Impacts of Forecasted Climate Change on Snowpack, Glacier Recession, and Streamflow in the Nooksack River Basin

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1. Introduction and Objectives

The Nooksack River drains an approximately 2000 km^2 watershed in the North Cascades in Whatcom County, Washington (Figure 1) and is a valuable freshwater resource for regional Tribes, municipalities, industry, and agriculture, and provides critical habitat for endangered salmon species. Nooksack River streamflow is largely influenced by precipitation and snowmelt in the spring, and glacial melt throughout the warmer summer months when precipitation is minimal. Mt. Baker has the largest contiguous network of glaciers in the North Cascades, including 3400 hectares in the Nooksack basin (Pelto and Brown, 2012; Figures 2 & 3).

Concern has grown over the effects that climate variability and change might have on glaciers, snowpack, and water resources in general in the Nooksack basin. Regional climate projections through the end of the 21st century indicate an increase in average annual air temperature, a decrease in summer precipitation, and an increase in winter precipitation. We employ publically available statistically derived gridded surface data and numerical modeling techniques to simulate the effects of forecasted climate change on the Upper Nooksack River with an emphasis on late summer low flows. Here, we focus on changes in streamflow, snowpack, and glacier melt contribution to streamfow throughout the 21st Century.

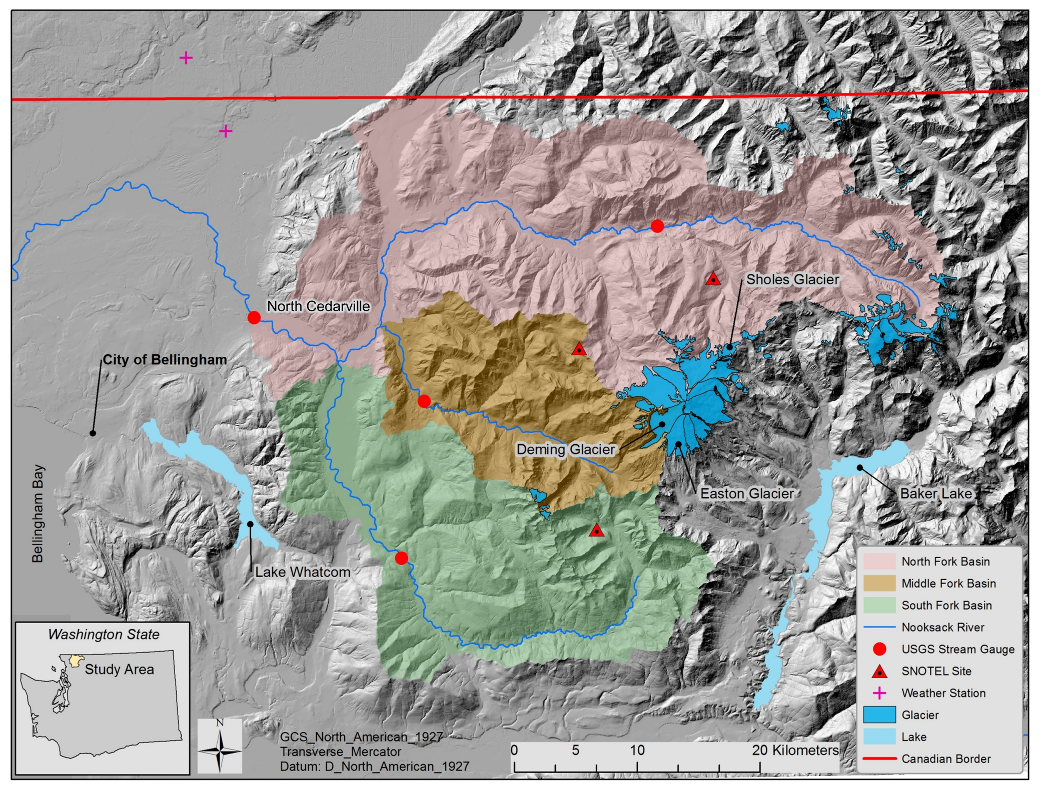


Figure 1. Location of the North, Middle, and South Fork basins in the upper Nooksack River watershed, northwest WA State.

