Climate Change Projections

for USFS lands

in Oregon and Washington

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Introduction

The purpose of this report is to summarize the projected climate change impacts to United States Forest Service (USFS) lands in Oregon and Washington. Particular attention is paid to variables that are likely to impact freshwater aquatic species, including projected changes in water availability, snowpack, and flood and low flow statistics.

Prior Work / Resources

The Climate Impacts Group (CIG) has recently released a report that included both a general summary of climate changes anticipated for the Pacific Northwest (Mote and Salathé, 2010), as well as more in-depth consideration of impacts on forest ecosystems (Littell et al., 2010b), aquatic ecosystems (Mantua et al., 2010), and on the hydrology (Elsner et al., 2010) of the region.

In addition to this report, CIG has recently produced two datasets that are pertinent to the current study. The first is an in-depth suite of high-resolution climate projections for the Columbia river basin and coastal drainages in Oregon and Washington, developed as part of the Columbia Basin Climate Change Scenarios Project (CBCCSP, Hamlet et al., 2010, http://www.hydro.washington.edu/2860/). Unless otherwise noted, this first dataset forms the basis for the projected changes described in the present report. The second dataset is a simpler set of high-resolution climate projections, aimed at producing a consistent set of analyses over the major basins of the Western U.S. (Littell et al., 2010a). In addition to being funded under a different USFS grant, the Littell et al. dataset includes summaries over relevant ecological and hydrologic domains throughout the region. This latter dataset is mentioned because it could be used to extend the present assessment to USFS lands in other regions. Additional data from the Littell et al. study, in both raw and summary form, can be obtained from the project website: http://cses.washington.edu/picea/USFS/pub/.

In addition to the web-accessible raw datasets described above, the specific results presented in this report (summary plots and statistics computed from the CBCCSP data) are all available online at: http://cses.washington.edu/picea/USFS_ORWA/pub/.

Methods / Data

Focus regions: ecosections and watersheds

Since individual national forests may contain numerous distinct ecological regimes and cross hydrologic boundaries, averaging over these has the potential to obscure important climatic changes and confound planning efforts. In order to avoid this pitfall, we chose to provide summaries that follow ecological and hydrologic boundaries, rather than administrative borders.

Climate projections for the study domain were summarized over both Bailey ecosections and Omernik level III ecoregions as well as the 8-digit and 10-digit Hydrologic Unit Code (HUC4/HUC5) basins (shown in Figure 1). The latter were used primarily to assess changes in runoff statistics and the snow season.

Data

As mentioned above, data from the Columbia Basin Climate Change Scenarios Project (CBCCSP) form the basis for the projections summarized in this report. Described in more detail in the above report, here we provide a brief synopsis of the methods used to produce the data.

The steps needed to produce high-resolution climate projections are as follows:

1. Produce a reliable, high-resolution, gridded meteorological dataset.
2. Select emissions scenario(s) and future time period(s) to use in projections
3. Rank and select Global Climate Models (GCMs) for use in projections.
4. Downscale low-resolution GCM projections to high-resolution grid.
5. Run hydrologic model using high-resolution gridded input data for both historical and projected future climate.
6. Summarize daily output from hydrologic model over ecologically- and/or hydrologically-defined domains

These are briefly described in the following paragraphs, and references are provided for those who desire further detail on any of the methods.

Gridded, high resolution meteorological data is needed to drive the hydrologic model and assess the small-scale implications of climate change. Following the methods of Maurer et al. (2002) and Hamlet and Lettenmaier (2005), Deems and Hamlet (2010) produced a gridded meteorological dataset using data from the National Climatic Data Center (NCDC) Cooperative Observer (COOP) network and Environment Canada (EC) station data. The method incorporates U.S. Historical Climate Network (HCN) and Historical Canadian Climate Database (HCCD) data to correct for temporal biases caused by

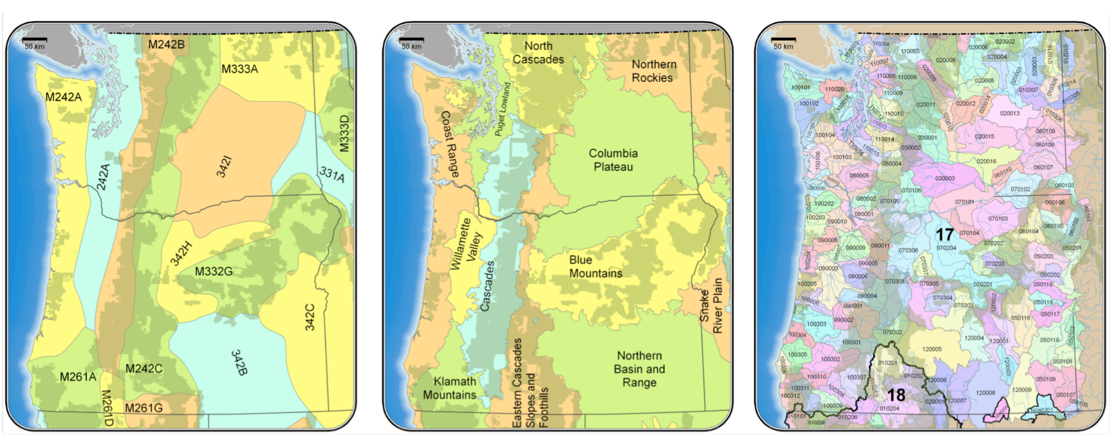

Figure 1 -- Map of the study region showing boundaries for Bailey ecosections (left panel), Omernik level III ecoregions (middle panel), and HUC4 basins (right panel). Flow statistics are also summarized over the smaller HUC5 basins (not shown). The light green shading on each map indicates USFS lands.

inhomogeneities in the COOP station records, and uses the Precipitation Regression on Independent Slopes (PRISM; Daly et al., 1994; 2002) monthly normals to scale precipitation and temperature. The final dataset extends from 1915 to 2006 at 1/16th degree resolution.

GCM simulations were obtained for the B1 and A1B emissions scenarios, which represent low and moderate emissions trajectories for the 21st century, respectively. Projected changes were assessed for 2 future decades: the 2040s and 2080s. Climate projections for the 21st century were obtained from Global Climate Model (GCM) simulations archived as part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3). These are the same GCM simulations that formed the basis of the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (e.g., Meehl et al., 2007 a,b). Following the methods described by Hamlet et al. (2010), a selection of 10 GCMs was chosen based on a ranking of model fidelity to the observed Pacific Northwest climate.

Low-resolution global simulations must be “downscaled” to obtain the final, high-resolution projections needed for impacts studies. Both “statistical” and “dynamical”

Table 1 – Key to variable and file names used in this report. The right-hand columns indicate the summary information provided for each variable and made available online.

variable	*variable name*	*units*	*monthly agg.*	*annual cycle table*	*annual cycle figure*	*map*	*summary table*	*summary plot*
average daily temperature	tavg	C	average	✔	✔		✔	✔
maximum daily temperature	tmax	C	average	✔	✔	✔	✔	
minimum daily temperature	tmin	C	average	✔	✔	✔	✔	
precipitation	precip	mm	total	✔	✔	✔	✔	✔
runoff	runoff	mm	total	✔				
baseflow	baseflow	mm	total	✔				
combined flow (runoff + baseflow)	combined flow	mm	total	✔	✔	✔		✔
flood statistics	flood_gridcell_strflw_maxdaily	cms	n/a	✔		✔	✔	
low flow statistics	lowflow_gridcell_strflw_7dyflow	cms	n/a	✔		✔	✔	
snow water equivalent (swe)	swe	mm	1st day	✔	✔	✔	✔	✔
peak swe	max_swe	mm	n/a	✔		✔	✔	
date peak swe	jd_max_swe	days	n/a	✔		✔		
date 10% accum	jd_10pc_accum	days	n/a	✔		✔		
date 90% accum	jd_90pc_melt	days	n/a	✔		✔	✔	
length of snow season *	numdays_10pcaccum_90pcmelt	days	n/a	✔		✔	✔	
relative humidity	rh	%	average	✔				
vapor pressure deficit	vpd	Pa	average	✔	✔		✔	
actual evapotranspiration	et	mm	total	✔	✔	✔	✔	✔
potential evapotranspiration 1 **	pet1	mm	total	✔	✔	✔	✔	✔
potential evapotranspiration 3 ***	pet3	mm	total	✔	✔	✔	✔	✔
soil moisture, layer 1	soilm1	mm	1st day	✔				
soil moisture, layer 2	soilm2	mm	1st day	✔				
soil moisture, layer 3	soilm3	mm	1st day	✔				
total column soil moisture	soilmoist	mm	1st day	✔	✔	✔	✔	✔

** the length of the snow season is defined here as the number of days between the date that 10% of the yearly maximum swe has accumulated and the date when 90% has melted*

***pet1 is calculated following the standard definition of potential evapotranspiration: natural vegetation (including stomatal and canopy resistance), and no water limit*

****pet3 is the same as pet1 except with vegetative resistance neglected: it includes only the effects of land surface characteristics and climate on evaporative demand.*

(modeling) approaches can be used to downscaling. The projections described in the present report make use of the “Hybrid-Delta Method” statistical downscaling approach (Hamlet et al., 2010). As the name implies, the latter is a hybrid approach in which monthly projected changes in the *probability distribution* of temperature and precipitation, as simulated by the GCMs, are applied to the gridded daily historical record. The result is a dataset that includes the time series properties (e.g., storm timing and spacing) of the historical record, but a mean and distribution that are scaled according to GCM projections.

The downscaled projections in temperature and precipitation are used to drive the Variable Infiltration Capacity (VIC) macroscale hydrologic model (Liang *et al*. 1996; Liang *et al*. 1998; Nijssen *et al*. 1997). VIC is a physically-based model, unique in its representation of the soil column and infiltration process. The model also includes a sophisticated parameterization for snow that operates on both sub-daily and subgrid scales, and represents multiple vegetation types and soil layers, allowing for variable infiltration and evaporation. VIC is used here to assess the implications of temperature and precipitation changes on hydrologic variables such as snowpack, runoff, and evapotranspiration.

