Winter 2018

# Modeling the Effects of Climate Change on Stream Temperature in the Nooksack River Basin

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# MODELING THE EFFECTS OF CLIMATE CHANGE ON STREAM TEMPERATURE IN THE NOOKSACK RIVER BASIN

By

Stephanie E. Truitt

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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# Master's Thesis

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Stephanie E. Truitt

February 23, 2018

**Modeling the Effects of Climate Change on Stream Temperature in the Nooksack River Basin**

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Stephanie Truitt
February 2018

**Abstract**

Stream temperatures in mountain streams in the western Cascade Mountains are heavily influenced by factors such as discharge, air temperature, and as in the case of the Nooksack River Basin in northwest Washington State; snow and glacial melt. The Nooksack basin is sensitive to warming climates due to the regions moderate Pacific maritime climate. Previous modeling studies in the upper Nooksack basins indicate a reduction in snowpack and spring runoff, and a recession of glaciers into the 21st century due to global climate change. How stream temperatures will respond to these changes is unknown. We use the Distributed Hydrology Soil Vegetation Model (DHSVM) coupled with a glacier dynamics model to simulate hydrology and the River Basin Model (RBM) to model stream temperature from present to the year 2090 in the North, Middle, and South forks of the Nooksack River basin.

We simulate forecasted climate change effects on hydrology and stream temperature using gridded daily statically downscaled data from 10 global climate models (GCMs) of the Coupled Model Intercomparison Project Phase Five (CMIP5) with two different representative concentration pathways (RCP) RCP4.5 and RCP8.5. Simulation results project a trending increase in stream temperature into the 21st century in all three forks of the Nooksack. There is a strong correlation between rising stream temperatures and warming air temperatures, decreasing stream discharge; and snow and glacial meltwater. We find that the highest stream temperatures and the greatest monthly mean 7-day average of the daily maximum stream temperature (7-DADMax) values are predicted in the lower relief, unglaciated South Fork basin. For the 30 years surrounding the 2075 time period, the mouth of the South Fork is forecasted to have a mean of 115 days above the 16 °C 7-day average of the daily maximum stream temperature threshold. Streams in the Middle and North fork basins with higher elevations that sustain more

snow and glacier ice are slower to respond to warming climates due to meltwater contributions, especially in the next 50 years.  Towards the end of this century, when snowpack and glacial volume is greatly decreased, the buffering effect of meltwater declines, and the North and Middle forks experience larger increases in mean daily stream temperature. For the 30 years surrounding the 2075 time period, the mouths of the Middle and North forks are forecasted to have means of 35 and 23 days, respectively, above the 16 °C 7-DADMax threshold.

**Acknowledgements**

Note that for publication purposes, I chose to use first-person plural rather than singular throughout the text because there will be multiple authors on the final manuscript submitted for publication.

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**1.0 Introduction**

The Nooksack River in northwest Washington State provides valuable habitat for salmon species that have an important cultural and economic value to regional First Nations Tribes (Figure 1). Projected warmer air temperatures into the 21$^{st}$ century may increase stream temperatures and alter migration and spawning habitat in the basin, especially in the late summer months, adding more stress on already endangered salmon. As such, it is critical to understand how stream temperatures will change in the Nooksack due to forecasted warming climates (Black et al., 2003).

In the Pacific Northwest (PNW), global climate models (GMCs) project that the mean air temperature will increase approximately 2 °C to 6°C from historic temperatures through 2099 (Morgan et al., 2017; Abatzoglou and Brown, 2012). In general, hydrology modeling in the PNW has predicted higher winter streamflow due to more precipitation falling as rain rather than snow, an earlier snowmelt season and lower spring streamflow due to a reduced snowpack; and a decrease in summer flows due to forecasted warming climates (Elsner et al., 2010; Vano et al., 2010). Similar trends were observed for the upper mountainous region of the Nooksack drainage (Morgan et al, 2017; Murphy, 2016; Dickerson-Lange and Mitchell, 2013). Modeling results of Murphy (2016) in the Nooksack basin predict that the snow water equivalent (SWE) may decrease by more than half, and the glacial extent is projected to decrease by up to 88% by the end of the 21$^{st}$ century. These projected changes result in significant reductions in summer baseflows supported by snow and ice melt, resulting in potentially higher stream temperatures (Murphy, 2016).

Stream temperature is an important indicator of the ecological health of a river system. Thermal load is considered by the U.S. Environmental Protection Agency (EPA) to be a

pollutant and is regulated under the Total Maximum Daily Load (TMDL) program (Butcher et al., 2016).  Changes in stream temperature can affect metabolic rates, physiology, and lifecycles of aquatic organisms (Poole and Berman, 2001). Permanent changes in stream temperature may result in a permanent alteration of the biology of a river system (Isaak et al., 2012), and thus, it is important to determine the magnitude and timing of stream temperature changes for river systems that are at risk. Climatic factors have the largest effect on stream temperatures, indicating that shifts in air temperature or precipitation will also cause changes in stream temperature. Physical characteristics of the stream also strongly influence stream temperature, including channel morphology, channel width and depth, as well as riparian canopy conditions (Sun et al., 2014).

Located in the North Cascades in northwest Washington State, the Nooksack River drains an area of 2300 km$^2$ with a mean annual discharge of approximately 110 m$^3$/s (3870 cfs) into Bellingham Bay in the Salish Sea (Dickerson-Lange and Mitchell, 2014). Elevation in the basin varies from sea level to 3286 m at the peak of Mt. Baker. Due to highly varied terrain, the Nooksack River Basin experiences a wide range of climate conditions.  During the historical period, 1981–2010, average annual precipitation varied from about 820 mm near sea level to 5655 mm near the summit of Mount Baker, and had a basin mean of about 2290 mm (PRISM Climate Group, 2017). About 70% of the precipitation occurs between October and April. The Nooksack basin is classified as a transient rain-snow basin due to its maritime climate, meaning forecasted warming climates will produce more rain than snow in the future (Dickerson-Lange and Mitchell, 2014).

The focus of our study is the upper 1550 km$^2$ of the basin, and includes three sub-basins, the South Fork Nooksack (South Fork), Middle Fork Nooksack (Middle Fork), and North Fork

Nooksack (North Fork). Both the North and Middle forks contain high elevation terrain; 49% of the North and Middle fork basins is above 1000 m in elevation (Table 1). The high elevations of the Middle and North forks basins contain glaciers, about 7.6 km$^2$ in the Middle Fork basin and about 25.8 km$^2$ in the North Fork basin (Table 1). Streamflow in the North and Middle forks rely in part, on glacial melt during the late summer, as well as snowmelt and precipitation (Bach, 2002; Grah and Beaulieu, 2013). Mass balance studies suggest that from 1990 to 2010, glaciers on Mt. Baker lost 12-20% of their entire volume (Pelto and Brown, 2012). Other glaciers found in the basin have followed similar trends of volume loss, which would affect any glacier-fed stream in the Nooksack River basin. Evidence suggests that this trend will continue from 2010 onward, which would have a cooling effect on headwater temperatures in the North and Middle forks (Pelto and Brown, 2012). The channels and stream forest buffers of the North and Middle forks have been minimally altered over the last 50 years since much of their area is in the Mount Baker National Forest. Only 25% of the South Fork basin is above 1000 m in elevation and thus it gets less snow than its higher elevation counterparts, the North and Middle forks. The maximum elevations in the South Fork basin are just over 2000 m and lack glaciers. As such, South Fork streamflow is supported by seasonal snowpack, precipitation, and groundwater, making it more susceptible to warming climates. The lower regions of the South Fork basin are dominated by agriculture, which has resulted in warmer stream temperatures (Butcher et al., 2016).

Several stream temperature modeling efforts have focused on the Puget Sound region, however many of these studies exclude the Nooksack River basin (e.g., Cao et al., 2016; Mantua et al., 2010; Battin et al., 2007). Cao et al. (2016) find that climate change will have a substantial effect on stream temperatures in all basins that drain into the Puget Sound, excluding the

Nooksack, especially during the summer months. On average, they find that stream temperatures will increase from 1 to 3.1 °C by late-century for the low emissions representative concentration pathways (RCP) RCP 4.5 scenario and 1.7 to 5.3 °C for the high emissions RCP 8.5 scenario for all basins south of the Nooksack which empty into the Puget Sound. Winter stream temperature increases are also significant in this study. Alternatively, modeling studies, which have included the Nooksack River region, are too coarse to inform watershed management practices (e.g., Wu et al., 2012; Hamlet and Lettenmaier, 2007). The large-scale PNW stream temperature modeling study of Wu et al. (2012) predicted stream temperature increases from 0.55 C in the 2020s to 1.68 C in the 2080s, though increases are higher for the summer months. These estimates are averages for several Washington, Idaho, and British Columbia river systems. Wu et al. also note that snow dominant basins are more influenced by climate change than transient and rain dominated basins. These estimates are much lower than Cao et al.'s stream temperature increase estimates, though the resolutions of these studies vary greatly. Mantua et al. (2010) also estimate the effects of climate change on stream temperature on the lowland portion of the Nooksack River. Our study provides higher resolution results using a dynamic stream temperature model.

The EPA, in cooperation with local stakeholders in the South Fork basin, produced a Total Maximum Daily Load (TMDL) for water temperature of the South Fork in 2014, as required by Section 303(d) of the Federal Water Pollution Control Act of 1972. Stream temperatures were modeled for future climate change conditions using the QUAL2KW stream temperature model (Pelletier et al. 2006). The results predicted that by the year 2080, the maximum average stream temperature for the South Fork will increase by over 5 °C, with the upper most reaches being most impaired (Butcher et al., 2016). They also found that the three variables, which contribute most to stream temperature, increase were an increase in air temperature, increase in tributary

and groundwater temperature, and decreased flow.  We chose to extend our study to include the South Fork for several reasons. Our modeling suite provides higher resolution results, includes more tributaries, and the River Basin Model (RBM; Yearsley, 2009; Yearsley, 2012; Sun et al., 2014) is a more robust, dynamic stream temperature model than the QUAL2KW. Also, in order to adequately compare the climate responses of three distinct basins, it is important to apply consistent modeling tools. Our study also uses 20 potential climate change scenarios to force the hydrology, which provides a range of future results, while the EPA used three future climate scenarios for their South Fork TMDL study. Additionally, the TMDL report focuses on extreme low flow events, rather than average conditions of the basin throughout the century. While extremes conditions can be useful for management purposes, they do not provide a good overall snapshot of basin wide conditions. The effects of snowmelt on stream temperature are also neglected in the TMDL, which proves to be an important variable in modeling stream temperature in the Nooksack Basin.

The upper reaches of the Nooksack River provide a unique modeling opportunity to examine how differences in hydrology, elevation, ice cover, and land use affect stream temperature. The proximity of these three basins allows us to determine not only how the physical characteristics of the basins differ, but also how these differences affect each basin's response to climate change. We use projected global climate scenarios and numerical models to examine future variability on streamflow and stream temperatures in the upper three forks of the Nooksack River basin at climate intervals surrounding the years 1995, 2025, 2050, and 2075.  We also address how the timing of maximum stream temperatures is affected by changes in air temperature, flow, and melt changes due to climate change.

**2.0 Methods**

*2.1 DHSVM Hydrology Modeling*

Hydrology modeling employs the model and methods of Murphy (2016), who used the Distributed Hydrology Soil Vegetation Model (DHSVM; Wigmosta et al., 1994) coupled with a glacier dynamics model (DHSVM-GLACIER; Naz et al., 2014; Clark et al., 2015; Frans et al., 2015). For our study, Murphy's calibrated DHSVM-GLACIER model was modified to include the algorithms of DHSVM 3.1.2 (or DHSVM-RBM; Sun et al. 2014) that produce the hydrology and energy inputs required for the RBM. Modifications included riparian shading algorithms, which consider tree height, buffer width, and monthly leaf area index (Sun et al. 2014). The hydrology model, herein referred to as the DHSVM-GLACIER-RBM, is physically based and requires meteorological inputs and physical basin characteristics and simulates hydrologic variables including stream discharge, snow water equivalent, and glacier melt. Physical layers include land cover, soil type, soil depth, elevation, and shadow maps derived from publicly available sources (Wigmosta et al., 1994). We use a 50 m grid for the Nooksack basin. Meteorological inputs for the DHSVM-GLACIER-RBM include air temperature, wind speed, precipitation, shortwave radiation, and longwave radiation. The model was calibrated using historical gridded meteorological data (Livneh et al., 2013) that were biased corrected and disaggregated into 3-hr time steps (Murphy, 2016). We simulate forecasted climate change effects, including glacial recession on streamflow, using gridded daily statistically downscaled data from 10 GCMs of the Coupled Model Intercomparison Project Phase Five (CMIP5) with RCP4.5 and RCP8.5 forcing scenarios developed using the multivariate adaptive constructed analogs method (MACA; Table 2; Abatzoglou and Brown, 2012). The gridded MACA data were also biased corrected and disaggregated into 3-hr times steps (Murphy, 2016).

*2.2 RBM Stream Temperature Modeling*

We use the RBM stream-temperature model (Yearsley, 2009; Yearsley, 2012; Sun et al., 2014) to simulate historical and forecasted stream temperatures in the upper Nooksack River basin. Energy and hydrology outputs from the DHSVM-GLACIER-RBM are inputs for the RBM stream temperature model, including stream inflow and outflow for each stream segment in a given basin. The RBM is a one-dimensional model, which solves time dependent equations for the conservation of thermal energy between the air-water interface using a semi-Lagrangian method (Yearsley, 2009, 2012). The model requires initial headwater temperatures. Downstream segment heat exchanges include net solar radiation, net longwave radiation, sensible heat flux, latent heat flux, groundwater, and advected heat from adjacent tributary segments. To obtain solutions to these equations, the model tracks parcels of water through the river basin and determines results for points on the river basin grid. The RBM has been used with the DHSVM in several river basins in the Pacific Northwest (Cao et. al., 2016, Sun et al., 2014).

The RBM requires two sets of parameters: Mohseni parameters, which determine the initial headwater conditions, and Leopold parameters, which determine the relationship between discharge, stream depth, and stream velocity (Figure 2). These parameters are calculated from existing data sets, such as those recorded at stream gauging stations managed by the USGS (Figure 1) as well as from field data (Table 3). A smoothing parameter is also applied to smooth high frequency fluctuations in air temperature derived from the equation below.

$$T_{smooth} = \tau * T_{air}(t) + (1 - \tau) * T_{air}(t - 1) \tag{1}$$

Where in this study,

$$\tau = \frac{1}{(smoothing\ period)} = \frac{1}{(7\ days * 8\ timesteps\ per\ day)} \qquad (2)$$

We measured stream width, depth, velocity, and discharge data at 17 streams across all three basins. These sites vary widely in stream order, elevation and distance from the mouth of the river, giving us a wide range of parameters to experiment with during the calibration phase. Most previous studies have used data at a single stream gage to calculate these parameters for river systems (Cao et al., 2016; Sun et al. 2014; Yearsley, 2009).

