UNIVERSITY of WASHINGTON

Hydrologic Impacts of Climate Change in the Skagit River Basin

Christina Bandaragoda, Chris Frans, Erkan Istanbulluoglu
Crystal Raymond and Larry Wasserman

Final report prepared for:
Skagit Climate Science Consortium, Mt Vernon, WA
Seattle City Light, Seattle, WA
12/31/2015

Watershed Dynamics

This project has been supported in part by the Skagit Climate Science Consortium, a 501 c(3) nonprofit comprised of a group of member research scientists from federal, state, municipal, tribal, university, and non-governmental organizations who work in the Skagit basin.

This project has been funded in part by the Climate Change Research Initiative, Seattle City Light, a public utility that serves the City of Seattle.

This project has been funded in part by the United States Environmental Protection Agency under Assistance Agreement to the Swinomish Indian Tribal Community and to the Sauk-Suiattle Indian Tribe. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Section D of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Special thanks is due to Jon Riedel for providing the North Cascades glacier mass observations, feedback and review over the course of the project; Andrew Fountain for providing historic glacier extent GIS data; Bart Nijssen for coordinating the use of meteorological data from the Integrated Scenarios Project, computing resources, and review over the course of the project; Matt Stumbaugh and Alan Hamlet for providing streamflow projections from Skagit River Lowlands Low Flow Study to integrate with results from this report and for review of the study design and report; and Claire Beveridge for review of this report.

Executive Summary

The focus of the *Hydrologic Impacts of Climate Change in the Skagit River Basin* study is to improve our understanding of the hydrology of the Skagit River system using a coupled glacio-hydrology model and develop projections of naturalized streamflow at Skagit River Hydroelectric Project reservoir locations (Ross, Diablo, Gorge) and at sixteen tributaries using future climate change scenarios. Our methods and scope of work for generating future streamflow projections are a reflection of the collaboration between Seattle City Light, Swinomish Indian Tribal Community, and the Sauk-Suiattle Indian Tribe administered by contracts with the Skagit Climate Consortium (SC2) and between SC2 and the University of Washington (UW). This project utilized data products from the *Integrated Scenarios of the Future Northwest Environment* project, which identified a core set of 10 global climate models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP5; Mote et al., 2015) as the best performing models based on comparisons of observed 20th century climate of the Pacific Northwest. To simulate streamflow, we used the Distributed Hydrology Soil Vegetation Model (DHSVM) – a coupled glacio-hydrology model. The model domain included the entire Skagit River basin at 150m digital elevation model (DEM) resolution, with nested models of 50m resolution of selected subbasins (Thunder Creek and Cascade Creek) that have the major glacier ice cover at their high elevations. The modeling steps included: (a) spin up of the glacier model to develop realistic glacier cover in the glaciated uplands prior to watershed hydrology and streamflow predictions; (b) calibration of DHSVM using select model parameters and climate forcing bias correction in select subbasins; (c) model validation using historical streamflow observations; (d) projections of streamflow into the future using CMIP5 models; (e) bias-corrections of modeled streamflow to match observations based on monthly mean and (f) low-flow corrections of modeled streamflow to match 90% exceedance probability flows in summer months. The glacio-hydrology model was calibrated using historical meteorological data and observed ice extent using the time frame of 1960-2010.Validation and corrections to the glacio-hydrology model were conducted using empirical data (collected by North Cascades National Park), naturalized flows at reservoir locations (three reservoirs), and observed stream gauges (where and when available at 16 Skagit River tributaries). Future projections were calculated using GCMs for multiple thirty year periods starting from 2010 to 2099.

Our analysis focused on locations and statistics that are applicable for multiple uses in climate change adaptation— planning for hydroelectric project operations for instream flows and hydropower generation along with prioritization of locations for salmon restoration. In this report we highlight changes applicable to mid-century planning (2050). In glaciated high elevation basins, the current conditions of approximately 100 km^2 of glacier ice are projected to decrease to less than 50 km^2 by 2050. If global emissions stop increasing by 2040, it is likely that the highest elevation glaciers will continue to store pockets of ice and provide some glacier melt in the summer months. If emissions are not reduced, most models project that Skagit glaciers will disappear by the end of the century. In snow dominated high

elevation basins, high flows are projected to increase by 2050 , with the frequency of high flows extending from the current November timing, into December, January and February. By 2050, the low flows will show a wide range of change conditioned on elevation. Low summer flows (August 90% Exceedence probability) are projected to change the least (-10%) in low-elevation rain-dominated tributaries, (e.g., Red Cabin Creek). Low summer flows are projected to change the most (-60% to -80%) in mid-elevation mixed rain and snow tributaries (e.g., South Fork Sauk). Processing of model outputs was done to faciliatate further analysis by partner organzitions beyond the scope of this project and will be made available online via the UW libaries ResearchWorks archival service (data publications pending coauthor review).

Contents

Definitions

High streamflow: any river overflow that causes or threatens damage. This may be measured with recurrence interval statistics such as the 1:100 year flood, 1:10 year flood, or peak flows given annual intervals or monthly observations. High flows may also be considered given the probablity that a streamflow level will exceed a given amount relative to observations in a river or stream reach, such as the 10% exceedence probability.

Low streamflow: any river flow that causes or threatens damage, usually due to lack of water volumes expected for irrigation or municipal supplies, or instream flow levels requires for fish habitat. The impact of low flow varies seasonally. Low flows may be measured with recurrence interval statistics such as the 7Q10, which is the 1:10 year low flow over a seven day average. Low flows may also be considered given the probablity that a streamflow level will be lower than a given amount relative to observations in a river or stream reach, such as the 90% exceedence probability.

Recurrence interval: also known as the return period or repeat interval, is an estimate of the likelihood of an event based on the number of years on record and the number or recorded occurences of an event. For streamflow recurrence intervals, maximum flows and minimum flows are selected for each year on record. A statistical relationship is used to predict the expected frequency of an event in an annual period.

Exceedance probability: also known as the flow duration, uses daily streamflow data to calculate the probability that specific streamflow values have been exceeded over a given time interval. A 10% exceedence probability represents a high flow that has been exceeded only 10% of all days in a 30 year period (for example). A 90% exceedence probability represents a low flow that has been exceeded 90% of all days in a period. These probabilities can be calculated for each month in the record and are useful for comparing daily streamflows characteristics between various historic and future time periods. Non-exceedance probability is also known as the cumulative frequency analysis.

Projection: a forecast of future climate or modeled streamflow based on future climate conditions. Although synonyms such as 'forecast' and 'prediction' are commonly used to define future model simulations, we use 'projection' to maintain a clear link of model outputs to the climate model inputs used to force the hydrology model. Outcomes of this study do not imply specific knowledge of future conditions beyond the model framework and assumptions described in this report.

Snow-dominated: sub-basins where surface runoff is produced from melting snow, generally resulting in single peak monthly streamflow hydrograph in the spring season.

Rain-dominated: sub-basins where surface runoff is produced from rainfall, generally resulting in single peak monthly streamflow hydrograph in the fall season.

Mixed rain and snow: sub-basins where surface runoff is produced both from rainfall and melting snow, generally resulting in two peaks in the monthly streamflow hydrograph in the fall and spring season.

Background

The Skagit River is the largest stream that drains into Puget Sound, providing ~20% of its fresh water inflows, and is the third largest river on the West Coast. The Skagit River originates in Canada, flows 160 miles through the North Cascades National Park, and drains 3,130 mi^2 of the most extensively glaciated watershed in the contiguous US. The water resources of the Skagit River support the Skagit Hydroelectric Project, which generates 20% of the power for the City of Seattle; salmon habitat for fish species listed under the Endangered Species Act; one of the largest and most diverse agricultural communities in western Washington; and diverse uses and ecological functions in a coastal floodplain. Between the basin's lowest elevations at the Pacific Ocean to its highest elevations at the crest of the Cascade mountains, strong temperature and precipitation gradients create complex hydrologic, snow, and glacier dynamics. To develop future management and resource protection plans, projections of future streamflows are needed to 1) inform and define reservoir operations for hydropower production and regulate low and high flows for salmon habitat, and 2) characterize the impacts of climate change and land management on both low flows and flood frequency and magnitude within salmon-bearing areas (i.e. glaciated tributaries, deltas, agricultural lands, and urban zones). A modeling study is developed here to project and investigate the impacts of climate change on the hydrologic response of streamflows across the Skagit River Basin with a focus on both glaciated and salmon-bearing tributaries. Further analysis of modeled and projected flows in the portion of the watershed dominated by agricultural and urban land uses is recommended for future work.

Project Collaborators

The *Hydrologic Impacts of Climate Change in the Skagit River Basin* project was designed and executed in collaboration between the University of Washington (UW) Civil & Environmental Engineering Watershed Dynamics Group and the Skagit Climate Science Consortium (SC2) by building on the joint efforts of SC2, Seattle City Light (SCL), the Swinomish Indian Tribal Community (SITC), and the Sauk-Suiattle Indian Tribe (SSIT). In a prior project, in collaboration with the UW Land Surface Hydrology Research Group and University of British Columbia (UBC), the UBC glacier dynamics model (Jarosh et al., 2013; Clark et al., 2015) was coupled with the Distributed Hydrology Soil Vegetation Model (DHSVM). In this project, the coupled glacio-hydrology model (Naz et al., 2014; Frans et al., 2015) herein referred to as DHSVM, has been used.

SC2 is a multidisciplinary group of scientists from universities and federal, municipal, and tribal governments and agencies working in the Skagit Basin (www.**skagitclimatescience**.org). In this report, we describe the modeling of glaciers and streamflow undertaken in SC2 collaborative projects from 2014-2015, with a project scope limited to highlighting the hydrologic impacts of interest to SCL, SITC, and SSIT.

Project Scope

This collaboration was executed under the scientific advisement of the SC2. United States Geological Survey (USGS) and National Park Service data (Reidel and Larrabee, 2015) and UW modeling resources were leveraged for the study. The goal of this study was to meet unique but complimentary requirements of project partners including SCL, SITC, and SSIT. SCL required streamflow projections with the following characteristics: 1) use of the DHSVM dynamic fine-scaled glacio-hydrology model driven by the most recent (CMIP5) climate modeling products, 2) representation of glacier dynamics and runoff, and 3) bias corrections of streamflow output for use in a reservoir operations model. SITC and SSIT were interested in streamflow projections sufficient to assess the consequences of long-term changes in streamflow to salmon habitat in the Skagit River basin and salmon bearing tributaries downstream of reservoirs.

This report is designed in eight sections. First we present the source of the climate data used in modeling (Section 1), followed by procedures used for correcting inconsistencies in the climate forcing data (Section 2), and time periods used for the climate change assessment (Section 3). Section 4 describes the DHSVM glacio-hydrology model, calibration for modeling fluctuations of glacier area and mass that are consistent with observations, and projections of future glacier extent and volume. In Section 5, the streamflow calibration and model testing and projected future streamflow are presented for one of the twenty locations, using the tributary area between the Newhalem to Marblemount gages for illustration. Finally, the projected streamflow results for reservoir management (Section 6) and for restoration planning (Section 7) are presented and are followed by conclusions in Section 8.

1. *DHSVM glacio-hydrology modeling of historic and future climate inputs*

1.1 HISTORIC CLIMATE FORCING

Historical hydrologic model simulations were conducted to calibrate the hydrologic model and develop baseline historical hydrologic conditions necessary to detect and quantify the impacts of projected climate change. The historic meteorological data for the Skagit River Basin are a subset from a regional dataset developed using approximately 20,000 National Climatic Data Center (NCDC) stations across the continental United States (Livneh et al., 2013), gridded to 211,687 points at a 1/16 degree spatial resolution (~6km), from January 1, 1915 to December 31, 2011. To represent the climate forcing in the Canadian portion of the basin, a smaller number of Enviro-Can stations are used (which do not appear to include the Abbotsford International Airport station). Referred to as 'Livneh data' in this report, this gridded climate forcing dataset includes daily temperature (minimum and maximum daily), precipitation, and wind speed. The Skagit basin area contains more than 300 Livneh data points. We selected this dataset as it is used as historical training data to downscale an ensemble of global climate model outputs of the Coupled Model Inter-Comparison Project 5 (CMIP5) using the Multivariate Adaptive Constructed Analogs (MACA) statistical downscaling methods (Abatzoglou and Brown, 2011) as part of the Integrated Scenarios of the Northwest Environment project (http://pnwcirc.org/projects/integrated-scenarios/). The historical dataset and downscaled future projections allowed us to run model simulations for 185 years (1915-2099). Solar radiation is calculated as follows: The Skagit basin area contains more than 300 Livneh data points. Solar radiation, longwave radiation, and relative humidity were calculated in preprocessing steps following Thornton and Running (1999) and Bohn et al. (2013). The hydrology model was run with a 150m grid resolution for the whole watershed and a finer 50m-resolution was used in Thunder creek and Cascade River, where glacial contributions are relatively significant compared to other areas in the Skagit. The meteorological forcing data from the 1/16 degree (~6 km) resolution have been interpolated to finer DHSVM hydrologic model resolutions.

During concurrent studies using DHSVM in the Skagit River Basin and other North Cascade glaciers, we discovered both temperature and precipitation biases in the Livneh dataset. In regions of high landscape relief and low station density, temperature of the Livneh data had significant cold biases as compared to the PRISM 1981-2010 climate normals. The monthly delta bias correction procedure (compares absolute differences between Livneh and PRISM) was conducted to match the mean monthly temperature in the Livneh data with the mean monthly temperature of the 800m-resolution PRISM data for the time period 1981-2010 (http://www.prism.oregonstate.edu/normals/). This monthly bias correction leads to spatially varying delta factors for each month, which were used to correct daily temperature time series of the

Livneh data. While we found that the Livneh data gives consistent precipitation amounts over large areas, we have seen problems with respect to distribution of the precipitation data with elevation when compared to local observations. To improve the spatial variability of the Livneh precipitation product we tested precipitation elevation correction factors obtained from PRISM to interpolate the Livneh precipitation data (~6 km) to the model element grid resolution (30-150m), but found consistent results using precipitation multipliers. Both temperature and precipitation bias correction methods used in this project are explained in Frans (2015). Future work should assess the bias of climate forcing datasets developed using PRISM, such as the most recent 1950-2013 dataset (Livneh et al., 2015) which is an area of active research (Henn, 2015; Gutmann, et al. 2012).