Data from the VIC simulations are summarized at monthly time scales and over ecologically- and hydrologically-relevant domains within the study region, following the Bailey, Omernik, and HUC delineations shown in Figure 1. Summaries are included for the variables listed in Table 2. Projected changes are summarized in tables, plots showing changes in the annual cycle, and maps showing the geographic pattern of changes. Many of these results are touched on in the sections below, though all can be accessed online at: http://cses.washington.edu/picea/USFS_ORWA/pub/.

PART 1:

Overview of changes to USFS lands in Oregon and Washington

Although the changes projected for specific regions do differ, many of the climatic changes in Oregon and Washington are broadly similar. Table 2 provides a summary of these changes.

Monthly average temperatures are projected to increase for all months of the year, with end-of-century warming reaching 2.8°C in winter and 4.6°C in summer. In the fairly mild climate of the Pacific Northwest, this results in a shift to above-freezing winter temperatures in a substantial part of the domain. Precipitation changes are more difficult to assess, but the central model tendency shows a trend towards wetter winters (10% increase, Nov-Feb) and drier summers (21% decline, Jun-Sep).

Snowpack is projected to experience sharp declines, with USFS lands losing on average 64% of their historical April 1st snowpack by the end of the 21st century (Figure 2). This is similarly reflected in the date of snowmelt (Figure 3, defined here as the date at which 90% of peak snow has melted), which is projected to occur on average approximately one month earlier on USFS lands by the end of the century. Although somewhat moderated by increasing winter precipitation, these changes are predominantly influenced by the projected changes in temperature. This is reflected in Figure 4, which shows a transition to a predominantly rain-dominant regime throughout much of the Pacific Northwest by the 2080s.

Table 2 – Summary of changes to USFS lands in Oregon and Washington (A1B, 2040s). Changes are highlighted in bold if all models agree on the sign of the change. All quantities are rounded to reflect two significant digits.

A1B 2040s	**SUMMARY**	monthly agg.	units	bailey_M242A CoastRange	omernik_1 CoastRange	omernik_4 Cascades	bailey_M242B W.Cascades	omernik_9 E.Cascades, slopes & foothills	bailey_M242C E.Cascades	omernik_77 N.Cascades	bailey_M333A NE.WA	omernik_15 N.Rockies	bailey_M332G Blue.Mtns	omernik_11 Blue.Mtns
Δ T (DJF)	↗	avg	C	**1.4**	**1.4**	**1.5**	**1.4**	**1.6**	**1.4**	**1.3**	**1.5**	**1.5**	**1.8**	**1.8**
Δ T (JJA)	↗	avg	C	**2.2**	**2.3**	**2.7**	**2.6**	**2.8**	**2.8**	**2.6**	**2.7**	**2.7**	**3.0**	**3.0**
Δ precip (NDJF)	↗	total	% chg	6.9	6.6	5.9	7.0	5.9	6.7	8.8	12.5	11.7	9.3	9.0
Δ precip (JJAS)	↘	total	% chg	**-22**	**-22**	**-21**	**-20**	-21	-20	**-19**	-16	-14	-18	-18
Δ SWE (Apr 1st)	↘	n/a	% chg	**-44**	**-53**	**-50**	**-39**	**-56**	**-38**	**-31**	**-47**	**-49**	**-45**	**-49**
Δ date 90% melt	↘	n/a	dys	**21**	**23**	**-19**	**-23**	**-19**	**-20**	**-24**	**-19**	**-22**	**-15**	**-14**
Δ length snow season*	↘	n/a	dys	**41**	**44**	**-15**	**-22**	**-23**	**-25**	**-29**	**-25**	**-29**	**-18**	**-17**
Δ runoff (DJF)	↗	total	% chg	7.6	6.4	**20**	**26**	**35**	**50**	**42**	**52**	**62**	**34**	30
Δ runoff (JJA)	↘	total	% chg	**-26**	**-21**	**-43**	**-44**	**-26**	**-41**	**-43**	**-16**	**-25**	**-18**	**-15**
Δ q100 (flood)	↗	n/a	% chg	17	16	14	**23**	17	28	**29**	2.5	13	21	17
Δ 7q10 (low flow)	↘	n/a	% chg	**-12**	**-11**	**-16**	**-25**	-2.3	**-6.6**	**-23**	1.2	-1.3	-0.4	-0.4
Δ aet (May-Jun)	↗	total	% chg	**7.7**	**7.5**	**12**	**15**	6.7	**12**	**19**	**8.2**	**10**	**8.8**	**7.9**
Δ aet (Aug-Sep)	↘	total	% chg	-6.8	-8.3	**-18**	**-12**	**-23**	**-23**	**-11**	-11	-13	-15	-15
Δ pet1** (JJAS)	↗	total	% chg	**14**	**14**	**13**	**13**	**12**	**12**	**13**	**10**	**10**	**12**	**11**
Δ pet3*** (JJAS)	↗	total	% chg	**8.5**	**8.7**	**6.4**	**5.8**	**6.1**	**5.5**	**4.5**	**5.3**	**4.0**	**5.5**	**5.6**
Δ soilmoist (JFMA)	↗	total	% chg	0.6	0.4	**3.8**	**4.7**	**9.0**	**11**	**9.7**	**16**	**16**	8.0	7.4
Δ soilmoist (JJAS)	↘	total	% chg	**-9.0**	**-8.8**	**-14**	**-15**	**-8.5**	**-11**	**-14**	-4.1	-6.8	-4.6	-4.3
Δ vpd (JJAS)	↗	avg	Pa	**0.2**	**0.21**	**0.28**	**0.21**	**0.19**	**0.24**	**0.18**	**0.24**	**0.23**	**0.21**	**0.21**

** the length of the snow season is defined here as the number of days between the date that 10% of the yearly maximum swe has accumulated and the date when 90% has melted.*

***pet1 is calculated following the standard definition of potential evapotranspiration: natural vegetation (including stomatal and canopy resistance), and no water limit*

****pet3 is the same as pet1 except with vegetative resistance neglected: it includes only the effects of land surface characteristics and climate on evaporative demand.*

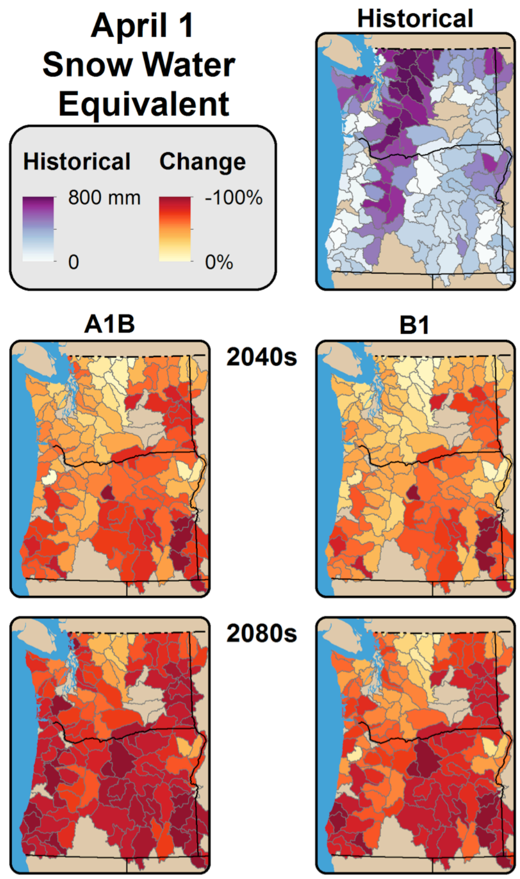

Figure 2 – Historical and projected change to April 1st Snow Water Equivalent (SWE, mm) for each HUC4 basin in OR/WA. Projections are for the composite delta downscaling (i.e., average of all climate model projections).

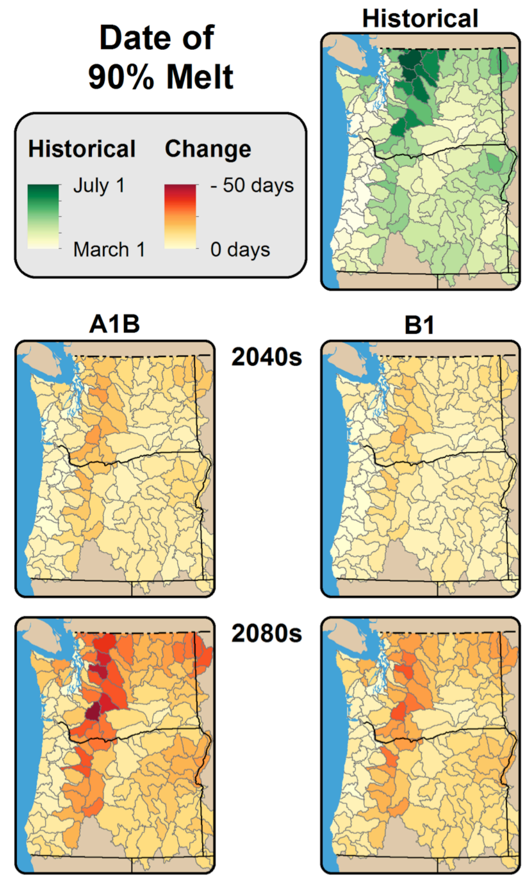

Figure 3 – As in Figure 2, except showing the date of 90% melt.

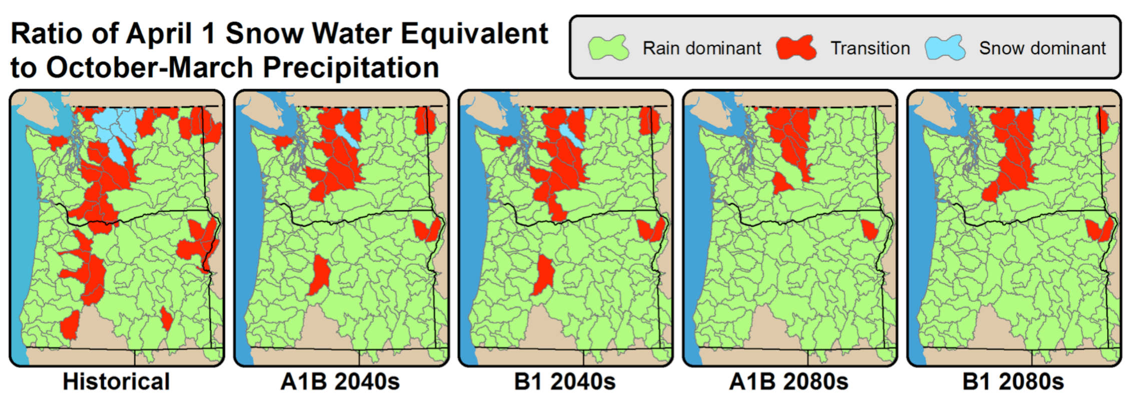

Figure 4 – As in Figure 2, except showing the ratio of peak snow water equivalent (swe) to cumulative winter precipitation (Oct-Mar). Colors denote rain-dominant (less than 10% of precipitation is stored as snow), "transient" (10-40%), and snow-dominant regions (more than 40%).