*2.2.1 Mohseni Parameters*

The RBM requires initial stream temperature conditions at headwater locations which we estimate using the Mohseni et al. (1998) statistical method. The Mohseni method uses the relationship between air temperature and stream temperature to estimate headwater temperature using the following nonlinear regression model:

$$T_{head} = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{smooth})}} \qquad (3)$$

The parameters α, β, γ, and μ are estimated using least squares minimization. The parameter $\alpha$ is an estimate of the minimum stream temperature, β represents air temperature at the inflection point of the function, γ represents the slope of the function, and μ represents the estimated minimum stream temperature (Mohseni et al., 1998). We use stream temperature measurements from the USGS stream gages (Figure 1) as well as data collected by the Nooksack Indian Tribe at several locations throughout the basin. In some cases, these measurements were

at headwaters, however, many of these stream temperature measurements were made at streams tributary to the main stems of each of the North, Middle, and South forks of the Nooksack River. Air temperature measurements at stream temperature measurements sites were obtained from the PRISM Climate Group when corresponding air temperature measurements were unavailable from field measurements. Distance between the stream gauging station and observed air temperature sites used for the calculations does not significantly impact the goodness of fit of the parameter calculations (Mohseni et al., 1998). From these air and stream temperature measurements we obtain the four Mohseni parameters ($\alpha$, $\beta$, $\gamma$, and $\mu$). The RBM has the flexibility to apply multiple sets of Mohseni parameters to one basin, if data are available. There are documented problems with using nonlinear regression models (such as the Mohseni method) to predict stream temperature of long time periods. Alternative methods proposed by Arismendi et. al. (2014) require extensive field measurement and computing power. However, the absence of long stream temperature time series and other basin wide observed data mean that linear and nonlinear regression models are a viable option for determining headwater stream temperatures. Arismendi et al. (2014) note that that net solar radiation, which is taken into account in determine down-stream temperatures in the RBM, is perhaps the most important variable in modeling stream temperature.

*2.2.2 Leopold Parameters*

The RBM estimates a change in water temperature across a stream segment using the speed of the water parcel, the water depth, and the energy budget at the air-water interface of the stream (Yearsley, 2009). The RBM uses the Leopold parameter to estimate stream speed, (u), as

well as depth, (D), for each stream segment in the basin using discharge values from the

DHSVM-GLACIER-RBM and the following relations.

$$D = aQ^b \tag{4}$$

$$u = cQ^d \tag{5}$$

Where D is depth, $u$ is velocity, Q is discharge, and $a$, $b$, $c$, and $d$ are empirical constants

determined from discharge rating curves (Yearsley, 2009; Leopold and Maddock, 1953). To

estimate the empirical constants, we used depth, velocity and discharge measurements at the

USGS stream gauges; and at other stream sites using the methods of Buchanan and Somers

(1969). Minimum depths and velocities can also be applied to each of the stream segments. For

this work, we used a default minimum depth of 0.5 feet. However, we did modify this value as

part of the parameter estimation and calibration process in each of the three basins. Leopold

parameters can also be assigned to individual reaches such that Leopold parameters can vary

from stream segment to stream segment within a basin.


2.2.3 *Riparian Shading*

Riparian shading inputs for the DHSVM-GLACIER-RBM model are based on riparian

conditions used in the Cao et al. (2016) study which were derived from Alberti et al. (2004). Cao

et al. modeled all basins that drain into the Puget Sound except for the Nooksack basin, and used

a variety of riparian conditions including those based on current (2002) climate conditions and

historical climate conditions. We use the 2002 riparian shading conditions from Cao et al. in our

Nooksack modeling. The Cao et al. study used a tree height of 10 m which is based on a King

County (2005) study, however we altered this tree height to 25 m to better represent the forests of the North Cascades. Generally, the Nooksack basin is characterized by second growth Douglas fir, western red cedar, and western hemlock (Brennan, 2007). We also changed the leaf area index (LAI) values to be more representative of the North Cascades forests (Table 4). The LAI can be altered on a month by month basis; however we chose to keep LAI values constant to represent the coniferous forests in the Nooksack basin. We also used a bank canopy distance of 0.01 m and a buffer width of 5 m, as in the Cao et al. study. To focus our assessment on the influence of snowmelt and glacier melt on stream temperature, we chose to maintain constant riparian vegetation conditions throughout all three basins for all modeling scenarios. This is a limitation, as there are likely differences between the three upper basins of the Nooksack, and they may change in the future.

*2.3 Stream Temperature Calibration*

The historical meteorological forcings (Livneh et al., 2013) and the calibrated DHSVM-GLACIER-RBM are used to produce energy variables, streamflow, snowmelt, glacial meltwater, and other outputs necessary for the RBM. Calibration of the RBM model includes comparison of modeled stream temperature against observed stream temperatures at the three USGS stream gages located on the main stems of each of the three forks (Figure 1): North Fork (12205000), Middle Fork (12208000), and South Fork (1221000). The North, Middle, and South Fork temperatures are calibrated for water years 2009-2011. The calibration time was limited by available stream temperature data at the USGS stream gauging sites (starting in 2009), and the time series limitation of the gridded historical meteorological data (Livneh et al., 2013) which terminates in 2011. The Nash-Sutcliffe Efficiency Coefficient (Nash and Sutcliffe, 1970) is used

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to determine how well the model performed when compared to observed historical data. We also calculate Root Mean Square Error (RMSE) and examine scatter plots of modeled versus observed temperatures to determine goodness of fit of the model. If the model did not accurately reproduce observed stream temperature during the calibration period, parameters were adjusted based on the physical characteristics of the basin. Modifiable parameters include the Leopold and Mohseni coefficients, as well as the smoothing parameter and riparian shading inputs to the hydrology model. We aggregated the 3-hr outputs and examined the calibration results for their accuracy at daily time intervals, focusing on the spring and summer months when stream temperature is the warmest.

*2.4 Future Stream Temperature Simulations*

We used the bias-corrected gridded MACA data (Abatzoglou and Brown, 2012) and the DHSVM-GLACIER-RBM to produce the necessary forecasted energy and hydrology outputs for the RBM. We chose ten different MACA GCMs based on their ability to represent future climate in the Pacific Northwest (Rupp et al., 2013). We used RCP4.5 and RCP8.5 narratives with each GCM. In total, 20 DHSVM-GLACIER-RBM simulations are performed for each of the three sub-basins of the Nooksack River. We performed these simulations using the Western Washington University Computer Science Department's computing cluster. Each node of the 22 node cluster consists of 2 x 6-core Xeon E5 processors, for a total of 24 threads per system and 128 GB of RAM. The cluster can perform many simulations simultaneously, reducing the computing time from several months to just a few weeks.

Outputs of the DHSVM-GLACIER-RBM are used in the RBM to simulate stream temperature at the mouth of each of the three forks. Stream temperature is simulated in 3-hr time

steps, for the years 2008 to 2098. All data analysis is performed using R, an open sourced

statistical computing package (R Core Team, 2015). In keeping with the methods of Murphy

(2016), we examined long term stream temperature trends in each of the three basins by

determining 30-year mean temperatures centered on 2025, 2050, and 2075 and compared them to

a 30-year mean hindcast from 1981 to 2011. We also examined the data for maximum values, by

calculating 30-year mean 7-DADMax stream temperatures. The 7-DADMax is the 7-day average

of the daily maximum stream temperature (Butcher et al., 2016) and is used by the EPA and

other government entities to determine viability of fish species. We examined the results for 7-

DADMax values which fall above 16°C, which is the temperature set by the Washington State

Department of Ecology (WSDOE) as the maximum safe temperature on the South Fork for "core

summer salmonid habitat, spawning, rearing, and migration." Additionally, we looked at the

correlation between stream temperature and discharge, snow and glacial melt, and air

temperature to determine if the relationships between these variables change as climate change

progresses. Correlation coefficients were calculated based on the daily means for all GCM and

RCP scenarios. The means of all RCPs 4.5 scenarios and all RCP 8.5 scenarios were then

calculated for the hindcast period, and the 30 years surrounding 2025, 2050, and 2075.


**3.0 Results**

*3.1 RBM Calibration*

After initial calibration trials on the South Fork, it became clear that from approximately

May 15th to July 15th of each year the RBM overestimated stream temperatures by up to 7.0

degrees Celsius compared to observed daily mean stream temperature from the South Fork

USGS stream gauge. We attribute this difference to snowmelt entering the headwaters of the

river system in spring and early summer at lower temperatures than what the model predicted for the headwaters using the Mohseni relationship. As air temperature increases, snowmelt also increases, causing cooler than expected stream temperatures on hot days. We anticipated this to be more of an issue in the high elevation, and glaciated Middle and North Fork basins.  To improve the model, we began by altering the Mohseni parameters at higher elevations nearer to the headwaters of the river, which produced better results than using Mohseni parameters near the main stem or on low elevation tributaries. Across the three basins, we had a total of 17 sites for which we calculated Mohseni parameters. Initially, we attempted to use all the Mohseni parameters calculated for each particular basin. However, these results proved unsatisfactory. Any calibration simulation performed with Mohseni parameters calculated at lower elevations overestimated stream temperatures during the summer months. We chose to use one high-elevation set of Mohseni parameters for each basin for this reason.

Minimum depths for each fork are also adjusted to better reproduce observed values during the calibration period. The minimum stream depths for each segment are user specified in the RBM, and we apply uniform minimum stream depths for each individual basin. Increasing minimum stream depth within the model prevents stream temperatures from increasing unrealistically high on days when air temperature is high. Stream depth measurements from our field sites substantiate these changes in minimum stream depth. For the South Fork, which is overall the warmest of the three forks, the minimum stream depth was set at 0.5 feet, and the cooler Middle and North Fork minimum depths were set at 1.5 feet and 1.75 feet respectively (Table 4). Note that these are not fixed stream depths, they represent minimum depths allowed by the model. Stream depths vary by time step within the simulations.

Adjusting the Mohseni and Leopold parameters did not adequately capture the snowmelt effect during the late summer in the South Fork of the Nooksack. To maintain the physically based nature of the stream temperature model and to capture the snowmelt effect, we developed an algorithm in the RBM based on a snowmelt threshold (SMT) to moderate summer temperatures.  The DHSVM-GLACIER-RBM produces basin wide average snowmelt at each time step that we processed as input to the RBM. We used this as a proxy since the snowmelt output does not account for what actually makes it to a stream. The RBM algorithm applies fixed cool headwater temperatures when a SMT is reached past Julian Day 120 (Table 4). The RBM algorithm reverts back to the air temperature-based Mohseni relation to estimate headwater temperatures after a minimum SMT is reached in the summer. The basin specific SMT values were determined by examining the snowmelt time series throughout the 21st century using RCP 8.5 GCMs to ensure the RBM algorithm would be applicable in our forecast modeling simulations. We compared observed stream temperature values and simulated values using the RBM without the SMT to daily basin average snowmelt values to determine what the melt value was during the time period where simulate stream temperatures were warmer than observed stream temperatures.

Murphy (2016) predicted that glacial meltwater would contribute from 15 to 50% of the total streamflow in the late summer in the Middle and North forks of the Nooksack into the 21st century. To account for the effects of glacier meltwater on headwater temperatures, we applied a glacial-melt threshold (GMT) algorithm in tandem with the SMT algorithm in the Middle and Nork fork basins. The SMT is most important in the spring and early summer, and the GMT is most important from July-October. We use the percent of glacial melt as streamflow as the variable to trigger the GMT. If the GMT threshold is met, the headwater temperatures are fixed

at a cooler temperature (Table 4). If the percent glacier melt is below the GMT, the model reverts to the Mohseni method. The volume of streamflow as melt is found by comparing DHSVM-GLACIER-RBM simulation hydrographs with and without the dynamic glacier module activated (Murphy 2016). For the Middle and North forks, we performed simulations using a combined glacial and snowmelt threshold in the RBM to determine what effect glacial meltwater has on stream temperature in the glaciated basins.

Ultimately, after adjusting Mohseni, Leopold, SMT and GMT values, we achieved satisfactory calibration at the USGS gages in each of the basins. The Nash-Sutcliffe efficiency coefficient (NSE) values for the North and Middle forks are 0.86 and 0.64 respectively for daily stream temperature values. Peak stream temperature values are very well captured in the North and Middle forks (Figure 3), while there is still some overestimation of stream temperature values in the summer. Late fall, winter, and early spring temperatures are well captured in the North Fork, with an overall RMSE value of 0.93 °C. The Middle Fork USGS gage only recorded stream temperature for the summers during the 2008-2011 calibration period, making it impossible to calibrate the winter period for the Middle Fork. The NSE value for the Middle Fork is 0.64, which is low compared to the North Fork. We attribute this low value to the fact that there are no observed winter or early spring stream temperature values during the calibration period at the USGS stream gage on the Middle Fork. As such, the NSE is calculated solely on the summertime values, rather than the entire year as with the South and Middle forks. The RMSE value for the Middle Fork is 1.19°C which is comparable to the North Fork value, and lower than the South Fork value. Stream temperatures in the South Fork are captured well throughout the year (Figure 3, Figure 4) with an NSE value of 0.89 and a RMSE value of 1.54 °C. Some simulated peak summer stream temperatures are overestimated even after accounting for

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snowmelt for the calibration period, though the modeled values throughout the rest of the year are matched well to the observed values.

*3.2 Forecasted RBM Stream Temperature Simulations*

For comparative purposes, we used the calibrated models and the historical gridded meteorological data to simulate 30-year hindcasts (1981-2011) and determined the daily average stream temperature at the mouths of the three forks in the Nooksack (Figure 5).

*3.2.1 South Fork*

Forecasted model results at the mouth of the South Fork indicate an increase in stream temperature when compared to the 30-year hindcast mean in all 20 modeling scenarios for means surrounding the 30 years surrounding 2050 and 2075 (Figure 6; Table 5). During the 2025 time period, however, stream temperatures increase only during the summer months. As expected, forecasted stream temperatures deviate from the hindcast scenario more appreciably during the summer months, ranging from a 2.1°C increase in temperature during August for the 2025 time period for RCP 4.5 scenario, up to 5.8°C during June for the 2075 time period for the RCP 8.5 scenario. Noticeable deviations between stream temperature means for the RCP 4.5 and 8.5 scenarios do not begin until after 2050. Later in the century (30-years surrounding 2075) the RCP 8.5 mean is warmer than the RCP 4.5 mean by 2 to 3°C during the peak temperature summer months. During late fall, winter, and early spring for all three study periods stream temperature between the two RCP scenarios deviates by approximately 1°C.

