National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Current and Future Freshwater Runoff into Glacier Bay National Park

Natural Resource Report NPS/GLBA/NRR—2017/1423

ON THIS PAGE
Photograph of glacial outflow, Glacier Bay.
Photograph courtesy NPS

ON THE COVER
Photograph of waterfall, Glacier Bay.
Photograph courtesy NPS

Current and Future Freshwater Runoff into Glacier Bay National Park

Natural Resource Report NPS/GLBA/NRR—2017/1423

David F. Hill[1], Jordan P. Beamer[2], Ryan Crumley[2]

[1]Civil and Construction Engineering, Oregon State University
207 Owen Hall
Corvallis, OR, 97331

[2]Water Resources Engineering, Oregon State University
Corvallis, OR, 97331

April 2017

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Please cite this publication as:

Hill, D. F., J. P. Beamer, R. Crumley. 2017. Current and future freshwater runoff into Glacier Bay National Park. Natural Resource Report NPS/GLBA/NRR—2017/1423. National Park Service, Fort Collins, Colorado.

NPS 132/137845, April 2017

Contents

Page

Figures iv

Tables v

Executive Summary vi

Acknowledgments 1

Introduction 2

Study Area 5

Data and Methods 6

- Water Balance and Hydrologic Partitioning 6
- Model Description 6
  - MicroMet 6
  - SnowModel 6
  - Soil Moisture Model (SoilBal) 7
  - HydroFlow 7
- Model Forcing Data 7
  - Elevation and Historic Land Cover Data 7
  - Future Land Cover Data 9
  - Hindcast Meteorological Forcing Data 11
  - Future Meteorological Forcing Data 12
- Model Calibration 13

Results 14

- Historic Climate, Snow, and Runoff 14
- Historic Runoff 17
- Future Climate and Snow 20
- Future Runoff 22

Discussion 24

Conclusions 25

Literature Cited 26

Figures

Page

Figure 1. Overview map of the Gulf of Alaska region, major river watersheds in the area, and glacier cover 2

Figure 2. Scope of model domain (left) and individual watersheds 5

Figure 3. Elevation data (SRTM / ASTER) used in the modeling study. 8

Figure 4. Land cover data (2006 NLCD) used in the modeling study. 9

Figure 5. Future glacier cover for various ELA increases 10

Figure 6. Hindcast mean annual precipitation (1979-2015) in the GOA, according to four different climate products. 12

Figure 7. January temperature (left) and precipitation (right) anomalies for the CCSM4 (RCP 4.5) model run 13

Figure 8. Historic mean annual precipitation (1979-2015) for the complete model domain........ 14

Figure 9. Seasonal climatology (1979-2015) of precipitation and temperatures for the model subdomains 15

Figure 10. Seasonal climatology (1979-2015) of the partitioning of precipitation into rainfall and snowfall 16

Figure 11. Grid cell runoff (left column) and snow-water-equivalent (right column) for two sample days in the water year. 17

Figure 12. Sample map of streamflow on the model grid. 18

Figure 13. Seasonal climatology (1979-2015) of the partitioning of runoff (R) into rainfall, snow-melt, and ice-melt. 19

Figure 14. Cumulative distribution function plot (left) and min / max / mean plot (right) for daily flows over the period 1979-2015........ 20

Figure 15. Seasonal climatology of precipitation and temperatures for the future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) and historic (1979-2015; solid line) conditions. 21

Figure 16. Seasonal climatology of stored snow-water-equivalent for the future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) and historic (1979-2015; solid line) conditions. 22

Figure 17. Seasonal hydrographs for historic (1979-2015; solid line) and future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) conditions 23

Figure 18. Precipitation inputs (a) to and fluxes (runoff, evapotranspiration) out (b) of the GOA-wide domain of Beamer et al. (2016)........ 24

Tables

Page

Table 1: Summary of SNAP-selected climate models. 12

Table 2: Mean annual runoff (1979-2015) constituents for the historic model run. 19

Executive Summary

A comprehensive modeling study of the freshwater runoff into the waters of Glacier Bay National Park and Preserve (GBNP) has been conducted. The modeling was done at a high spatial (250 m and 1 km) and temporal (sub-daily) resolution to capture the rich structure of the runoff due to individual storm events and the seasonal variation in rainfall, snowmelt, and ice melt. The model framework involved several steps. First, weather data were downscaled from a coarse grid to the high spatial resolution of the model grid. This meteorological model additionally partitioned the precipitation into rainfall and snowfall. Second, a snow and ice evolution model was used to compute the storage and eventual melt of the annual snowpack as well as the melt of the glacier ice. Finally, a runoff routing model was used to transport water across the landscape to the coastal boundary.

A hindcast simulation was carried out for the period 1979-2015. Based on this simulation, the mean annual runoff volume into the GBNP domain (excluding the Alsek River drainage) was 46.6 km^3 with a standard deviation of 4.1 km^3. This value excludes precipitation falling directly on the surface of the water, and this domain is defined by hydrologic catchment, not park boundaries. The runoff was partitioned into 24% rainfall, 60% snow-melt and 16% ice-melt. Considerable spatial variability was observed. Generally, regions in the northwest receive a greater fraction of snowfall than those in the southeast. Additionally, regions in the northwest contribute greater ice melt than those in the southeast.

Forecast simulations were then carried out for the period 2071-2100. Several climate models and several emissions scenarios were considered. The simulations specifically considered the sensitivity of GBNP runoff to changes in meteorological forcing (precipitation and temperature) and to changes in landcover (glacier retreat). In general, there will be a significant ‘flattening’ of the mean annual hydrograph. The strong summer peak, presently attributable to ice-melt, will be diminished and there will be greater influence of the late spring snowmelt and the late autumn rainfall.

These simulations provide an unprecedented look at the hydrologic budget of GBNP and reveal the complex mix of processes that contribute to coastal runoff. A second component of this project focuses on the development of informative and visually appealing graphics and animations relevant to hydrosphere and cryosphere processes in GBNP.

Acknowledgments

The authors thank the National Park Service for providing the funding to carry out this work. Funding was provided by the National Park Service and Glacier Bay National Park and Preserve under Pacific Northwest CESU Agreement \#H8W0711001 and Federal Grant \#P15AC01065. The authors also wish to acknowledge funding from the Oil Spill Recovery Institute and the North Pacific Research Board. They are grateful to Anthony Arendt, Dan McGrath, Glen Liston, and Eran Hood who have all collaborated on recent work related to this project.

Introduction

Southeast and southcentral Alaska (Figure 1) experience unique hydrological cycles due to the rapid transition from marine estuaries and fjords to temperate rainforests to high mountain ranges over relatively short distances from the coast (O'Neel et al. 2015). Steep topography and a coastal marine climate combine to produce extreme rates of precipitation and the formation of extensive glaciers. The runoff of rainfall, snow-melt, and ice-melt into the Gulf of Alaska (GOA) has strong effects on local (Etherington et al. 2007) and regional (Weingartner, Danielson, and Royer 2005) oceanography. Looking forward, the timing and magnitude of this freshwater flux is likely to change under climate warming scenarios due to enhanced snow and ice melting (Radic and Hock 2013), changes to the snow/rain fraction and possible changes to future rates of precipitation. A useful summary of future climate scenarios for southeast Alaska is provided by Shanley et al. (2015).

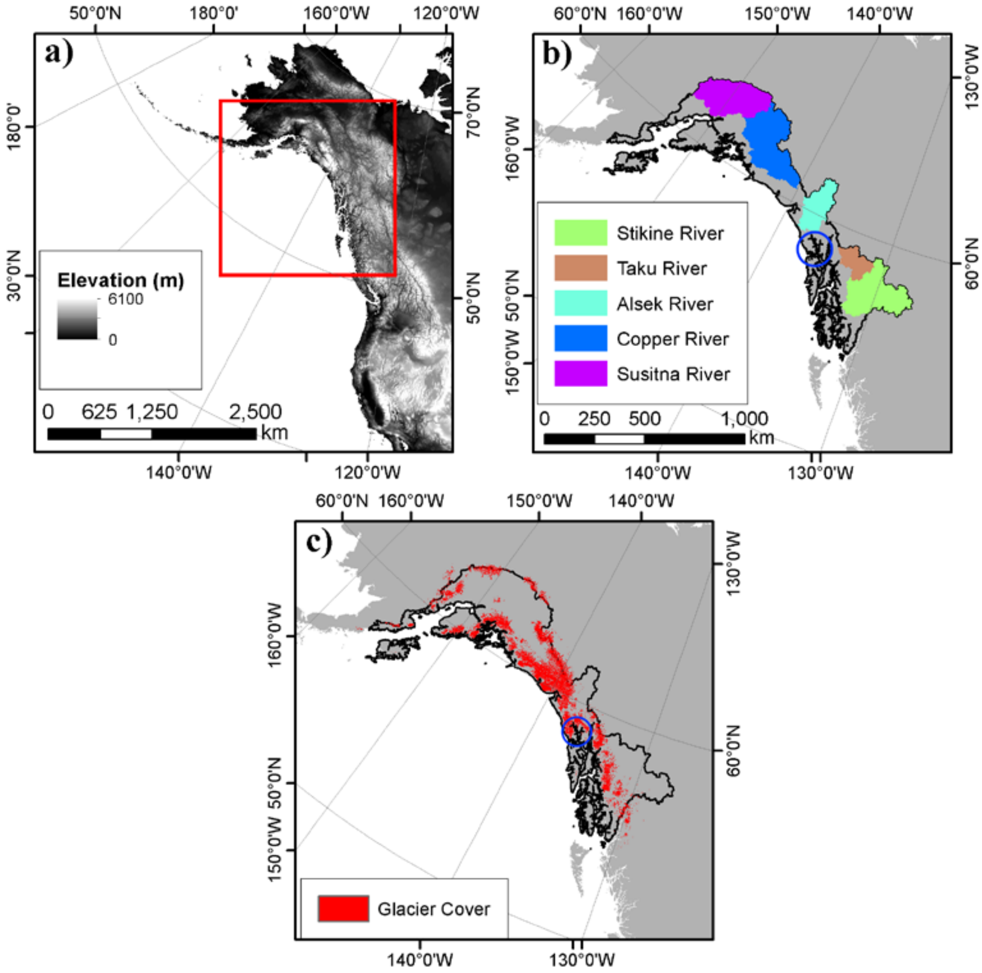

Figure 1. Overview map of the Gulf of Alaska region, major river watersheds in the area, and glacier cover. Blue circles in panels (b) and (c) indicate Glacier Bay.

Several previous studies have focused on quantifying the freshwater discharge from the total GOA watershed (Royer 1982; Wang et al. 2004; Neal, Hood, and Smikrud 2010; Hill et al. 2015).

Although there are considerable differences in resolution and design of these studies, all predict similar mean annual GOA runoff values (700-900 km^3 yr^{-1} water equivalent; w.eq.) during the period 1961-2009. However, little to no attention has been paid to the watershed-scale physical processes that control the release of water from storage in snowpack and glaciers, and the partitioning of rainfall and meltwater into evapotranspiration (ET) and runoff (snow melt, ice melt, and rainfall runoff). An increased understanding of these processes and their sensitivity to climatic changes is valuable in terms of water quantity and water quality. Regarding water quality, runoff from glaciers and seasonal snow is an important control on the physicochemical properties of freshwater and nearshore marine ecosystems along the GOA. From a physical standpoint, glaciers and snow cover strongly influence summer stream temperatures (Fellman et al. 2014) and thus the timing of salmon spawning (Lisi et al. 2013) in coastal watersheds. From a biogeochemical standpoint, discharge from glaciers has been shown to be an important source of bioavailable carbon for heterotrophic microorganisms in rivers (Singer et al. 2012; Fellman et al. 2015) and nearshore marine ecosystems (Hood and Berner 2009; Fellman et al. 2010). As a local example, a recent study in Glacier Bay, Alaska, Reisdorph and Mathis (2014) demonstrated that the amount of freshwater input to the Bay can influence the impacts of ocean acidification on this system through reductions in biologically-important carbonate minerals. Freshwater runoff, particularly from tidewater glacier discharge, is low in total alkalinity and reduces the buffering capacity of surface waters and enhances the vulnerability of the estuary to further changes in pH. Thus, understanding the magnitude of freshwater runoff as well as the spatial and temporal variation in this input to the Bay is crucial in understanding how the system will respond to additional uptake of anthropogenic carbon dioxide.