1.2 Future climate forcing

Although several hundred different climate model outputs have been used in the CMIP5 project, not all of them have daily outputs of all the necessary variables for hydrologic modeling applications (i.e., minimum/maximum temperature, precipitation, wind). This project utilized data products from the *Integrated Scenarios of the Future Northwest Environment* project (Integrated Scenarios Project) of the Climate Impacts Research Consortium (Mote et al., 2015). Rupp et al. (2013) published an evaluation of CMIP5 climate simulations of a subset of 41 GCMs that produce suitable climate variables for hydrologic modeling using various metrics to assess the performance of the GCMs for the Pacific Northwest. They identified a core set of 10 global climate models (GCMs) as the best performing models among a set of 20 GCMs that were compared to observed 20th century climate of the Pacific Northwest and surrounding area. One of the outcomes of the Integrated Scenarios Project was the future data generated using the MACA statistical downscaling method or 'MACA data', which uses historical training data (1950-2005), and greenhouse gas emissions daily outputs of the available CMIP5 GCMs for two future scenarios (2006-2100) (see Figure 2 and description of future scenarios RCP 4.5 and RCP 8.5 later in this section). Abatzoglou and Brown (2012) describes the statistical downscaling methods used. In this study, we used MACA data for the 10 optimal GCMs used as the meteorological forcing data. For the projection of future streamflow in the Skagit River Basin, we used (and would recommend using) all available information, as is suggested in Rupp et al. (2013) and developed in Mote et al. (2015), to explore agreement between GCMs. Projections made using an ensemble of GCMs should be done with the consideration that the ability of a GCM to predict the past well may or may not be an indication of its ability to predict the future well; ongoing work is assessing the ability of each GCM to represent major global weather patterns (e.g., jet stream).

Figure 1 illustrates the 'Chain of Models' required in the collaborative effort to link global emissions scenarios to an assessment of hydrologic impacts for us in watershed management. The chain starts at the upper left (black) with global climate data available in a grid on a scale of approximately 100-300 km (CMIP5). This information is used in the MACA algorithms to downscale climate forcings to a 1/16 degree (~5 km) grid cell size (green; collaborative work by Oregon State University and the University of Idaho). We (UW; yellow) use the DHSVM-glacier model (collaborative model development by UW and University of British Columbia; Naz et al et al., 2014; Frans et al. 2015) to generate streamflow predictions at Skagit River reservoirs, gages, and other tributary locations. The locations with model outputs were identified by SCL, SSIT, and SITC (19 total) and include salmon bearing tributaries below the reservoirs (Appendix A; Figures A1-A3). For streamflow inputs to the reservoir, the modeled streamflow was bias corrected using naturalized flows as calculated by SCL, a combination of Snover et al. (2003) methods, a probability mapping approach for correcting streamflow data used for monthly time scale reservoir inputs, and a linear subsurface storage-release model that regulates the final streamflow output from the model to implicitly represent the effects of groundwater memory during summer low flows. More details of the streamflow calibration process are provided in Section 5.

Streamflow bias correction is considered necessary when accurate magnitudes of model predictions are desired to aid decision making especially during low flow seasons when subtle deviations of model predictions from observations result in large percentages of change in streamflows. Streamflow bias correction used in this study targets errors in the climate forcing data as well as difficulty in predicting groundwater flow response during low flows. SCL is in the process of developing methods to use bias-corrected streamflows as inputs for reservoir operations modeling and resource adequacy planning. Projected flows will also be used for planning and evaluating habitat protection and restoration for salmon and steelhead by the SSIT, SITC, and SCL. In-depth details on climate forcing data is available in Section 1.3.

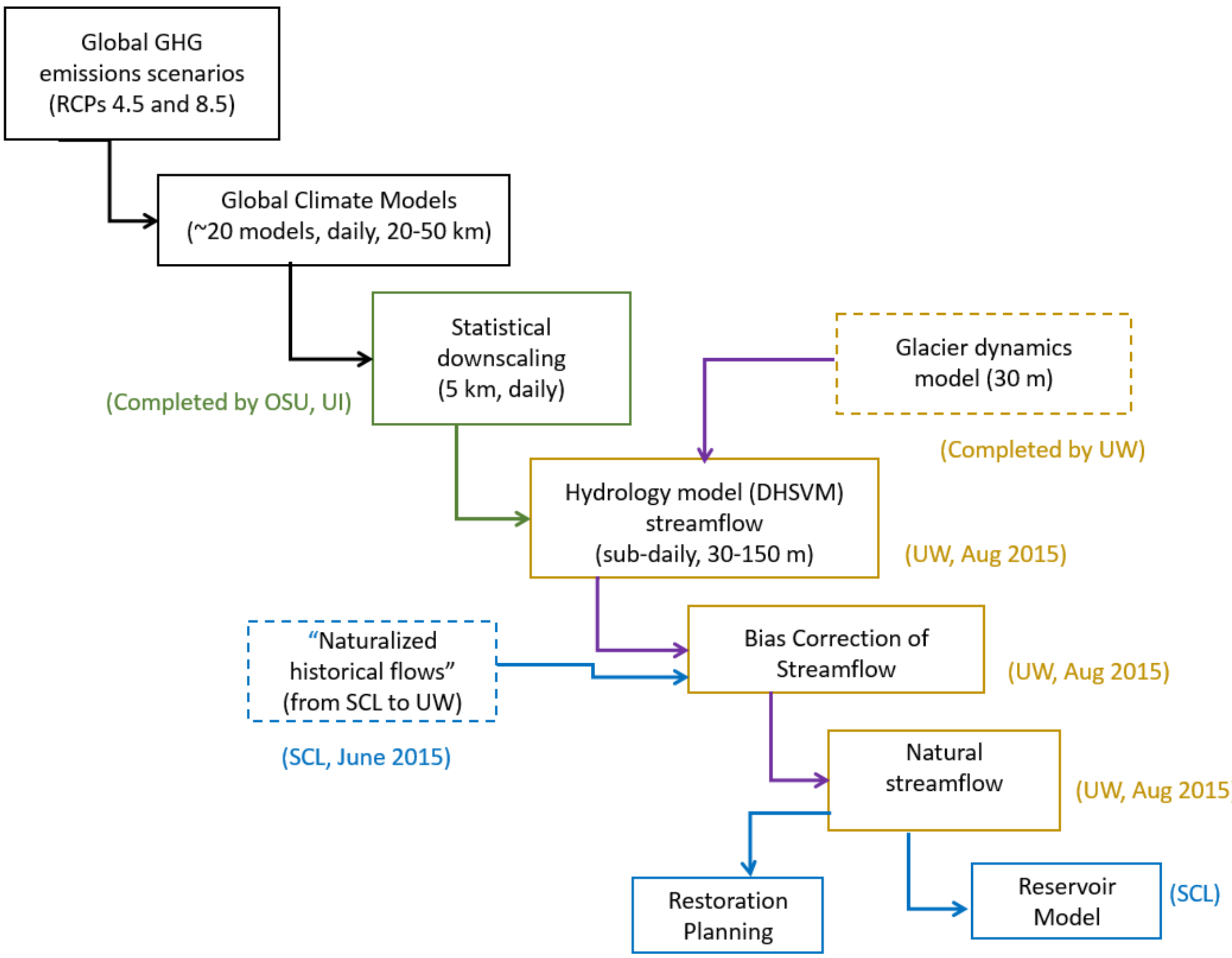


Figure 1. Chain of models linking global emissions scenarios to hydrologic impacts in the Skagit River Basin. At the top, black boxes are products of CMIP5 (World Climate Research Programme's Working Group on Coupled Modelling (Taylor et al., 2012)); the next green box is a product developed by a collaboration of Oregon State University (OSU) and the University of Idaho (UI) (Abatzoglou and Brown, 2012); the following yellow boxes are tools and data developed in collaborations at the University of Washington (UW) (Wigmosta et al., 1994; Clarke et al., 2015; Naz et al., 2014); and the blue boxes are data inputs and outputs developed in collaboration during this project with Seattle City Light (SCL) and the Skagit Climate Consortium.

The global greenhouse gas (GHG) emissions scenarios used in this study focused on two possible futures named after radiative forcing values in the year 2100 (+4.5 W/m^2 and +8.5 W/m^2) derived from representative concentration pathways (RCP) (RCP 4.5 and RCP 8.5). Figure 2a shows total CO_2 emissions between 1990 and 2100 used for CMIP 5 and CMIP 3 simulations and Figure 2b shows projected temperature changes from the historic time period (1950 to 2100) for the Pacific Northwest under RCP 4.5 and RCP 8.5 scenarios (Mote, et al., 2014). In practical terms, RCP 8.5 corresponds to the *business as usual scenario* (conservative future) in which GHG emissions continue to grow, and atmospheric CO_2 concentrations more than triple by 2100 relative to pre-industrial levels (dashed gray lines). The optimistic future is a climate future in which global GHG emissions peak in 2040 (RCP 4.5; light blue in Figure 2a and yellow lines in Figure 2b). The models selected in the Integrated Scenarios Project show a fairly wide range of temperature response for the commonly used scenarios RCP 8.5 and RCP 4.5 (Figure 2b), yellow region represent only models driven by RCP 4.5., the orange region is the response space shared by both scenarios, and the red region represents output of RCP 8.5 scenarios. The model ensemble for RCP 4.5 shows an increase in annual temperature of 6°F by 2100 and the model ensemble for RCP 8.5 shows an increase of 11°F by 2100.

Outputs from the selected 10 best GCMs delivered to SC2 for model implementation in the Skagit River Basin include: Beijing Climate Center, China Meteorological Administration (BCC-CSM1-1-M), National Center of Atmospheric Research, USA (CCSM4), National Centre of Meteorological Research, France (CNRM-CM5), Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia (CSIRO-Mk3-6-0), Canadian Centre for Climate Modeling and Analysis (CanESM2), Met Office Hadley Center, UK (HadGEM2-CC & HadGEM2-ES), Institut Pierre Simon Laplace, France (IPSL-CM5A-MR), Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC5), and Norwegian Climate Center, Norway (NorESM1-M). For the 10 GCMs, the two emissions scenarios for each model are included for a total of 20 future time series of daily climate and streamflow.

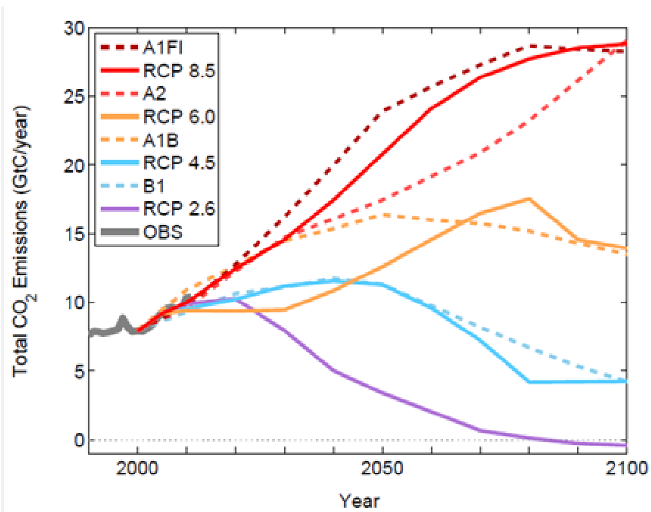


Figure 2a. The relationship between total CO2 emissions from the historic time period (1990) to 2100 for RCP scenario ensembles (solid lines). Dashed lines show the SRES predictions for comparison. (Figure 3-1 in Snover et al., 2013; sourced from UW Climate Impacts Group, based on data used in IPCC 2007 and IPCC 2013).

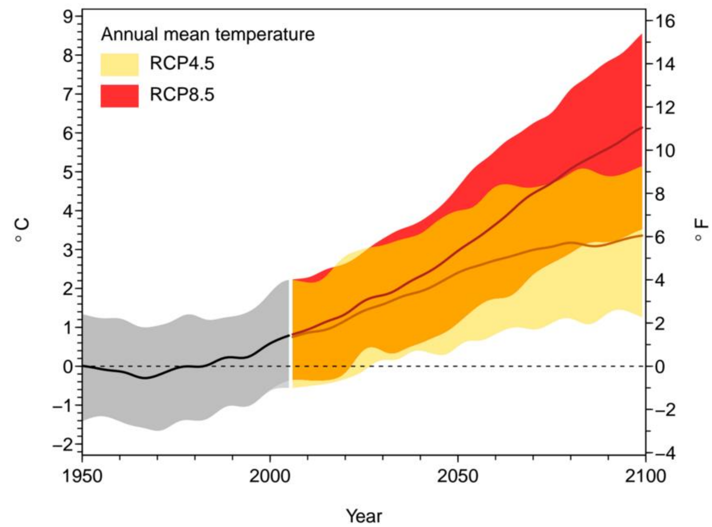
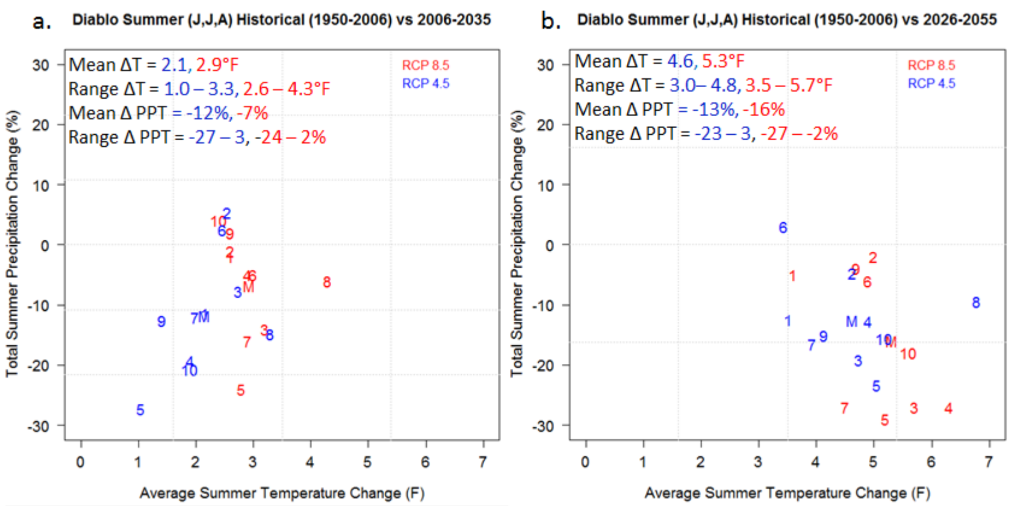


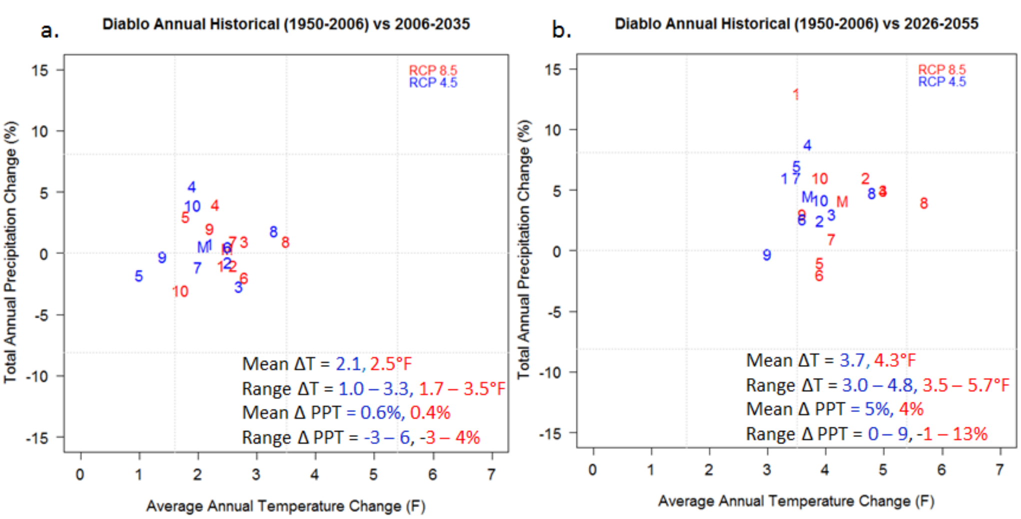
Figure 2b. Projected changes in annual mean temperature for the Pacific Northwest from the Integrated Scenarios Project (Mote, et al., 2014). The RCP 4.5 scenario run for each GCM assumes that greenhouse gas emissions will peak in 2040. The RCP 8.5 scenario assumes that greenhouse gas emissions will continue to increase to the end of the 21st Century.