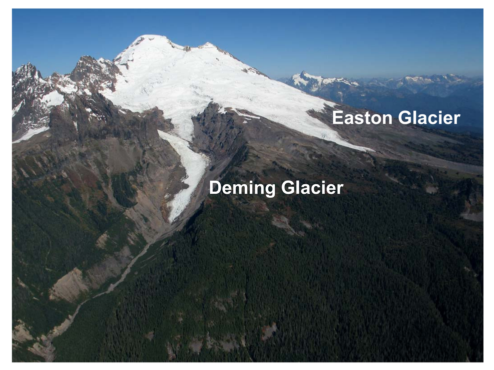


Figure 2. Mt. Baker and the Deming and Easton Glaciers (photo by John Scurlock).

Figure 3. Coleman Glacier terminus in the North Fork Nooksack basin (photo by John Scurlock).

2. Climate Inputs

Historical Forcings for Calibration

The ultimate goal of our project was to assess the impacts of climate change on Nooksack basin hydrology using the Distributed Hydrology Soil Vegetation Model (DHSVM) version 3.2 with an integrated glacier dynamics model (Clarke et al., 2015). Due to a lack of spatially distributed long-term historical weather observations in the basin, we applied publically available statistically derived gridded surface data developed by Livneh et al. (2013; Figure 4) to calibrate the model. The advantage of the Livneh data, is that it is gridded at the same resolution as the future climate grid and was used to train the future forcings data set that we apply for simulations throughout the 21st Century.

The Livneh dataset was created by incorporating daily observations from National Weather Service Cooperative Observer stations across the USA and monthly precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; PRISM Climate Group). Temperatures are adjusted with elevation using a 6.5ºC/km lapse rate. The resulting daily data includes minimum and maximum temperature, precipitation, and wind speed from 1950-2011. For this project, the Livneh grids were disaggregated to 3-hr time-steps for use in the DHSVM.

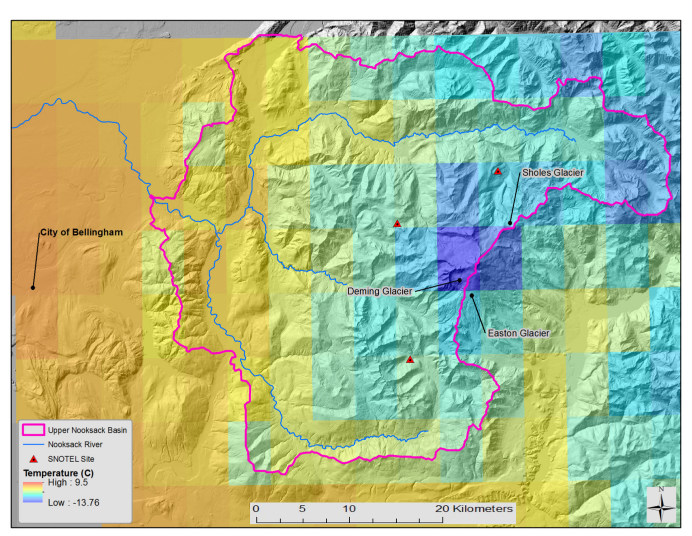


Figure 4. Example of Livneh/MACA grid resolution in the upper Nooksack basin.

Bias Correction

A cold bias was noted in the Livneh grid when compared to modern PRISM normals (1981-2010). A delta method correction was applied to all Livneh cells within each of the three sub-basins to adjust to the PRISM temperature normals. A precipitation bias was also identified in the Linveh data; in some locations, lower elevation cells showed a considerably higher precipitation than those at higher elevations. A correction was applied by incorporating a monthly precipitation correction factor derived using observed precipitation and elevation relationships between the nearby Abbotsford weather station and the basin SNOTEL sites. In the Middle Fork basin, precipitation correction was not required and uncorrected Livneh data was used for precipitation inputs.

Future Climate Forcings

Future simulations were forced with downscaled climate projections developed using the multivariate adaptive constructed analogs method (MACA; Abatzoglou and Brown, 2011). The MACA downscaled data incorporates 20 general circulation models (GCMs) of the CMIP5 using RCP4.5 and RCP8.5 forcing scenarios and uses the Livneh meteorological grids for the training dataset. For this project, the 10 GCMs most suitable for the Pacific Northwest were used as future climate forcings (Rupp et. al., 2013). Bias corrections that were applied to the Livneh historical meteorology were also applied to the MACA future climate grids to maintain consistency.

3. Modeling Tools

Distributed Hydrology Soil Vegetation Model

The DHSVM developed at the University of Washington and Pacific Northwest National Laboratory, uses meteorological and spatially distributed physical data to simulate a water and energy balance at the pixel scale of a digital elevation model (Figure 5; Wigmosta et al., 1994). The model predicts snowpack evolution, evapotranspiration, soil infiltration and storage, saturated subsurface flow, and surface runoff, for each pixel over a user-defined time step.

