SEAN dataset allows the historical freshwater analysis of Glacier Bay to be contextualized. These results will add to the understanding developed by Etherington et al. (2007) and will provide constrained estimates of potential changes in runoff in GBNPP under the RCP 8.5 projection scenario.

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2 Study Area

The study area lies mostly within the boundary of Glacier Bay National Park and Preserve and includes the many watersheds that flow to Glacier Bay, as well as watersheds along the Pacific Coast south of the Alsek River. The aggregated watersheds in the study area (GBNPP) include some watersheds that originate outside the National Park boundary, and are located partially in Canada. These watersheds are included in the analysis because the international boundary in this region resembles a straight line, fragmenting the natural watershed boundaries. The elevation in GBNPP ranges from sea level to heights in excess of 4500 m on Mt. Fairweather. The study area is divided into nested hydrologic units, which include 3 individual watersheds, 4 grouped watersheds, and the fully aggregated GBNPP model domain. These various domains have been selected to illustrate the gradients in hydrologic inputs and outputs that exist in the region. See Table 1 and the following paragraph for more details about the spatial extent, average elevations, and glacier coverage of each grouped and individual watershed.

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Within the GBNPP study area, there are four grouped watersheds. The northern group of watersheds (North; Figure 2b) supplies freshwater to the mouth of Glacier Bay and constitutes the largest sub-group in the study area (see Table 1). The western group of watersheds (West; Figure 2b) delivers freshwater to the Pacific Ocean directly. We further subdivide a portion of the North watershed into two smaller aggregated regions near the western (West-Arm; Figure 2c) and eastern (East-Arm; Figure 2c) regions of Glacier Bay. The two arms of Glacier Bay have notable differences in elevation, glacier cover, and water column properties, and the aggregated watersheds shown in Figure 2c correspond to similar regions investigated by Etherington et al. (2007) and a large portion of the domain from Hill et al. (2009).

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Finally, we examine several individual watersheds within GBNPP. The first is a small group of watersheds that includes the Margerie and Grand Pacific tidewater glaciers terminating in the Tarr Inlet in the Western arm of Glacier Bay (Tarr; Figure 2d). The second is a highly glacierized region that includes Carroll Glacier, a land-terminating glacier with outlet lobes that deliver freshwater to the East-Arm and West-Arm of Glacier Bay (Carroll; Figure 2d). The last is a low-elevation, rain dominated watershed in the Dundas River region that experiences occasional glacial-lake outburst floods from the adjacent Brady Icefield (Dundas; Figure 2d). We chose these three individual watersheds to illustrate and examine the various ice-melt, snowmelt, and rainfall dominated runoff patterns and the changes they may experience in the projection scenario. The results of this study are categorized into the eight watersheds mentioned above. However, the focus of the results is on the aggregated GBNPP domain, and the appendices contain the supplemental grouped and individual watershed results.

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3 Data and Methods

3.1 Models

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In this study we use a set of models to simulate freshwater runoff to Glacier Bay for two climatological periods; 1979-2015 and 2070-2099. First, MicroMet (Liston and Elder, 2006a) is used to distribute the gridded reanalysis forcing data throughout the model domain. Second, SnowModel (Liston and Elder, 2006b) is used to evolve the snowpack and melt glacier ice using energy-balance methods. This set of models has been widely used in high latitude, highly glacierized environments including Alaska (Beamer et al., 2016; Beamer et al., 2017), the Arctic (Mernild et al., 2011; Liston and Hiemstra, 2011; Liston and Mernild, 2012; Mernild and Liston, 2012; Mernild et al., 2013; Mernild et al., 2014) and the Andes (Mernild et al., 2017a-d). Below we only briefly review the model components. Readers are directed to the source publications for full details on model algorithms and to Beamer et al. (2016) for full details on the application of SnowModel to the GOA.

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MicroMet (Liston and Elder, 2006a) is a meteorological distribution system for weather forcing datasets in high spatial resolution, distributed terrestrial modeling applications. The model relies upon the Barnes objective analysis scheme (Barnes, 1964; Barnes, 1973) for spatial interpolation of atmospheric variables, generating data fields at each time step and grid cell in the model domain for eight atmospheric variables. The atmospheric variables required by MicroMet include surface level precipitation, wind speed and direction, relative humidity, and air temperature. Sub-models of MicroMet will calculate radiation fluxes if they are not available as inputs. Landcover and elevation datasets are also employed by MicroMet to establish relationships based on topographically and seasonally varying temperature lapse rates, and topography dependent wind and solar radiation fields.

SnowModel (Liston and Elder, 2006b) is a physically based model for estimating snowpack accumulation and ablation processes over a water year. Sub-models within SnowModel estimate the energy fluxes of the snowpack and generate the snow depths and snow water equivalence for each cell in the gridded domain. The primary input for SnowModel is the gridded forcing dataset of atmospheric conditions that vary throughout the simulation time period and get distributed throughout the model domain by MicroMet. SnowModel does have the ability to melt glacier ice after the annual snowpack has fully melted away, but it does not include dynamic adjustments to the glacier cover volumes or extent. Therefore, SnowModel is able to simulate the hydrologic response of a fixed landscape, but it cannot simulate century-scale evolution of glacier cover. For this study, the timestep of SnowModel is 3-hourly, and the results are aggregated to produce the monthly historical and projection scenario climatologies.

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Water fluxes for all watersheds are given in terms of depths (m) rather than volumes (km^3). This normalization by watershed area enables straightforward comparison between individual and grouped watersheds. Ice-melt is runoff generated when glacial ice is melted after the seasonal snow disappears in each glacier grid cell. This definition of ice-melt, as a runoff component, does not necessarily represent glacier volume loss, due again to the fact that SnowModel does not dynamically change glacier extent or volumes. These runoff component values for a watershed of interest are calculated by aggregating the values for all model grid cells in each watershed. Unlike the work of Beamer et al. (2016; 2017) we did not route the runoff across the landscape to the coastline. In GBNPP, the average distance from a grid cell to its coastal outlet is only 9.0 km. Given this short distance, and the fact that our interest here is in seasonal climatologies of runoff, and not daily time series, this is a justifiable simplification.

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3.2 Model Forcing Data

3.2.1 Elevation and Land Cover

The land surface elevation dataset is the Natioanl Aeronautics and Space Administration's Shuttle Radar Topography Mission (NASA; SRTM; Farr et al., 2007) 90 m digital elevation model (DEM) resampled to 250 m. A model grid resolution of 250 m was selected for the present study as a compromise between desired high spatial resolution and the accompanying computational demands. The 250 m North American Land Cover Monitoring System 2010 (NALCMS) dataset was used for the land cover characterization. In order to obtain the most recent data on glacier coverage we used the Randolph Glacier Inventory (RGI; v.3.2; Pfeffer et al., 2014).

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3.2.2 Historical Climate Data

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The Modern-Era Retrospective Analysis for Research and Applications (MERRA) weather reanalysis product from NASA's Global Modeling and Assimilation office was chosen as the forcing meteorologic dataset for SnowModel during the simulation

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period. MERRA uses a data assimilation method for conventional observations of atmospheric data from irregularly spaced weather stations from around the world, collected by the National Climatic Data Center (Rienecker et al., 2011). The MERRA data are available at a nominal spatial resolution of 67 km and a temporal resolution of 3 hr. Variables available from the MERRA dataset include precipitation, 2 m air temperature and relative humidity, and 10 m wind speed and direction.

3.2.3 Historical Evapotranspiration Data

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Beamer et al. (2016) developed a soil moisture and evapotranspiration sub-model for the MicroMet and SnowModel framework. They demonstrated good agreement with Moderate Resolution Imaging Spectroradiometer (MODIS) satellite estimates of evapotranspiration (ET). For this study, MODIS-based ET values are calculated from the MOD16A2 8-day, 1 km resolution product. Monthly and annual climatologies based on averages from January 2000 through December 2014 are derived for each of the eight grouped and individual watersheds. These monthly MODIS-based ET values are plotted on the historical runoff figures but not calculated as a loss in the water balance because the ET values are derived separately from the modeling process.