We used the selected 10 best-performing GCMs for the Pacific Northwest and their ensemble average (Mote et al., 2014) to examine the projected changes in climate for the Diablo Coop Station by plotting % change in precipitation (y-axis) with respect to absolute change in temperature (x-axis) between historic averages and projected 30-year future averages. The plots are developed for summer (Figure 3) and annual averages (Figure 4) using a near future period (2006-2035) and a longer future period (2026-2055). Figure 3 shows changes in the summer climate, and Figure 4 shows changes in annual climate for the Diablo Coop Station, both for historic and future mean temperature and precipitation. The future data is based on the selected 10 best-performing GCMs for the Pacific Northwest and their ensemble average (Mote et al., 2014). Figures 3a and 4a compare the historic period (1950-2006) to the near future period (2006-2035); Figures 3b and 4b compare the historic period (1950-2006) to the longer term future period (2026-2055).



1 – MIROC5
2 – IPSL-CM5A-MR
3 – HadGEM2-ES365
4 – HadGEM2-CC365
5 – CSIRO-Mk3-6-0
6 – CNRM-CM5
7 – CCSM4
8 – CanESM2
9 – bcc-csm1-1-m
10 – NorESM1-M
M – model ensemble

Figure 3. Summer temperature and precipitation change for (a) the historic period (1950-2006) to the near future period (2006-2035) and (b) the historic period (1950-2006) to the far future period (2026-2055) in the Skagit River Basin.



1 – MIROC5
2 – IPSL-CM5A-MR
3 – HadGEM2-ES365
4 – HadGEM2-CC365
5 – CSIRO-Mk3-6-0
6 – CNRM-CM5
7 – CCSM4
8 – CanESM2
9 – bcc-csm1-1-m
10 – NorESM1-M
M – model ensemble

Figure 4. Annual temperature and precipitation change for (a) the historic period (1950-2006) to the near future period (2006-2035) and (b) the historic period (1950-2006) to the far future period (2026-2055) in the Skagit River Basin.

Meteorological data used as model inputs show a near future annual temperature increase from approximately 2-4 degrees F (Figure 4) and a near future summer temperature increase up to approximately 5 degrees F (Figure 3). The precipitation change is relatively small on an annual scale (Figure 4), but most GCMs project a larger percentage decrease in precipitation change in summer (Figure 3). A large percentage decrease in summer precipitation corresponds to only a small amount of precipitation because precipitation is already low during these months (as large as a -16% change; Figure 3).

1.3 Methods for DHSVM glacio-hydrology climate forcing correction

The historic and future datasets, developed at the macro-scale resolution (6 km grid cell) for regional applications, require testing and correcting before applying them at finer grid resolutions (30-150 m grid cell) for watershed modeling. The following correction and processing steps performed on the climate data delivered to SC2 for use in their modeling work are listed here:

1. Temperature correction to Livneh daily data set (climate forcing bias correction) was done using monthly average PRISM (2004; 800 meter grid cell resolution) temperature data in using bilinear interpolation of 1/16 degree area of each meteorological data grid cell. The linear method used (e.g., Watanabe et al., 2012) calculates the difference between the monthly PRISM and Livneh temperature data and adds the differences to the Livneh data. Monthly corrections are assumed to apply for each day of the Livneh dataset.

2. Run Variable Infiltration Capacity (VIC) model to disaggregate daily data to 3-hr data and obtain solar radiation and relative humidity forcing for DHSVM inputs. VIC climate data inputs are maximum temperature, minimum temperature, precipitation, and wind speed. VIC climate data outputs are solar radiation and relative humidity, in addition to downscaled climate inputs at 3-hr time steps. The disaggregation method is based on Thornton and Running (1999) as implemented by Bohn et al. (2013).

3. Elevation correction methods for gridded precipitation implemented were provided to SC2 to develop corrections to Skagit Basin grid cells where a relationship between elevation and precipitation was not evident in the Livneh dataset but expected based on local knowledge of the meteorological gradients in the basin and model performance in generating accumulations of ice/glaciers. This approach was tested in the Thunder Creek nested glacier model and gave comparable results to the precipitation multipliers which were applied to the Thunder Creek and Cascade Creek nested glacier models.

2. DHSVM Glacio-hydrological model

We used the distributed hydrology soil vegetation model (DHSVM; Figure 5a; Wigmosta et al., 1994; 2002) for the numerical simulation of glacio-hydrological processes. DHSVM has been widely applied in the mountainous western United States for snowmelt (e.g., Cristea et al., 2014; Jost et al., 2009) and climate change impact predictions on streamflow (e.g., Elsner et al., 2010; Cuo et al., 2011). In partially glaciated catchments ice flow is required to evolve glacier thickness and area over long time scales in response to surface accumulation, ablation, and gravitational processes. Projecting glacier change is essential for the projection of low flows in a changing climate. Several model developments have been recently accomplished to incorporate the representation of glaciers and improve the representation of snow processes. First, a glacier dynamics model (Clarke et al., 2015) based on a shallow ice approximation of the continuum mechanics equations governing ice deformation and sliding was integrated into the model to simulate the lateral movement of ice (Figure 5b., Naz et al., 2014). This can be a significant source of mass accumulation for valley glaciers and play a significant role in runoff generation (Ragettli et al., 2015). To incorporate the effects of the gravitational redistribution of snow (avalanche), the empirical "snowslide" model of Bernhardt and Schulz (2010) was incorporated in DHSVM.

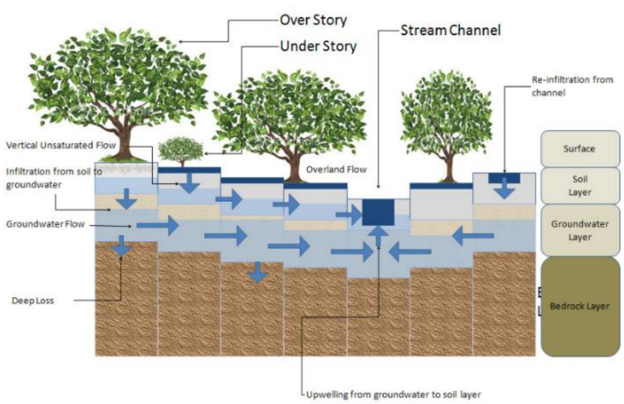


Figure 5a. Illustration of multi-layer vegetation canopy representation, and vertical and lateral water fluxes within each grid cell of the DHSVM model (From Wigmosta et al., 2002).

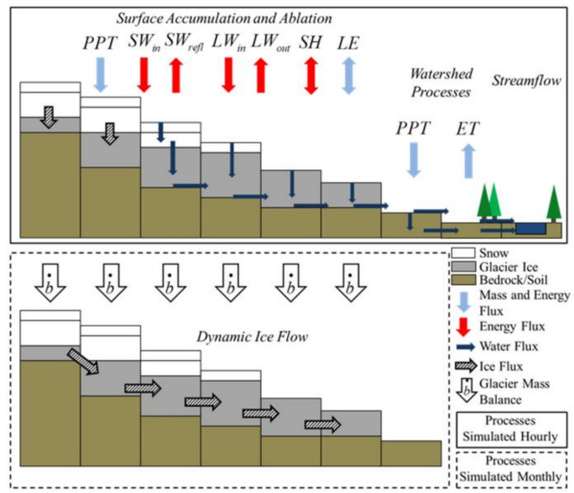


Figure 5b. Illustrations of: snow accumulation, melt, and resulting lateral melt-water flow of the hydrology component of DHSVM (top); net glacier mass balance from DHSVM hydrology component and lateral ice flow driven by gravity in the glacier dynamics component of DHSVM (Clarke et al. 2015; figure from Frans et al., 2015).

3. Time periods for climate change assessment

Distributed glacio-hydrologic modeling requires streamflow calibration and the additional steps of initializing glacier ice thickness and calibration of surface accumulation and ablation of glacier mass. Below we describe the model initialization and calibration steps, followed by simulations conducted for different watershed planning activities. The following time periods were chosen based on data availability and relevance to policy, regulations, and long term planning in the Skagit watershed:

Glacier Mass balance and Hydrology Calibration – 1991 -2012

Observations are compared to the model prediction over this specific time period in order to be consistent with Northern Cascades (NOCA) National Park Service (NPS) glacier mass observations. Additionally, modeled streamflow is compared with observed streamflow during this period for model evaluation and calibration. For these calibration steps that utilize a short period of record, the glacier areas are fixed to the observed extents of 1987.

Glacier Model confirmation – 1960-2009

To confirm that the ice extent obtained through this iterative glacier calibration method was realistic, the model was run from when it was initialized in 1960 using observed climate and matched to 1987 and 2009 Landsat ice extent. See Section 4 and Frans (2015) or Frans et al. (2015) for further information.

Current conditions model – 1980-2010

To compare future climate change impacts on glacio-hydrologic response, a historical baseline period is needed. Percent change from current conditions to future conditions is assessed using a 30 year period from 1980 to 2010 as baseline. This includes a transition from Livneh data through 2005 and MACA data from 2006. The future models scenarios of RCP 4.5 and 8.5 are both run with the differences between GCMs occurring only in the 2006-2010 period. For the following three time periods, the future model scenarios of RCP 4.5 and RCP 8.5 are both run for 10 GCMs.

Resource planning horizon – 2010-2039

SCL's Integrated Resource Plan is updated every two years, and the climate and streamflow output will be used for a preliminary assessment of climate impacts on resource adequacy in SCL's 2016 Integrated Resources Plan (IRP). This time period represents the near term future resource planning horizon of 20 years, but a 30-year window is used for consistency in comparisons between other time periods and historical 30-year normals.

Salmon and Steelhead Protection and Restoration - 2035-2065

Salmon and steelhead protection and restoration planning requires a longer term estimate of climate impacts around mid-century because it is developed to support recovery over the next century. The time period represents a 30 year average centered on the year 2050. Projections through the 2050s will also be used in planning for the next Skagit Hydroproject Relicensing that will begin in 2025.

CLIMATE Mitigation policy horizon–2070-2099

This time period represents the time period furthest in to the future, projecting the average over the last 30 years of the 21st century. Emissions reductions and mitigation efforts on the global scale will impact this planning horizon. Results for this time period can show differences in the climate impacts between the two GHG emissions scenarios (RCP 4.5 and RCP 8.5), demonstrating the benefits of mitigation policies that cause global GHG emissions to decline after 2040.

4. Glacier Initialization, Mass Calibration, Model Testing & Projected Future Results

4.1 Glacier Initialization

A physically consistent glacier cover in terms of area extent and thickness is needed for hydrological simulations. Glacier extent can be obtained from mapping, however assigning thickness to ice cannot be currently done by measurements. The glacier dynamics model represents the flow of ice mass downslope from high to low elevations driven by gravity and ice thickness. To develop a physically consistent glacier cover with observed glacial extent in high elevations, the glacier model was spun up using a representative ice mass balance field as model forcing. Where snow consistently accumulates at high glacier elevations, the annual mass balance of ice is positive. In lower elevations where snow is seasonal (or absent) and ice melts through ablation, the annual mass balance of ice is negative. How ice mass balance field has changed in space and time over the historical development of glacier ice is unknown. Therefore, we used an annual average mass balance grid generated from a representative average range of climate forcing from 2000 to 2008. Next, the glacier dynamics model was run for 1,000 years based on the mass balance grid to generate a steady state grid of ice thickness. If the ice initialization is too thick, the glacier extends beyond observed boundaries; if the ice initialization is too thin, the glacier does not extend far enough to match observed boundaries. During model spin up the mass balance field was adjusted in repeated simulations until the glacier extent initialization was matched with the NOCA-24k glacier extent dataset developed from 1:24,000 topographic maps, which represents glacier extent around approximately 1960 (Dick, 2013). To further confirm that the glacier extent obtained through this iterative glacier calibration method was realistic, the model was run from 1960 onward using actual observed climate and matched to 1987 and 2009 Landsat ice extent. See Frans (2015) or Frans et al. (2015) for further information.

4.2 Glacier Mass Calibration

In the two nested subbasins (Figure 6; Cascade and Thunder), we calibrated the model using climate forcing variables and surface energy balance model parameters that govern the accumulation and ablation of snow and ice at high elevations in order to capture the observed glaciological measurements (Reidel and Larrabee, 2011). Measurements used for model calibration include winter, summer, and net annual balance of ice in meters water equivalent (m.w.e., measured as change in depth of ice from the beginning to the end of the two seasons) for the North Klawatti glacier in Thunder Creek (NPS; Riedel et al., 2011) and South Cascade glaciers (USGS), and observed estimates of glacier area from remotely sensed Landsat imagery.

In the Cascade and Thunder Creek basins the model was implemented using grid resolutions of 50m and 30m, respectively, for an improved representation of glacier ice dynamics in these regions where glacier melt provide significant contribution of low flows. In the rest of the domain that includes Silver and South Cascade glaciers the model was run at a 150m grid resolution. Glaciers with observations in the 150m discretized domain (Silver, Noisy; NPS; Riedel and Larrabee, 2011) were not used in calibration, but were used for validation and compared to model results.