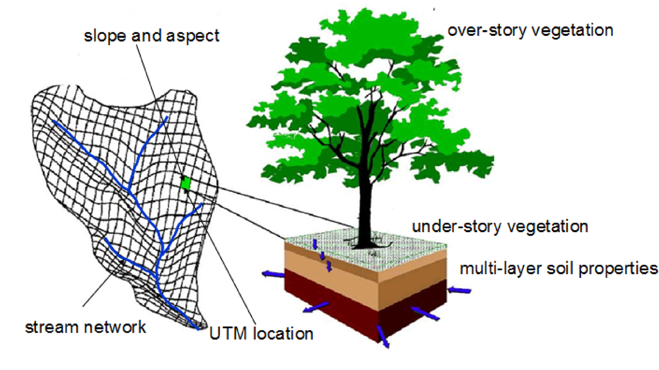


Figure 5. Conceptual model of DHSVM structure (from Wigmosta, et al., 1994).

DHSVM Setup

Physical model inputs (Figure 6) to the DHSVM include a stream network and the following 50-meter resolution GIS data sets:

- Digital Elevation Model (USGS)
- Soil Thickness (generated in ArcInfo AML)
- Soil Type (STATSGO database)
- Landcover/Glaciers (NOAA Landsat/GLIMS)
- Stream Network (generated in ArcInfo AML)
- Solar/Shadow Map (generated in ArcInfo AML)

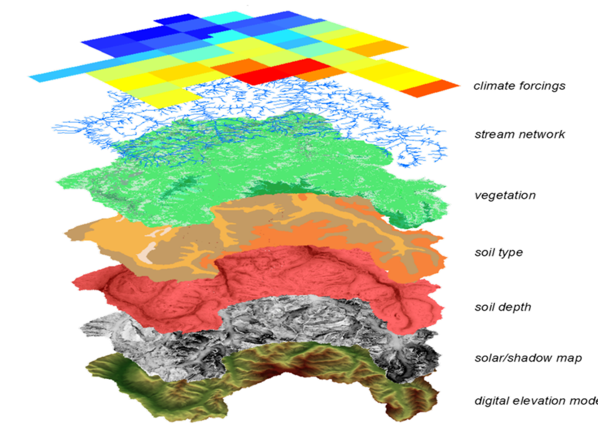


Figure 6. Input grids for the DHSVM.

Glacier Dynamics Model

A recently developed glacier dynamics model is integrated into the DHSVM (Naz et al., 2014). On a monthly time step, the glacier dynamics model estimates the (Figure 7):

- Mass balance (ice accumulation and ablation) for each grid cell covered with a glacier.
- Flow of ice as determined by the surface mass balance fluctuations.
- Updated thickness and extent of glacier ice in response to the simulated dynamic ice flow.

Glacier ice melt contribution to streamflow can be estimated by subtracting the stream discharge results of a simulation with no glacier from one incorporating glacial processes.

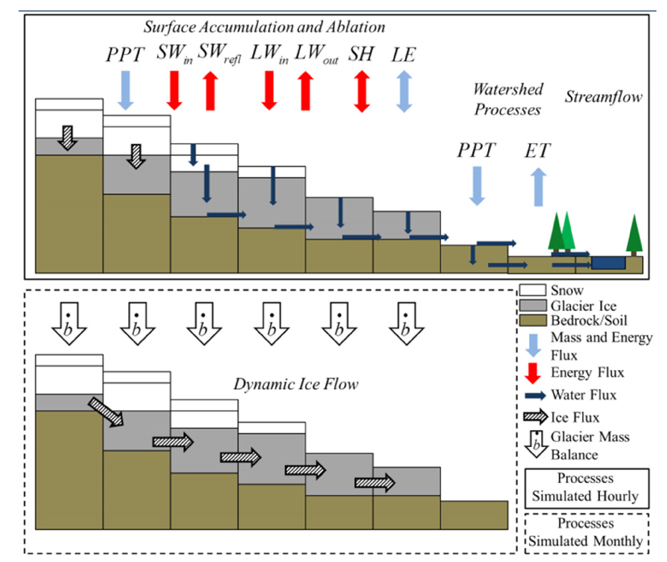


Figure 7. Glacier model processes (Naz et al., 2014).