The seasonal pattern of runoff reflects these changes as well, showing a more pronounced winter peak resulting from increasing precipitation, which falls in greater proportion as rain rather than snow, and a less pronounced peak in runoff resulting from spring melt.

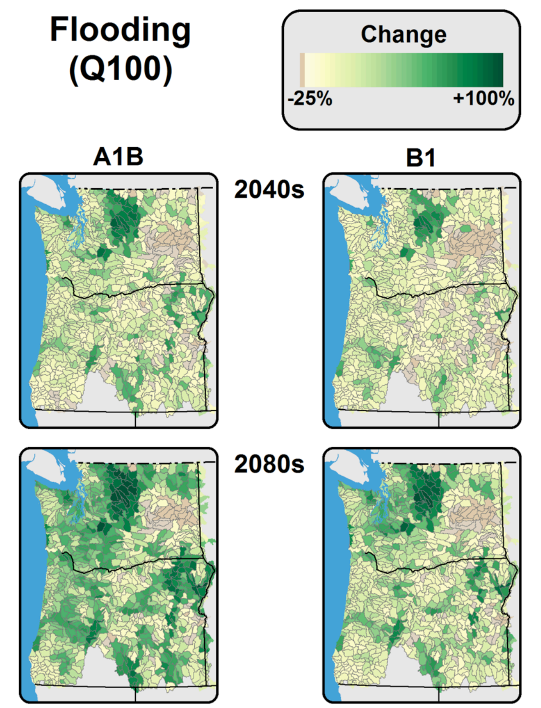

Figure 5 – As in Figure 2, except showing changes in the 100-year flood potential (q100) for single-day flood events for all HUC5 basins in OR/WA.

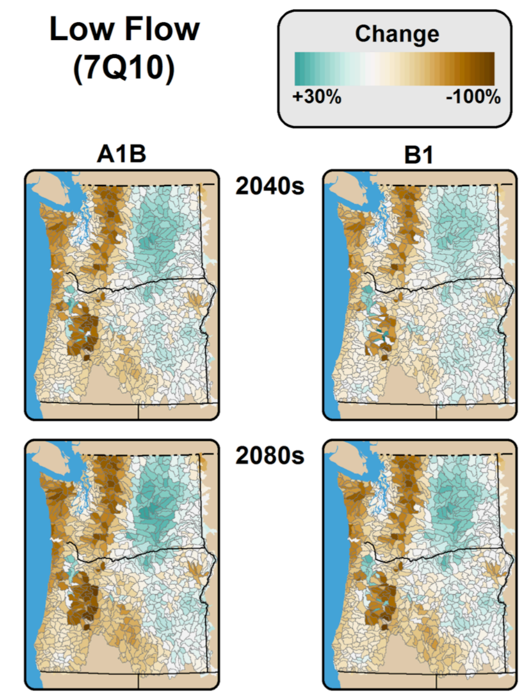

Figure 6 – As in Figure 2, except showing changes in the 10-year return period for 7-day low flows (7q10) for all HUC5 basins in OR/WA.

The specific character of these changes varies slightly among regions, with some showing a very bimodal transition from a snow- to rain-dominant hydrograph, while others show more of a shift towards an earlier spring runoff peak resulting from the shift to earlier melt dates. The daily statistics of runoff are projected to change as well: all USFS regions are projected to see an increase in the volume of 100 year floods, with some showing increases of more than 50%. As shown in Figure 5, projected increases in flood risk are largely confined to mountainous areas, where precipitation is greatest. Low flow statistics are shown in Figure 6. These are less reliable, due to a greater dependence on model calibration, and projections vary substantially among models. Bearing these caveats in mind, projections suggest modest declines in extreme dry-season flow. Note that the flow calculations are based on a simple average of runoff in all gridcells within each basin: for the flood and low flow projections, routing the runoff following stream networks might result in slightly different projections, in particular for larger watersheds. For comparison with the daily flow statistics, seasonal changes in total runoff are shown for winter (Dec-Feb, Figure 7) and summer (Jun-Aug, Figure 8) as well.

As a consequence of increasing temperatures, potential evapotranspiration (pet) is projected to increase. In this study we include two definitions of pet, which for historical reasons we refer to as pet1 and pet3. The first (pet1) is the potential evapotranspiration of the actual vegetation within a given grid cell: the atmospheric demand for water vapor, mitigated by vegetation, e.g., through canopy and stomatal resistance, leaf area index (LAI), etc. The second (pet3) neglects vegetative impacts, and is thus an estimate of the effects of climate and land surface characteristics alone (i.e.: pet3 is an estimate of the atmospheric demand for water vapor). Neither calculation imposes any limit on water

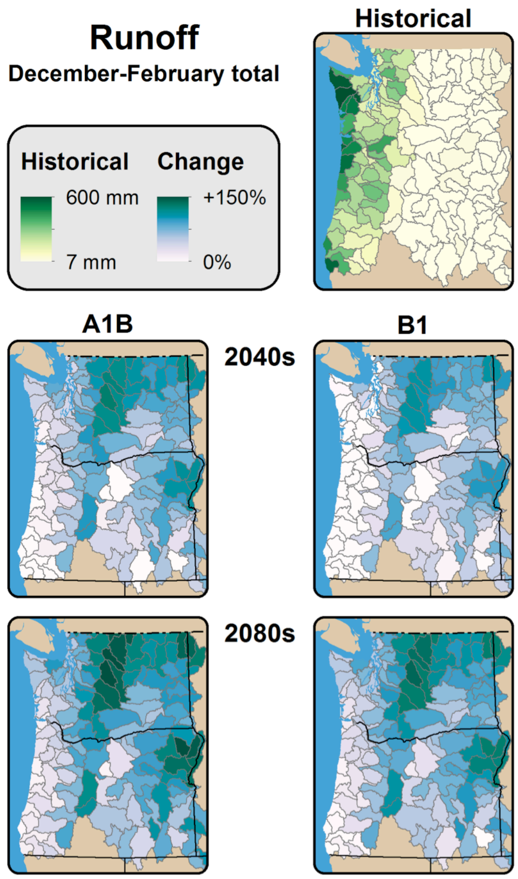

Figure 7 – As in Figure 2, except showing average total runoff for December-February.

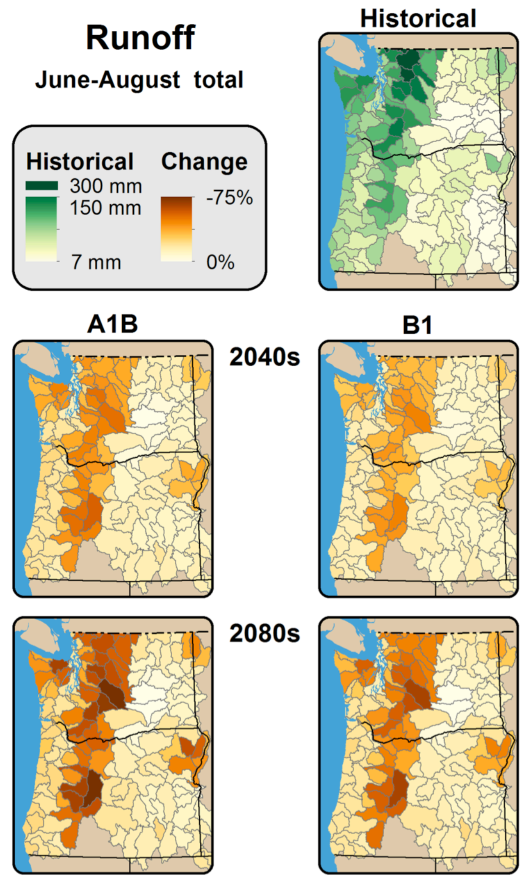

Figure 8 – As in Figure 2, except showing average total runoff for June-August. Note that the historical color scale is discontinuous, to accommodate the small number of basins with particularly high summer runoff.

availability. The difference between pet1 and pet3 gives an indication of the role played by vegetation in moderating atmospheric demand for water. Both pet1 and pet3 show a marked increase in summer (See Figures 9 and 10; overall increase of 20% for pet1 and 9% for pet3), with moderate increases throughout the remainder of the year.

Actual evapotranspiration (aet) and soil moisture are influenced by both changes in the snow season as well as increases in pet. This results in an interesting change pattern, in which both quantities are higher in winter and spring and lower in late summer, a consequence of both the transition towards a rain-dominant hydrograph and greater evaporative demand. Specifically, projections for late spring (May-June) show an increase in aet of 20%, while projections for late summer (Aug-Sep) show a decrease of 22%. Similarly, soil moisture is projected to increase in late winter (Jan-Apr, by 11%; see Figure 11) and decrease in summer (Jun-Aug, by 12%; see Figure 12).