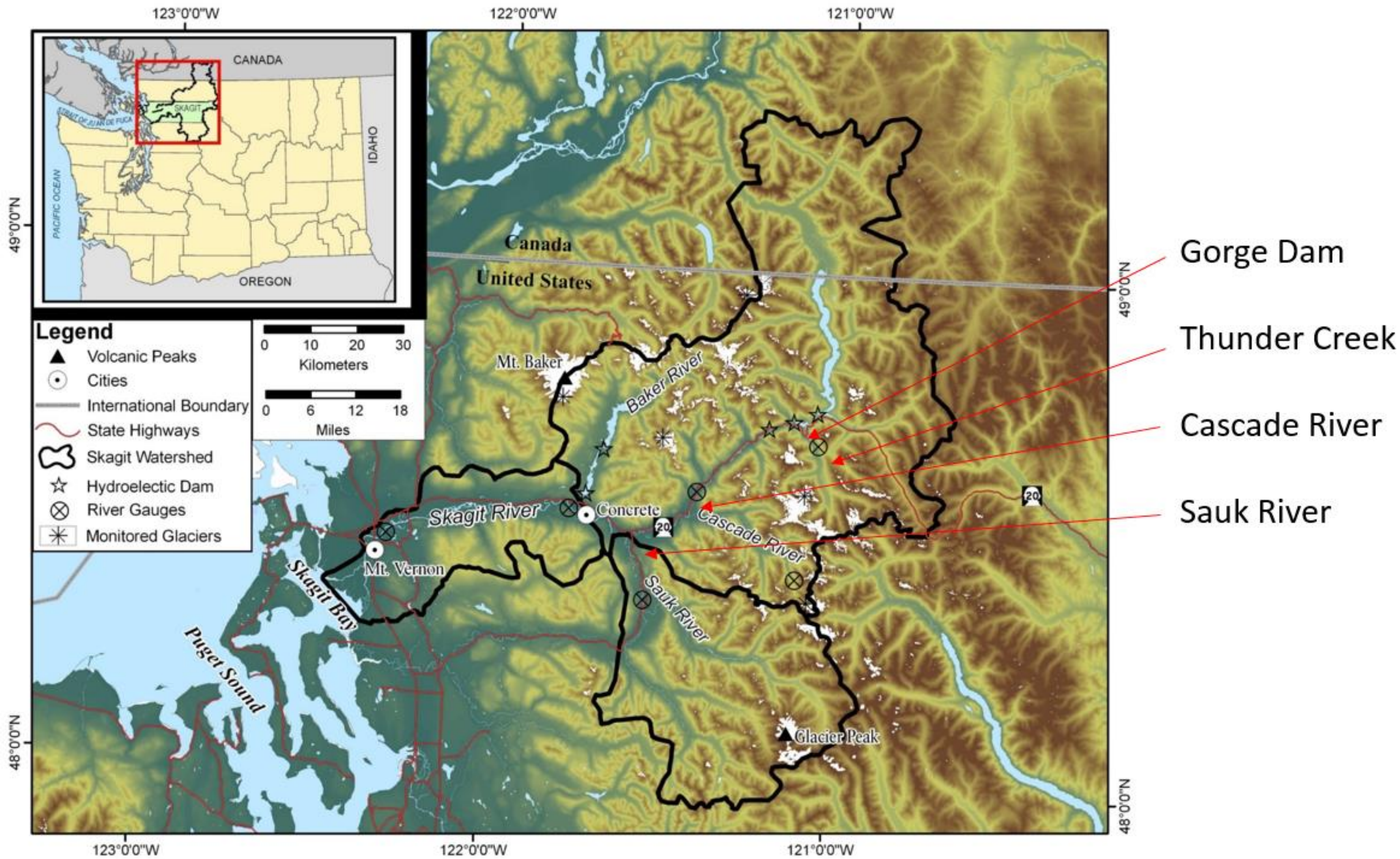


Figure 6. Skagit River Basin extent (black boundary line), topography, and selected project locations. Map courtesy of North Cascades National Park.

Using narrow, physically plausible ranges of model parameters, we used an automatic multi-objective calibration technique (MOCOM-UA, Yapo, 1999) to sample and evaluate different parameter sets in reconstructing seasonal and annual observations of glacier mass balance. Calibrated model parameters are local lapse rate of temperature (applied to the bias-corrected regional Livneh data), precipitation multipliers, maximum snow albedo used in snow albedo decay functions (Laramie and Schaake, 1972; Wigmosta et al. 2002), glacier albedo, and a constant for the aerodynamic roughness length over snow and ice surfaces. The objectives that were minimized were root mean square error (RMSE) of winter, summer, and net mass balance along with the absolute error in cumulative mass balance at the end of the calibration period. These procedures were implemented in Thunder and Cascade subbasins.

Figure 7 displays the performance of the model in simulating glacier mass fluctuations in the four glaciers in the Skagit basin with long-term records of observations. For the glaciers in the calibrated model domain with a 50m grid resolution (Cascade and Thunder subbasins using mass balance observations at N. Klawatti and S. Cascade glaciers), the model does reasonably well at reproducing observed time series of net annual mass fluctuations (r^2= 0.81). The Silver and Noisy glaciers were modeled at the full Skagit 150m grid cell resolution with temperature and precipitation PRISM bias corrections to the Livneh dataset, but no additional corrections were applied. This provided a validation for glaciers modeled with the full Skagit 150m resolution domain with no precipitation multipliers; compared to the Thunder and Cascade nested model with 50m resolution domain with precipitation multipliers. The full Skagit model was run in 150m grid resolution without detailed local calibrations of precipitation fields, therefore results in the Silver and Noisy glacier illustrate how an uncalibrated model, used for the entire Skagit basin, predicts local glacier mass balance. It is critical to note however that streamflow predicted by the model was bias-corrected at the end of the hydrologic simulations. These results demonstrate the need for calibration and improved temperature and precipitation data that is able to capture the local heterogeneities and micro-meteorology of the North Cascades range. Watershed modeling using only PRISM corrections to the Livneh dataset significantly underpredicts glacier mass balance in the 1990-2010 time frame where NOCA NPS glacier observations are available.

4.3 Glacier Model outputs and Future Results

Next we evaluated the distribution of modeled glacier ice using the hypsometry of modeled and observed glacier area and its change over the historical period to demonstrate model spatial predictions in relation to elevation (Figure 8). We composited modeled (black, right side of each box) and observed (gray, left side of each box) glacier area into 100 meter elevation intervals for 1960 (dashed lines) and 2005 (solid shapes).

The higher the symmetry in the vertical plots, the better the model performance becomes in predicting glacier area. The total glacier area is reported in the dashed boxes and filled areas for the historical and recent date, respectively. The relative amount of modeled area change in the nested subbasins shows agreement with the observations. Following the performance in the simulation of mass balance, the accuracy of the model is less in the 150m resolution grid domain (rightmost box) compared to the 50m nested models (leftmost and center boxes). As previously noted this is a function of the need for further subbasin scale calibration of model parameters.

It is notable that the high elevation glaciers are modeled more accurately in both the 50m and 150m resolution models as compared to the lower elevation glaciers in the 150m resolution model. We recommend future model improvements in downscaling ~6 km by ~6 km climate forcing grids tested for a range of grid cells (30m, 50m, 90m, 150m) using daily temperature and precipitation lapse rates to increase the glacier predictions at lower elevations (below 2000 m). For the purpose of long term water resources predictions, accuracy of glacier predictions at elevations greater than 2000m elevation is of primary importance as these high elevation glaciers will be dynamic and persist into the future. Figure 9 shows the projected Skagit glacier area and volume from 1960 to 2100. If atmospheric concentrations of GHGs start to decrease after 2040 (RCP 4.5), it is possible that the highest elevation glaciers will continue to store pockets of ice and provide some glacier melt in the summer months; if atmospheric concentrations of GHGs continue to increase at current rates (RCP 8.5), most models predict that Skagit glaciers will disappear by the end of the century.

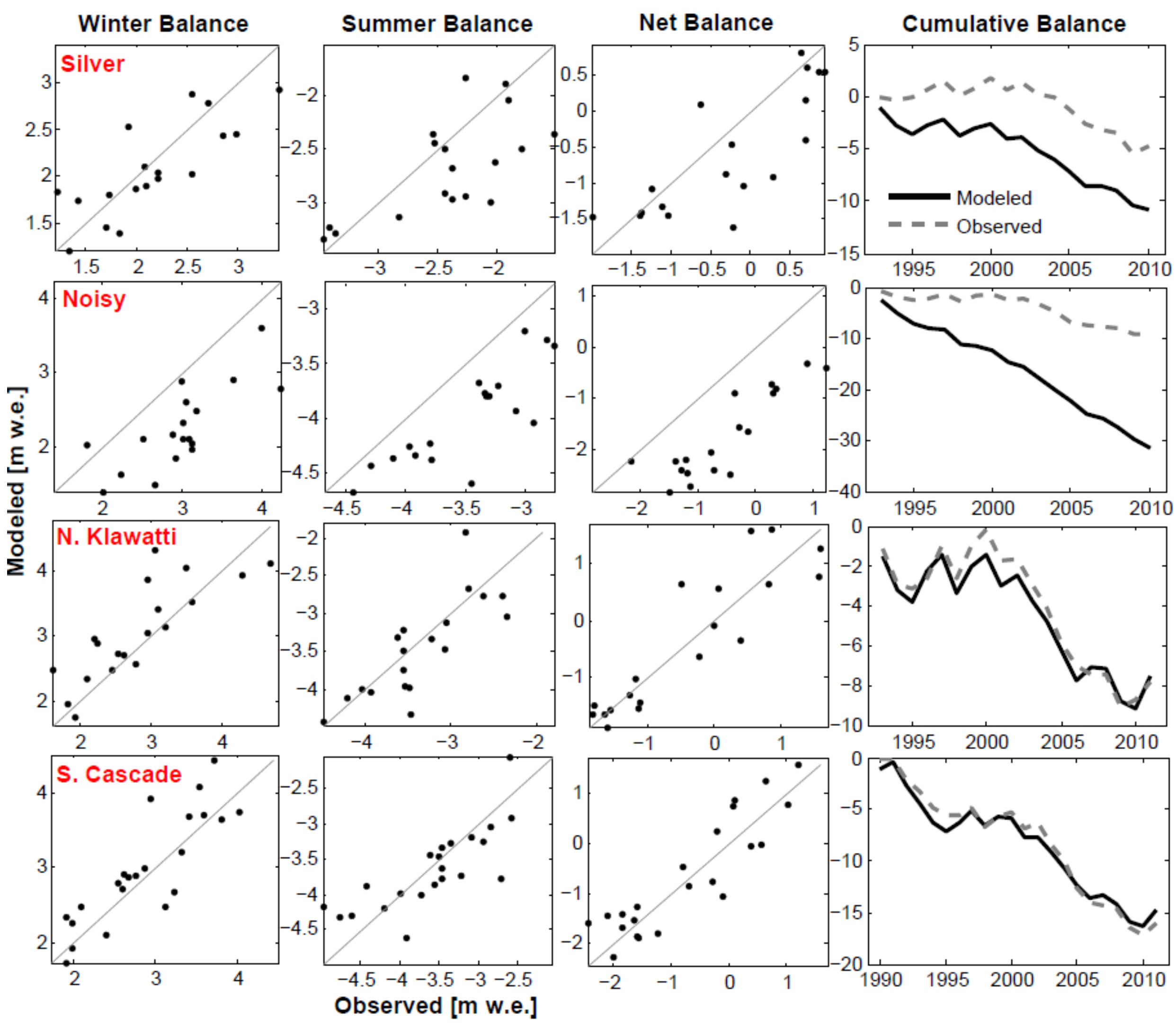


Figure 7. Comparison of modeled and observed winter, summer, and annual net glacier mass balance (first 3 columns), and cumulative mass balance with respect to time (last column) with local calibration (N. Klawatti and S Cascade glaciers) and without local calibration (Silver and Noisy glaciers) of model forcing data in the Skagit basin with long-term records of observations

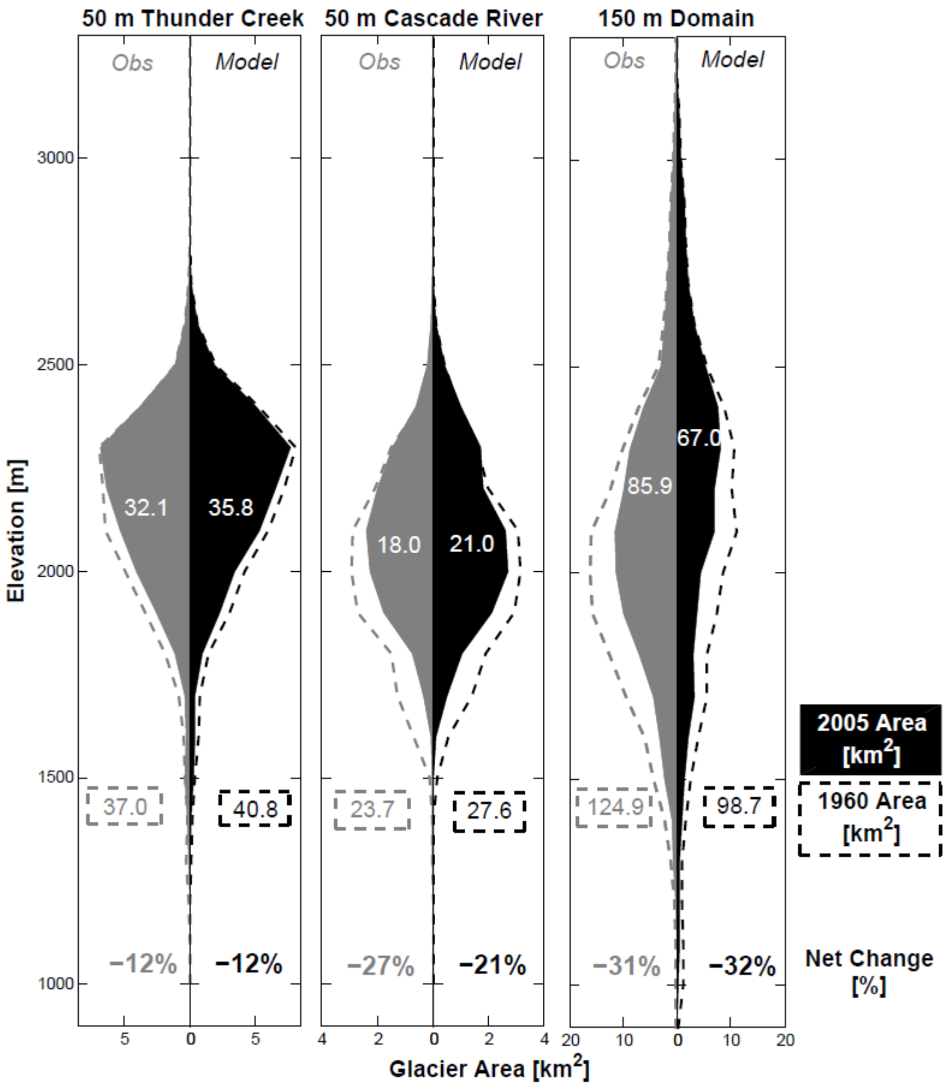


Figure 8. Glacier area (x-axis) plotted with respect to elevation (y-axis) using modeled and observed data at each 100 m of elevation interval. Modeled and observed data are in black and gray, respectively. Dashed lines indicate 1960 (Raup, et al., 2007) and solid area indicate 2005 data (Dick, 2013). The net change reported in percent (%) is the glacier extent difference between 1960 and 2005.