Glacier Bay National Park and Preserve is an ideal scaled-down local domain in which to study this complex regional hydrology. The park boundaries encompass enormous spatial gradients in topography, land cover, and precipitation. Additionally, the park has experienced dramatic change on century time scales and it is of interest to consider the future trajectory of this change. Further assets in the park's favor are (i) that it has seen considerable previous study of its climate and oceanography, providing ideal initial findings on which to build, and (ii) it has received considerable monitoring attention over the past decades. An excellent introduction to Glacier Bay is provided by Etherington et al. (2007) who also review the oceanographic measurements and demonstrate the strong seasonal and spatial gradients in near-surface salinity. These gradients reflect the ever-shifting balance between runoff, which seeks to stratify the water column, and tidal mixing, which seeks to vertically mix the water column. This study was followed up by Hill et al. (2009) who estimated various discharge statistics into Glacier Bay and incorporated these runoff estimates into a barotropic circulation model of the Bay. This work used regression equations from the United States Geological Survey (USGS) for the runoff. An important limitation of these equations is that they were obtained from observational watersheds with limited glacier cover. As a result, they are not expected to fully capture the flow characteristics from the heavily glaciated watersheds found in Glacier Bay. Additionally, the brief runoff estimates provided by (Hill et al. 2009) were only for flow exceedances and for peak flows, and not daily or monthly flows.

This report summarizes a recent comprehensive modeling study of the hydrology of Glacier Bay National Park and Preserve. This study uses high resolution process based models to quantify the precipitation inputs, the snowpack and ice processes, and the routing of runoff across the landscape to the coastline. With methods rooted in physical processes, the modeling framework is ideal for and was applied to scenarios of climate change. These are the first studies of their kind for Glacier Bay National Park and Preserve and the results help to quantify major terms in the current and future water balance for the park. The sections that follow briefly review the methods and key results for this study.

Study Area

Figure 2 shows the rectangular model domain used for this study. There is a natural tradeoff between desired spatial resolution and desired spatial coverage. Our primary criterion was a 250 m spatial model grid, as this would resolve many of the topographical features (smaller rivers, etc.) of interest. With this high spatial resolution, the spatial extent was necessarily limited, to provide reasonable model run times. Our domain covers all of Glacier Bay itself, and all of Icy Strait / Cross Sound. Along the open coast, it runs to a point slightly northwest of Fairweather Glacier. The Alsek River traverses a portion of Glacier Bay National Park. However, the watershed of the Alsek River is very large and could not be modeled with our 250 m grid. Fortunately, in this project, we are able to leverage previous modeling results that were carried out for the entire GOA watershed at 1 km resolution. So, only the coarser 1 km results will be reported here for the Alsek drainage.

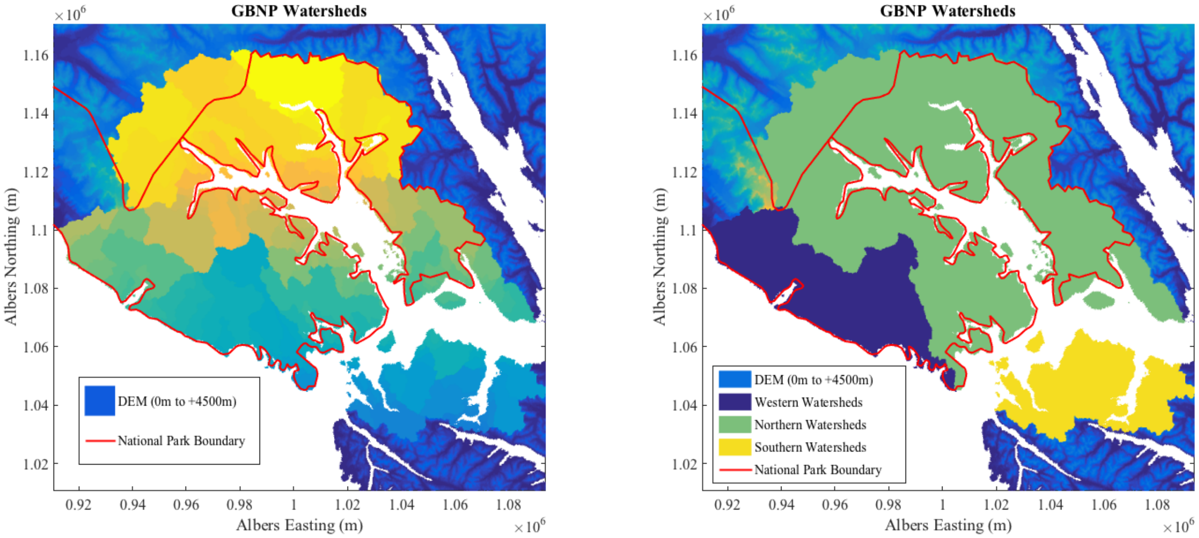

Figure 2. Scope of model domain (left) and individual watersheds. Right panel indicates the major sub-domains used to aggregate model results.

Figure 2 also shows three primary sub-domains that will be referred to in this report. Glacier Bay National Park ‘North’ (GBNP-N) drains all of the land forming the northern boundary of the Icy Strait / Cross Sound system. It should be noted that GBNP-N includes some lands outside of the park's eastern boundary. From a hydrological modeling point of view, it is most logical to study regions that correspond to catchments, rather than arbitrary boundaries. A southern domain (GBNP-S) was defined in order to contrast GBNP-N with the volume of water flowing into Icy Strait / Cross Sound from the south. It should be noted that GBNP-S includes lands that are entirely outside of the park boundary to the south. Finally, a western domain (GBNP-W) drains the land on the open coast, running from Cape Spencer on the south, to Fairweather Glacier on the north. Note that our modeling is done on a rectangular grid and all components of the hydrologic cycle are available at any grid cell of interest. Aggregating these cells to the three primary sub-domains referred to here is a useful way of providing the ‘overall’ picture of runoff in GBNP.

Data and Methods

Water Balance and Hydrologic Partitioning

A basic water balance is given by

$$\frac{dS}{dt} = P - (ET + SU) - R - D$$

where S is stored water, P is precipitation input, ET is evapotranspiration, SU is snow sublimation, R is runoff, and D is ice discharge (from tidewater glaciers). If we consider the Glacier Bay watershed as a whole, then the coastal freshwater discharge is R. We partition this R into contributions coming from direct rainfall onto snow-free surface, meltwater from the base of the snowpack, and meltwater from ice surfaces once the snowpack has been removed. We can also partition R into runoff from glacier and non-ice land surfaces.

Model Description

SnowModel-HydroFlow is a suite of distributed, physically-based meteorological [MicroMet; Liston and Elder (2006a)], energy-balance snow and ice melt [SnowModel; Liston and Elder 2006b)], and linear-reservoir runoff routing [HydroFlow; Liston and Mernild (2012)] models designed for climates and landscapes where snow and ice are present. We have added to this suite a simple soil water balance model (SoilBal) that simulates the pathways of precipitation and snowmelt in evapotranspiration, infiltration into soils, surface and baseflow runoff. The following sections give a very brief description of each of the sub-models we used, and how the input data (elevation, land cover, soil texture, and weather) were generated. Readers should refer to original publications for more detailed model descriptions. Additionally, readers should refer to Beamer et al. (2016) for a thorough description of the application of this model framework to regional GOA runoff studies. The local modeling effort herein leverages the results (best weather forcing product, calibration strategies, etc.) of that study.

MicroMet

MicroMet (Liston and Elder 2006a) is a data assimilation and interpolation scheme that defines meteorological forcing conditions at the same high resolution of the digital elevation and land cover grids. We used MicroMet to downscale air temperature, precipitation, humidity, wind speed and wind direction from coarse-resolution weather grids (described below), based on known relationships between weather variables and topography. We also used MicroMet to generate solar and incoming longwave radiation estimates based on topographic slope, aspect and cloud cover derived from relative humidity and temperature observations.

SnowModel

SnowModel (Liston and Elder 2006b), is a spatially-distributed snow evolution modeling system designed for application in landscapes and conditions where snow and ice occur. The model uses meteorological input from MicroMet to compute the full evolution of snow water equivalent (SWE) which includes: (1) accumulation from snow precipitation; (2) blowing-snow redistribution and sublimation; (3) snow-density and mass transfer evolution; and (4) snowpack ripening, refreezing, and melt water flow. SnowModel uses a surface energy balance approach to calculate the magnitude and timing of snow and ice melt. SnowModel was originally developed for glacier free landscapes, and was modified to simulate glacier ice-melt after winter snow accumulation had ablated for glacier mass balance studies in Greenland (Mernild et al. 2006; Mernild, Liston, and Hiemstra 2014). Here we used SnowModel to solve the surface energy balance and associated hydrologic fluxes on a sub-daily timestep, which enabled us to capture the diurnal fluctuations in snow- and ice-melt, including hydrologically important rain-on-snow events.

Soil Moisture Model (SoilBal)

Hill et al. (2015) used remotely sensed data from MODIS to estimate an annual ET volume from the larger Gulf of Alaska (GOA) domain of 135 km^3 yr^{-1}, roughly 17% of the annual runoff volume, highlighting the importance of the ET term in the water balance of coastal Alaskan watersheds. Previous applications of SnowModel have excluded calculation of ET because the simulations occurred during the winter season or in areas largely dominated by glaciers and ice sheets (Greenland) where ET fluxes are small.

The significance of the ET flux in the GOA basin motivated the following additions to the SnowModel model structure. First, we calculated potential evaporation (PET) using the Priestley-Taylor equation (Priestley and Taylor 1972) which uses modeled daily air temperature and top-of-canopy net radiation, R_n. The R_n calculation takes into account variations in surface albedo from different vegetation types. Second, routines were added to solve a soil water balance (Flint et al. 2013) using SnowModel grid-cell runoff and PET as hydrologic input, and gridded soil water storage at field capacity and wilting point. These two processes together make up the submodel SoilBal (Beamer et al. 2016). SoilBal produced daily grids of actual evapotranspiration (ET), surface, and baseflow runoff. The resulting surplus runoff and baseflow output were then used to drive the runoff simulations.

HydroFlow

The HydroFlow runoff routing model (Liston and Mernild 2012; Mernild and Liston 2012) simulates the routing of surface runoff produced from rainfall, snow-, and ice-melt across glaciers and land to downslope areas and basin outlets. Runoff is transported through the drainage network by a series of linear reservoirs, each grid cell containing a slow and fast response reservoir. The slow response reservoir accounts for the time meltwater and rainfall takes to move through the snow/ice/soil matrices down to the fast response reservoir, which moves the water down network and simulates channel flow. A coupled system of equations solves for fast- and slow-response flow and the final solution yields a discharge hydrograph for each grid cell. HydroFlow contains parameters that were adjusted to match simulated discharge hydrographs to available observations. By identifying all coastal grid cells and summing their hydrographs, the discharge into the entire GBNP domain was obtained.

Model Forcing Data

Elevation and Historic Land Cover Data

A digital elevation model (DEM) spanning the USA - Canada international border is required. As noted above, the results in this report come from two separate modeling efforts. For the Alsek River runs, results are drawn from (Beamer et al. 2016) who used the GTOPO (Global 30 Arc-Second Elevation; USGS, https://lta.cr.usgs.gov/GTOPO30) digital elevation model. For the GBNP runs (at the finer 250 m resolution), a combination of SRTM (Shuttle Radar Topography Mission; NASA, http://www2.jpl.nasa.gov/srtm/) and ASTER (Advanced Spaceborne Thermal Emission and Reflection; NASA, https://asterweb.jpl.nasa.gov/gdem.asp) DEM products was used. Figure 3 shows the elevation in the finer-scale model domain.

