Department of Energy

Bonneville Power Administration
P.O. Box 3621
Portland, Oregon 97208-3621

FREEDOM OF INFORMATION ACT/PRIVACY PROGRAM

October 19, 2021

In reply refer to: FOIA #BPA-2021-00092-F

Jeremy Hainsworth
Glacier Media
303 West 5th Ave
Vancouver, BC V5Y1J6
Email: jhainsworth@glaciermedia.ca

Dear Mr. Hainsworth,

This communication concerns your agency records request submitted to the Bonneville Power Administration (BPA), made via the Freedom of Information Act, 5 U.S.C. § 552 (FOIA). BPA received your request on October 28, 2020; formally acknowledged your request on November 18, 2020; provided you a first partial response of records on June 25, 2021; and provided you a second partial release of records on September 14, 2021.

Request
"All reports, memos and briefing notes regarding the effects on US water supply and power supply as a result of the effects of climate change on watersheds in the Canadian province of British Columbia. All communications regarding the effects of climate change from the government of British Columbia regarding water and power supply to the United States. This is a media request."

Agreement to Re-scope Responsive Records
On February 23, 2021, after communicating with the agency, you agreed to re-scope your request to: "All reports and briefing notes regarding the effects on US water supply and power supply as a result of the effects of climate change on watersheds in the Canadian province of British Columbia."

Third Partial Response
Records were collected by knowledgeable agency personnel familiar with the subject of your FOIA request. This partial response comprises records that BPA was required by 5 U.S.C. § 552(b)(4) (Exemption 4) to solicit objections from third parties prior to their release. The records contain information created by the University of Idaho and the University of Washington's Climate Impacts Group. Those outreaches are complete, and their records are being released in full.

This release also comprises records that BPA was required by 5 U.S.C. § 552(b)(5) (Exemption 5) to solicit objections from the U.S. Bureau of Reclamation (Bureau) prior to their release. That

outreach is complete, and their records are being released in full. Please note, this release does not comprise all Bureau records; additional records were jointly authored with the U.S. Army Corps of Engineers (Corps), and those records continue to be reviewed as described below at 'Ongoing Processing – Corps.'

In this third partial release, BPA is releasing 342 pages in full, with no redactions applied.

Certification
Pursuant to 10 C.F.R. § 1004.7(b)(2), I am the individual responsible for the third partial FOIA response described above.

Ongoing Processing – Corps
Prior to publicly releasing agency records, BPA is required to review responsive records for possible exemptions under Exemption 5. Exemption 5 protects agency records showing the deliberative or decision-making processes of the agency. The majority of records collected for your request were jointly created by the River Management Joint Operating Committee, which consists of the Corps and the Bureau. BPA sent approximately 30,000 pages of records to the Corps and the Bureau for their examination. We received a response from the Bureau, and we now wait for the Corps to complete their review. Please note, BPA does not control their processing time.

Target Date
In light of the required consultation with the Corps, BPA currently estimates the completion of a response to your FOIA request by December 9, 2021. BPA invites you to contact us to discuss this estimated completion date.

Lastly, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer. The contact information for OGIS is as follows:

Office of Government Information Services
National Archives and Records Administration
8601 Adelphi Road-OGIS
College Park, Maryland 20740-6001
E-mail: ogis@nara.gov
Phone: 202-741-5770
Toll-free: 1-877-684-6448
Fax: 202-741-5769

Questions about this communication or the status of your FOIA request may be directed to FOIA Public Liaison Jason Taylor at jetaylor@bpa.gov.

Sincerely,

Candice D. Palen
Freedom of Information/Privacy Act Officer

Responsive agency information accompanies this communication.

A Comprehensive Hydrologic Data Base Incorporating IPCC Climate Change Scenarios to Support Long-Range Water Planning in the Columbia River Basin

Meteorological Data, Downscaling, Streamflow Site Selection

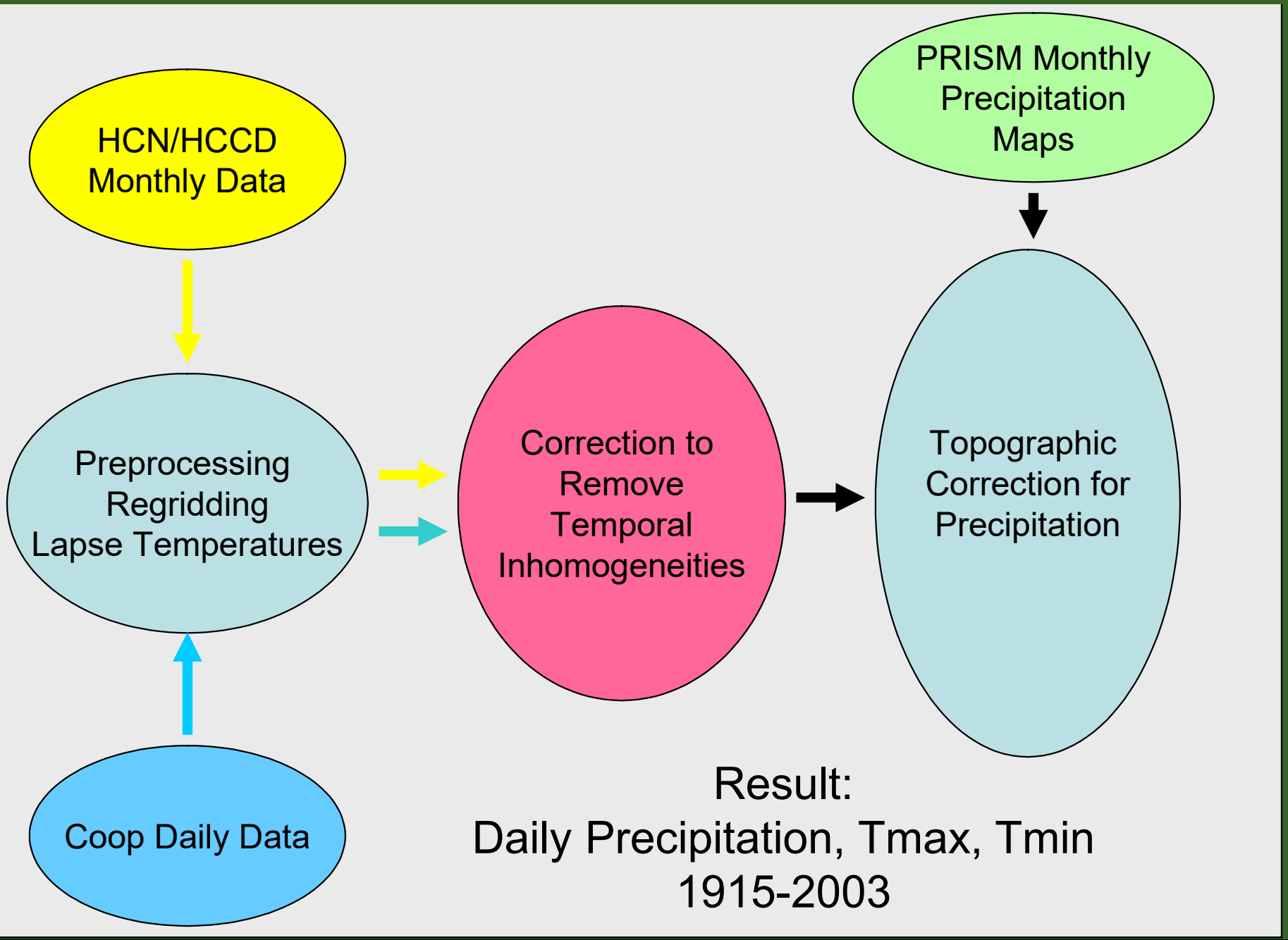
Alan F. Hamlet
Jeff Deems

•JISAO/CSES Climate Impacts Group
•Dept. of Civil and Environmental Engineering
University of Washington

Department of Civil and Environmental Engineering

Meteorological Driving Data

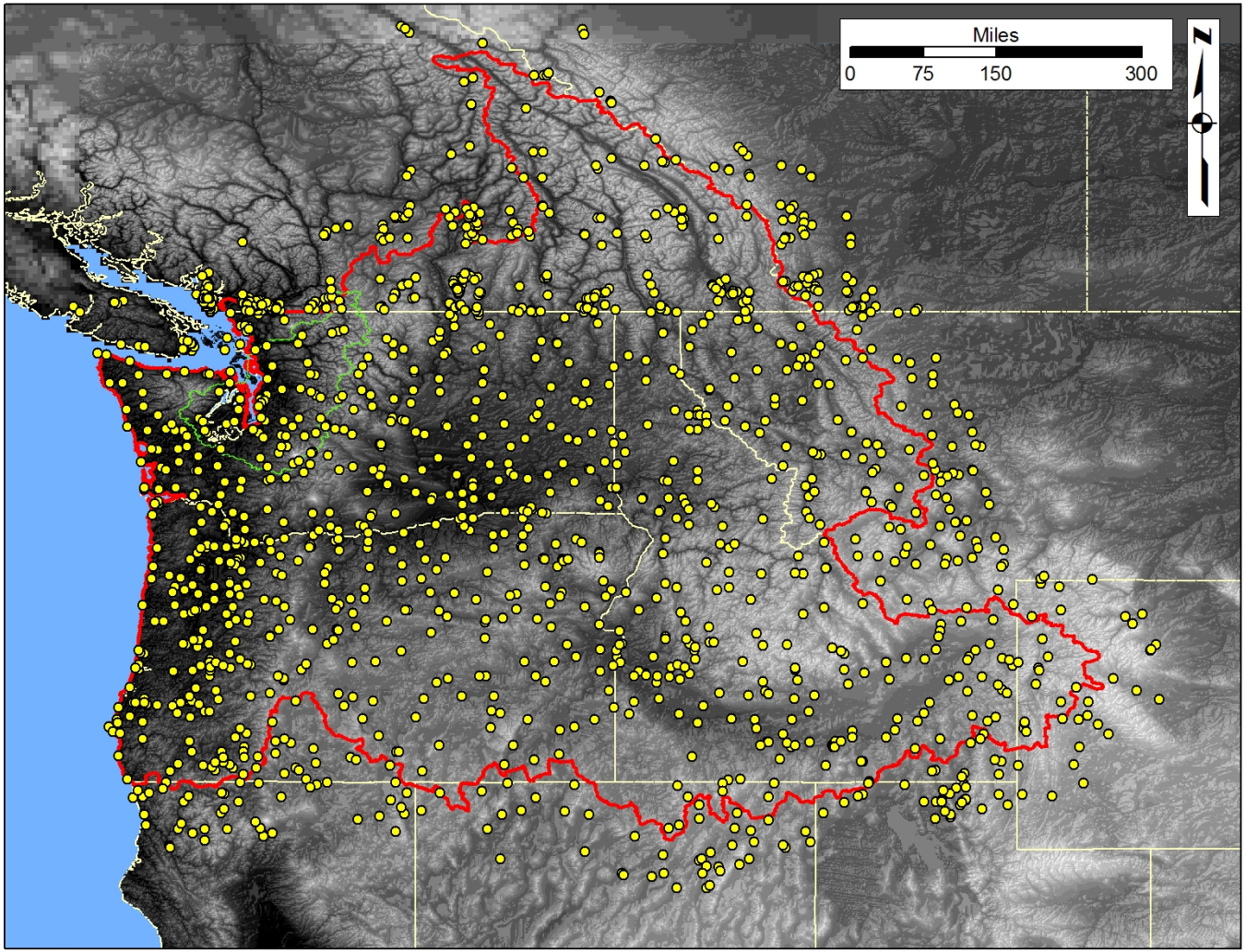
Existing Methods Used to Produce 1/8th Degree MET Products



Key Objectives for 2860 Project:

- Increase spatial resolution to 1/16th degree
- Extend data through 2006
- Select stations to include in gridding exercise more carefully
- Incorporate more data from Canada and improve quality control
- Resolve data processing issues identified in past efforts related to temporal corrections (tighter coupling to HCN data)
- Update to incorporate 1971-2000 PRISM means at 30 arc second resolution
- Incorporate the PRISM temperature maps and explore their utility in improving temperature lapse rates.
- Explore the use of different station lists in some parts of the domain (mainly effects the Puget Sound drainages)
- Create and archive derived meteorological data bases using the VIC model as a preprocessor.

Primary Meteorological Stations Used to Create Gridded Product (1915-2006)



Status of Met Data Sets:

Data set has been completed, and has been thoroughly exercised in preliminary VIC simulations and the 1303 assessment.

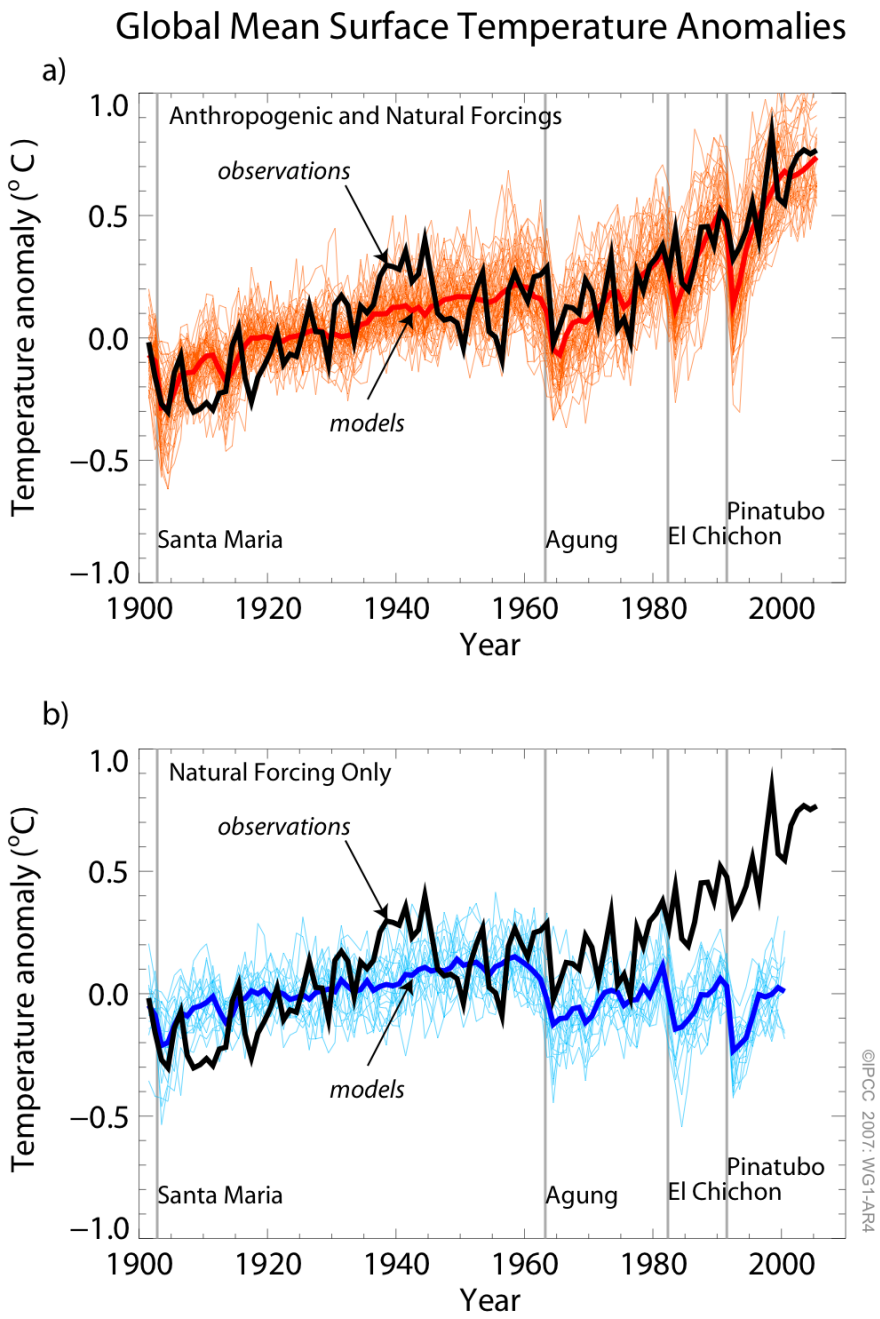
Preliminary derived data bases from VIC (Marketa's presentation) have been produced, and have been exercised in 1303 effort. Some initial problems with VPD reported by several users are now being investigated, and some changes in the code may result. These will be resolved before final VIC calibration is carried out.

Journal article is in progress, and will include comparisons with past data sets at 1/8th degree.

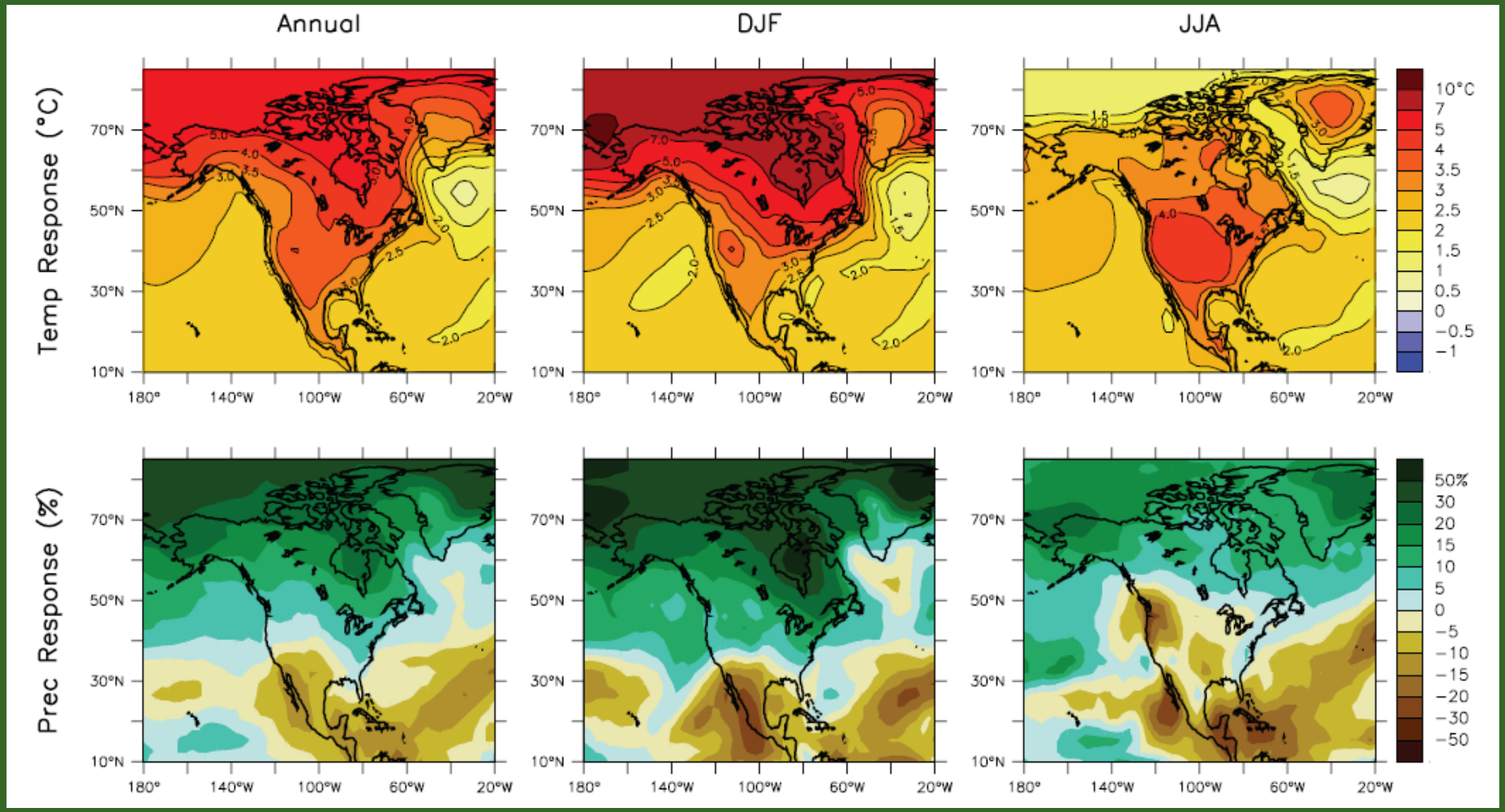
Downscaling Global Climate Change Scenarios for the PNW

1) Global climate modeling experiments reproduce history of global temperatures remarkably well.

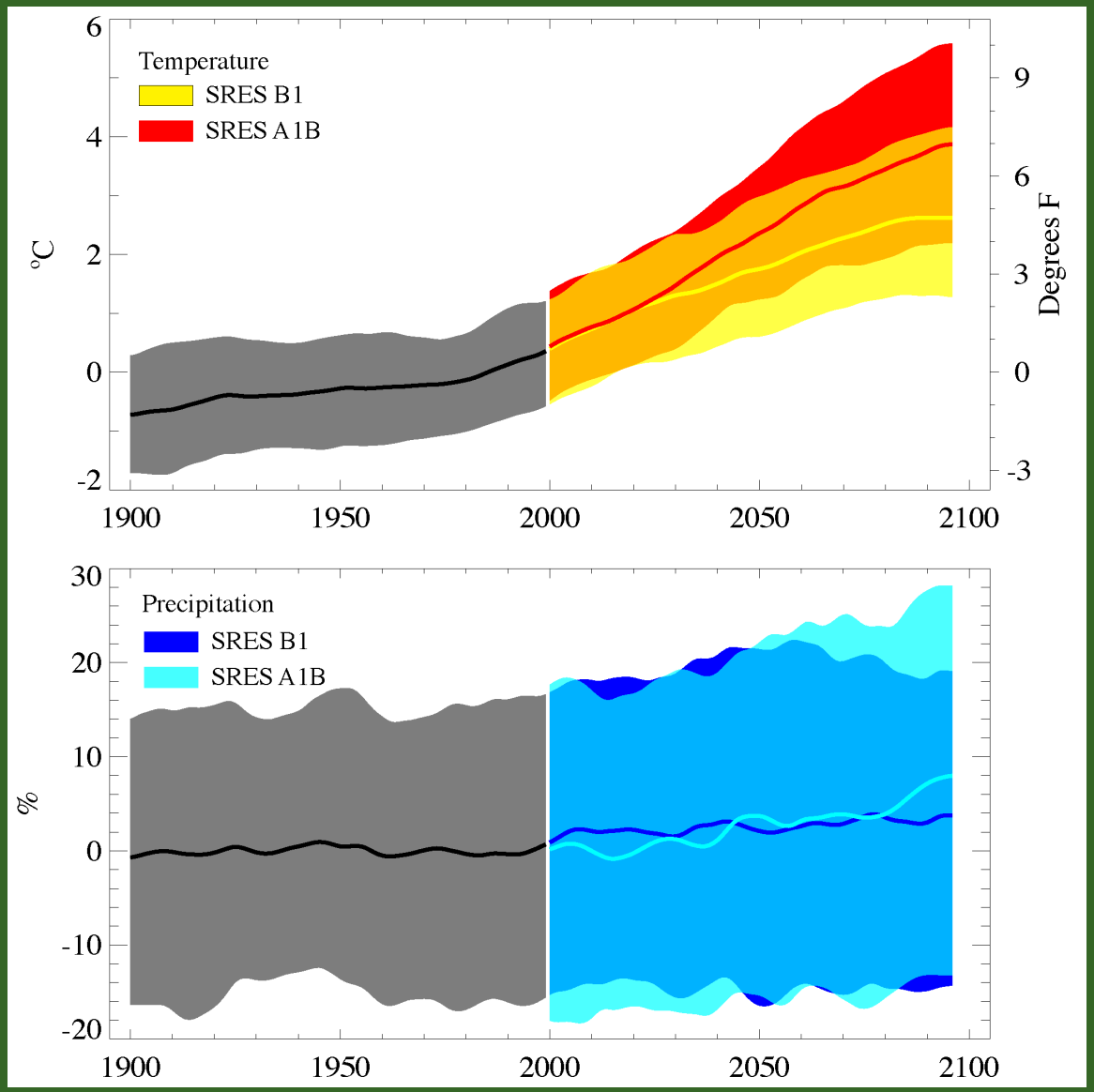
2) Natural forcings (e.g. volcanic eruptions and variations in solar radiation) alone cannot explain the rapid rise in temperature at the end of the 20th century.



Consensus Forecasts of Temperature and Precipitation Changes from IPCC AR4 GCMs



21st Century Climate Impacts for the Pacific Northwest Region



Mote, P.W. and E. P. Salathe Jr., 2009: Future climate in the Pacific Northwest (in review)

Overview of Downscaling Approaches:

Delta Method

•Realistic daily time series and spatial variability.

•90 years of variability associated with each time frame and emissions scenario.

•Only incorporates changes in mean T and P.

Bias Adjusted and Downscaled GCM Downscaling

•Incorporates more information from the GCMs, but as a result may also inherit undesirable aspects of GCMs as well.

•Facilitates trend analysis, examination of altered variability.

Hybrid Methods

•Takes time series and spatial behavior from the observed record, but incorporates more detailed statistical changes from the GCMs.

Dynamic Downscaling

•Uses meso-scale climate models. (Not proposed for this study.)

Status:

A number of delta method runs were made for the entire Columbia basin for the 1303 effort, including a full ensemble of runs for the 2020s over the Yakima basin, and results are generally very encouraging.

Initial transient downscaling results showed many undesirable artifacts at daily time scales in smaller basins. At the current level of development these are probably not acceptable for this application.

Hybrid methods will likely resolve these issues satisfactorily in the time available, and these methods are currently being coded and tested by Eric Salathé.

Streamflow Site Selection

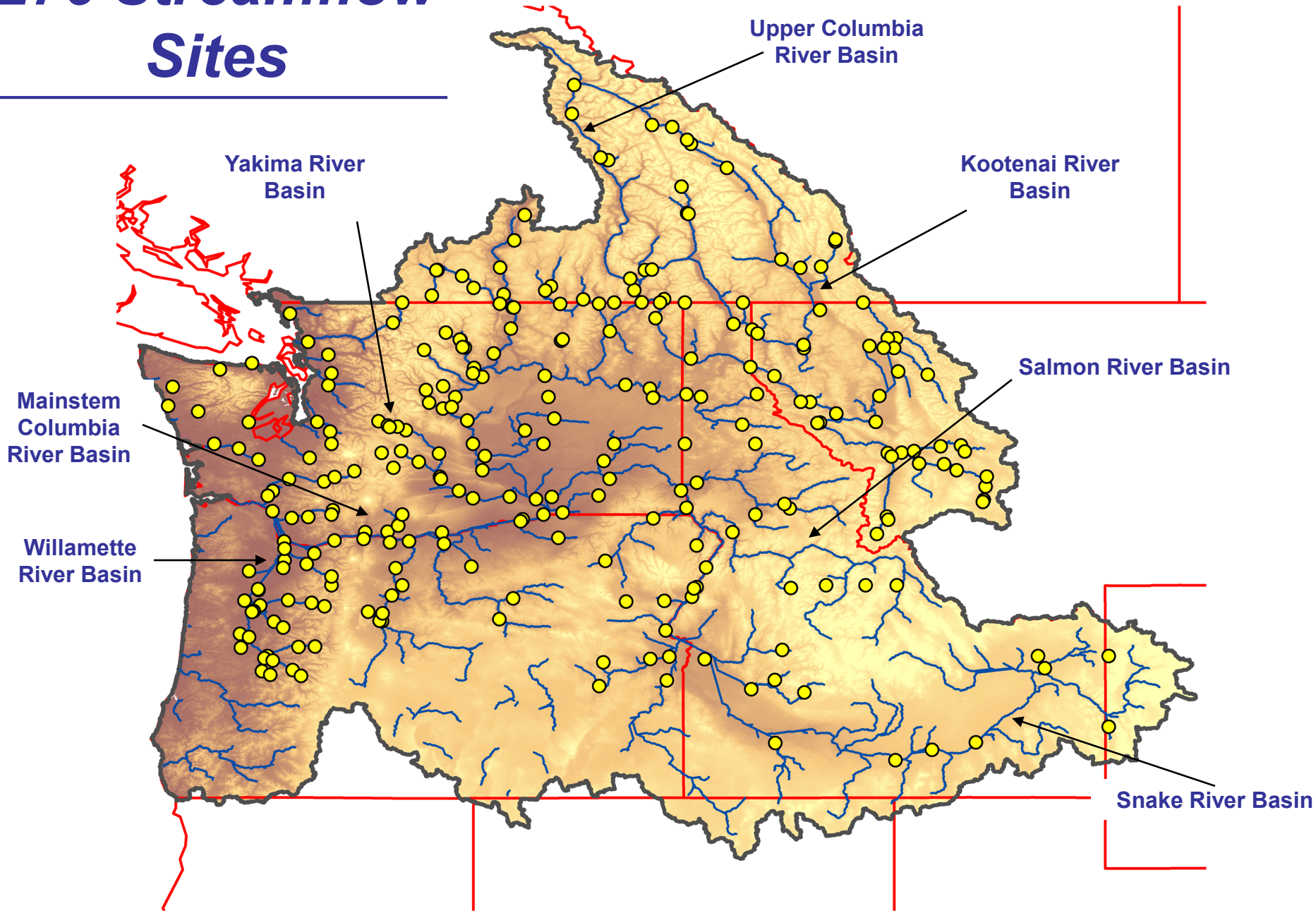
Criteria for Streamflow Site Selection:

We requested prioritized site selection suggestions from all stakeholder groups (50 from each).

Contractually we were only required to produce data for 200 sites, but we made the decision to include all sites suggested by our stakeholders. (note that calibration may not be equally good across all sites)

Additional naturalized data and diversion/return information was provided for a specific group of sites in Washington, and a special set of products for these sites will produced.