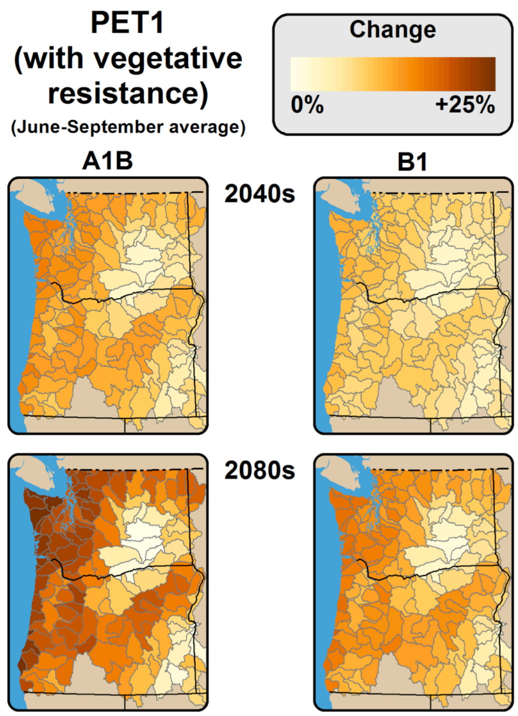

Figure 9 – As in Figure 2, except showing potential evapotranspiration *with* vegetative resistance (pet1) for June-September.

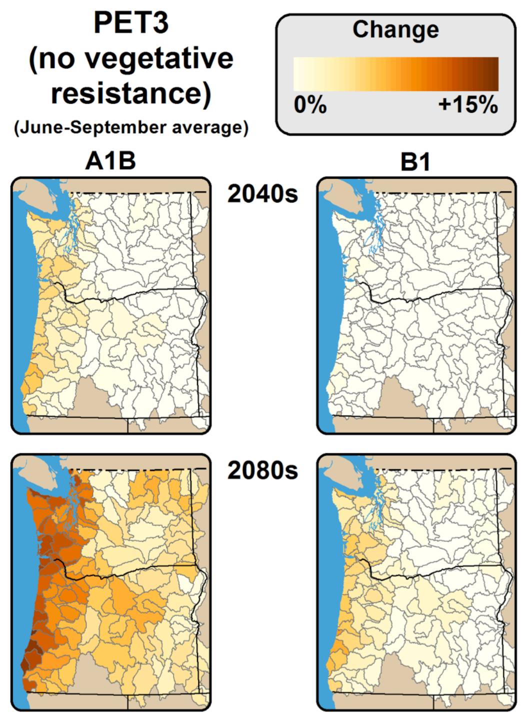

Figure 10 – As in Figure 2, except showing potential evapotranspiration *without* vegetative resistance (pet1) for June-September.

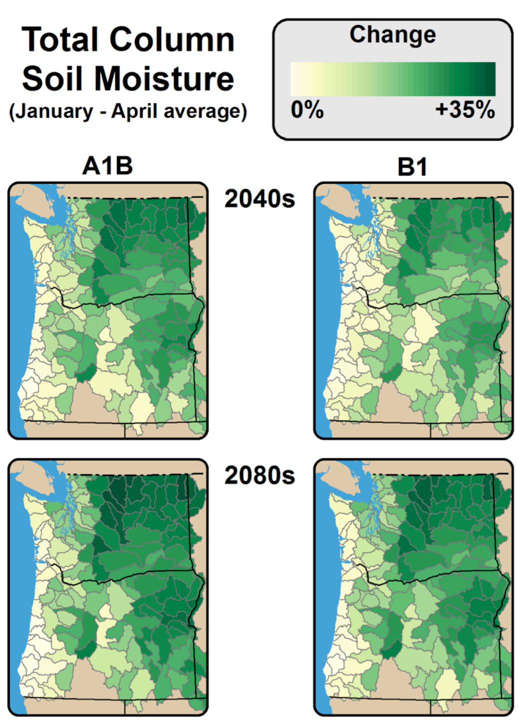

Figure 11 – As in Figure 2, except showing average soil moisture for January-April.

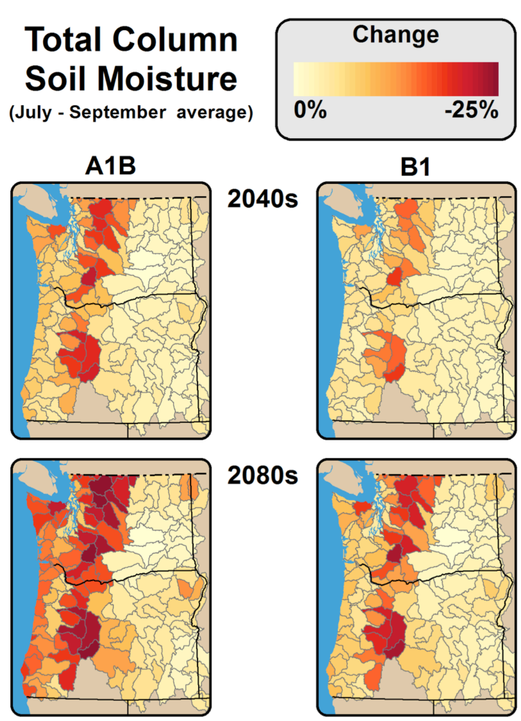

Figure 12 – As in Figure 2, except showing average soil moisture for June-September.

PART 2:

Summary of changes for Bailey Ecosections and Omernik Ecoregions

Coast Range (Bailey M242A, Omernik 1)

The coast range has historically been defined by a climate of mild temperatures and wet winters. Monthly average temperatures typically range from 4°C in winter to 15°C in summer. Average monthly rainfall totals approach 400 mm (~16 in.) in the peak rainfall months of November-January, while dropping to 30 mm (~1.2 in.) in July and August. Temperature is projected to increase throughout all months of the year, with end-of-century increases reaching 2.5°C in winter (Dec-Feb) and 3.9°C in summer (Jun-Aug). Precipitation changes vary significantly among models, but the central tendency shows a 9% increase in total winter (Nov-Feb) precipitation and a 24% decrease in total summer (Jun-Sep) precipitation.

The region is predominantly rain-dominant, receiving the vast majority of its precipitation as rain instead of snow. This characteristic is accentuated in the projections, showing a 69-78% decline in April 1st swe and a greater early-season peak in runoff. Though snow accumulation is fairly minor in this region, areas that consistently receive snow are projected to experience a lengthening of the snow season, in stark contrast with the remainder of the Pacific Northwest. This is likely a result of the cloudy, cool conditions that characterize the climate of the coast range, combined with projected increases in winter precipitation.

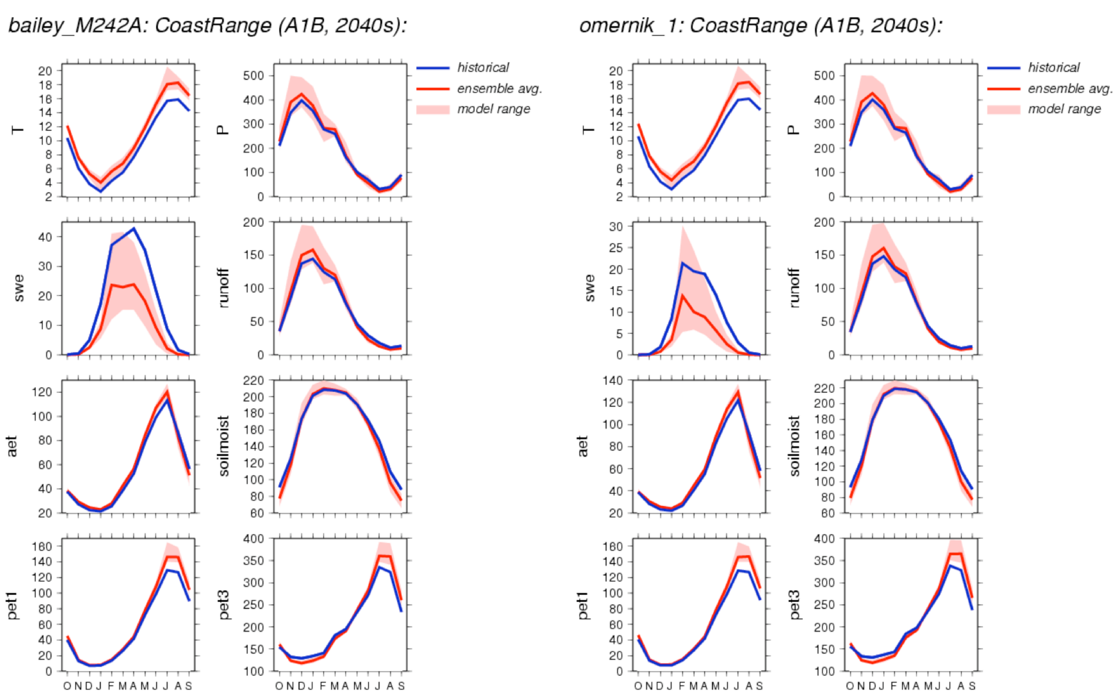

Figure 4 – Summary projections for Bailey ecosection M242A and Omernik Level III ecoregion 1, Coast Range (A1B, 2080s). All units are in millimeters (mm), except temperature, which is in degrees Celsius (C). These and similar plots are available online (scenarios A1B, B1; 2020s, 2040s and 2080s).