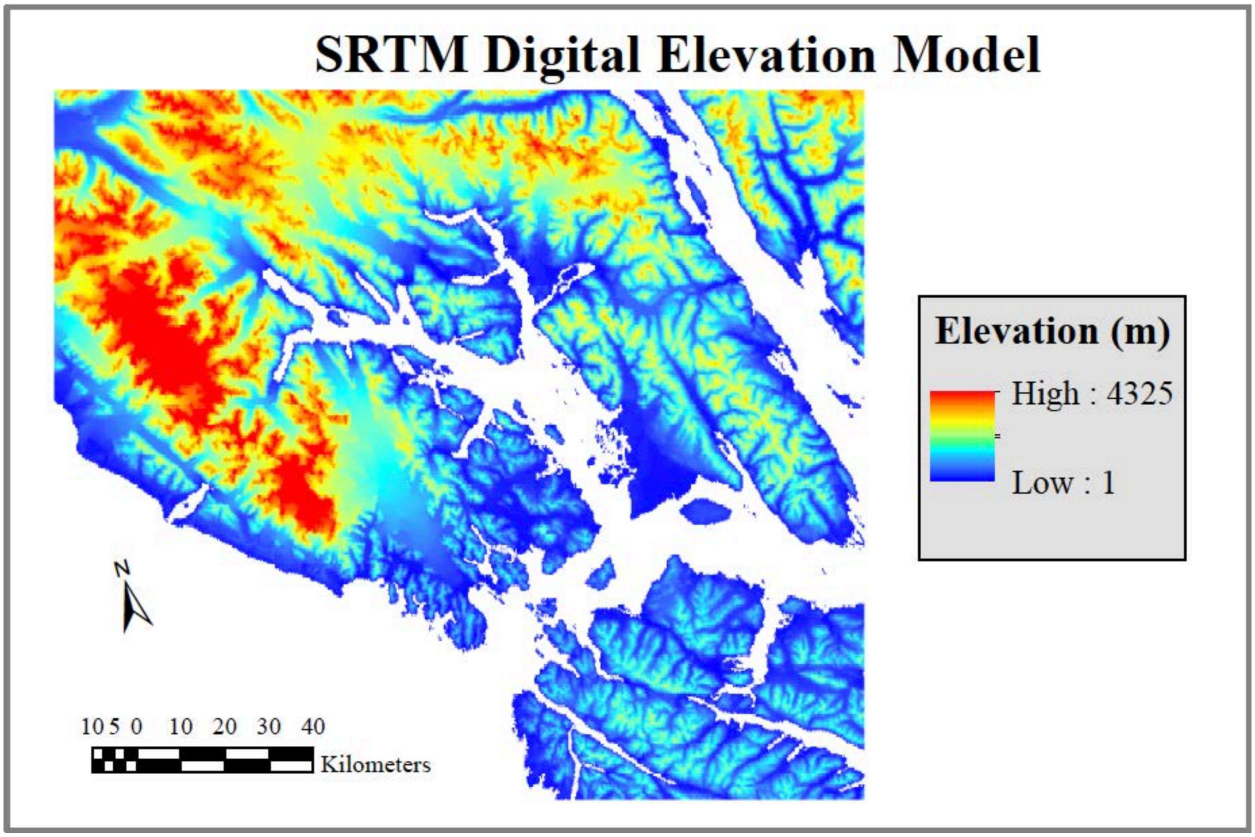

Figure 3. Elevation data (SRTM / ASTER) used in the modeling study.

Vegetation classes for each grid cell were obtained from the 2006 National Land Cover Database (NLCD; Figure 4). The land cover grid was aligned with the DEM and reclassified to the vegetation classes defined in Liston and Elder (2006b). Glacier ice cover was obtained from the Randolph Glacier Inventory (RGI; Version 3.2) (Pfeffer et al. 2014) and these data were used as the permanent ice land cover class in the SnowModel simulations. RGI shapefile polygons were converted to a 50-m grid, and then resampled to the resolution of the model grid. Only grid cells with more than 50% glacier cover were re-classified as glacier covered cells. Soil texture data for the SoilBal model were obtained from the gridded Harmonized World Soil Dataset (HWSD, Version 1.2; ISRIC, http://www.isric.org/content/data), available at 1-km resolution.

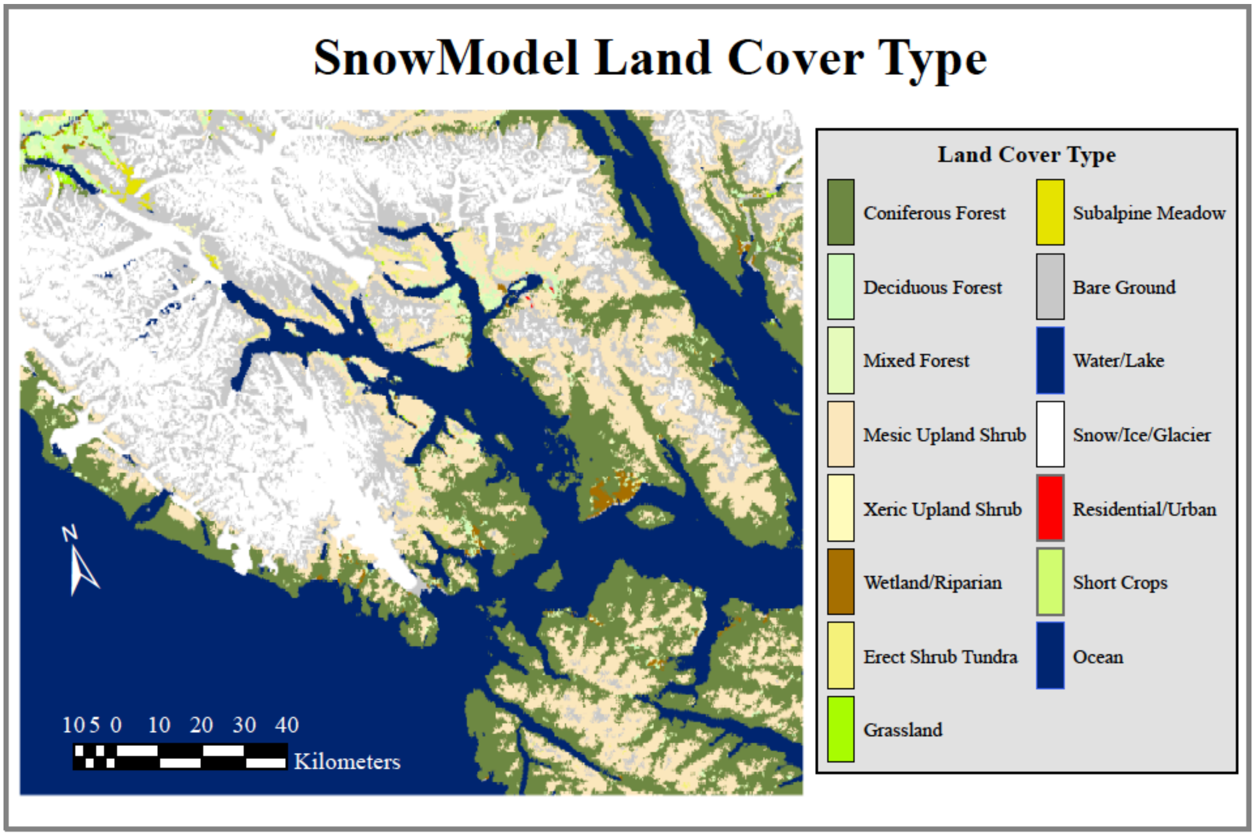

Figure 4. Land cover data (2006 NLCD) used in the modeling study.

Future Land Cover Data

For the climate change runs, it is essential that the landscape be adjusted to reflect likely future glacier cover. In this model framework, glaciers act as a supply of additional melt water once the seasonal snowpack has melted away. In the future, as the climate warms, most glaciers will retreat. Failure to retreat the glaciers in the model will expose ice to increased temperatures and therefore over estimate glacier melt.

The most physically based approach would be to conduct multi-decadal runs with a fully coupled model that linked evolving climate to hydrology and also to glacier dynamics. One example of this approach is Huss and Hock (2015). Here, we choose a simpler approach that is designed to test the “sensitivity” of the hydrology to both climate changes and landscape changes (glacier retreat). We do not expressly model the glacier retreat. Instead, we study the response of a future, likely, static landscape (new glacier cover) to new climate forcing.

We used a hypsographic model based on the approach presented in Paul et al. (2007) for assessing changes in glacier number, area and volume as a function of changes in equilibrium line altitude (ELA) elevation. The equilibrium line of a glacier is the elevation contour line that separates the accumulation zone (above) from the ablation zone (below). This method relies on the documented relationship between increasing air temperatures with increasing ELA. To inform our selection of appropriate ELA change for the hypsographic model, we utilized the modeled ELA from Figure S9 of Huss and Hock (2015) for the Alaska Region glaciers (90% of which are in the GOA). We calculate the difference between modeled ELA averaged from 2070 to 2100 with the 2010 value and find a 200 m increase for the RCP4.5 scenario and 400 m increase for the RCP8.5 scenario. By way of introduction, RCP stands for ‘Representative Concentration Pathway.’ The RCP4.5 scenario is a ‘mid-range’ scenario and the RCP8.5 scenario is a ‘high-range’ scenario consistent with the lack of enacted climate policy in the future. The updated glacier cover from these ELA increases was used to generate a new SnowModel land cover file. Each glacier ice cell that is removed due to ELA increase is replaced with bare ground cover cell; we do not account for vegetation / soil succession, only changing glacier cover.

The extension of this modeling work to climate change studies was not part of the original scope of work. However, we are able to make use of other recent modeling efforts and extract the results for GBNP from those simulations. Figure 5 shows the expected glacier cover in Glacier Bay for several different sample ELA increases. Note that the spatial resolutions of this figure and all climate change results in this report are 1 km, not 250 m.

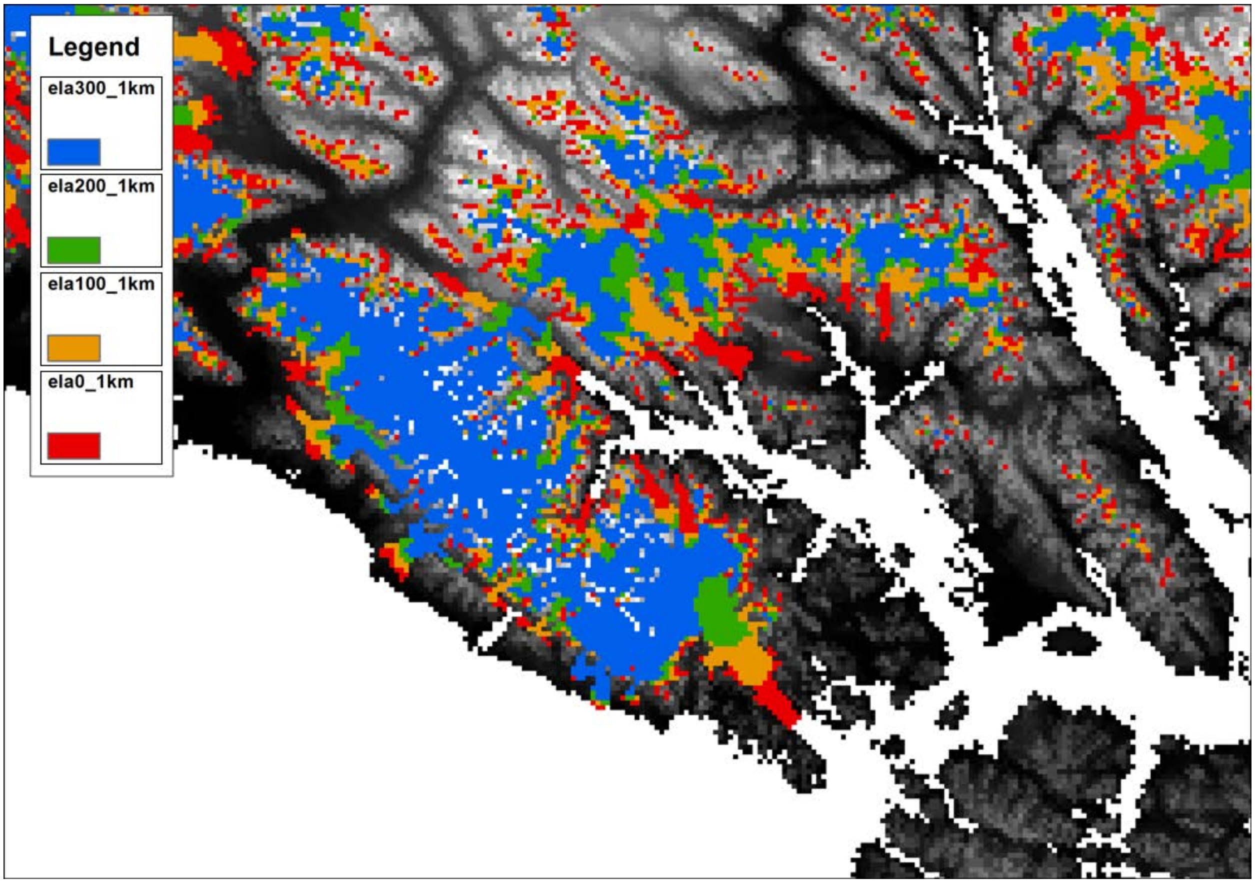

Figure 5. Future glacier cover for various ELA increases. The colors aggregated together indicate present glacier cover. An ELA increase of 100 m will result in the loss of the red cells, or a ‘retreat’ to the orange cells. An ELA increase of 200 m will result in the loss of the orange cells, or a ‘retreat’ to the green cells. Similarly for blue.