276 Streamflow Sites



A Comprehensive Hydrologic Data Base Incorporating IPCC Climate Change Scenarios to Support Long-Range Water Planning in the Columbia River Basin

Project Overview

Alan F. Hamlet

•JISAO/CSES Climate Impacts Group
•Dept. of Civil and Environmental Engineering
University of Washington

Department of Civil and Environmental Engineering

Study Partnerships

Funding Partners:

WA Department of Ecology
Bonneville Power Administration
Northwest Power and Conservation Council
Oregon Water Resources Department
BC Ministry of the Environment

Collaborative Partners:

Montana Department of Natural Resources
Idaho Department of Water Resources
USBR, Boise Regional Office
USACE, Seattle and Portland Districts

Key Study Objectives:

Provide comprehensive hydrologic data bases to support water planning at a range of spatial and temporal scales in the Columbia River basin and PNW.

Increase spatial resolution of hydrologic models to capture smaller basins relevant to planning.

Conduct pilot studies using fine scale hydrologic simulation tools and compare to macro-scale tools that are currently being more widely implemented.

Improve range of products and services available, and construct tools and data processing methods to make future updates easier (and less expensive) to produce.

Increasing Model Resolution Increases Coverage of Sites in WA

Table 1 All WA Streamflow Sites in USGS Summary (with no overlap with BPA Modified Flow Locations)

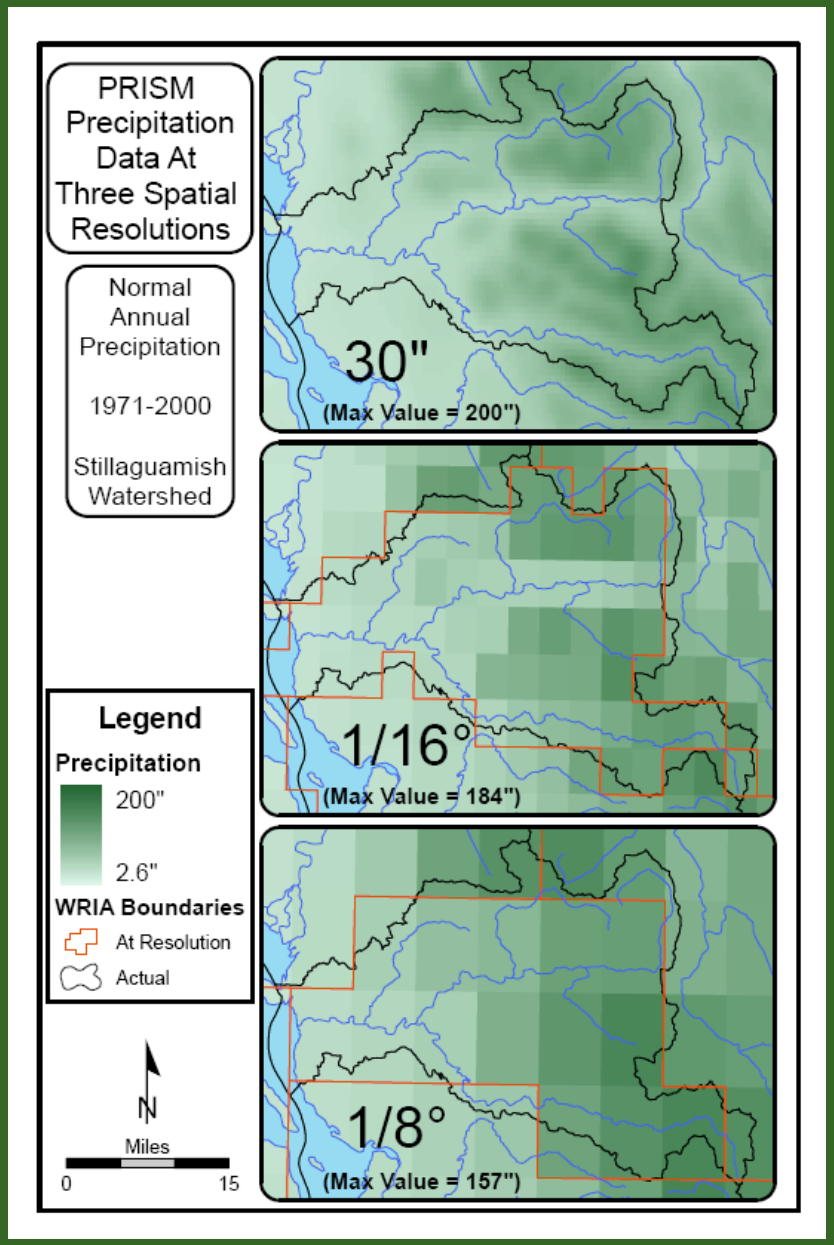
Description	Number of Sites	Percent of Total
All sites	78	100
Less than 200 sq mi**	22	28
Greater than or equal to 200 sq mi	56	72
Greater than or equal to 800 sq mi	24	31
Natural flow sites	23	29
Natural flow sites greater than or equal to 200 sq mi	11	14

**Note that four sites overlap anticipated DHSVM efforts in the Walla Walla and Wenatchee basins, and two have very small drainage areas.

Conclusions:

- Increasing VIC resolution from 1/8th degree to 1/16th degree increases the number of WA sites that can be captured from 31% (1/8th degree) to 72% (1/16th degree).
- Fine scale modeling would potentially capture an additional 28% of total sites available.
- Using 1/16th degree VIC, 56 of the available sites would be captured, of which 11 would currently have naturalized observations available for model calibration and evaluation.

Increasing Model Resolution Improves Performance



Topographic variations in precipitation in model driving data, and simulated snow accumulation and melt play crucial roles in model performance in the context of climate change assessments.

In small basins, edge effects at 1/8th degree tend to over or understate the fraction of high elevation areas in the basin, which can effect the sensitivity to warming.

A 1/16th degree grid shows a marked improvement in both the spatial pattern of precipitation, the simulated basin area, and the representation of the fraction of the basin area at high elevation.

Key Deliverables:
This section lists key deliverables for the research project.

Deliverable 1	Hydrologic data base of water balance variables and streamflow scenarios (both natural and "regulated") for up to 200 Ecology selected streamflow locations for both historic and 21st century climate conditions. (See detailed description of these deliverables below.)	
Deliverable 2	Journal articles and/or technical reports	
Deliverable 3	Develop a user friendly web-based product for accessing and summarizing the VIC hydrologic and meteorological data bases. (See detailed description below.)	
Deliverable 4	Summary report describing the VIC data base and web server.	
Deliverable 5	Additional analysis in pilot watersheds comparing VIC and DHSVM results and associated technical reports or journal articles describing these studies. (See detailed description below.)	

Track I: Historic Driving Data, Downscaling Procedures, Climate Change Scenarios

Task 1	Develop historic driving data at 1/16th degree from 1915- 2005	
Task 2	Develop temperature and precipitation downscaling procedures suitable for both monthly water supply planning and subsequent flood analysis	
Task 3	Produce downscaled 1/16th degree driving data sets associated with each of 10 GCM scenarios for “2020” “2050” “2080” time periods	
Task 4	Produce a high resolution driving data set for four sub-watersheds at 150m resolution	
Task 5	Summary Reports	

Track II: Development of Hydrologic Models and Hydrologic Data Bases		
Task 1	Develop a 1/16th degree VIC model over the Columbia River basin.	
Task 2	Calibrate and develop statistical bias correction procedures for the 1/16th degree VIC model for up to 150 streamflow locations in the Columbia River Basin to be determined by Ecology.	
Task 3	Run the 1/16th degree VIC model for each of 10 GCM scenarios for the three time periods, and produce streamflow scenarios for up to 200 sites to be determined by Ecology.	
Task 4	Using available diversion and return data and typical patterns of regulation (to be provided by Ecology), adjust natural flow scenarios to estimate monthly "regulated" flows for up to 200 sites (as above).	
Task 5	Develop and archive a comprehensive hydrologic data base	
Task 6	Develop a high-resolution DHSVM implementation for four sub basins in the Columbia River basin at 150m resolution, and calibrate the model for both streamflow and water temperature.	
Task 7	Summary Reports	

Track III: Preliminary User Interviews, Development of Web-Based Data Server, and Summary Report for the User Community.

Task 1	Conduct interviews with key stakeholders such that adequate feedback is obtained regarding deliverables desired.	
Task 2	Develop a user friendly web based product for accessing and summarizing hydrological and meteorological data.	
Task 3	Develop summary reports for the potential user communities.	

Key Personnel:

Marketa McGuire Elsner (Project coordinator and VIC implementation)

Staff Researchers and Post Docs:

Jeff Deems (driving data)
Eric Salathé (downscaling)
Erin Rogers (DHSVM implementation)
Ingrid Tohver (flood statistics)
Lara Whitely Binder (survey and web design coordinator)
Carrie Lee (survey report)

Students:

Kristian Mickelson (routing network, 7Q10 methods, bias correction implementation for reservoir models)

Se-Yeun Lee (routing network, bias correction implementation, regulated streamflow products).

Additional Collaborations:

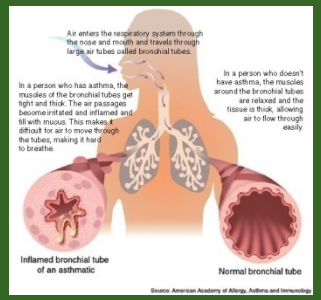
UW Land Surface Hydrology Group:
Lan Cuo (DHSVM implementation for Puget Sound)
Shrad Scukla (VIC calibration)

Pacific Climate Change Consortium (PCIC):
Katrina Bennett
Arelia Werner
Markus Schnorbus

Overlap with the Washington State Climate Impacts Assessment HB 1303

A comprehensive climate change impacts assessment for Washington State

Human Health



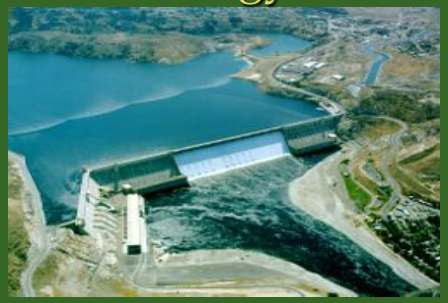
Infrastructure

Agriculture/Economics

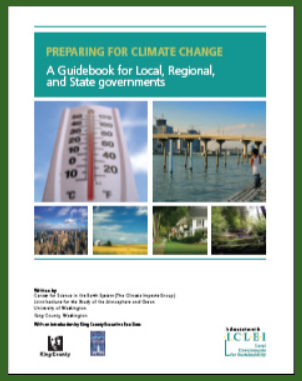
Water Resources

Coasts

Energy



Forest Resources



Adaptation

Salmon

Project Domain: WA and the PNW

To assess impacts in water and other sectors, the analysis must include all of the PNW = **wide range of data available for all the PNW!**

Detailed case studies for water supply are being done for the Puget Sound Region and Yakima Basin

Overview of Progress to Date

- 1/16th degree meterological driving data set complete for 1915-2006

- 1/16th degree VIC implementation and routing network are complete. Calibration and evaluation phase is in progress. Pilot calibration efforts in the Yakima basin are complete. Initial delta method experiments were completed for six scenarios as part of the 1303 effort.

- 3 of 5 DHSVM pilot watersheds are implemented and are entering the calibration and evaluation phase. (Erin Rogers is leaving the team as of Feb 1, and a new hire will probably need some start-up time for training resulting in delays.)

- Statistical downscaling techniques have undergone extensive testing, but several specific problems were encountered that we are resolving now. Revised downscaling products will be ready by May.

Overview of Progress to Date (cont.)

•Surveys of stakeholder needs and preferences were carried out in the first few months of the study, and a summary document is available.

•Pilot versions of many derived products (e.g. Q100 and 7Q10 analysis) have been implemented and tested on preliminary data, and are now awaiting final calibrated hydrologic simulations. Several projects, including the regulated flow estimates for selected basins, will begin in February.

•Web services portion of the project will begin in February. we are currently searching for a full-time web programmer/ designer.

•Report and journal articles will be prepared starting in February and continue through the spring.

Comprehensive Hydrologic Database – VIC Implementation and Preliminary Results

Marketa McGuire Elsner
University of Washington
JISAO/CSES Climate Impacts Group
Department of Civil and Environmental Engineering

In cooperation with:
Alan F. Hamlet, Nathan Mantua, Dennis P. Lettenmaier

January 30, 2009
HB2860 Progress Report

Department of Civil and Environmental Engineering

UNIVERSITY OF WASHINGTON

Assessment Overview: Study Region

Progress Report

- Track I

  Historic driving data, downscaling procedures, climate change scenarios

- Track II

  Development of Hydrology Models and Hydrologic Data Bases

- Track III

  Preliminary User Interviews, Development of Web-Based Data Server, and Summary Report for User Community

Task II: Development of Hydrology Models and Hydrologic Data Bases

Task 1

- Develop 1/16th degree VIC model over the Columbia River Basin

Task 2

- Calibrate and develop statistical bias correction procedures

Task 3

- VIC model runs at 1/16th degree for GCM scenarios for 3 time periods & produce streamflow at ± 200 sites

Task 4

- Adjust naturalized flow scenarios to estimate monthly “regulated” flows at select sites

Task 5

- Develop and archive hydrologic database

Task 6

- Develop high-resolution DHSVM models for 4 sub-basins at 150m resolution – calibrate for streamflow and temperature

Task 7 – Summary Reports

Outline

Task 1 - Develop 1/16th degree VIC model over the Columbia River Basin

- VIC Model overview and configuration
- Development of VIC model stationary inputs (veg, soils, etc.)
- Streamflow routing

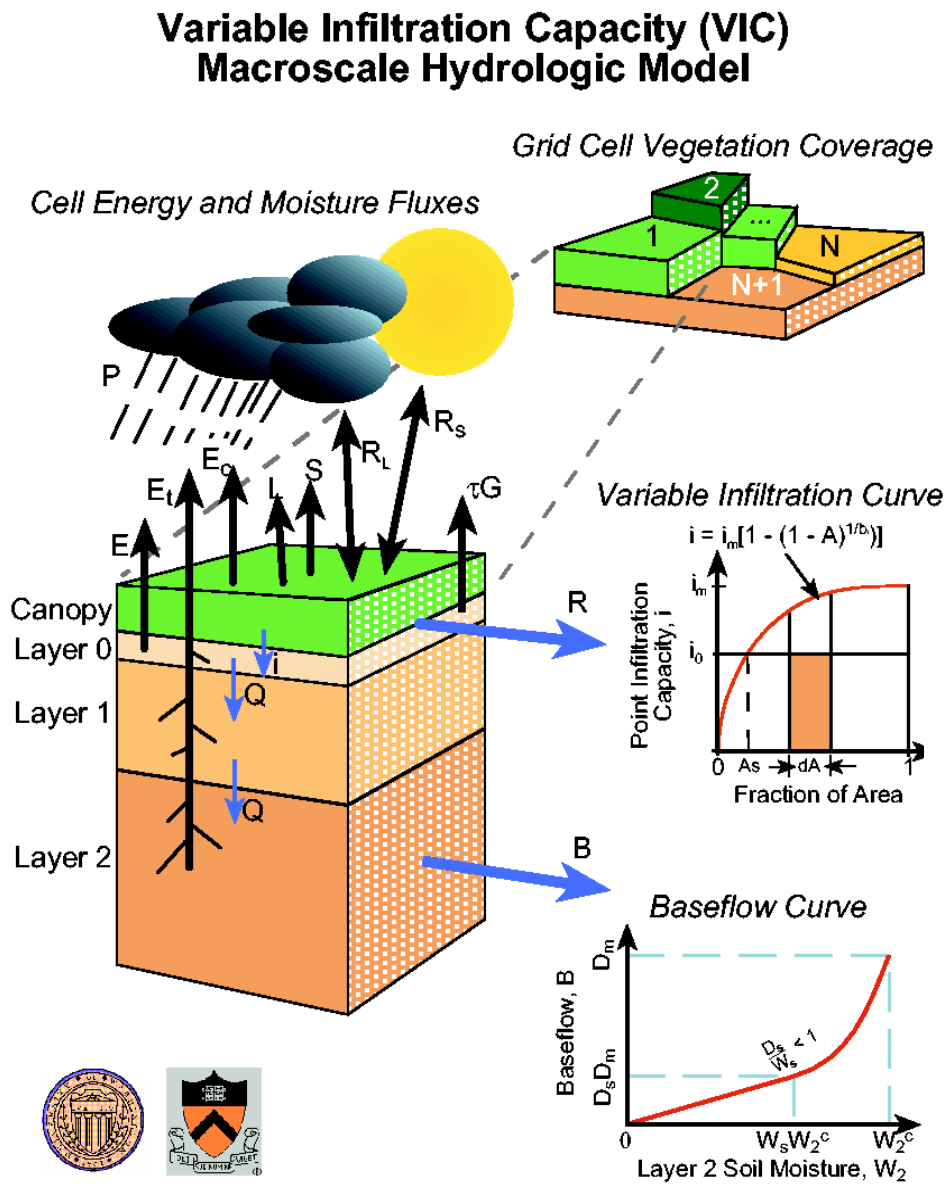
Task 2 - Calibrate and develop statistical bias correction procedures

- Calibration watersheds
- Calibration procedure

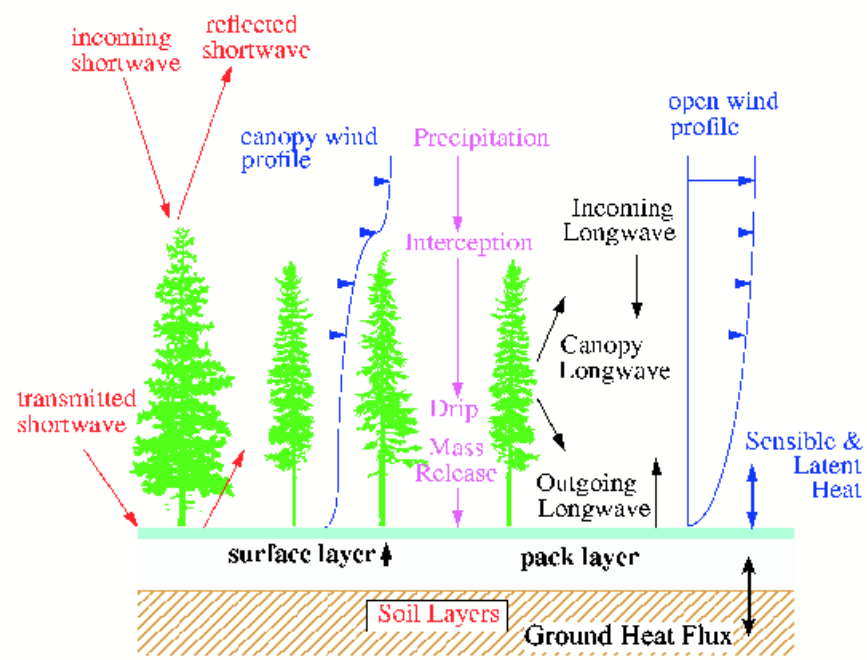
Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods & produce streamflow at ± 200 sites

- Incorporation of climate change information and uncertainty
- Preliminary results: grid-based and site specific

Task 1 - Develop 1/16th degree VIC model over the Columbia River Basin



VIC Model Overview



VIC model

Snow model within VIC

VIC Model Configuration

- Development of 1/16th degree VIC model
  - model grid cells are 5km latitude x 6km longitude
  - model parameter files (vegetation, elevation bands, soils)
- Development of routing network
- Model improvements:
  - Output of potential evapotranspiration (currently testing)
  - Output of vapor pressure deficit (currently testing)
- Historical "baseline" simulation 1915-2006

Status:

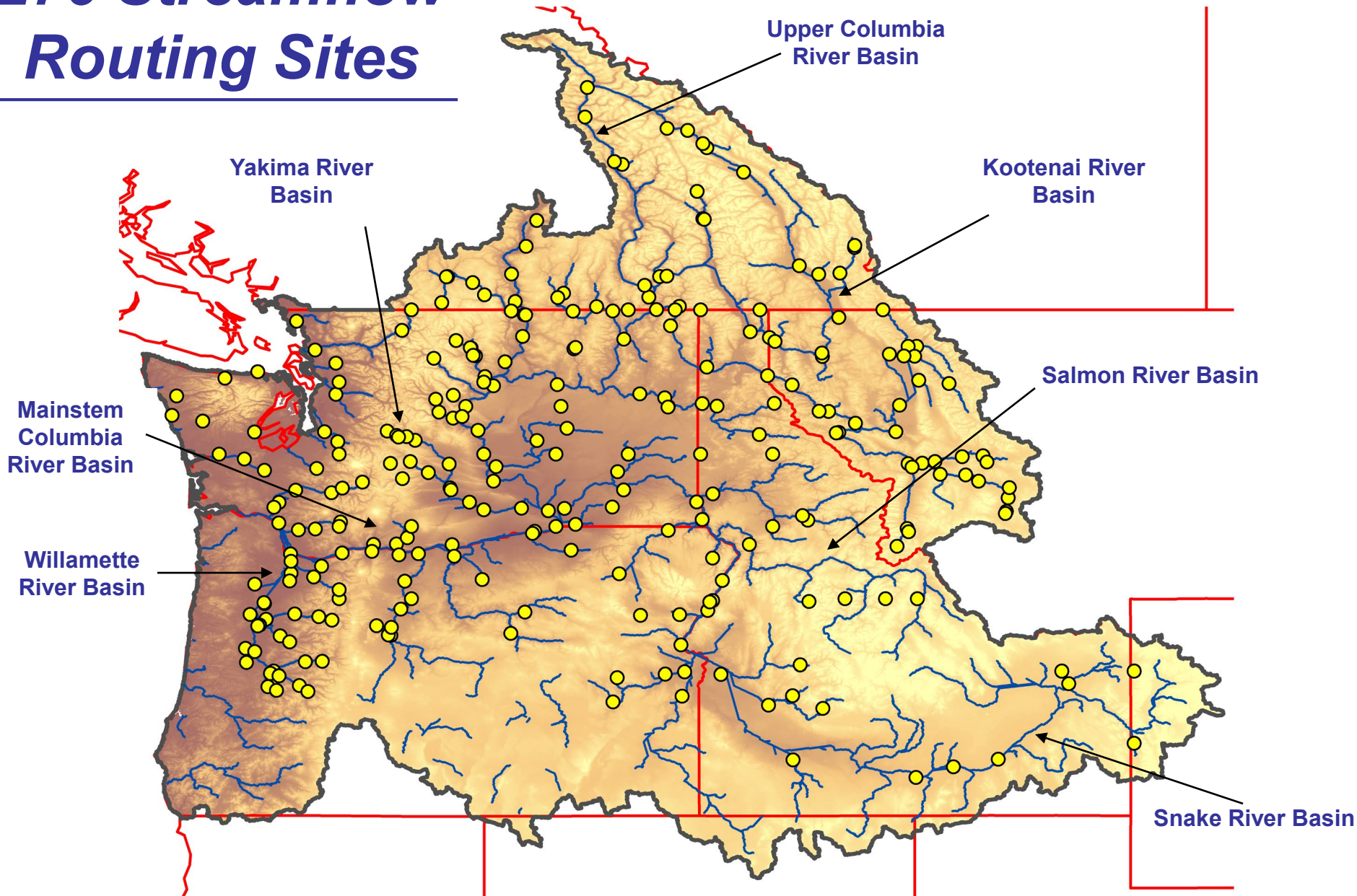
- 1/16th degree implementation is complete with preliminary model calibration parameters

VIC Model Configuration - input parameter files

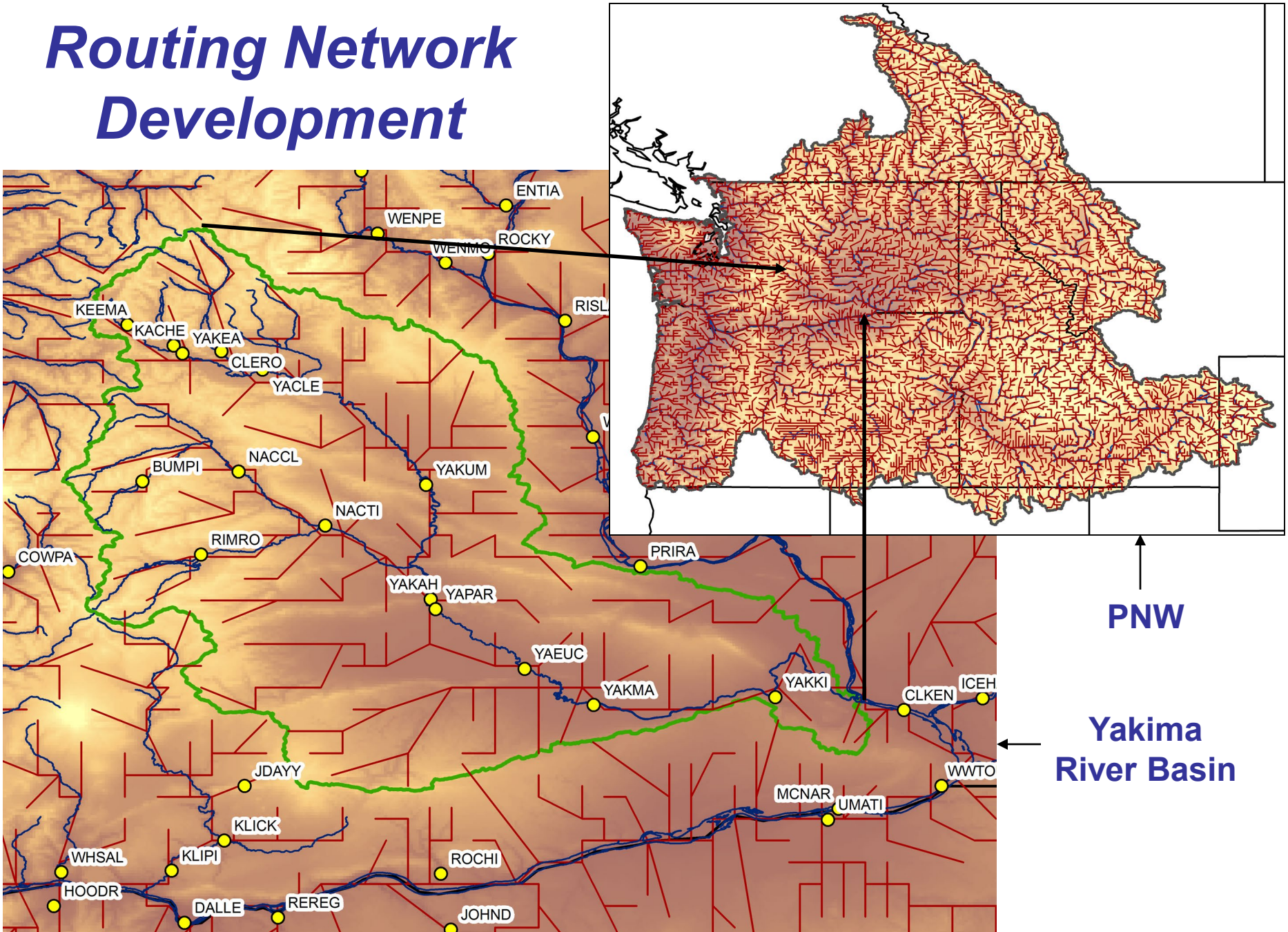
- Vegetation parameter file
  - Based on 1km global land cover product (U of MD)
  - Disaggregated from 1/8th degree to 1/16th degree
- Elevation band file
  - Based on 1km Digital Elevation Model (DEM) and 1/16th degree grid cells
- Soil parameter file
  - Based in NOAA LDAS soil product (Land Surface Data Assimilation System)
  - First disaggregated from 1/8th degree to 1/16th degree, then updated based on new historical dataset

Task 1 - Develop 1/16th degree VIC model over the Columbia River Basin

276 Streamflow Routing Sites



Routing Network Development



Model Improvements

- Incorporation of DHSVM soil depth scheme
- Output of potential evapotranspiration
  - Open water PET (pan evaporation)
  - Natural vegetation PET
  - Reference crop PET
- Output of vapor pressure deficit (VPD)