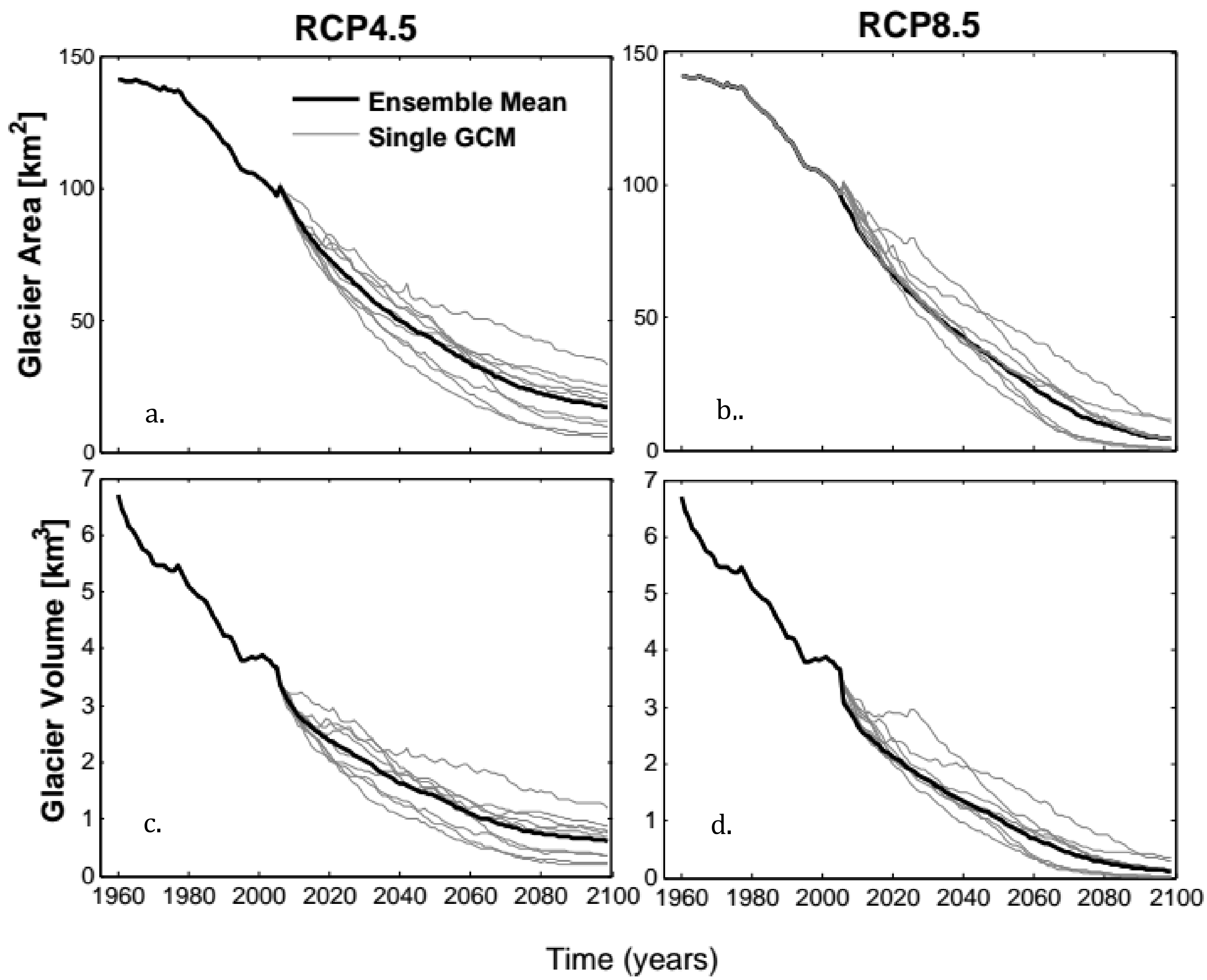


Figure 9. Projected glacier area (a, b) and volume (c, d) for scenarios RCP4.5 (a, c) and RCP8.5 (b, d).

5. *Streamflow Results*

5.1 Calibration to exceedance probability curves: Highlights at Newhalem to Marblemount

The exceedance probability statistic has been in general use since 1915 (Foster, 1924). It does not show the chronological sequence of flows, but a ranking of the range of flows in the order of their magnitudes. Strictly speaking, the curve applies only to the time period from which data were used to develop the curve. It is generally useful for studying the flow characteristics of a stream and for comparing between basins (Searcy, 1959) and in this work it is useful for comparing between time periods. The exceedance probability curve (distribution of daily flows) should not be confused with an annual recurrence interval curve (single minimum or maximum event in each year) used for extreme event frequency estimation (see *Definitions* section). The monthly distribution of 90% exceedance probability statistics are commonly used to determine instream flow requirements for various fish life stages. In Figure 10, we used the monthly exceedance probability curves to highlight a calibration statistic specific in the assessment of how these streamflow projections are required for instream flow and fish habitat assessment. We discuss the results specifically for the future projections of tributary inflows from Newhalem to Marblemount portion of the Skagit River (using the difference between main stem Skagit River USGS gauges at Newhalem (12178000) and Marblemount (12181000)), downstream of SCL reservoirs, because the sum of the gauged (Bacon Creek) and ungauged tributary inflows to this stretch of the Skagit River is critical for determining operating procedures for the Skagit Project to set reservoir releases that meet instream flow requirements for fish. These gages have an extensive historic record and have been in operation since 1920.

In Figure 10, the monthly exceedance probabilities curves are plotted on a log scale by month starting at the beginning of the water year (October). The time period for the data included in each month is 1990-2005. The time period begins at 1990 in order to correspond with the beginning of the calibration period determined by glacier mass balance observations and ends in 2005 which is the historical data used to train the MACA data. This figure is an example of the steps required to fit model simulations to observed distribution of flows; the corrections made to match observed trends are then applied to future projections. In comparing the magnitude of streamflow between observed (black) and calibrated DHSVM model (green), nuances of model fit beyond the monthly mean can be detected. Generally, low flows in the winter (February), low flows in the summer (July-September), and the low flow tail of October are underpredicted. This underprediction is improved by using a bias correction to the streamflow (blue dash), but lowest flows in July through October, in the range of the 90% exceedance probability values, required further low flow correction (red dash).

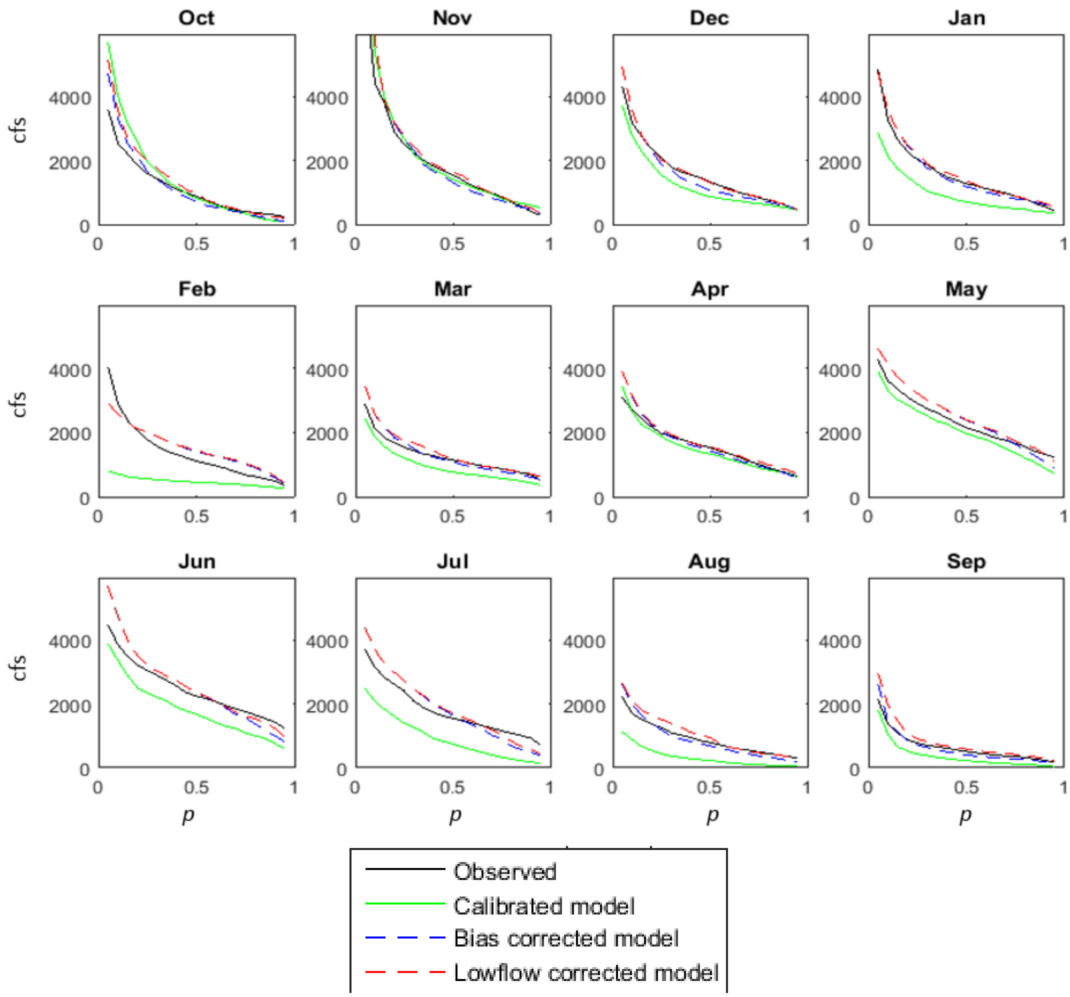


Figure 10. Monthly exceedance probability curves [where exceedance probability, p, is associated with ordered observation q(i) in cubic feet per second (cfs)] for observed, calibrated, bias and lowflow corrected streamflow results for the Newhalem to Marblemount drainage area of the Skagit River. The model was calibrated using annual cumulative, monthly mean, and daily nash-sutcliffe statistics. The bias correction was required to adjust for errors in the forcing data inputs, model structure, and parameterization. The low flow correction was able to improve the representation of low flows, which were otherwise modeled as lower than observed. These corrections that were determined using historic observed data were applied to future results in order to generate a comparison between streamflow changes over time.

The low flow correction was applied as a post-processing step to further improve the representation of low flows. The low flows in the winter are controlled by temperature and precipitation forcings as well as lapse rates, which increase precipitation and decrease temperature with elevation. Hence, first we use DHSVM to simulate streamflow, second we apply a bias correction to the streamflow, and finally we use a streamflow threshold (specific to each individual location) below which to correct the lowest streamflow values using a linear model. The final model simulations were evaluated in the 1990-2005 period and applied to the streamflow time series of future projections.

This bias and low flow correction was also conducted and available for six other locations with sufficient data: Gorge, Ross, and Diablo dams (using naturalized flows estimated by SCL), Thunder Creek, Sauk River near White Chuck, and Sauk River near Sauk. The historic model was compared to naturalized/observed flows and the annual cumulative bias, mean monthly bias, and daily Nash-sutcliffe efficiency statistic that met the objectives of < 5% annual cumulative bias, < 20% mean monthly bias, and > 0.6 Nash-Sutcliffe daily efficiency over the 1991-2010 calibration period.

5.2 Future Projections: Highlights at Newhalem to Marblemount

Although low flow corrections lead to numerically small changes (on the order of 1% of peak flows) on the annual and monthly average time scales, the importance of an improved low flow correction can be explored further in Table 1, which reports monthly low flows that are exceeded 90% of the time in a given month for different durations and model runs. The first gray column shows the observed USGS streamflow used in the Revised Fisheries Settlement Agreement (2011) between SCL and multiple federally recognized entities (Federal Energy Regulatory Commission [FERC] No.553; Appendix M-Tributary Percent Exceedance Flow Between Newhalem and Marblemount). The second gray column shows that the observed values in the 1980-2010 period, and it is notable that the October 90% exceedance probability was 230 cubic feet per second (cfs) lower than the longer term (1944-2012) average due to a shift to an earlier spring snow melt peak and higher summer temperatures. The four tan columns show the four modeled 30 year periods to compare relative changes in model projections of future flows. It is notable that the low flow correction described above was able to bring the August-October model projected streamflow within 50 cfs of observations. Monthly changes to the low flows (as represented by the 90% exceedance probability) are projected to decrease most significantly in June, but in general are projected to decrease April-October.

Median flows (50% exceedance probability) are shown in Table 2, with a marked decrease in flows from April –October in the mid-century (2035-2065) and end of the century (2070-2099) compared to the historic thirty year period (1980-2010). The biggest decrease in median flows is projected for June and July, and increased flows in November-February, as the snowmelt pulse that historically occured in June-July is projected to be rainfall runoff in winter months instead of being stored as snow. High flows (herein defined as 10% exceedance probability) are shown in Table 3. High flows in December and January are projected to almost double in magnitude from ~3500 cfs to ~6000 cfs in the end of the century (2070-2099) compared to the historic thirty year period (1980-2010).

Table 1. Newhalem to Marblemount tributary contributions. DHSVM-glacier projected **RCP 4.5** scenario future low flows (90%) compared to settlement instream flows based on observed USGS streamflow monthly average 1944-2012 (FERC, 2011) compared to observed USGS streamflow 1980-2010, and model projected thirty year periods. This includes a transition from Livneh data 1980- 2005 to MACA data 2006-2010, so the observed and modeled data should not be directly compared.

90% Exceedance Flow (cfs)

RCP 4.5	USGS*	USGS*	DHSVM-glacier model projections			
Month/Years	1944-2012	1980-2010	1980-2010	2010-2040	2035-2065	2070-2099
January	730	550	622	771	845	908
February	596	470	608	606	707	791
March	793	690	645	572	562	635
April	1063	750	798	615	601	624
May	1842	1360	1084	967	920	796
June	1859	1595	1068	655	437	378
July	1193	1020	554	331	179	165
August	529	405	353	274	227	232
September	363	270	248	204	193	170
October	530	300	256	240	247	231
November	724	570	532	561	517	592
December	776	560	535	631	738	757

Table 2. Newhalem to Marblemount tributary contributions. DHSVM-glacier projected **RCP 4.5** scenario future median flows (50%) compared to settlement instream flows based on observed USGS streamflow 1980-2010, and model projected thirty year periods. This includes a transition from Livneh data 1980-2005 to MACA data 2006-2010, so the observed and modeled data should not be directly compared.

50% Exceedance Flow (cfs)

RCP 4.5	USGS	DHSVM-glacier model projection			
Month/Years	1980-2010	1980-2010	2010-2040	2035-2065	2070-2099
January	1280	1255	1381	1683	1814
February	1110	1293	1290	1405	1599
March	1165	1091	1014	1027	1136
April	1500	1391	1115	1102	1137
May	2215	2189	1757	1663	1481
June	2480	2301	1543	1205	959
July	1670	1520	952	721	582
August	840	827	529	446	393
September	580	624	446	423	354
October	880	945	813	822	873
November	1650	1350	1280	1368	1536
December	1240	1050	1233	1491	1647

Table 3. Newhalem to Marblemount tributary contributions. DHSVM-glacier projected **RCP 4.5** scenario future high flows (10%) compared to settlement instream flows based on observed USGS streamflow 1980-2010, and model projected thirty year periods. This includes a transition from Livneh data 1980-2005 to MACA data 2006-2010, so the observed and modeled data should not be directly compared.