4. Calibration and Historical Results

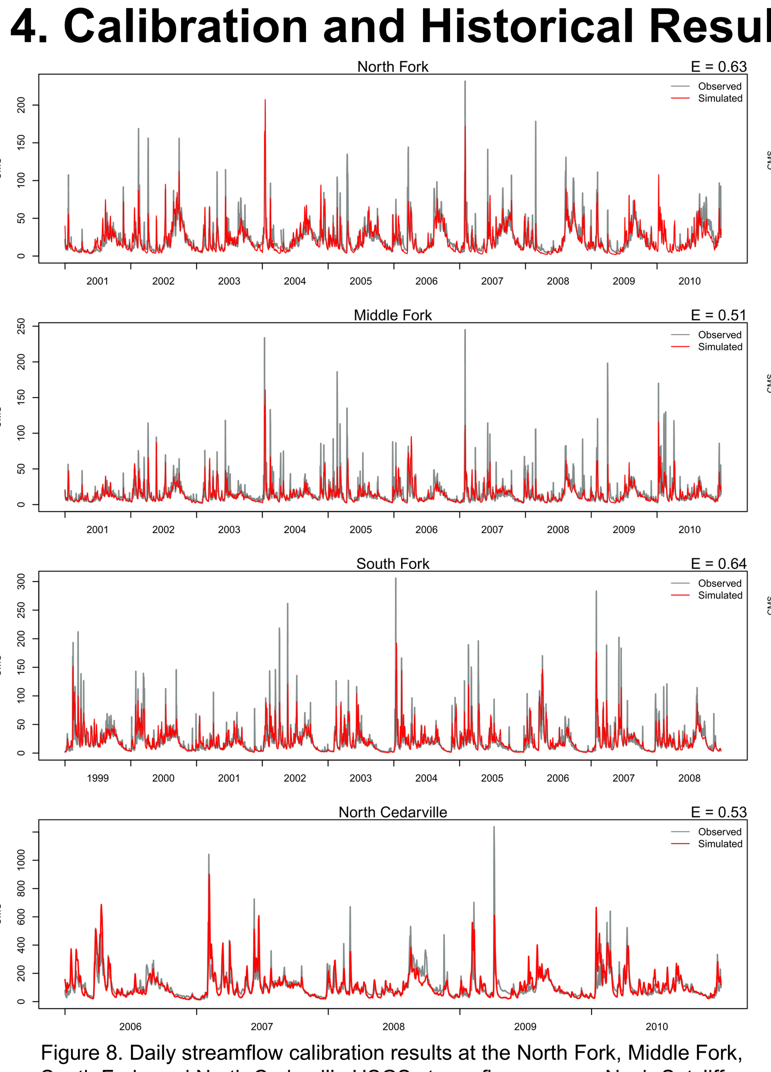


Figure 8. Daily streamflow calibration results at the North Fork, Middle Fork, South Fork, and North Cedarville USGS streamflow gauges. Nash-Sutcliffe efficiency scores are shown in the upper right of each plot.