Table 3 – Summary of projected changes for Bailey M242A and Omernik 1 (A1B scenario)

Coast Range			**2040s**		**2080s**	
			bailey_M242A	**omernik_1**	**bailey_M242A**	**omernik_1**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.4 (0.6, 1.9)	1.4 (0.6, 1.8)	2.5 (1.2, 4.0)	2.5 (1.2, 4.0)
Δ T (JJA)	avg	C	2.2 (1.6, 3.6)	2.3 (1.6, 3.7)	3.9 (2.5, 6.1)	3.9 (2.5, 6.2)
Δ precip (NDJF)	total	%	6.9 (-4.7, 23.4)	6.6 (-5.0, 24.1)	9.0 (-4.0, 35.1)	8.7 (-4.9, 36.1)
Δ precip (JJAS)	total	%	-22 (-43, -4)	-22 (-43, -4)	-24 (-52, -6)	-24 (-52, -6)
Δ SWE (Apr1st)	n/a	%	-44 (-64, -11)	-53 (-75, -6)	-69 (-94, -34)	-78 (-98, -43)
Δ date 90% melt	n/a	dys	21 (12, 31)	23 (14, 35)	43 (18, 72)	47 (21, 80)
Δ length snow season	n/a	dys	41 (18, 60)	44 (20, 65)	79 (34, 127)	85 (37, 138)
Δ runoff (DJF)	total	%	7.6 (-5.8, 29.3)	6.4 (-7.5, 29.6)	10 (-10, 47)	8.7 (-12.2, 47.3)
Δ runoff (JJA)	total	%	-26 (-38, -16)	-21 (-32, -12)	-33 (-45, -19)	-26 (-40, -9)
Δ q100 (flood)	n/a	%	17 (-2, 46)	16 (-6, 46)	29 (11, 54)	26 (6, 52)
Δ 7q10 (low flow)	n/a	%	-12 (-19, -3)	-10 (-16, -3)	-17 (-23, -9)	-14 (-19, -8)
Δ aet (May-Jun)	total	%	7.7 (3.8, 10.7)	7.5 (3.4, 10.7)	14 (9, 19)	13 (9, 18)
Δ aet (Aug-Sep)	total	%	-6.8 (-19.1, 3.5)	-8.3 (-21.5, 2.5)	-11 (-28, 2)	-13 (-31, 1)
Δ pet1 (JJAS)	total	%	14 (9, 24)	14 (9, 24)	22 (14, 35)	22 (14, 36)
Δ pet3 (JJAS)	total	%	8.5 (4.2, 16.4)	8.7 (4.5, 16.6)	13 (7, 23)	13 (7, 24)
Δ soilmoist (JFMA)	total	%	0.60 (-2.00, 4.10)	0.40 (-2.20, 3.80)	0.40 (-3.00, 5.50)	0.20 (-3.20, 5.00)
Δ soilmoist (JJAS)	total	%	-9.0 (-15.8, -3.5)	-8.8 (-15.8, -3.4)	-13 (-21, -6)	-12 (-20, -5)
Δ vpd (JJAS)	avg	Pa	0.18 (0.11, 0.41)	0.21 (0.13, 0.43)	0.34 (0.17, 0.68)	0.36 (0.19, 0.66)

Increases in temperature drive a summer (Jun-Sep) increase in pet1 of 22% and pet3 of 13%. Although soil moisture does not change appreciably in winter, in summer (Jun-Sep) the increase in evaporative demand appears to result in substantial declines (12-13%) in available moisture. This has consequences for aet, which shows increases of 13-14% in late spring (May-Jun) due to the earlier melt season and decreases of 11-13% in late summer (Aug-Sep), a symptom of the decline in soil moisture.

West Cascades (Bailey M242B, Omernik 4)

The climate of the west Cascades has historically been fairly mild and wet. Winters are substantially cooler on average than in the coast range, with monthly average temperatures just reaching 0°C in January, and rising from there to typical averages of 15°C in summer. Average monthly precipitation totals are slightly less than in the coastal range, exceeding 325 mm (~13 in.) in the peak months of Nov-Jan, while dropping below 35 mm (~1.4 in.) in July and August. Temperature is projected to increase by the end of the century by 2.7°C in winter (Dec-Feb) and 4.5°C in summer (Jun-Aug). Projections for precipitation vary significantly among models, but on average show an increase of 8-10% in winter (Nov-Feb) and a decrease of 22% in summer.

Historically, the annual hydrograph has exhibited the classic dual-peaked shape that is characteristic of transient basins: an earlier peak resulting from runoff due to rain, and a later peak resulting from snowmelt. The projections indicate that by the end of the 21st century the western Cascades will exhibit a more rain-dominant character, with a substantial increase in early season runoff and a significant decrease in spring melt. These changes are of course strongly impacted by the changes in temperature, which show a shift from near-freezing temperatures in winter to mean monthly temperatures that are well above freezing by the end of the century. The consequences of this change are evident in the annual cycle of swe, which shows about a 64-77% decline in accumulation relative to the historical period, and melt dates that occur approximately 28-37 days earlier on average. Changes in evaporative demand resemble those seen for the coast range, with summer increases in pet1 of 20% and pet3 of 9-10%. As a result of earlier melt, soil moisture is projected to increase by 5-7% in the winter (Jan-Apr) and decrease

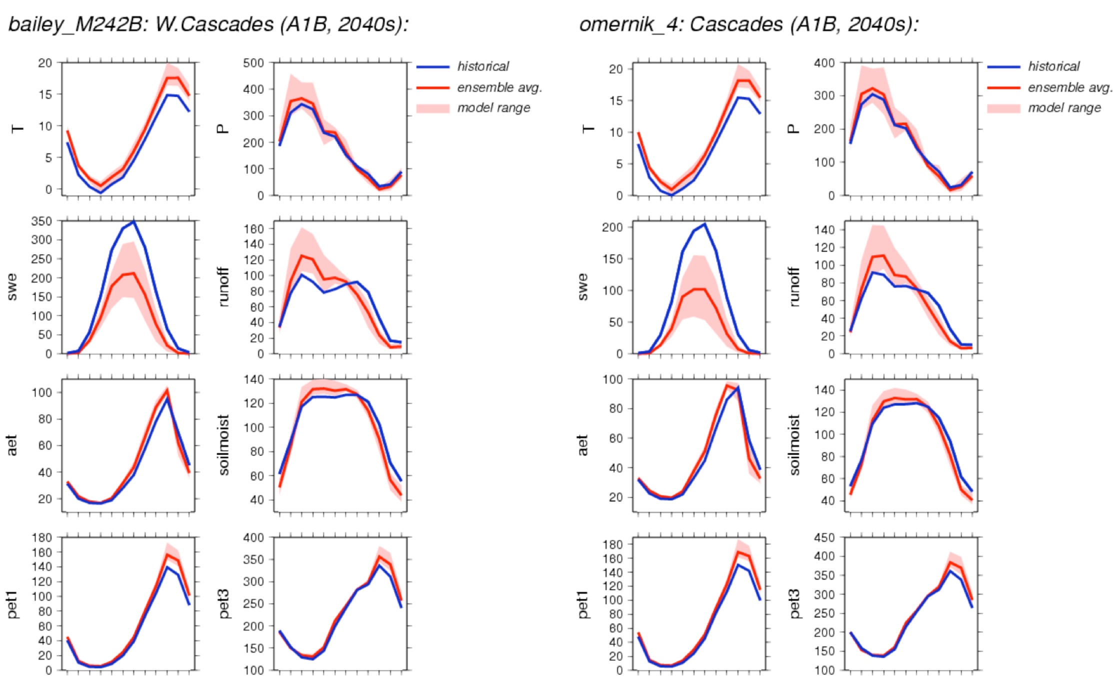

Figure 5 – Summary projections for Bailey ecosection M242B and Omernik Level III ecoregion 4.

Table 4 – Summary of projected changes for Bailey M242B and Omernik 4 (A1B scenario)

W. Cascades			**2040s**		**2080s**	
			bailey_M242B	**omernik_4**	**bailey_M242B**	**omernik_4**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.4 (0.6, 2.1)	1.5 (0.6, 2.1)	2.7 (1.4, 4.4)	2.7 (1.4, 4.4)
Δ T (JJA)	avg	C	2.6 (1.7, 4.2)	2.7 (1.8, 4.3)	4.5 (2.7, 6.8)	4.4 (2.7, 7.0)
Δ precip (NDJF)	total	%	7.0 (-7.5, 23.2)	5.9 (-8.7, 26.1)	9.7 (-5.6, 35.6)	8.0 (-9.3, 38.5)
Δ precip (JJAS)	total	%	-20 (-40, -1)	-21 (-42, -1)	-22 (-49, 1)	-22 (-54, 6)
Δ SWE (Apr1st)	n/a	%	-39 (-58, -15)	-50 (-74, -24)	-64 (-88, -29)	-77 (-98, -43)
Δ date 90% melt	n/a	dys	-23 (-36, -10)	-19 (-30, -8)	-37 (-54, -19)	-28 (-35, -17)
Δ length snow season	n/a	dys	-22 (-32, -14)	-15 (-20, -11)	-30 (-35, -21)	-14 (-23, 1)
Δ runoff (DJF)	total	%	26 (11, 58)	20 (6, 55)	40 (14, 90)	30 (6, 84)
Δ runoff (JJA)	total	%	-44 (-66, -31)	-43 (-61, -29)	-60 (-70, -49)	-57 (-66, -47)
Δ q100 (flood)	n/a	%	23 (0, 60)	14 (-9, 52)	36 (3, 74)	26 (-4, 67)
Δ 7q10 (low flow)	n/a	%	-25 (-35, -13)	-16 (-22, -6)	-31 (-40, -23)	-20 (-27, -15)
Δ aet (May-Jun)	total	%	14 (9, 23)	12 (8, 17)	24 (16, 34)	20 (15, 26)
Δ aet (Aug-Sep)	total	%	-12 (-23, -1)	-18 (-32, -5)	-19 (-36, -2)	-25 (-45, -8)
Δ pet1 (JJAS)	total	%	13 (8, 22)	13 (8, 22)	20 (13, 33)	20 (12, 32)
Δ pet3 (JJAS)	total	%	5.8 (2.3, 12.3)	6.4 (2.8, 13.2)	9.2 (3.9, 17.6)	9.9 (5.0, 18.4)
Δ soilmoist (JFMA)	total	%	4.7 (2.2, 9.9)	3.8 (0.6, 9.7)	6.7 (2.9, 13.2)	4.8 (0.4, 12.6)
Δ soilmoist (JJAS)	total	%	-15 (-24, -9)	-14 (-21, -8)	-21 (-28, -12)	-19 (-26, -12)
Δ vpd (JJAS)	avg	Pa	0.21 (0.12, 0.39)	0.28 (0.18, 0.47)	0.36 (0.19, 0.65)	0.43 (0.28, 0.67)

by 19-21% in the summer (Jun-Sep). This again impacts aet, which shows substantial increases (20-25%) in May-Jun and decreases (19-25%) in Aug-Sep.

East Cascades (Bailey M242C, Omernik 9)

The climate of the east Cascades is substantially drier, receiving about 40% as much precipitation as the west Cascades, ranging from 125-150 mm (5-6 in.) in peak winter months (Nov-Jan) to less than 20 mm (0.8 in) in summer months (Jul-Aug). Although historically summers have only been slightly warmer than on the western slopes, winters are typically much cooler, with mean January temperatures reaching -2.5°C and below. End-of-century projections for this region show temperatures increasing ~2.8°C in winter (Dec-Feb) and ~4.6°C in summer (Jun-Aug). Projected changes in precipitation vary significantly among models, but show an average trend towards wetter winters (Nov-Feb, 9-10% change) and drier summers (Jun-Sep, 19-21% decrease).