Scenario	**10% Exceedance Flow (cfs)**				
RCP 4.5	USGS*	DHSVM-glacier model projections			
Month/Years	1980-2010	1980-2010	2010-2040	2035-2065	2070-2099
January	3255	3570	4316	5184	6108
February	2678	2351	2521	2660	3037
March	2075	2435	2094	2213	2678
April	2755	2944	2319	2331	2480
May	3945	3961	3191	3070	2819
June	4160	4306	3229	2833	2228
July	3245	3506	2340	1920	1443
August	1685	1733	1234	1135	978
September	1345	1677	1369	1313	1274
October	2640	2851	2462	2746	2957
November	4335	4969	3683	4443	4776
December	3095	3605	3880	4976	5594

6. Projected streamflow results for reservoir management

The location of Gorge dam is shown in the Figure 6; it is the most downstream of the three dams (Gorge, Diablo, Ross) of the Skagit River Hydroelectric Project. Reservoir releases from Gorge dam are used for multiple purposes: provide flood control, manage instream flows for fish, and generate electricty. Figure 11 shows the median (50% exceedance proabilitity) naturalized streamflows projected for Gorge. The historic time period (1980-2010; black line) has higher snowmelt runoff in May-September and low streamflows in the winter when precipitation is stored as snow November-March (Figure 11a is for RCP 4.5 and Figure 11b is RCP 8.5). The winter flows are projected to become increasingly higher, and the May-September flows to become continously lower progressively through time, from 2025 (2010-2040 period; blue line) to 2050 (2035-2065; purple line) to the end of the century (2070-2099; pink line). The ensemble mean of the GCMs is shown as the solid lines within the shaded area (borders generated by minimum and maximum values; darker areas show the overlap between time periods) derived from the minimum and maximum of each GCM used to make projections. Comparing Figure 11a to Figure 11b, the future scenario with more warming predicted (RCP 8.5) not only projects more significant changes in the timing of the hydrograph, but the results are also more variable (larger spread between GCM projections in RCP 8.5 compared to RCP 4.5). Figure 12 used the daily streamflow data selected from August for each of the thirty year periods and shows the monthly exceedence probability curve. The lowest flows in August are currently ~2000 cfs at Gorge dam, but projected (RCP 4.5; Figure 12a) to decrease steadily by ~500 cfs in each 30 year period into the future, and may be lower than 500 cfs in August (RCP 8.5) by the end of the century (Figure 12b; 2070-2099; pink line).

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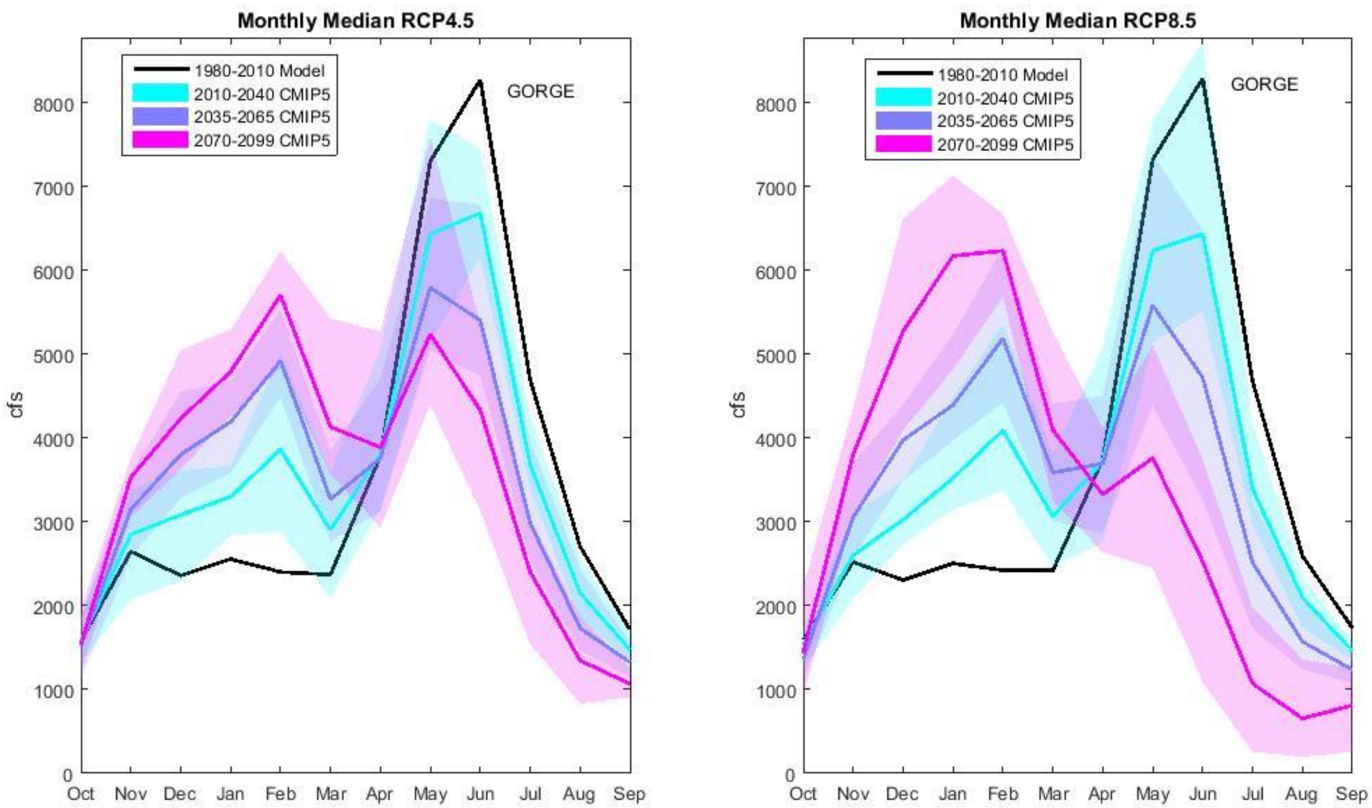

Figure 11. Gorge dam monthly median (50% exceedence probability) projected changes for a) RCP 4.5; moderate warming and b) RCP 8.5; high warming. The ensemble mean of the GCMs is shown as the solid lines and shaded areas indicate the minimum and maximum of each GCM used to make projections.

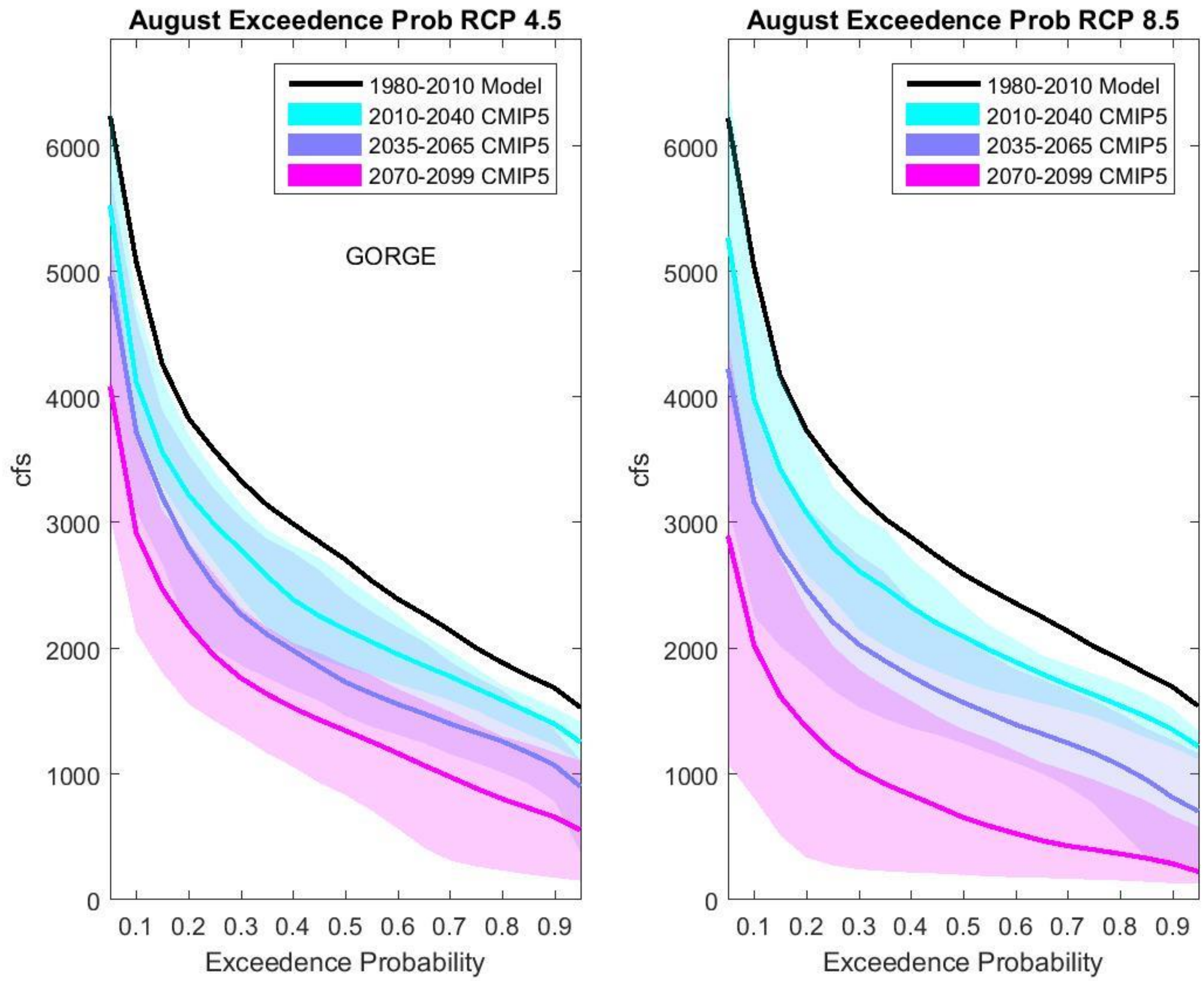

Figure 12. Gorge dam August (see also Table 1 for values at 0.9 on the x-axis; 90% exceedence probability) projected changes for a) RCP 4.5; moderate warming and b) RCP 8.5; high warming.

Thunder Creek is the most glaciated basin in the Skagit, and drains into the Skagit Hydroelectric Project upstream of Diablo Dam (Figure 6). Figure 13 shows the Thunder Creek monthly median (50% exceedence probability) projected changes for a) RCP 4.5 and b) RCP 8.5. Comparing Figure 11a (Gorge Dam) to Figure 13a (Thunder Creek), the monthly median (50% exceedance probability) streamflow values are less sensitive to climate change in the higher elevation glaciated Thunder Creek in the RCP 4.5 scenario. The changes projected in Thunder Creek for the RCP 8.5 projection are more significant in the late summer (August-September); where the historic model simulations estimate 600 cfs in August are projected to decrease progressively to as low as 100 cfs (RCP 8.5) to 200 cfs (RCP 4.5). Figure 14 shows the historic and future projection of the distribution of August flows (monthly exceedance probability curve). Currently, August flows (modeled historical data and observed records, which match well) in Thunder Creek range from between 500 to 2000 cfs; the future streamflow is projected to decrease to a range of 400- 1400 cfs by mid-century (Figure 14a; blue line; RCP 4.5). We estimate that Thunder Creek provides approximately 6% of all SCL hydropower generation in drought years; a 40-50% decrease in streamflow contribution in August (from change in snow and glacier melt) is of significant importance for planning and reservoir management.

7. Projected streamflow results for protection and restoration planning

While Figures 11-14 are important for understanding location specific projections and model simulations at different elevations and locations in the Skagit River basin, there is value in exploring how these statistics compare between multiple streamflow locations. Will some tributaries become intermittent streams in the future? Which tributaries are most sensitive to climate change? Figure 15 is a ranking of percent change of the low flows using the August 90% exceedance probability from historic (1980-2010) to 2050 (mid-century; 2035-2065). The black bars show the ensemble mean for percent change, the blue square is the minimum percent change projected, and the red square is the maximum percent change projected by all GCMs used in this project. Locations marked with one asterisk (*) have sufficient length of observations to conduct a streamflow bias correction (greater than 30 years). Locations marked with two asterisks (**) are part of the Skagit Lowlands Low Flow Study (SC2-UW Project in 2013; Stumbaugh and Hamlet, 2015). The percent change for the lowest elevation locations, including Red Cabin Creek, project little change in the August 90% exceedance probability. In these drainages, precipitation falls year round as rainfall, and this is not projected to change in the future. Higher elevation locations, most notably the South Fork of the Sauk River, are projected to experience the most significant percent change (decrease) of ~80%.

What is the magnitude of streamflow changes for this amount of percent change? For example, tributary contributions (as measured by the August 90% exceedance probability) between Newhalem to Marblemount are currently ~ 350 cfs and projected to decrease to 230 cfs; about a 35% decrease. Smaller low elevation tributaries, e.g., Red Cabin Creek, do have a consistent decrease in the projected future streamflows, but the streamflows are small and hence the absolute changes are small—from 0.14 cfs currently to a project 0.13 cfs. The very large ~80% decrease projected in the South Fork Sauk is a decrease from 14 cfs to a future projection of 3 cfs for the August 90% exceedance probability. While this does not represent a large proportion of the annual volume of streamflow, it does represent a significant change in salmon habitat during a critical period. Figures 16 and 17 use a similar layout as Figure 15 where black is GCM ensemble median; red is the maximum GCM projected change in streamflow; and blue is the minimum GCM projected change in streamflow. In contrast to Figure 15, in Figure 16 (relatively larger streamflows) and Figure 17 (relatively smaller streamflows), the magnitude of streamflow (cfs) is shown rather than percent change; the black is the historic modeled values, and the gray is the 2050 ensemble mean (mid-century; 2035-2065). Streamflow changes in August are most significant in Sauk River near Sauk for the larger drainage areas shown in Figure 16; and most significant for Sauk River near Whitechuck and South Fork Sauk for smaller drainage areas shown in Figure 17.

Figure 18 is the same style as Figure 15, but rather than comparing historic to projected low flows, Figure 18 compares the percent change in 100 year flood values for a range of locations. The spread between the red and blue squares (range of GCM predictions) and the relatively smaller percent changes in extreme flood events are more difficult to interpret than the changes predicted in monthly mean or 10% high flows in Table 3 (for Newhalem to Marblemount). Results are mixed also when looking only at November high flows (10% exceedance probability; not shown in figure here); further analysis of high flows in December and January, and the changes in the timing and frequency of extreme events in each month may increase understanding of how peak extreme events are projected to change in the future.

In a similar format as Figures 11 and 12 for Gorge Dam, and Figures 13 and 14 for Thunder Creek, the monthly mean projected streamflows and August exceedance probability curve for Sauk River near Sauk is given in Figures 19 and 20. The Sauk River near Sauk is projected to have significantly more increases in winter time (November-January) streamflow and decreases in summer time (July-September) streamflow. Gorge Dam and Thunder Creek are projected to shift from a snow dominated pulse of summer peak flows to a bi-model annual hydrograph with peaks in both the winter (from rainfall) and summer (from snowmelt). The Sauk River currently has a bimodal annual hydrograph, and is projected to progressively lose the summer peak (from snowmelt) and increase the winter peak (from rainfall); by the end of the century, the Sauk River annual hydrograph is projected to have a single peak consistent with hydrograph timing of rain-dominated systems. The impacts of this shift will be most apparent in the August low flow changes (Figure 20), from a current range of ~1500-5500 cfs to more than a 60% decrease in August flows (Figure 15).

8. Conclusions

Our analysis explored how low streamflows and peak annual flood streamflow in the Skagit River and tributaries are projected to respond to climate change using the DHSVM glacio-hydrology model (Figures 11-20) with highlighted discussions on selection locations (of 20 model output locations). This study incorporated the role of glacial melt on future hydrology flows, which was omitted in the previous modeling studies. Future streamflow is projected to have significant variation on a monthly average scale, which can be used to assess the relevancy of policy and regulation measures to provide critical salmon habitat along the stream network. The outputs from Skagit watershed modeling using CMIP5 are consistent with previous work using CMIP3 and CMIP4, where low flows are projected to be progressively lower in future low flow summer seasons and high flows will be higher in the future (Stumbaugh and Hamlet, 2015; Lee and Hamlet, 2011). The Sauk River basin is the most sensitive drainage area in the Skagit, with low flows projected to decrease 35-80%.