Hindcast Meteorological Forcing Data

The GOA in general has a limited number of weather stations, with existing stations biased to low elevations. In GBNP, the situation is even more severe. In addition to the lack of data, the complex topography of coastal Alaska limits the spatial representativeness of the available data (Royer 1982; Wang et al. 2004). To address this lack of data, we used several gridded climate reanalysis products, including the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) (Mesinger et al. 2006), the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011), and the Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), which have (nominal) spatial resolutions of 32-km, 67-km, and 38-km respectively and temporal resolutions of 3-hr, 3-hr, and 6-hr respectively. A fourth product was created by bias-correcting the NARR dataset to weather grids created by Hill et al. (2015). This bias correction process had the effect of altering the mean values of the NARR dataset, which was found to be too warm and too dry. All of these reanalysis data products begin in 1979 and are kept current (to present day). In this study, a hindcast period of 1979-2015 was used and when hindcast ‘mean’ results are presented, it will be understood that the mean is over this climatological period.

An an example of the variability of weather products, the MicroMet precipitation output for the whole GOA is shown in Figure 6. It is clear that the NARR dataset is relatively dry and the MERRA product is relatively wet. The bias-corrected NARR dataset is extremely wet compared to the others. Maps of mean annual temperature show similar variability among the reanalysis products. The work of Beamer et al. (2016) concluded that the CFSR runs had the best overall performance, in a regional sense, for the Gulf of Alaska. Locally, it is possible for one of the other reanalysis products to outperform CFSR. Lacking adequate in-situ weather data in GBNP to directly test this, the regional conclusion that CFSR is the best forcing product for Alaska was adopted for the current study.

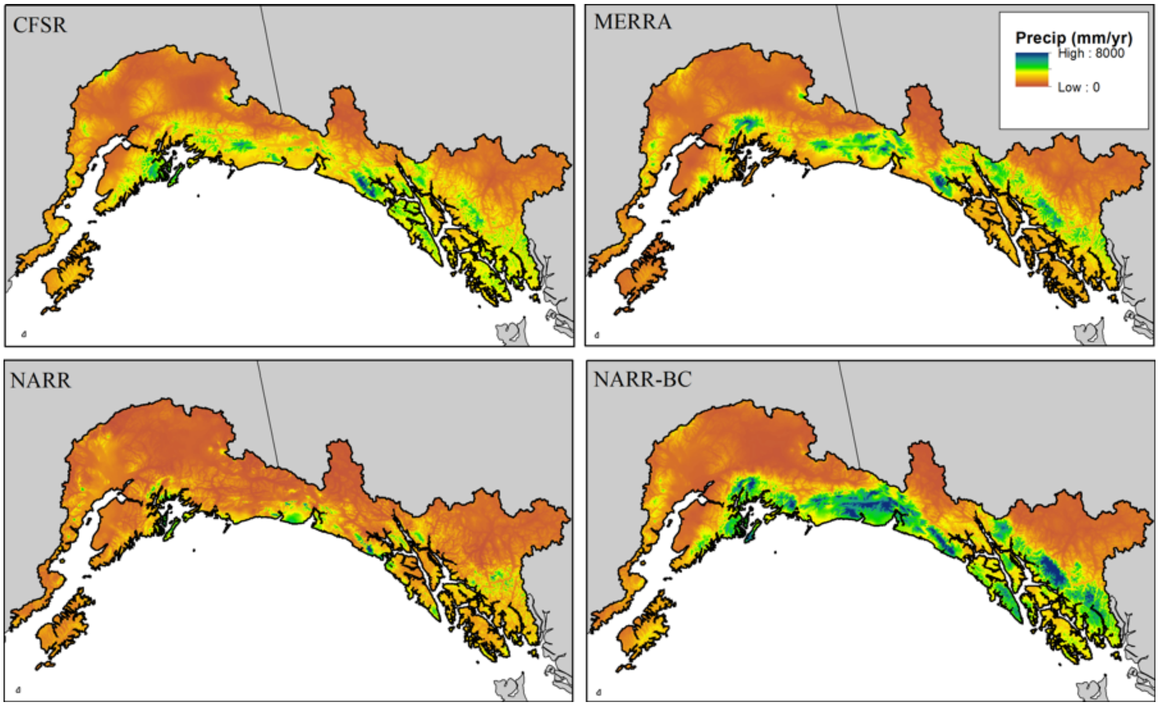

Figure 6. Hindcast mean annual precipitation (1979-2015) in the GOA, according to four different climate products.

Future Meteorological Forcing Data

Future meteorological data for the period 2070-2100 were obtained by perturbing the CFSR reanalysis data with monthly anomalies. These anomalies were obtained from the Scenarios Network for Alaska Planning (SNAP) and are based upon Coupled Model Intercomparison Project Phase 5 (CMIP5) climate scenarios. The SNAP project makes available high-spatial resolution (2 km) historic and future climatologies. These climatologies are 30-year averages and are available for each month of the year. The SNAP project evaluated all 22 climate models that contributed to CMIP5 and identified the five (Table 1) that 'best performed' in the Alaska region. For this report, only RCP (Representative Concentration Pathway) 8.5 results will be presented. RCP 8.5 is the 'worst case' pathway considered in the CMIP5 ensemble of scenarios.

Table 1: Summary of 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	ISPL Coupled Model v5A	IPSL-CM5A-LR
Meteorological Research Institute	Coupled GCM v3.0	MRI-CGCM3

To construct the temperature anomaly for each month (and for a given model), the historic climatology was subtracted from the future climatology. For precipitation, the future climatology was divided by the historic. As an illustrative example, the January anomalies (RCP 4.5 in this case) for the broader GOA region are shown in Figure 7. These anomalies were then applied to the CFSR time series, producing future time series of precipitation and temperature that (i) retained the high spatial resolution of the climatologies, (ii) retained the high temporal resolution of the CFSR weather data and (iii) retained the characteristics (mean values, seasonal variation) of the modeled future climate.

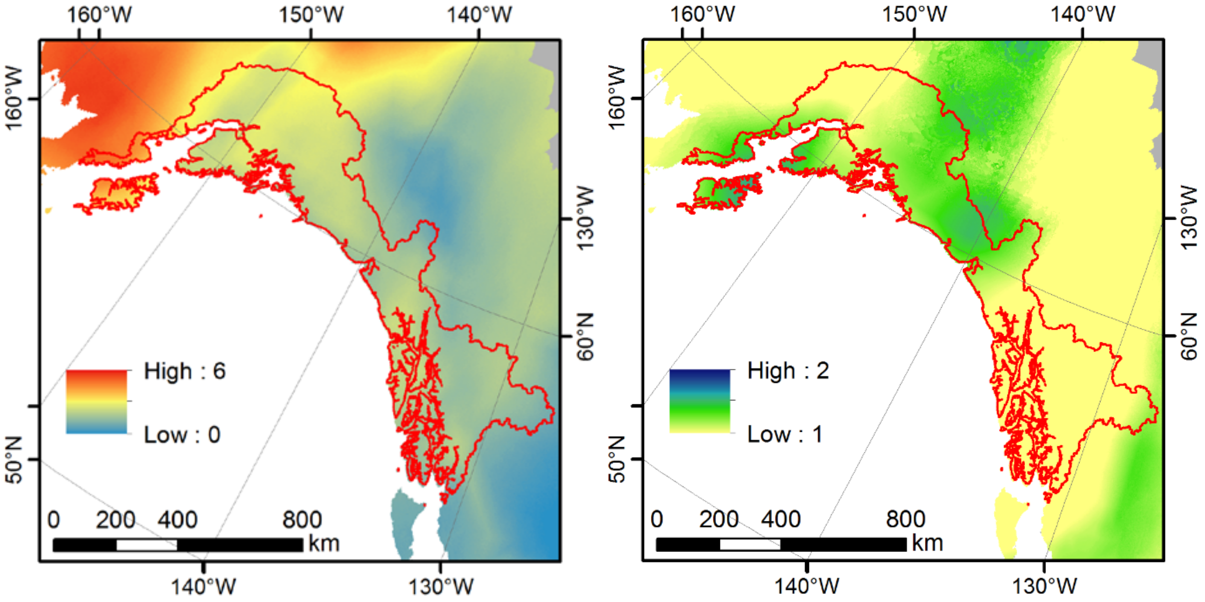

Figure 7. January temperature (left) and precipitation (right) anomalies for the CCSM4 (RCP 4.5) model run. Temperature anomaly is in degrees C and precipitation anomaly is a dimensionless ratio.

By doing runs with these five models, it was possible to determine the level of ‘uncertainty’ in runoff associated with the choice of climate model. The bulk of the results presented herein, however, will focus only the mean results of the 5-model ensemble.

Model Calibration

The distributed hydrologic model used in this study has a large number of parameters. Ideally, a broad portfolio of field data, including streamflow, snow-water-equivalent (from a SnoTel station), and glacier mass balance data would all be available in the Glacier Bay model domain. This is not the case, however. As a result, parameter selection was informed by the study of Beamer et al. (2016) who used four catchments in southeast and southcentral Alaska for the calibration of their larger model domain. Those catchments were on Wolverine, Gulkana, Mendenhall, and Eklutna glaciers and both long-term streamflow and surface mass balance datasets were available. Their calibrated model produced coefficients of determination (r^2) values of 0.63-0.77 for seasonal point glacier mass balance and Nash-Sutcliffe efficiencies of 0.85-0.91 for streamflow.

Results

In the remainder of this report, we present information on the inputs to and outputs from the Glacier Bay landscape. As noted above, we have chosen to aggregate our results into three primary watersheds, GBNP North, South, and West. We will also present results for the Alsek River watershed, a portion of which lies in GBNP boundaries. The presentation of results will roughly follow the sequence of the model workflow: climate, snowpack / ice processes, and streamflow. When ‘mean’ results are presented, they are for the periods 1979-2015 and 2070-2100 for the historic and future work, respectively.

Historic Climate, Snow, and Runoff

Figure 8 shows the mean annual precipitation for the entire computational domain. As expected, there are strong spatial gradients, driven by large elevation differences and also distance from the coast (rain shadow). When aggregated over the three domains, it is found that GBNP-N receives 30.9 km^3 yr^{-1} of precipitation, GBNP-S receives 5.7, and GBNP-W receives 10.4. Of course, the three domains have different sizes. Dividing the precipitation volume by the horizontal area of each domain provides mean annual precipitation depths (a better comparative measure) of 3.5, 3.3, and 4.6 m, respectively.

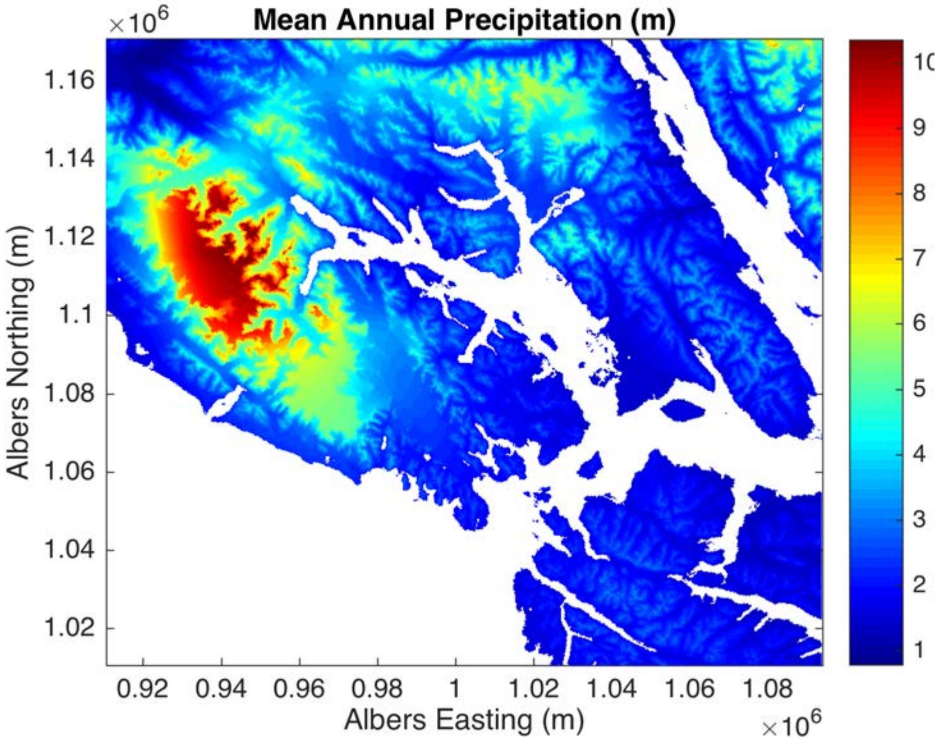

Figure 8. Historic mean annual precipitation (1979-2015) for the complete model domain.