Snowpack is projected to decrease substantially (64-81% decline in April 1st swe, 2080s) for this region, with the average date of snowmelt occurring 32-35 days earlier by the end of the century. Along with the increase in early-season precipitation, this has substantial consequences for the character and timing of runoff, with the rain-dominant future annual hydrograph contrasting sharply with the snow-dominant historical annual cycle in runoff. This substantial reduction in the spring runoff peak and shift to earlier peak flows is clearly reflected in the projected changes in soil moisture, which show 9-12% increases in total winter (Jan-Apr) water content, followed by substantial decreases (12-16%) in summer (Jun-Sep) soil moisture. Projected changes in aet also reflect this change, with late spring (May-Jun) increases of 9-18% and late summer (Aug-Sep) decreases of 27-31%. As above, the decrease in aet and depletion of soil moisture are also a consequence of increased evaporative demand, with summer (Jun-Sep) pet1 showing an increase of 18% and pet3 showing an increase of 9%.

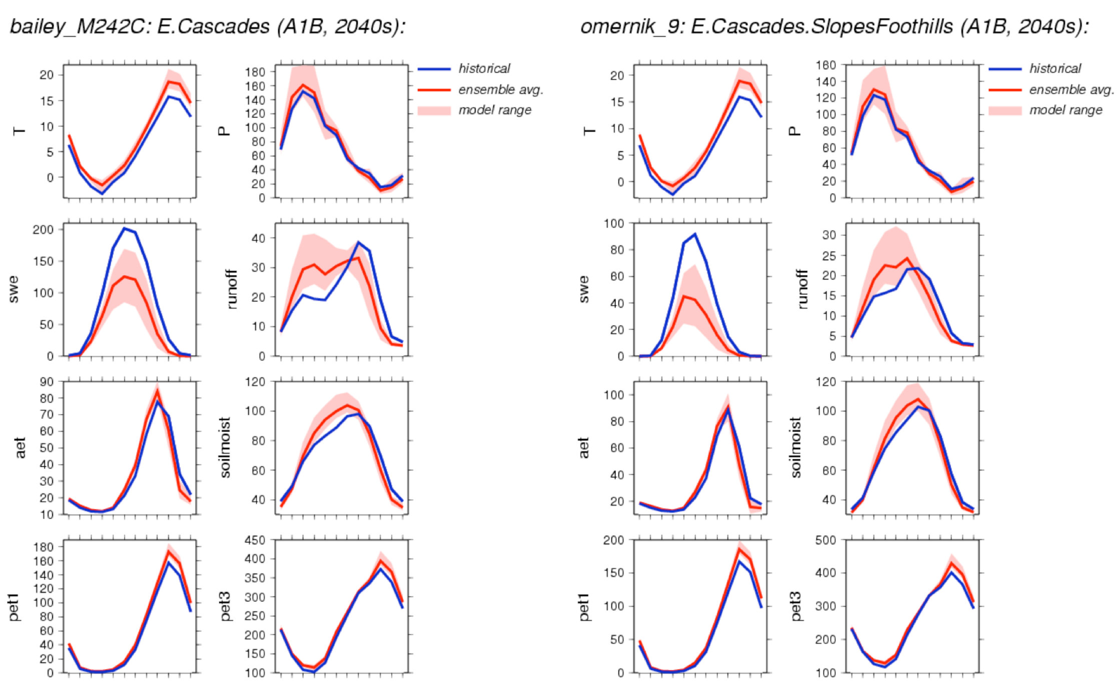

Figure 6 – Summary projections for Bailey ecosection M242C and Omernik Level III ecoregion 9.

Table 5 – Summary of projected changes for Bailey M242C and Omernik 9 (A1B scenario)

E. Cascades			**2040s**		**2080s**	
			bailey_M242C	**omernik_9**	**bailey_M242C**	**omernik_9**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.4 (0.6, 2.1)	1.6 (0.8, 2.2)	2.7 (1.4, 4.6)	2.9 (1.5, 4.9)
Δ T (JJA)	avg	C	2.8 (1.8, 4.5)	2.8 (1.9, 4.7)	4.6 (2.7, 7.3)	4.7 (2.7, 7.4)
Δ precip (NDJF)	total	%	6.7 (-8.1, 23.7)	5.9 (-9.4, 26.1)	9.6 (-7.1, 36.4)	8.5 (-10.5, 39.5)
Δ precip (JJAS)	total	%	-20 (-40, 1)	-21 (-39, 0)	-21 (-49, 5)	-19 (-55, 28)
Δ SWE (Apr1st)	n/a	%	-38 (-60, -16)	-56 (-80, -28)	-64 (-91, -27)	-81 (-99, -47)
Δ date 90% melt	n/a	dys	-20 (-33, -8)	-19 (-31, -8)	-35 (-57, -17)	-32 (-48, -17)
Δ length snow season	n/a	dys	-25 (-37, -14)	-23 (-33, -14)	-41 (-54, -21)	-34 (-40, -21)
Δ runoff (DJF)	total	%	50 (26, 99)	35 (13, 82)	83 (40, 168)	54 (14, 136)
Δ runoff (JJA)	total	%	-41 (-61, -27)	-26 (-39, -17)	-57 (-68, -44)	-34 (-40, -28)
Δ q100 (flood)	n/a	%	28 (-0, 64)	17 (-6, 50)	50 (9, 102)	30 (-1, 83)
Δ 7q10 (low flow)	n/a	%	-6.6 (-14.6, -0.2)	-2.3 (-8.4, 1.6)	-9.2 (-14.0, -4.0)	-3.2 (-8.3, 1.5)
Δ aet (May-Jun)	total	%	12 (8, 19)	6.7 (-0.4, 16.2)	18 (11, 30)	8.7 (-3.0, 23.0)
Δ aet (Aug-Sep)	total	%	-23 (-34, -7)	-23 (-36, -0)	-31 (-51, -12)	-27 (-56, 7)
Δ pet1 (JJAS)	total	%	12 (7, 19)	12 (8, 20)	18 (11, 25)	18 (12, 26)
Δ pet3 (JJAS)	total	%	5.5 (2.4, 11.1)	6.1 (2.9, 11.7)	8.5 (3.6, 16.2)	9.4 (5.1, 16.9)
Δ soilmoist (JFMA)	total	%	11 (5, 21)	9.0 (2.2, 21.0)	16 (7, 31)	12 (0, 30)
Δ soilmoist (JJAS)	total	%	-11 (-20, -7)	-8.5 (-15.8, -3.9)	-16 (-22, -10)	-12 (-17, -6)
Δ vpd (JJAS)	avg	Pa	0.24 (0.14, 0.45)	0.19 (0.10, 0.40)	0.41 (0.23, 0.74)	0.35 (0.18, 0.73)

North Cascades (Omernik 77)

The north Cascades are somewhat distinct in climate from both the west and east Cascades. Historically, winter temperatures are cooler than elsewhere in the Cascades, with average monthly temperatures reaching -3°C in winter and slightly cooler average temperatures in summer. The region receives a substantial amount of precipitation, nearly as much as in the western Cascades. Similar to other regions, temperature is projected to increase in the region by 2.7°C in winter (Dec-Feb) and 4.5°C in summer (Jun-Aug). Projected changes in precipitation vary substantially among models, but the central trend shows an increase of 12% in winter (Nov-Feb) and a decrease of 22% in summer (Jun-Sep).

Historically, the north Cascades have been characterized as solidly snow-dominant, with much of the annual precipitation stored as snow. Projections indicate that this characteristic will be substantially altered by the end of the century. April 1st swe is projected to decrease by 56% by the 2080s, and the date of 90% melt is projected to arrive 44 days earlier than it has historically. These changes in the snow season are reflected in the substantial changes in the annual runoff, which shows a near-doubling of the early-season runoff peak, and both a decrease and shift to earlier dates in the spring melt peak. Soil moisture, as a consequence, shows an increase of 15% in late winter (Jan-Apr) and a decrease of 21% in summer (Jun-Sep). The changes in water availability impact aet, which increases substantially (32%) in late spring (May-Jun) and decreases (18%) in late summer (Aug-Sep). Potential evapotranspiration, an important driver of this late-season drying, is projected to increase substantially by the 2080s, with summer (Jun-Sep) increases in pet1 and pet3 of 20% and 7.6%, respectively.

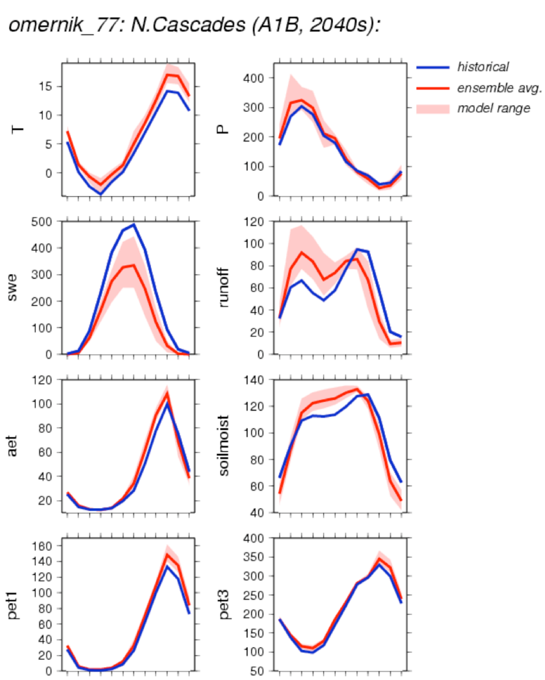

Figure 7 – Summary projections for Omernik Level III ecoregion 77.