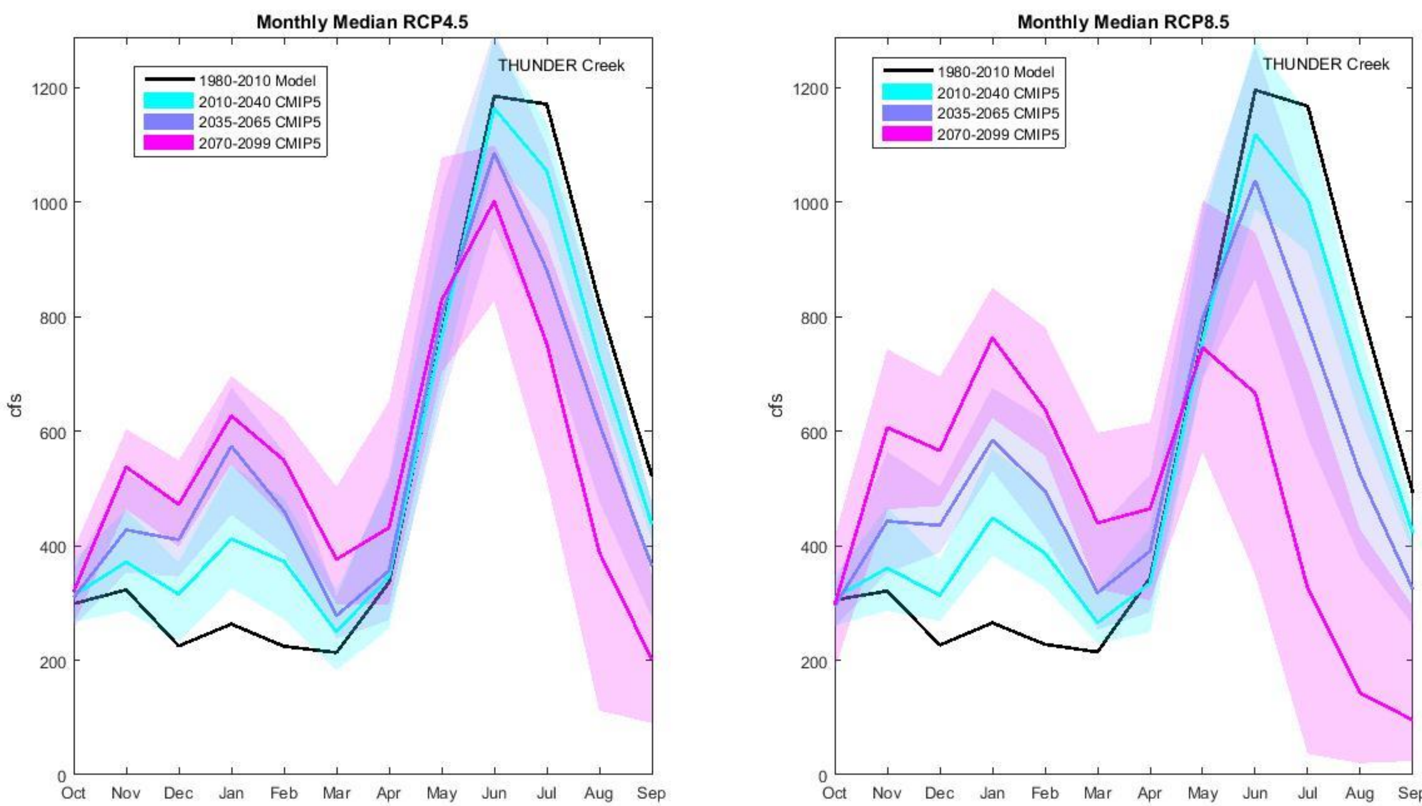

Figure 13. Thunder Creek monthly median (50% exceedence probability) projected changes for a) RCP 4.5 and b) RCP 8.5.

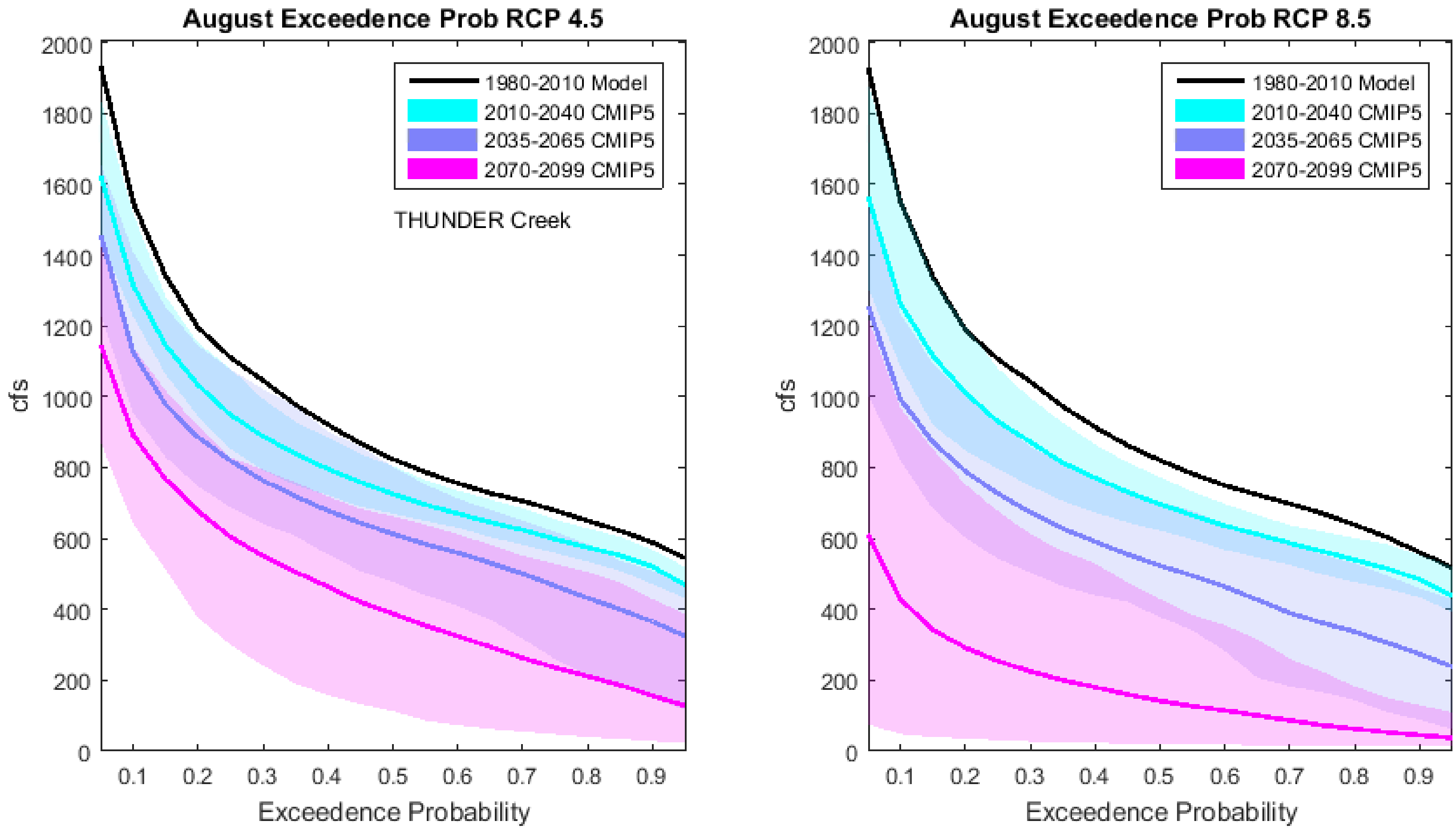

Figure 14. Thunder Creek August projected changes for a) RCP 4.5 and b) RCP 8.5.

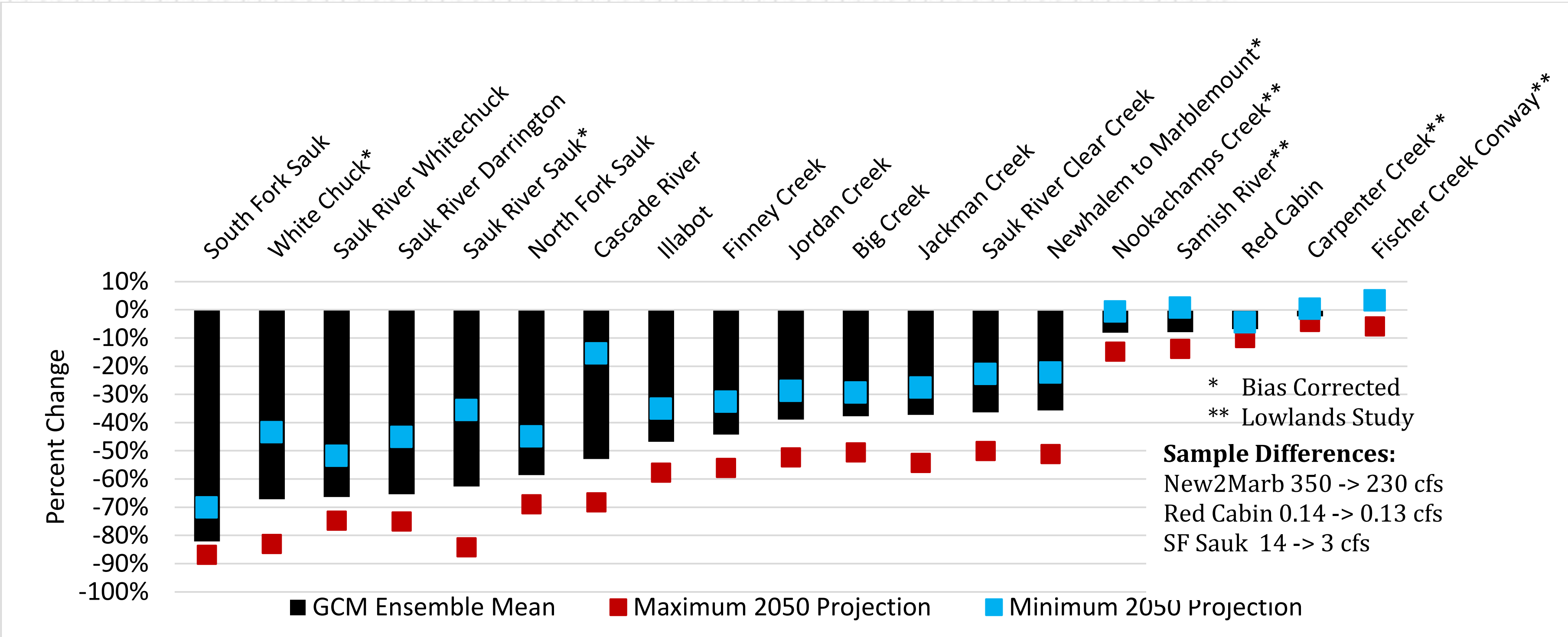

Figure 15. August 90% Exceedence probability percent change from historic to mid-century (2050). Baseline flows were taken from the historic period 1980-2010 and compared to the future period 2035-2065. Squares indicate the maximum (red) and minimum (blue) change projected by the ensemble of GCMs. Locations marked with one asterisk (*) have sufficient length of observations to conduct a streamflow bias correction. Locations marked with two asterisk (**) are part of the Skagit Lowlands Low Flow Study (SC2-UW Project in 2013; Stumbaugh and Hamlet, 2015).

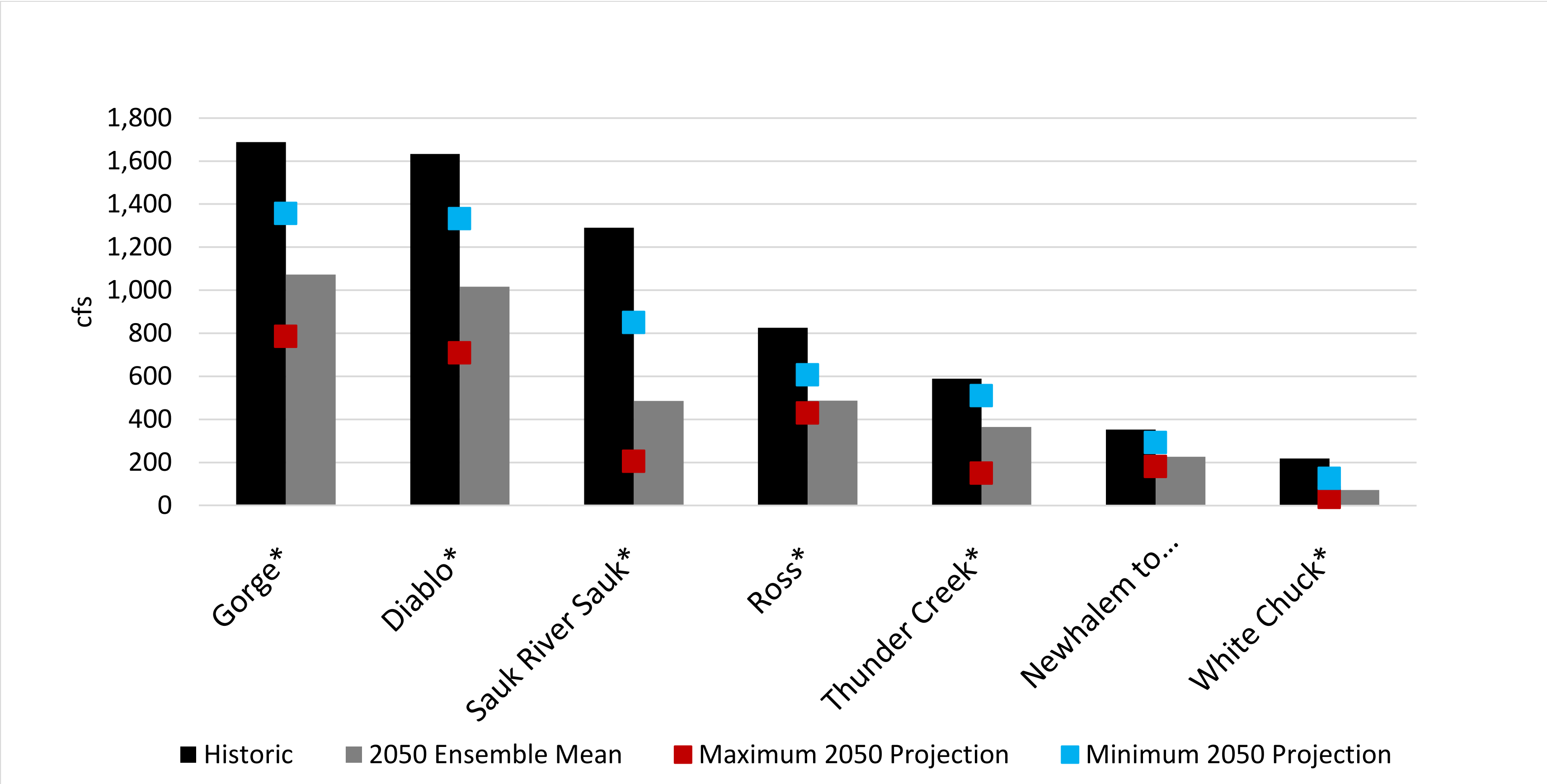

Figure 16. August 90% Exceedance probability streamflow magnitudes for historic to mid-century (2050). Baseline flows (black) were taken from the historic period 1980-2010 and compared to the future (gray) 2035-2065. Squares indicate the maximum (red) and minimum (blue) change projected by the ensemble of GCMs. Locations marked with one asterisk (*) have sufficient length of observations to conduct a streamflow bias correction. These locations represent a subset of locations with

sufficient length of observations to conduct a streamflow bias correction. Newhalem to Marbemount* is truncated to "Newhalem to …" for label brevity.