The seasonal variation of the precipitation and temperature is shown in Figure 9. All regions have October peaks in the precipitation inputs and summer peaks in temperature. There are slight differences in summer temperatures with the western domain being the coolest and the southern domain being the warmest. Regarding the Alsek watershed, note that it has different vertical axes than the other three plots. The three primary GBNP watersheds were plotted with identical axes for the purposes of comparison. The Alsek, being a colder interior watershed, displays much cooler winter temperatures than the other subdomains.

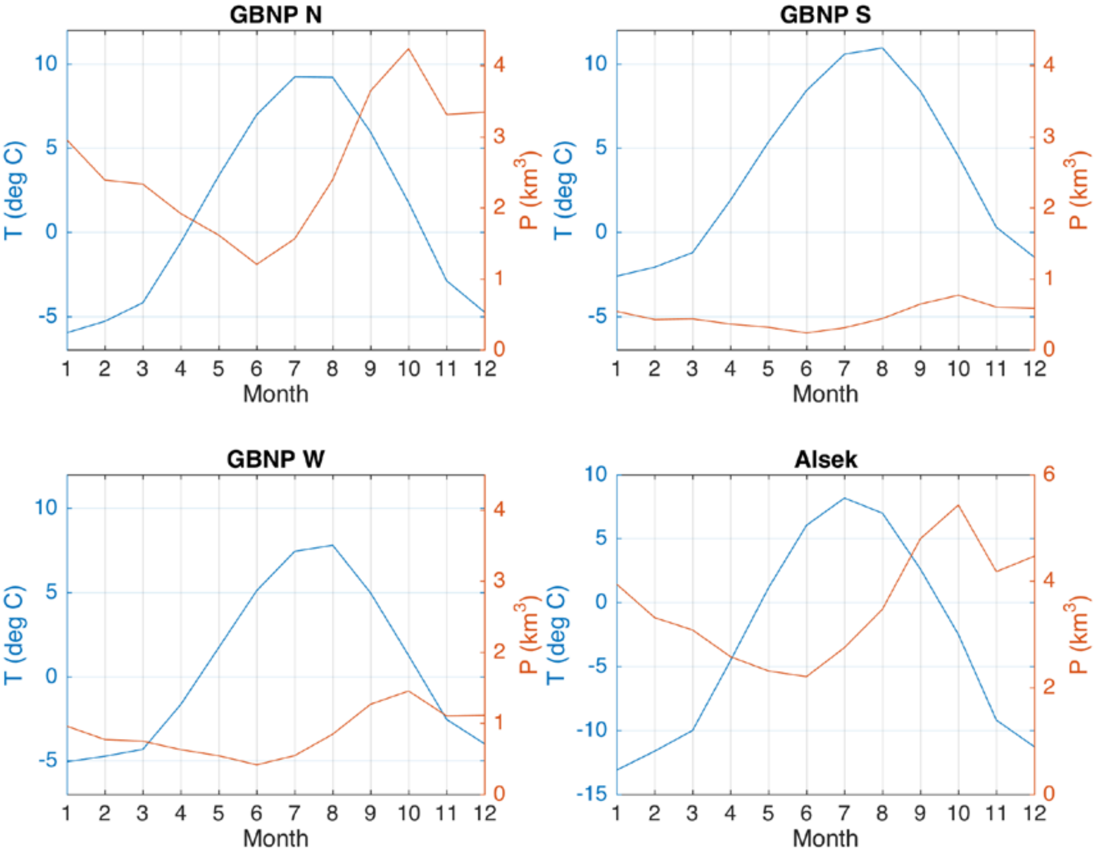

Figure 9. Seasonal climatology (1979-2015) of precipitation and temperatures for the model subdomains. Note that the Alsek sub-figure has different vertical axes than the other three sub-figures.

The seasonal partitioning of the precipitation into rainfall vs.\ snowfall is shown in Figure 10. The western and northern sub-domains have similar patterns where snow dominates in winter months and rain dominates from May to October. Even in the summer time, however, there is still a non-negligible input of snow. The GBNP-S domain has a very different behavior. Here, snow never exceeds rainfall, though the two are roughly equal from January through March. From May until October there is essentially zero snow input. The colder temperatures found in the Alsek watershed result in essentially zero rainfall for the first several months of the year, with all precipitation falling as snow. Again, the Alsek sub-figure has different vertical axis limits than the others.

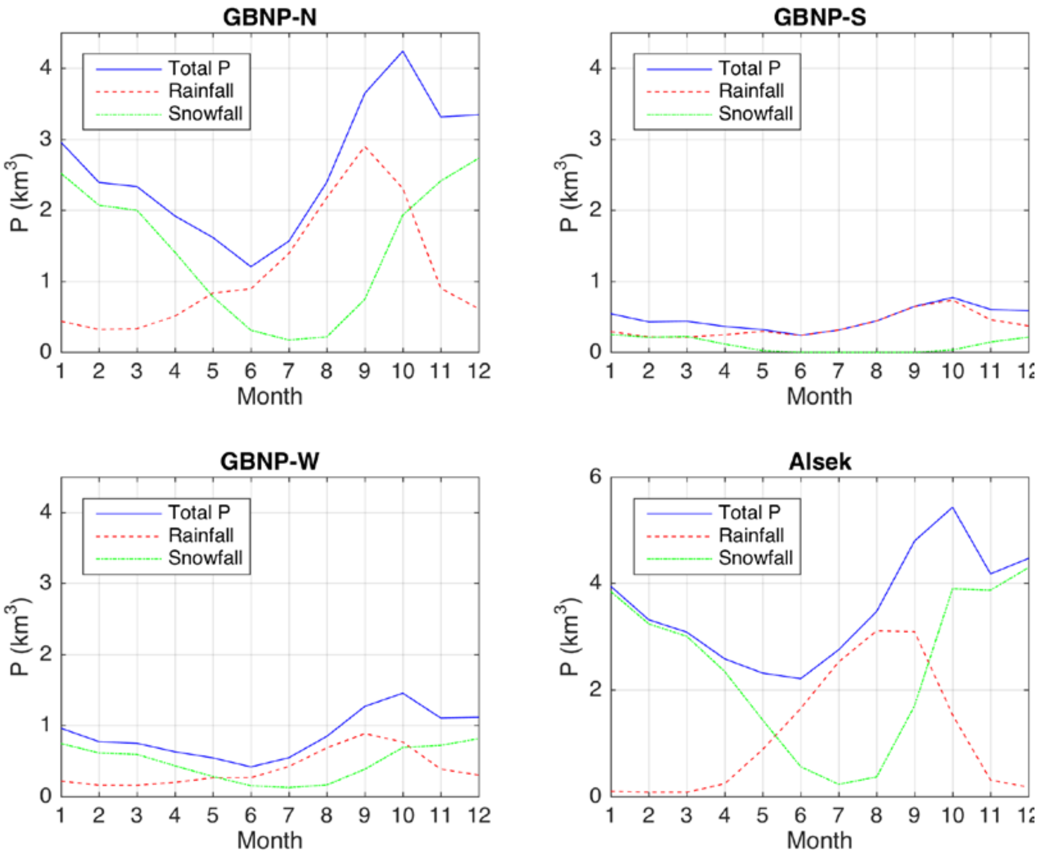

Figure 10. Seasonal climatology (1979-2015) of the partitioning of precipitation into rainfall and snowfall. Note that the Alsek sub-figure has different vertical axes than the other three sub-figures.

During the course of a year, this precipitation input is party stored (as snow) and then later released (as snowmelt). Figure 11 shows a few illustrative figures related to this. The right column of this figure shows, for two different days of the year (April and July), the snow-water-equivalent of the snow stored on the ground. The color bars are the same between the two figures, and it is clear that much of the annual snowpack has been lost by July. The left column of this figure shows the ‘cell runoff.’ This is not the same as streamflow. The cell runoff is the amount of water released from a model grid cell (due to rainfall, snow-melt and ice-melt at that grid cell) on a given day. In the upper panel (April) the runoff is zero at higher elevations since there is no melt yet. At the lower elevations, there is some runoff due in part to melt and in part to rainfall. In the lower panel (July), there is considerable runoff from the higher elevations since the summer temperatures are causing considerable melt.

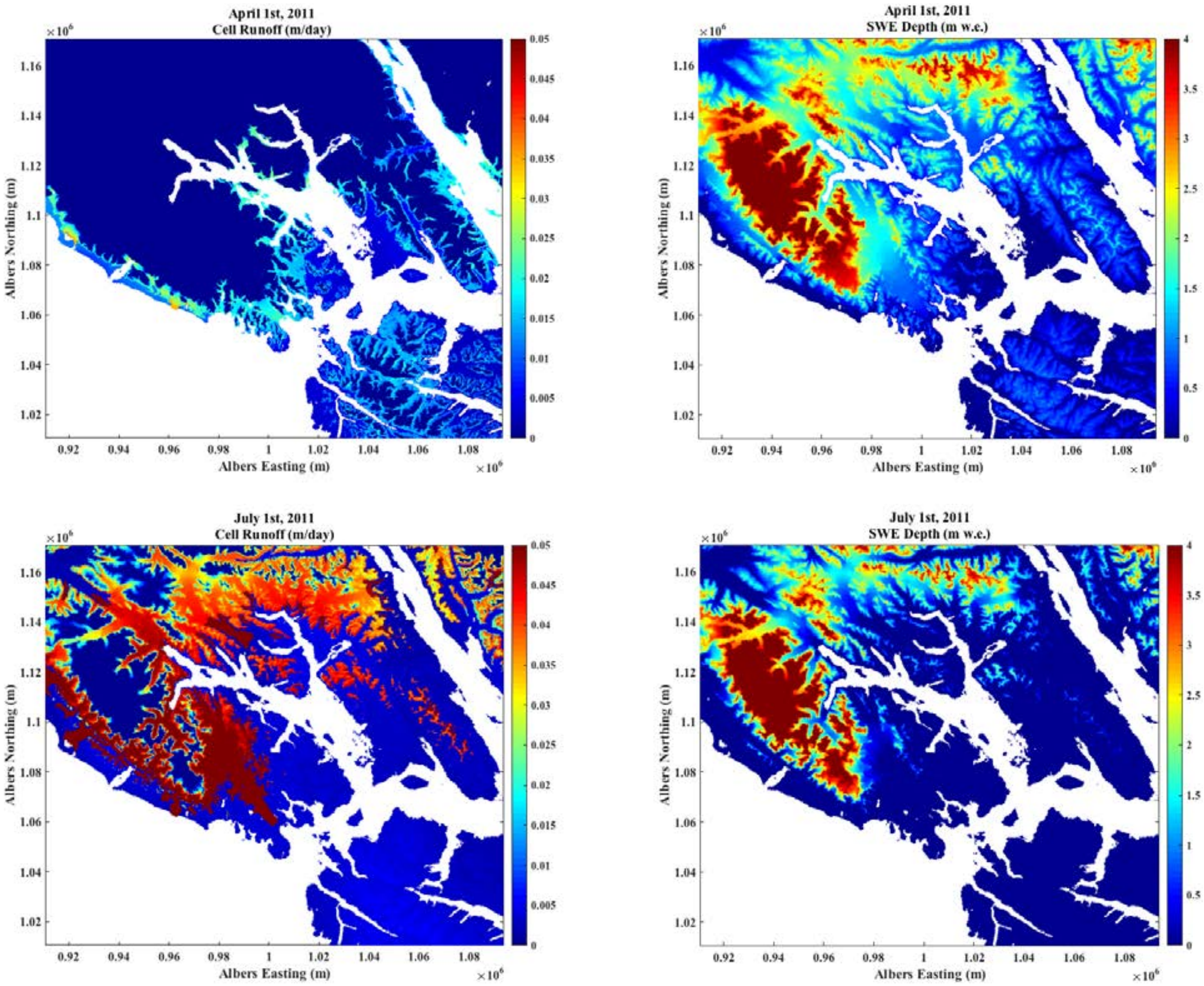

Figure 11. Grid cell runoff (left column) and snow-water-equivalent (right column) for two sample days in the water year.