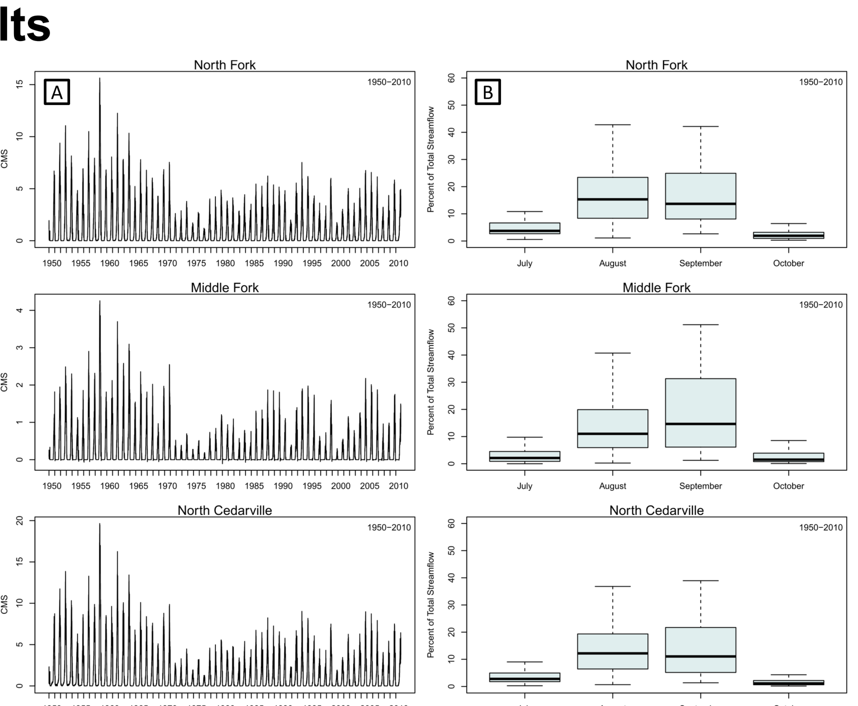


Figure 9. (A) Modeled daily glacier melt contribution magnitudes for the 60-yr (1950-2010) historical simulation for all three sub-basins. (B) Modeled daily glacier melt contribution to streamflow for summer months for the 60-yr (1950-2010) historical simulation.

Calibration Summary

Modeled streamflow was generally well captured with Nash-Sutcliffe efficiencies (E) > 0.5 (Figure 8; Nash and Sutcliffe, 1970). Modeled historical ice melt indicates that glaciers provide a significant source for summertime streamflow in the Middle and North Fork basin (Figure 9). However, the calibrated glacier ice extent was over-simulated in some areas, particularly in the lower elevations in the North Fork basins on Mount Baker (Figure 10).

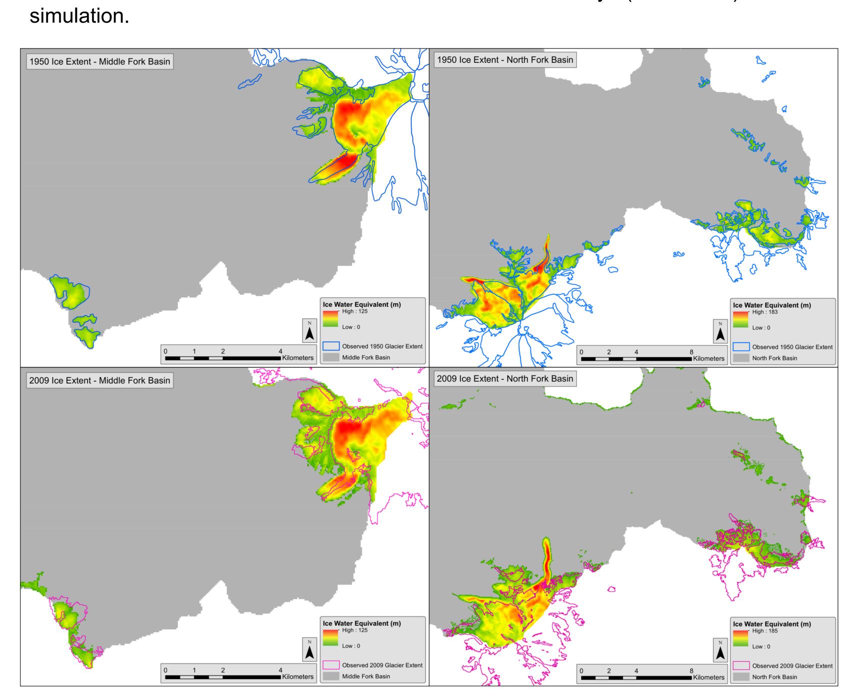


Figure 10. Ice thickness and ice extent produced by model spinup (top plots) and the resulting ice thickness and extent after a 60-yr historical calibration simulation (bottom plots). Estimated 1950 and 2009 historical observed ice extent is shown in blue and pink respectively.