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3.3 Oceanographic Data

Standard oceanographic conditions for GBNPP are taken from a long-term (1993-present) observational SEAN dataset created by the U.S. National Park Service. The SEAN dataset includes depth profiles of water column properties, including temperature and salinity, from CTD sensor casts at each of twenty-two active stations (Figure 2a). As of the sampling protocol imposed in 2014, all stations are sampled in midsummer (July) and midwinter (Dec), and a subset of eight stations are also sampled monthly from March through October to capture the rapid temporal variability of the spring-summer season (Johnson and Sharman, 2014). Prior to 2014, stations were sampled between four and nine times per year, at various months, providing sufficient sampling data to calculate long-term monthly averaged conditions. The CTD station locations are spaced throughout GBNPP approximately 9 km apart. The vertical resolution of the CTD casts is approximately one meter.

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3.3.1 Oceanographic Data Analysis

Well-defined isohalines present in the oceanographic dataset allow for point estimates of freshwater content (FWC) at station locations within GBNPP (McPhee et al., 2009). FWC can be calculated as the depth-integrated freshwater anomaly relative to a defined reference salinity, following McPhee et al. (2009) and earlier work by Carmack et al. (2008):

$$FWC = \int_{z_{lim}}^{0} (1 - S(z)/S_{ref})dz \qquad (1)$$

where $S(z)$ is the depth-dependent salinity (practical salinity scale, unitless) and FWC has dimensions of length. The lower limit of integration z_{lim} is taken to be the bathymetric depth at each station. At the lower limit, several casts appear to have terminated after reaching depth-invariant salinity readings, rather than reaching the bathymetric depth. For these casts, the final recorded salinity was used to extend the salinity profile to z_{lim}. Missing data at the upper limit of the profile were filled using spline interpolation, and for data gaps exceeding 5 m from the surface, the cast was ignored.

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Representative of highly saline inflowing waters of the GOA, S_{ref} was chosen as an upper-end reference salinity of 34.8 practical salinity (Carmack et al., 2008). In this analysis, choice of S_{ref} was found to have no significant influence on seasonal changes in FWC at a given location. FWC values at individual stations were then interpolated to the entire bay surface and spatially integrated,

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allowing for the calculation of a freshwater volume (FWV). This interpolation was done using a splines with tension method (Wessel and Bercovici, 1997).

3.4 Model Calibration

Recent studies (Beamer et al., 2016; Lader et al., 2016) have investigated the accuracy and biases of the MERRA reanalysis product in coastal Alaska compared to other reanalysis products such as ERA-Interim (Dee et al., 2011), CFSR (Saha et al., 2010), NCEP-NCAR (Kalnay et al, 1996), NARR (Mesinger et al., 2006), and others. Many SnowModel parameters were tested by doing a sensitivity analysis for each reanalysis product, including monthly precipitation adjustment factors, snow/rain temperature thresholds, snow and ice albedo factors, and more (see Beamer et al. (2016) their Table 2). For each of 4 reanalysis products, they calibrated model parameters based on observations of streamflow (Q) and glacier mass balance (B). The MERRA simulation Coefficient of Determination scores (r^2) for glacier mass balance (B) and stream discharge (Q) for the Beamer et al. (2016) study were 0.80 and 0.95, respectively, and the Nash Sutcliffe Efficiency (NSE) scores were 0.67 and 0.91, respectively. While Beamer et al. (2016) identified the CFSR product as the 'best overall' for the GOA region, they found that MERRA was superior at the Mendenhall Glacier observational station, which is the closest calibration point (< 25 km) to GBNPP. For these reasons, in this study we rely on the model calibration of Beamer et al. (2016; their section 3.4) and we adopt their calibration parameters for SnowModel from their Table 2 and Table A1.

Long-term glacial mass balance programs and long-term streamgage datasets do not exist within the GBNPP study area, thus constraining our ability to conduct additional calibration efforts. While the Mendenhall Glacier observation station is close in proximity to Glacier Bay, the glacier has receeded and thinned significantly since the early 1900's, glacial wastage is a significant component of annual streamflow (17%), and glacial meltwater contributes heavily to streamflow in the summer (50%; Motyka et al., 2003). As a result of these similarities in geography and hydrology, we rely on the calibration process, parameters, and best-performing reanalysis product (MERRA) from Beamer et al. (2016) for our study.

3.5 Model Projection Scenario Datasets

3.5.1 Projection Scenario Climate

Local to regional scale studies of future runoff are complicated by the fact that future climate model outputs are typically produced at a spatial resolution of 1 – 2°. Beamer et al. (2017) dealt with this by using high-resolution (2 km) historical and projection scenario climatologies (30-year averages available for each month of the year) to perturb the historical weather reanalysis datasets. This 'delta' or 'scaling' method of constructing future weather datasets is widely used in climate change studies (see Fowler et al., 2007 for a review). While it has the disadvantage of not capturing future changes in the frequency distributions of weather variables, if the primary interest is in monthly averages or climatologies, this deficiency is of little consequence (Mpelasoka and Chiew, 2009). Beamer et al. (2017) used the climatologies from the Scenarios Network for Alaska Planning (SNAP) project which are based upon CMIP5 climate scenarios. SNAP has results for the five best performing (for Alaska; see Table 2) climate models as well as a result representing the mean of the 5-model ensemble.

Although future climate simulations from SNAP exist for numerous RCP scenarios, in this study we restrict ourselves to the RCP 8.5 scenario and to the 5-model mean. The other RCP scenarios (RCP 2.5, RCP 4.5, RCP 6.0) represent concentrations of greenhouse gases (GHGs) in the atmosphere that peak earlier in the 21st Century or at lower levels of GHGs than the RCP 8.5

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Many SnowModel parameters were tested by doing a sensitivity analysis for each reanalysis product, including monthly precipitation adjustment factors, snow/rain temperature thresholds, snow and ice albedo factors, and more (see Beamer et al. (2016) their Table 2). The calibration at the Mendenhall Glacier observation station from the Beamer et al. (2016) study established that the MERRA reanalysis product performed best in the GBNPP portion of the Gulf of Alaska region. The MERRA simulation Coefficient of Determination scores (r^2) for glacier mass balance (B) and stream discharge (Q) for the Beamer et al. (2016) study were 0.80 and 0.95, respectively, and the Nash Sutcliffe Efficiency (NSE) scores were 0.67 and 0.91, respectively. This study adopts the calibration parameters from Table 2 and Table A1 outlined in Beamer et al. (2016). …

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Additionally, for this study the historical and projection scenario temperature results are used to calculate a freezing-line altitude (FLA). We calculate the historical and projection scenario FLAs by averaging the winter and summer temperatures across all historical years (1979-2015) and all projection scenario years (2070-2099) and extract the elevation bands that correspond with the 0 °C or rain-to-snow transition line.

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3.5.2 Future Glacier Cover

Since SnowModel does not model glacier dynamics (i.e., glacier advance, retreat and thinning), the historical and projection scenarios represent the response of a particular landscape to the climate. For the historical simulation, the landscape represents the RGI 2014 glacier extent. For the projection scenario simulation, the glacier mask is adjusted as described in Beamer et al. (2017). Essentially, the glacier cover is adjusted, using the accumulation area ratio (AAR) method of Paul et al. (2007), under the assumption that glaciers will be in equilibrium with climatic conditions. We note that there are modeling efforts that attempt to directly model ice flow dynamics (e.g., Clarke et al., 2015; Ziemen et al., 2016) but those efforts come with significant input data requirements. Our approach can be thought of as a leading-order test of the sensitivity of the hydrologic scale to plausible landscape changes.

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To evolve the glacier extent using the AAR method of Paul et al. (2007), two key parameters are required. The first is the value of the AAR, which is the ratio of the accumulation area of a glacier to the total area of the glacier. The second is the change in the equilibrium line altitude (ELA) of the glacier, due to changing climatic conditions. The steady-state AAR (AAR_0) was chosen to be 0.65, based on the observations of several benchmark Alaskan glaciers by Mernild et al. (2013). While some studies have suggested that AAR_0 values change in the future, Beamer et al. (2017) found that the assumption of AAR_0 (i.e., keeping AAR fixed at 0.65 for the future runs) provided estimates of future glacier changes that are in accord with other published values (Huss and Hock, 2015; their figure S10; McGrath et al., 2017). As a result, we similarly assume AAR_0 to be equal to 0.65 for the future runs. Regarding the ELA, we use the results of Huss and Hock (2015; their figure S9) and assume an ELA increase of 400 m for the RCP 8.5 scenario, based on their modeled ELA changes between 2010 and 2100.