We also calculate the 7-DADMax for each time period for the South Fork, where the greatest increases occur from May through August. The mean 7-DADMax values from the RCP 4.5 and 8.5 scenarios do not differ until the 2075 time period (Table 6). In the peak stream temperature month of August 7-DADMax increases by approximately 1.7 °C for RCP 4.5 and

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1.8 °C for RCP 8.5 from the hindcast period to 2025, and by 3.67 °C and 5.4 °C for RCPs 4.5 and

8.5 respectively, by the 2075 time period. The South Fork experiences multiple days above a 16

°C 7-DADMax; the temperature set by the WSDOE as the maximum temperature on the South

Fork of the Nooksack for "core summer salmonid habitat, spawning, rearing, and migration"

(Butcher et al., 2016).  The mean number of days above this 7-DADMax threshold for the

hindcast is 41 days. By 2025, both RCPs project an average of 78 days per year where the stream

temperature above 16 °C, and by the 30 years surrounding the 2075 time period this number

increases to 115 days above the 16 °C threshold (Figure 7).  Note that these values are based on

means of the MACA ensemble. Warmer stream temperatures are predicted with the warmest

projected GCM (HadGEM2-ES RCP 8.5; Table 7).

There is a correlation between deceasing snowmelt and stream discharge with increasing

stream temperatures into the 21st century. During the hindcast period, snowmelt begins to

decrease rapidly during the month of July. By 2025 the snowmelt begins to taper off in May and

by late century, this decline begins as early as March. The correlation coefficient between

snowmelt and stream temperature increases from -0.77 during the hindcast period up to -0.90 for

the 2075 time period for the RCP 4.5 mean stream temperature scenario (Table 8, Figure 8).

Correspondingly, spring and summer discharge also begins to decline earlier and earlier by 2075

(Figure 8) and the correlation coefficient between discharge and stream temperature increases

from -0.77 during the hindcast period to -0.93 for RCP 4.5 in 2075 (Table 8).


*3.2.2 Middle Fork*

Forecasted model results at the mouth of the Middle Fork indicate that the largest change

in stream temperature occurs mid-to late century (Figure 6; Table 5). By the 2075 time period

there is much greater variability in the spread of mean temperatures between the two RCP

scenarios for each of the 10 GCMs. The means of the RCP 4.5 and 8.5 scenarios do not vary

greatly through 2050. By 2050 there is a 1 to 2 °C difference during the months of July through

September, but by 2075 the difference reaches almost 5 °C for July through September (Figure

6). Although mean summer temperature increase in 2025 is around 1.4°C, this increase reaches

5.6°C for RCP 4.5 and 8.2°C for RCP 8.5 by 2075 (Table 5).

The 7-DADMax temperatures also increase the greatest amount during the summer,

particularly during the month of August (Table 6). In July the 7-DADMax temperatures increase

by approximately 0.8 °C for RCPs 4.5 and 8.5. By 2075, the 7-DADMax stream temperatures

increase from the hindcast period by 5.2°C for RCP 4.5 and by 7.7°C for RCP 8.5. The number

of days above the 16 °C threshold increases from an average of one day per year during the

hindcast period to an average of five days for RCPS 4.5 and 8.5 for the 2025 time period, to an

average of 35 days during the 2050 time period, to 62 days during the 2075 time period (Figure

7). Warmest stream temperatures are predicted by the HadGEM2-ES RCP 8.5 scenario (Table 7).

Similar to the trend in the South Fork, snowpack melts out earlier in the year into the 21st

century in the Middle Fork. The hindcast results indicate that snowmelt declines rapidly to zero

in mid-July in the Middle Fork (Figure 9), however by 2025, snowmelt begins a rapid decline in

June. The timing of snowmelt is similar in 2050, and by late century snowmelt decline begins as

early as April for RCPs 4.5 and 8.5. The correlation coefficient for snowmelt and stream

temperature is -0.47 indicate a somewhat weak negative correlation between the two variables.

By 2075 the correlation coefficient between snowmelt and glacial melt and stream temperature

rises to a stronger negative correlation of -0.77 and -0.75 for RCPs 4.5 and 8.5 respectively

(Table 8). Discharge in the Middle Fork follows a similar pattern to snowmelt throughout the

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century with discharge for RCPs 4.5 and 8.5 beginning to ebb earlier in the year by 2050. The correlation coefficient between discharge and stream temperature increases from -0.72 during the hindcast period to -0.92 and -0.90 for RCPs 4.5 and 8.5 respectively by the 2075 time period.

*3.2.3 North Fork*

Like the Middle Fork, the forecasted model results at the mouth of North Fork indicate that the largest change in summer stream temperature occurs mid-to late century (Figure 6; Table 5). The mean stream temperatures for RCP scenarios 4.5 and 8.5 show little difference through the year 2050, though these means begin to diverge by several degrees by 2075 during the summer months (Figure 6). Both mean stream temperatures for RCP scenarios 4.5 and 8.5 remain similar during the winter and spring months, and are slightly warmer than the hindcast stream temperatures. By 2075 summer stream temperatures may increase anywhere from 3.7°C for RCP 4.5 and up to 5.5°C for RCP 8.5, while winter stream temperatures also increase significantly by up to 2°C (Table 5).

The increase in 7-DADMax stream temperatures is greatest during the months of July and August for the 2025, 2050, and 2075 time periods (Table 6). For the month of August 7-DADMax values increase by 0.8°C for RCPs 4.5 and 8.5 by the 2025 time period. By the 2075 time period, the 7-DADMax temperature increases by 4.1°C and 5.8°C for RCPs 4.5 and 8.5 respectively. During the hindcast period, the North Fork does not exceed the 16°C 7-DADMax threshold set by WSDOE for the South Fork. This trend continues during the 2025 time period, where the modeled results indicate that no days will exceed the 16 °C threshold. However, by the 2050 time period, an average of five days per year will exceed this threshold, and by the 2075

time period, 23 days per year will exceed this threshold (Figure 7). Warmest stream temperatures are predicted by the HadGEM2-ES RCP 8.5 scenario (Table 7).

As with the South and Middle forks, stream temperature in the North Fork increases with air temperature throughout the century (Figure 10). Air temperature and stream temperature are least similar during the summer months, because other factors such as melt water influence stream temperature. The correlation coefficients between air temperature and stream temperature remains steady at 0.97 and 0.98 for all three study periods. This high correlation coefficient is due to the advection of thermal energy within the water column. This timing of the minimum discharge begins to occur earlier in the calendar year which correlates with peak stream temperatures occurring several days to a few weeks earlier in the year by 2075 (Figure 6, Figure 10). The correlation coefficient between discharge and stream temperature increases from -0.39 during the hindcast to -0.91 by 2075. Similarly, the correlation coefficient between snow and glacial melt and stream temperature increases from -0.32 to -0.81 for the same time periods. While the mean daily stream temperature for RCPs 4.5 and 8.5 do not differ greatly, the values for mean snowmelt vary during early summer between RCP scenarios. Less volume of melt is predicted as the century advances. The air temperature-stream temperature relationship remains strong throughout the century, though the influence of discharge and melt on stream temperature increases throughout the century.

*3.2.4 Glacial Melt Influence: North and Middle Forks*

We performed an additional 20 simulations in the Middle and North fork basins without the GMT algorithm to assess the effect of glacier melt water on stream temperatures. The glacial melt effect is negligible in the Middle Fork particularly for the years surrounding 2025 and 2075

(Figure 11). Simulated stream temperatures produced using the GMT and SMT combined are approximately a quarter of a degree cooler than those temperatures simulated using only the SMT for the RCP 8.5 scenarios surrounding the year 2050 in the Middle Fork. This difference is even less for the mean of RCP 4.5 scenarios during the same time period. Because of the larger glacier area in the North Fork, combining the SMT and GMT produced somewhat greater stream temperature decreases during the months of August and September when the percent of glacial melt in streamflow is the highest. This difference is apparent in all three time periods surrounding 2025, 2050, and 2075 and remains relatively consistent throughout the century and between RCP 4.5 and 8.5 scenarios. The largest difference between simulated stream temperatures with and without the GMT is approximately 1.25 degrees and occurs during August in the years surrounding 2050. For the 2025 and 2075 time periods, August is also the month with the largest difference between simulations with and without the GMT, however the difference is greatest during the 2050 time period. The difference between simulations with and without the GMT decreases through August and September, and by the end of September, there is almost no difference between the two simulations as air temperatures and subsequent glacier melt decrease (Figure 11).

## 4.0 Discussion

We examine the effects of climate change on stream temperature in the upper reaches of the Nooksack River using RCP 4.5 and RCP 8.5 scenarios for each of 10 GCMs to force a hydrology model (DHSVM-GLACIER-RBM) and a stream temperature model (RBM). The three upper basins of the Nooksack provide an ideal opportunity for examining how basins with varying degrees of elevation relief respond to climate change. The South Fork basin is

meteorologically and topographically different from the high elevation, glaciated North and Middle Fork basins. These differences allow us to explore what physical processes govern stream temperature in different mountainous environments in northwestern Washington.

*4.1 Stream Temperature Calibration*

The calibration period for this study (water year 2008-2010) is based on the availability of stream temperature data. The USGS gages did not record stream temperature before 2008, and the time series for our meteorological data ends in 2011, resulting in a 3-year window for calibration. Moreover, the USGS stream gage on the Middle Fork did not record stream temperature from October to April of each calibration year, the time frame when the RBM most accurately captures stream temperature in the South and North forks. Cao at al. (2016) also use relatively short calibration periods of approximately 2-years along with a 2-year validation period for most of the streams in their Puget Sound stream temperature study.

Snowmelt, and in some cases glacier melt, in the Nooksack basin have an important influence on the spring and summer initial headwater temperatures required in the RBM. Normally, the RBM estimates headwater temperatures from air temperatures using the Mohseni method (Yearsley, 2009; 2012; Mohseni et. al., 1998). During seasons when melt water is not entering streams in significant quantities such as late fall and winter, the Mohseni method does a reasonable job of predicting stream temperature during the calibration period (Figure 3). We tested Mohseni parameters derived from many locations along the river and its tributaries and found the best calibration statistics, including NSE and RMSE, using the highest elevation field site parameters closest to the headwaters. However, during late spring and early summer, when melt water is contributing to the river system in substantial quantities, the Mohseni derived

headwater temperatures are warmer than expected due to warmer air temperatures, resulting in higher than expected down-stream temperatures. The effects of glacial and snowmelt influence these headwater temperatures during the spring and summer months. Our first-order meltwater algorithm modifications in the RBM capture the effects of snow and glacier melt by fixing the headwater temperatures to be cooler during high-melt runoff (Table 4) resulting in more accurate modeled mainstem, stream temperatures. Our approach is consistent with others. Haag et al. (2008) use a water temperature maximum for runoff entering the river system using the LARSIM-WT water temperature model. Ficklin et al. (2012) also applied a method which incorporates snowmelt contribution and the temperature of the snowmelt into the calculation of the initial temperature conditions in the SWAT model, which are analogous to the headwater conditions in the RBM.

We find that stream depth is an important factor in simulating stream temperature in the three forks of the Nooksack River. The Leopold parameters, which reflect the relationship between depth, speed and discharge of the stream, are also different for each basin (Table 4). Unlike the Mohseni parameters which are calculated at high elevation streams, we find that using Leopold parameters calculated at the USGS calibration sites on the main stems to be most effective. Solar radiation has a large effect on stream temperature and heats a shallower water column more quickly. For the South Fork, which is overall the warmest of the three forks, we set a lower minimum stream depth than both the North and Middle forks within the model. Both the North and Middle forks receive more snow and are glaciated; during low flow periods, these forks have a higher volume of melt-based baseflow than the South Fork. We adjusted the Leopold parameters to reflect these real-world observations. Field work in all three basins

corroborates this statement, as the South Fork tributaries consistently had lower depths and flows during the late summer than did tributaries of a similar size on the Middle and North forks.

Though the NSE values for all three basins are within the range of acceptable for model performance (Mohseni et. al. 1998), the Middle Fork has a notably lower NSE value than the other two forks. We attribute this due the limited data available for the Middle Fork during the calibration time period. Without winter stream temperature values, which are more easily captured by the RBM, the NSE statistic will always be lower than the North and Middle forks, even if summer temperatures are captured similarly in all three forks. Stream temperature data is only available from approximately May to September from 2008 to 2011. We hypothesize that were data available throughout the year for the Middle Fork, the NSE value for the calibration period would likely be higher.

*4.2 Forecasted Simulations*

In all of our forecasted modeling results, the projected stream temperature means under RCP 4.5 and 8.5 scenarios do not noticeably deviate until the later part of the 21st century. Similar results are observed in the modeling results of Murphy (2016). The RCP 4.5 narratives are designed to decrease anthropogenic greenhouse gas emissions to mitigate warming, which may take decades to reach equilibrium (e.g., Hansen et al., 2005). Therefore, the RCP 4.5 results are similar to the RCP 8.5 results until later in the century, after the more aggressive mitigating RCP 4.5 narratives take hold and attenuate the rate of climate warming.

*4.2.1 South Fork*

Our model results indicate an overall increasing trend in stream temperature throughout the 21st century in the South Fork Nooksack River. Mean-stream temperatures increase throughout the year, though increases are highest in the summer and winter months (Table 5; Figure 6). The 7-DADMax stream temperatures in the South Fork also increase steadily throughout the century (Figure 7).The increases reflect the air temperature increases predicted by the forecasted MACA data (Abatzoglou and Brown, 2012). In the winter, the predicted 2 to 5 °C air temperature increases will cause headwater temperatures to be warmer. More precipitation will also fall as rain rather than snow in the lower elevations in the South Fork basin, resulting in a transition from a transient basin to rain dominated basin by the end of the century. By mid-century Murphy (2016) predicts a 40 to 80 % increase in winter discharge in the South Fork. Cao et al. (2016) predicted similar responses for the physically and meteorologically comparable Stillaguamish and Snohomish basins to the south. Murphy (2016) also predicts over a 50% reduction in SWE by midcentury which leads to less melt in the spring and summer. Air temperatures are predicted to increase by 2 to 7.5 °C in the summer (Abatzoglou and Brown, 2012). A combination of warmer headwater temperatures and lower discharge due to less snowmelt and drier forecasted summers cause higher increases in summer stream temperatures. Initially, stream temperatures are a function of the warmer headwater temperatures. Downstream from the headwaters, solar radiation becomes the primary driver, and shallower, slower streamflow gains heat quicker, especially when it is no longer buffered by meltwater.