5. Future Forecasted Results

Glacier Melt

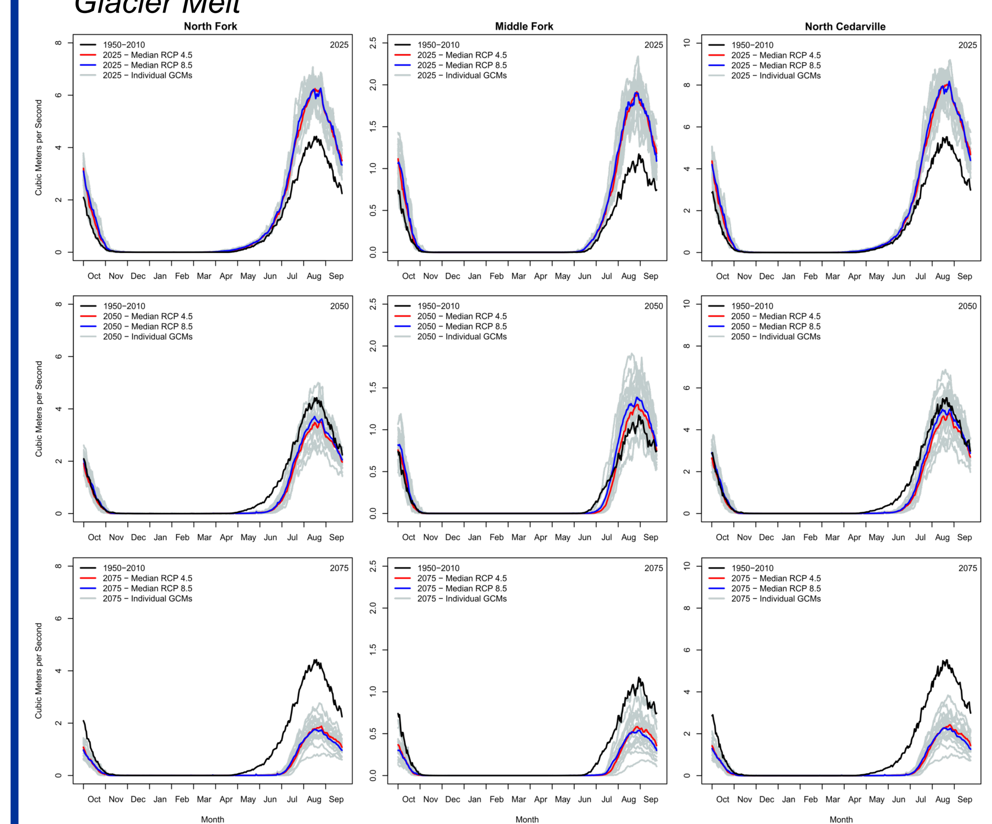


Figure 11. Modeled 30-year median daily glacier ice melt centered on 2025, 2050, and 2075 for RCP 4.5 (red) and 8.5 (blue) scenarios in the North and Middle Fork basins and North Cedarville. Historical (1950-2010) median daily ice melt is shown in black. 30-yr normal flows for individual GCMs are shown in gray.

Snow Water Equivalent

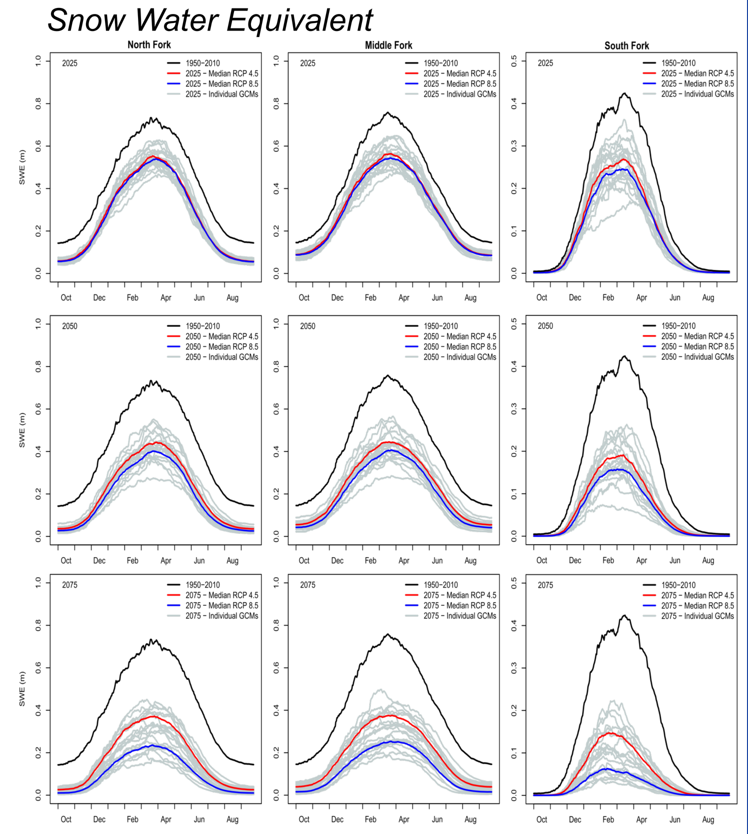


Figure 12. Modeled 30-year median daily snow water equivalent (SWE) centered on 2025, 2050, and 2075 for RCP 4.5 (red) and 8.5 (blue) scenarios. Historical (1950-2010) median daily SWE is shown in black. 30-yr normal SWE magnitudes for individual GCMs are shown in gray.