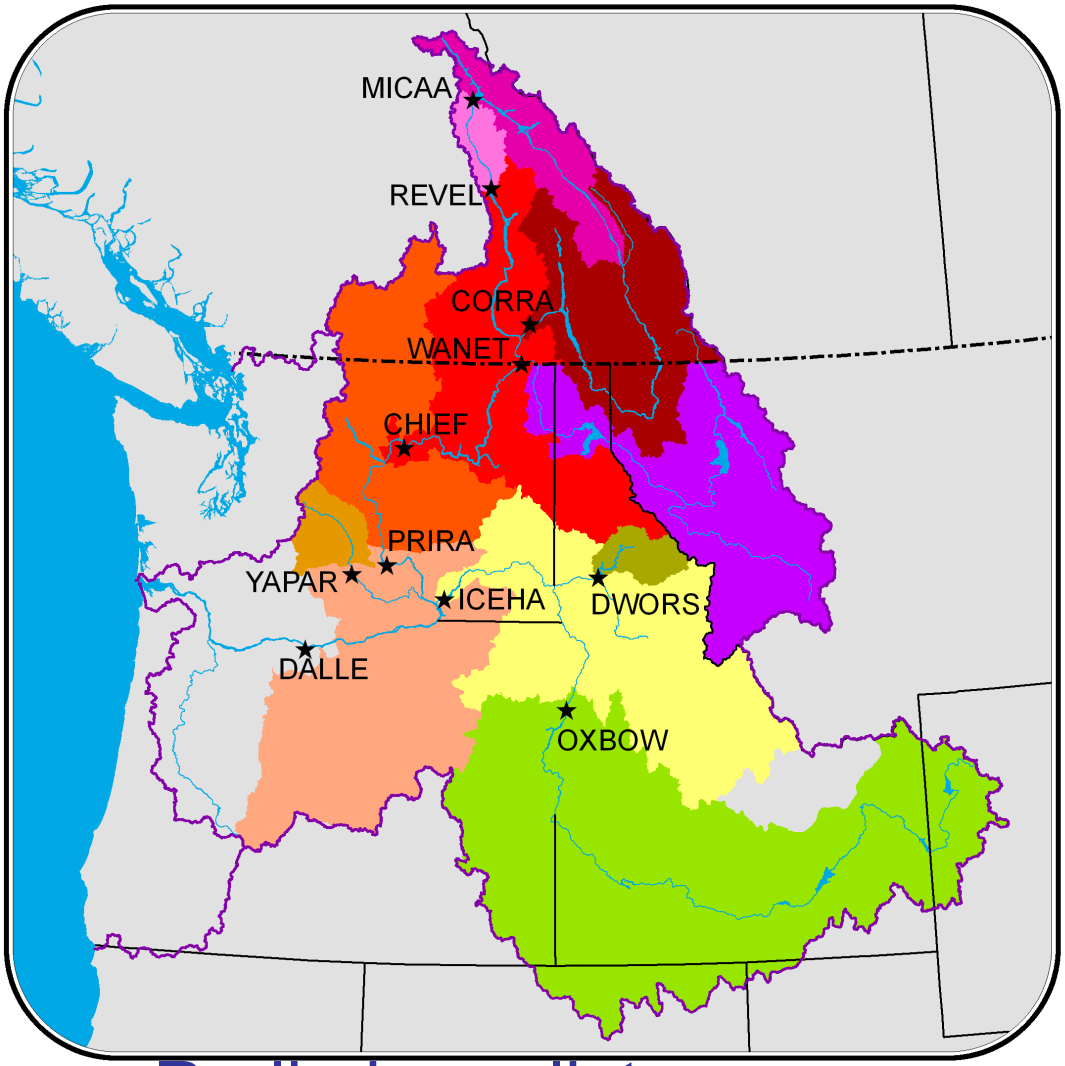
Status:

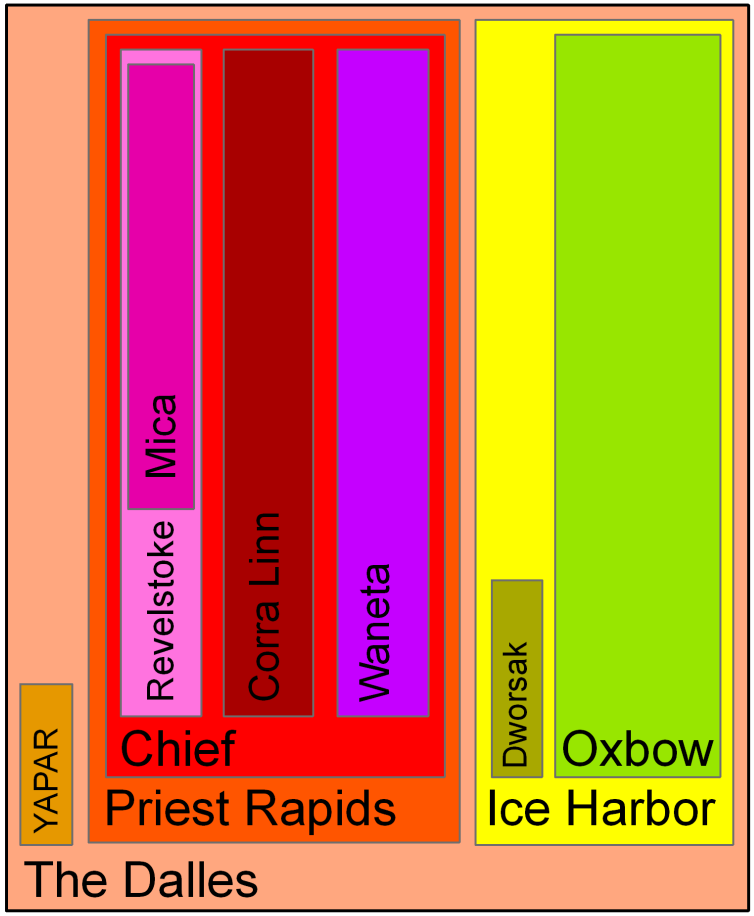
- Developed preliminary soil depth map based on DHSVM soil depth scheme (testing underway).
- Comparing VIC simulations of historical PET with observations and other known historical datasets
- Compare VIC simulations of historical VPD with computations using Kimball et al (1997) dewpoint algorithm

Task 2 - Calibrate VIC model and develop statistical bias correction procedures

- Calibration watersheds
- Calibration procedure

Calibration Watersheds





- Preliminary list
- Willamette will be added as calibration basin

VIC Model Calibration Procedure

- Calibrate model to simulated streamflow by changing soil parameters (uncertainty in subsurface processes)
- Compare simulated and historical streamflow using summary statistics
  - e.g. R^2, Nash-Sutcliffe Efficiency, annual volume error
- Use split sample calibration/validation approach
- Utilize auto-calibration tool developed by U. of AZ

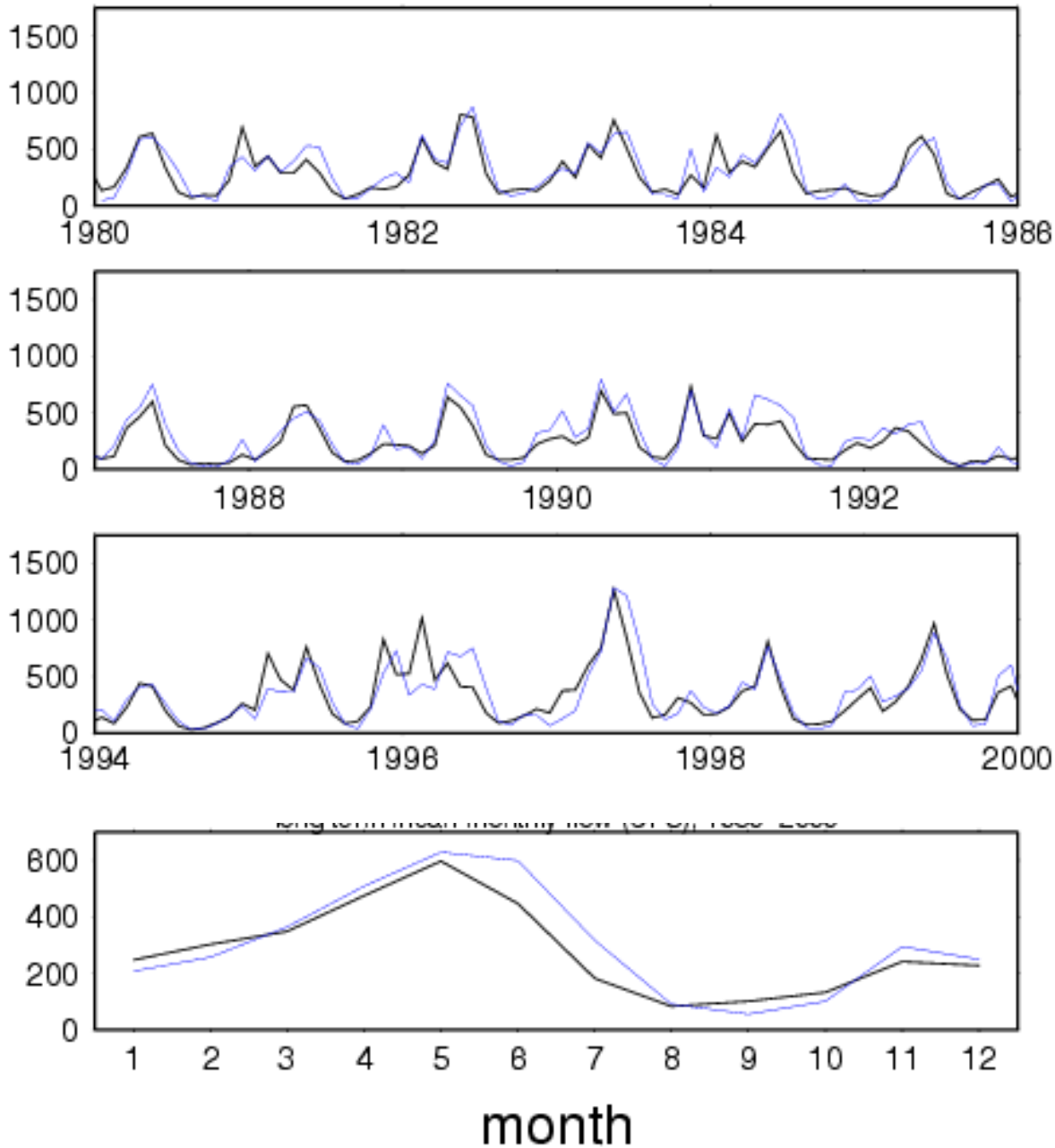
Status:

- Testing of auto-calibration routine is underway
- Model calibration for 10-15 Columbia River sub-watersheds will occur in March/April

Yakima River at Parker
Net Monthly Mean Flow (units of 1000AF)

Naturalized Flow

Simulated Flow



Summary Statistics

R^2: 0.88
N-S Efficiency: 0.71
Avg. Ann. Flow,
Sim/Nat: 1.08

Long-term Monthly Mean (1980-2000)

Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods & produce streamflow at ± 200 sites

- Model output variables
- Preliminary results: grid-based and site specific
  - Historic and projections

Downscaling Procedures

Global Climate Models

20 GCMs
2 SRES Scenarios – A1B (medium) & B1 (low)
---
39 Total CC Scenarios (Monthly Time Series)

↓

Regional Climate Change Scenarios

1. Delta Method Approach
   - Daily Time Series of Perturbed Historical Record (1915-2006)

2. Bias Correction & Statistical Downscaling (BCSD)
   - Daily Time Series of Future Record (2001-2099)

↓

Hydrologic Models

VIC (5km latitude x 6km longitude grid)
DHSVM (150m grid)

Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods

Delta Method

Advantages

- Address impacts of historical climate variability
- Realistic daily time series and spatial variability
- Many realizations of variability for each scenario

Challenges

- Do not incorporate future climate variability introduced by GCMs

BCSD

Advantages

- Incorporate future climate variability projected by GCMs
- Facilitates trend analysis

Challenges

- Current method may introduce unrealistic daily climate
- Inherits weaknesses of specific GCMs

Status:

- Delta method simulations complete for composite A1B and B1 scenarios for the 2020s, 2040s, 2080s as well as all ensembles for the 2020s for the Yakima River basin.
- Statistical downscaling technique is currently under development

VIC Model Output Variables

- Daily time step
- Spatial maps of data anomalies/patterns of mean changes
- Excel or ASCII (text) data format

Data Variable
276 Sites
Naturalized streamflow
Regulated streamflow
Changes is flood frequency (100 yr flood)
Changes in low flow (7Q10)
Drought frequency, severity, duration analysis
Analysis of streamflow timing shifts
Gridded Data (1/16th degree)
Min/Max temperature
Precipitation
Soil Moisture
Potential evapotranspiration
Snowpack (SWE, depth)
Date of peak SWE
Date of 90% SWE melt
Fraction of precipitation as rain

VIC Model Preprocessor Outputs

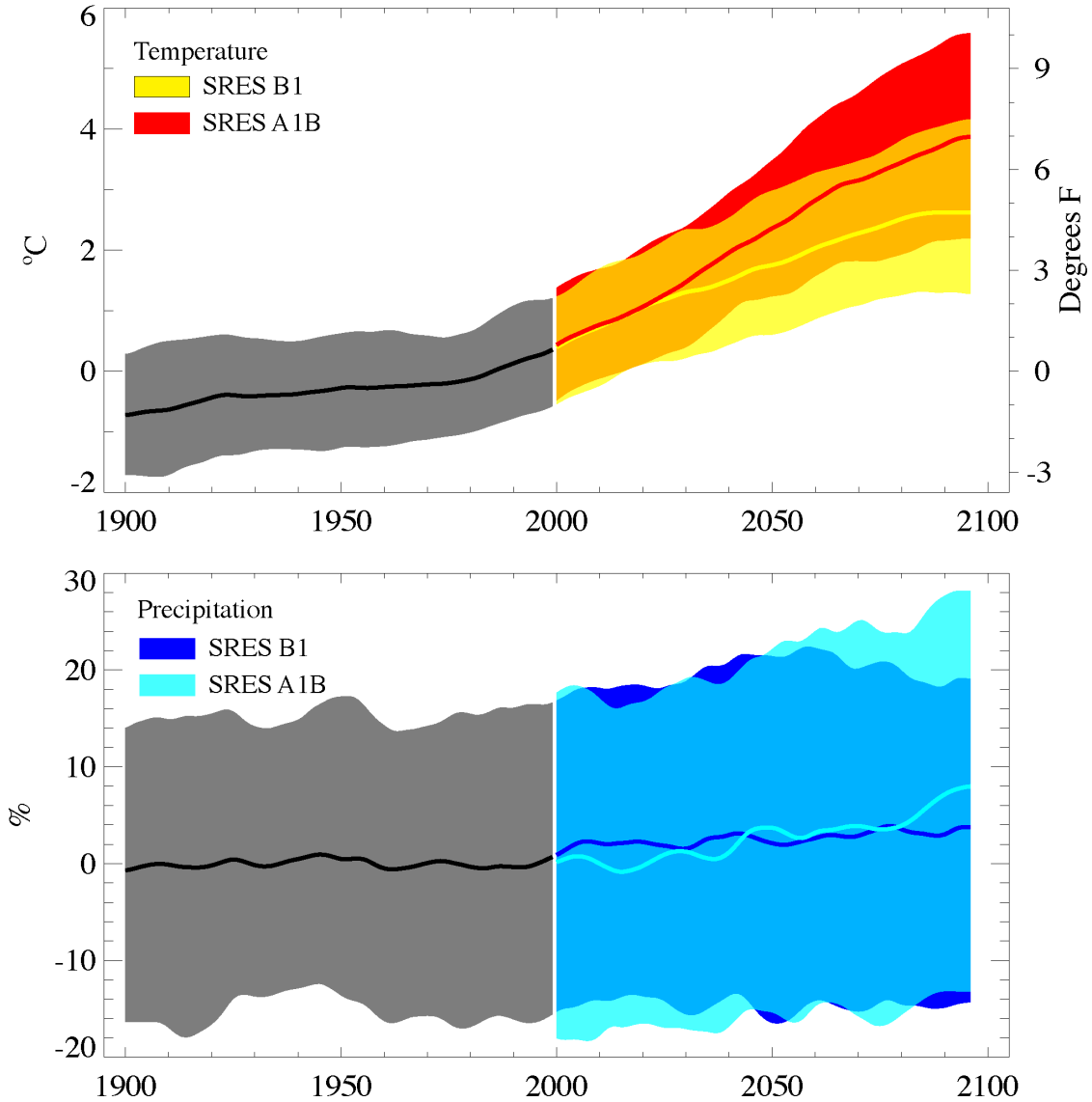
- Air Temperature
- Incoming Shortwave Radiation
- Incoming Longwave Radiation
- Atmospheric Density
- Atmospheric Pressure
- Vapor Pressure
- Vapor Pressure Deficit

Benefit:

- Many unmeasured values with complete spatial coverage
- These variables may be used as inputs to other hydrology models (e.g. DHSVM)

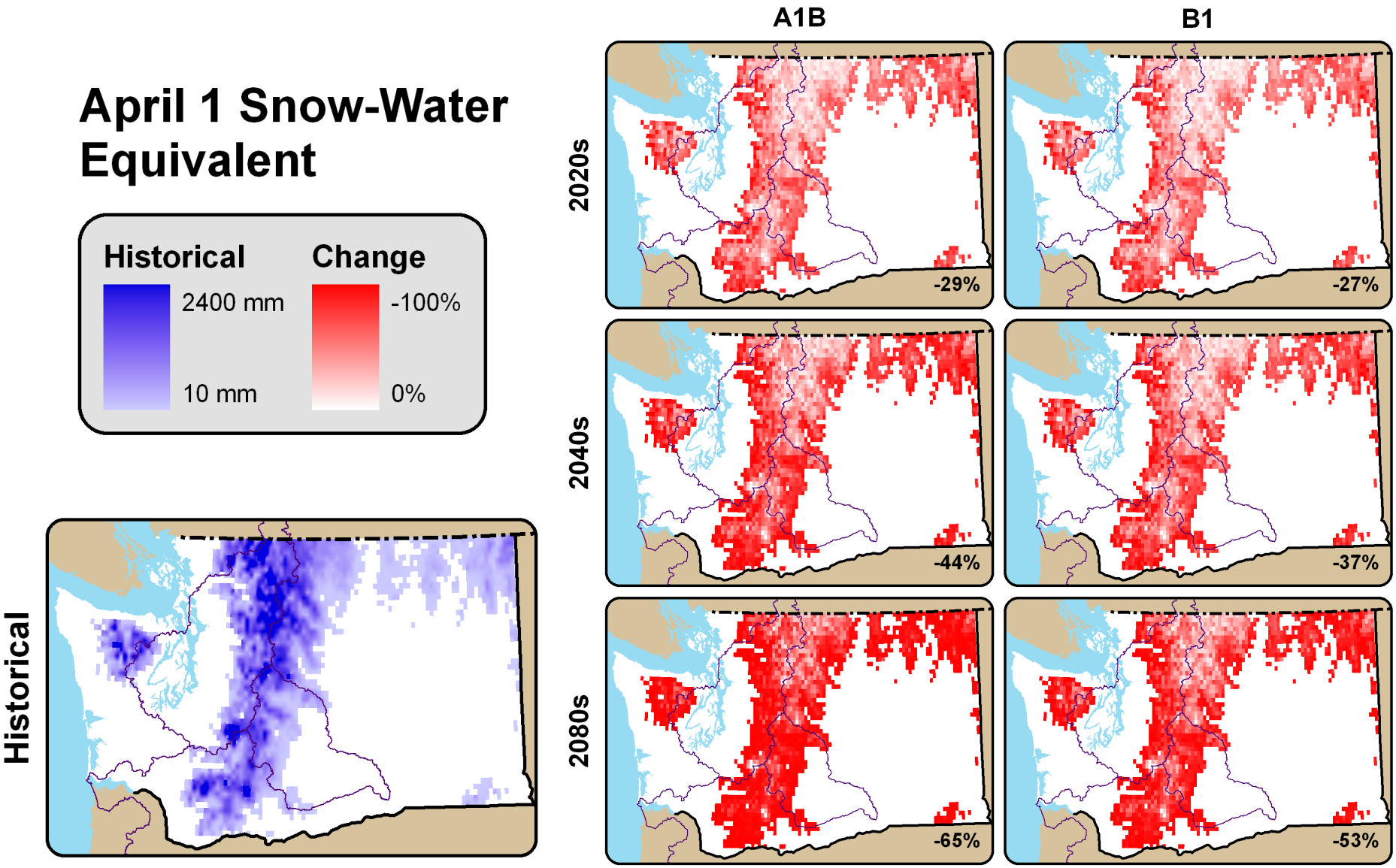
Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods

21st Century Climate Impacts for the Pacific Northwest Region



Mote, P.W. and E. P. Salathe Jr., 2009: Future climate in the Pacific Northwest (in review)

Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods

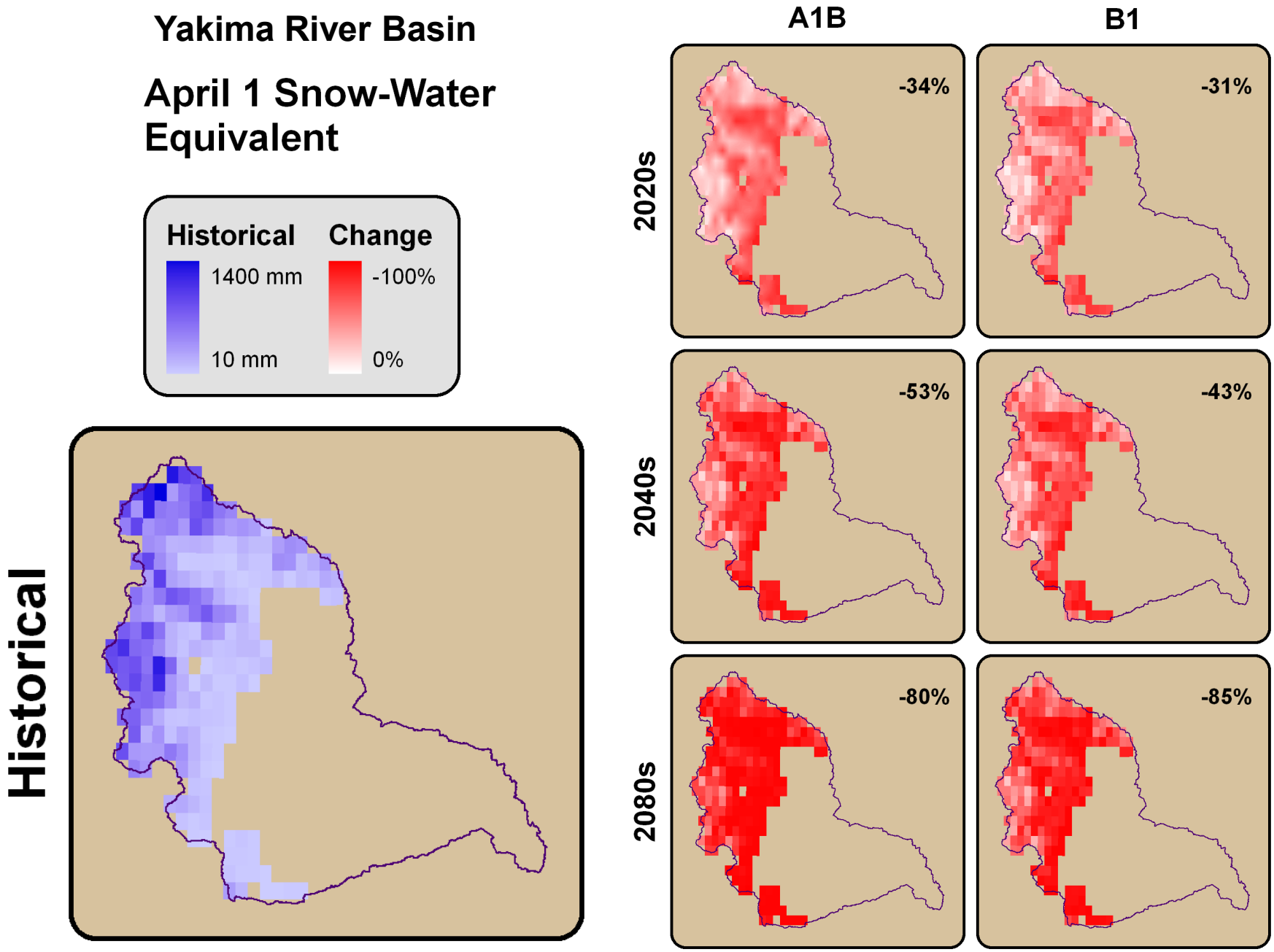


Elsner, M.M. et al. 2009: Implications of 21st Century climate change for the hydrology of Washington State (in review)

Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods

Yakima River Basin

April 1 Snow-Water Equivalent



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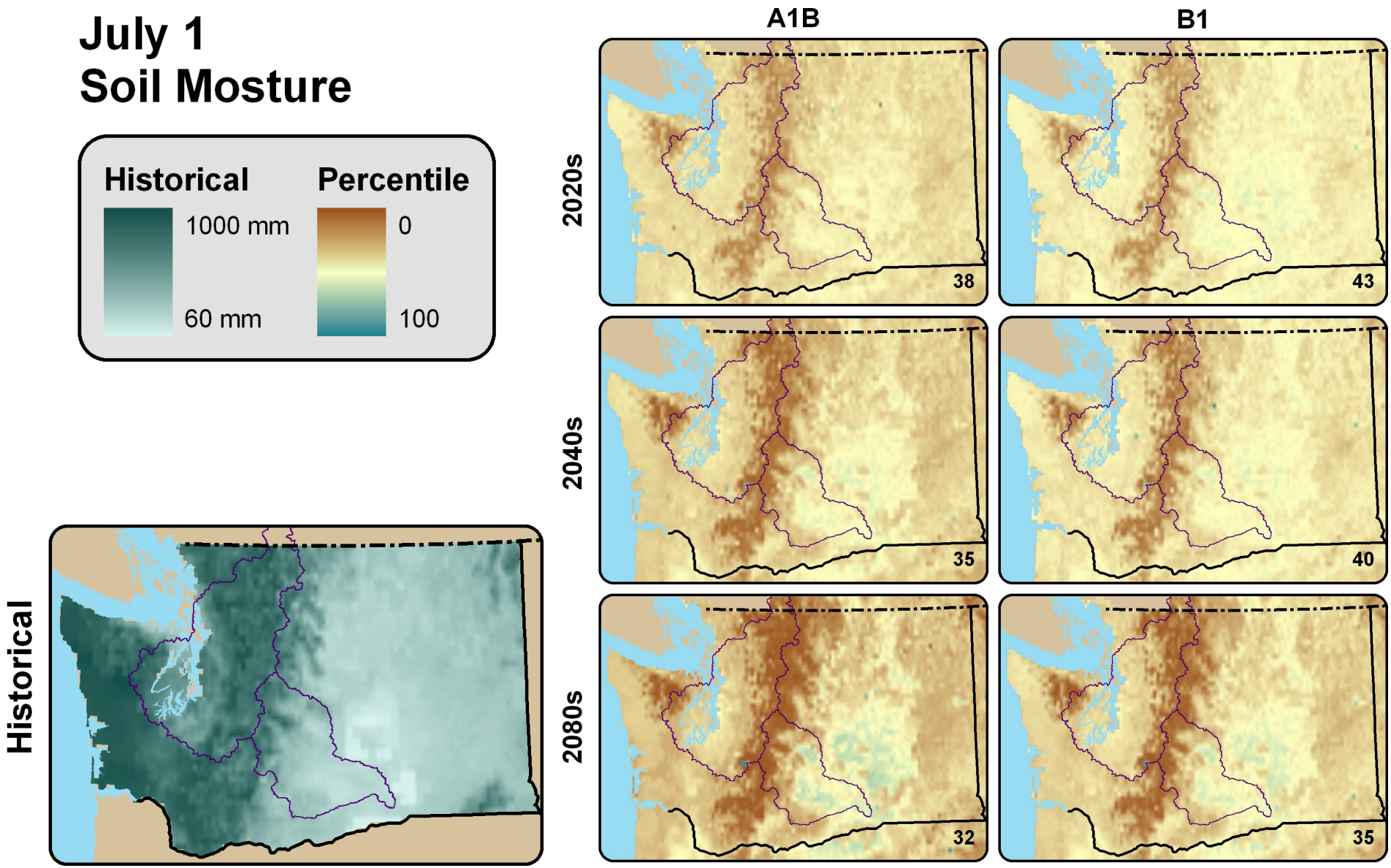