Our findings for the South Fork agree with the findings of other studies in this region. Cao et al. (2016) produced stream temperature results for the Skagit, Stillaguamish, and Snohomish Rivers. Although the 7-DADMax and temperature increases results of Cao et al. are

similar to those of the South Fork, a direct comparison of 7-DADMax and mean stream temperature values is not possible. Our study uses different time periods and metrics to assess the effects of climate change on stream temperature. It is also difficult to compare our results to the South Fork TMDL conducted by the EPA. The EPA TMDL study performs simulations based on worst case scenario conditions, i.e., the lowest 7-day average flow which occurs once every 10 years and the 90th percentile annual air temperatures (Butcher et al., 2016). Our study focuses on mean values based on a range of conditions, not on specific flow or air temperature ranges. In general, however, both the TMDL and our study indicate that stream temperature is warming overall in the South Fork, particularly in the summer. Because of the EPA's approach, the predicted stream temperature increases are higher. For example, by 2080, the TMDL predicts that average stream temperature at the mouth of the South Fork during August (which is considered to be a critical period due to a combination of low flows and high air temperatures) under current riparian shading conditions and high-climate warming conditions will be 22.13°C. Our GCM mean with the RCP 8.5 scenario for the 2075 time period is approximately 20.41°C for August. However, our warmest forecast (HadGEM2-ES365 with RCP 8.5) predicts a 22.30°C mean for August over the 30 years surrounding 2075 (Table 7). Fish kills can occur when weekly maximum stream temperatures reach 21°C (Mantua et al., 2010). The TMDL study may be over-predicting stream temperature because the QUAL2Kw model (Chapra et al., 2008) used does not take into account snow melt entering the stream during the spring and summer months (Mantua et al., 2010). While our results generally agree with those produced by the TMDL, our study captures a range of stream temperatures associated with climate change.

*4.2.2 Middle and North Forks*

Meltwater plays a more significant role in buffering the stream temperatures in the North and Middle forks. Currently, there are approximately 7.60 km$^2$ of glacial area in the Middle Fork, and 2.58 km$^2$ in the North Fork (Table 1). The two forks also have a have more northerly exposed aspects and higher percentages of areas with elevations between 1000 m and 3000 m that receive and accumulate snow. Moreover, the higher elevations have cooler air temperatures that yield cooler headwater temperatures. Therefore, the mean monthly hindcast stream temperatures are cooler than those observed in the South Fork, especially those of the North Fork (Table 5). As such, our projected changes in the Middle and North forks are relative to cooler hindcast temperatures.

Murphy (2016) found that glacial melt as a percentage of streamflow will double in the Middle Fork and more than triple in the North Fork during the earlier to mid part of the 21$^{st}$ century when the largest surface area of ice is available for melt. Murphy also simulated excess thin ice coverages in the early part of the century causing more glacier meltwater than expected. The higher elevations in the Middle Fork and North Fork (Table 1) also support more snowpack. Mid-century basin-wide SWE medians in the Middle and North forks are twice the SWE magnitudes in the South Fork basin (Murphy, 2016). Moreover, as stated above, the higher elevations in the Middle and North forks have cooler air temperatures that yield cooler headwater temperatures. As a result, stream temperatures increase more slowly in the North and Middle forks as compared to the South Fork in the first half of the 21$^{st}$ century. Glacier meltwater is especially substantial in the more heavily glaciated North Fork, resulting in lower stream and 7-DADMax temperatures than observed in the Middle and South forks through mid-century

(Tables 5 & 6; Figure 7). Importantly, temperatures for the most part remain below the 16 ℃ threshold in the glaciated basins during the first half of the century.

Late into the 21$^{st}$ century stream temperatures in the North and Middle forks increase similarly to the South Fork (Table 5; Figure 6). During the first half of the century, higher levels of snowmelt and glacial melt buffer rising stream temperatures during the summer, however later in the century, smaller glaciers and a reduced snowpack and warmer headwater temperatures cause stream temperatures to increase in the summer months late in the century. Murphy (2016) predicts glacier area in the two basins to decrease by up to 80% and the SWE to decrease by up to 75% compared to historical averages for RCP 8.5 scenarios.   As such, late century stream temperature in the Middle Fork increase by approximately 71% for the RCP 8.5 scenario. Similarly, in the North Fork, stream temperature increases by up to 82% from the hindcast for the same 2075 time period and RCP 8.5 scenario during the summer.   Although the North and Middle forks experience much higher stream temperature increases in the summer under climate change conditions versus the South Fork, their maximum magnitudes are still lower. Mitchell et al. (2017) found that winter snowpack will persist above 1500 m in elevation in all three basins late into the 21$^{st}$ century. As such, because of the higher elevations in Middle and especially in the North Fork (Table 1) snowmelt and some glacier melt and cooler headwater temperatures will continue to buffer the overall stream temperatures in the summer (Table 5; Figure 6).

*4.3 Implications for Salmonids*

The Nooksack River is home to nine species of salmonids, including the endangered Chinook salmon (Grah and Beaulieu, 2013). Because the effects of climate change on stream temperature are different for each of the three upper basins of the Nooksack River, the responses

on how to mitigate any negative effects on fish populations will necessarily be different as well. The South Fork average 7-DADMax temperature for August during the hindcast period is 16.8℃. By the 2075 time period, two months for RCP 8.5 are above 21℃, the temperature at which fish kills begin to occur. The Middle Fork does not reach the average monthly 7-DADMax 16℃ threshold until the 2050 time period in August. In the North Fork, the monthly average 7-DADMax reaches the 16℃ threshold for two months by the 2075 time period (Table 6; Figure 7). Note that our results represent the daily means over 30 year intervals for 20 GCMs. There are GCMs that would produce warmer streams temperatures (Table 7). Our results are also for the mouths of the three forks. Batten et al. (2007) note in their study of salmon in the Snohomish River that the largest risk to salmon in their study were the upstream spawning and rearing areas, indicating the importance of focusing on mitigation and remediation actions in all areas of the basin, not just the main stem of the river.

*4.4 Uncertainty*

We address qualitative uncertainties that were either inherited from data sources, or created by assumptions or methods that we used for this study. We used the calibrated DHSVM model of Murphy (2016) to produce historical and forecasted hydrology and glacier responses in the Nooksack basins as inputs to the RBM. Murphy points out that a major source of uncertainty is the use of gridded, statistically downscaled, and disaggregated meteorological data. The gridded data required bias corrections, and the disaggregation in to 3-hr time steps introduces error which can be propagated through the modeling process (e.g., Margulius and Entekhabi, 2001). There is also uncertainty in the GCMs, which have effects on the hydrologic predictions (Barnett et al., 2005; Radić et al., 2013; Clarke et al., 2015). However, we examine trends

produced by the means of 20 different climate warming scenarios. Note too, that the RBM ignores certain factors that influence stream temperature such as hyporheic groundwater exchange and turbidity influences on solar gain. The Middle Fork calibration site lacked winter temperatures altogether. Nevertheless we found that the RBM simulations captured stream temperatures very well in the North and South forks during the winter time period. We have, therefore, assumed that the same holds true for the Middle Fork. Murphy (2016) notes that future work in hydrology modeling should focus on refining the gridded meteorological data and lapse rates to better capture the high elevation snow and glacier attributes. More model development is needed to better capture the effects of both glacial and snowmelt on stream temperature in basins where snowmelt and glaciers provide significant baseflow. The methods we have described here capture many of the features of the effects of glacial melt and snowmelt cessation on stream temperatures in the North and Middle forks of the Nooksack River. Nevertheless, we believe it is important to conduct further research that will improve our ability to model the effects of these processes on stream temperature.

**5.0 Conclusion**

In general, our modeling study predicts increasing stream temperatures in the three forks of the Nooksack River. As expected, there is a strong correlation between increased stream temperatures and forecasted warming climates and predicted lower summer stream discharges. Snow and ice melt have a buffering effect on increasing stream temperatures and influence the timing of peak stream temperatures in the upper reaches of the Nooksack River. The highest stream temperatures and the greatest monthly average 7-DADMax values are predicted in the lower relief, unglaciated South Fork basin, which loses substantial snowpack into the 21st

century, meaning low elevation transient basins in the western Cascades are more susceptible to stream temperature increases. Streams in basins with higher elevations, such as the Middle and North forks, that sustain more snow and glacier ice are slower to respond to warming climates due to meltwater contributions, especially in the next 50 years.  Towards the end of this century, when snowpack and glacial volume is greatly decreased, the buffering effect of meltwater declines, and the North and Middle forks experience more extreme increases in mean daily temperature. Although the higher elevation basins show large increases in temperature later in the century, enough high elevation meltwater and cooler headwater temperatures continue to buffer the increases to keep stream temperature 16 ºC thresholds to a minimum. It is important to recognize that from an ecological point of view, even a small increase in maximum temperatures lasting only a few days could have detrimental impacts on the salmon lifecycle. Stakeholders in the Nooksack River may now be better equipped to make stream temperature conservation decisions, mitigating the negative effects of stream temperature rise on salmon.

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**7.0 Tables**

**Table 1.** Area above 1,000, 1,500, and 2,000 meters in each of the three upper basins of the Nooksack River. Glacial area and modeled, historical 30-year (1981-2011) mean annual discharge at the river mouths is also recorded.

| Basin | All Areas in km² | | | | | | m³/second |
|---|---|---|---|---|---|---|---|
| | Basin Area | Area> 500m | Area > 1000m | Area > 1500m | Area > 2000m | 2009 Glacier Area | Mean Annual Discharge |
| South Fork | 475.7 | 311.4 | 118.6 | 9.5 | 0.1 | 0.0 | 38.8 |
| Middle Fork | 259.7 | 220.3 | 127.5 | 28.7 | 7.4 | 7.6 | 19.1 |
| North Fork | 735.4 | 250.3 | 360.6 | 125.7 | 19.0 | 25.8 | 56.7 |

**Table 2.** List of GCMs used as climate forcings for the DHSVM futuristic modeling in the upper reaches of the Nooksack River basin.

| Model Name | Model Country | Model Agency | Ensemble Used | Resolution (lat x long) |
|---|---|---|---|---|
| bcc-csm1-1-m | China | Beijing Climate Center, China Meterological Administration | r1i1p1 | 2.7906 x 2.8125 |
| CanESM2 | Canada | Canadian Centre for Climate Modeling and Analysis | r1i1p1 | 2.7906 x 2.8125 |
| CCSM4 | USA | National Center of Atmospheric Research | r6i1p1 | 0.9424 x 1.25 |
| CNRM-CM5 | France | National Centre of Meteorological Research | r1i1p1 | 1.4008 x 1.40625 |
| CSIRO-Mk3-6-0 | Australia | Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence | r1i1p1 | 1.8653 x 1.875 |
| HadGEM2-ES | United Kingdom | Met Office Hadley Center | r1i1p1 | 1.25 x 1.875 |
| HadGEM2-CC | United Kingdom | Met Office Hadley Center | r1i1p1 | 1.25 x 1.875 |
| IPSL-CM5A-MR | France | Institut Pierre Simon Laplace | r1i1p1 | 2.5352 x 2.5 |
| MIROC5 | Japan | Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | r1i1p1 | 1.4008 x 1.40625 |
| NorESM1-M | Norway | Norwegian Climate Center | r1i1p1 | 1.8947 x 2.5 |

**Table 3.** Leopold and Mohseni parameters calculated at USGS Stream gages and field sites based on field observations.

| Site | Fork | Location | Leopold Parameters | | | | Mohseni Parameters | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *a* | *b* | *c* | *d* | *α* | *β* | *γ* | *μ* | smooth |
| USGS | North | 48.90123, -121.86781 | 0.1 | 0.49 | 0.16 | 0.49 | 15 | 13.5 | 0.1 | 0 | 0.15 |
| Ruth | North | 48.89474, -121.65212 | 0.27 | 0 | 0.25 | 2.76 | 15 | 14.7 | 0.13 | 0.73 | 0.08 |
| Boyd | North | 48.88198, -121.85893 | 0.27 | 0.31 | 0.27 | 0.22 | 32 | 23.2 | 0.07 | 2 | 0.04 |
| Thompson | North | 48.88768, -121.90129 | 3.79 | 2.2 | 0.4 | 0 | 32 | 25.2 | 0.1 | 2 | 0.09 |
| Bell | North | 48.84842, -122.16024 | 0.13 | 0.09 | 0.65 | 0.53 | 32 | 22.6 | 0.09 | 2 | 0.37 |
| Racehorse | North | 48.88464, -122.1344 | 0.27 | 0.24 | 0.44 | 0.67 | 32 | 22.8 | 0.09 | 2 | 0.25 |
| Kenny | North | 48.85192, -122.14423 | 0.07 | 0.02 | 22 | 1.29 | 31.96 | 25 | 0.07 | 2 | 0.3 |
| Maple | North | 48.92187, -122.07192 | 0.15 | 0 | 2.7 | 1.2 | 15 | 7.05 | 0.12 | 0 | 0.34 |
| Canyon | North | 48.90715, -121.99025 | 0.78 | 0.14 | 0.23 | 0.45 | 19.35 | 14.5 | 0.19 | 1.96 | 0.2 |
| Bagley | North | 48.86566, -121.68409 | 1 | 0.02 | 0.15 | 0.64 | | | | | |
| Dobbs | North | 48.8271, -121.82458 | 0.2 | 0.36 | 0.81 | 0.34 | 15 | 8.43 | 0.13 | 0 | 0.4 |
| Sholes | North | 48.82073, -121.76177 | 0.16 | 0.46 | 0.93 | 0.45 | 15 | 13.5 | 0.53 | 1.32 | 0.03 |
| USGS | Middle | 48.77784, -122.10552 | 0.36 | 0.29 | 0.12 | 0.51 | 21.53 | 22.1 | 0.11 | 2 | 0.07 |
| Sisters | Middle | 48.75468, -121.99009 | 0.11 | 0.47 | 0.4 | 0.42 | 15 | 12.9 | 0.14 | 2 | 0.11 |
| Ridley | Middle | 48.7304, -121.91172 | 0.44 | 0 | 0.37 | 0.43 | 15 | 17.2 | 0.11 | 0.57 | 0.15 |
| Rankin | Middle | 48.73277, -121.92163 | 0.14 | 0 | 6.13 | 1.39 | | | | | |
| Warm | Middle | 48.75565, -121.97557 | 0.37 | 0.52 | 0.32 | 0 | 32 | 25.2 | 0.11 | 2 | 0.06 |
| Porter | Middle | 48.79414, -122.11638 | 0.44 | 0.23 | 0.46 | 0.7 | 29.72 | 30 | 0.06 | 2 | 0.14 |
| Canyonlake | Middle | 48.83355, -122.13612 | 0.26 | 0.23 | 0.46 | 0.32 | | | | | |
| Clearwater | Middle | 48.77463, -122.04501 | 0.34 | 0.88 | 0.49 | 0.15 | 17.89 | 13 | 0.2 | 1.27 | 0.15 |
| USGS | South | 48.67789, -122.16515 | 0.19 | 0.4 | 0.08 | 0.51 | 15.52 | 6.51 | 0.7 | 0 | 0.4 |
| Skookum | South | 48.67143, -122.14161 | 0.51 | 0.27 | 0.16 | 0.51 | 32 | 20.8 | 0.12 | 0 | 0.11 |
| Cavanaugh | South | 48.64537, -122.11942 | 0.31 | 0.15 | 0.47 | 0.6 | 32 | 22.3 | 0.11 | 2 | 0.15 |
| Edfro | South | 48.66064, -122.1205 | 0.12 | 0.04 | 1.22 | 0.51 | 32 | 25.9 | 0.06 | 2 | 0.4 |
| Jones | South | 48.71848, -122.21414 | 0.23 | 0.33 | 0.86 | 0.33 | 32 | 16.8 | 0.11 | 2 | 0.15 |
| McCarty | South | 48.72868, -122.23967 | 0.36 | 0.39 | 0.86 | 0.43 | 18.51 | 9.74 | 0.18 | 0.38 | 0.4 |
| Wanlick | South | 48.65457, -121.86288 | 0.31 | 0.11 | 0.48 | 0.46 | 15 | 10.8 | 0.23 | 1.61 | 0.13 |
| Unknown | South | 48.75952, -122.22165 | 0.15 | 0.02 | 1.73 | 0.78 | | | | | |