Historic Runoff

Recall that, in this distributed hydrological model framework, the streamflow is computed at every model grid cell. Figure 12 shows an example of the streamflow network on a given model day. While it is possible to extract model output at a single grid cell for the purposes, for example, of comparison to stream gauge data, it can be more useful to aggregate the results over a watershed of interest. In the subsequent figures, results have been aggregated to the principal watersheds defined above for GBNP.

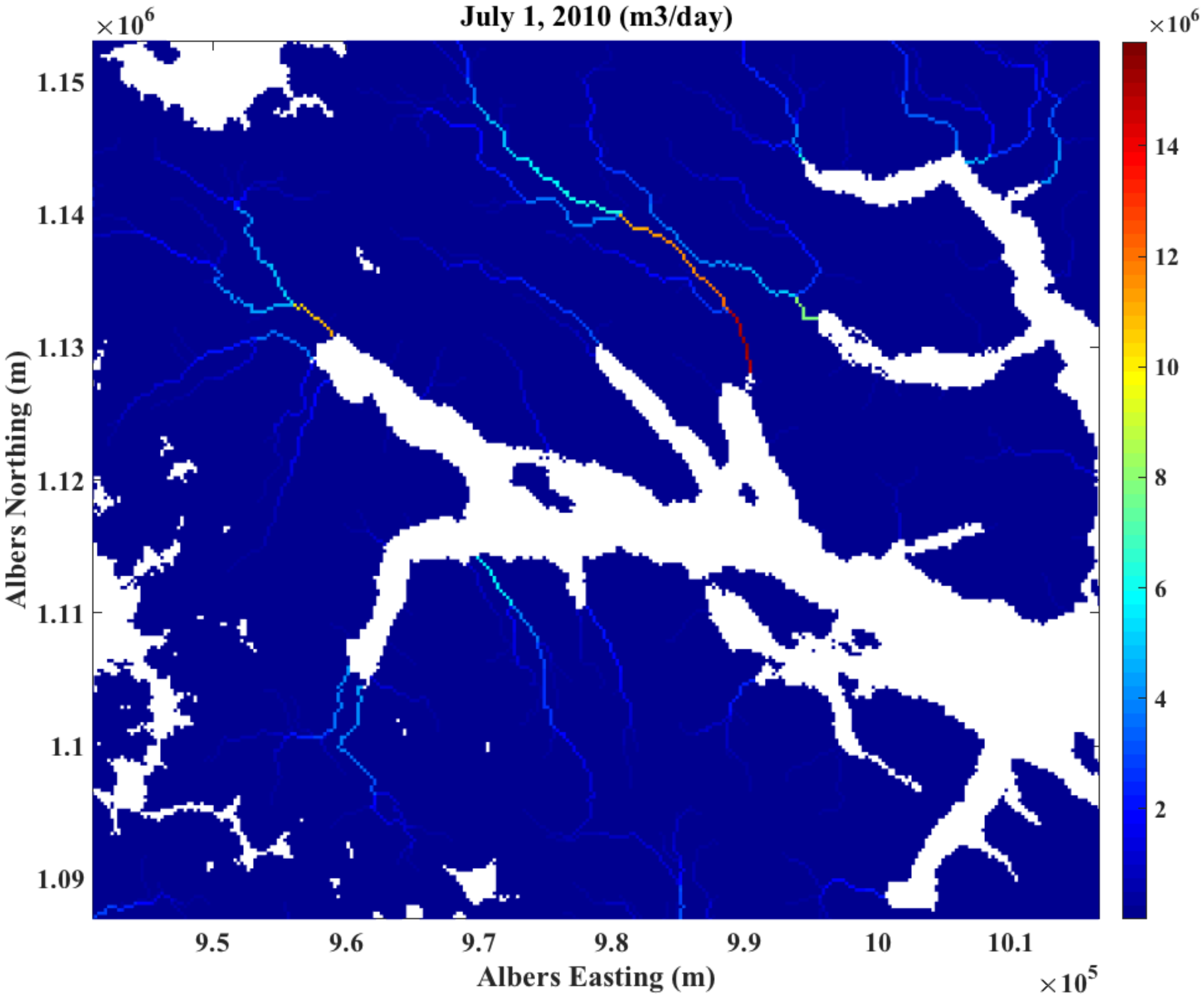

Figure 12. Sample map of streamflow on the model grid.

The seasonal climatology of runoff, partitioned into its constituent sources, is shown in Figure 13 This figure clearly demonstrates the different hydrologic regimes present in GBNP. The GBNP-S domain is dominated by lower elevation, forested watersheds. The runoff hydrograph is essentially bi-modal with one peak due to snow-melt coming in May and a second peak due to rainfall coming in October. There is essentially zero ice-melt contribution. The GBNP-N hydrograph is very different. Here, the hydrograph is dominated by May-June snow-melt. Ice-melt in the summer months then sustains the runoff until the rains in autumn arrive. The result is a strong, broad late-spring to early-autumn peak in runoff. The GBNP-W domain is relatively similar to the GBNP-N domain, but with a slightly later and less symmetrical peak, due to later snow melt. Finally, the Alsek watershed has the most flow and most closely resembles GBNP-N, with the exception that for the Alsek, ice melt contributes more runoff than rainfall and the vice-versa is true for GBNP-N. Table 2 summarizes the runoff from the various constituent sources for the four domains.

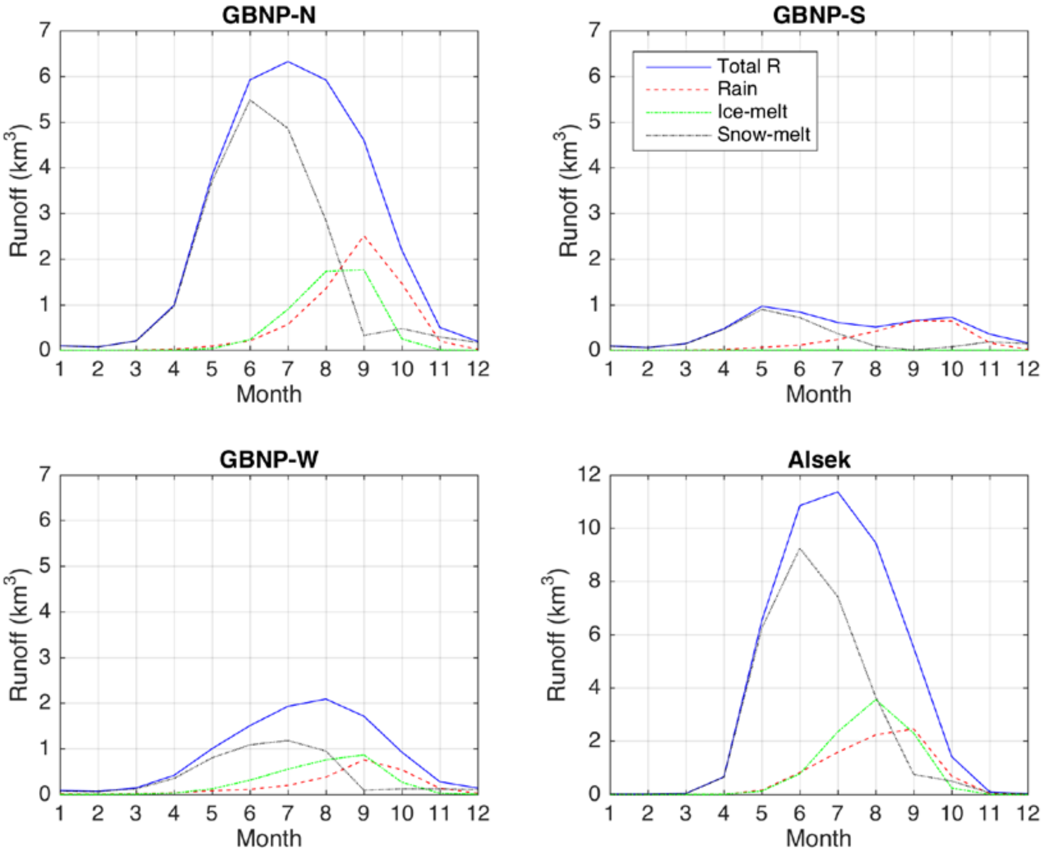

Figure 13. Seasonal climatology (1979-2015) of the partitioning of runoff (R) into rainfall, snow-melt, and ice-melt.

Table 2: Mean annual runoff (1979-2015) constituents for the historic model run.

Domain	**R (km^3)**	**Rain (km^3)**	**Snowmelt (km^3)**	**Ice-melt (km^3)**
GBNP-N	30.85	6.44	19.49	4.93
GBNP-S	5.59	2.32	3.23	0.03
GBNP-W	10.28	2.29	5.06	2.94
Alsek	45.92	7.99	28.59	9.34

A different view of the runoff in GBNP can be obtained by looking at the statistics of the daily flows. For example, Figure 14, on the left hand side, shows the cumulative distribution function (CDF) of the daily flows summed over the GBNP-N, GBNP-S, and GBNP-W domains. This figure illustrates the variability of the flow. A watershed with constant runoff (no variability) would have a CDF that was a vertical line. A watershed in which there was an equal probability of all flows occurring would have a CDF that was a diagonal line. For this current example, it is observed that a flow of 5000 $m^3 s^{-1}$ has a cumulative probability of 95%. Thus, flows are less than or equal to 5000 $m^3 s^{-1}$ 95% of the time. The right panel of Figure 14 shows a min / max / mean plot for daily flows, based on the 35 year historical simulation. This figure indicates that maximum flows have much greater variability than minimum flows and that the variability is greatest in autumn months (due to rainstorms, rather than snow / ice melt).

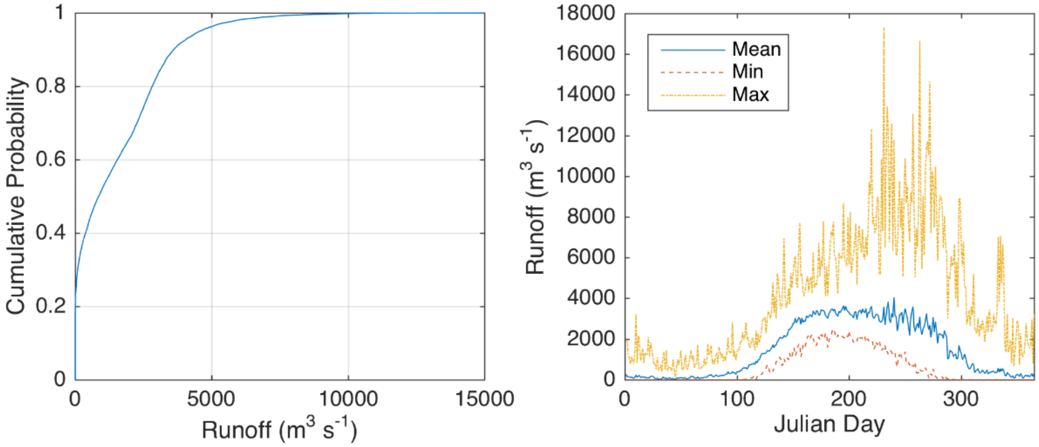

Figure 14. Cumulative distribution function plot (left) and min / max / mean plot (right) for daily flows over the period 1979-2015. Flows are aggregated over all three GBNP sub-domains (Alsek is excluded).

Future Climate and Snow

Figure 15 shows the future climatologies of precipitation and temperature for the RCP8.5 / ELA400 scenario. Precipitation increases are modest; on the order of about 10% for GBNP proper (closer to 20% for the Alsek), with the bulk of the increase coming in autumn. Temperature increases are far more dramatic and are relatively uniform throughout the year. The effect on the partitioning of the precipitation is dramatic. In the GBNP-S domain, which is comparatively low-lying, the future snowfall is only 16% that of the historic case. The GBNP-N and GBNP-W domains are much higher elevation, which means that they are able to somewhat buffer losses in snow. Even so, those two domains will only receive 45-50% of the snowfall that they presently do.