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3.5.3 Future Climatologies

The MERRA reanalysis data were used with the model configuration described above to produce a 30-year historical simulation of runoff. The daily output was temporally aggregated to monthly values and then climatologies were produced for each month of the year. The future runoff estimates were obtained using the coarser (1-km) model results of Beamer et al. (2017) and a scaling method similar to that described in Section 3.4.1 in the context of meteorological variables. Scaling methods are rooted in the idea of a separation of scales. A certain variable, say precipitation, may have a high degree of spatial variability, but *changes* in this variable (from historical to projection scenario conditions) have a much lower degree of spatial variability. In this way, climatologies from coarse (degree scale) climate model output can be used to create anomaly fields that may be recombined with high-resolution historical results to create high-resolution future projections. In the context of runoff, the Beamer et al. (2017) 1 km historical and future results are used to create runoff scaling factors per watershed that are applied to the higher resolution (250

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m) historical runoff results created for Glacier Bay in this study. At the end of this process, we have both historical and projection scenario climatologies of runoff per watershed that allow us to quantify seasonal changes in the delivery of freshwater to Glacier Bay.

4 Results

The following results for changes in temperature, precipitation, SWE, and runoff are based on the 36-year historical climatologies from the MERRA-forced, 250 m model output. The 30-year projection scenario climatologies are based on Beamer et al. (2017), which is CFSR-forced, 1 km model output derived from the scaling factors discussed previously in section 3.4. The historical and projection scenario results are spatially aggregated by watershed and discussed below.

4.1 Changes in Temperature

The changes in watershed average temperature from the historical to projection scenario reveal the most substantial temperature increases occur from October to December, followed by May to July, for the aggregated GBNPP watersheds (Figure 3a). The temperature changes in Figure 3a are described by Eq. (2):

$$\Delta_{TEMP(C)i,k} = \mathrm{Temp}_{i,k}^{proj} - \mathrm{Temp}_{i,k}^{hist} \qquad (2)$$

where *i* is the month, *k* is the watershed, *Temp* is the climatological average temperature (C), *proj* is the projection scenario, and *hist* is the historical scenario. As a result of the model runs, all months in all watersheds experience a temperature change greater than 3 °C from the historical to the projection scenario. This is likely amplified by the high elevation gradients in GBNPP topography and the high latitude environment that create temperature changes of more than 4 °C for many of the watersheds in multiple months (Figure 3a). The historical average winter (DJF) temperature in GBNPP is -4.1 °C, while the projection scenario average DJF temperature is only slightly below zero, at -0.2 °C. These changes in average seasonal, monthly, and annual temperatures are driving many of the changes in the modeled precipitation, snowfall vs. rainfall partitioning, snowpack evolution and ablation, glacier ELA and AAR, and the seasonality of the modeled runoff climatologies.

4.2 Changes in Precipitation

The changes in precipitation in GBNPP from the historical to projection scenario can be divided into three categories: changes in total precipitation, changes in monthly partitioning of rainfall vs snowfall, and changes in the ratio of snowfall w.eq. to total precipitation ratio. First, the changes in total precipitation include increases in precipitation in GBNPP from the historical average of 3.40 m yr^{-1} to a projection scenario average of 3.71 m yr^{-1}, which represents a 9.0% average annual increase in precipitation. These average total precipitation changes (%) include variability among watersheds and between seasons, with October and November containing the largest increases in precipitation, and January containing the largest decreases in precipitation (Figure 3b). The precipitation changes in Figure 3b are described by Eq. (3):

$$\Delta_{PREC(\%)i,k} = \left(\frac{\mathrm{Prec}_{i,k}^{proj} - \mathrm{Prec}_{i,k}^{hist}}{\mathrm{Prec}_{i,k}^{hist}}\right) \mathrm{x}\,100 \qquad (3)$$

where *i* is the month, *k* is the watershed, *Prec* is the climatological average precipitation (m) value, *proj* is the projection scenario, and *hist* is the historical scenario.

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We use a common metric to characterize annual and monthly change in snowfall from the historical to projection scenario simulations: the snowfall w.eq. (SFE) to total precipitation (P) ratio (SFE/P; Mote, 2003; Mote, 2005; Knowles et al., 2006; Zhang et al., 2000). The SFE/P metric can illuminate the snowfall trends within a region, where 1 represents all precipitation falling as snow and 0 represents no snowfall in the watershed over the time period of interest. Changes in SFE/P in Figure 3c are described by Eq. (4):

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$$\Delta_{SFE/P_{i,k}} = \left(\frac{\mathrm{SFE}_{i,k}}{\mathrm{Prec}_{i,k}}\right)^{proj} - \left(\frac{\mathrm{SFE}_{i,k}}{\mathrm{Prec}_{i,k}}\right)^{hist} \qquad (4)$$

where *i* is the month, *k* is the watershed, *Prec* is the climatological average precipitation (m), *SFE* is the climatological average snowfall equivalent (m), *proj* is the projection scenario, and *hist* is the historical scenario. Characterized this way, when $\Delta_{SFE/P}$ is negative it means more precipitation is falling as rain in the projection scenario and when $\Delta_{SFE/P}$ is positive, more precipitation is falling as snow. All eight watersheds experience negative annual $\Delta_{SFE/P}$ from the historical to the projection scenario model runs, even though annual changes in precipitation are primarily increasing from the historical to projection scenario (Figure 3c). The highest and lowest mean elevation watersheds, Tarr and Dundas, respectively, display an opposite behavior in the magnitude of their seasonal SFE/P values and this relationship will be further investigated in the discussion section. These results are congruent: the changes in temperature, changes in total annual precipitation, changes in snowfall vs. rainfall partitioning, and changes in SFE/P all point towards a landscape that is less dominated by snowfall and is increasingly influenced by rainfall in the projection scenario.

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To supplement the $\Delta_{SFE/P}$ analysis, the results of the historical and projection scenario precipitation are analyzed in terms of monthly snowfall vs. rainfall partitioning for each watershed. While this type of precipitation partitioning may be a relatively crude characterization of a complex atmospheric system, where mixed snowfall and rainfall occur simultaneously, this distinction is practical and appropriate for our research questions and the application of SnowModel. For the purposes of this paper, the dominant process is simply the one that is ≥50% of total precipitation. The precipitation partitioning results for GBNPP (Figure 4) display an annual average that shifts from snowfall dominated precipitation historically (58.2% snowfall vs. 41.8% rainfall) to a rainfall dominated precipitation regime in the projection scenario (24.1% snowfall vs. 75.9% rainfall). Additional historical and projection scenario precipitation climatologies can be found in *Appendix A* for each of the eight grouped and individual watersheds. In summary, the low-elevation Dundas watershed is the only rainfall dominated watershed in the historical model runs, while all other watersheds are snowfall dominated. In contrast, only the highly glacierized and high-elevation Tarr and Carroll watersheds remain snowfall dominated in the projection scenario. All others switch to rainfall as the primary annual precipitation process.

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4.3 Changes in Glacier Coverage

The glacier change map (Figure 5) displays the static glacier cover used for the historical simulations as well as the static glacier cover used for the projection scenario runs. Recall that SnowModel does not dynamically adjust glacier extent, so these glacier changes represent two distinct landscapes that remain in equilibrium with their environment for the duration of the modeled time period. In the aggregated GBNPP watersheds, the projection scenario contains a 58.8% decrease in glacier cover compared with the RGI 2014 glacier map, from a total historical surface area of 4092 km^2 to 1687 km^2 in the projection scenario.