**Table 4.** Parameters used for stream temperature calibration in the RBM model and applied to future stream temperature simulations for the North, Middle, and South forks.

| | | Leopold | | Mohseni | | Other RBM Inputs | | Vegetation Parameters | |
|---|---|---|---|---|---|---|---|---|---|
| South Fork | Min. Velocity 0.5 cfs | a | 0.31 | α | 15.00 | Smooth Coefficient | 0.0178 | Tree Height (m) | 25.00 |
| | | b | 0.11 | β | 10.76 | T_head Max (°C) | 7.00 | Buffer Width (m) | 5.00 |
| | Min. Depth | c | 0.48 | γ | 0.23 | Snowmelt (m³/3hrs) | 0.003 | LAI | 0.80 |
| | 0.5 ft | d | 0.46 | μ | 1.61 | Glacial Melt (%) | NA | Canopy-Bank Distance (m) | 0.01 |
| Middle Fork | Min. Velocity 0.5 cfs | a | 0.27 | α | 15.00 | Smooth Coefficient | 0.0178 | Tree Height (m) | 25.00 |
| | | b | 0.00 | β | 14.72 | T_head Max (°C) | 5.00 | Buffer Width (m) | 5.00 |
| | Min. Depth | c | 0.25 | γ | 0.13 | Snowmelt (m³/3hrs) | 0.005 | LAI | 0.80 |
| | 1.5 ft | d | 2.76 | μ | 0.73 | Glacial Melt (%) | 15.00 | Canopy-Bank Distance (m) | 0.01 |
| North Fork | Min. Velocity 0.5 cfs | a | 0.10 | α | 15.00 | Smooth Coefficient | 0.0178 | Tree Height (m) | 25.00 |
| | | b | 0.49 | β | 13.47 | T_head Max (°C) | 5.00 | Buffer Width (m) | 5.00 |
| | Min. Depth | c | 0.16 | γ | 0.10 | Snowmelt (m³/3hrs) | 0.005 | LAI | 0.80 |
| | 1.75 ft | d | 0.49 | μ | 0.00 | Glacial Melt (%) | 15.00 | Canopy-Bank Distance (m) | 0.01 |

**Table 5.** Modeled stream temperature magnitude in degrees Celsius averaged over each month for the North, Middle, and South forks of the Nooksack River basin for 30-years surrounding 2025, 2050, 2075, and the hindcast period.

| | Month | Hindcast °C | RCP 4.5 | RCP8.5 | RCP 4.5 | RCP8.5 | RCP 4.5 | RCP8.5 |
|---|---|---|---|---|---|---|---|---|
| | | | 2025 | | 2050 | | 2075 | |
| South Fork | Jan | 4.7 | 3.8 | 4.0 | 4.3 | 4.6 | 4.6 | 5.7 |
| | Feb | 5.2 | 4.7 | 4.8 | 5.2 | 5.5 | 5.7 | 6.8 |
| | Mar | 6.4 | 5.6 | 5.8 | 6.3 | 6.6 | 6.9 | 8.0 |
| | Apr | 8.4 | 7.8 | 7.9 | 8.4 | 8.8 | 9.1 | 10.3 |
| | May | 9.8 | 10.0 | 10.2 | 10.7 | 11.3 | 11.5 | 13.1 |
| | Jun | 11.9 | 13.4 | 13.5 | 14.5 | 15.3 | 15.4 | 17.2 |
| | Jul | 15.1 | 16.8 | 17.0 | 17.8 | 18.8 | 18.7 | 20.7 |
| | Aug | 15.3 | 17.4 | 17.6 | 18.5 | 19.2 | 19.2 | 21.1 |
| | Sep | 14.5 | 15.0 | 15.1 | 16.0 | 16.7 | 16.7 | 18.5 |
| | Oct | 11.8 | 10.1 | 10.4 | 11.0 | 11.7 | 11.5 | 13.0 |
| | Nov | 7.5 | 6.2 | 6.4 | 6.9 | 7.4 | 7.3 | 8.3 |
| | Dec | 5.6 | 4.6 | 4.9 | 5.3 | 5.6 | 5.5 | 6.5 |
| Middle Fork | Jan | 2.6 | 2.9 | 3.1 | 3.3 | 3.5 | 3.5 | 4.2 |
| | Feb | 3.0 | 3.6 | 3.7 | 4.0 | 4.2 | 4.3 | 5.0 |
| | Mar | 3.8 | 4.4 | 4.5 | 4.9 | 5.1 | 5.3 | 6.0 |
| | Apr | 4.9 | 5.9 | 6.0 | 6.3 | 6.6 | 6.8 | 7.6 |
| | May | 6.4 | 7.6 | 7.7 | 8.1 | 8.4 | 8.6 | 9.7 |
| | Jun | 7.5 | 9.3 | 9.4 | 10.1 | 10.7 | 10.7 | 12.6 |
| | Jul | 9.6 | 11.8 | 12.0 | 13.5 | 14.7 | 14.7 | 17.6 |
| | Aug | 11.1 | 12.5 | 12.7 | 15.1 | 16.0 | 16.7 | 19.3 |
| | Sep | 9.9 | 10.7 | 10.7 | 12.4 | 13.1 | 13.5 | 15.4 |
| | Oct | 6.6 | 7.3 | 7.5 | 8.0 | 8.6 | 8.4 | 9.6 |
| | Nov | 4.1 | 4.6 | 4.8 | 5.1 | 5.4 | 5.3 | 5.9 |
| | Dec | 2.8 | 3.4 | 3.6 | 3.9 | 4.1 | 4.1 | 4.7 |
| North Fork | Jan | 2.0 | 2.7 | 2.8 | 3.0 | 3.2 | 3.2 | 3.8 |
| | Feb | 2.4 | 3.3 | 3.4 | 3.6 | 3.7 | 3.8 | 4.4 |
| | Mar | 3.3 | 4.0 | 4.1 | 4.4 | 4.6 | 4.7 | 5.4 |
| | Apr | 4.3 | 5.2 | 5.3 | 5.5 | 5.8 | 5.9 | 6.6 |
| | May | 5.6 | 6.3 | 6.4 | 6.7 | 7.0 | 7.1 | 8.2 |
| | Jun | 6.5 | 7.6 | 7.7 | 8.4 | 9.0 | 9.1 | 10.9 |
| | Jul | 8.1 | 9.6 | 9.7 | 11.3 | 12.2 | 12.5 | 14.9 |
| | Aug | 9.5 | 10.0 | 10.1 | 11.9 | 12.4 | 13.2 | 15.0 |
| | Sep | 8.6 | 8.7 | 8.8 | 10.0 | 10.4 | 10.9 | 12.4 |
| | Oct | 6.0 | 6.5 | 6.7 | 7.2 | 7.6 | 7.6 | 8.6 |
| | Nov | 3.7 | 4.3 | 4.4 | 4.7 | 5.0 | 4.9 | 5.5 |
| | Dec | 2.4 | 3.3 | 3.4 | 3.7 | 3.9 | 3.8 | 4.4 |

**Table 6.** Modeled 7-DADMax stream temperature averaged over each month for the North, Middle, and South forks of the Nooksack River basin for 30-years surrounding 2025, 2050, 2075, and the hindcast.

| | Month | Hindcast °C | RCP 4.5 2025 | RCP8.5 2025 | RCP 4.5 2050 | RCP8.5 2050 | RCP 4.5 2075 | RCP8.5 2075 |
|---|---|---|---|---|---|---|---|---|
| South Fork | Jan | 3.9 | 4.3 | 4.4 | 4.7 | 5.0 | 5.1 | 6.1 |
| | Feb | 4.5 | 5.2 | 5.4 | 5.8 | 6.0 | 6.2 | 7.3 |
| | Mar | 5.5 | 6.3 | 6.4 | 6.9 | 7.2 | 7.6 | 8.6 |
| | Apr | 6.9 | 8.5 | 8.6 | 9.1 | 9.5 | 9.9 | 10.9 |
| | May | 9.2 | 10.8 | 11.0 | 11.6 | 12.0 | 12.4 | 13.9 |
| | Jun | 11.7 | 14.5 | 14.6 | 15.6 | 16.3 | 16.6 | 18.3 |
| | Jul | 15.3 | 18.0 | 18.2 | 19.1 | 20.0 | 20.0 | 21.8 |
| | Aug | 16.8 | 18.4 | 18.6 | 19.6 | 20.1 | 20.4 | 22.2 |
| | Sep | 14.8 | 15.8 | 15.9 | 16.9 | 17.5 | 17.6 | 19.3 |
| | Oct | 10.5 | 10.6 | 10.9 | 11.5 | 12.2 | 12.1 | 13.4 |
| | Nov | 6.6 | 6.7 | 6.8 | 7.3 | 7.8 | 7.7 | 8.7 |
| | Dec | 4.7 | 5.1 | 5.3 | 5.8 | 6.0 | 6.0 | 6.9 |
| Middle Fork | Jan | 3.1 | 3.4 | 3.5 | 3.7 | 3.9 | 4.0 | 4.7 |
| | Feb | 3.7 | 4.2 | 4.3 | 4.6 | 4.8 | 4.9 | 5.6 |
| | Mar | 4.6 | 5.2 | 5.3 | 5.7 | 5.8 | 6.1 | 6.8 |
| | Apr | 5.8 | 6.9 | 6.9 | 7.3 | 7.6 | 7.9 | 8.6 |
| | May | 7.4 | 8.4 | 8.6 | 9.0 | 9.3 | 9.5 | 10.6 |
| | Jun | 8.7 | 10.4 | 10.5 | 11.3 | 11.8 | 12.0 | 13.8 |
| | Jul | 11.0 | 13.0 | 13.2 | 14.8 | 15.9 | 16.2 | 18.9 |
| | Aug | 12.8 | 13.6 | 13.7 | 16.3 | 17.2 | 18.0 | 20.5 |
| | Sep | 11.8 | 11.5 | 11.6 | 13.4 | 14.0 | 14.6 | 16.2 |
| | Oct | 8.2 | 8.0 | 8.2 | 8.7 | 9.2 | 9.1 | 10.1 |
| | Nov | 5.2 | 5.2 | 5.3 | 5.6 | 5.9 | 5.9 | 6.4 |
| | Dec | 3.7 | 4.0 | 4.1 | 4.4 | 4.6 | 4.6 | 5.2 |
| North Fork | Jan | 2.9 | 3.0 | 3.2 | 3.3 | 3.5 | 3.6 | 4.1 |
| | Feb | 3.3 | 3.7 | 3.7 | 4.0 | 4.1 | 4.2 | 4.8 |
| | Mar | 4.1 | 4.6 | 4.6 | 5.0 | 5.1 | 5.3 | 5.9 |
| | Apr | 5.0 | 5.9 | 6.0 | 6.3 | 6.5 | 6.7 | 7.4 |
| | May | 6.3 | 7.1 | 7.2 | 7.5 | 7.7 | 7.9 | 8.9 |
| | Jun | 7.1 | 8.5 | 8.5 | 9.3 | 9.9 | 10.0 | 11.8 |
| | Jul | 8.8 | 10.6 | 10.7 | 12.4 | 13.2 | 13.7 | 15.8 |
| | Aug | 10.1 | 10.9 | 11.0 | 12.9 | 13.3 | 14.2 | 15.9 |
| | Sep | 9.5 | 9.5 | 9.5 | 10.8 | 11.2 | 11.7 | 13.1 |
| | Oct | 7.0 | 7.0 | 7.2 | 7.7 | 8.1 | 8.1 | 9.0 |
| | Nov | 4.7 | 4.7 | 4.8 | 5.1 | 5.3 | 5.3 | 5.8 |
| | Dec | 3.5 | 3.7 | 3.8 | 4.1 | 4.2 | 4.2 | 4.7 |

**Table 7.** Mean and 7-DADMax stream temperature values for GCM HadGEM2-ES RCP 8.5, the most extreme climate change scenario, for the hindcast period, and the 30 years surrounding 2025, 2050, and 2075