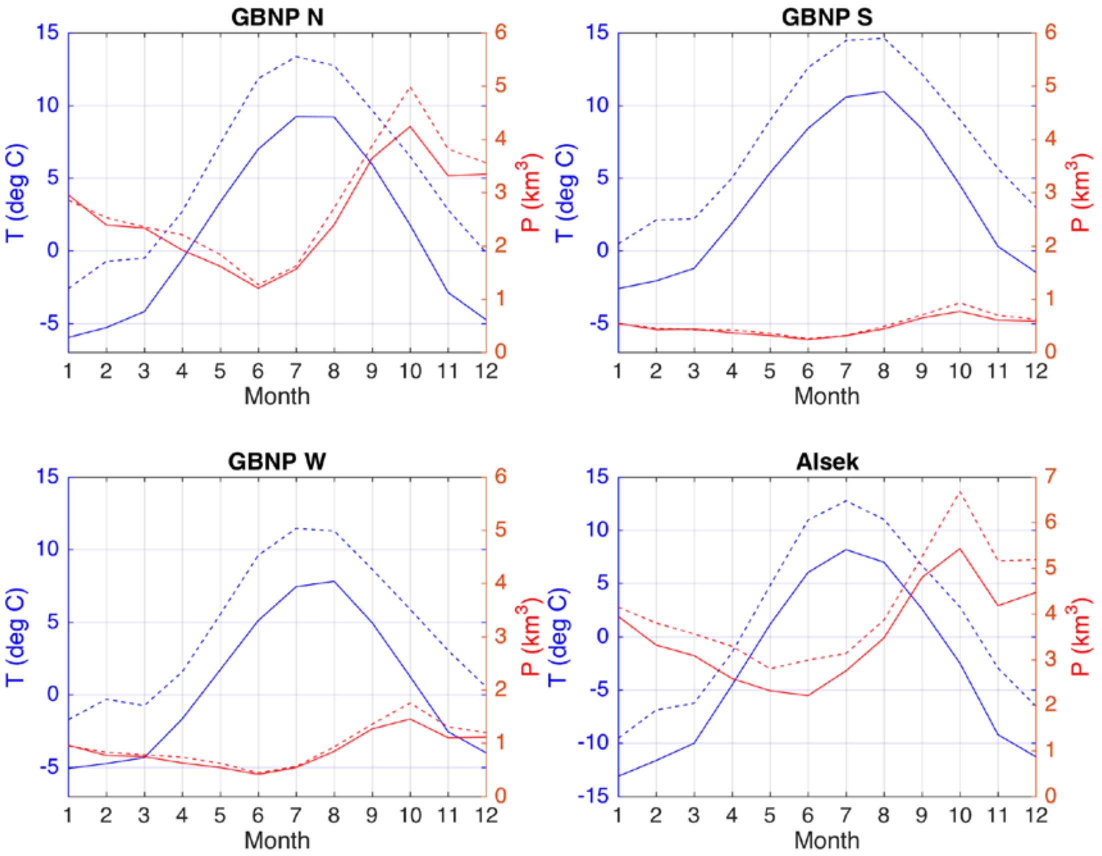

Figure 15. Seasonal climatology of precipitation and temperatures for the future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) and historic (1979-2015; solid line) conditions.

In addition to less precipitation falling as snow, warmer temperatures earlier in the year mean that snow that does fall will melt earlier. Figure 16 shows a comparison of historic and future climatologies of snow-water-equivalent. For the north and west domains, the mean annual SWE is roughly cut in half, while for the south domain, SWE nearly disappears entirely. In the Alsek domain, SWE is reduced to 65% of the historic value, a smaller decrease than the other domains. This is due to the facts that (i) precipitation went up more dramatically in the Alsek and (ii) the colder baseline temperatures in the Alsek mean that it is less susceptible to loss of snow than other domains with temperatures closer to the freezing point.

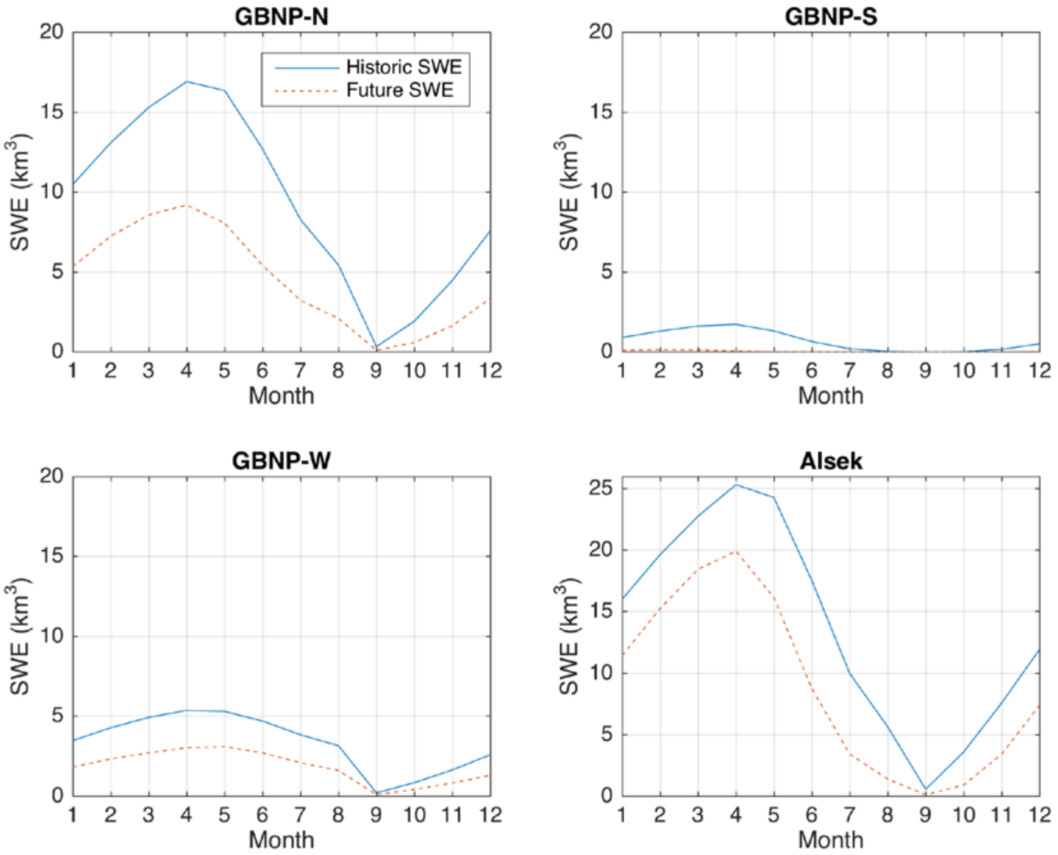

Figure 16. Seasonal climatology of stored snow-water-equivalent for the future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) and historic (1979-2015; solid line) conditions.

Future Runoff

Figure 17 compares the future seasonal hydrographs to the historic ones. Note that, in this figure, the vertical axes for the four domains have different scales, in order to best bring out the details for each domain. First, in GBNP-N, there is a dramatic change in that the broad summer peak is nearly changing to a bi-modal distribution. This is caused by a reduction in summer ice-melt and an increase in fall rains. Another notable feature is the strong increase in winter flows.

GBNP-S is a watershed that, for historic conditions, was seen to have a strong bi-modal hydrograph, lacking any significant ice melt in the summer. In the future, it is found that there will be very strong (factor of 5) increases in winter flows. Additionally, the strong historic late spring snow-melt contribution nearly disappears. As a result, the hydrograph switches to a fully rain-dominated one with a single strong peak in late autumn. GBNP-W lies somewhere in the middle. A reduction in snow-melt and increase in rainfall somewhat broaden the overall hydrograph and push its peak later in the year. However, the overall change in shape is less dramatic than for the other two domains. Finally, the Alsek hydrograph sees very considerable changes, which are different from the other domains. Here, the strong loss in summer flows is due to a combination of loss of ice-melt (although that is offset by increased rain runoff) in late summer and a loss of snowfall in early summer. There is still a strong snow-melt signature, but it is moved a full month earlier in the calendar.

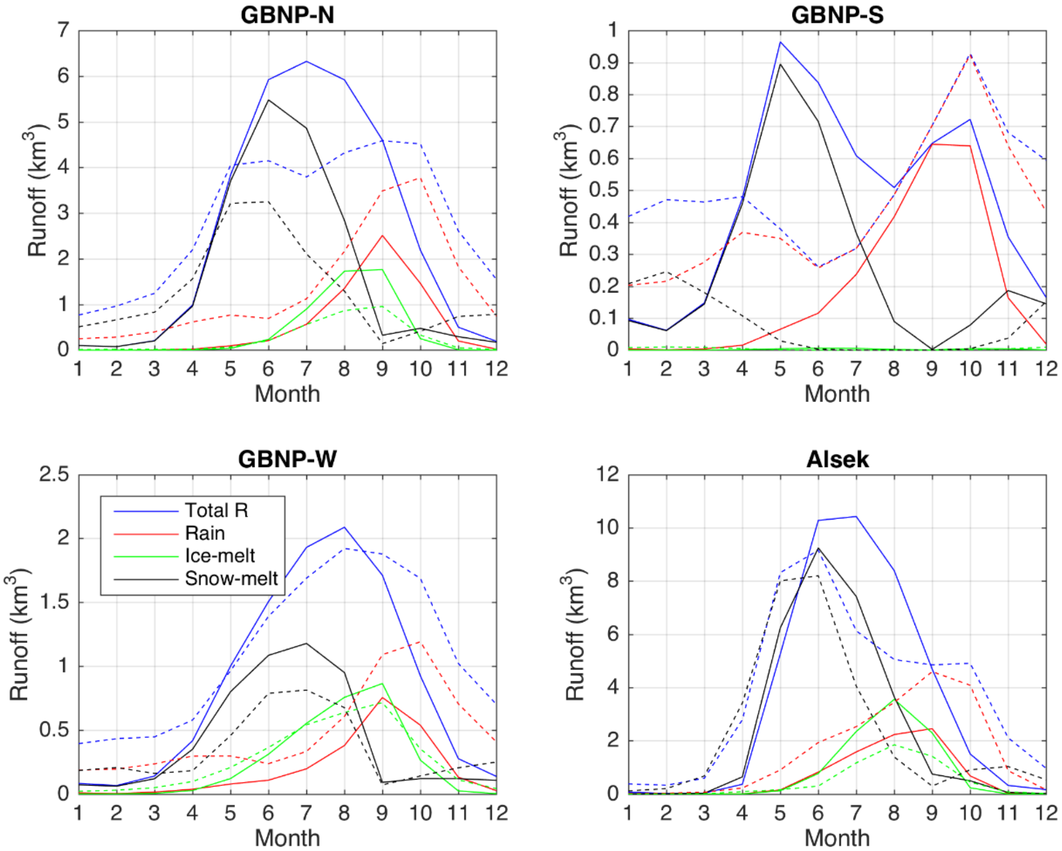

Figure 17. Seasonal hydrographs for historic (1979-2015; solid line) and future (2070-2100; dashed line) (RCP8.5 / ELA400 scenario) conditions. The total runoff R is shown as well as its constituent sources. Note the different vertical scales.

With regards to mean annual runoff volumes, the north, south, and Alsek domains are expected to have runoff increases of about 10-15%, while the west domain is found to have a runoff increase of about 25-30%.

Discussion

The results of this study provide a solid understanding of the hydrology of Glacier Bay. It is worth noting that hydrological models depend crucially upon (i) their ability to model or parameterize relevant physical processes and (ii) their input data. We believe that our choice of a physical process based model, rather than a temperature index model, is the right choice for GBNP, given the complex mix of snow and ice processes present. With regards to input data, it has been shown by previous studies (Figure 18) that historic climate reanalysis products for Alaska predict very different amounts of rainfall (and snowfall). This variability in 'forcing' to the hydrologic system results in a great deal of variability in the outputs (runoff) of the system.