Table 6 – Summary of projected changes for Omernik 77 (A1B scenario)

N. Cascades			**2040s omernik_77**	**2080s omernik_77**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.3 (0.5, 2.0)	2.7 (1.3, 4.5)
Δ T (JJA)	avg	C	2.6 (1.6, 4.0)	4.5 (2.8, 6.7)
Δ precip (NDJF)	total	%	8.8 (-4.8, 20.3)	12 (1, 31)
Δ precip (JJAS)	total	%	-19 (-38, -0)	-22 (-48, 5)
Δ SWE (Apr1st)	n/a	%	-31 (-48, -9)	-56 (-84, -19)
Δ date 90% melt	n/a	dys	-24 (-39, -10)	-44 (-76, -18)
Δ length snow season	n/a	dys	-29 (-46, -15)	-52 (-80, -23)
Δ runoff (DJF)	total	%	42 (25, 72)	71 (34, 122)
Δ runoff (JJA)	total	%	-43 (-68, -30)	-62 (-78, -45)
Δ q100 (flood)	n/a	%	29 (12, 66)	50 (12, 106)
Δ 7q10 (low flow)	n/a	%	-23 (-34, -12)	-31 (-39, -20)
Δ aet (May-Jun)	total	%	19 (12, 31)	32 (22, 45)
Δ aet (Aug-Sep)	total	%	-11 (-25, -1)	-18 (-35, -2)
Δ pet1 (JJAS)	total	%	12 (6, 21)	20 (12, 32)
Δ pet3 (JJAS)	total	%	4.5 (1.1, 10.2)	7.6 (0.8, 15.9)
Δ soilmoist (JFMA)	total	%	9.7 (6.0, 15.3)	15 (10, 22)
Δ soilmoist (JJAS)	total	%	-14 (-24, -8)	-21 (-29, -12)
Δ vpd (JJAS)	avg	Pa	0.18 (0.06, 0.37)	0.34 (0.15, 0.67)

Northeast Washington (Bailey M333A, Omernik 15)

The climate of northeast Washington exhibits cooler winters, warmer summers, and much drier conditions than the other regions considered in this study. Average monthly winter temperatures reach -5.0°C, while monthly summer temperatures exceed 18°C. Annual precipitation, in sharp contrast with other regions, has historically remained less than 650 mm (26 in.), with peak monthly winter precipitation just exceeding 80 mm (3.1 in.), while average monthly summer precipitation falls below 25 mm (1 in). Projections for the 2080s show monthly average temperatures rising slightly more than in other regions: by ~2.8°C in winter (Dec-Feb) and 4.6°C in summer (Jun-Aug). Projected changes in precipitation vary widely among models, but, as with other regions, the central tendency is for an increase of 19% in total winter (Nov-Feb) precipitation, and a decrease of 19-21% in total summer (Jun-Sep) precipitation.

This region qualifies as transitional snow regime, historically accumulating 23-24% of its winter precipitation as snow. In the future, this ratio decreases to 3-13%, due to the above increases in winter precipitation and a 71-74% decline in April 1st swe. The date of 90% melt is also projected to occur substantially earlier (33-38 days) by the end of the century. Shifts in the timing and magnitude of runoff are symptomatic of these changes. Although projections vary widely among models, the central tendency is for an increase in early-season runoff and a shift towards earlier peak flows. The result is a much more broad annual cycle of runoff, and lower flows in spring and summer. Projections for soil moisture reflect a strong response to these changes, with average monthly water content increasing by 23-24% in late winter (Jan-Apr) and decreasing by 7-10% in summer (Jun-Sep). Actual evapotranspiration is likewise impacted by the changes in temperature and

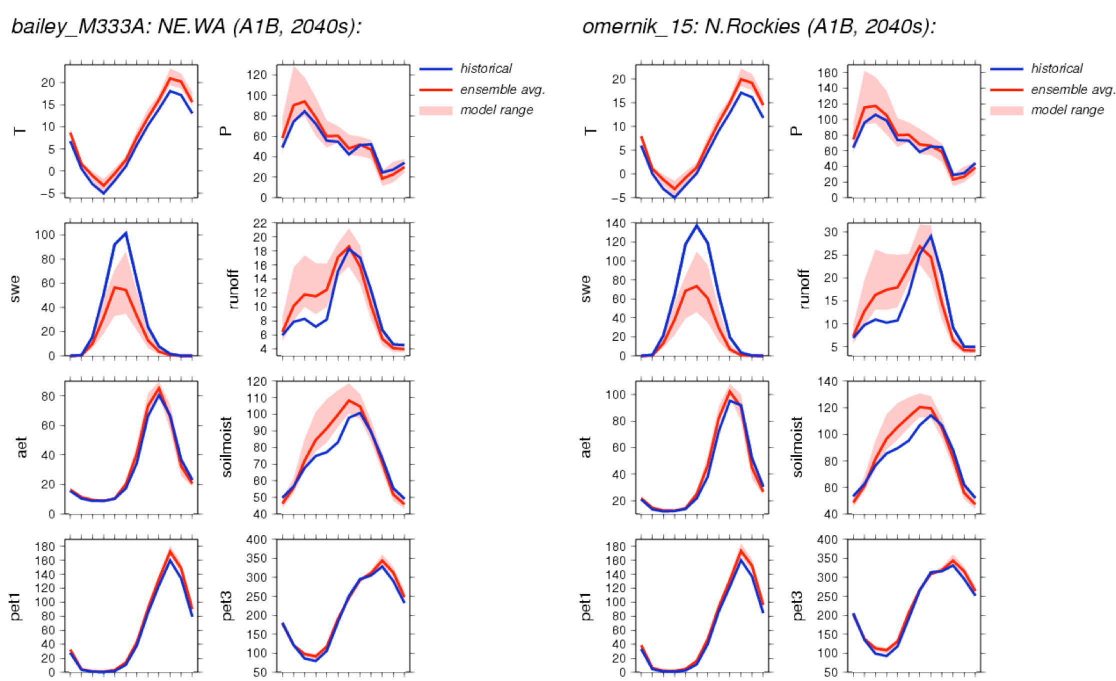

Figure 8 – Summary projections for Bailey ecosection M333A and Omernik Level III ecoregion 15.

Table 7 – Summary of projected changes for Bailey M333A and Omernik 15 (A1B scenario)

NE WA / N. Rockies			2040s		2080s	
			bailey_M333A	**omernik_15**	**bailey_M333A**	**omernik_15**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.5 (0.5, 2.4)	1.5 (0.7, 2.6)	2.8 (1.4, 4.2)	2.9 (1.5, 4.4)
Δ T (JJA)	avg	C	2.7 (1.6, 4.3)	2.7 (1.6, 4.4)	4.6 (2.8, 7.0)	4.6 (2.8, 6.9)
Δ precip (NDJF)	total	%	12 (-4, 30)	12 (-5, 30)	19 (6, 48)	19 (1, 49)
Δ precip (JJAS)	total	%	-16 (-33, 6)	-14 (-30, 4)	-21 (-40, 22)	-19 (-39, 22)
Δ SWE (Apr1st)	n/a	%	-47 (-66, -14)	-49 (-71, -20)	-71 (-91, -30)	-74 (-92, -35)
Δ date 90% melt	n/a	dys	-19 (-28, -6)	-22 (-34, -8)	-33 (-45, -13)	-38 (-52, -17)
Δ length snow season	n/a	dys	-25 (-38, -11)	-29 (-45, -14)	-40 (-54, -17)	-47 (-64, -21)
Δ runoff (DJF)	total	%	52 (28, 106)	62 (30, 131)	87 (48, 171)	108 (69, 215)
Δ runoff (JJA)	total	%	-16 (-30, -7)	-25 (-40, -16)	-23 (-33, -8)	-35 (-44, -22)
Δ q100 (flood)	n/a	%	2.5 (-19.2, 27.5)	12 (-15, 53)	22 (-6, 66)	41 (5, 130)
Δ 7q10 (low flow)	n/a	%	1.2 (-5.2, 8.3)	-1.3 (-6.3, 5.4)	1.2 (-3.1, 8.0)	-1.9 (-5.3, 5.1)
Δ aet (May-Jun)	total	%	8.2 (2.1, 17.4)	10 (6, 18)	13 (5, 25)	16 (10, 27)
Δ aet (Aug-Sep)	total	%	-11 (-25, 2)	-13 (-26, 1)	-19 (-32, 10)	-21 (-33, 4)
Δ pet1 (JJAS)	total	%	10 (5, 16)	10 (5, 16)	16 (10, 21)	17 (10, 24)
Δ pet3 (JJAS)	total	%	5.3 (1.7, 9.6)	4.0 (0.8, 7.8)	9.3 (2.4, 15.2)	7.7 (1.6, 13.4)
Δ soilmoist (JFMA)	total	%	16 (7, 34)	16 (7, 32)	23 (13, 42)	24 (15, 41)
Δ soilmoist (JJAS)	total	%	-4.1 (-11.0, 2.1)	-6.8 (-14.7, 0.3)	-6.5 (-11.2, 0.7)	-10 (-16, -2)
Δ vpd (JJAS)	avg	Pa	0.24 (0.10, 0.41)	0.23 (0.10, 0.36)	0.42 (0.24, 0.70)	0.40 (0.22, 0.61)

streamflow timing, showing increases of 13-16% in late spring (May-Jun) and decreases of 19-21% in late summer (Aug-Sep). Driven primarily by temperature, total summer (Jun-Sep) pet is projected to increase by 16-17% for pet1 and 8-9% for pet3.

Blue Mountains (Bailey M332G, Omernik 11)

As in northeast Washington, the climate of the Blue Mountains exhibits cooler winters, warmer summers, and much drier conditions than the other regions considered in this study. Average monthly winter temperatures reach -3.5°C, while average monthly summer temperatures exceed 17.5°C. Precipitation, as in northeast Washington, is quite low: averaging below 600 mm (24 in) annually, with peak monthly winter precipitation just in excess of 75 mm (3 in) and the minimum in summer below 17 mm (0.67 in). By the 2080s, monthly average temperature is projected to increase by ~3.3°C in winter (Dec-Feb) and 5.0°C in summer (Jun-Aug). Projected changes in precipitation resemble those for northeast Washington: projections vary significantly among models, but the central tendency is for increased precipitation (~15%) in winter (Nov-Feb) and decreased precipitation (17%) in summer (Jun-Sep).