| | | Mean | 7DADM | Mean | 7DADM | Mean | 7DADM | Mean | 7DADM |
|---|---|---|---|---|---|---|---|---|---|
| | Month | Hindcast | | 2025 | | 2050 | | 2075 | |
| South Fork | Jan | 4.7 | 4.2 | 3.8 | 4.2 | 4.6 | 4.9 | 5.9 | 6.3 |
| | Feb | 5.2 | 5.1 | 4.7 | 5.1 | 5.9 | 6.3 | 8.1 | 8.6 |
| | Mar | 6.4 | 6.6 | 6.0 | 6.6 | 8.2 | 8.9 | 10.1 | 10.8 |
| | Apr | 8.4 | 10.0 | 9.3 | 10.0 | 10.8 | 11.6 | 12.7 | 13.5 |
| | May | 9.8 | 11.2 | 10.4 | 11.2 | 11.7 | 12.6 | 14.1 | 15.0 |
| | Jun | 11.9 | 15.5 | 14.5 | 15.5 | 16.2 | 17.3 | 19.3 | 20.6 |
| | Jul | 15.1 | 18.2 | 17.1 | 18.2 | 18.9 | 20.1 | 21.7 | 23.1 |
| | Aug | 15.3 | 18.9 | 17.9 | 18.9 | 19.5 | 20.8 | 22.3 | 23.8 |
| | Sep | 14.5 | 16.2 | 15.3 | 16.2 | 17.0 | 18.2 | 19.5 | 20.8 |
| | Oct | 11.8 | 11.6 | 10.9 | 11.6 | 12.4 | 13.2 | 14.0 | 14.8 |
| | Nov | 7.5 | 7.2 | 6.7 | 7.2 | 7.7 | 8.2 | 8.8 | 9.4 |
| | Dec | 5.6 | 5.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.6 | 7.1 |
| Middle Fork | Jan | 2.6 | 3.3 | 2.9 | 3.3 | 3.5 | 3.9 | 4.4 | 4.7 |
| | Feb | 3.0 | 4.1 | 3.7 | 4.1 | 4.4 | 4.9 | 5.8 | 6.3 |
| | Mar | 3.8 | 5.4 | 4.7 | 5.4 | 6.0 | 6.9 | 7.2 | 8.2 |
| | Apr | 4.9 | 7.9 | 6.8 | 7.9 | 7.8 | 9.0 | 9.1 | 10.4 |
| | May | 6.4 | 8.9 | 7.9 | 8.9 | 8.8 | 9.8 | 10.5 | 11.6 |
| | Jun | 7.5 | 11.2 | 10.1 | 11.2 | 11.7 | 12.9 | 15.4 | 16.7 |
| | Jul | 9.6 | 13.6 | 12.5 | 13.6 | 15.8 | 17.2 | 20.2 | 21.9 |
| | Aug | 11.1 | 14.6 | 13.4 | 14.6 | 17.3 | 18.8 | 21.5 | 23.2 |
| | Sep | 9.9 | 11.9 | 11.0 | 11.9 | 14.0 | 15.2 | 17.2 | 18.5 |
| | Oct | 6.6 | 8.7 | 7.9 | 8.7 | 9.2 | 10.1 | 10.3 | 11.2 |
| | Nov | 4.1 | 5.6 | 5.0 | 5.6 | 5.6 | 6.1 | 6.2 | 6.8 |
| | Dec | 2.8 | 4.0 | 3.4 | 4.0 | 4.2 | 4.7 | 4.7 | 5.3 |
| North Fork | Jan | 2.0 | 3.0 | 2.7 | 3.0 | 3.4 | 3.4 | 3.9 | 4.2 |
| | Feb | 2.4 | 3.6 | 3.3 | 3.6 | 4.2 | 4.2 | 5.0 | 5.4 |
| | Mar | 3.3 | 4.7 | 4.2 | 4.7 | 5.9 | 5.9 | 6.4 | 7.1 |
| | Apr | 4.3 | 6.7 | 6.0 | 6.7 | 7.7 | 7.7 | 8.0 | 9.0 |
| | May | 5.6 | 7.3 | 6.6 | 7.3 | 8.1 | 8.1 | 9.0 | 9.8 |
| | Jun | 6.5 | 9.1 | 8.2 | 9.1 | 10.8 | 10.8 | 13.3 | 14.4 |
| | Jul | 8.1 | 10.9 | 10.0 | 10.9 | 14.0 | 14.0 | 16.7 | 17.8 |
| | Aug | 9.5 | 11.5 | 10.5 | 11.5 | 14.2 | 14.2 | 16.8 | 17.9 |
| | Sep | 8.6 | 9.7 | 8.9 | 9.7 | 11.9 | 11.9 | 13.9 | 14.9 |
| | Oct | 6.0 | 7.6 | 7.0 | 7.6 | 8.8 | 8.8 | 9.3 | 9.9 |
| | Nov | 3.7 | 5.1 | 4.6 | 5.1 | 5.6 | 5.6 | 5.8 | 6.2 |
| | Dec | 2.4 | 3.8 | 3.3 | 3.8 | 4.3 | 4.3 | 4.4 | 4.8 |

**Table 8.** Correlation Coefficients between stream temperature and air temperature, glacial and snowmelt, and discharge for the North, Middle, and South forks for 30-years surrounding 2025, 2050, 2075, and the hindcast.

| | | Hindcast | RCP 4.5 | RCP8.5 | RCP 4.5 | RCP8.5 | RCP 4.5 | RCP8.5 |
|---|---|---|---|---|---|---|---|---|
| | | 1995 | 2025 | | 2050 | | 2075 | |
| South Fork | Air Temp | 0.98 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 1.00 |
| | Discharge | -0.76 | -0.93 | -0.94 | -0.94 | -0.93 | -0.93 | -0.93 |
| | Melt | -0.77 | -0.91 | -0.91 | -0.90 | -0.91 | -0.90 | -0.87 |
| Middle Fork | Air Temp | 0.96 | 0.98 | 0.99 | 0.98 | 0.98 | 0.97 | 0.98 |
| | Discharge | -0.72 | -0.92 | -0.93 | -0.93 | -0.93 | -0.92 | -0.90 |
| | Melt | -0.47 | -0.58 | -0.57 | -0.71 | -0.73 | -0.77 | -0.75 |
| North Fork | Air Temp | 0.96 | 0.98 | 0.98 | 0.97 | 0.98 | 0.97 | 0.98 |
| | Discharge | -0.39 | -0.77 | -0.82 | -0.90 | -0.90 | -0.91 | -0.91 |
| | Melt | -0.32 | -0.60 | -0.60 | -0.73 | -0.75 | -0.80 | -0.81 |

**8.0 Figures**
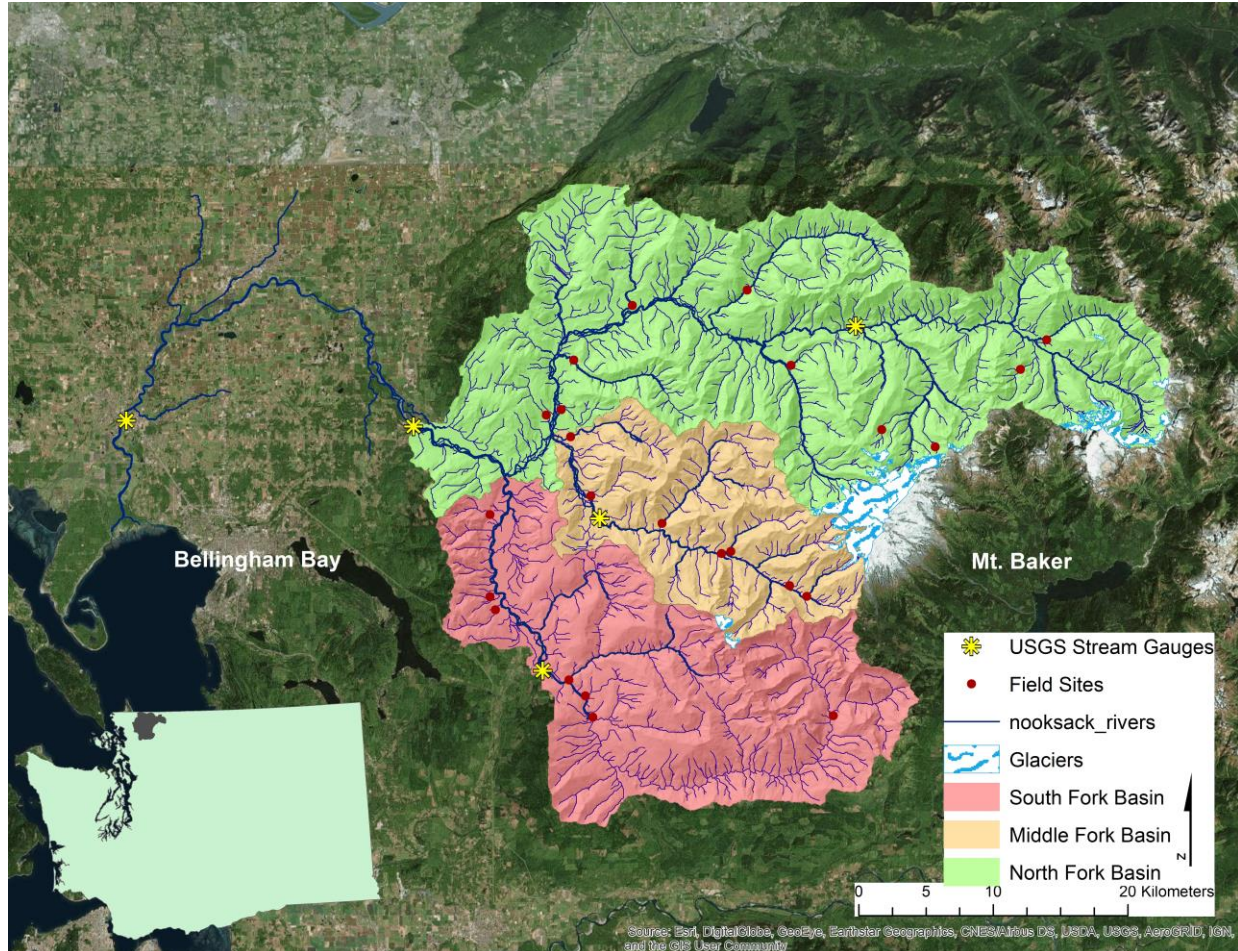


**Figure 1.** The upper reaches if the Nooksack River Basin in Whatcom County, Washington. Field sites are identified by red dots, and USGS gages are yellow stars. Mt Baker and Bellingham Bay are also highlighted in this map.
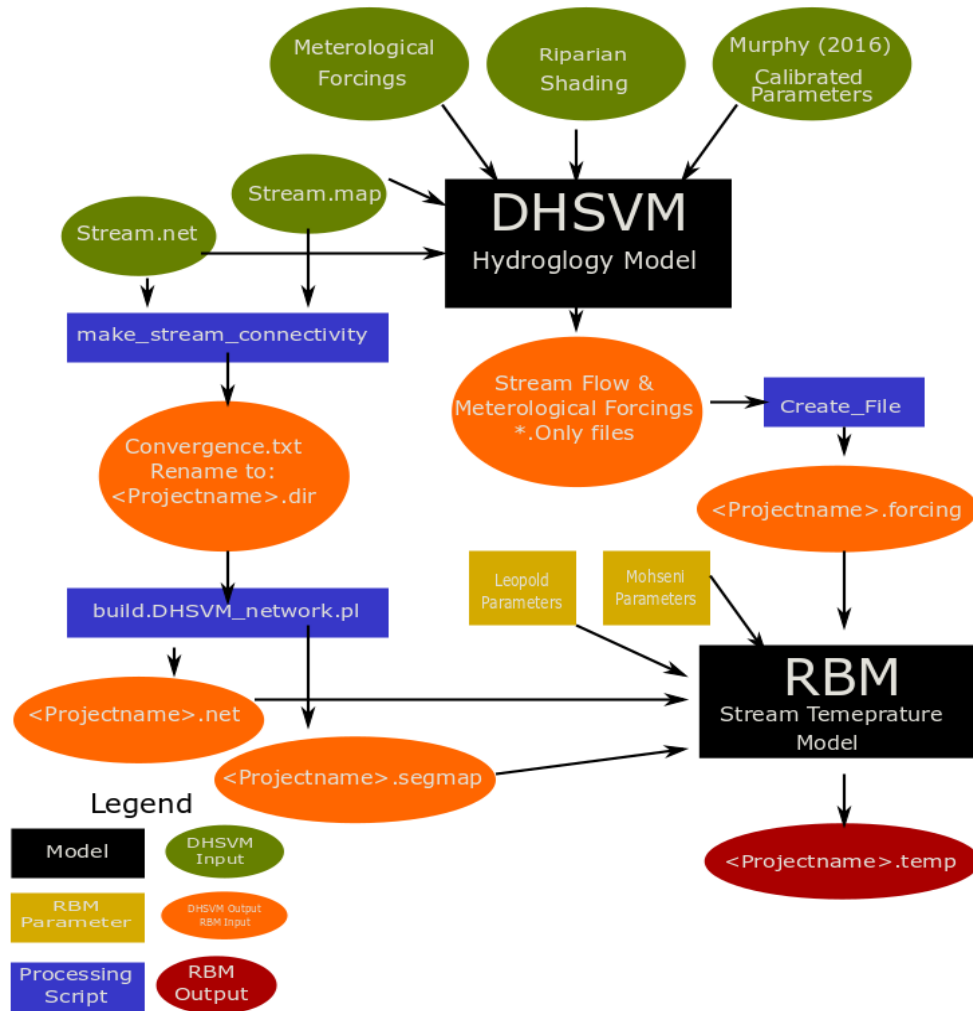
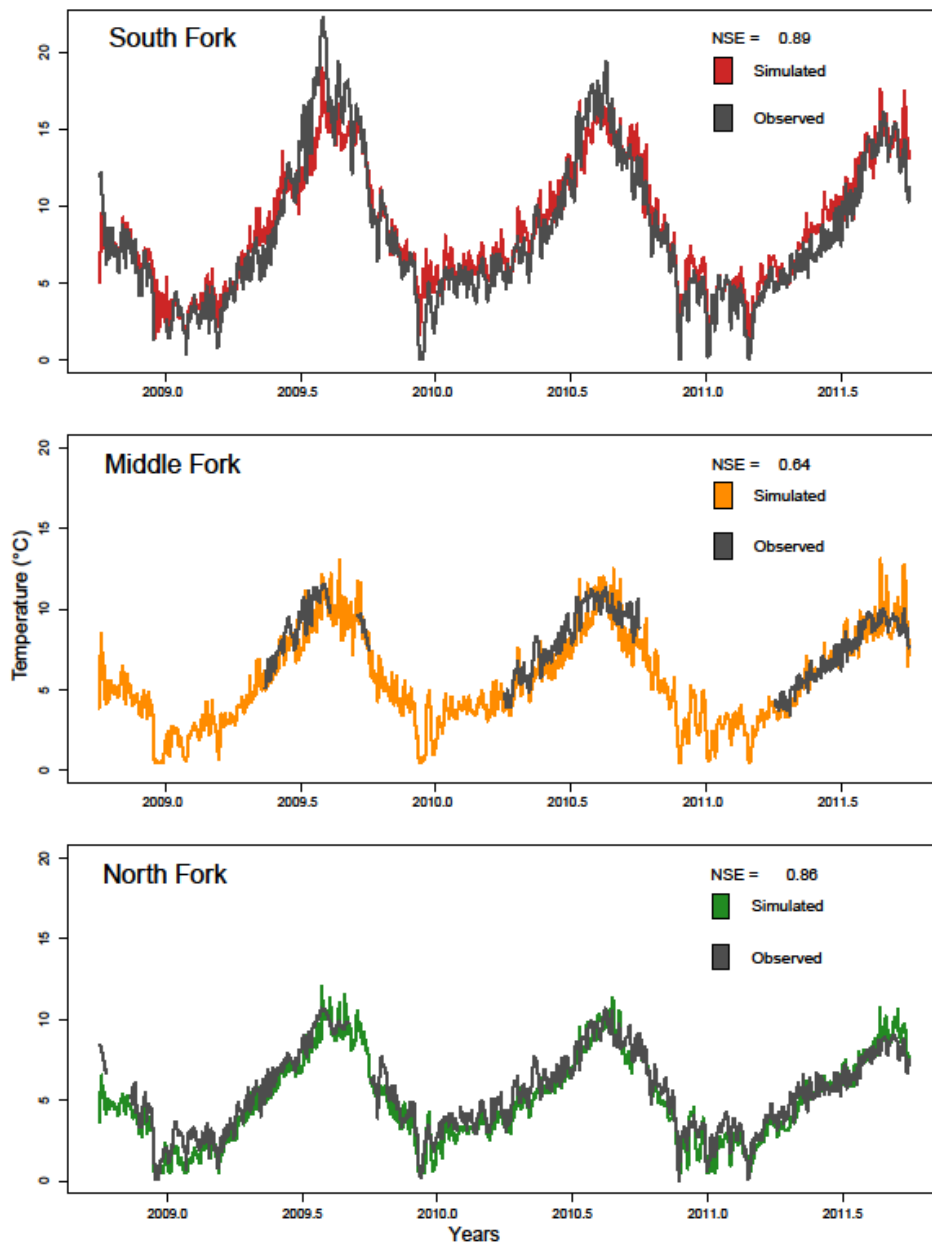**Figure 2.** Work flow for DHSVM and RBM, including inputs, outputs, parameters, and processing scripts.