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4.4 Changes in Snow Water Equivalent

Snow water equivalence (SWE) was modeled for the historical and projection scenarios and aggregated for all GBNPP watersheds by mean monthly depth (Figure 6). Peak SWE historically occurs in April and while the timing remains unchanged in the projection scenario, GBNPP watersheds lose 46% of mean peak SWE in the projection scenario. The monthly relative changes in SWE from the historical period to projection scenario range from -44% in March to -70% in September. These losses are in line with Shi and Wang's (2015) investigation into Northern Hemisphere changes in SWE based on the RCP 8.5 scenario (their Figures 4c & 6f). The magnitude of the SWE losses in the projection scenario will directly affect the timing and volume of runoff generated from snowmelt.

4.5 Changes in Runoff

The historical runoff hydrograph for GBNPP is partitioned into the components of ice-melt, snowmelt, and rain runoff, and includes the MODIS-based ET values (Figure 7a). The historical and projection scenario volumes can be found in Table 3 and Table 4 shows the estimated ET values by watershed. The historical runoff hydrograph for GBNPP displays low runoff quantities during the winter months, with snowmelt dominating spring and early summer, ice-melt supplementing runoff in mid-summer, and rain runoff dominating early fall (Figure 7a). The average MODIS-based ET loss for GBNPP is 0.28 m yr^{-1}, while the average historical precipitation is 3.40 m yr^{-1}, which makes ET loss 9% of precipitation on average for all watersheds. The projection scenario runoff total for GBNPP is 3.96 m yr^{1}, and displays a distinct flattening of the annual runoff hydrograph in terms of quantity and timing of snowmelt, as well as a decrease in ice-melt to Glacier Bay (Figure 7b). The historical and projection scenario runoff hydrographs for each grouped and individual watershed can be found in Appendix B, and Figure 8 presents changes in the runoff components in the projection scenario. In many of the watersheds in the GBNPP domain, there is an overall annual increase of runoff volumes in the projection simulations, with much of that increase sourced from changes in rain runoff. These increases in rain runoff originate from higher temperatures in the projection scenario, losses in glacier area, increases in overall precipitation, and increases in the rainfall component of precipitation.

4.6 Historical Freshwater in Glacier Bay

A climatology of the month-to-month changes in FWV (ΔFWV) for various sub-regions of Glacier Bay is shown in Figure 9. The seasonal timing of changes in freshwater is similar for all three regions. Positive values of ΔFWV are observed in summer months when the strong runoff fluxes from snow and ice-melt outpace the ability of water to flush out through the bay mouth. Negative values are observed in winter months when runoff is low and the bay is able to flush out the accumulated freshwater. The larger values in the West Arm (vs. the East Arm) are due to the larger watershed area, higher mean elevation, and greater glacier coverage.

Long-term changes in July FWC are also examined. July is chosen since that month has the most measurements throughout the bay. Spatially averaged July FWC, or $\overline{\mathrm{FWC}}$, for various bay sub-regions, is found by interpolating July FWC observations across GBNPP and then averaging across each bay sub-region. Analysis of long-term changes in $\overline{\mathrm{FWC}}$ in all watersheds indicate little change in $\overline{\mathrm{FWC}}$ over the study period (1993-2017). The West-Arm July $\overline{\mathrm{FWC}}$ observations are the exception, increasing with a rate of 8.3 cm per year (p-value of 0.109) but this change is not statistically significant.

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Deleted: Each component is given in mean monthly depth (m) instead of total volume (km^3). This normalization by watershed area enables straightforward comparison between individual and grouped watersheds. The historic and forecast volumes can be found in Table 3. Ice-melt is runoff generated when glacial ice is melted after the seasonal snow disappears in each glacier grid cell. This definition of ice-melt, as a runoff component, does not necessarily represent glacier volume loss, due again to the fact that SnowModel does not dynamically change glacier extent or volumes. These runoff component values for a watershed of interest are calculated by summing the values for all model grid cells in each watershed. Unlike the work of Beamer et al. (2016; 2017) we did not route the runoff across the landscape to the coastline. In GBNPP, the average distance from a grid cell to its coastal outlet is only 9.0 km. Given this short distance, and the fact that our interest here is in seasonal climatologies of runoff, and not daily time series, this is a justifiable simplification.¶

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5 Discussion

The distinct changes observed in the study area watersheds motivate investigation into the controlling physical characteristics of the various landscapes within GBNPP. For example, in Figure 3c, the patterns of $\Delta_{SFE/P}$ in the Tarr and Dundas watersheds have opposing seasonal trends. The Tarr watershed has a comparatively high mean elevation and sees only small magnitudes of winter $\Delta_{SFE/P}$. This may be because much of the watershed remains above the snow line in the projection scenario (see Figure 10a). Tarr also displays high magnitudes of summer $\Delta_{SFE/P}$, and it has historically been one of the few watersheds that receives significant snowfall precipitation throughout the summer, again due to the high elevation. As a point of contrast, the Dundas watershed has the lowest mean elevation of the eight study watersheds (see Table 1 and Figure 10a). Dundas experiences high magnitudes of $\Delta_{SFE/P}$ in the winter, but very small magnitudes in the summer. The former is attributable to the projection scenario FLA in Dundas increasing above the maximum watershed elevation and the latter is due to very small amounts of historical summer snowfall precipitation in Dundas. This initial comparison between the changes in Tarr and Dundas suggests a need to further investigate landscape dependencies and the seasonal aspect of snow precipitation, especially with elevation.

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Snow distribution and elevation in mountain environments is highly correlated (Bales et al., 2006; Fassnacht et al., 2003; Welch et al., 2013) and in maritime regions, understanding the role of elevation distributions within a watershed is important in the context of changing climate and the snow-to-rain transition zone (Jefferson 2011). Histograms of elevation, along with polar coordinate plots of slope and aspect for GBNPP, Dundas, and Tarr are given in Figure 10 to help illuminate the relationships between elevation, temperature and precipitation change, and process change. Recall that these changes take the form of negative $\Delta_{SFE/P}$ values in all watersheds (Figure 3c). When considered in relation to the monthly or seasonal average FLA, the magnitudes of the Dundas and Tarr seasonal SFE/P changes (Figure 3c) begin to make sense. For this analysis, the most important aspect may be the proportion of the watershed area located between the historical seasonal FLA and projection scenario seasonal FLA. In Dundas, the winter FLA increase of several hundred meters in the projection scenario means that a large proportion of the watershed would receive rainfall when it previously received snowfall. In contrast, when the Tarr watershed is subjected to the same several hundred meter winter FLA increase, only a small proportion of the watershed is affected by that increase (see Figure 10a), thus undergoing lower magnitudes of $\Delta_{SFE/P}$ than Dundas. The summer FLA increase of >1000m means that Dundas will likely receive insignificant summer snowfall in the projection scenario, but Tarr will experience higher magnitudes of $\Delta_{SFE/P}$. This is because a large proportion of the Tarr watershed lies between the historical and projection scenario summer FLAs, but Dundas always received insignificant snowfall historically during the summer.

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Similarly, the distribution of snowpack on the land surface has landscape dependencies on aspect and slope. Regarding topographic slope, Tarr has proportionally more steep slopes than GBNPP and Dundas, and steep slopes tend to accumulate snow in the same locations year after year by way of sloughing, avalanching, and wind drift, distributing snow to the lesser inclined accumulation areas (Figure 9b; Bloschl and Kirnbauer, 1992; Grunewald el al., 2010; Grunewald et al., 2014). The average aspect in Tarr is dominated by the northeastern direction, which increases shading and creates more oblique angles of incoming solar radiation, which affects SWE distribution and timing of meltwater. Alternately, the average aspect in GBNPP and Dundas is South to Southwestern and these aspects receive more direct incoming solar radiation angles and will affect accumulation patterns and meltwater patterns differently in these watersheds (Elder et al., 1989, Marks et al., 1999). This study acknowledges these landscape dependencies and we attempt to briefly characterize some of them as controls on the modeled processes. However, further

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characterization of the landscape spatial gradients and controls is beyond the scope of this study, while higher resolution observations and modeling will be necessary to better understand their effects on runoff processes in the future.