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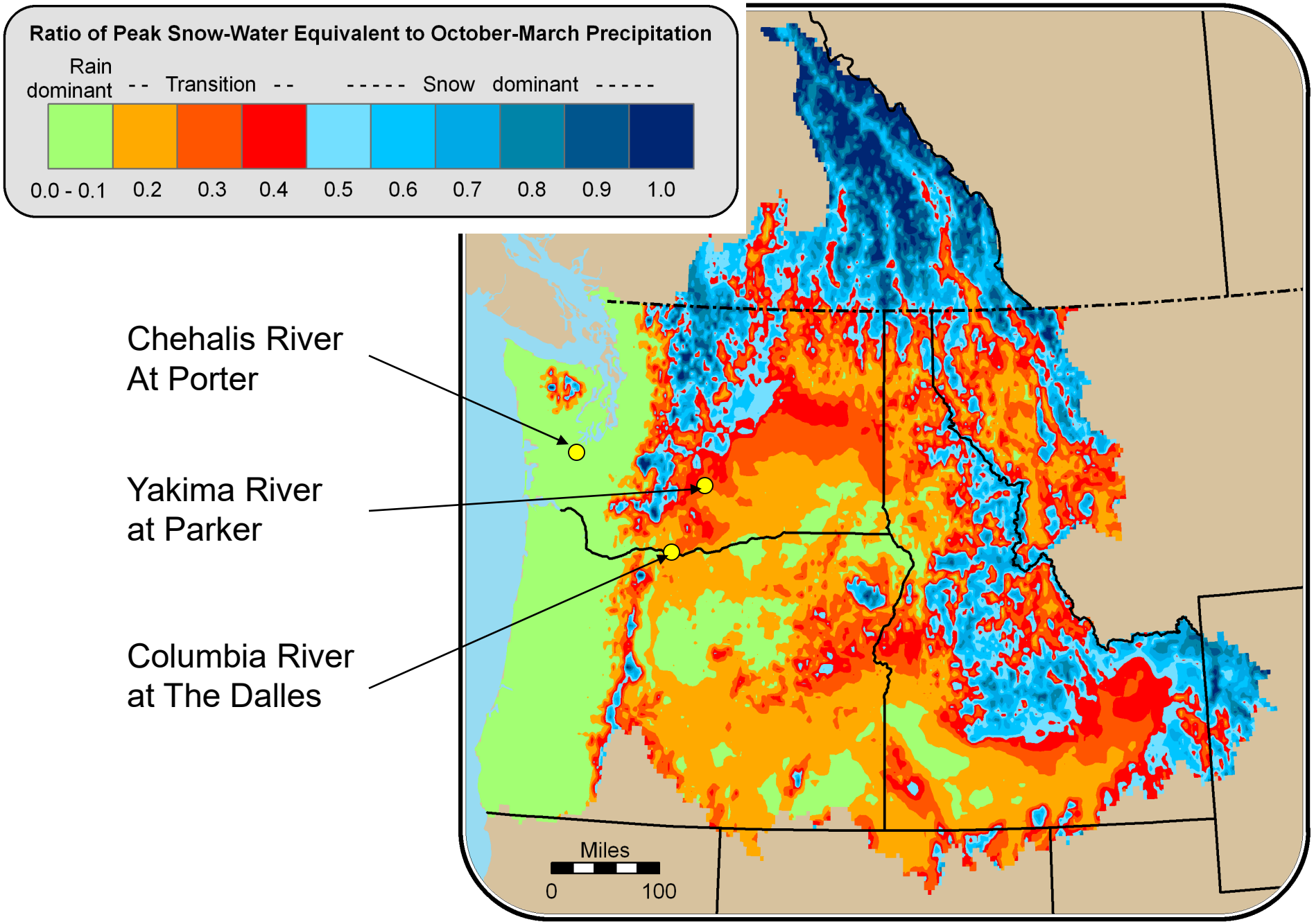
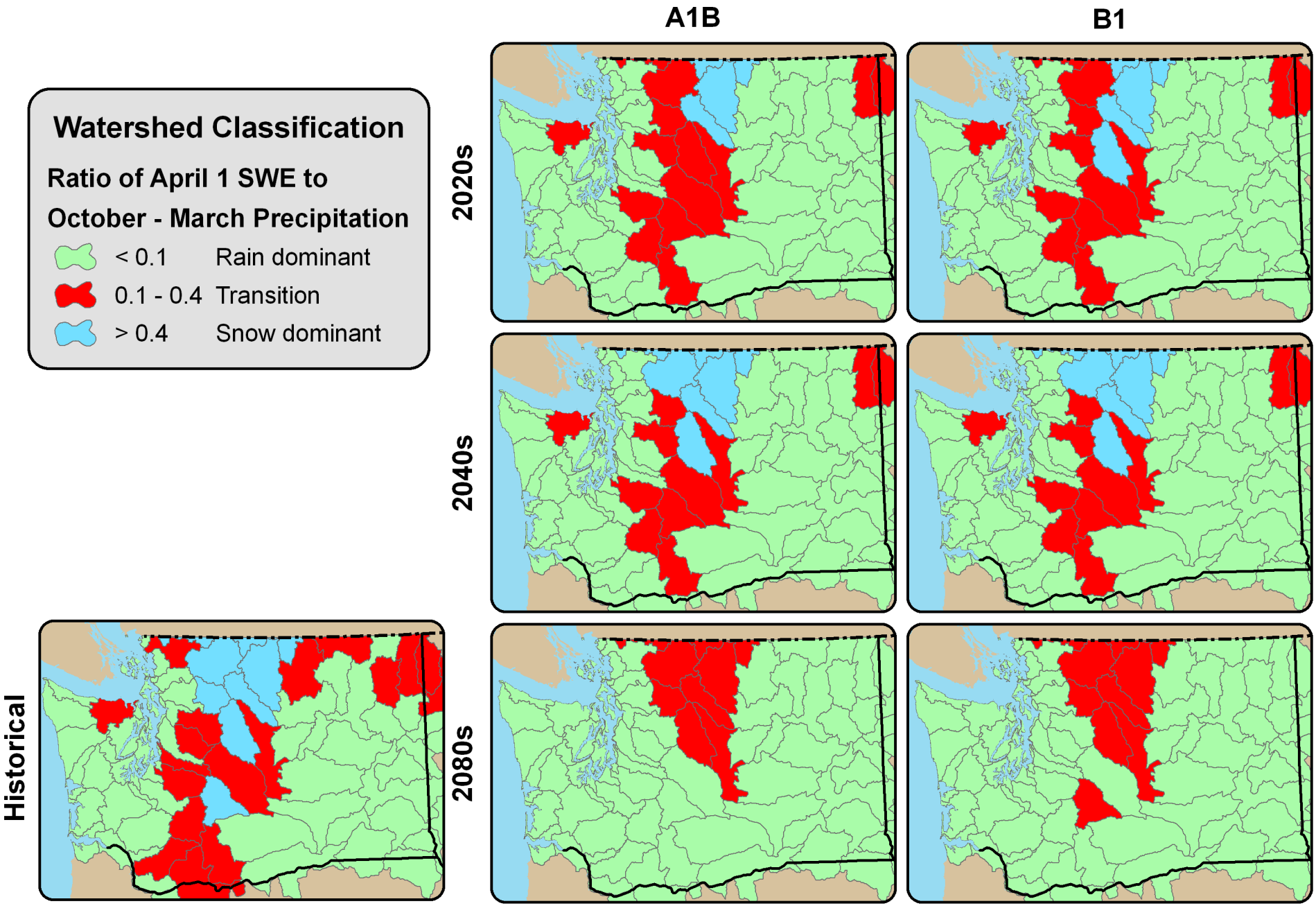
Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods

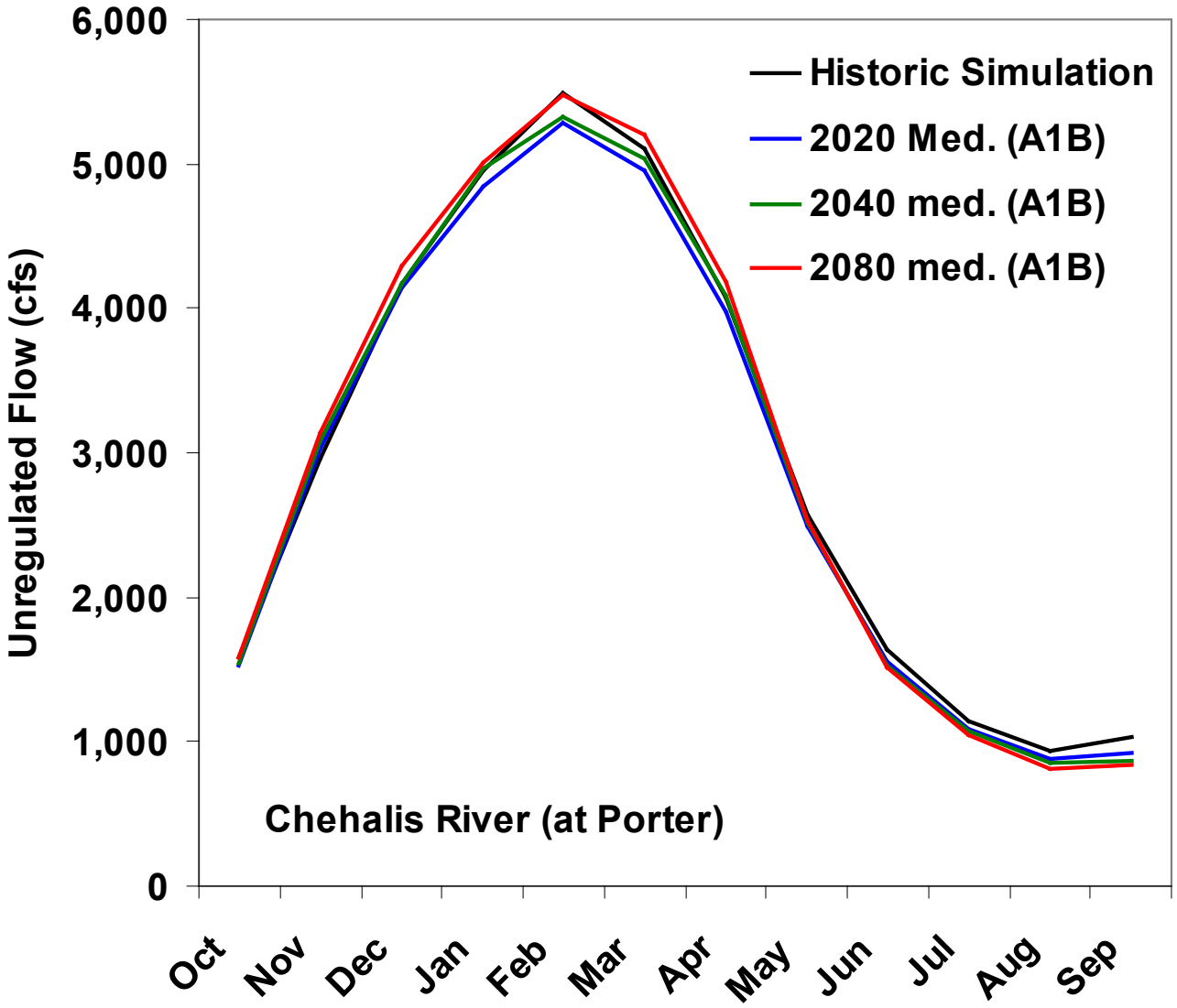


Task 3 - VIC model runs at 1/16th degree for GCM scenarios for 3 time periods



West Side of the Cascades

Historical and Projected 21st Century Flows for the A1b Scenario



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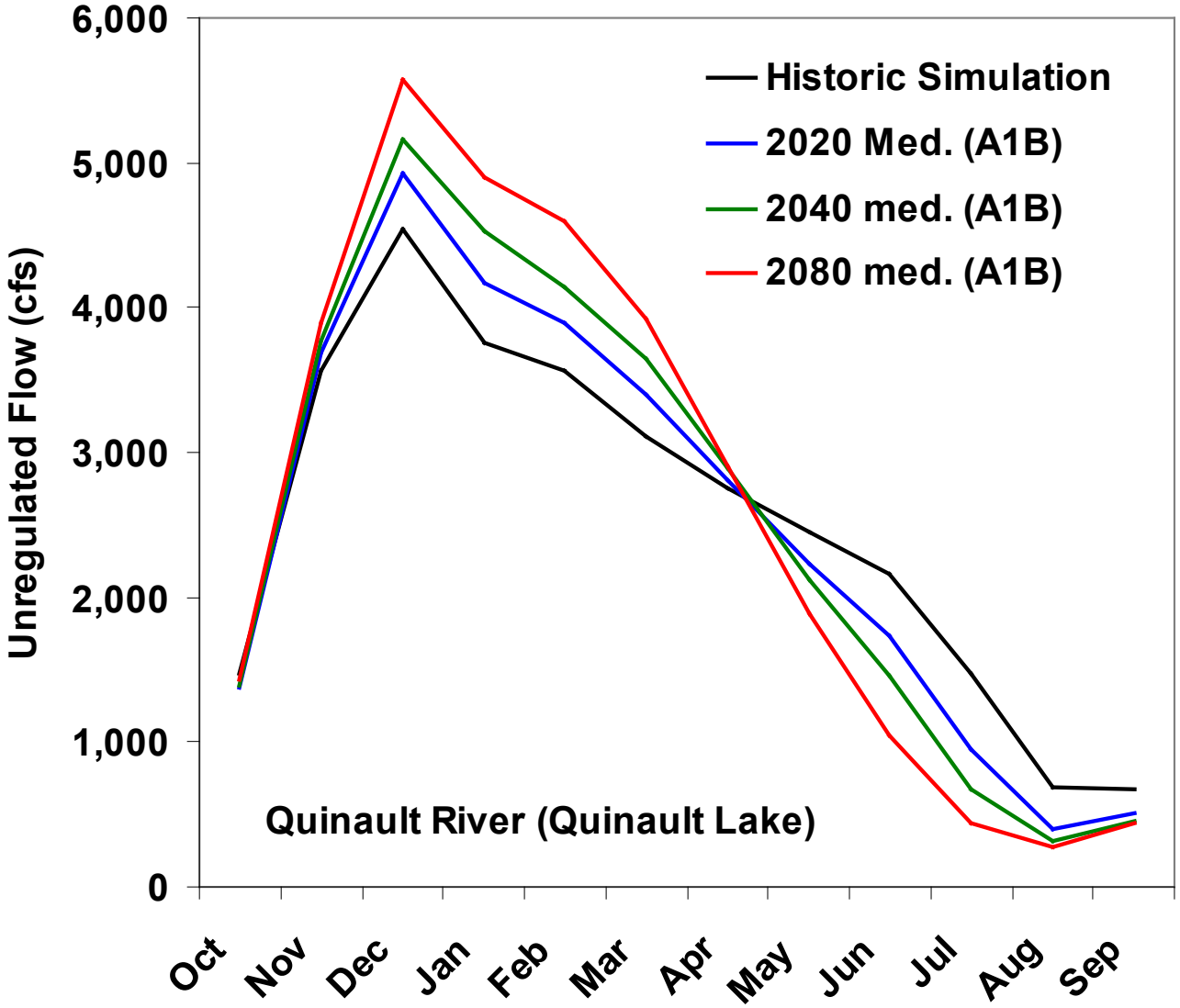
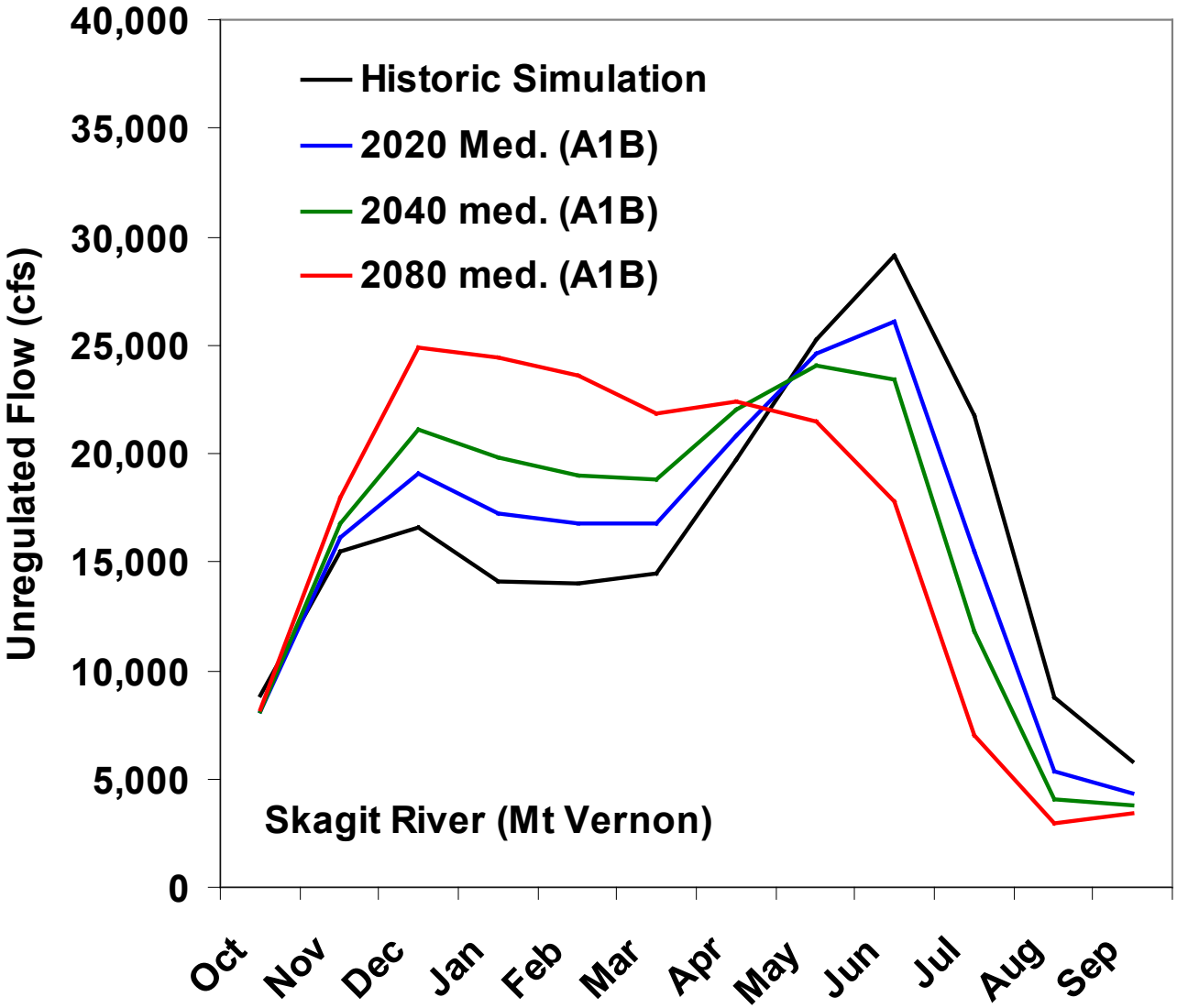


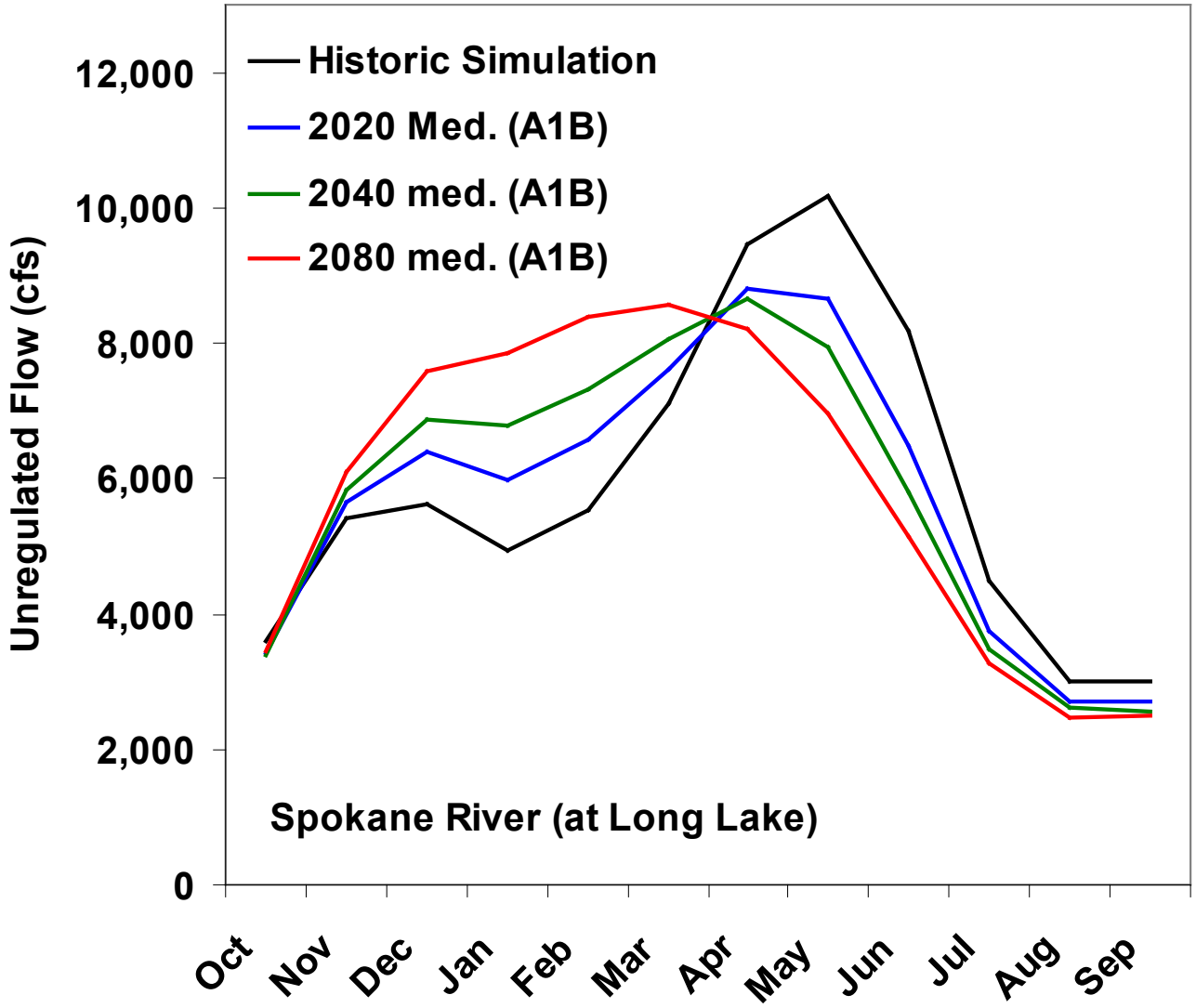
West Side of the Cascades

Historical and Projected 21st Century Flows for the A1b Scenario



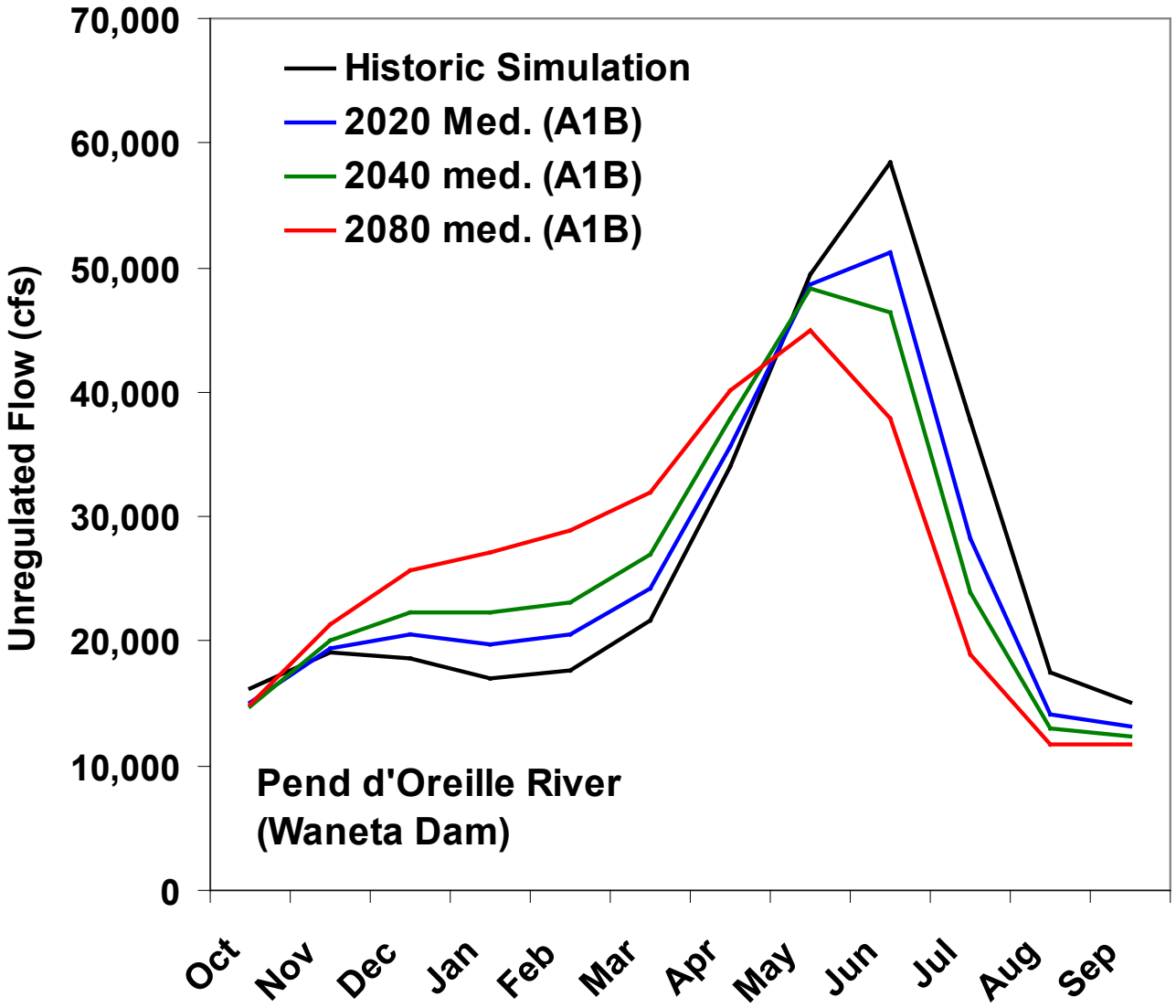
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



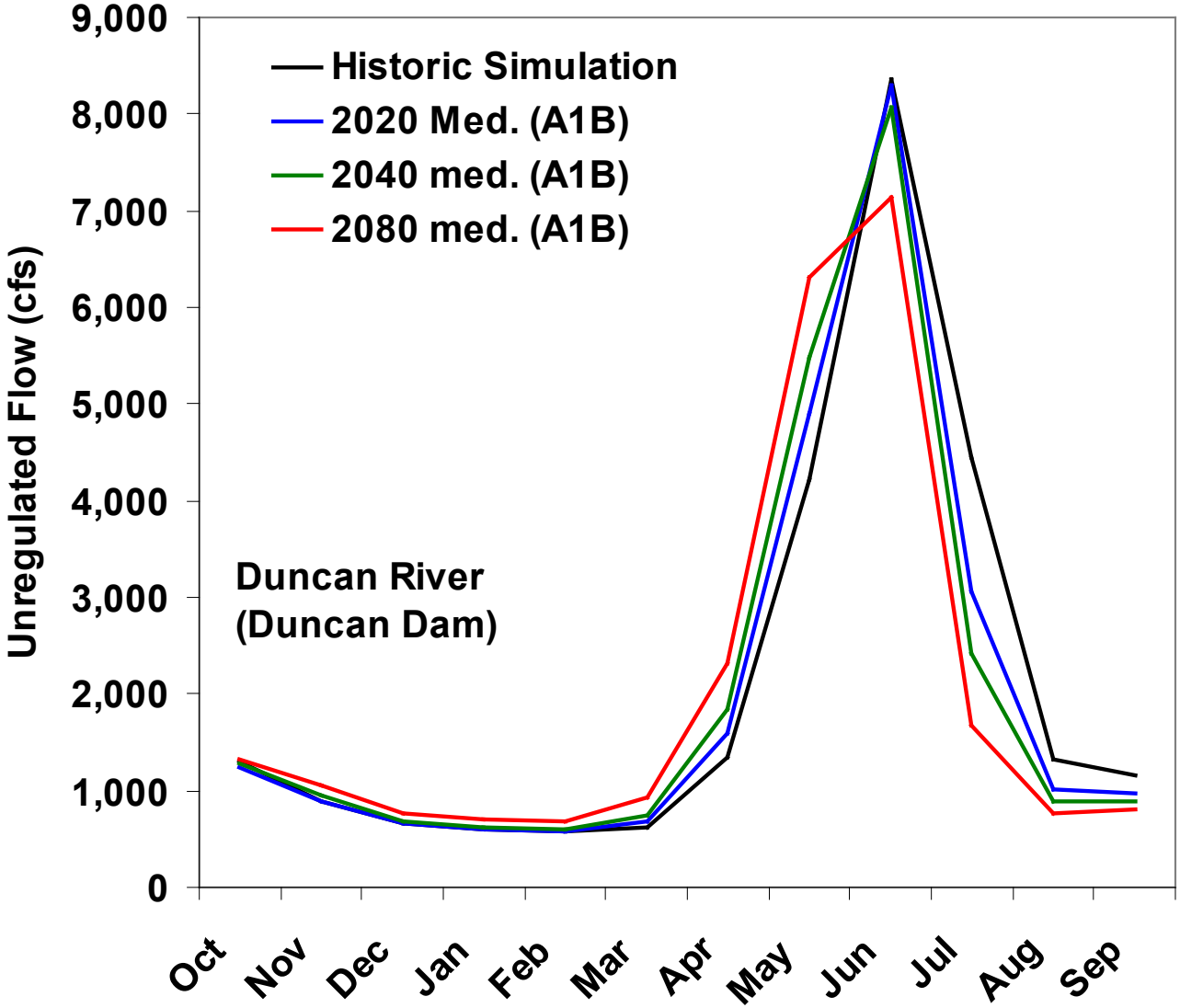
East Side of the Cascades (Canada)

Historical and Projected 21st Century Flows for the A1b Scenario



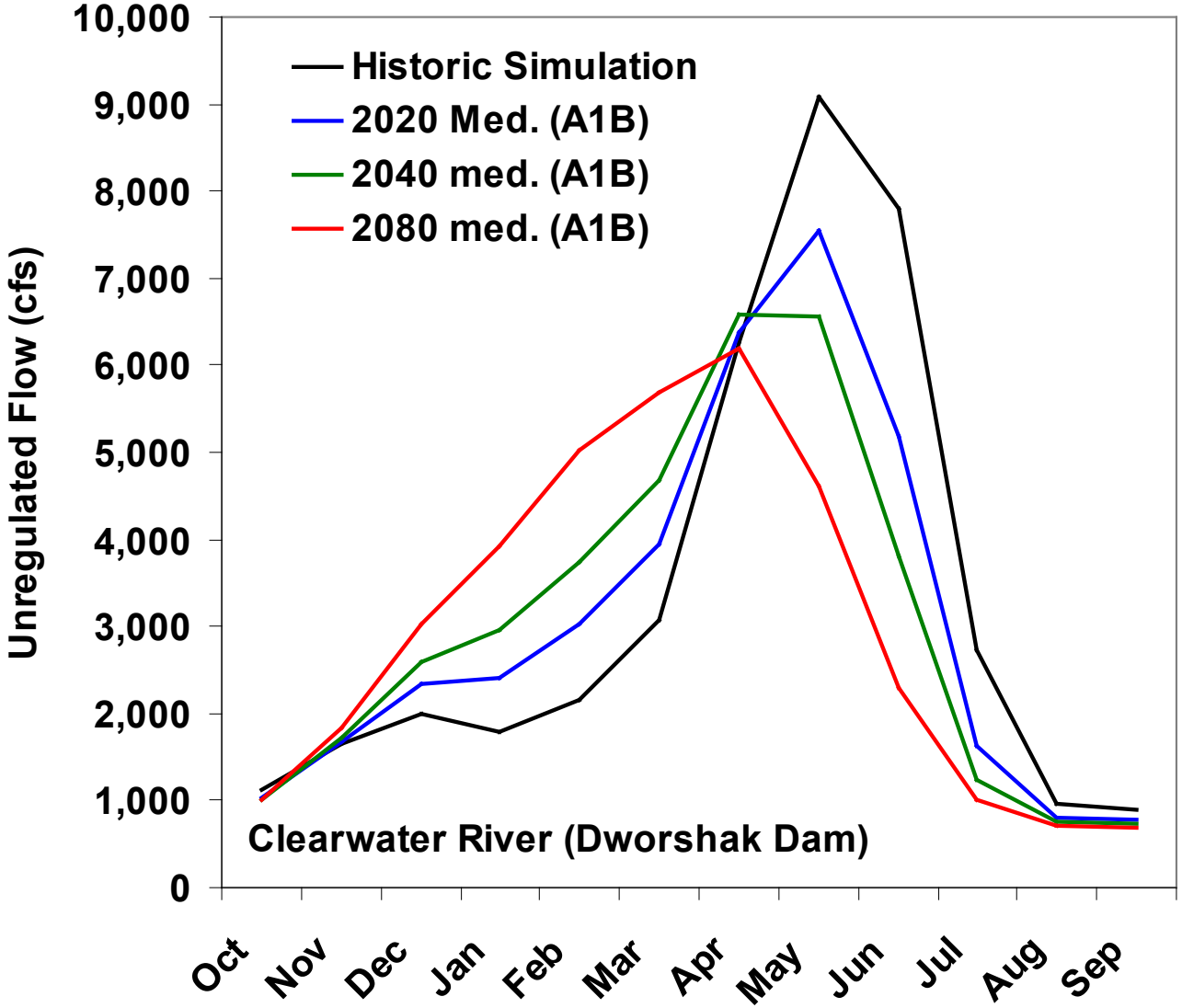
East Side of the Cascades (Canada)