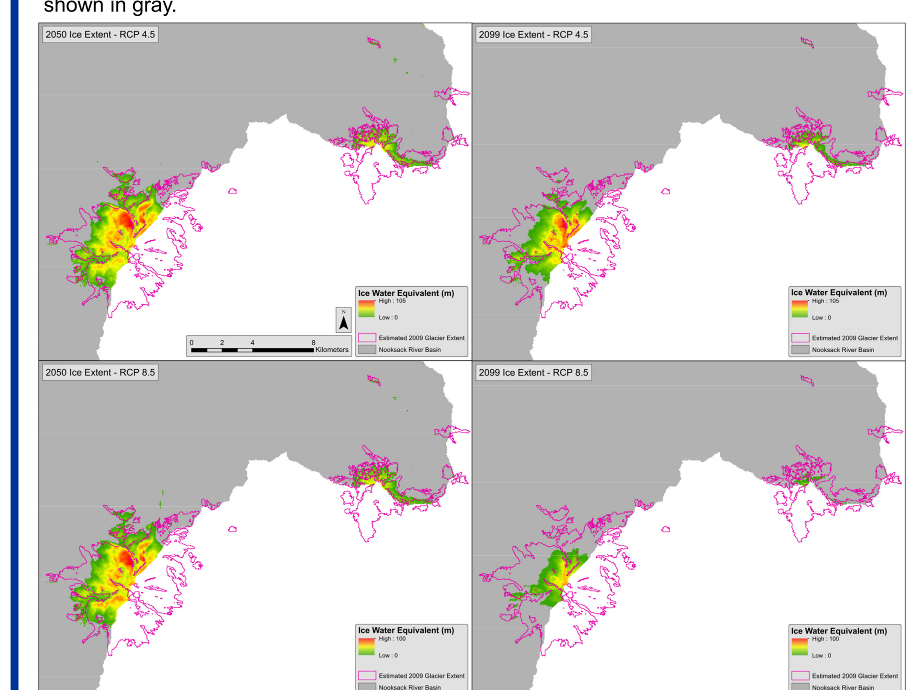


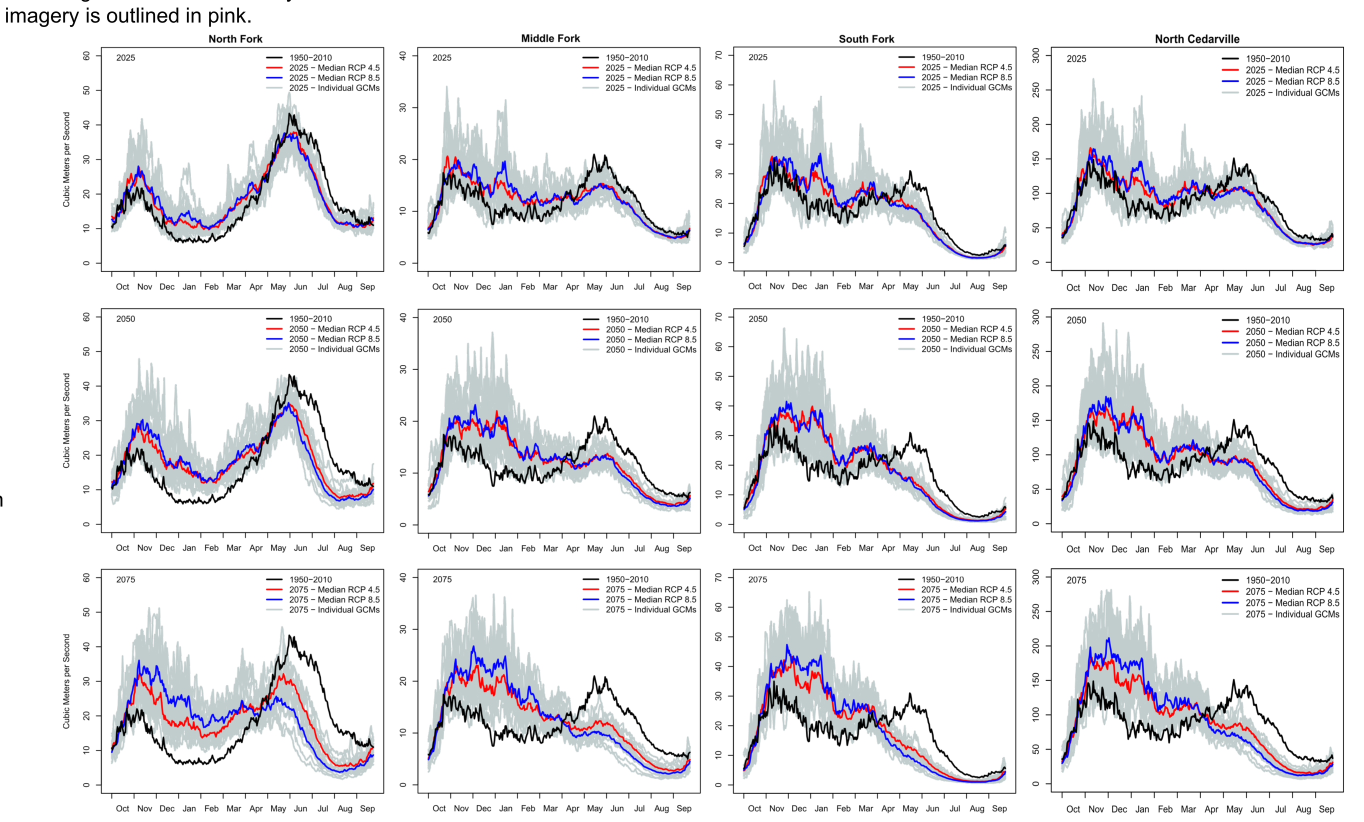
Figure 13. Modeled Nooksack River basin mean ice water equivalent and ice extent for the RCP 4.5 (top figures) and RCP 8.5 (bottom figures) GCM ensembles for 2050 (left figures) and 2099 (right figures). Each mapped ice extent is the average of the 10 ice thickness rasters produced by the model throughout the 21st Century under each GCM. Estimated 2009 ice extent from Landsat imagery is outlined in pink.