UNI

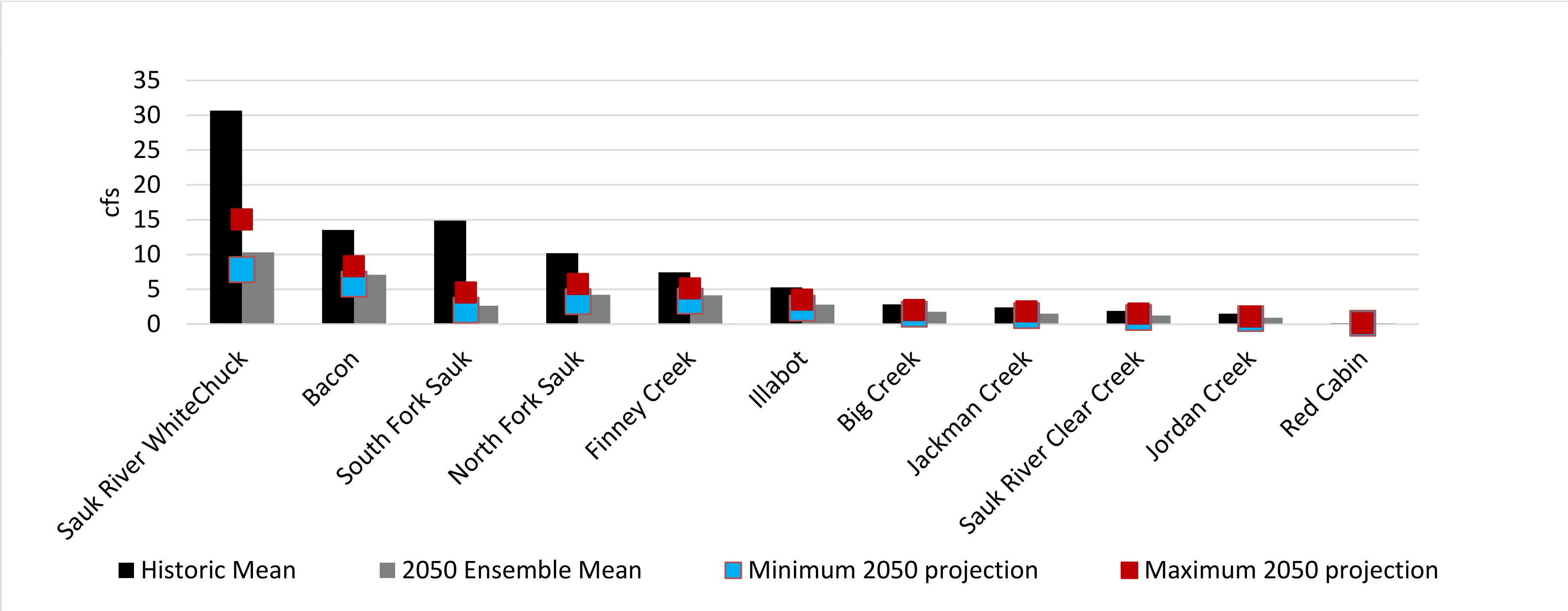

Figure 17. August 90% Exceedance probability streamflow magnitudes for historic to mid-century (2050). Baseline flows (black) were taken from the historic period 1980-2010 and compared to the future period (gray) 2035-2065. Squares indicate the maximum (red) and minimum (blue) change projected by the ensemble of GCMs. Locations marked with one asterisk (*) have sufficient length of observations to conduct a streamflow bias correction. These locations represent a subset of small salmon bearing tributaries of the Skagit River.

Watershed
Dynamics

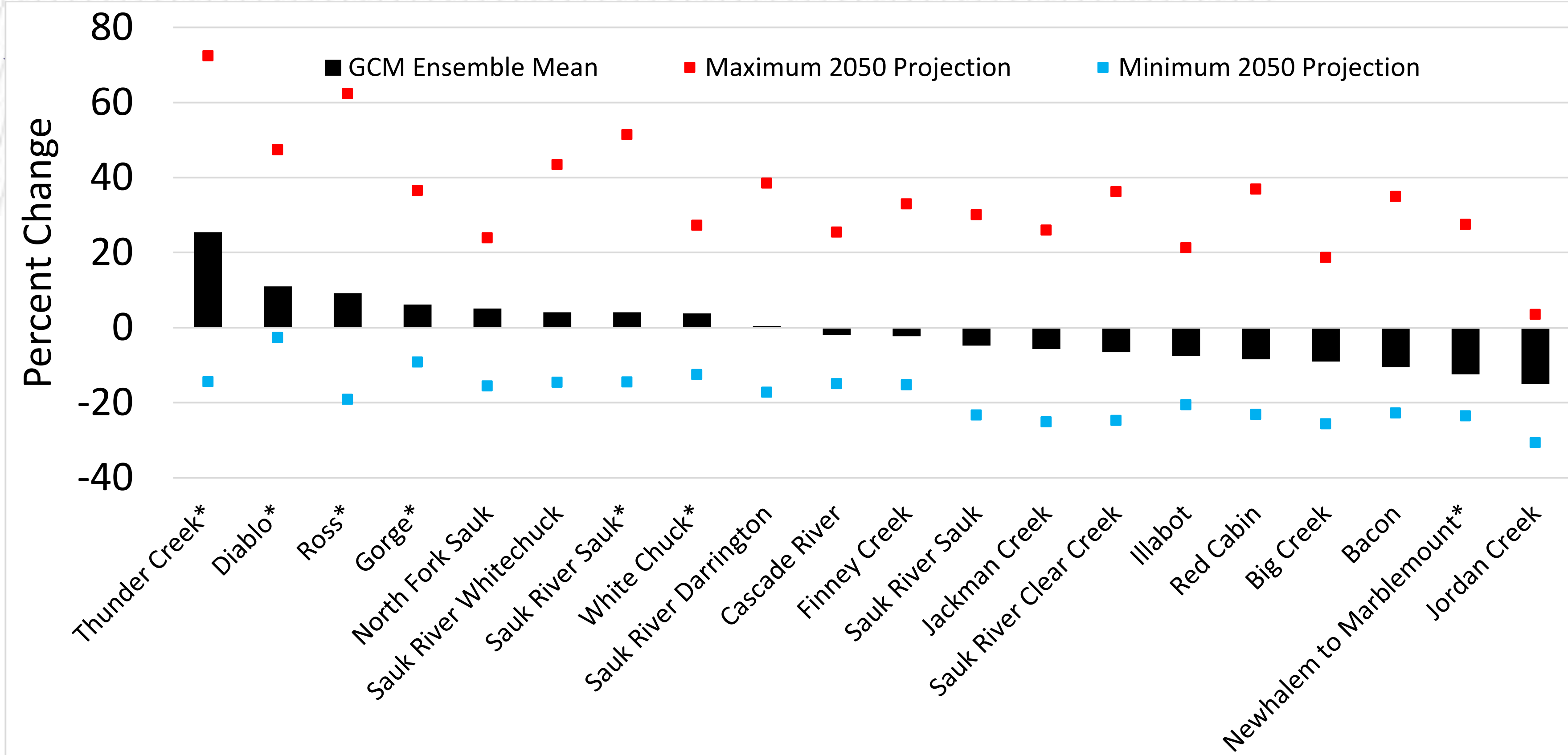

Figure 18. Distibution of 100 year flood (1:100 recurrence interval). Baseline 100 year flood values were taken from the historic period 1980-2010 and compared to the mid-century period 2035-2065, and the percent change is shown. Squares indicate the maximum (red) and minimum (blue) change projected by the ensemble of GCMs. Locations marked with one asterisk (*) have sufficient length of observations to conduct a streamflow bias correction.

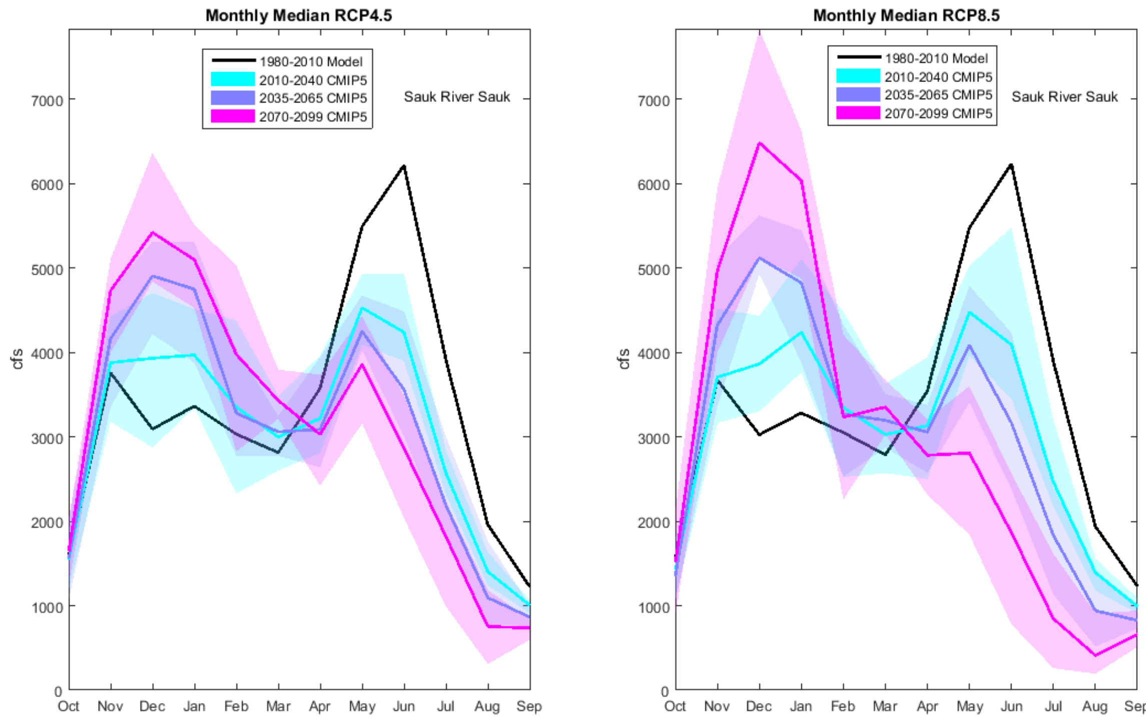

Figure 19. Monthly median (50% exceedence probability) for the Sauk River near Sauk for the current conditions (black line) and three future 30 year periods (blue, purple, pink). The lines represent the GCM model ensemble mean, the shaded areas represent the range of GCM predictions for each time period. Panel (a) gives shows model results for RCP 4.5 and panel (b) shows results for RCP 8.5.

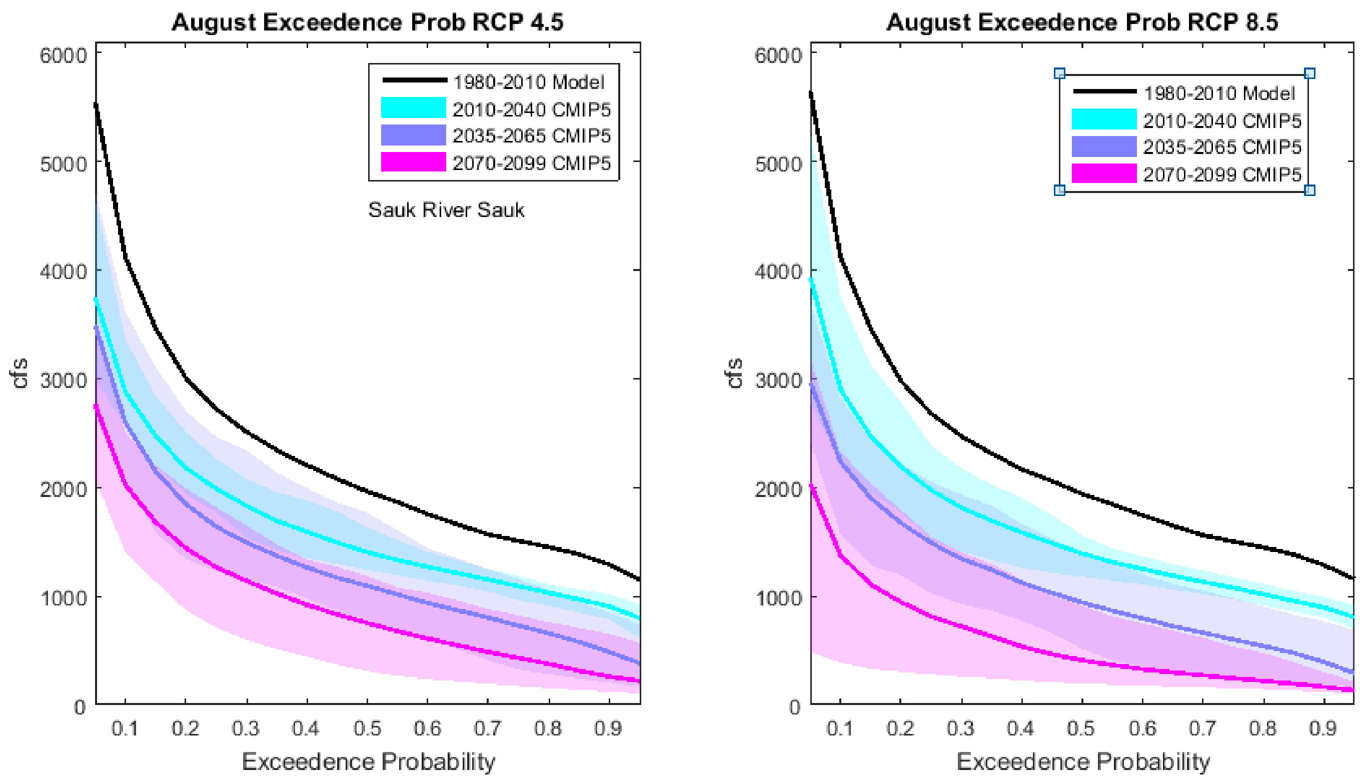

Figure 20. Distibution of August streamflow (5%-95% exceedence probability) for the Sauk River near Sauk for the current conditions (black line) and three future 30 year periods (blue, purple, pink). The lines represent the GCM model ensemble mean, the shaded areas represent the range of GCM predictions for each time period. Panel (a) gives shows model results for RCP 4.5 and panel (b) shows results for RCP 8.5.

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