This examination of the source components of runoff to Glacier Bay is partially limited by a lack of long-term validation datasets for stream flow and other long-term weather station forcing datasets within the GBNPP model domain. However, an effort to parameterize and calibrate SnowModel based on the results of other recent, larger-scale modeling projects was made, as previously noted in Section 3.4 according to Beamer et al. (2016; 2017). While implementation of SnowModel using additional validation and forcing datasets would likely improve the accuracy of the results, no regional stream flow, SWE observations, or weather station datasets exist at the appropriate locations or scales. This highlights the need for multiple types of monitoring systems to be implemented in GBNPP in order to decipher future changes in glaciers, snowpack and precipitation, and runoff processes in GBNPP. Additionally, other important fluxes were not characterized in this study due to decisions in the modeling process, most notably snow density characterization which allows for rain on snow (ROS) events to be examined. For this project, when rain precipitation occurs on top of an existing snowpack, ROS was characterized simply as increasing the snow water equivalent in the snowpack. Even though it is known that ROS runoff events generally occur at snow densities greater than ~550 kg m^{-3}, the final results do not describe the volume or frequency of ROS events since the snow density output was not necessary or desirable for our research interests. However, the results of this study reveal a shift from snowmelt dominated runoff historically to rain runoff in the projection scenarios, and understanding the timing and spatial extent of ROS events may prove to be an important area of research in the future.

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We include the historical freshwater analysis of Glacier Bay because long-term meteorological datasets or streamflow datasets do not exist for the study area. The inclusion of the observational CTD dataset allows the modeling effort to be contextualized. The most notable is the monthly timing of the historical runoff in GBNPP (Figure 7a) as it relates to the monthly fluctuations of freshwater volumes from the CTD analysis (Figure 9). Not only is the runoff timing confirmed by the observations, but the relative magnitude of the proportion of freshwater originating from the West-Arm and East-Arm watersheds is also confirmed by the observations (Figure 7a; Figure 9). Since the modeled runoff volumes for the projection scenario (Figure 7b; Appendix B) exhibit differences in timing and magnitude from the historical model runs (Figure 7a; Appendix B), we can assume that the influx of freshwater from the land surface to Glacier Bay in the projection scenario will reflect those changes in timing and magnitude. From the historical simulations, July is the month with the most combined runoff from the various freshwater sources. The modeled changes in timing and magnitude of runoff from the land surface into Glacier Bay will have effects on bay ecology in the future if the projection scenario climate conditions come to pass.

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A key source of uncertainty in the present study is the determination of the future glacier cover. We relied on the findings of Beamer et al. (2017) to guide assumptions of future ELA increases and AAR changes, if any. Their decisions were, in turn, based on regional-scale (Alaska-wide) modeling studies of glacier change (Huss and Hock, 2015) and on decadal-scale observational studies of glacier mass balance based on altimetry (Larsen et al., 2015) and gravimetry (Arendt et al., 2008). Our results for GBNPP show a change of -58% in glacier covered area. Huss and Hock (2015) give a figure of -32% for change in glacier volume in all of Alaska. It is difficult to directly compare these two, given that they are for different domains (local vs. regional) and for different variables (area vs. volume). To our knowledge, local-scale modeling studies of glacier change in GBNPP are not available. We note the work of Alifu et al. (2016) who use a variety of remote sensing products to quantify observational changes in mean snow line altitude (MSLA) and mean snow accumulation area ratio (MAAR) in GBNPP during 2000-2012. Their results support the

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general trends of the present study, in terms of reductions in area change and increases in MSLA, but the duration of their study is quite short in comparison to the century-scale processes investigated in the present study.

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6 Conclusions

In this study, a high spatial resolution, distributed snow evolution and ablation model, SnowModel, is used to estimate current and future freshwater runoff into Glacier Bay, Alaska. The model is forced using the MERRA weather reanalysis product to create 36-year historical climatologies of precipitation, temperature, and the source components of runoff, including rainfall, snowmelt, and ice-melt. The future scenario applies the SNAP temperature and precipitation anomalies from the mean of 5 climate models for the years 2070-2099 based on the RCP 8.5 projection scenario. The physical complexity and variability of the region produces a variety of historical and projection scenario hydrographs within GBNPP, including rainfall, snowmelt, and ice-melt dominated responses depending on the season and watershed. The timing and relative scaling of the historical inputs of freshwater from the study area watersheds are contextualized by a long-term oceanographic dataset from the Southeast Alaska Inventory and Monitoring Network in Glacier Bay. The mean annual runoff to Glacier Bay in the projection scenario will increase by 13% from the historical average, with much of the increased runoff sourced from rain inputs. The peak flows to the Glacier Bay fjord estuary will shift from late-summer to early-fall, and the effects of these changes in freshwater runoff timing will be experienced across the estuarine environment and biological communities within Glacier Bay.

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7 Author Contributions

Ryan Crumley and David Hill designed the research questions, chose the methods, and the oversaw the analysis of the results for the manuscript. Jordan Beamer and Ryan Crumley developed the scripts that were applied to the model output and performed the model simulations. Elizabeth Holzenthal contributed the oceanographic data analysis. Ryan Crumley prepared the manuscript with contributions from all co-authors.

8 Competing Interests

The authors declare that they have no conflict of interests.

9 Acknowledgements

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Figures

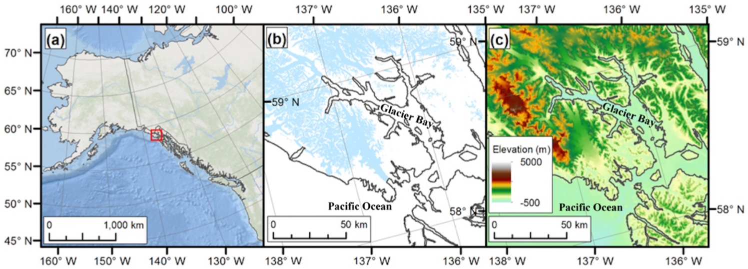


Figure 1: Study Area Map: (a) – Overview of northern Gulf of Alaska; red box shows extent of panels (b) and (c). (b) – Glacier cover (blue) in the Glacier Bay region from the Randolph Glacier Inventory (RGI; Pfeffer et al., 2014). (c) – Bathymetry and elevation in the Glacier Bay region from the Southern Alaska Coastal Relief Model (Lim et al., 2011).

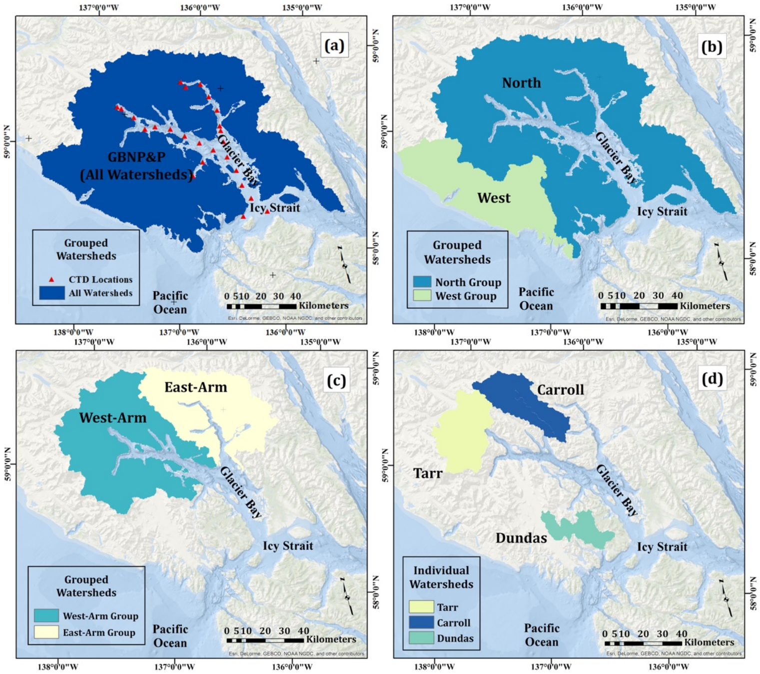
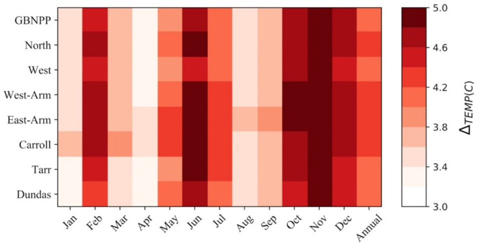
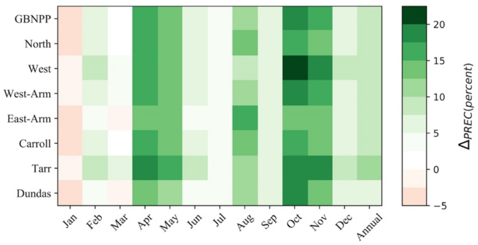


Figure 2: Watershed Maps: (a) – All watersheds in the GBNPP group and the locations of the CTD casts (discussed in 3.3). (b) – North and West grouped watersheds. The North delivers freshwater to the main stem of Glacier Bay, and the West delivers water to the Pacific Ocean. (c) – The upper-bay grouped watersheds that deliver freshwater to the East-Arm and West-Arm of Glacier Bay. (d) – The 3 individual watersheds: Tarr, Carroll, and Dundas.