	Month	1950-2010	RCP 4.5 2025	RCP 8.5 2025	RCP 4.5 2050	RCP 8.5 2050	RCP 4.5 2075	RCP 8.5 2075
North Fork	May	0%	1%	1%	0%	0%	0%	0%
	Jun	1%	2%	2%	0%	0%	0%	0%
	Jul	4%	12%	13%	7%	9%	2%	4%
	Aug	16%	51%	51%	39%	47%	29%	38%
	Sep	16%	42%	44%	32%	37%	21%	23%
	Oct	2%	8%	9%	4%	5%	2%	2%
Middle Fork	May	0%	0%	0%	0%	0%	0%	0%
	Jun	0%	0%	0%	0%	0%	0%	0%
	Jul	2%	4%	4%	1%	2%	0%	0%
	Aug	12%	25%	27%	22%	28%	12%	17%
	Sep	16%	33%	32%	27%	32%	17%	19%
	Oct	2%	4%	4%	2%	3%	1%	1%
North Cedarville	May	0%	0%	0%	0%	0%	0%	0%
	Jun	1%	1%	1%	0%	0%	0%	0%
	Jul	3%	5%	6%	3%	4%	1%	1%
	Aug	13%	26%	27%	19%	24%	12%	16%
	Sep	13%	23%	23%	17%	20%	10%	12%
	Oct	1%	3%	3%	1%	2%	1%	1%

Table 1. Modeled percent of monthly median streamflow component derived from glacier ice melt for the North and Middle Fork basins and North Cedarville for historical and RCP 4.5 and 8.5 future scenarios. Historical melt component is a monthly median representing a 60-year simulation period from 1950-2010. Future results represent 30-year medians centered on 2025, 2050, or 2075.

Streamflow

Figure 14 (right). Modeled 30-year median daily streamflows centered on 2025, 2050, and 2075 for RCP 4.5 (red) and 8.5 (blue) scenarios. Historical median daily flows (1950-2010) are shown in black. 30-yr normal flows for individual GCMs are shown in gray.



Summary

Modeled estimates of historical glacier melt indicate a significant melt component in the late summer months (10-15% of total streamflow; Figure 9). We project an increase in total percent of streamflow derived from ice melt throughout the first half of the 21st Century with a decrease back to near historical levels by 2075 (Table 1). Similarly, the magnitude of ice melt is projected to increase throughout the first half of the 21st Century but decrease to approximately half of historical levels by 2075 as glacier area and volume decreases (Figures 11 & 13). Snowpack is modeled to decrease substantially by 2025 and continue decreasing as transitional elevations become rain rather than snow dominated, leading to reduced spring snowmelt runoff and increased winter streamflow (Figures 12 & 14). Late summer streamflows are expected to decrease as well, with glacier melt playing an important role in sustaining summer baseflows as snowpack is reduced.

Acknowledgements

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