Despite low winter temperatures, only enough snow is accumulated to qualify the region as a transitional snow regime: neither snow- nor rain-dominant in character. This is reflected in the annual variations in runoff, which show an early spring peak with some evidence of early-season runoff due to rain. Projections for the end of the century are for a 69-72% decrease in April 1st snowpack, with the date of 90% melt occurring 23-25 days earlier. The projected changes in runoff likewise show a shift towards earlier peak flows and an increasing prevalence of early-season flows. Projected changes in soil moisture reflect this change, showing increases in average winter amount (12-13%, Jan-Apr) and decreases in average summer storage (4-7%, Jun-Sep). Actual evapotranspiration likewise shows an increase in late spring (12-14%, May-Jun) and a decrease in late summer (18-19%, Aug-Sep). Potential evapotranspiration, as in other regions, increases

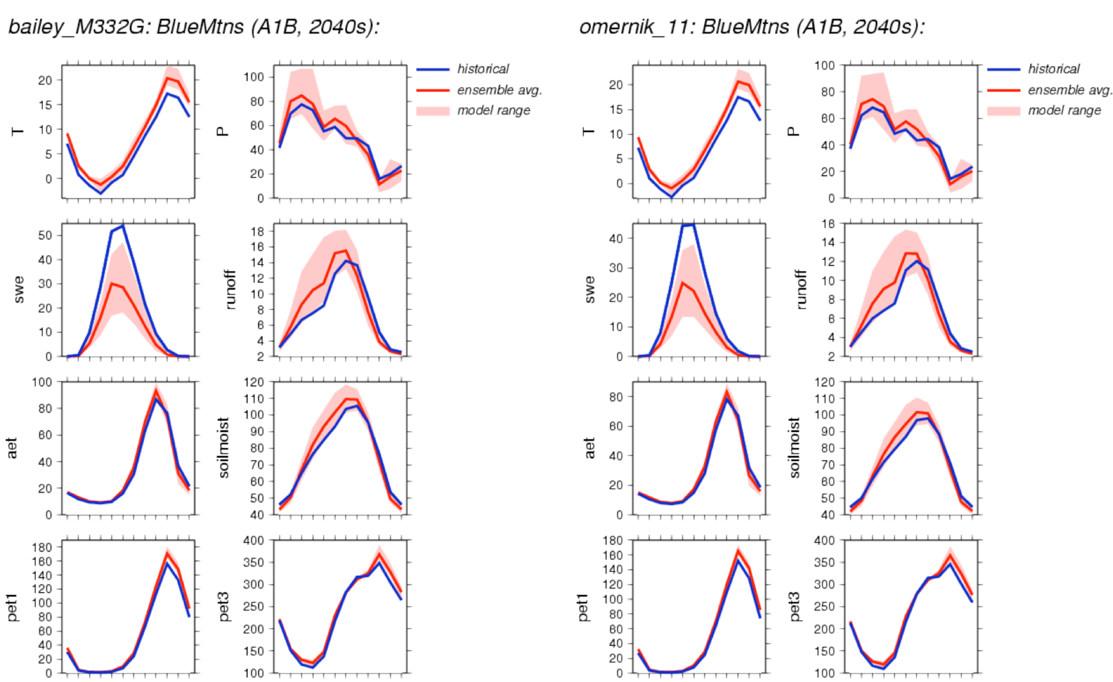

Figure 9 – Summary projections for Bailey ecosection M332G and Omernik Level III ecoregion 11.

Table 8 – Summary of projected changes for Bailey M332G and Omernik 11 (A1B scenario)

Blue Mountains			**2040s**		**2080s**	
			bailey_M332G	**omernik_11**	**bailey_M332G**	**omernik_11**
variable	*monthly_agg*	*units*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*	*avg (min, max)*
Δ T (DJF)	avg	C	1.8 (0.8, 2.9)	1.8 (0.8, 2.8)	3.4 (1.6, 5.5)	3.3 (1.6, 5.4)
Δ T (JJA)	avg	C	3.0 (1.9, 5.0)	3.0 (1.9, 5.0)	5.0 (3.0, 7.6)	5.0 (2.9, 7.6)
Δ precip (NDJF)	total	%	9.3 (-8.4, 29.9)	9.0 (-8.5, 30.3)	16 (-2, 45)	15 (-3, 46)
Δ precip (JJAS)	total	%	-18 (-34, 4)	-18 (-35, 4)	-17 (-51, 22)	-17 (-52, 21)
Δ SWE (Apr1st)	n/a	%	-45 (-65, -12)	-49 (-68, -15)	-69 (-92, -28)	-72 (-93, -32)
Δ date 90% melt	n/a	dys	-15 (-28, -4)	-14 (-26, -4)	-25 (-37, -12)	-23 (-34, -11)
Δ length snow season	n/a	dys	-18 (-25, -9)	-17 (-23, -9)	-26 (-32, -13)	-23 (-30, -13)
Δ runoff (DJF)	total	%	34 (2, 86)	30 (-0, 78)	65 (14, 152)	55 (8, 137)
Δ runoff (JJA)	total	%	-18 (-30, -8)	-15 (-27, -5)	-25 (-36, -14)	-21 (-34, -9)
Δ q100 (flood)	n/a	%	21 (-18, 64)	17 (-21, 65)	45 (6, 92)	38 (-1, 86)
Δ 7q10 (low flow)	n/a	%	-0.40 (-6.10, 5.10)	-0.40 (-7.60, 7.30)	-0.80 (-8.00, 5.70)	-1.1 (-10.9, 9.2)
Δ aet (May-Jun)	total	%	8.8 (4.0, 14.4)	7.9 (2.9, 14.0)	14 (7, 24)	12 (5, 23)
Δ aet (Aug-Sep)	total	%	-15 (-27, 6)	-15 (-27, 6)	-19 (-49, 10)	-18 (-50, 12)
Δ pet1 (JJAS)	total	%	12 (7, 18)	11 (7, 17)	17 (12, 22)	16 (11, 20)
Δ pet3 (JJAS)	total	%	5.5 (1.9, 10.4)	5.6 (2.2, 10.4)	8.8 (3.5, 13.4)	8.8 (3.7, 13.7)
Δ soilmoist (JFMA)	total	%	8.0 (-1.0, 17.3)	7.4 (-1.5, 17.3)	13 (0, 27)	12 (-2, 27)
Δ soilmoist (JJAS)	total	%	-4.6 (-9.7, 1.7)	-4.3 (-9.7, 1.9)	-6.8 (-14.5, 1.4)	-6.3 (-14.5, 1.7)
Δ vpd (JJAS)	avg	Pa	0.21 (0.10, 0.43)	0.21 (0.10, 0.45)	0.39 (0.20, 0.72)	0.40 (0.20, 0.72

substantially, with total summer (Jun-Sep) projected increases of 16-17% for pet1 and 9% for pet3.

References

Daly, C., R. P. Neilson, and D. L. Phillips (1994) *A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain*. Journal of Applied Meteorology, **33**, 140-158.

Daly, C., W. P. Gibson, G. Taylor, G. L. Johnson, and P. Pasteris (2002) *A knowledge-based approach to the statistical mapping of climate,* Climate Research, **22**, 99-113.

Deems, J., A. F. Hamlet (2010) *Historical Meteorological Driving Data Set: Chapter 3, Columbia Basin Climate Change Scenarios Project (CBCCSP) report*.

Elsner, M. M., L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. A. Vano, K. E. B. Mickelson, S.-Y. Lee, D. P. Lettenmaier, 2010, *Implications of 21st century climate change for the hydrology of Washington State,* Climatic Change, Volume 102, Numbers 1-2, 225-260, DOI: 10.1007/s10584-010-9855-0

Hamlet, A.F., P. Carrasco, J. Deems, M.M. Elsner, T. Kamstra, C. Lee, S-Y Lee, G. Mauger, E. P. Salathe, I. Tohver, L. Whitely Binder, 2010, *Final Project Report for the Columbia Basin Climate Change Scenarios Project*, http://www.hydro.washington.edu/2860/report/".

Hamlet, A. F. and D. P. Lettenmaier (2005) *Production of Temporally Consistent Gridded Precipitation and Temperature Fields for the Continental United States* Journal of Hydrometeorology, **6**, 330-336.

Liang X, Wood EF, Lettenmaier DP (1996) *Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications*. Glob Planet Chang 13: 195-206

Liang X, Wood EF, Lohmann D, Lettenmaier DP, and others (1998) *The project for intercomparison of land-surface parameterization schemes (PILPS) phase-2c Red-Arkansas River basin experiment: 2. Spatial and temporal analysis of energy fluxes*, J Glob Planet Chang 19: 137-159

Littell, J.S., M.M. Elsner, G. S. Mauger, E. Lutz, A.F. Hamlet,, and E. Salathé. 2010a. Regional Climate and Hydrologic Change in the Northern US Rockies and Pacific Northwest: Internally Consistent Projections of Future Climate for Resource Management. DRAFT report.

Littell J. S., E. E. Oneil, D. McKenzie, J. A. Hicke, J. A. Lutz, R. A. Norheim, and M. M. Elsner, 2010b, *Forest ecosystems, disturbance, and climatic change in Washington State, USA*, Climatic Change, Volume 102, Numbers 1-2, 129-158, DOI: 10.1007/s10584-010-9858-x

Mantua, N., I. Tohver, and A. F. Hamlet, 2010, *Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State,* Climatic Change, Volume 102, Numbers 1-2, 187-223, DOI: 10.1007/s10584-010-9845-2

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002) *A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States,* Journal of Climate, **15**, 3237-3251.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor, 2007a. *The WCRP CMIP3 multi-model dataset: A new era in climate change research*, Bulletin of the American Meteorological Society, 88, 1383-1394.

Meehl, GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, and Zhao Z-C 2007b. *Global climate projections. in 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, et al., (eds)]*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Mote, P. W. and E. P. Salathé, 2010: *Future Climate in the Pacific Northwest*, Climatic Change, Volume 102, Numbers 1-2, 29-50, DOI: 10.1007/s10584-010-9848-z

Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E. F. Wood (1997) *Streamflow simulation for continental-scale river basins*. Water Resour. Res, **33**, 711-724.