**Figure 3.** Calibrated stream temperature results for Water Years 2009 to 2011 for the South, Middle, and North forks. The modeled results are colored, the observed values from USGS stream gages are in grey. The Nash-Sutcliffe Efficiency Coefficient (NSE) is located in the upper right-hand corner.
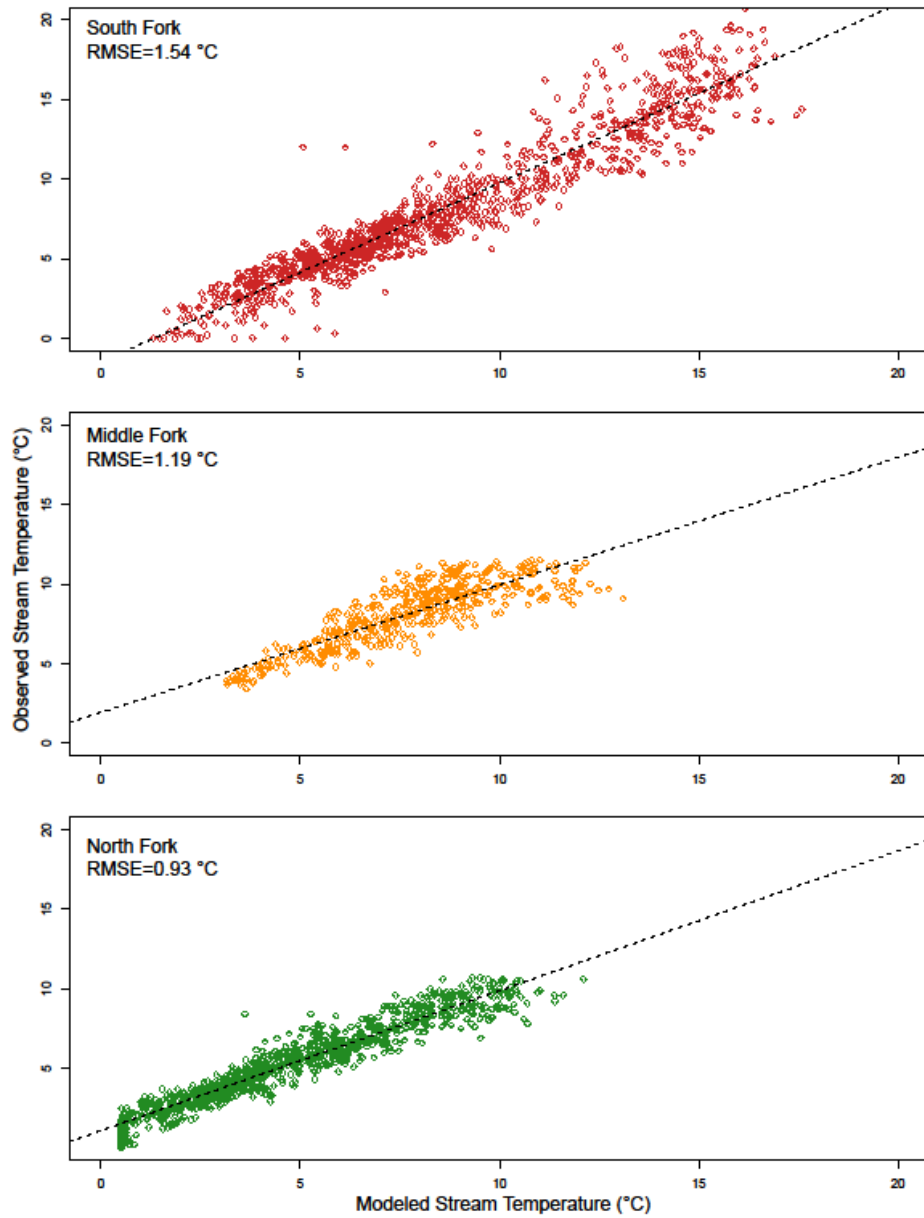
**Figure 4**. Scatter plots of modeled versus observed stream temperature for Water Years 2009-2011 at the USGS gages in the South, Middle, and North Fork. Root mean square error values in the upper left-hand corners.
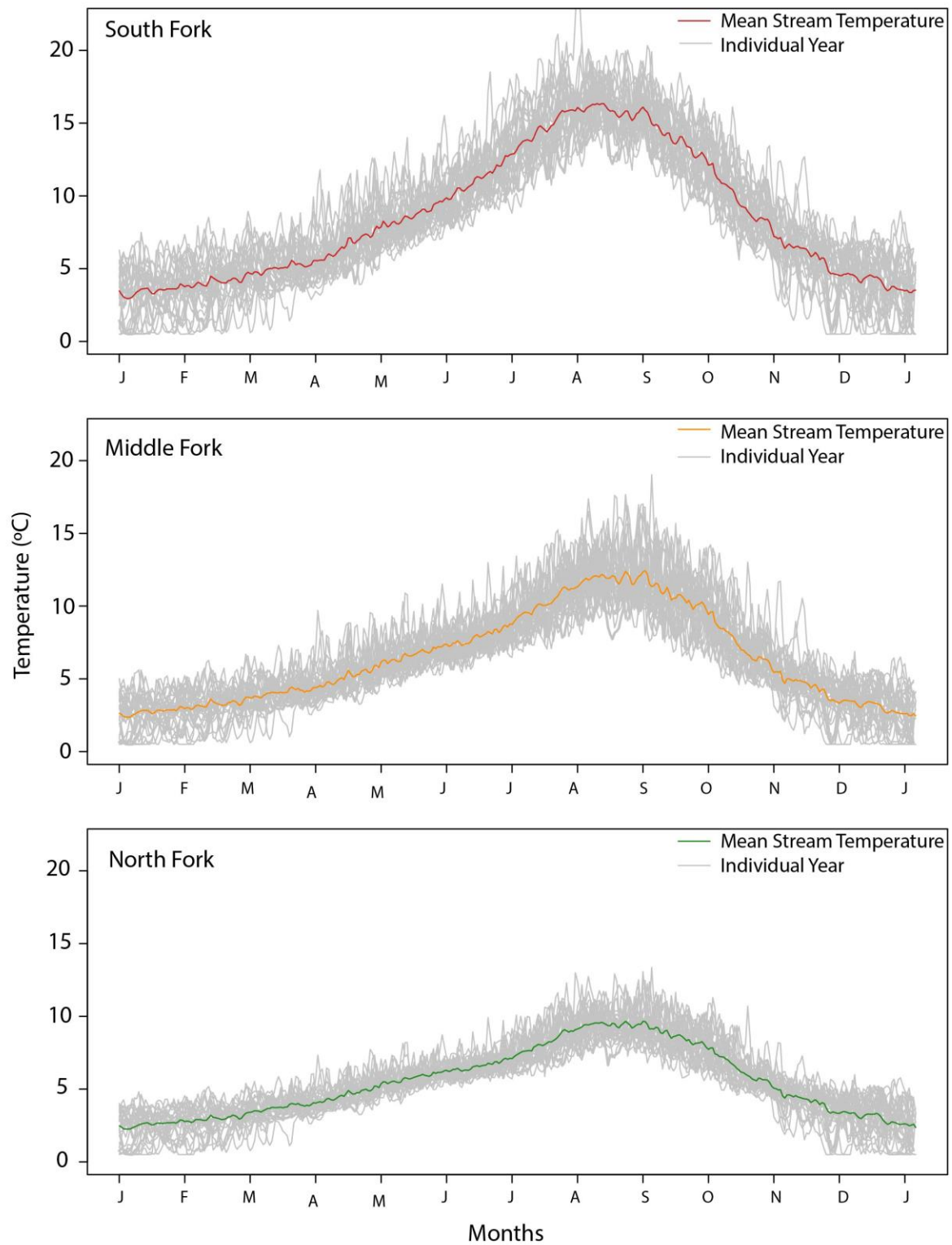
**Figure 5.** Mean daily stream temperature for the hindcast period of 1981 to 2011 for the South, Middle and North forks. The mean of the hindcast stream temperatures is colored for each fork.