Historical and Projected 21st Century Flows for the A1b Scenario



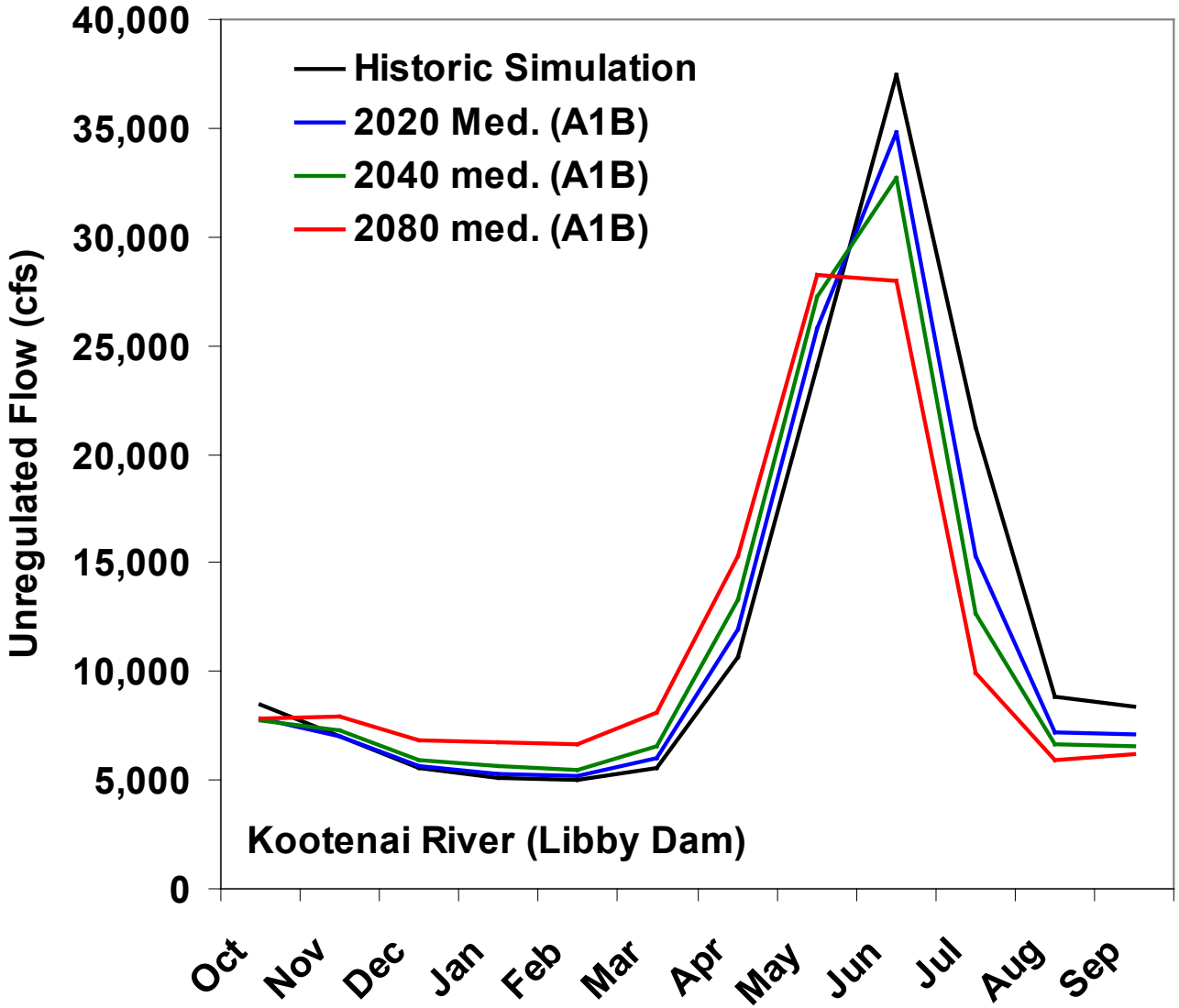
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



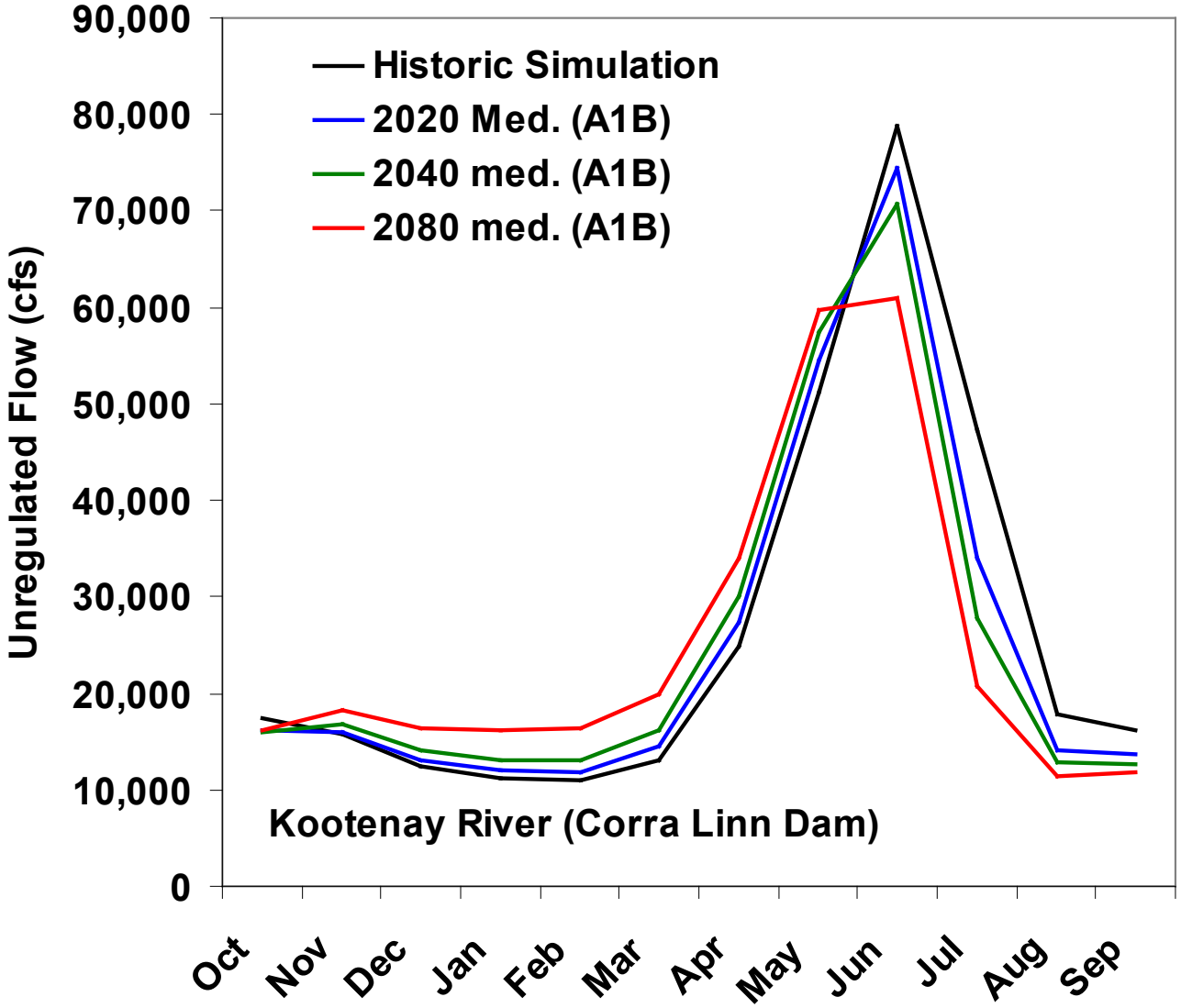
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



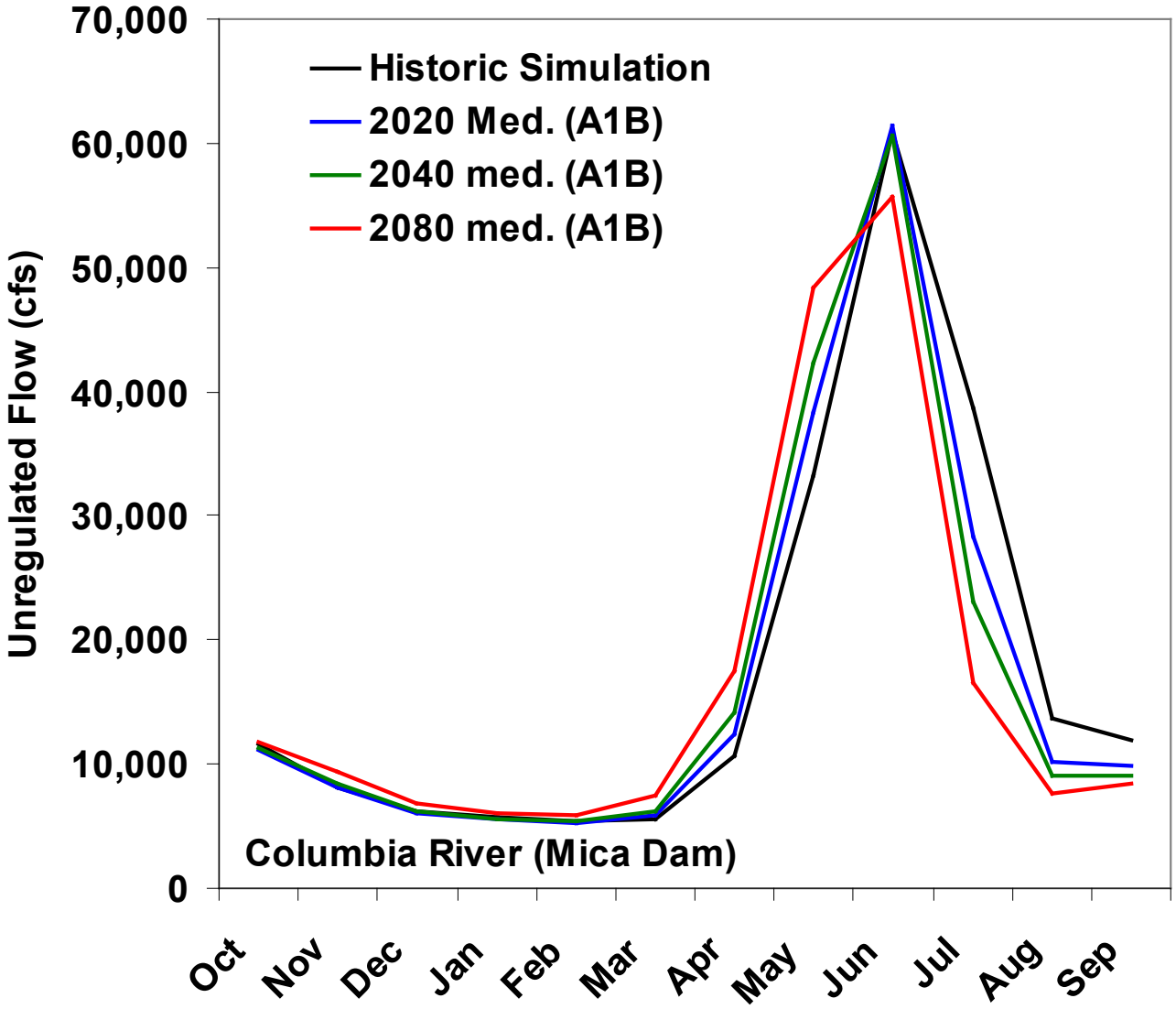
East Side of the Cascades (Canada)

Historical and Projected 21st Century Flows for the A1b Scenario



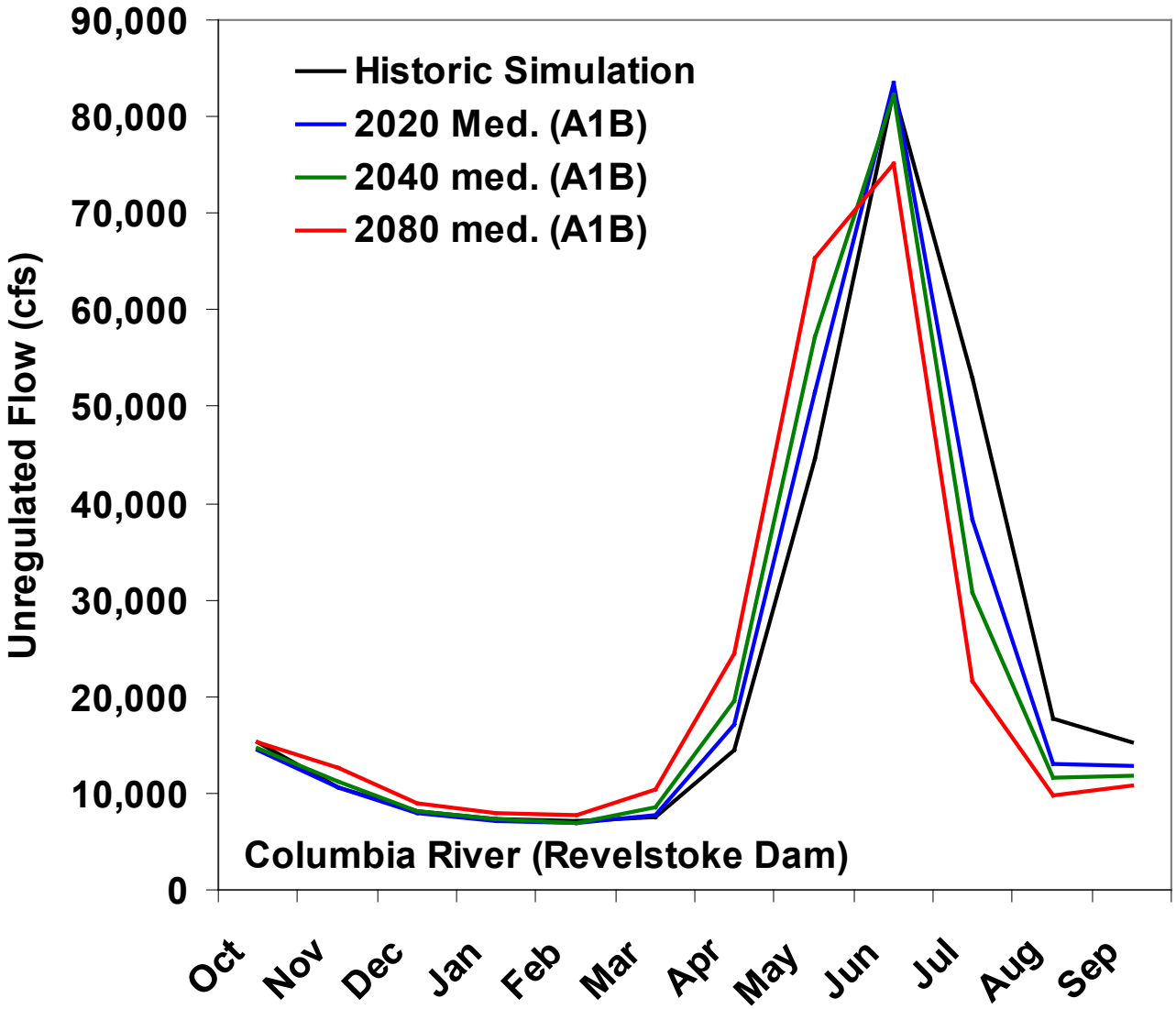
East Side of the Cascades (Canada)

Historical and Projected 21st Century Flows for the A1b Scenario



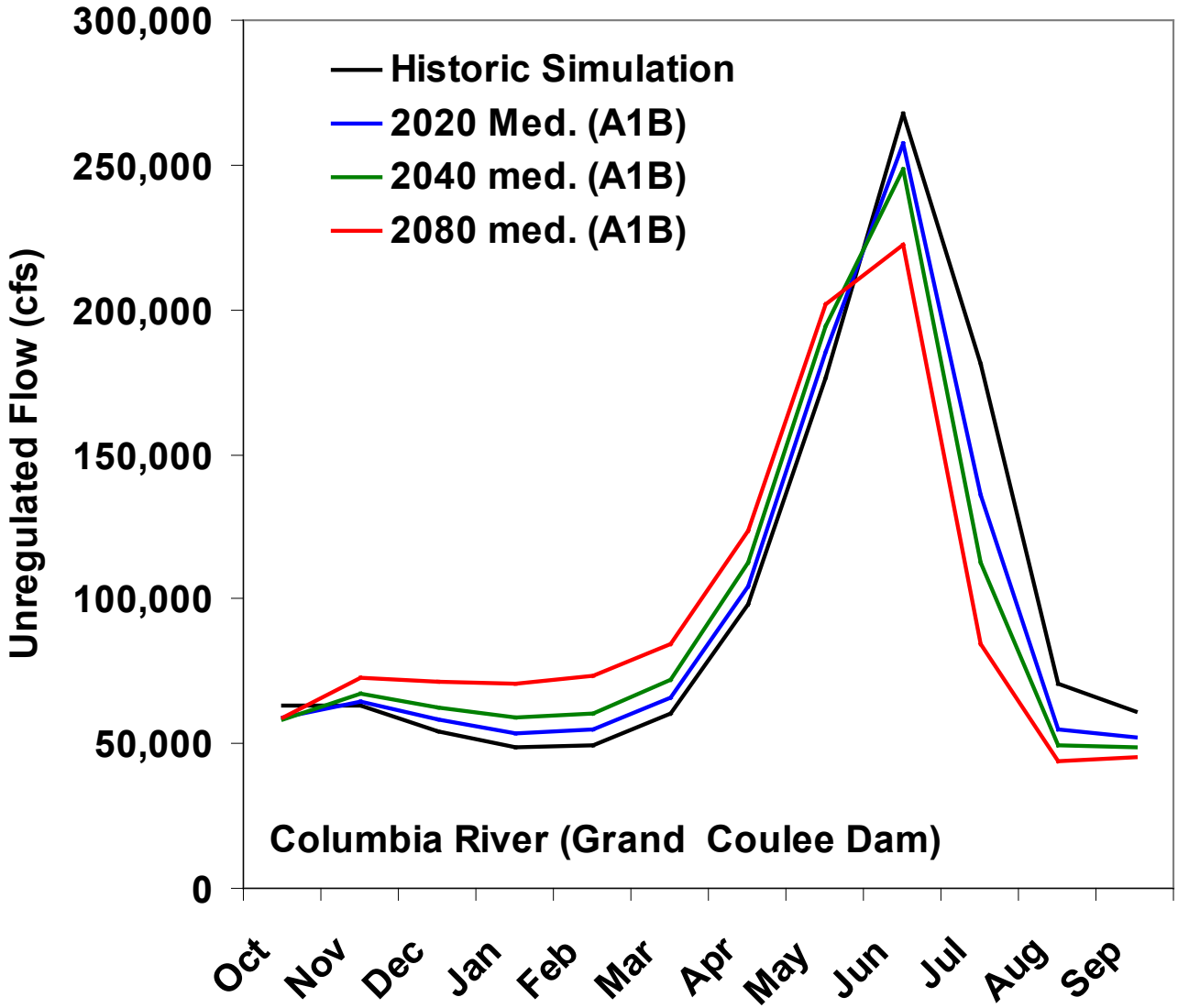
East Side of the Cascades (Canada)

Historical and Projected 21st Century Flows for the A1b Scenario



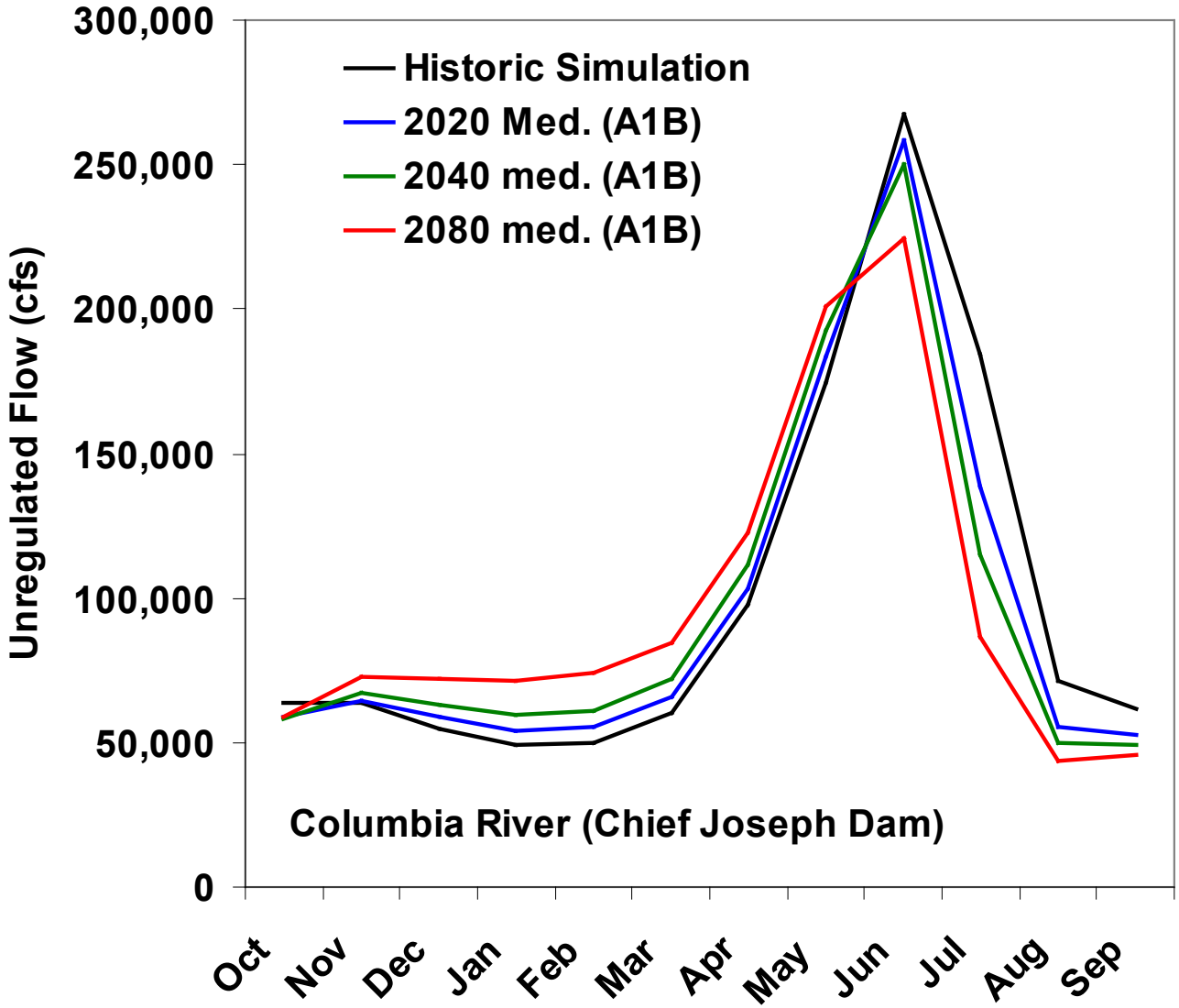
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



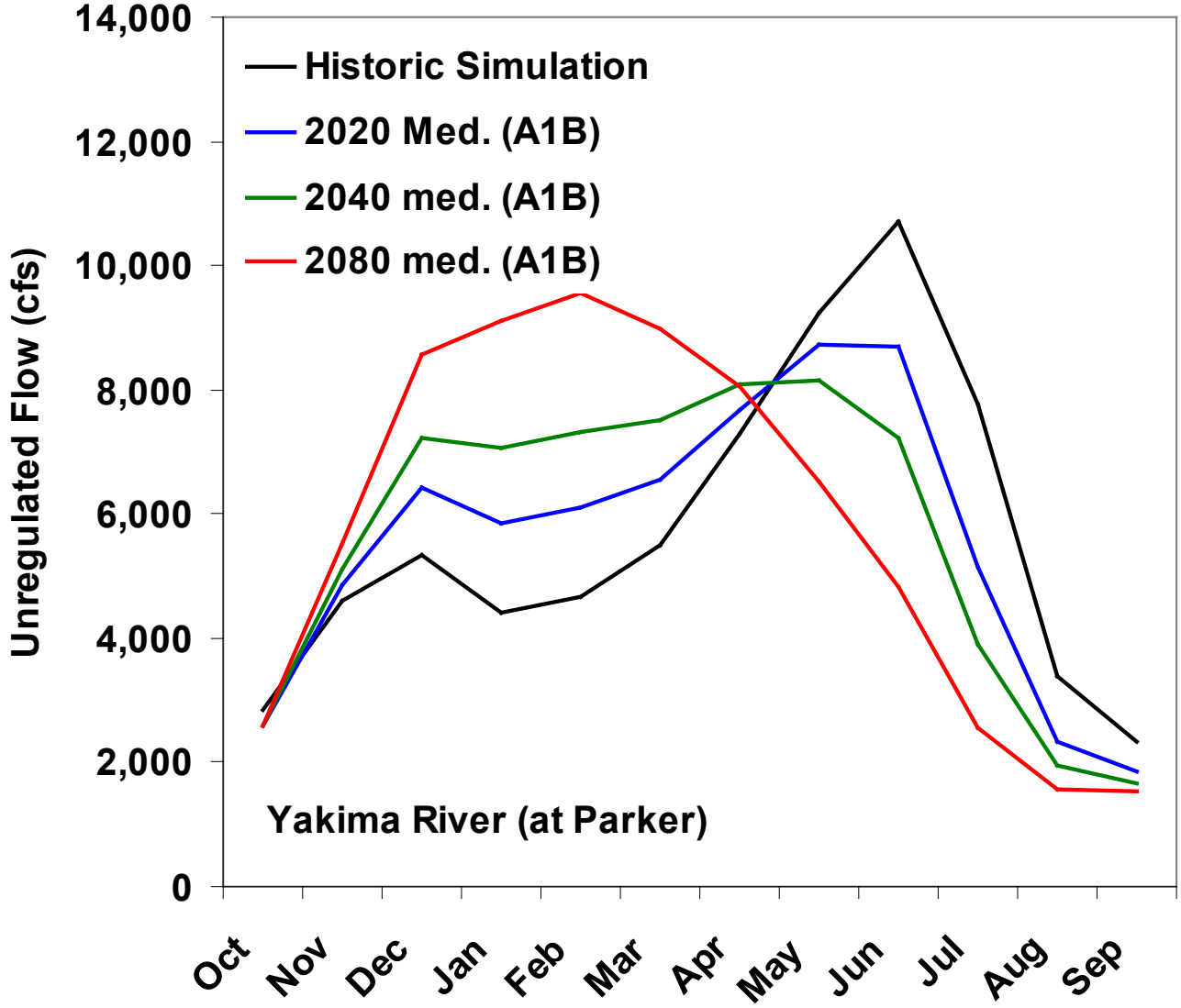
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