(a) Changes in Temperature



(b) Changes in Precipitation



(c) Changes in SFE/P

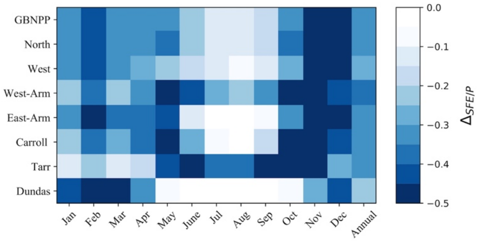


Figure 3: Temperature and Precipitation Changes: (a) – Monthly and annual temperature changes (°C) from historical (1979-2015) values by watershed, based on temperature anomalies from the RCP8.5 scenario (2070-2099). (b) – Monthly and annual precipitation changes (%) from historical (1979-2015) values by watershed, based on the RCP8.5 scenario (2070-2099). (c) – Monthly and annual snowfall water equivalent to precipitation (SFE/P; unitless) changes from historical (1979-2015) values by watershed, based on the RCP8.5 scenario (2070-2099).

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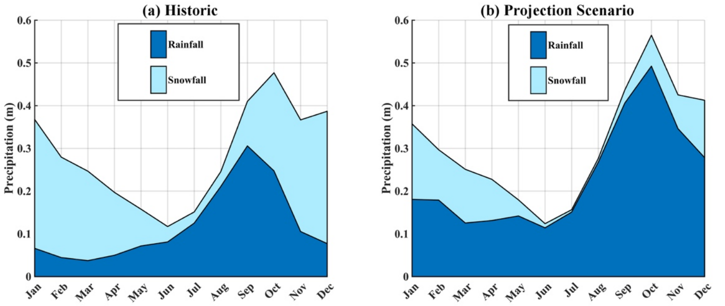

Figure 4: Precipitation Climatologies: (a) – The domain aggregated GBNPP historical (1979-2015) precipitation climatology, partitioned into snowfall and rainfall constituents. (b) – The domain averaged and aggregated GBNPP projection scenario (2070-2099) precipitation climatology, partitioned into snowfall and rainfall constituents.

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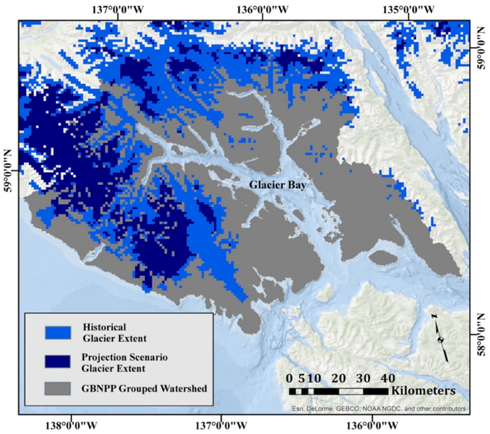

Figure 5: Glacier Change Map: Changes in glacier extent in the study area based on the Randolph Glacier Inventory (RGI) 2014 glacier locations for the historical period (1979-2015) and the +400 m change in equilibrium line altitude for the projection scenario (2070-2099) using the RCP 8.5 scenario.

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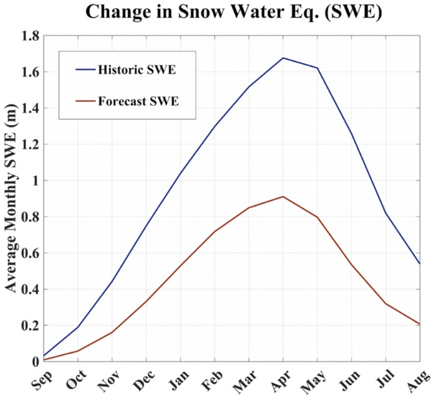

Figure 6: Monthly snow water equivalence (m) averaged for the entire GBNPP domain for both the historical (1979-2015) and projection (RCP 8.5 scenario; 2070-2099) scenarios.

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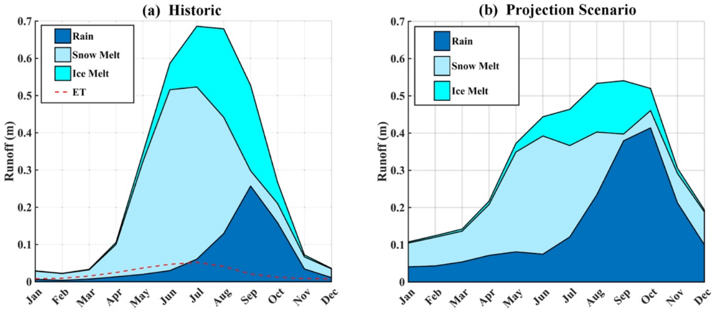

Figure 7: Runoff Climatologies: (a) – The domain averaged and aggregated, historical (1979-2015) GBNPP runoff climatology partitioned into the constituents of snowmelt, ice-melt, and rain runoff. The historical (2001-2014) MODIS-based evapotranspiration estimates are included on the historical plots, but the amounts are not subtracted from the modeled runoff climatology because they were derived separately from the modeling process. (b) – The domain averaged and aggregated GBNPP projection scenario (RCP 8.5 scenario; 2070-2099) runoff climatology. Appendix B contains the historical and projection scenario runoff climatologies for each of the eight grouped and individual watersheds in the study area.

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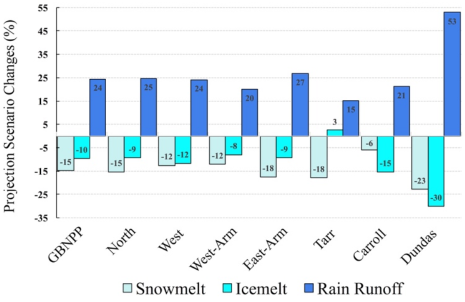

Figure 8: Runoff process change by watershed in the projection scenario (RCP 8.5 scenario; 2070-2099), partitioned into snowmelt, ice-melt, and rain runoff.

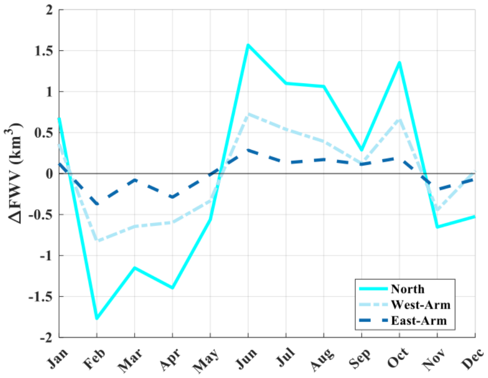

Figure 9: Month to month changes in freshwater volume (ΔFWV) for the historical period of record (1993 to present) for various subregions (see Figure 2) of Glacier Bay.