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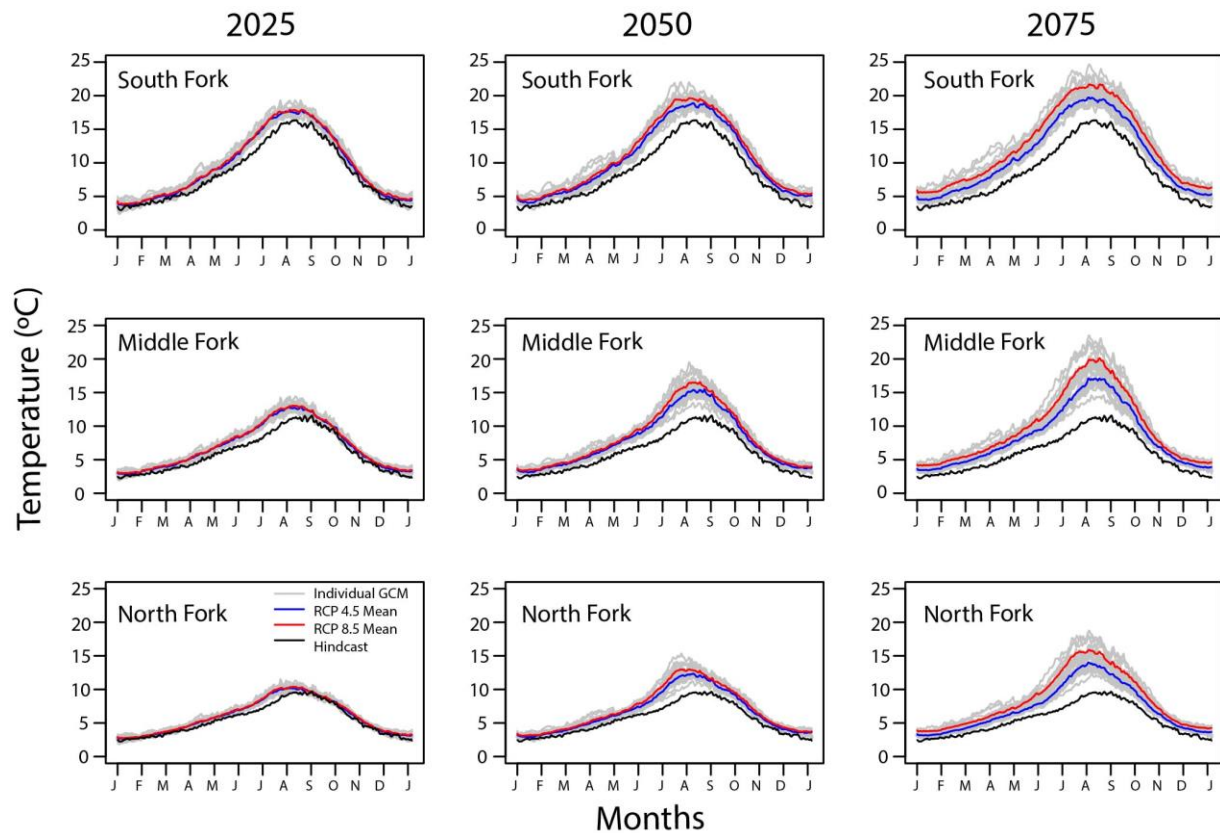
**Figure 6.** Mean daily stream temperature centered around 2025, 2050, and 2075 for the South (top), Middle (middle), and North (bottom) forks of the Nooksack River. The blue line represents the mean of all RCP 4.5 scenarios, the red line represents the mean of all RCP 8.5 scenarios, the black line is the hindcast, and the light grey lines represent each individual RCP scenario.
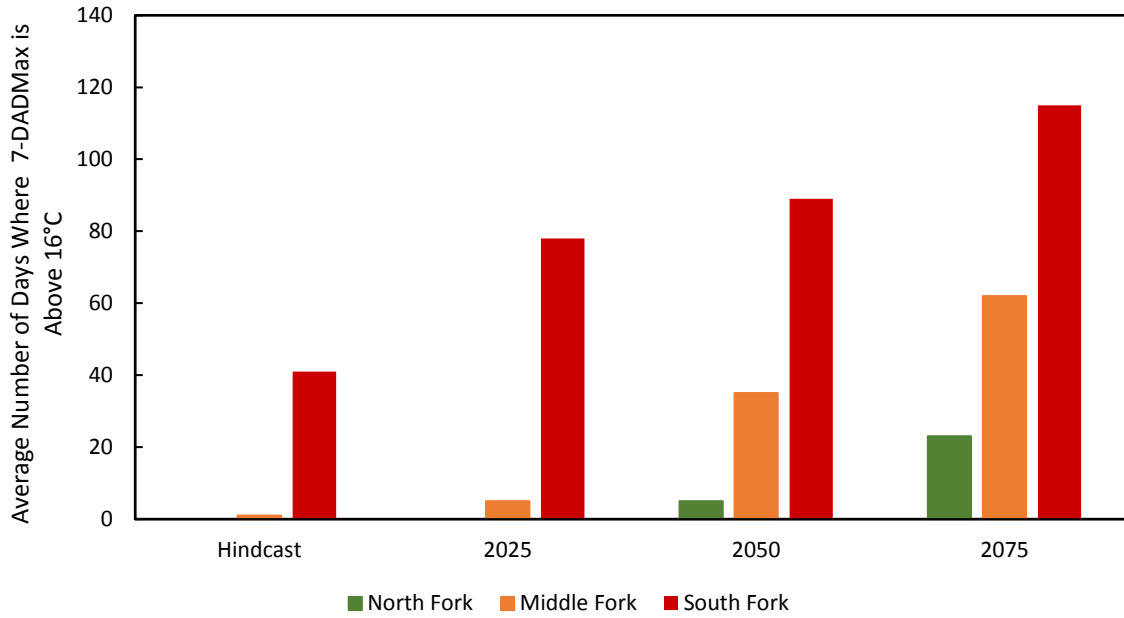
**Figure 7.** The average number of days that the 7-DADMax stream temperature exceeds 16℃, which is the threshold for the South Fork for summer salmonid habitat (Butcher et al., 2016). The values represent the average 7-DADMax value for the 30 year periods surrounding 1995 (hindcast), 2025, 2050, and 2075 for all GCM and RCP scenario.
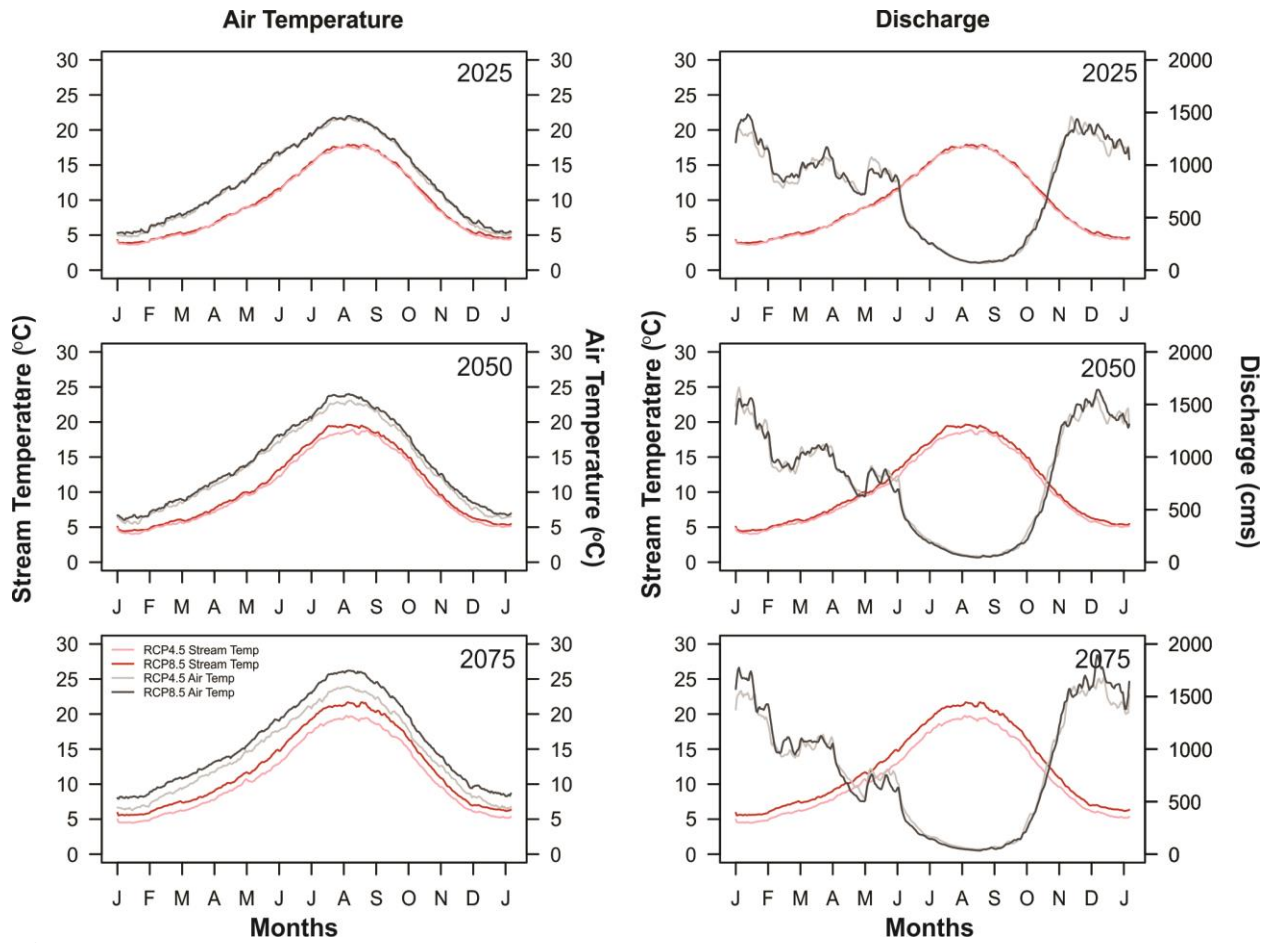
**Figure 8.** Mean daily stream temperature for the 30-years surrounding 2025, 2050, and 2075 plotted against air temperature (left) and discharge (right) for the South Fork. The mean of RCP 4.5 scenarios is in yellow, the mean of RCP 8.5 scenarios is in orange. Air temperature and discharge are all represented in grey in their respective columns. RCP 4.5 is represented in light grey and RCP 8.5 is represented in dark grey.
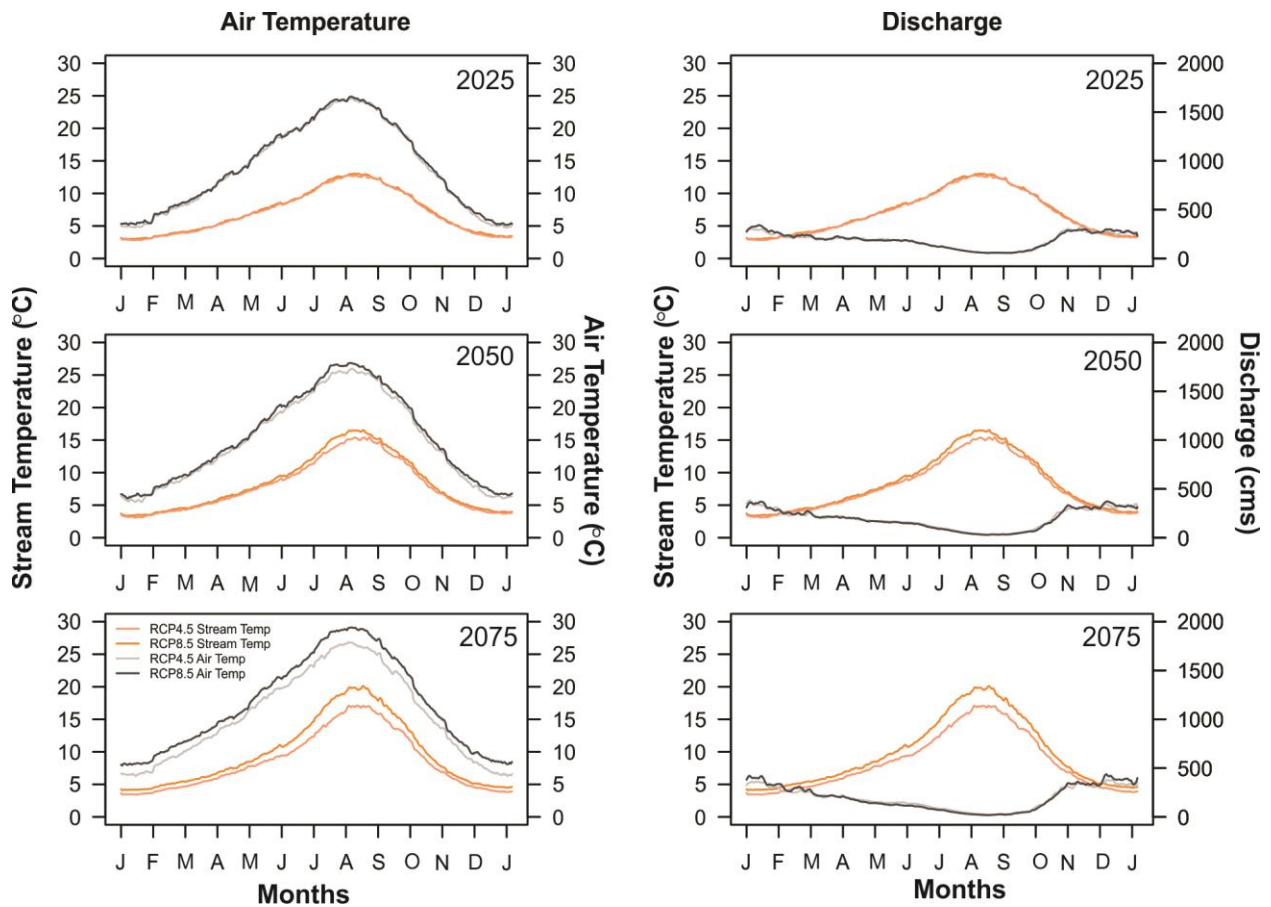
**Figure 9.** Mean daily stream temperature for the 30-years surrounding 2025, 2050, and 2075 plotted against air temperature (left) and discharge (right) for the Middle Fork. The mean of RCP 4.5 scenarios is in yellow, the mean of RCP 8.5 scenarios is in orange. Air temperature and discharge are all represented in grey in their respective columns. RCP 4.5 is represented in light grey and RCP 8.5 is represented in dark grey.
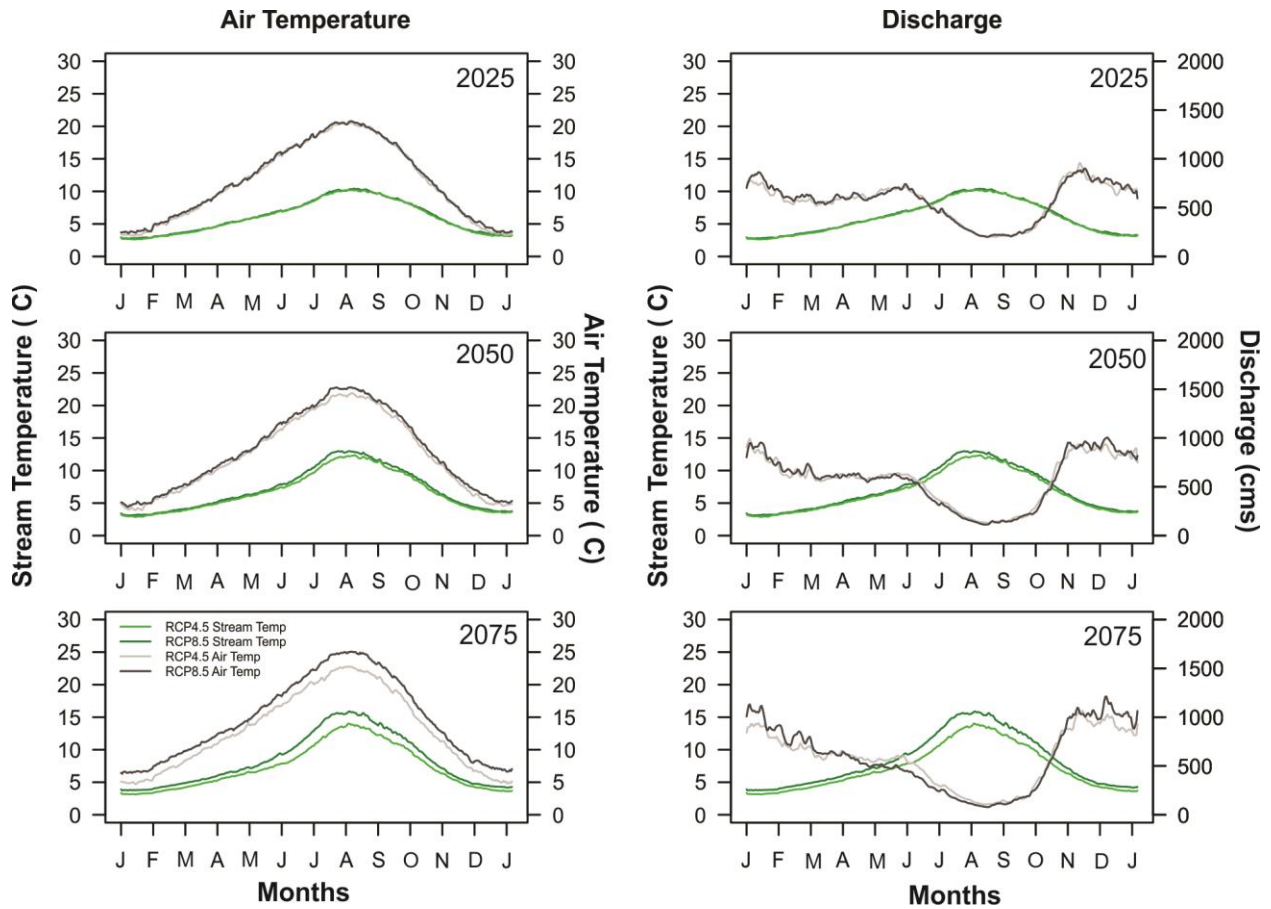
**Figure 10.** Mean daily stream temperature for the 30-years surrounding 2025, 2050, and 2075 plotted against air temperature (left) and discharge (right) for the North Fork. The mean of RCP 4.5 scenarios is in yellow, the mean of RCP 8.5 scenarios is in orange. Air temperature and discharge are all represented in grey in their respective columns. RCP 4.5 is represented in light grey and RCP 8.5 is represented in dark grey.
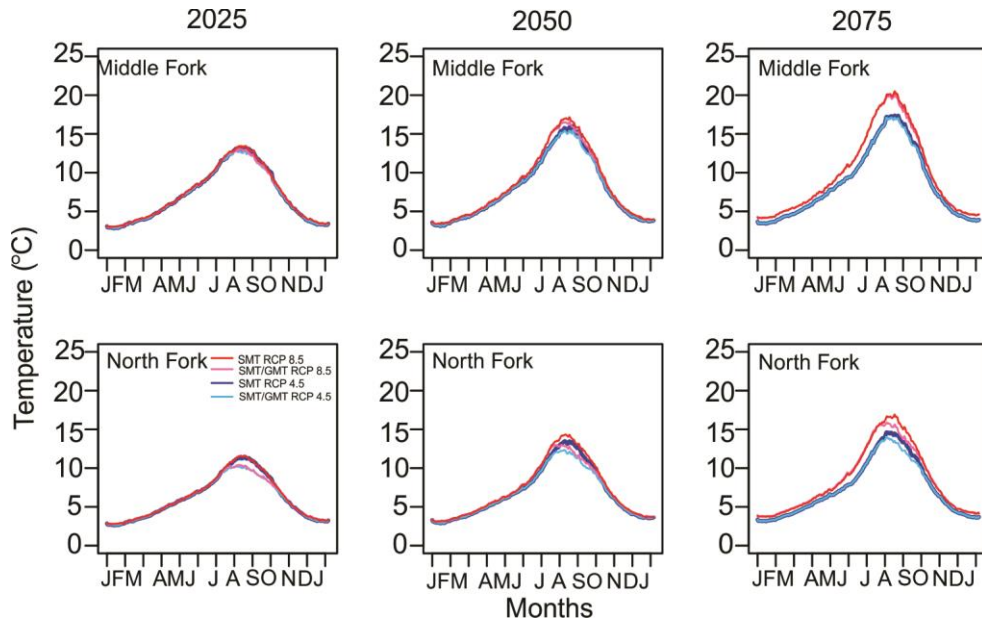
**Figure 11.** Mean stream temperatures on the Middle and North forks for simulations using the snowmelt threshold for RCP 4.5 scenarios (dark blue) and RCP 8.5 scenarios (dark red) along with mean stream temperatures for simulations using the snow and glacial melt thresholds for RCP 4.5 scenarios (light blue) and RCP 8.5 scenarios (pink) for the 30-years surrounding 2025, 2050, and 2075.