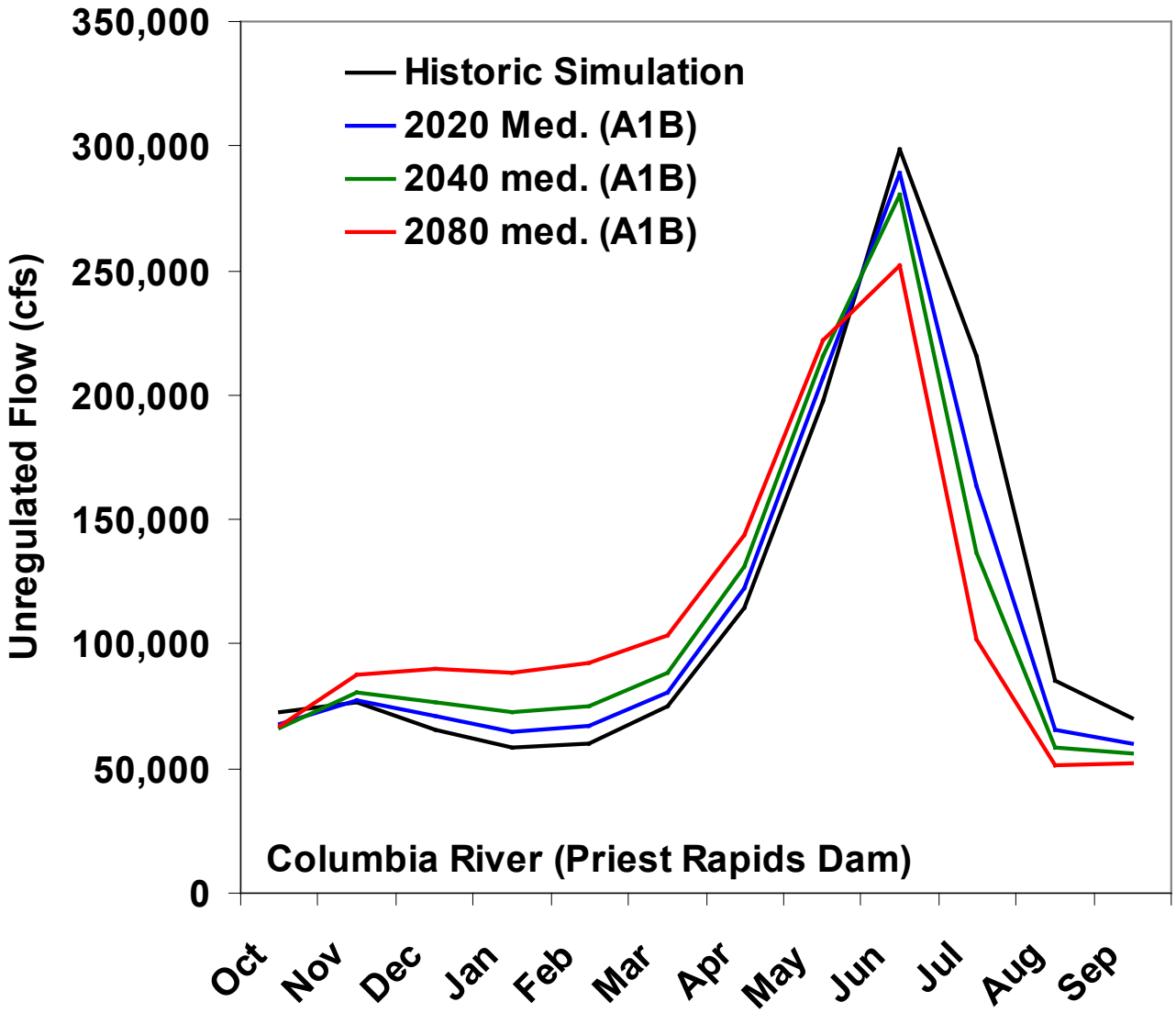
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



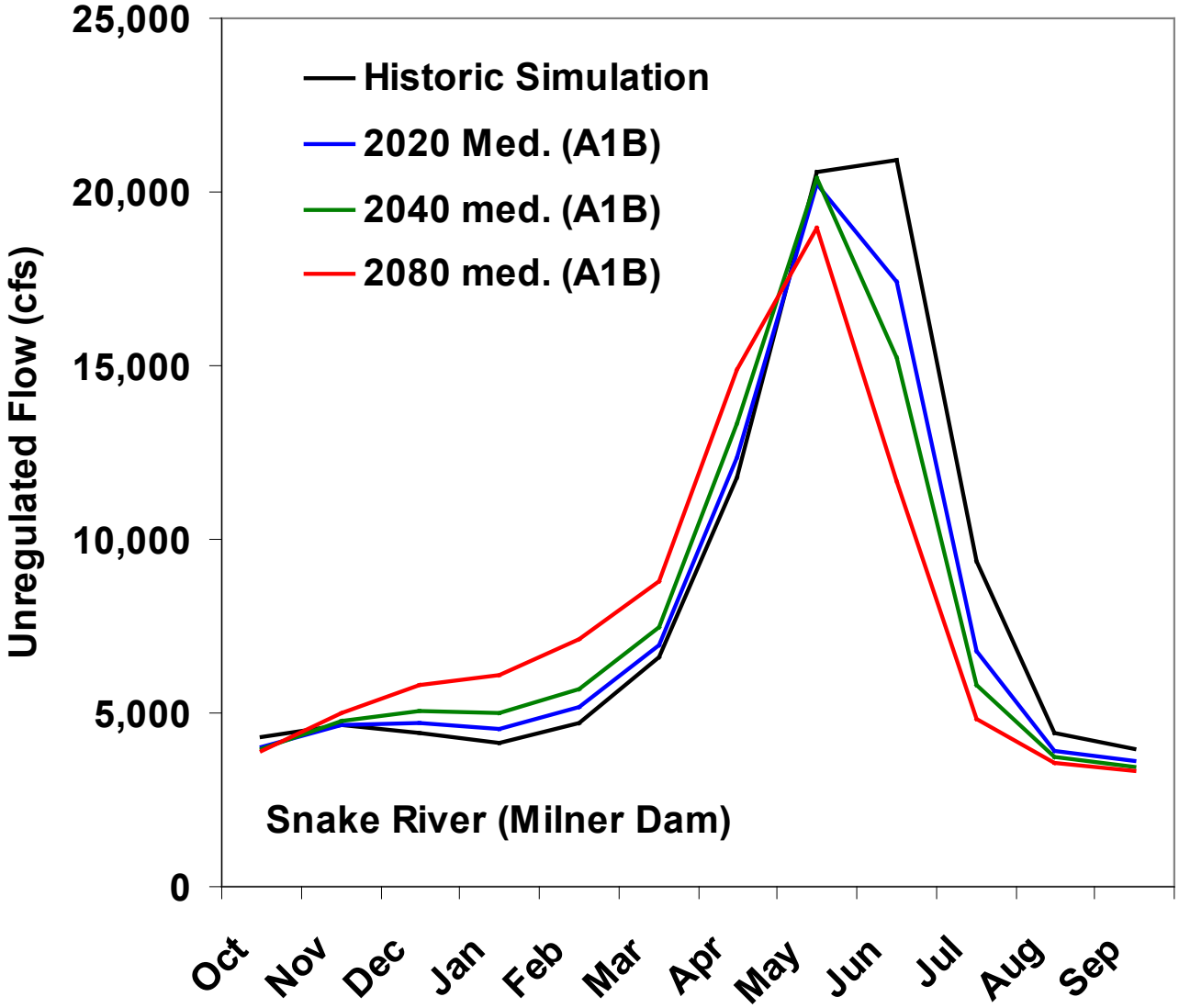
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



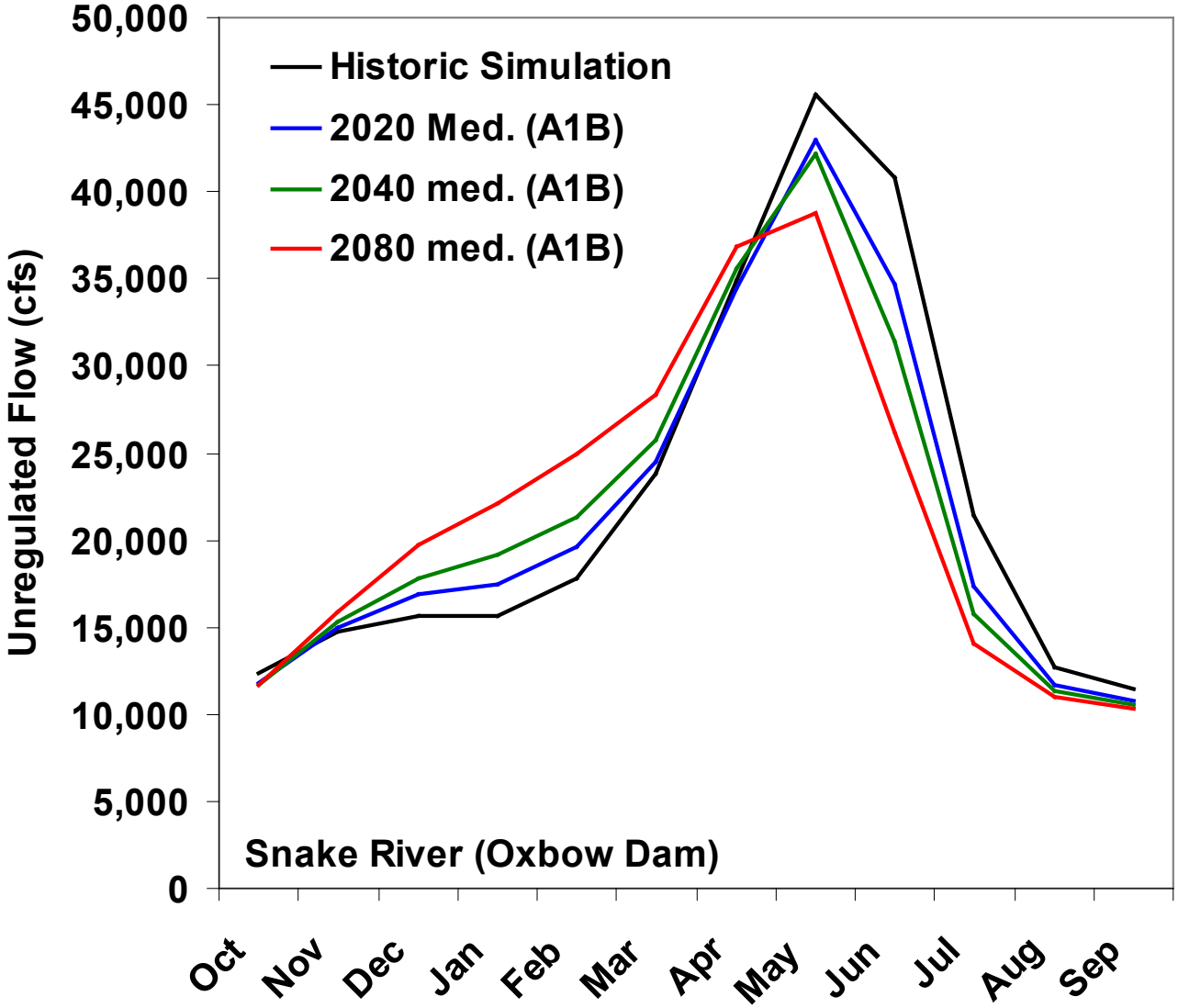
East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



East Side of the Cascades (US)

Historical and Projected 21st Century Flows for the A1b Scenario



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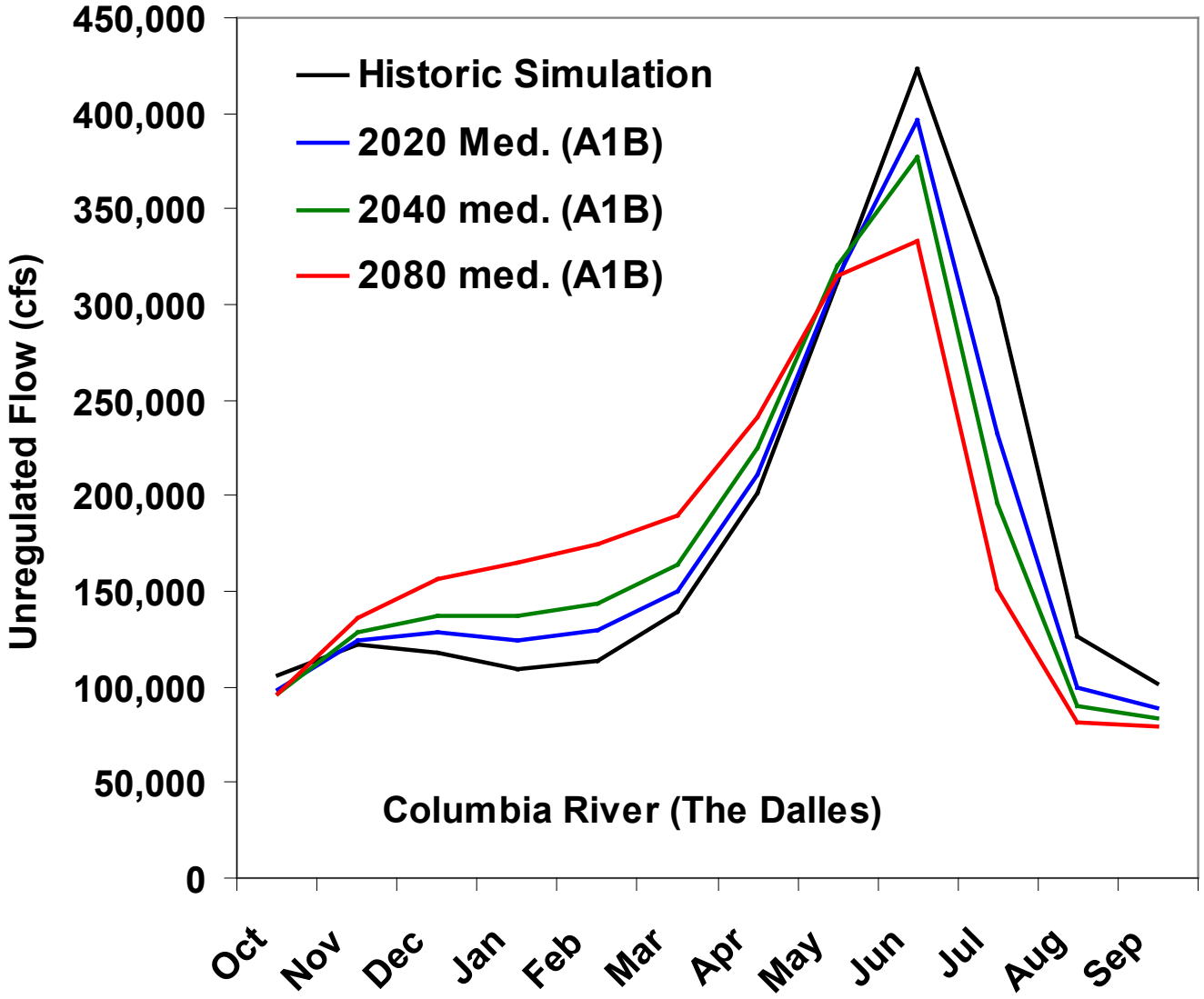
Historical and Projected 21st Century Flows for the A1b Scenario



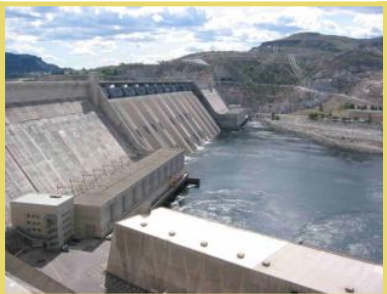
For more information:

The Climate Impacts Group

www.cses.washington.ed/cig

Marketa McGuire Elsner

mmcguire@u.washington.edu

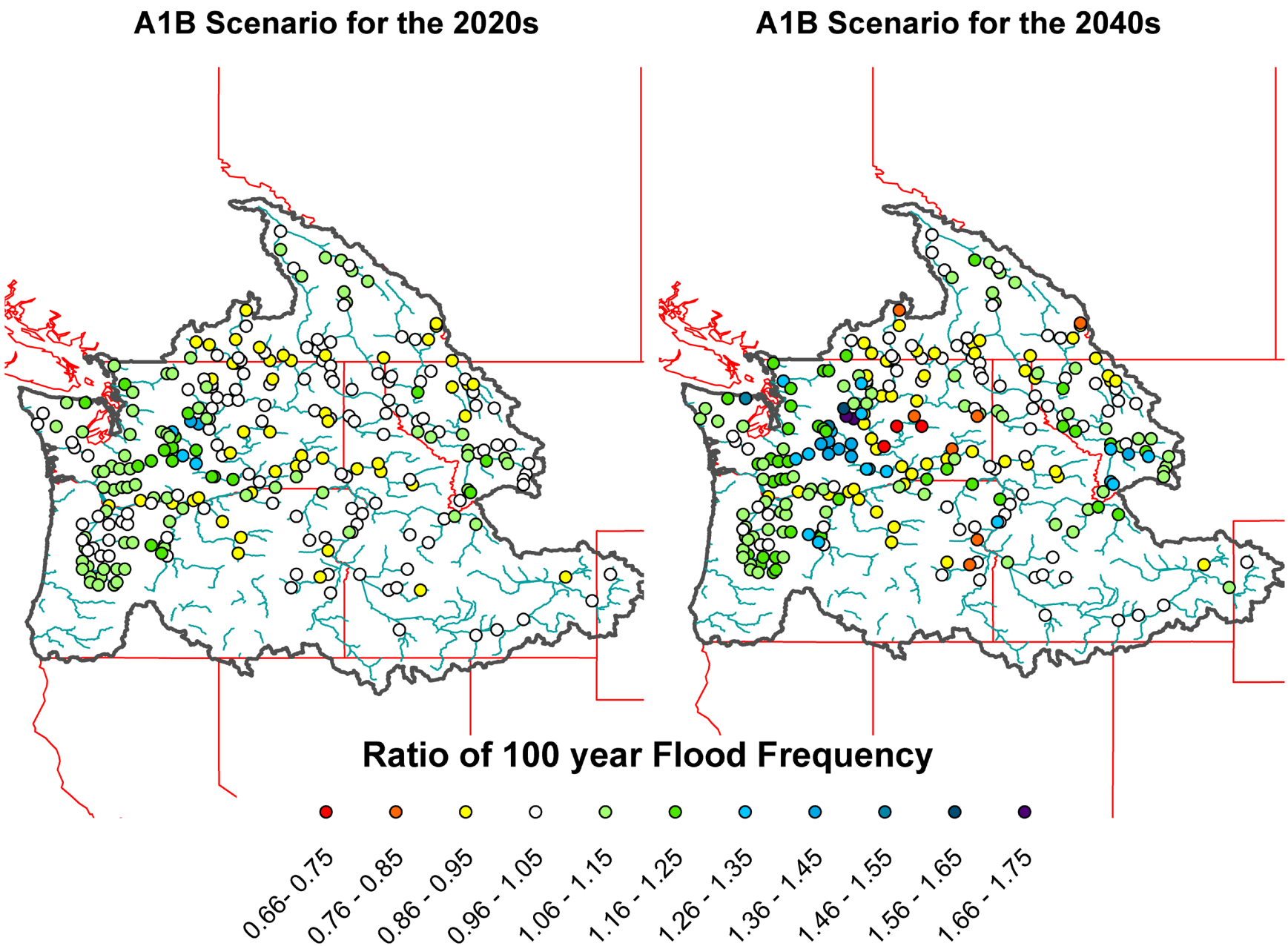


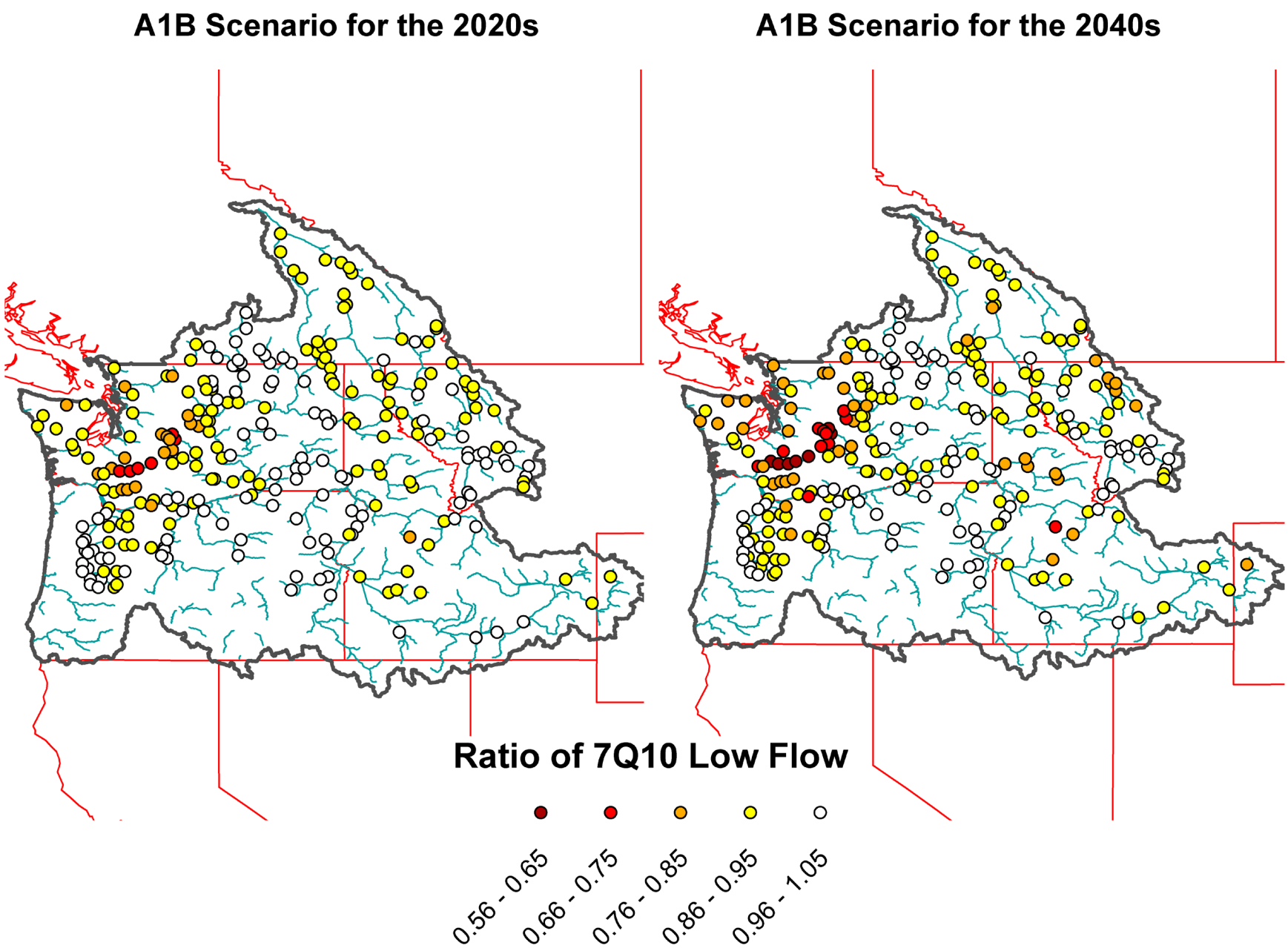
Department of Civil and Environmental Engineering

UNIVERSITY OF WASHINGTON

VIC Model Calibration Parameters

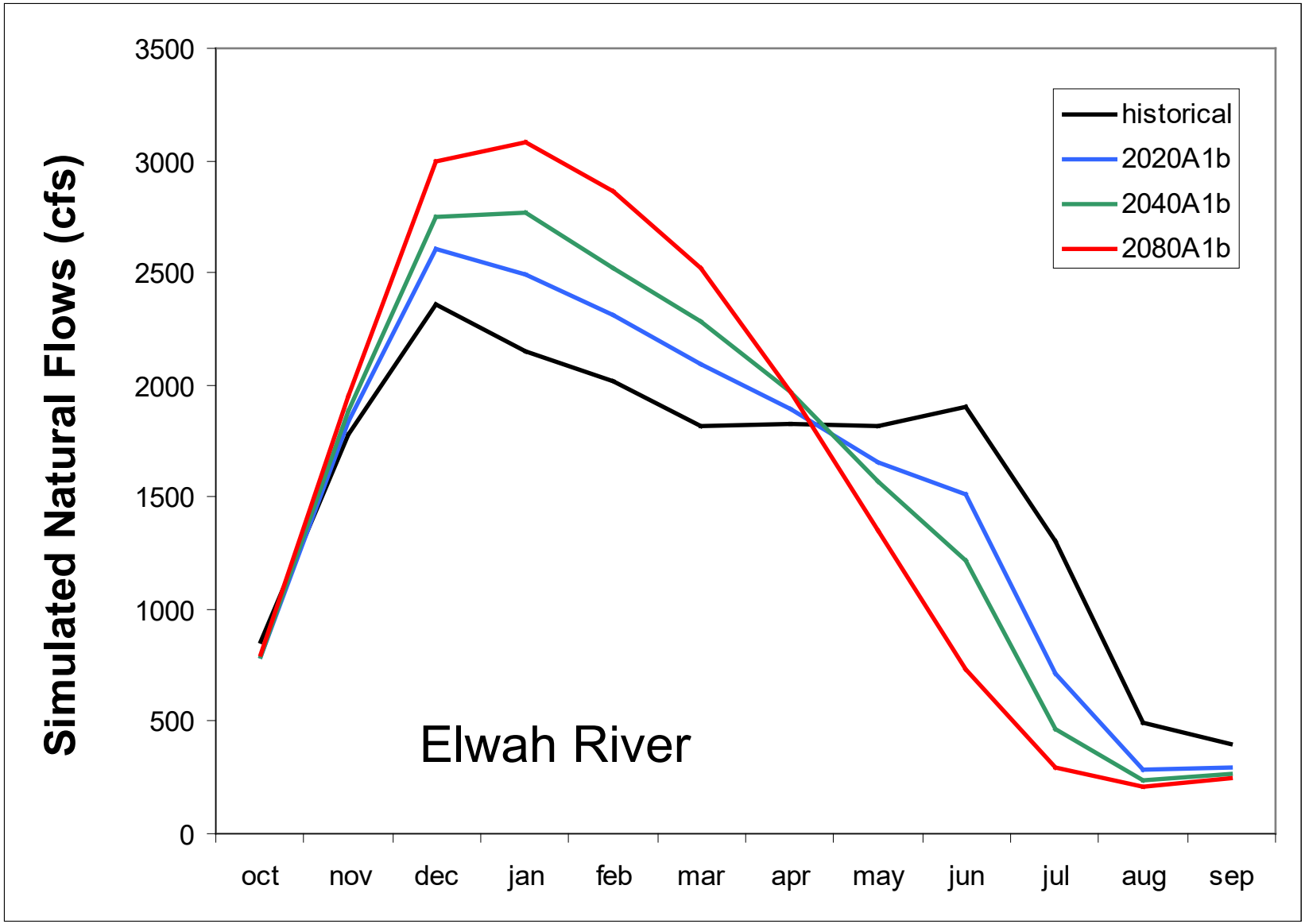
- B_i – infiltration parameter
- D_s – fraction of maximum subsurface flow rate
- W_s – fraction of maximum soil moisture
- D_s,max – maximum subsurfact flow rate (mm/day)


A1B Scenario for the 2020s
A1B Scenario for the 2040s
Ratio of 100 year Flood Frequency
0.66- 0.75
0.76 - 0.85
0.86 - 0.95
0.96 - 1.05
1.06 - 1.15
1.16 - 1.25
1.26 - 1.35
1.36 - 1.45
1.46 - 1.55
1.56 - 1.65
1.66 - 1.75


A1B Scenario for the 2020s
A1B Scenario for the 2040s
Ratio of 7Q10 Low Flow
0.56 - 0.65
0.66 - 0.75
0.76 - 0.85
0.86 - 0.95
0.96 - 1.05

West Side of the Cascades

Historical and Projected 21st Century Flows for the A1b Scenario



Effects of Climate Variability and Change on the Columbia River Basin

Alan F. Hamlet
Philip W. Mote
Dennis P. Lettenmaier

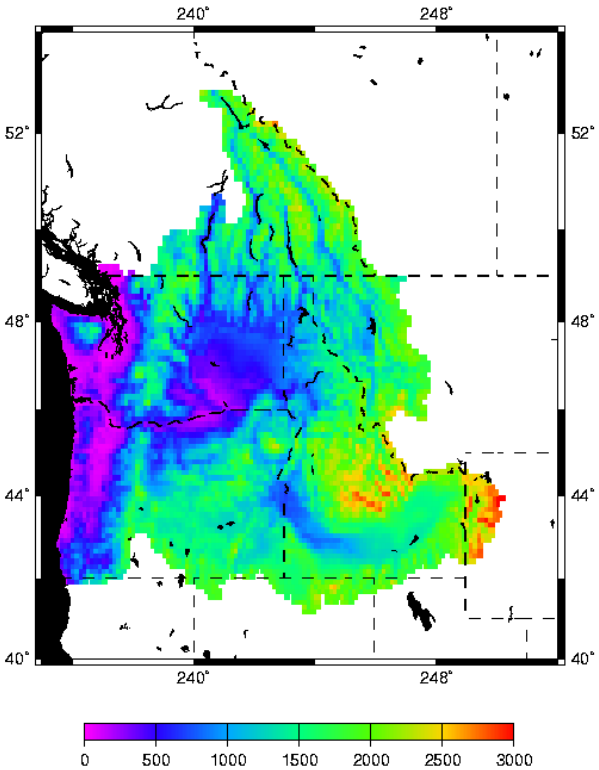
JISAO/CSES Climate Impacts Group
Dept. of Civil and Environmental Engineering
University of Washington

CLIMATE IMPACTS GROUP

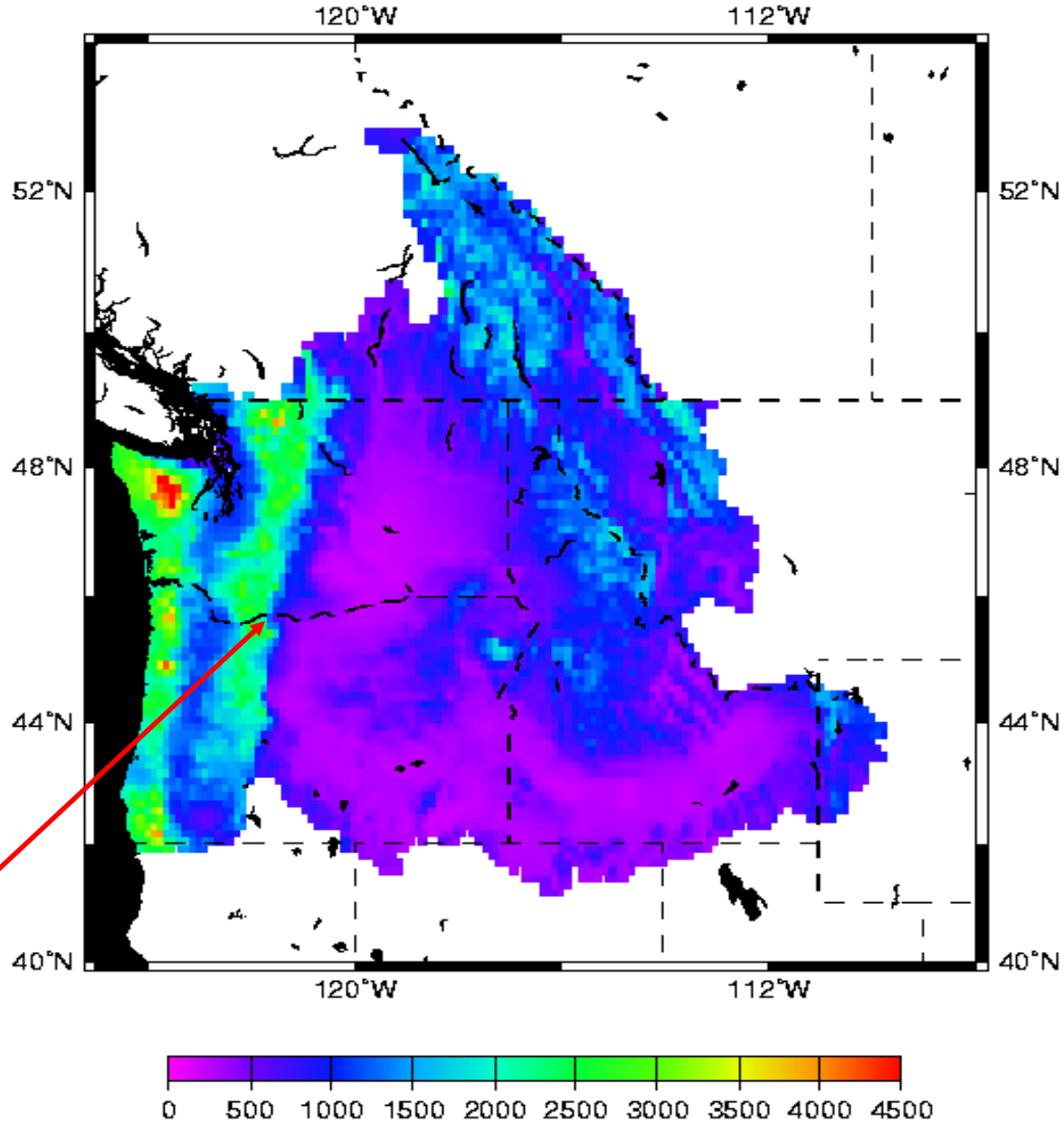
Department of Civil and Environmental Engineering

Hydroclimatology of the Pacific Northwest

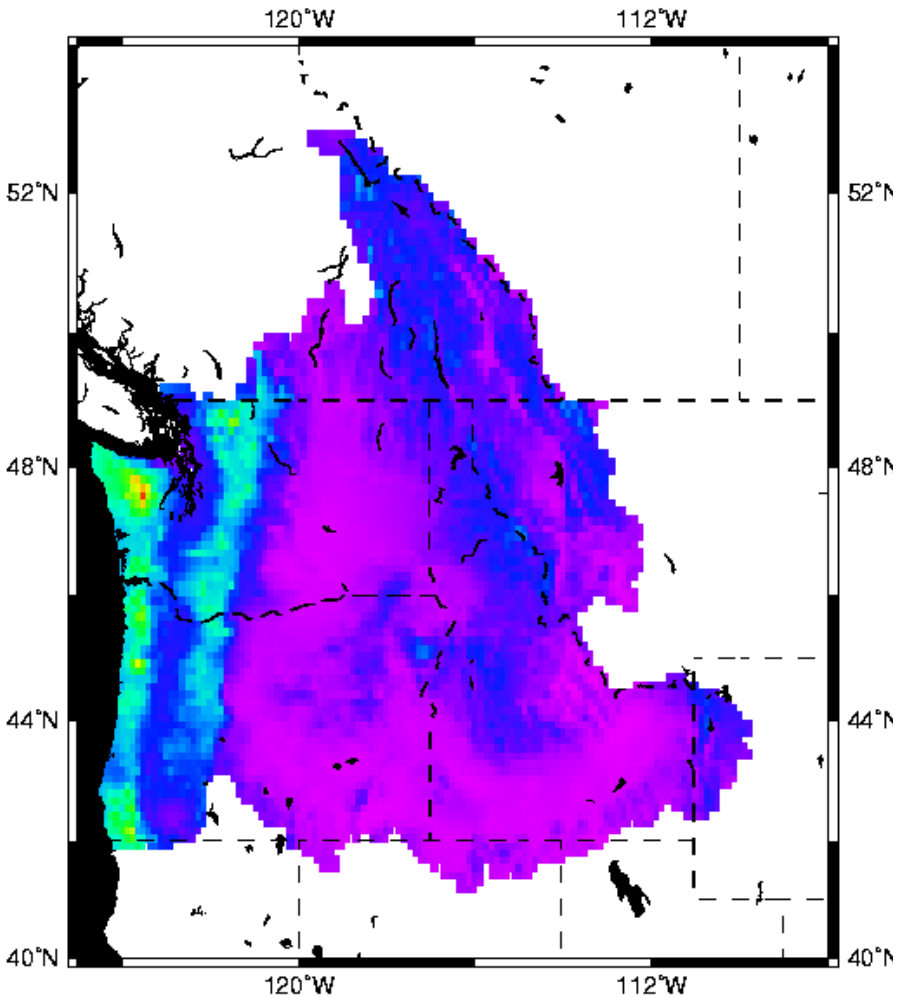
Annual PNW Precipitation (mm)



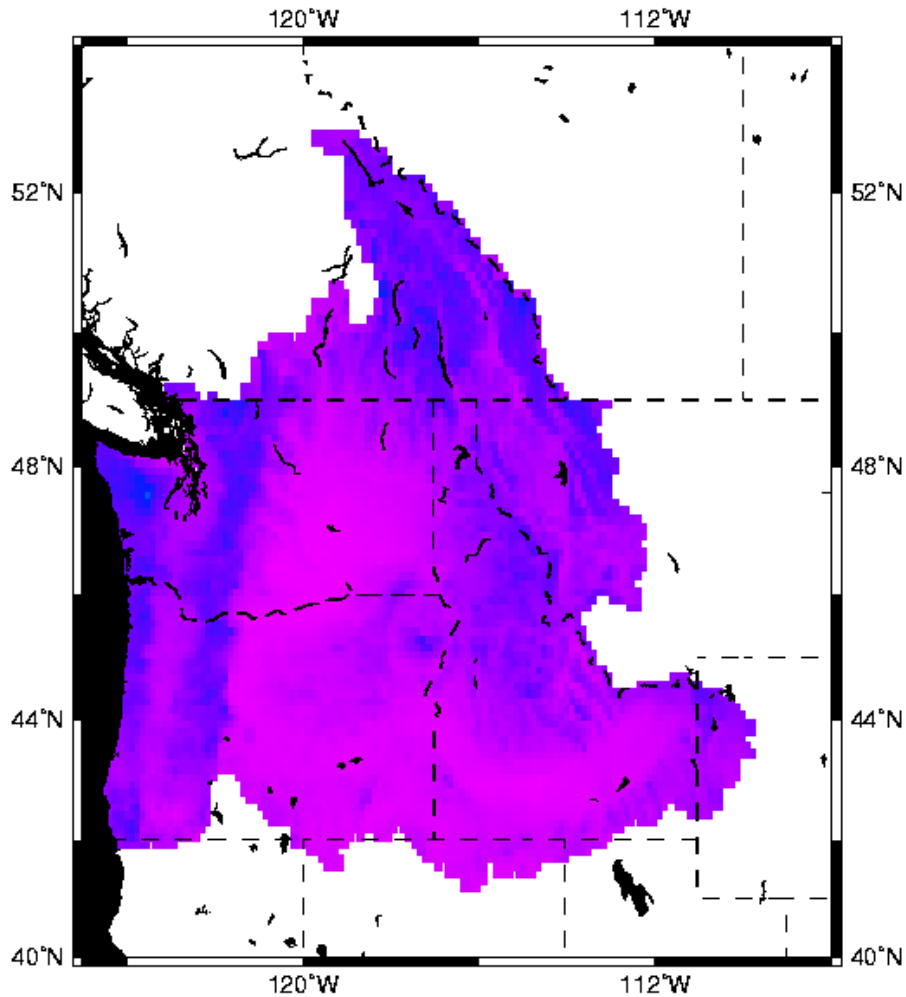
Elevation (m)



The Dalles



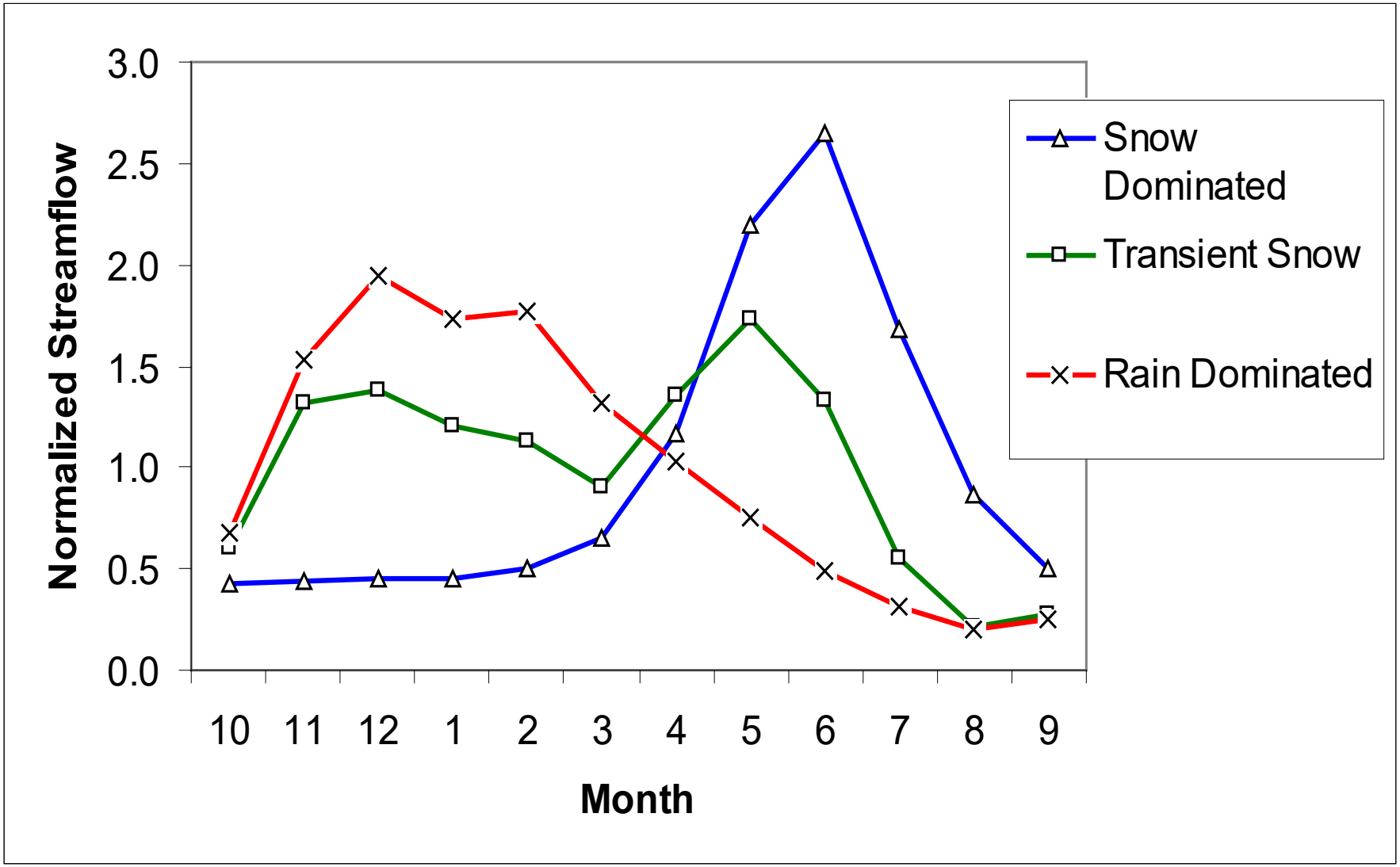
(mm)



Winter Precipitation

Summer Precipitation

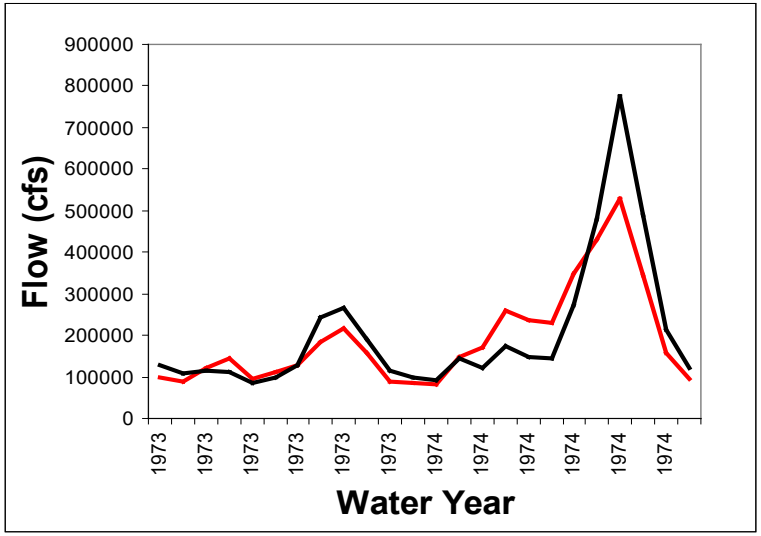
Hydrologic Characteristics of PNW Rivers



Sensitivity of Snowmelt and Transient Rivers to Changes in Temperature and Precipitation

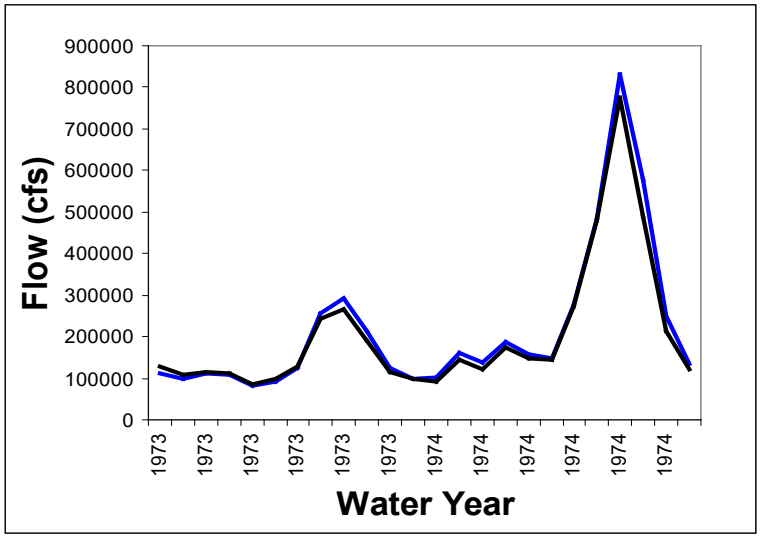
Temperature warms, precipitation unaltered:

•Streamflow timing is altered
• Annual volume stays about the same

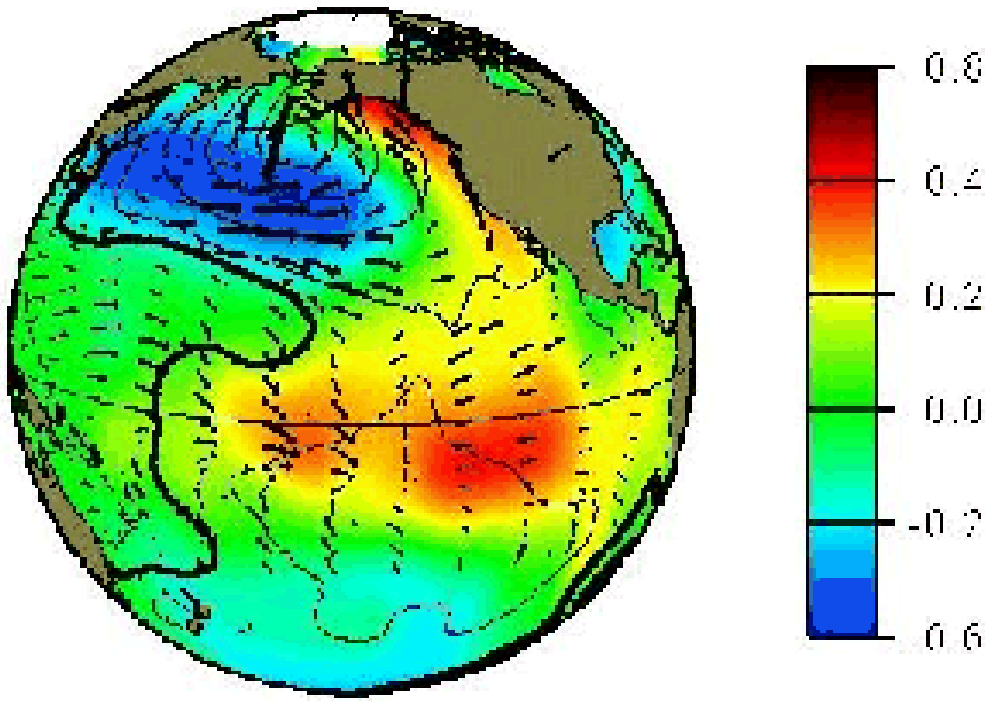


Precipitation increases, temperature unaltered:

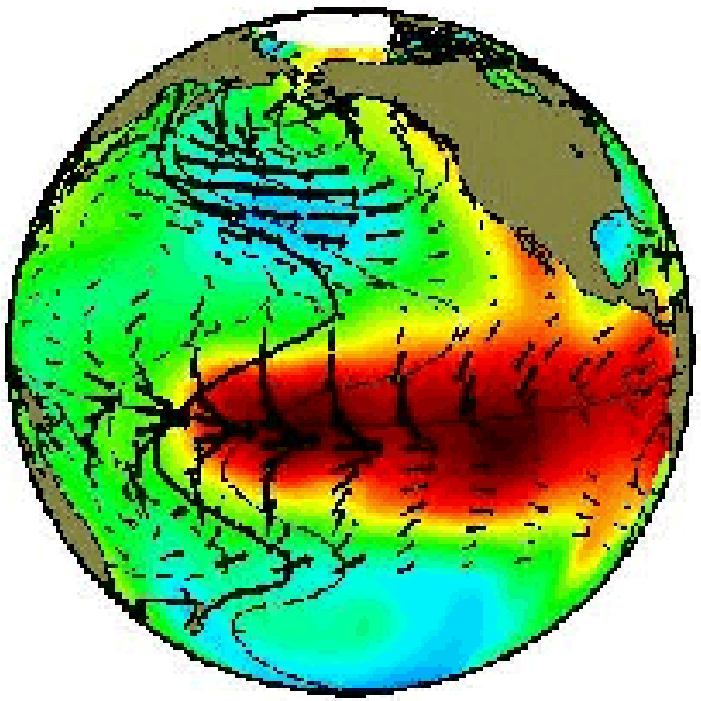
•Streamflow timing stays about the same
•Annual volume is altered



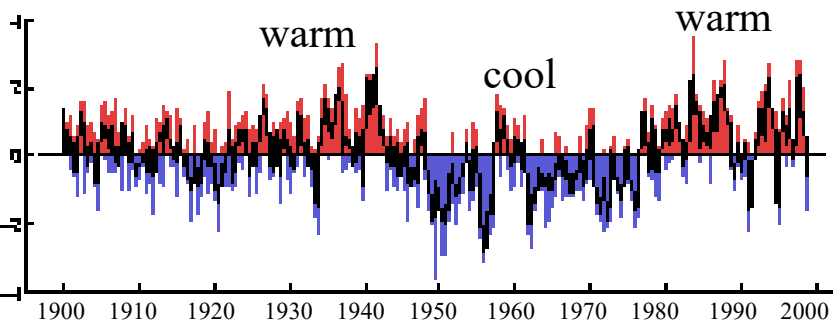
Pacific Decadal Oscillation



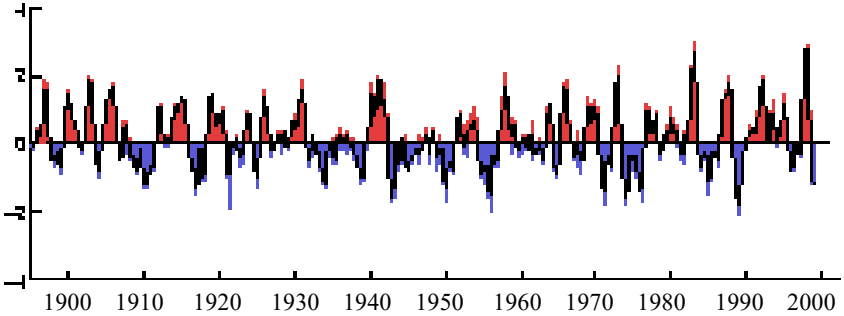
El Niño Southern Oscillation



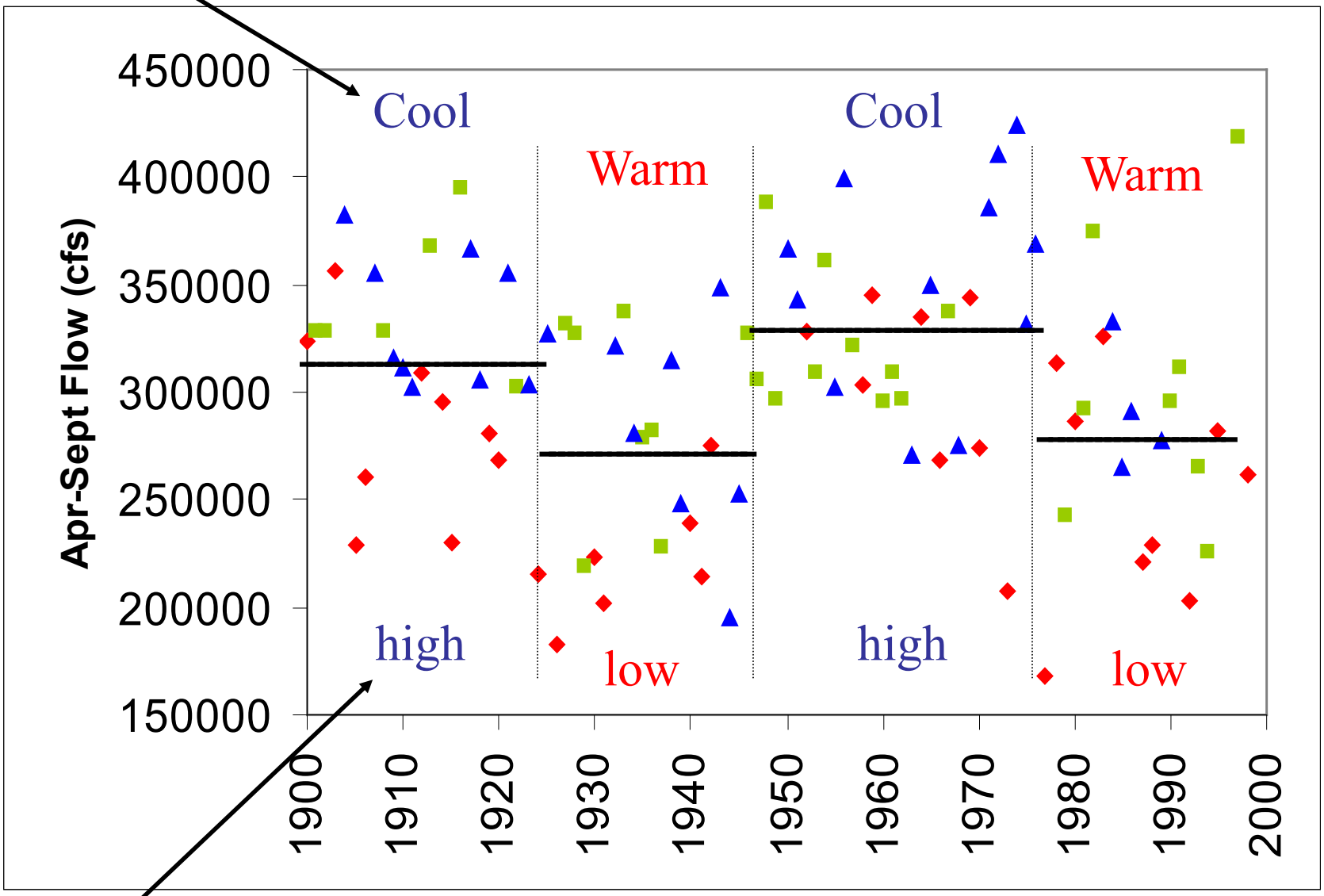
A history of the PDO



A history of ENSO

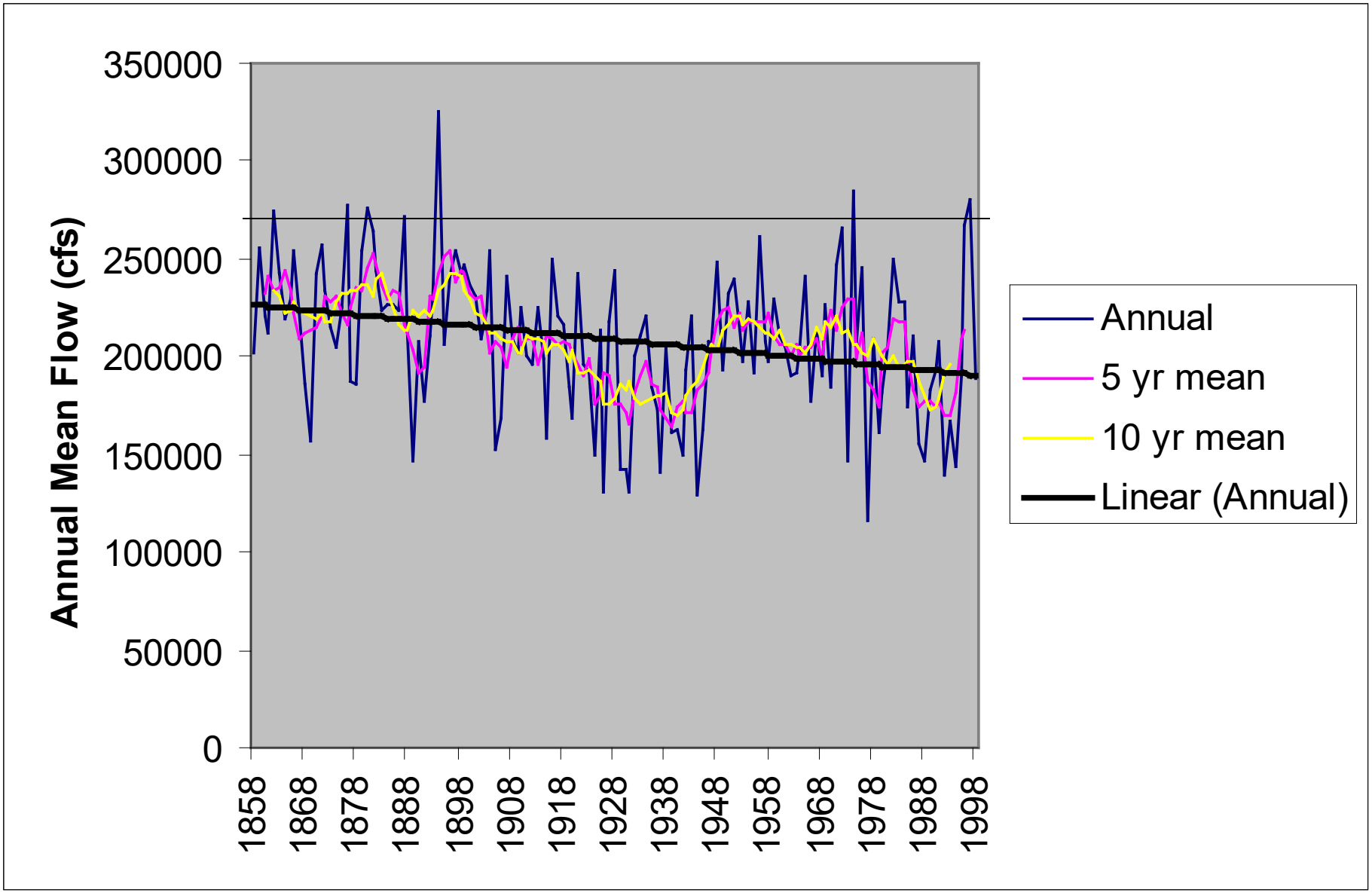


Effects of the PDO and ENSO on Columbia River Summer Streamflows

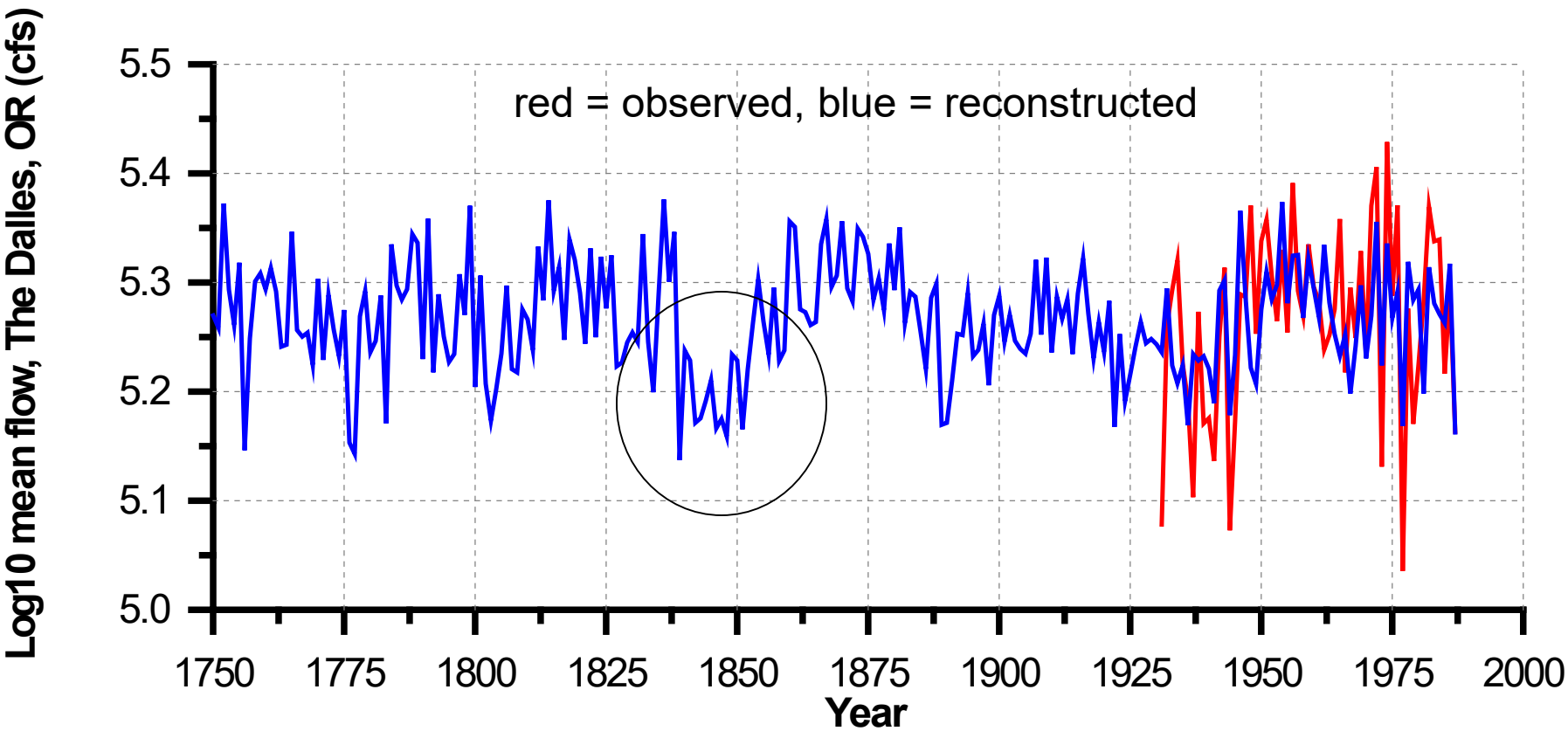


Long-Term Trends in Temperature, Precipitation, and Streamflow

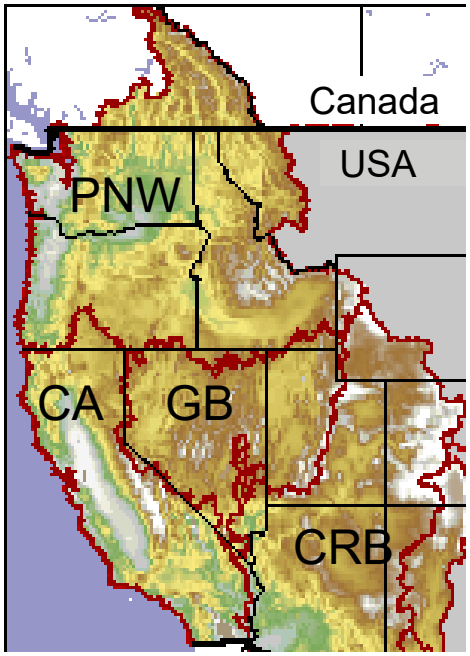
Trends in Annual Streamflow at The Dalles from 1858-1998 are strongly downward.