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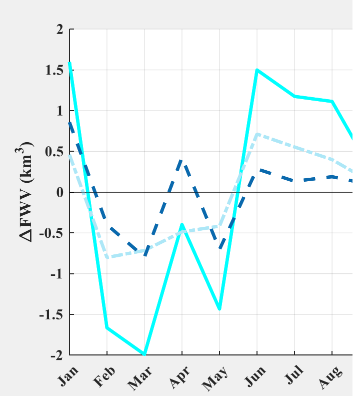

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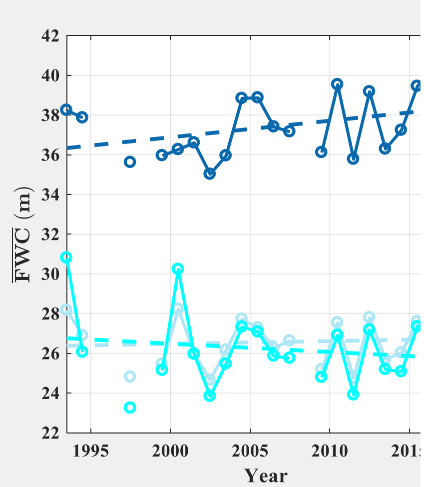

Figure 10: Spatially averaged July freshwater content ($\overline{\text{FWC}}$) from 1993 to present, interpolated from the 22 active CTD locations within Glacier Bay (see Figure 2). Linear trends are indicated by dashed lines.

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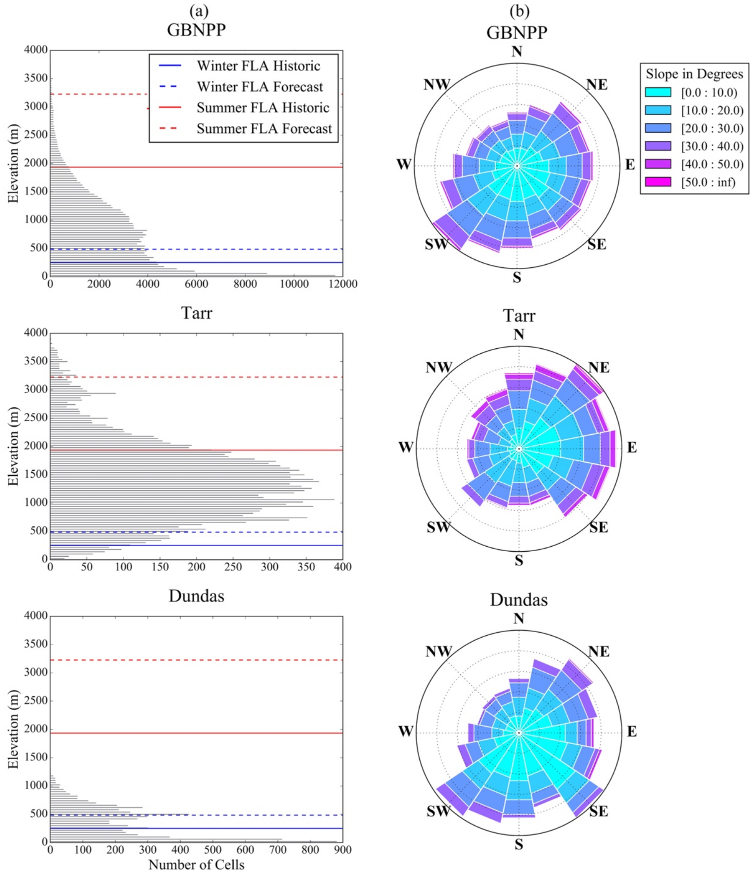

Figure 10: Landscape Characteristics: (a) – Elevation histograms for GBNPP, Tarr, and Dundas watersheds with the average winter and summer freezing line altitudes (FLA) plotted in blue and red, respectively. Historical scenario (1979-2015) lines are solid and projection scenario (RCP 8.5; 2070-2099) are dashed. (b) – Polar coordinate plots for GBNPP, Tarr, and Dundas displaying the binned aspect and slope distributions within each watershed.

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Tables

Table 1: Key physical characteristics of the 8 sub-watersheds in the study area.

Watershed Name	Area (km²)	2014 Glacier Coverage (%)	Mean Elevation (m)	Max Elevation (m)
(All) GBNPP	10085	37.7	584	4190
(Grouped) North	7824	33.9	657	3905
West	2261	51.0	790	4190
West-Arm	3098	54.2	1165	3905
East-Arm	2064	37.8	686	2216
(Individual) Tarr	927	65.8	1453	3905
Carroll	793	68.1	897	2113
Dundas	386	17.6	331	1279

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Table 2: Summary of the SNAP selected climate models.

Center	Model	Acronym
National Center for Atmospheric Research	Community Earth System Model 4	NCAR-CCSM4
NOAA Geophysical Fluid Dynamics Laboratory	Coupled Model 3.0	GFDL-CM3
NASA Goddard Institute for Space Studies	ModelE/Russell	GISS-E2-R
Institut Pierre-Simon Laplace	IPSL Coupled Model v5A	IPSL-CM5A-LR
Meteorological Research Institute	Coupled GCM v3.0	MRI-CGCM3

Table 3: Historical (1979-2015) and projection scenario (RCP 8.5 scenario; 2070-2099) runoff in km^3 and m yr^{-1} for all watersheds.

		Historical Runoff		Projection Scenario Runoff	
	Watershed Name	(km^3)	(m yr^{-1})	(km^3)	(m yr^{-1})
(All)	GBNPP	34.2	3.4	40.0	4.0
(Grouped)	North	24.5	3.1	27.5	3.5
	West	9.7	4.3	12.4	5.5
	West-Arm	10.6	3.4	13.4	4.3
	East-Arm	7.5	3.6	7.5	3.7
(Individual)	Tarr	2.7	2.9	4.3	4.6
	Carroll	2.3	2.9	2.3	2.9
	Dundas	1.2	3.1	1.2	3.2

Table 4: Estimated historical (2002-2014) and evapotranspiration (ET) in m yr^{-1} for all watersheds.

	Watershed Name	Historical MODIS ET (m yr^{-1})	Percentage of Annual Precipitation (%)	Adjusted Annual Runoff (m yr^{-1})
(All)	GBNPP	0.3	9	3.1
(Grouped)	North	0.3	9	2.8
	West	0.2	5	4.1
	West-Arm	0.2	5	3.2
	East-Arm	0.3	9	3.3
(Individual)	Tarr	0.2	3	2.7
	Carroll	0.2	8	2.7
	Dundas	0.4	9	2.7

Deleted: Table 3: Historic (1979-2015) and forecast (RCP 8.5 scenario; 2070-2099) runoff in km^3 for all watersheds.¶
Watershed Name ... [1]