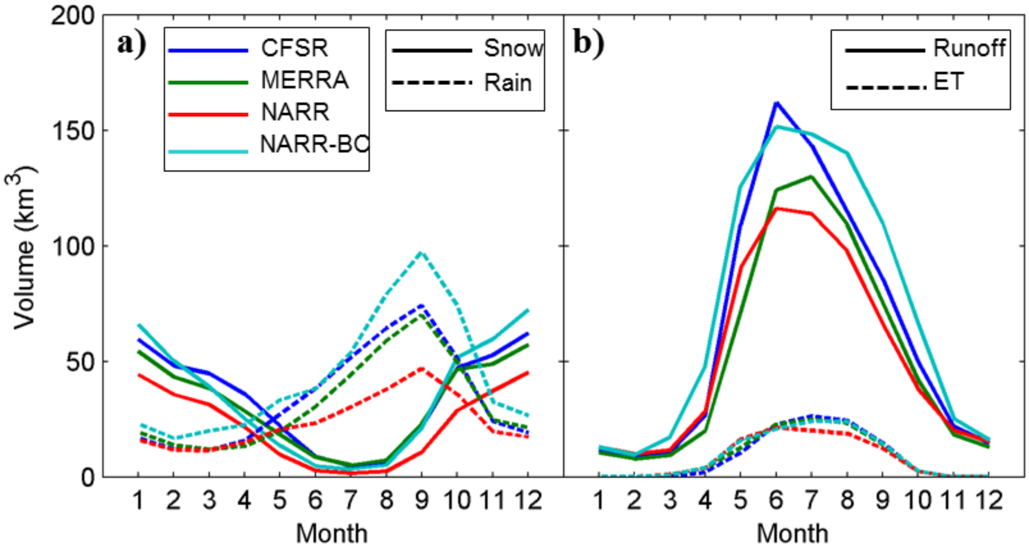

Figure 18. Precipitation inputs (a) to and fluxes (runoff, evapotranspiration) out (b) of the GOA-wide domain of Beamer et al. (2016).

In the present study, a particular weather product was selected based on previous regional-scale modeling of the GOA domain. With the lack of long-term weather data in GBNP, it is difficult to determine which weather product is locally best. To improve future modeling work of GBNP it is recommended that continual monitoring of weather data and streamflow data be carried out. These data sets will improve the performance and calibration of physical models of the Park.

Conclusions

This report has presented a comprehensive look at the hydrologic inputs to and outputs from the GBNP domain. There are spatial differences both in the historic conditions and in the response of the system to future changes in climate and land cover. Generally speaking, with changing climate will come a flattening of seasonal hydrographs. The ice melt contribution will diminish due to less glacier cover, the snow melt contribution will come earlier in the year, and moderately increasing autumn rains will sustain the hydrograph later into the year. These data should be of use to scientists looking for linkages between the physical freshwater system and the ecological system. They should also be of considerable value to physical oceanographers looking to better understand the spatial and temporal variations in the water column of Glacier Bay and surrounding coastal waters.

The data from these studies are available in a wide variety of formats and interested parties should contact the PI, Dr. David Hill at david.hill@oregonstate.edu.

Literature Cited

Beamer, J. P., D. F. Hill, A. Arendt, and G. E. Liston. 2016. “High-Resolution Modeling of Coastal Freshwater Discharge and Glacier Mass Balance in the Gulf of Alaska Watershed.” *Water Resources Research*, n/a – n/a. doi:10.1002/2015WR018457.

Etherington, L., P. Hooge, E. Hooge, and D. Hill. 2007. “Oceanography of Glacier Bay, Alaska: Implications for Biological Patterns in a Glacial Fjord Estuary.” *Estuaries and Coasts* 30 (6): 927–44.

Fellman, Jason B., Eran Hood, Peter A. Raymond, John Hudson, Maura Bozeman, and Mayumi Arimitsu. 2015. “Evidence for the Assimilation of Ancient Glacier Organic Carbon in a Proglacial Stream Food Web.” *Limnology and Oceanography* 60 (4): 1118–28. doi:10.1002/lno.10088.

Fellman, Jason B., Sonia Nagorski, Sanjay Pyare, Andrew W. Vermilyea, Durelle Scott, and Eran Hood. 2014. “Stream Temperature Response to Variable Glacier Coverage in Coastal Watersheds of Southeast Alaska.” *Hydrological Processes* 28 (4): 2062–73. doi:10.1002/hyp.9742.

Fellman, Jason B., Robert G. M. Spencer, Peter J. Hernes, Rick T. Edwards, David V. D’Amore, and Eran Hood. 2010. “The Impact of Glacier Runoff on the Biodegradability and Biochemical Composition of Terrigenous Dissolved Organic Matter in near-Shore Marine Ecosystems.” *Marine Chemistry* 121 (1–4): 112–22. doi:10.1016/j.marchem.2010.03.009.

Flint, Lorraine E, Alan L Flint, James H Thorne, and Ryan Boynton. 2013. “Fine-Scale Hydrologic Modeling for Regional Landscape Applications: The California Basin Characterization Model Development and Performance.” *Ecological Processes* 2 (1): 25. doi:10.1186/2192-1709-2-25.

Hill, D. F., N. Bruhis, S. E. Calos, A. Arendt, and J. Beamer. 2015. “Spatial and Temporal Variability of Freshwater Discharge into the Gulf of Alaska.” *Journal of Geophysical Research: Oceans* 120 (2): 634–46. doi:10.1002/2014JC010395.

Hill, D. F., S. J. Ciavola, L. Etherington, and M. J. Klaar. 2009. “Estimation of Freshwater Runoff into Glacier Bay, Alaska and Incorporation into a Tidal Circulation Model.” *Estuarine, Coastal and Shelf Science* 82: 95–107.

Hood, Eran, and Logan Berner. 2009. “Effects of Changing Glacial Coverage on the Physical and Biogeochemical Properties of Coastal Streams in Southeastern Alaska.” *Journal of Geophysical Research: Biogeosciences* 114 (G3): G03001. doi:10.1029/2009JG000971.

Huss, Matthias, and Regine Hock. 2015. “A New Model for Global Glacier Change and Sea-Level Rise.” *Cryospheric Sciences*, 54. doi:10.3389/feart.2015.00054.

Lisi, Peter J., Daniel E. Schindler, Kale T. Bentley, and George R. Pess. 2013. “Association between Geomorphic Attributes of Watersheds, Water Temperature, and Salmon Spawn Timing in Alaskan Streams.” *Geomorphology* 185 (March): 78–86. doi:10.1016/j.geomorph.2012.12.013.

Liston, Glen E., and Kelly Elder. 2006a. “A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet).” *Journal of Hydrometeorology* 7 (2): 217–34. doi:10.1175/JHM486.1.

———. 2006b. “A Distributed Snow-Evolution Modeling System (SnowModel).” *Journal of Hydrometeorology* 7 (6): 1259–76. doi:10.1175/JHM548.1.

Liston, Glen E., and Sebastian H. Mernild. 2012. “Greenland Freshwater Runoff. Part I: A Runoff Routing Model for Glaciated and Nonglaciated Landscapes (HydroFlow).” *Journal of Climate* 25 (17): 5997–6014. doi:10.1175/JCLI-D-11-00591.1.

Mernild, Sebastian H., and Glen E. Liston. 2012. “Greenland Freshwater Runoff. Part II: Distribution and Trends, 1960–2010.” *Journal of Climate* 25 (17): 6015–35. doi:10.1175/JCLI-D-11-00592.1.

Mernild, Sebastian H., Glen E. Liston, Bent Hasholt, and Niels T. Knudsen. 2006. “Snow Distribution and Melt Modeling for Mittivakkat Glacier, Ammassalik Island, Southeast Greenland.” *Journal of Hydrometeorology* 7 (4): 808–24. doi:10.1175/JHM522.1.

Mernild, Sebastian H., Glen E. Liston, and Christopher A. Hiemstra. 2014. “Northern Hemisphere Glacier and Ice Cap Surface Mass Balance and Contribution to Sea Level Rise.” *Journal of Climate* 27 (15): 6051–73. doi:10.1175/JCLI-D-13-00669.1.

Mesinger, Fedor, Geoff DiMego, Eugenia Kalnay, Kenneth Mitchell, Perry C. Shafran, Wesley Ebisuzaki, Dušan Jović, et al. 2006. “North American Regional Reanalysis.” *Bulletin of the American Meteorological Society* 87 (3): 343–60. doi:10.1175/BAMS-87-3-343.

Neal, E. G., E. Hood, and K. Smikrud. 2010. “Contribution of Glacier Runoff to Freshwater Discharge into the Gulf of Alaska.” *Geophysical Research Letters* 37 (L06404).

O’Neel, Shad, Eran Hood, Allison L. Bidlack, Sean W. Fleming, Mayumi L. Arimitsu, Anthony Arendt, Evan Burgess, et al. 2015. “Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem.” *BioScience* 65 (5): 499–512. doi:10.1093/biosci/biv027.

Paul, F., M. Maisch, C. Rothenbühler, M. Hoelzle, and W. Haeberli. 2007. “Calculation and Visualisation of Future Glacier Extent in the Swiss Alps by Means of Hypsographic Modelling.” *Global and Planetary Change* 55 (4): 343–57. doi:10.1016/j.gloplacha.2006.08.003.

Pfeffer, W. Tad, Anthony A. Arendt, Andrew Bliss, Tobias Bolch, J. Graham Cogley, Alex S. Gardner, Jon-Ove Hagen, et al. 2014. “The Randolph Glacier Inventory: A Globally Complete Inventory of Glaciers.” *Journal of Glaciology* 60 (221): 537–52. doi:10.3189/2014JoG13J176.

Priestley, C. H. B., and R. J. Taylor. 1972. “On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters.” *Monthly Weather Review* 100 (2): 81–92. doi:10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2.

Radic, Valentina, and Regine Hock. 2013. “Glaciers in the Earth’s Hydrological Cycle: Assessments of Glacier Mass and Runoff Changes on Global and Regional Scales.” *Surveys in Geophysics* 35 (3): 813–37. doi:10.1007/s10712-013-9262-y.

Reisdorph, Stacey C., and Jeremy T. Mathis. 2014. “The Dynamic Controls on Carbonate Mineral Saturation States and Ocean Acidification in a Glacially Dominated Estuary.” *Estuarine, Coastal and Shelf Science* 144 (May): 8–18. doi:10.1016/j.ecss.2014.03.018.

Rienecker, Michele M., Max J. Suarez, Ronald Gelaro, Ricardo Todling, Julio Bacmeister, Emily Liu, Michael G. Bosilovich, et al. 2011. “MERRA: NASA’s Modern-Era Retrospective Analysis for Research and Applications.” *Journal of Climate* 24 (14): 3624–48. doi:10.1175/JCLI-D-11-00015.1.

Royer, T. C. 1982. “Coastal Fresh Water Discharge in the Northeast Pacific.” *Journal of Geophysical Research* 87 (C3): 2017–21.

Saha, Suranjana, Shrinivas Moorthi, Hua-Lu Pan, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, et al. 2010. “The NCEP Climate Forecast System Reanalysis.” *Bulletin of the American Meteorological Society* 91 (8): 1015–57. doi:10.1175/2010BAMS3001.1.

Shanley, C.S., Pyare, S., Goldstein, M.I., Alaback, P.B., Albert, D.M., Beier, C.M., et al. 2015. "Climate change implications in the northern coastal temperate rainforest of North America." *Climatic Change* 130: 155-170.

Singer, Gabriel A., Christina Fasching, Linda Wilhelm, Jutta Niggemann, Peter Steier, Thorsten Dittmar, and Tom J. Battin. 2012. “Biogeochemically Diverse Organic Matter in Alpine Glaciers and Its Downstream Fate.” *Nature Geoscience* 5 (10): 710–14. doi:10.1038/ngeo1581.

Wang, J., M. Jin, D. Musgrave, and M. Ikeda. 2004. “A Hydrological Digital Elevation Model for Freshwater Discharge into the Gulf of Alaska.” *Journal of Geophysical Research* 109.

Weingartner, Thomas J., Seth L. Danielson, and Thomas C. Royer. 2005. “Freshwater Variability and Predictability in the Alaska Coastal Current.” *Deep Sea Research Part II: Topical Studies in Oceanography*, U.S. GLOBEC Biological and Physical Studies of Plankton, Fish and Higher Trophic Level Production, Distribution, and Variability in the Northeast Pacific, 52 (1–2): 169–91. doi:10.1016/j.dsr2.2004.09.030.

NPS 132/137845, April 2017

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov