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Modeling the effects of climate change projections on streamflow in the Nooksack River basin, Northwest Washington

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Abstract:

The Nooksack River has its headwaters in the North Cascade Mountains and drains an approximately 2000 km^2 watershed in northwestern Washington State. The timing and magnitude of streamflow in a snowpack-dominated drainage basin such as the Nooksack River basin are strongly influenced by temperature and precipitation. Projections of future climate made by general circulation models (GCMs) indicate increases in temperature and variable changes in precipitation for the Nooksack River basin. Understanding the response of the river to climate change is crucial for regional water resources planning because municipalities, tribes, and industry depend on the river for water use and for fish habitat.

We combine three different climate scenarios downscaled from GCMs and the Distributed-Hydrology-Soil-Vegetation Model to simulate future changes to timing and magnitude of streamflow in the higher elevations of the Nooksack River. Simulations of future streamflow and snowpack in the basin project a range of magnitudes, which reflects the variable meteorological changes indicated by the three GCM scenarios and the local natural variability employed in the modeling. Simulation results project increased winter flows, decreased summer flows, decreased snowpack, and a shift in timing of the spring melt peak and maximum snow water equivalent. These results are consistent with previous regional studies, but the magnitude of increased winter flows and total annual runoff is higher. Increases in temperature dominate snowpack declines and changes to spring and summer streamflow, whereas a combination of increases in temperature and precipitation control increased winter streamflow.

KEY WORDS hydrologic modeling; DHSVM; climate change impacts

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INTRODUCTION

The Nooksack River drains a 2000 km^2 watershed with three sub-basins (North, Middle, and South Forks) in the peaks and foothills of the west slope of the North Cascades range (Figure 1). A seasonal snowpack supplies much of the spring and summer flows in the three forks, and glaciers situated at the headwaters of the North and Middle Forks on Mt. Baker contribute to late summer flows. Downstream of the confluence of the three forks, the Nooksack River flows west through lowlands before discharging to Bellingham Bay with an annual mean discharge of 3000–4000 ft^3/s (80–110 m^3/s, USGS, 2011). The Nooksack River is an important source of fresh water in Whatcom County, Washington, and is critical to the supply for municipal drinking water, agriculture, industry, and salmon and shellfish habitat.

Climate change scenarios project a warming rate over the next century of 0.1–0.6 °C/decade and variable changes in precipitation for the Pacific Northwest (PNW), which is driving planning strategies by stakeholders for regional rivers (e.g. CIG, 2010; Mote and Salathé, 2010; Vano *et al.*, 2010). Decades of studies on the effects of climate change on water resources indicate that both temperature and precipitation affect the timing and magnitude of streamflow in western U.S. rivers. Climate-driven effects on streamflow include changes to the ratio of precipitation in the form of rain to snow, amount of total precipitation, timing of snowmelt, and seasonal changes in soil moisture content (e.g. Lettenmaier and Gan, 1990; Gleick and Chalecki, 1999; Elsner *et al.*, 2010). In the PNW, climate change is expected to result in higher winter and spring streamflow, decreased snowpack, and an earlier melt season for transient basins, i.e. basins having an average winter temperature within about 5 °C of freezing and a ratio of snow water equivalent (SWE) to October–March precipitation of 0.1–0.4, which is

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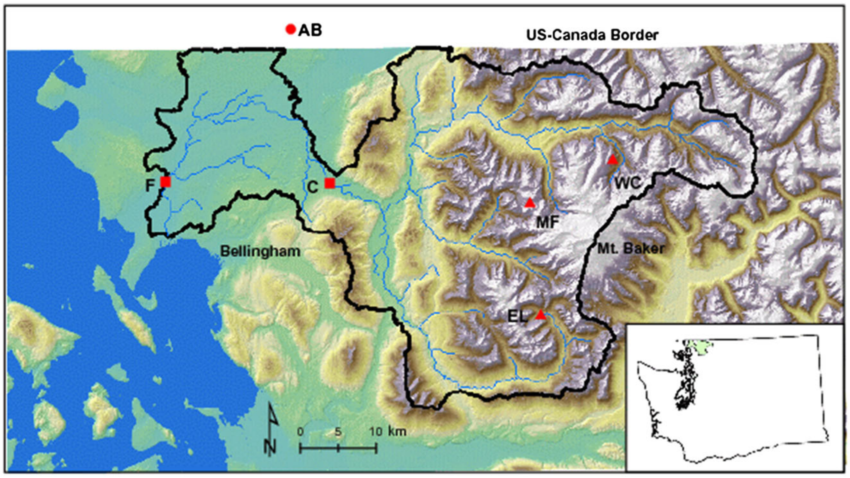

Figure 1. Hillshade map of the Nooksack River watershed with inset location map of the watershed within Washington State. The locations of USGS stream gauges at Ferndale (F) and North Cedarville (C) are indicated by red squares; Abbotsford (AB) meteorological station by a red circle; and SNOTEL stations at Wells Creek (WC), Middle Fork (MF), and Elbow Lake (EL) by red triangles

common within the maritime climate of the PNW (Hamlet and Lettenmaier, 2007; Elsner *et al*., 2010). Mote *et al*. (2005) documented a decreasing trend in SWE in the Western U.S. from 1925 to 2000 based on observed historical data and found that the largest relative decreases were in the PNW, because of the increased sensitivity of SWE to elevation in transient basins. As temperature increases in the future, the typical two-peak hydrograph of a transient watershed will transition to a single-peak hydrograph characteristic of a rain-dominated watershed (Tohver and Hamlet, 2010). The projected temperature increases will also result in decreased summer flows at the height of water usage demand and potential increases in frequency and magnitude of winter floods (Hamlet and Lettenmaier, 2007; Wiley and Palmer, 2008).

In an effort to address the requests of governments, tribal nations, public utilities, industries, and other water resources stakeholders in the PNW, the Climate Impacts Group (CIG) at the University of Washington has led several major modeling initiatives which have focused on projecting climate change effects on streamflow in western Washington watersheds. In 2006–2007, the Climate Change Technical Committee (CCTC), a collaborative outreach effort of CIG, used projected climate data sets as meteorological input for the Distributed-Hydrology-Soil-Vegetation Model (DHSVM) to simulate climate change impacts on streamflow in five watersheds in the western Cascades, east of the Seattle-Tacoma metropolitan area (Palmer, 2007). The DHSVM is a spatially distributed, physically explicit hydrology model developed for mountainous regions (Wigmosta *et al*., 1994). The CCTC made their methodology and results available in a series of eight technical reports (e.g. Polebitski *et al*., 2007a). In general, the CCTC modeling results include a positive net increase in annual flow, with increasingly negative changes to summer flow and increasingly positive changes to winter flow in the next 75 years (Polebitski *et al*., 2007b).

The CIG's Columbia Basin Climate Change Scenarios Project (CBCCSP) produced a database of climate-impacted hydrologic scenarios for the PNW using the Variable Infiltration Capacity (VIC) model, which is a macro-scale hydrologic model, at 1/16° resolution (Liang *et al*. 1994; CIG, 2010). The CBCCSP results include projections for streamflow, SWE, and other hydrologic factors for 297 locations in the Columbia River basin and coastal watersheds in the PNW, including the Nooksack River. Their results document similar winter and summer streamflow trends as the CCTC studies for western Washington rivers. Both initiatives also project a decreased snowpack and overall shift in the hydrographs to an earlier spring melt for transient basins on the western flanks of the Cascades (Elsner and Hamlet, 2010).

The CIG's Washington Climate Change Impacts Assessment implemented VIC at 1/16° resolution and DHSVM at 150 m resolution to simulate future streamflow, snowpack, and reservoir operations based on general circulation model (GCM) projections for the Columbia River basin and Puget Sound watersheds (Elsner *et al*., 2010; Vano *et al*. 2010). Results for the Cedar River, Green River, South Fork Tolt River, and Sultan River, all of which drain the west slopes of the Cascades to the Puget Sound, include a decrease of 69–85% of SWE by the 2040s and a shift in the hydrograph toward a one-peak, rain-dominant response.

Although general future trends in snowpack and streamflow under warming climate conditions have been documented in the PNW, the response of an individual river, like the Nooksack, can be highly variable and nonlinear due to unique basin characteristics and local and regional climate (Leung and Wigmosta, 1999). The Nooksack River basin has highly variably local weather patterns and elevation-dependent temperature and precipitation effects. Observed temperature and precipitation patterns in the basin reflect the moderate wet winters and mild dry summers indicative of the maritime climate of the region. Fronts coming in off the Pacific Ocean produce about 70% of the region's precipitation between October and March. The temporal variability in temperature and precipitation is strongly influenced by recurrent interannual El Niño Southern Oscillations and interdecadal Pacific Decadal Oscillations (Mantua and Hare, 2002). The relief in the basin ranges from sea level at mouth of the Nooksack River to 3286 m at the peak of Mt. Baker. About 67% of the basin resides in the Cascade foothills and mountains (elevations greater than 300 m), which has a large influence on precipitation magnitude distributions due to orographic effects. During the climate-normal period, 1971–2000, average annual precipitation ranged from 812 mm near sea level to 5584 mm near the summit of Mount Baker, and had a basin mean of 2327 mm (PRISM Climate Group, 2008). Analysis of average annual PRISM precipitation magnitudes in 500 m elevation bands in the basin yielded an average linear precipitation lapse rate of about 0.0012 m/m. Precipitation can fall as rain or snow in the higher elevations, but a consistent snowpack exists from November to June, or later, at the Natural Resources Conservation Service snow telemetry (SNOTEL) station near Elbow Lake (elevation 926.6 m; Figure 1), and elevations above 2000 m typically accumulate 8–10 m of snow (Bach, 2002). The Mt. Baker Ski Area (elevation of 1280 m) holds the U.S. record for snowfall; a total of 28.96 m was recorded in the 1989–1999 snow season (Mass, 2008).

Streamflow in the Nooksack River reflects the influence of local climate and the key role of snowpack in the upper basin. Higher flows occur in fall and early winter as precipitation increases and in the spring of the year as snowmelt accelerates. Occasional floods occur when Pacific storms set up rain-on-snow events in the late fall and early winter, e.g. a maximum discharge of 57 000 ft^3/s (1610 m^3/s) was recorded at Ferndale on November 10, 1990 (USGS, 2011). Streamflow typically falls below 1000 ft^3/s (28 m^3/s) in the late summer as the snowpack diminishes, the soil dries out, and the weather is dry and warm. Under these late summer conditions, the contributions of meltwater from glaciers on Mt. Baker become more important in the Nooksack River system.

To examine the response of the Nooksack River to climate change, we combine three different downscaled GCM scenarios with the DHSVM and extend the techniques of the CCTC to this more northern, high relief basin. To capture the unique attributes of the Nooksack River basin, we model the basin at 150 m spatial resolution using current digital data and employ 50 years of regional meteorological data in our downscaling process to incorporate temporal variability. We simulate snowpack and streamflow evolution in the basin at climate intervals surrounding the years 2000, 2025, 2050, and 2075.

METHODOLOGY

Climate change scenarios

Streamflow and snowpack in the PNW are highly dependent on natural climate variability resulting from interannual and interdecadal climate cycles and localized weather patterns. Thus, both the overall trends in future climate and the local variability were incorporated into our meteorological forcing data in order to model climate change impacts on hydrology of the Nooksack basin. General circulation models (GCMs) provide coarse resolution projections of future climate based on the positive radiative forcing represented in a possible future greenhouse gas emissions scenario. Salathé *et al*. (2007) analyzed 2040s climate conditions in the PNW derived from 20 GCM–emissions scenario couples from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007) and found that all models project an increase in average temperature, and most models project an increase in winter precipitation and a slight decrease in summer precipitation. They also indicated that the 20 couples formed three loose clusters of temperature and precipitation change and suggested a choice of three couples, one to represent each cluster, in order to provide a range of future conditions on which to base subsequent work on climate change effects in the PNW. As such, we chose an ensemble approach in our modeling by using three GCM–emissions scenario couples to represent a range of possible future conditions.

The three couples include: the IPSL_CM4_A2 (GCM from the *Institut Pierre Simon Laplace*, with A2 emissions scenario, hereafter IPSL_A2*)* which represents multiple GCM–emissions scenario couples that project an increase in temperature of 2.0–5.0 °C and an 8–9% increase in precipitation by 2040; the Echam5_A2 (GCM from the *Max Planck Institute for Meteorology*, with A2 emissions scenario, hereafter Echam_A2), which represents a group of middle scenarios with a 1.5–3.0 °C temperature increase and a 1–5% precipitation increase by 2040; and the GISS_ER_B1 (GCM from the *Goddard Institute for Space* Studies, with B1 emissions scenario, hereafter GISS_B1), which represents a group of couples that projects a 2–5 °C increase in temperature along with a

0.5–4.0% decrease in precipitation (Salathé *et al*., 2007). The A2 scenarios describe future emissions based on continued population increase and a future economy based on fossil fuels, whereas the B1 scenarios characterize a future world population peak and subsequent decline, with alternative choices around energy and economies (IPCC, 2000).

In order to develop a basin-scale meteorological data set, the monthly GCM data were statistically downscaled, first from the scale of the GCM (approximately 200 km grid size) to 1/8° (approximately 10 km grid size) resolution and then to the local, station scale following a hybrid delta' approach (Polebitski *et al*., 2007c; Hamlet *et al*., 2010). In particular, projected GCM-scale temperature and precipitation are used as predictors of future, local-scale temperature and precipitation, which are the critical inputs for hydrologic modeling (Widmann *et al*., 2003). Three general types of statistical downscaling are recognized: a bias-correction statistical downscaling method (BCSD), a delta method, and a hybrid delta method (Hamlet *et al*., 2010). The BCSD method (e.g. Wood *et al*. 2002; Salathé *et al*., 2007) uses the time series of the GCM data directly, which allows for characterization of future weather patterns and interannual variability, but relies on the GCM to accurately represent the local weather effects of a particular watershed. In contrast, both the delta method and the hybrid method utilize a shifted version of the time series of historical meteorological observations as the future projection. The delta method uses the average monthly change projected by the GCM (e.g. April temperature) for a future time period (e.g. 2030 to 2059 to represent the future climate of the 2040s) and applies that mean change to each month in the historical time series (e.g. Hamlet and Lettenmaier, 1999). The hybrid delta method uses the same approach, but applies a different scaling factor to each month of the historic time series based on where it falls in the probability distribution of monthly values (e.g. the 30th percentile of April mean temperature). Empirical cumulative distribution functions (eCDFs) are calculated for monthly temperature and precipitation data from the historic record and from GCM simulations of the same period; transform functions are created from the relationship between the two data sets and are used to shift the local meteorological record to reflect the statistics of the GCM projections. The advantage of the hybrid delta approach is that the distribution of projected future climate is mapped onto the historic record of climate, whereby incorporating the underlying future climate trend while preserving the full range of temporal variability of weather at a local level.

We began with GCM data that were previously downscaled following the BCSD method to 1/8° resolution for the specific grid cell in which the local meteorological station is located (WCRP, 2009). These 1/8° resolution data from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set were produced following the methods of Wood *et al*. (2002; 2004) and Maurer (2007), using gridded historical data from Maurer *et al*. (2002). The GCM output data for the future period (2000–2099) were first bias-corrected based on the difference between the gridded historical data (aggregated to the spatial resolution of the GCM output) and the hindcast GCM output. Temperature and precipitation scaling factors were calculated from the historical comparison and applied to the future projections using a quantile mapping approach (Wood *et al*., 2002; Wood and Lettenmaier, 2006; Salathé *et al*., 2007), described below. The bias-correction assumes that the bias structure of the historical time period remains constant for the future time period. The bias-corrected projections were then spatially downscaled from the resolution of the GCM to 1/8° resolution based on the comparison between the different resolution data sets for the same time period, also using a quantile mapping approach. The bias-corrected, downscaled CMIP3 forecast data were downloaded from their website in ASCII format for January 1950 through December 2099 for the specific grid cell in which the local station is located (Latitude bounds: 49.0, 49.125, Longitude bounds: −122.375, −122.25).

Following the work of Wiley and Palmer (2008), Salathé *et al*. (2007), Hamlet *et al*. (2010), and Polebitski *et al*. (2007a, c), we subsequently downscaled the 1/8° CMIP3 projections using a hybrid delta approach to the Abbotsford meteorological station (49.03° N, 122.36° W; NCDIA, 2009) in British Columbia, Canada to produce a climate-impacted future time series at the Abbotsford station for forcing the hydrologic model. Ultimately, the DHSVM can use the meteorological forcing from a point station and distribute the variables to the grid cells in the watershed via temperature and precipitation lapse rates based on elevation. The Abbotsford station was chosen for its proximity to the west side of the watershed, which is the direction from which most weather systems arrive, and for its long and complete record of observations.

To account for the difference in spatial scales between the 1/8° projection data and the point location at which we were modeling, we compared 50 years (1950–1999) of Abbotsford observations to 50 years (1950–1999) of 1/8° gridded meteorological data (Maurer *et al*., 2002) to identify difference due to spatial resolution in the two historical records, and to subsequently downscale the 1/8° CMIP3 projections to the local station using quantile mapping. The comparison between the historical Abbotsford record and the historical 1/8° gridded record provided a framework for how observations at a single point station relate to the gridded product derived from observations at many point stations. For the example, the distribution of April mean temperature is slightly warmer at the Abbotsford station than for the coarser resolution gridded data that includes the location of the Abbotsford data (Figure 2a). In quantile mapping, the values of two data sets are compared based on the non-exceedance probability of each value rather than its location in the time series, which is termed an equiprobability' transformation by Panofsky and Brier (1958). For each month, we computed the eCDF for monthly mean temperature or monthly total precipitation based on observed frequency and compared values between the Abbotsford historical point data and the gridded 1/8° historical data that had the same probability. For example, 50 years (1950–1999) of April mean temperature were binned and ranked from lowest to highest, without regard to their order in the time series. The monthly eCDF (Figure 2a) for each variable was calculated by using the Wiebull plotting position formula as a proxy for non-exceedance probability (P_{ne}), which is the probability that the value (e.g. temperature) will be less than or equal to a specific value in the distribution:

$$P_{ne} = \frac{z}{n+1}$$

where z is equal to the rank of the value in order from lowest to highest (i.e. the lowest value has a rank of 1), and n is equal to the total number of values (Stedinger *et al.*, 1993). Then, comparing the eCDFs of the two historical data sets, we calculated the difference in temperature (ΔT) or a ratio of precipitation (ΔP) between values that had equal P_{ne}. The result was a quantile map for each month, consisting of a table of P_{ne} and the associated ΔT or ΔP value between the Abbotsford data set and the historical 1/8° gridded data set (Wood *et al.*, 2002). The delta factors derived from the historical data sets were then applied to the 1/8° projections month by

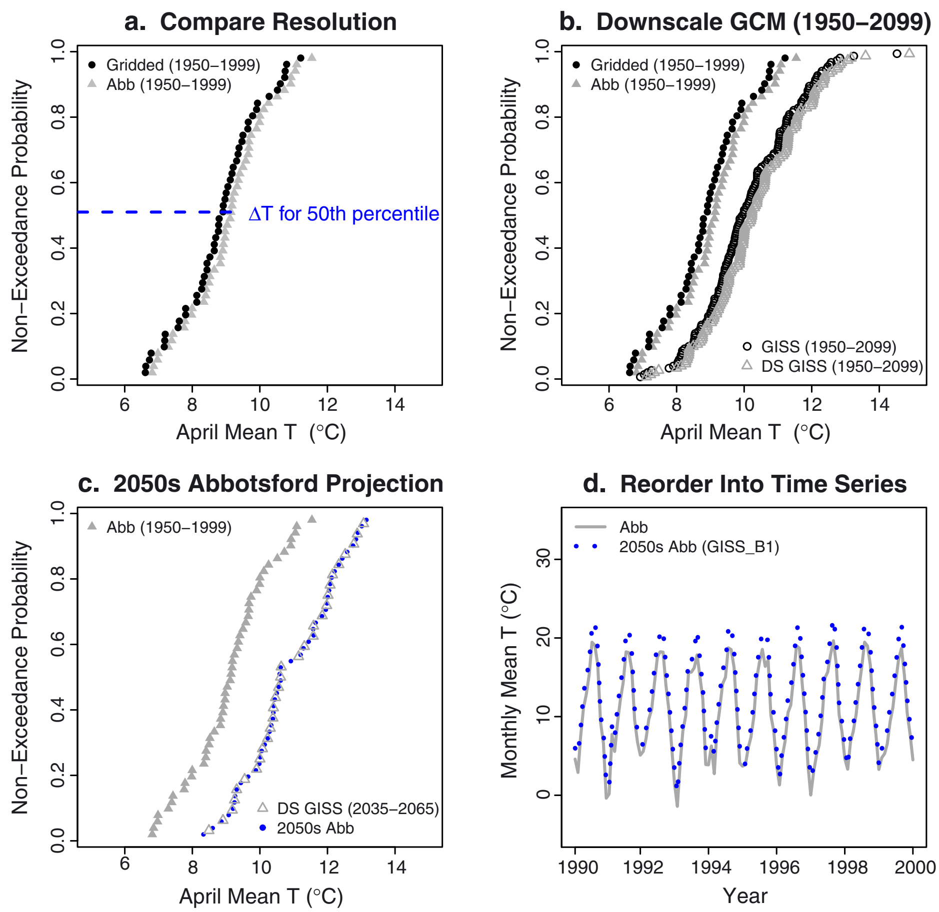

Figure 2. Example of downscaling methodology for April mean temperature: a. Comparison of empirical cumulative distribution functions (eCDFs) for historical data at the point station (Abb) and for the 1/8° gridded data to build a quantile map of ΔT values for each non-exceedance probability. b. Application of the quantile map to the GCM projections (GISS), resulting in downscaled projections (DS GISS). c. The eCDF of a 31-year slice, centered on 2050, of the DS GISS projections is used to shift the eCDF of historical Abbotsford observations to create a 2050s projection for the Abbotsford location. d. Time series order is restored to force the hydrology model (note that only 10 of the 50 years are shown)

month to derive a downscaled climate projection for the Abbotsford station (Figure 2b). The downscaled monthly temperature and precipitation projections are given by:

$$T_{ds} = T_{proj} + \Delta T$$
$$P_{ds} = P_{proj} * \Delta P$$

Where T_{ds} and P_{ds} are the downscaled monthly projections, T_{proj} and P_{proj} are the monthly values from the 1/8° CMIP3 projections, and ΔT and ΔP are the difference in temperature and the ratio of precipitation, respectively, between equal probability values in the different resolution historical data sets. Since the observed data set is shorter than the projected data set, additional delta values were interpolated and extrapolated using a spline technique.

We applied one final quantile mapping step to derive a shifted 50-year Abbotsford time series to represent projected climate in a specific future period to use for hydrological modeling. We restored the time series order of the downscaled projection data and extracted a 31-year slice, centered on the year of interest (e.g. 2050). The 31-year length of the slice was chosen to represent the steady state of climate centered on 2000, 2025, 2050, and 2075; 30 years is commonly used as the time period that is representative of climate. We the calculated monthly eCDFs of temperature and precipitation for the projections and compared them to the monthly eCDF of 50-year historical data set (Figure 2c). The difference between the eCDFs was used to create another set of quantile maps used to translate the 50-year historical daily data set to incorporate the trends of the 31-year climate surrounding the year of interest, while maintaining the temporal variability recorded in the historical observations. We completed the downscaling procedure for each month and each variable (T and P) and then restored the time series order of the shifted Abbotsford data (Figure 2d). Thus, each local climate change data set used to force the DHSVM is the 50-year Abbotsford time series (1950–1999) that has been shifted to represent the 31-year climate trend centered on 2000, 2025, 2050, and 2075 for each GCM–emissions scenario couple. Finally, the daily values were disaggregated into a 3-h time step and used to estimate the other DHSVM meteorological inputs (e.g. incoming solar radiation). Validation of the local projections and downscaling methodology is provided via comparison between Abbotsford observations and downscaled hindcast data for the historical time period. Boxplots of the distributions of temperature and precipitation values for the downscaled GCM data sets for the 50-year period 1950–1999 are similar to the distributions of observed values at Abbotsford for the same period (Figure 3).

Hydrologic modeling

The DHSVM is a physically based, spatially distributed hydrology model that was developed at the University of Washington and the Pacific Northwest National Laboratory, and originally tested and validated in the Middle Fork Flathead River basin in Montana (Wigmosta *et al*., 1994). The model combines spatially explicit physical characteristics of the watershed, including topography, land cover, soil type and thickness, and a streamflow network, with meteorological forcing data provided at a user-defined time step (e.g. 1 h to 1 day). A constant precipitation lapse rate of 0.001 m/m and a monthly varying temperature lapse rate ranging from −0.0062 to −0.0090 °C/m was used to extrapolate the meteorological forcings from the Abbotsford station to each grid cell based on elevation. We used a 3-h time step to capture sub-daily fluctuation in water and radiation inputs and to preserve computational efficiency. The model provides simultaneous solutions for the algorithms that govern the net mass and energy flux in each grid cell, and transfers mass and energy across grid cells at each time step. The algorithms governing the relationships are described in detail in the literature (e.g. Wigmosta *et al*., 1994; Wigmosta *et al*., 2002).

The DHSVM output includes streamflow for a designated stream segment, typically chosen based on the location of a streamflow gauge. Additionally, individual pixels can be designated to save time step data including SWE, soil moisture, and evapotranspiration. With snowpack of key interest, pixels at the three SNOTEL stations were designated to capture continuous output of SWE for the entire duration of each simulation. Thus, calibration and validation of the model included the comparison of modeled output to historic observations of streamflow from USGS gauging stations and SWE from SNOTEL stations (Figure 1) for water years 2006–2007 (calibration) and 2008–2009 (validation). The North Cedarville USGS gauging station, which is located at river mile 30.9 (49.7 km) at the downstream terminus of the modeling extent, has recorded continuous discharge data since 2006, and we used all available discharge data when we completed the modeling portion of this study. Metrics such as total annual streamflow and SWE, the Nash and Sutcliffe (1970) efficiency (E), and the coefficient of determination (r^2; Krause *et al*., 2005) were used to establish the goodness of fit between the modeled output and the historic observations. We used discharge at the North Cedarville USGS gauging station as the observational data against which to calibrate the model because of its ideal location downstream of the confluence of all three forks of the Nooksack, but upstream of the agricultural and industrial lowland floodplain. However, due to the USGS quality rating as fair’ for discharge data collected at the North Cedarville USGS gauging station, the higher quality streamflow record

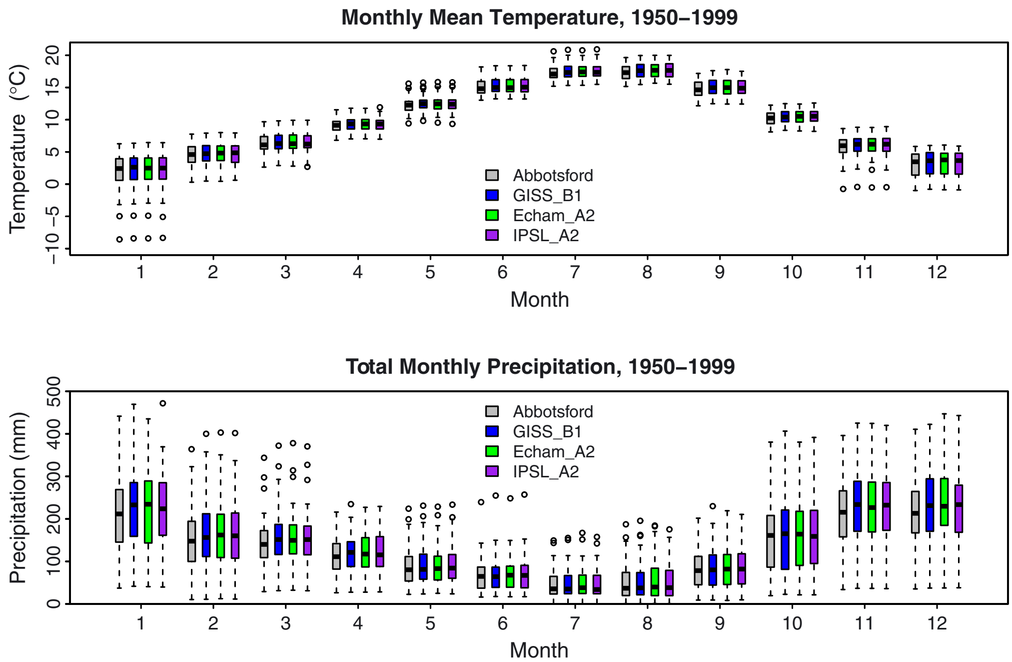

Figure 3. Boxplots of 50 years of monthly mean temperature and total monthly precipitation for observations from 1950 to 1999 at the Abbotsford station, and for hindcasts for 1950–1999 from the three downscaled GCMs

at Ferndale was also used as part of the calibration and validation process. The Ferndale station is located at river mile 5.8 (9.3 km) which is 40.4 km downstream from the North Cedarville station. There are agricultural and municipal inputs and outputs to the river in between the stations; however, the streamflow records from the two stations are similar ($E = 0.78$, $r^2 = 0.79$ for water years 2006–2009), and the longer record and more accurate observations at Ferndale served as a useful proxy record for comparing modeled streamflow.

The 50-year simulations were run with a calibrated and validated model using the downscaled climate change data sets from three GCM–emissions scenario couples to represent four periods of climate: 2000, 2025, 2050, and 2075. Additionally, simulations were performed using the historical daily Abbotsford 50-year time series disaggregated to 3-h intervals for comparison with future simulations. Initial conditions were created by starting with a dry state and running the calibrated model through water years 2006–2009. The resulting basin conditions at the end of 2009 were used as the initial state for all 50-year simulations.

RESULTS

Downscaled, local climate change projections include three possibilities for periods centered on 2000, 2025, 2050, and 2075. Since all the downscaled data sets incorporate the same historical Abbotsford time series, the temperature and precipitation differences between the projections correspond to each GCM–emissions scenario couple. All three downscaled scenarios project an increase in monthly mean temperature in all months relative to the observed Abbotsford historic temperature data, for all four future periods of climate (Table I). The magnitude of temperature increases vary seasonally, with the greatest increases in the summer. The largest increases in temperature are associated with the two projections that utilize the A2 emissions scenario, but all three projections consistently indicate a warming trend through time.

In contrast, the precipitation projections vary in both direction and magnitude between seasons and between the three GCMs (Table I). In most cases, the three projections include increases in precipitation relative to historic Abbotsford observations in all seasons except summer. The IPSL_A2 and Echam_A2-based projections indicate overall increases in winter precipitation through time. The GISS_B1-based projection indicates a decreasing trend from 2000 to 2075, but an overall magnitude of precipitation that is greater than the historic period for all projected periods.

The DHSVM was considered calibrated and validated to the Nooksack River basin with Nash and Sutcliffe (1970) efficiencies of $E = 0.43$ and $E = 0.55$ for daily median streamflow for the calibration and validations periods, respectively, and coefficients of determination (Krause *et al*., 2005) of $r^2 = 0.67$ and $r^2 = 0.56$. Calibration metrics for monthly median streamflow were $E = 0.73$ and $E = 0.48$ for the calibration and validations periods,

Table I. Mean seasonal changes in monthly mean temperature (T) and total monthly precipitation (P) for the three downscaled climate change projections relative to historic values (Abbotsford Station, 1950–1999; Spring = March, April, May; Summer = June, July, August; Autumn = September, October, November; Winter = December, January, February). Note that the projections consist of a 50-year time series that has been shifted based on the statistics of the 31-year period centered on the year of the projection (i.e. 2000 is characterized by the climate of 1985–2015)

	Spring			Summer			Autumn			Winter		
	T (°C)	P (mm)		T (°C)	P (mm)		T (°C)	P (mm)		T (°C)	P (mm)	
Historic	9.2	116		16.5	55		10.2	151		3.2	196	
	ΔT (°C)	ΔP (mm)	*ΔP (%)*	ΔT (°C)	ΔP (mm)	*ΔP (%)*	ΔT (°C)	ΔP (mm)	*ΔP (%)*	ΔT (°C)	ΔP (mm)	*ΔP (%)*
GISS_B2												
2000	0.8	13	*12*	1.3	3	*6*	0.6	34	*22*	0.9	27	*14*
2025	1.5	20	*17*	1.9	0	*0*	1.2	37	*24*	1.3	21	*11*
2050	1.8	16	*14*	2.4	−8	*−15*	1.7	39	*26*	1.3	13	*7*
2075	1.8	28	*24*	2.8	−7	*−13*	1.9	26	*17*	1.9	21	*11*
Echam_A2												
2000	0.4	17	*15*	1.0	4	*8*	0.7	23	*15*	0.2	27	*14*
2025	1.4	16	*13*	1.4	16	*28*	1.3	26	*17*	1.7	22	*11*
2050	1.8	29	*25*	2.8	6	*10*	1.8	23	*16*	2.3	30	*15*
2075	3.4	20	*18*	4.5	8	*15*	3.3	28	*19*	5.1	52	*27*
IPSL_A2												
2000	0.9	17	*15*	1.2	5	*10*	1.2	27	*18*	0.5	24	*12*
2025	1.4	7	*6*	2.0	11	*20*	1.7	35	*23*	1.7	37	*19*
2050	2.6	20	*17*	3.5	−2	*−3*	2.7	28	*18*	2.4	42	*21*
2075	4.0	25	*22*	5.2	0	*0*	4.3	30	*20*	4.1	75	*38*

respectively, and $r^2 = 0.88$ and $r^2 = 0.52$. Whereas the error statistics were generally lower than the threshold that is considered a good fit (i.e. $E > 0.7$, Elsner *et al.*, 2010), examination of the hydrographs shows that peak flows account for most of the difference. Since observations of peak flows at the North Cedarville USGS station are rated as fair to poor when estimated during high flows, agreement with the downstream daily discharge record ($E = 0.67$ and $r^2 = 0.73$ for an additional 4-year validation period of water years 2001–2005) at the Ferndale station provided confidence in the modeled flows. The 2-year annual sum of daily simulated streamflow total was within 10% of observed streamflow for the calibration and validation periods. Furthermore, the modeling experiment was designed to capture the change in monthly distributions of discharge and SWE values relative to baseline simulations for a representative, but limited, range of GCM projections. Thus, the validation was considered sufficient to proceed with the analysis based on the rationale that the detection of relative shifts in distributions would be robust.

The simulations also closely matched the recorded SWE at the Middle Fork Nooksack SNOTEL ($E = 0.85$ and $r^2 = 0.86$) and Wells Creek SNOTEL ($E = 0.61$ and $r^2 = 0.73$) stations in the North Fork basin. Calibration to the Elbow Lake SNOTEL station proved to be problematic, in part due to the microclimate nature of the site. The most sensitive DHSVM calibration parameters for the Nooksack basin were the rain/snow threshold temperature and the precipitation- and temperature-lapse rate values. Soil type and thickness proved to be secondary to the parameters that control the type and amount of precipitation in this mountainous watershed.

Snow water equivalent at the Middle Fork SNOTEL station is projected to decrease through time for every month (Figure 4). The variable rates of decrease for SWE correspond to the GCM projections. By 2050, a 33 to 45% decrease in monthly median SWE is projected for the Middle Fork, with faster and higher magnitude decreases projected by the DHSVM when simulated with climate projections from IPSL_A2 and Echam_A2 than with GISS_B1. The Middle Fork SNOTEL site is the highest elevation (1506 m) of the three SNOTEL stations in the Nooksack basin and therefore most resistant to effects of increased temperature. The DHSVM simulations project higher rates of SWE decrease at the lower elevation SNOTEL stations.

April 1 is typically considered the timing of peak SWE in western U.S. river basins, but SWE projections based on all three climate scenarios result in a shift of the timing of the peak SWE to earlier in the year. At the Middle Fork SNOTEL, peak SWE is projected to shift to March or earlier by 2075 by the Echam_A2 and IPSL_A2 simulations. In the 2025 simulations, the change in median day of year of peak SWE ranges from 18 days earlier for the GISS_B2 projection to 25 days earlier for the ISPL_A2 projections. The change in peak SWE for the 2050s scenarios ranges from 23 to 45 days. Projections for the lower elevation SNOTEL stations include shifts to March or earlier by 2025. Additionally, with melting of the snowpack occurring earlier in the year, the number of months with no snowpack at the SNOTEL sites increases.

Simulations of future streamflow in the Nooksack River project increases in winter streamflow, decreases in summer streamflow, and shifting of the spring melt peak (Figure 5). Results for the magnitude of future streamflow are variable, with increases in median winter discharge ranging from 34 to 60% by 2050 and decreases in summer flow on the order of −20% to −30% (Table II). Simulations using the GISS_B1 scenario indicate more moderate changes to streamflow, whereas the Echam_A2 and IPSL_A2 climate scenarios project larger changes. The timing of the spring peak flow tracks the timing of peak SWE, and the magnitude of the projected shift is similar in magnitude to the range for peak SWE. The GISS_B1-based simulations project a shift of the spring melt peak from June to May by 2050. The hydrological simulations based on Echam_A2 and IPSL_A2 climate scenarios indicate a flattening out of the spring melt peak by 2050, leading to a one-peak hydrograph for the Nooksack River, typical of a rain-dominated basin. Boxplots of 50 years of monthly median discharge illustrate that the range of winter flows is expanded in the Echam_A2 and IPSL_A2 simulations (Figure 5). Extreme high flows in the winter months and extreme low flows in the summer months surpass historical extremes.

DISCUSSION

Simulations of future streamflow in the Nooksack River project increasing winter flows, decreasing summer flows, and a shift in timing of the spring melt peak. The simulated increases in winter streamflow are due to the combination of increased winter temperatures and precipitation. The GISS_B1-based simulation projects more modest winter increases of 1.3 °C and 13 mm (7%) precipitation by 2050, hence a moderate impact on winter streamflow. Winter flows simulated with the ISPL_A2 and Echam_A2 are higher because the projections exhibit larger winter temperature and precipitation increases of 2.3–2.4 °C and 30–42 mm (15–21%) precipitation by 2050.

Higher winter temperatures during precipitation events have the dual effect of creating a larger contributing area for runoff because the snow level increases in elevation and accelerating snowmelt (Marks *et al.*, 1998). The result is higher streamflow during warm winter precipitation events, especially when coupled with higher precipitation magni-

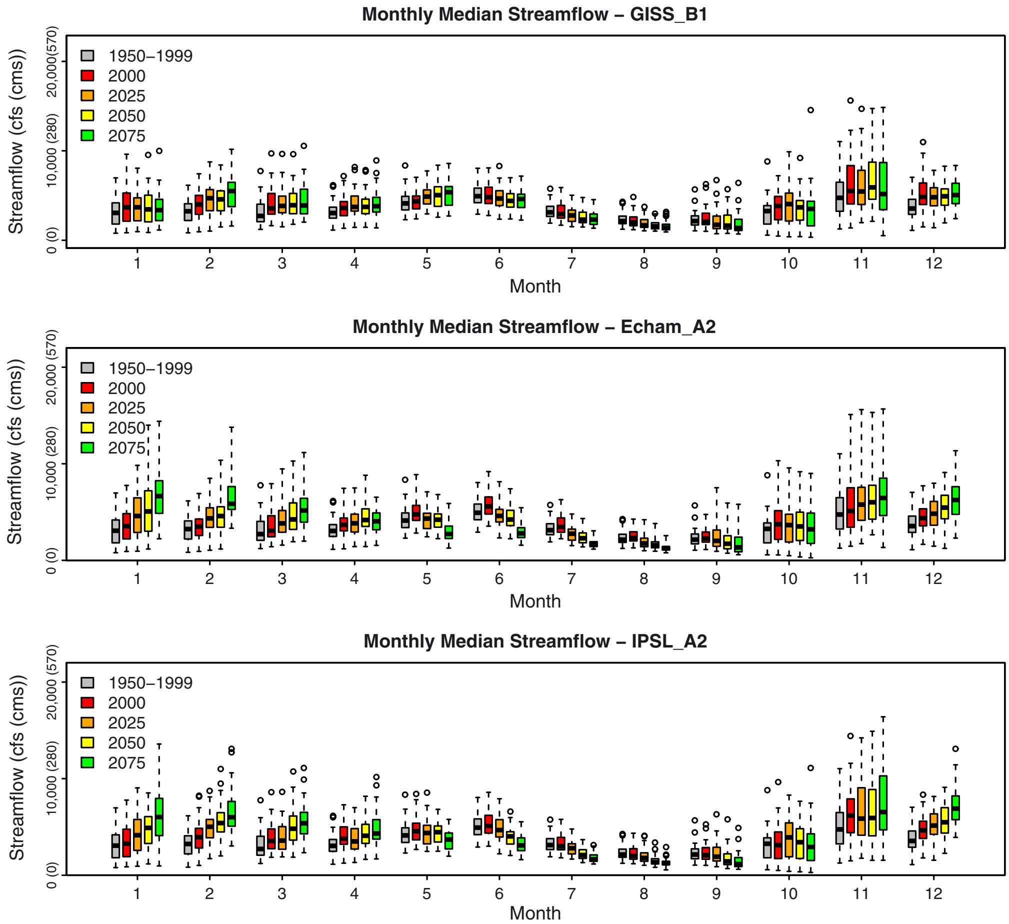

Figure 4. Boxplots of 50 years of monthly median streamflow at the North Cedarville USGS station for the historical simulation (1950–1999) and for simulations of future climate conditions using forecasts downscaled from three GCMs

tudes projected by GCMs for the PNW. Increased temperatures contribute to reduced snowpack, both depth and spatial extent, which affect the timing of spring runoff and flood peaks (Conway and Benedict, 1994; Adam *et al.*, 2009). Although increased temperatures may enhance evapotranspiration, the effects on runoff will be less pronounced between October and February when the PNW receives the majority of its precipitation. Evapotranspiration during this time interval is at a minimum because of lower radiation, lower temperatures, and higher humidity (Barnett *et al.*, 2005).

With a growing area contributing to runoff and less snow to attenuate winter rain as temperatures warm, the frequency and magnitude of Nooksack River floods will likely increase. Currently, the flood risk declines later in the winter season because the area contributing to runoff shrinks and the snowpack reaches a threshold thickness for attenuating rainfall. Due to future warming, the basin will have a reduced snowpack for a longer period of time; our results support a shift from November into December or January as the dominant time period for flood risk. Our results also show an increase in annual flood peak magnitudes due to larger precipitation extremes projected by the GCMs in the winter months, especially with the ISPL_A2 and Echam_A2 scenarios (Figure 6). The increased annual maxima also correspond to a shift of return period magnitudes. For example, our analyses of annual floods modeled with the ISPL_A2 and Echam_A2 projections indicate that the magnitude of a historical 10-year flood is projected to have a return interval of 3 years by 2050.

Modeled SWE shows a clear decreasing trend through time regardless of increasing precipitation. These results are consistent with Hamlet *et al.* (2005). They found that for transient watersheds, increased snow accumulation at higher elevations due to increased precipitation was insufficient to offset losses in SWE resulting from increased temperatures. In the Nooksack basin, less precipitation will fall as snow at lower elevations due to higher temperatures, and melting will increase. The decline of SWE and warmer temperatures also causes the peak SWE to occur earlier in the year. The rate and amount of shift are determined by the magnitude of temperature increase. The IPSL_A2 and Echam_A2

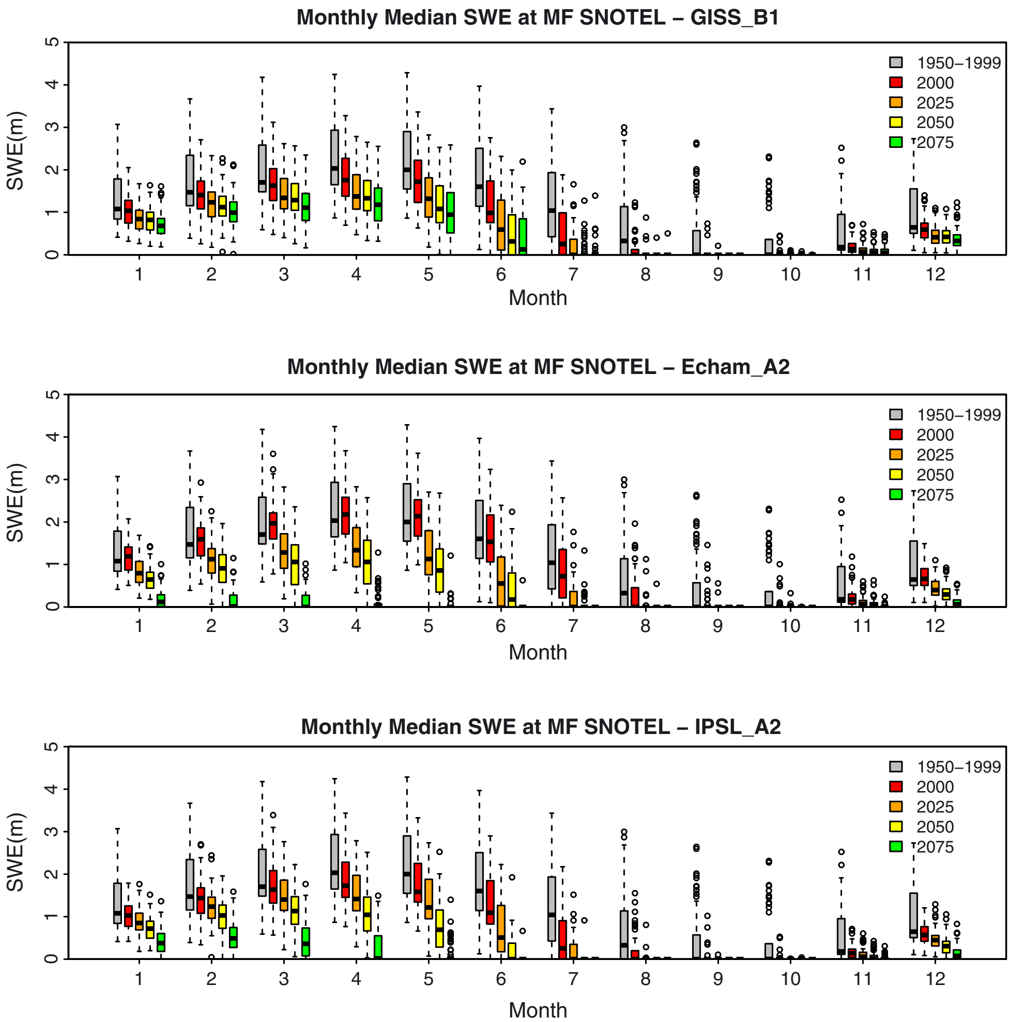

Figure 5. Boxplots of 50 years of monthly median SWE at the at the Middle Fork SNOTEL station for the historical simulation (1950–1999) and for simulations of future climate conditions using projections downscaled from three GCMs

projections indicate similar mean increases in spring and summer temperatures, ranging from 1.8° to 3.5° C by 2050, and both sets of streamflow projections indicate that the spring peak will shift early enough in the year to coalesce with winter peak flows by the 2050s. The GISS_B1 scenario projects more modest spring and summer temperature increases by 2050 of 1.8° and 2.5° C, respectively. The average annual hydrograph simulated using the GISS_B1 scenario shows a 1-month shift of the spring peak to earlier in the year by 2050. With snowmelt as the primary water input during the summer months, reduced SWE due to warmer temperatures will cause lower summer streamflows. For example, our simulations project sharp decreasing trends in summer streamflow of −21 to −33% by the 2050s, which cannot be accounted for by the modest summer declines or gains in precipitation in the projected climate data. We did not thoroughly examine the impact of glacier recession on the future summer streamflow, but warming temperatures and a reduction in glacier extent will also affect late summer streamflow in the Nooksack River.

Modeling projections for the Nooksack River are similar in trends but not magnitudes to other western Washington rivers (e.g. Polebitski *et al.*, 2007b; CIG, 2010). Our simulations project the Nooksack River to change more quickly and to a greater extent than the five western Washington rivers modeled by the CCTC (Polebitski *et al.*, 2007b). In particular, projections for future spring and winter streamflows, and total annual streamflow in the Nooksack basin are higher than the projections made for the southern rivers. Since we used similar modeling techniques as the CCTC, the difference is likely due to regional weather differences and basin characteristics that result in a higher precipitation and SWE and hence more runoff in the Nooksack basin. Basin relief in the in the Nooksack is particularly high, with four peaks over 2000 m, including Mt. Baker which reaches elevations over 3000 m. Higher relief creates more

Table II. Percent change in median seasonal streamflow simulated using three GCM-based projections for the periods centered on 2000, 2025, 2050, and 2075, relative to the historic simulation (1950–1999) of streamflow (Spring = March, April, May; Summer = June, July, August; Autumn = September, October, November; Winter = December, January, February). Note that the projections consist of a 50-year time series that has been shifted based on the statistics of the 31-year period centered on the year of the projection (i.e. 2000 is characterized by the climate of 1985–2015)

	Spring	Summer	Autumn	Winter	Annual
GISS_B1					
2000	16%	−3%	16%	28%	18%
2025	28%	−12%	10%	28%	18%
2050	28%	−22%	16%	34%	15%
2075	31%	−26%	−5%	39%	14%
Echam_A2					
2000	19%	11%	8%	13%	15%
2025	21%	−16%	13%	35%	17%
2050	29%	−28%	8%	44%	19%
2075	19%	−50%	1%	86%	13%
IPSL_A2					
2000	19%	−1%	6%	22%	17%
2025	17%	−13%	10%	49%	20%
2050	35%	−35%	−7%	60%	22%
2075	33%	−48%	−17%	88%	20%

precipitation, and therefore runoff, due to lapse rate influences. Our results substantiate the uniqueness of the Nooksack basin and the importance of conducting high-resolution, basin-specific studies to quantify the impacts of climate change for management purposes.

Our modeled results show similar trends to those projected for the Nooksack basin by the CBCCSP, e.g. increases in winter streamflow, decreases in summer streamflow, and a flattening out of the spring peak of the hydrograph (CIG, 2010). Our projections indicate an overall increase in total runoff of 15 to 19% by 2050, whereas the results of the CBCCSP project a modest average decrease of −4% by 2040. However, the modeled data are not entirely comparable due to the choice of different GCM–emissions scenario couples and numerical models. The CBCCSP implemented the VIC model at the 1/16° resolution, whereas our grid resolution in the DHSVM is 150 m. A finer resolution may result in more precipitation and runoff at higher elevations due to a greater sensitivity to modeled precipitation and temperature lapse rates, which increase precipitation with elevation. Although both studies project similar decreases in SWE with time, our results are based on modeled values at SNOTEL locations at lower elevations and do not incorporate SWE at higher elevations. The CBCSSP averaged SWE over the entire basin.

As with any modeling study, there is uncertainty in our projections. Simulated trends and magnitudes for temperature are associated with less uncertainty than for precipitation because the processes that control precipitation (e.g. cloud formation) are often below the resolution of GCMs and are typically parameterized. Therefore, modeled SWE and spring and summer streamflow, for which temperature is the primary driver, may be associated with more certainty in the Nooksack basin. Changes which rely on a combination of future temperature and precipitation such as simulated winter flows, flood frequency, and peak flows have a higher degree of uncertainty.

Uncertainty is inherent in future climate projections, which is why we chose an ensemble approach in the Nooksack basin to bracket a range of future climate conditions and the resulting hydrological responses. Whereas the three scenarios are consistent in their projection of the trend of increasing temperatures, they vary with respect to the magnitude of temperature increases and both the direction and magnitude of future precipitation. Recent CO_2 emissions are within the middle to upper range of the pathways described by our emissions scenarios, but substantial divergence of the pathways is not projected to occur until after 2025 (Manning *et al*., 2010). Thus, at this point, each of the scenarios used in the ensemble remains a plausible version of future climate.

There is also uncertainty in using historical data for futuristic projections. Our downscaling procedure mapped the trends of GCM projections onto 50 years of historical weather observations at the Abbotsford station in order to account for the natural regional temporal variability. Many cycles of the interannual El Nino Southern Oscillation (ENSO) and the majority of two epochs of the interdecadal Pacific Decadal Oscillation are captured by these historical observations, including a cool phase from 1947 to 1976 and a warm phase that began in 1977 (Mantua and Hare, 2002). However, natural variability may be fundamentally altered by changing climate conditions. For example, global temperature change may possibly play an important role in

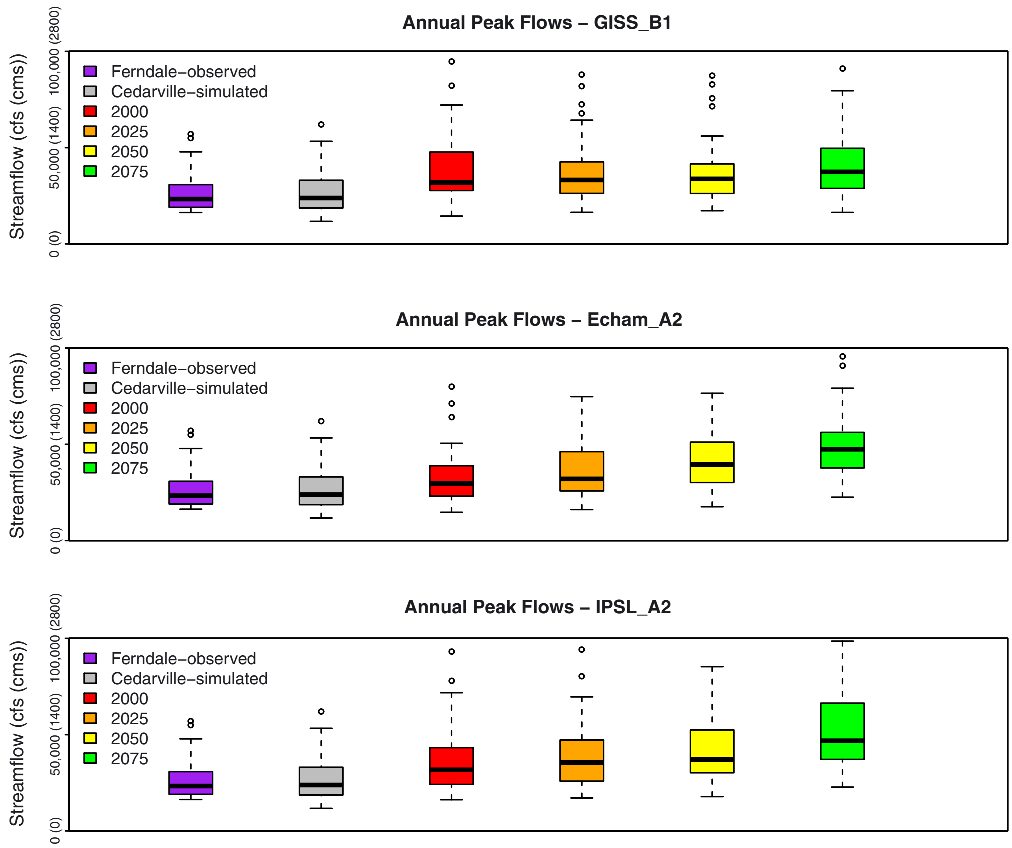

Figure 6. Boxplots of 50 years (1950–1999) of annual peak flows for observations at the Ferndale USGS station (downstream of the North Cedarville USGS station, which is the location for all simulated values), for the historical simulation, and for simulations of future climate conditions using downscaled projections from three GCMs

theseasonal timing of ENSO (Tsonis *et al*., 2003). Thus, the accuracy of modeled future streamflow may be limited because future weather patterns and cycles are not represented in the climate change projections.

Despite the inherent uncertainty with these simulated projections, the results provide an indication of how the distribution of flows may shift under a range of possible climate conditions. The range of flows will inform planning by local governments, tribal nations, and industry within Whatcom County, WA when assessing levee design, in-stream flows for fish habitat, municipal and industrial water use, and irrigation.

CONCLUSIONS

Even with uncertainty around future climate on a local scale, streamflow in the Nooksack River will shift with a changing climate in ways that are characteristic of other transient, mountainous watersheds. Due to the sensitive nature of the seasonal snowpack in such watersheds, the typical two peak hydrograph will coalesce to mimic the behavior of rain-dominated watersheds. Precipitation that historically would have been stored as snow until late spring or summer will instead contribute to higher winter flows, which will exacerbate already difficult challenges related to winter floods and summer shortages. The magnitude and rate of that change are closely tied to the GCM and the emissions scenario coupled with each GCM. Slower and more modest effects are seen when the GISS_B1 projection is used to force the model as opposed to the two GCMs that are coupled with the more drastic A2 emissions scenario. The results of this study provide a basis from which local government and industry can proactively plan for future water resources, and also illustrate the benefits of potential mitigation of greenhouse gas emissions on a national and global level.

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REFERENCES

Adam JC, Hamlet AF, Lettenmaier DP. 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes* **23**(7): 962–972. DOI: 10.1002/hyp7201

Bach A. 2002. Snowshed contributions to the Nooksack River watershed, North Cascades Range, Washington. *Geographical Review* **92**(2): 192–212. DOI: 10.2307/4140970

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**(7066): 303–309. DOI: 10.1038/nature04141

Climate Impacts Group (CIG). 2010. Columbia Basin Climate Change Scenarios Project (PI: Alan F. Hamlet), University of Washington, Seattle, WA. Available from: http://www.hydro.washington.edu/2860/report/ (accessed September 2011)

Conway H, Benedict R. 1994. Infiltration of water into snow. *Water Resources Research* **30**(3): 641–649. DOI: 10.1029/93WR03247

Elsner MM, Hamlet A. 2010. Macro-scale Hydrologic Model Implementation. Columbia Basin Climate Change Scenarios Project (PI: Alan F. Hamlet), University of Washington, Seattle, WA; 31 pp. Available from: http://www.hydro.washington.edu/2860/report/ (accessed September 2011)

Elsner MM, Cuo L, Voisin N, Deems JS, Hamlet AF, Vano JA, Mickelson KEB, Lee SY, Lettenmaier DP. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* **102**: 225–260. DOI: 10.1007/s10584-010-9855-0

Gleick PH, Chalecki EL. 1999. The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin River basins. *Journal of the American Water Resources Association* **35**(6): 1429–1441. DOI: 10.1111/j.1752-1688.1999.tb04227.x

Hamlet AF, Lettenmaier DP. 1999. Effects of climate change on hydrology and water resources of the Columbia River basin. *Journal of the American Water Resources Association* **35**: 1597–1624. DOI: 10.1111/j.1752-1688.1999.tb04240.x

Hamlet AF, Lettenmaier DP. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. *Water Resources Research* **43**(6): W06424. DOI: 10.1029/2006WR005099

Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. *Journal of Climate* **18**(21): 4545–4561. DOI: 10.1175/JCLI3538.1

Hamlet AF, Salathé EP, Carrasco P. 2010. Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies. Columbia Basin Climate Change Scenarios Project (PI: Alan F. Hamlet), University of Washington, Seattle, WA; 28pp. Available from: http://www.hydro.washington.edu/2860/report/ (accessed September 2011)

Intergovernmental Panel on Climate Change (IPCC). 2000. IPCC Special Report: Emissions Scenarios, Summary for Policymakers. A Special Report of Working Group III, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 27 pp.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 996.

Krause P, Boyle DP, Bäse F. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences* **5**: 89–97.

Lettenmaier DP, Gan TY. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming. *Water Resources Research* **26**(1): 69–86. DOI: 10.1029/WR026i001p00069

Leung LR, Wigmosta MS. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. *Journal of the American Water Resources Association* **35**(6): 1463–1471. DOI: 10.1111/j.17521688.1999.tb04230.x

Liang X, Lettenmaier DP, Wood EF, Burges SJ. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research* **99**(D7): 14415–14428. DOI: 10.1029/94JD00483

Manning MR, Edmonds J, Emori S, Grubler A, Hibbard K, Joos F, Kainuma M, Keeling RF, Kram T, Manning AC, Meinshausen M, Moss R, Nakicenovic N, Riahi K, Rose SK, Smith S, Swart R, van Vuuren DP. 2010. Misrepresentation of the IPCC CO_2 emission scenarios. *Nature Geoscience* **3**(6): 376–377.

Mantua NJ, Hare SR. 2002. The Pacific decadal oscillation. *Journal of Oceanography* **58**(1): 35–44. DOI: 10.1023/A:1015820616384

Marks D, Kimball J, Tingey D, Link T. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrological Processes* **12**: 1569–1587. DOI: 10.1002/(SICI)1099-1085(199808/09)12:10/11<1569::AID-HYP682>3.0.CO;2-L

Mass C. 2008. The Weather of the Pacific Northwest. Seattle University Press: Seattle, WA; 280.

Maurer EP. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios. *Climatic Change* **82**(3-4): 309–325. DOI: 10.1007/s10584-006-9180-9

Maurer EP, Wood AW, Adam JC, Lettenmaier DP, Nijssen B. 2002. A long-term hydrologically based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate* **15**(22): 3237–3251. DOI: 10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2

Mote PW, Salathé EP. 2010. Future climate in the Pacific Northwest. *Climatic Change* **102**(1-2): 29–50. DOI: 10.1007/s10584-010-9848-z

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in western North America. *Bulletin of the Meteorological Society* **86**(1): 39–51. DOI: 10.1175/BAMS-86-1-39

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models; Part I, A discussion of principles. *Journal of Hydrology* **10**(3): 282–290.

National Climate Data and Information Archive (NCDIA). 2009. Environment Canada. Available from: http://climate.weatheroffice.ec.gc.ca (accessed September 2011)

Palmer RN. 2007. Final report of the Climate Change Technical Committee. A Report Prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA; 29 pp. Available from: http://cee.umass.edu/water-climate-society/projects/climatechangeimpacts/tech-committee (accessed January 2013)

Panofsky HA, Brier GW. 1958. Some applications of statistics to meteorology. Mineral Industries Extension Services, College of Mineral Industries, Pennsylvania State University, University Park: PA, USA; 224.

Polebitski A, Traynham L, Palmer RN. 2007a. Technical Memorandum #4: Approach for Developing Climate Impacted Meteorological Data and Its Quality Assurance/Quality Control. A Report Prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA; 29 pp. Available from: http://cee.umass.edu/water-climate-society/projects/climatechangeimpacts/tech-committee (accessed January 2013)

Polebitski A, Traynham L, Palmer RN. 2007b. Technical Memorandum #5: Approach for Developing Climate Impacted Streamflow Data and Its Quality Assurance/Quality Control. A Report Prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA; 72 pp. Available from: http://cee.umass.edu/water-climate-society/projects/climatechangeimpacts/tech-committee (accessed January 2013)

Polebitski A, Wiley MW, Palmer RN. 2007c. Technical Memorandum #2: Methodology for Downscaling Meteorological Data for Evaluating Climate Change. A Report Prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA; 13 pp. Available from: http://cee.umass.edu/water-climate-society/projects/climatechangeimpacts/tech-committee (accessed January 2013)

PRISM Climate Group. 2008. Oregon State University. Available from: http://prism.oregonstate.edu

Salathé EP, Mote PW, Wiley MW. 2007. Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States pacific northwest. *International Journal of Climatology* **27**(12): 1611–1621. DOI: 10.1002/joc.1540

Stedinger JR, Vogel RM, Foufoula-Georgiou E. 1993. Frequency Analysis of Extreme Events. Handbook of Hydrology, Maidment DR (ed). McGraw-Hill, Inc.: New York, NY; 18.1–18.66.

Tohver I, Hamlet A. 2010. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. Columbia Basin Climate Change Scenarios Project (PI: Alan F. Hamlet), University of Washington, Seattle, WA; 31 pp. Available from: http://www.hydro.washington.edu/2860/report/ (accessed September 2011)

Tsonis AA, Hunt AG, Elsner JB. 2003. On the relation between ENSO and global climate change. *Meteorology and Atmospheric Physics* **84**(3-4): 229–242. DOI: 10.1007/s00703-003-0001-7

United States Geological Survey (USGS). 2011. USGS Water Science Center, Annual Water-Data Reports. Available from: http://wa.water.usgs.gov/cgi/adr.cgi?12210700 (accessed September 2011)

Vano JA, Voisin N, Cuo L, Hamlet AF, Elsner MM, Palmer RN, Polebitski A, Lettenmaier DP. 2010. Climate change impacts on water management in the Puget Sound region, Washington State, USA. *Climatic Change* **102**: 261–286. DOI: 10.1007/s10584-010-9846-1

Widmann M, Bretherton CS, Salathé EP. 2003. Statistical precipitation downscaling over the northwestern United States using numerically simulated precipitation as a predictor. *Journal of Climate* **16**: 799–816. DOI: 10.1175/1520-0442(2003)016<0799:SPDOTN>2.0.CO;2

Wigmosta MS, Vail LW, Lettenmaier DP. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research* **30**(6): 1665–1679. DOI: 10.1029/94WR00436

Wigmosta MS, Nijssen B, Storck P. 2002. The distributed hydrology-soil-vegetation model. In Mathematical Models of Small Watershed Hydrology and Applications, Singh VP, Frevert D (eds). Water Resources Publications: Highlands Ranch, CO; 7–42.

Wiley MW, Palmer RN. 2008. Estimating the Impacts and Uncertainty of Climate Change on a Municipal Water Supply System. *Journal of Water Resources Planning and Management* **134**(3): 239–246. DOI: 10.1061/(ASCE)0733-9496(2008)134:3(239)

Wood AW, Maurer EP, Kumar A, Lettenmaier DP. 2002. Long-range experimental hydrologic forecasting for the eastern United States. *Journal of Geophysical Research* **107**(D20): 4429. DOI: 10.1029/2001JD000659

Wood AW, Leung LR, Sridhar V, Lettenmaier DP. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Climatic Change* **62**(1-3): 189–216. DOI: 10.1023/B:CLIM.0000013685.99609.9e

Wood AW, Lettenmaier DP. 2006. A test bed for new seasonal hydrologic forecasting approaches in the Western United States. *Bulletin of the American Meteorology Society* **87**: 1699–1712. http://dx.doi.org/10.1175/BAMS-87-12-1699

World Climate Research Programme (WCRP). 2009. LLNL-Reclamation-SCU downscaled climate projections derived from the WCRP's CMIP3 multi-model data set, stored and served at the LLNL Green Data Oasis, Statistically Downscaled WCRP CMIP3 Climate Projections. Available from: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html#Welcome (accessed September 2009)