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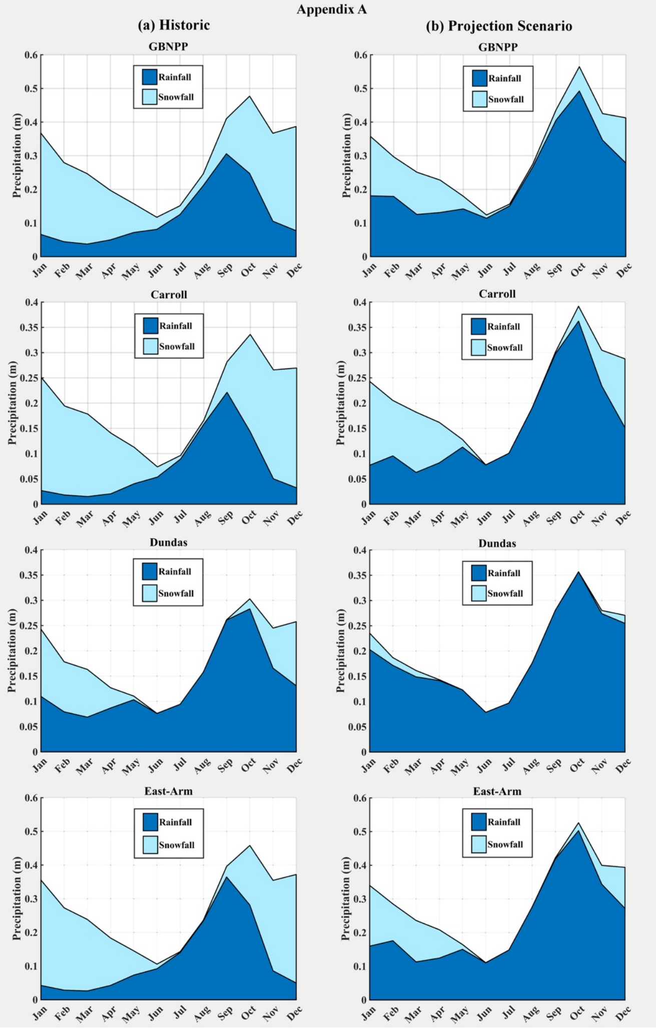
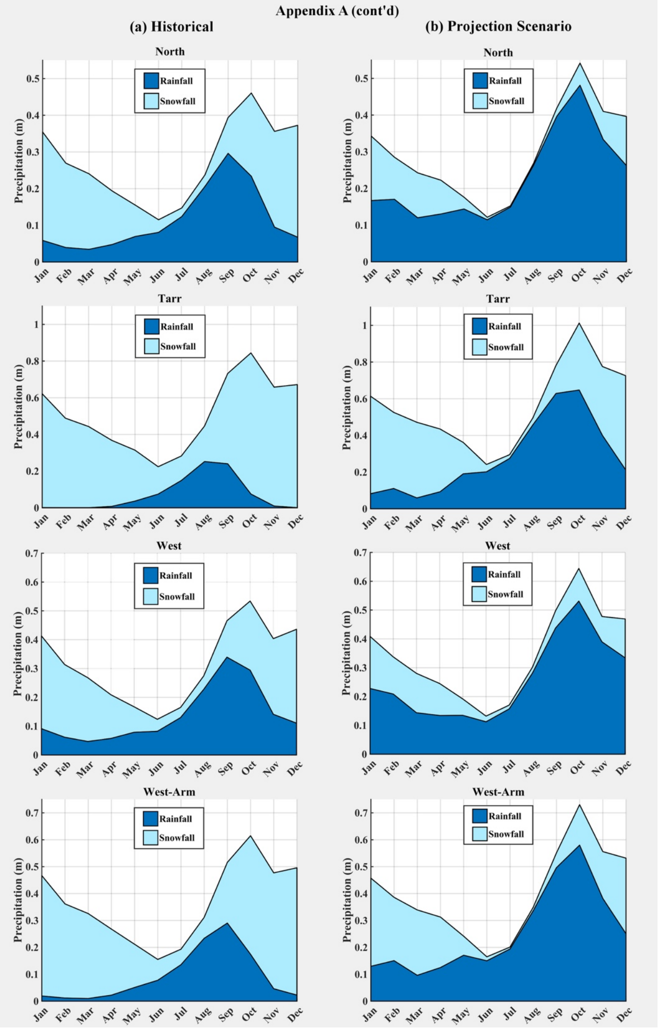
Appendices

Appendix A





Appendix A. (a) – The historical precipitation climatologies by watershed, partitioned into snowfall and rainfall constituents. (b) – The projection scenario precipitation climatologies by watershed, partitioned into snowfall and rainfall constituents.

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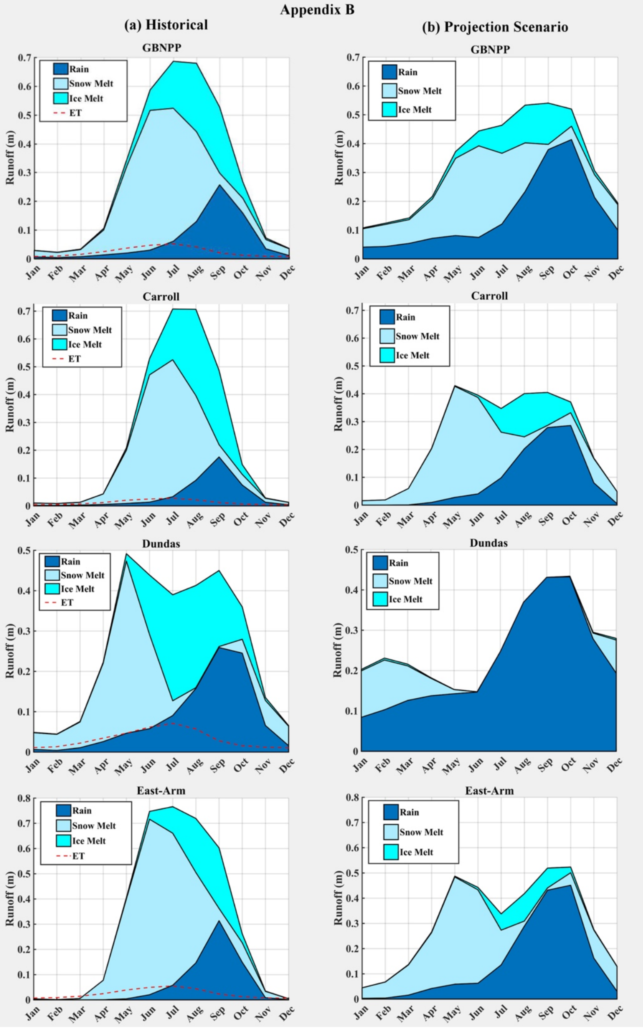
Appendix B


(a) Historical
(b) Projection Scenario
GBNPP
Carroll
Dundas
East-Arm
Rain
Snow Melt
Ice Melt
ET
Runoff (m)
Jan
Feb
Mar
Apr
May
Jun
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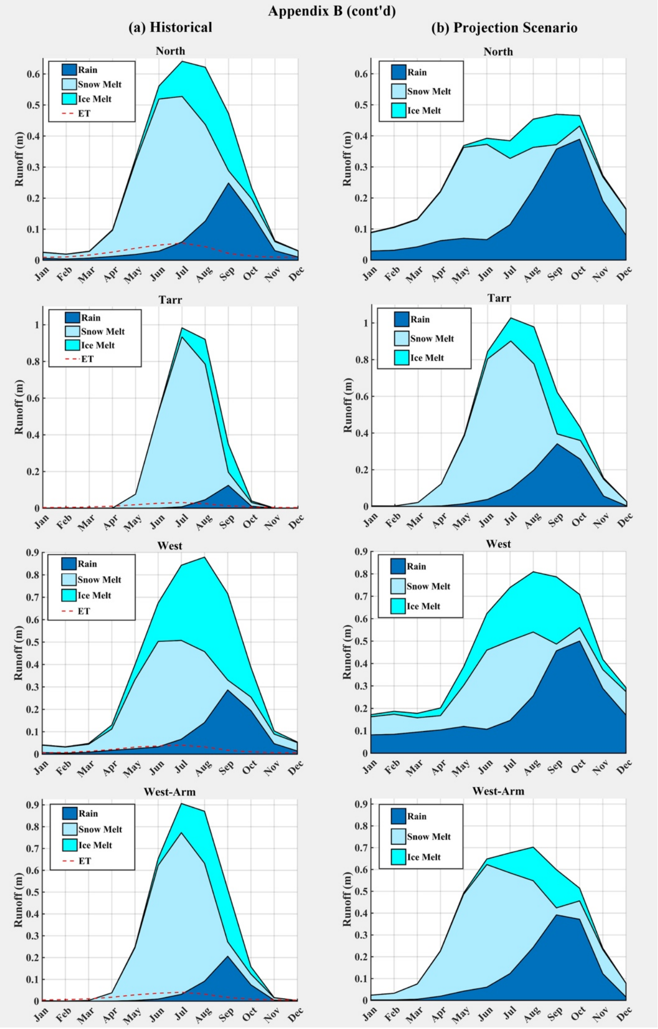

Appendix B. (a) – The historical runoff climatologies by watershed, partitioned into the constituents of snowmelt, ice- melt, and rain runoff. The historical MODIS-based evapotranspiration estimates are included on the historical plots, but the amounts are not subtracted from the modeled for runoff climatology because they were derived separately from the modeling process. (b) – The projection scenario runoff climatologies by watershed.

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