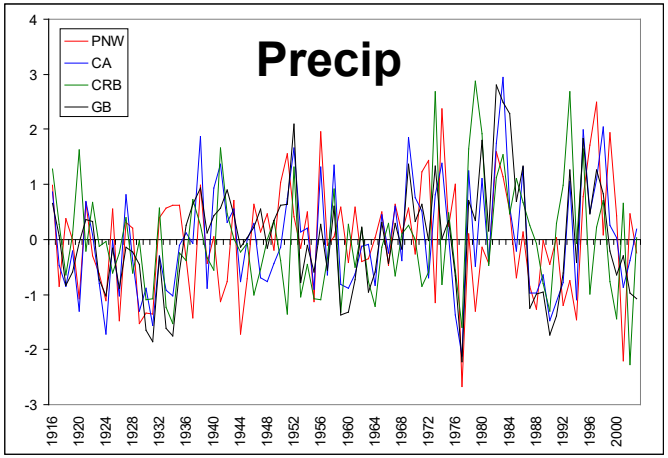


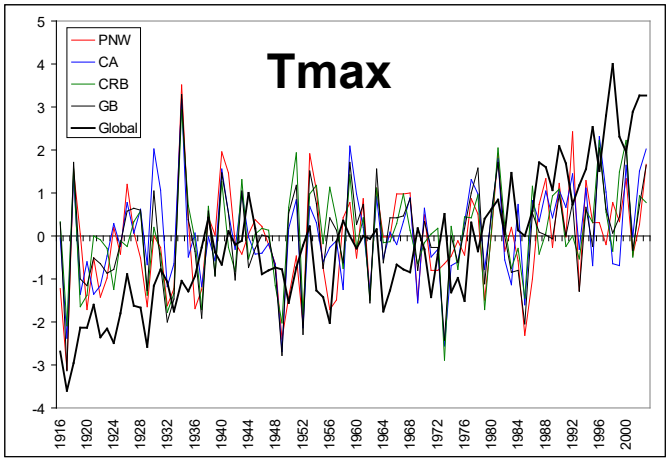
The Dust Bowl was probably not the worst drought sequence in the past 250 years



Source: Gedalof, Z., D.L. Peterson and Nathan J. Mantua. (in review). Columbia River Flow and Drought Since 1750. Submitted to Journal of the American Water Resources Association.


Canada
USA
PNW
CA
GB
CRB


Precip
PNW
CA
CRB
GB
4
3
2
1
0
-1
-2
-3
1916
1920
1924
1928
1932
1936
1940
1944
1948
1952
1956
1960
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000


Tmax
PNW
CA
CRB
GB
Global
5
4
3
2
1
0
-1
-2
-3
-4
1916
1920
1924
1928
1932
1936
1940
1944
1948
1952
1956
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1964
1968
1972
1976
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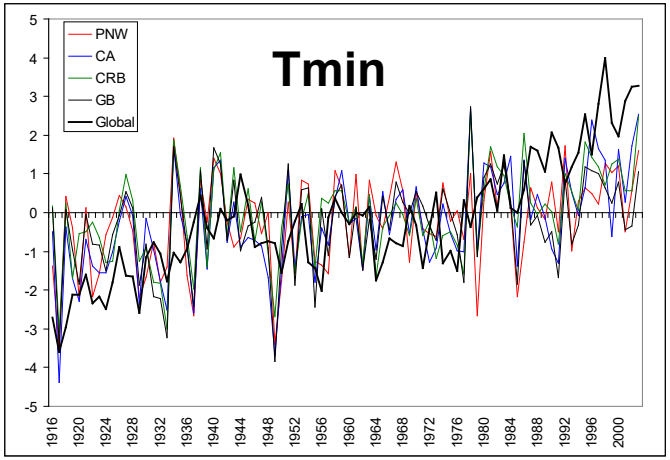
2000


Tmin
PNW
CA
CRB
GB
Global
5
4
3
2
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-3
-4
-5
1916
1920
1924
1928
1932
1936
1940
1944
1948
1952
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1964
1968
1972
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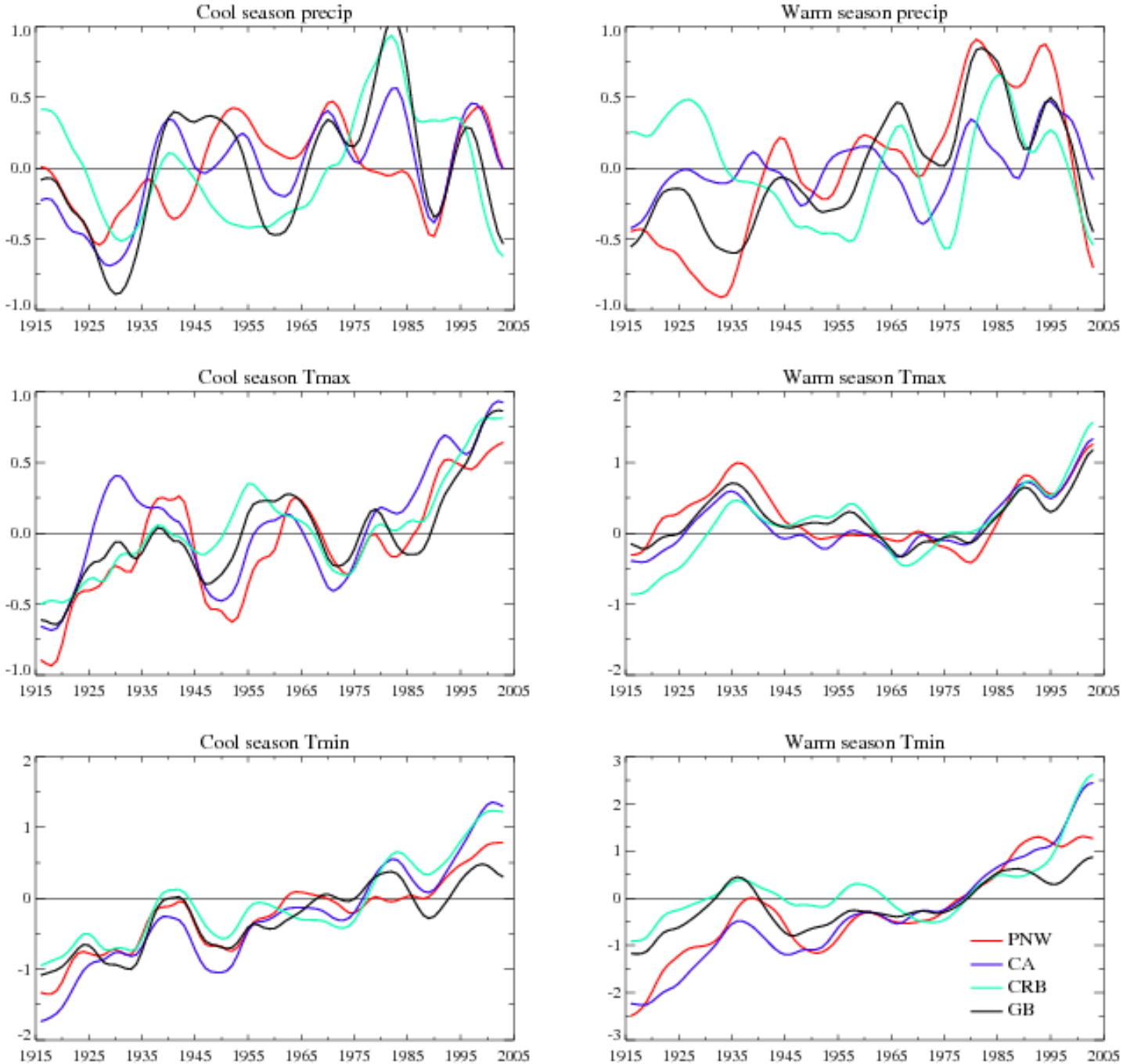
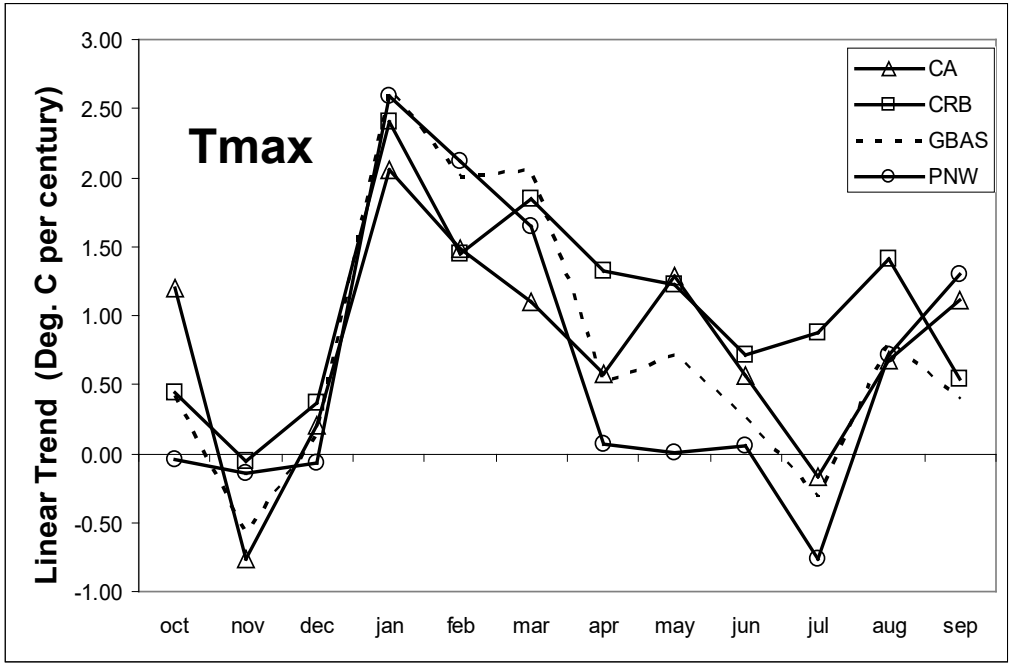
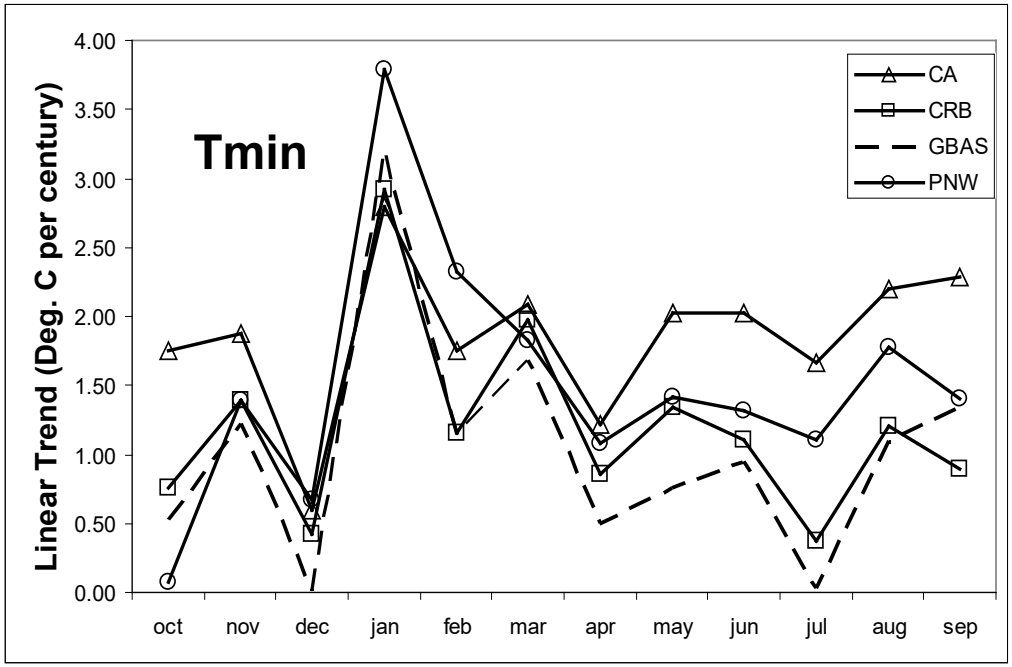
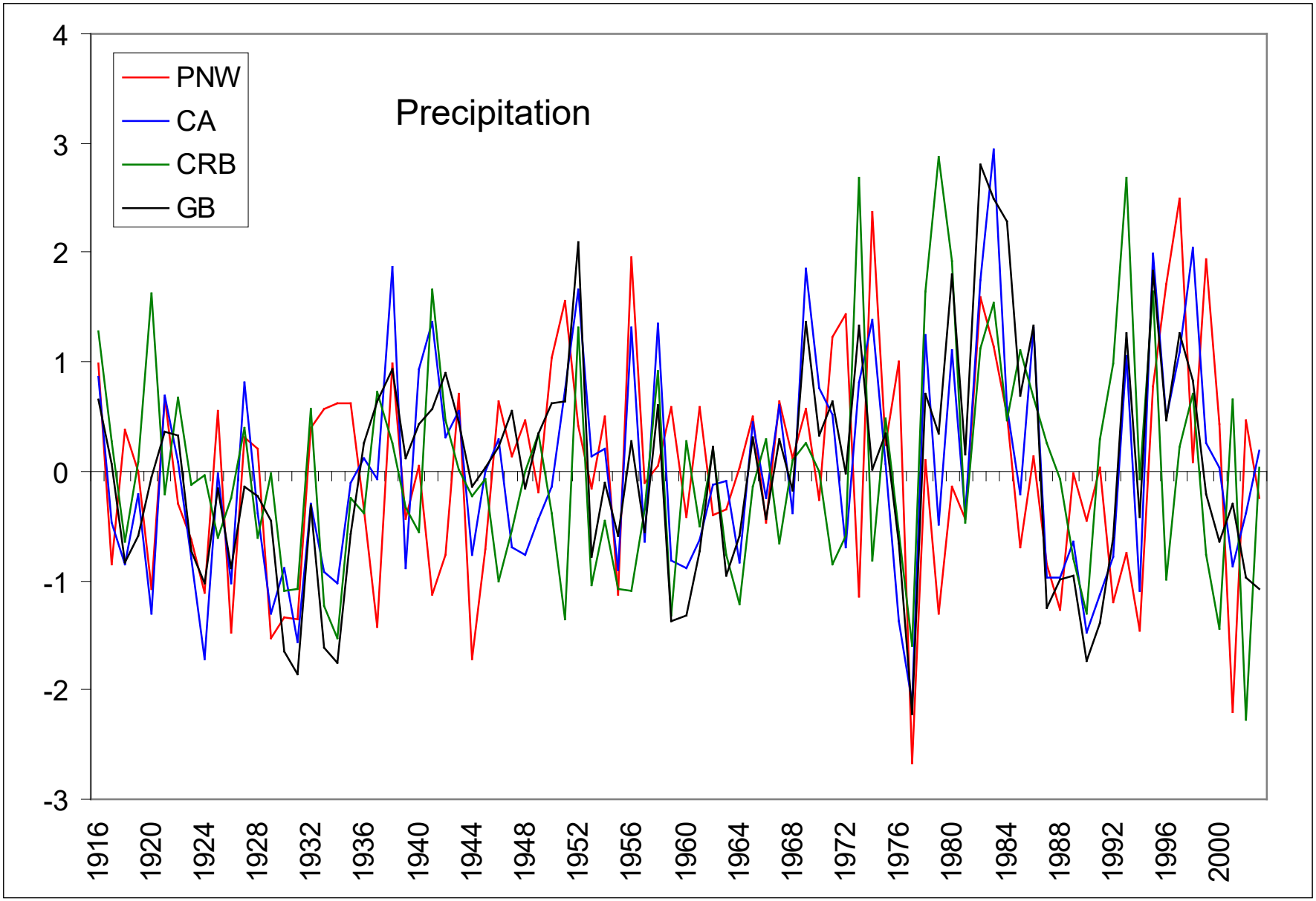
1980
1984
1988
1992
1996
2000

A Time Series of Temporally Smoothed, Regionally Averaged Met Data for the West



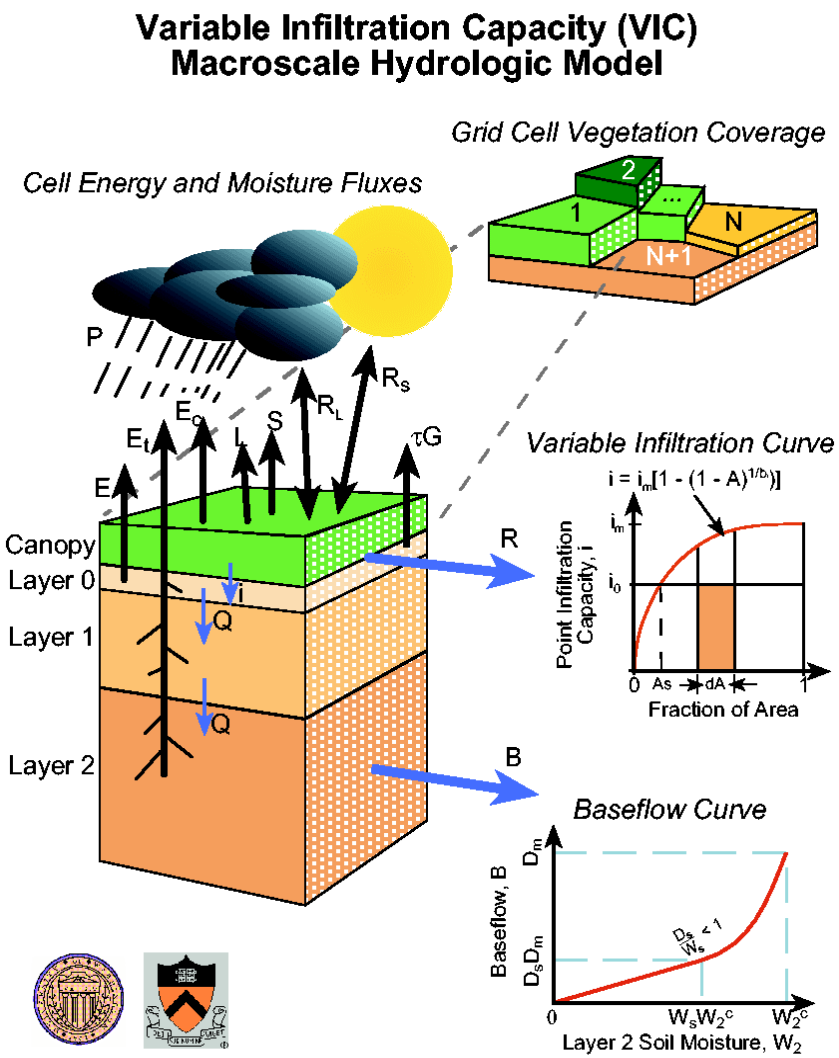

Tmax
Linear Trend (Deg. C per century)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
oct
nov
dec
jan
feb
mar
apr
may
jun
jul
aug
sep
CA
CRB
GBAS
PNW

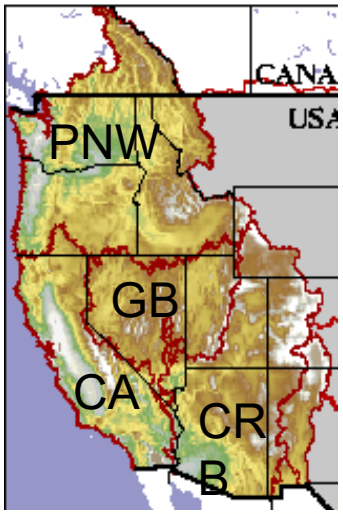

Tmin
Linear Trend (Deg. C per century)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
oct
nov
dec
jan
feb
mar
apr
may
jun
jul
aug
sep
CA
CRB
GBAS
PNW

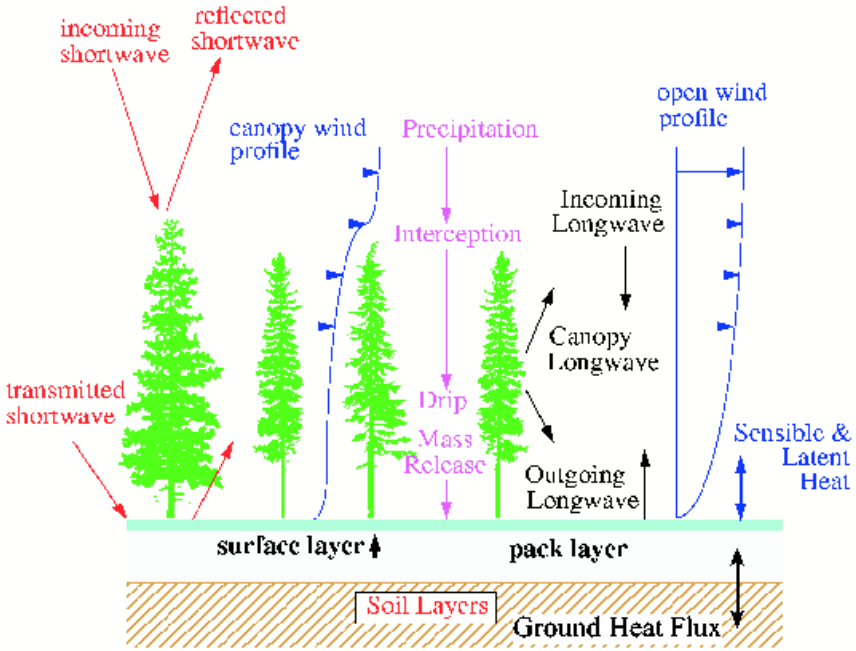

Precipitation
PNW
CA
CRB
GB
4
3
2
1
0
-1
-2
-3
1916
1920
1924
1928
1932
1936
1940
1944
1948
1952
1956
1960
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000

20th Century Trends in Hydrologic Variables

Schematic of VIC Hydrologic Model and Energy Balance Snow Model

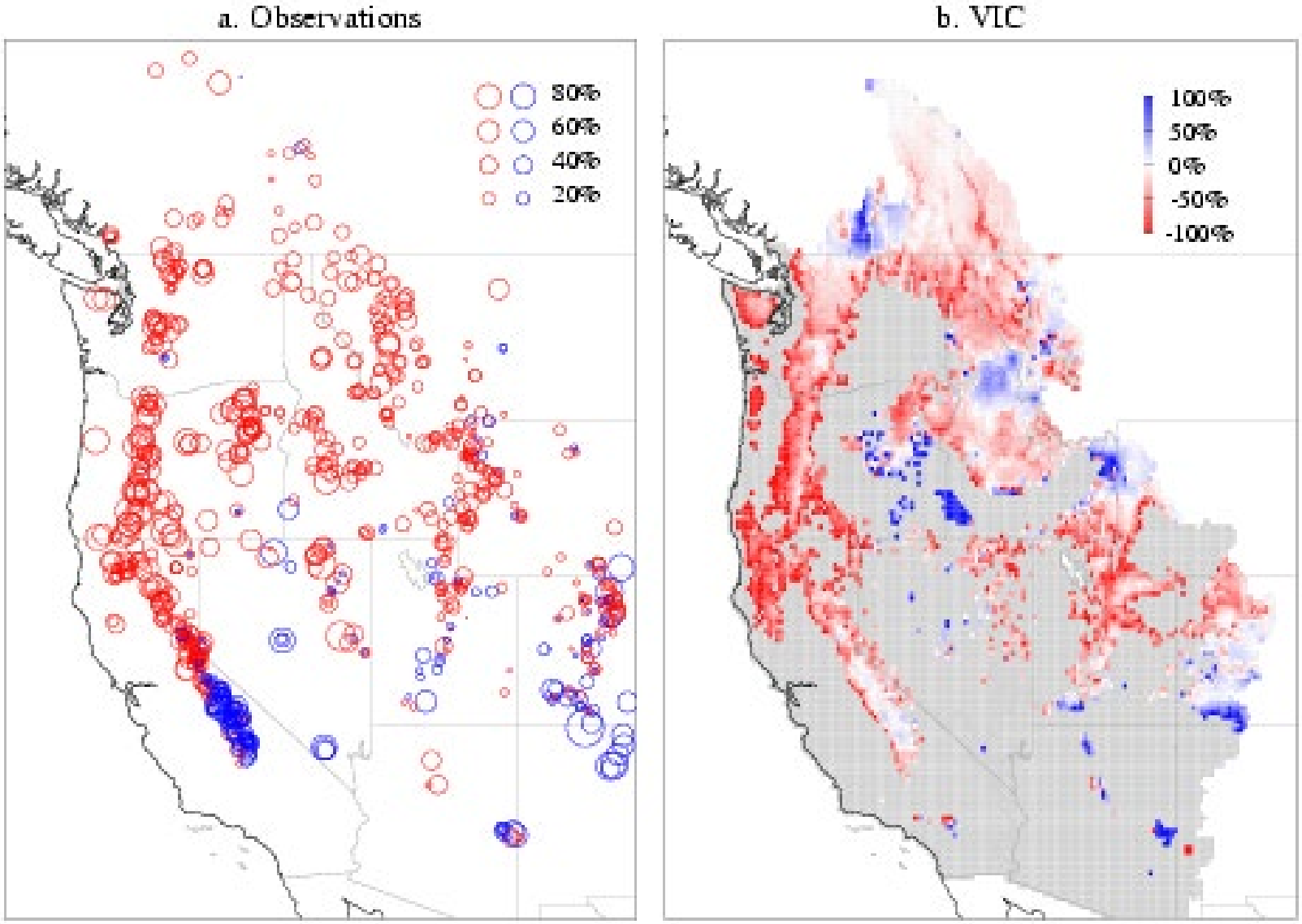






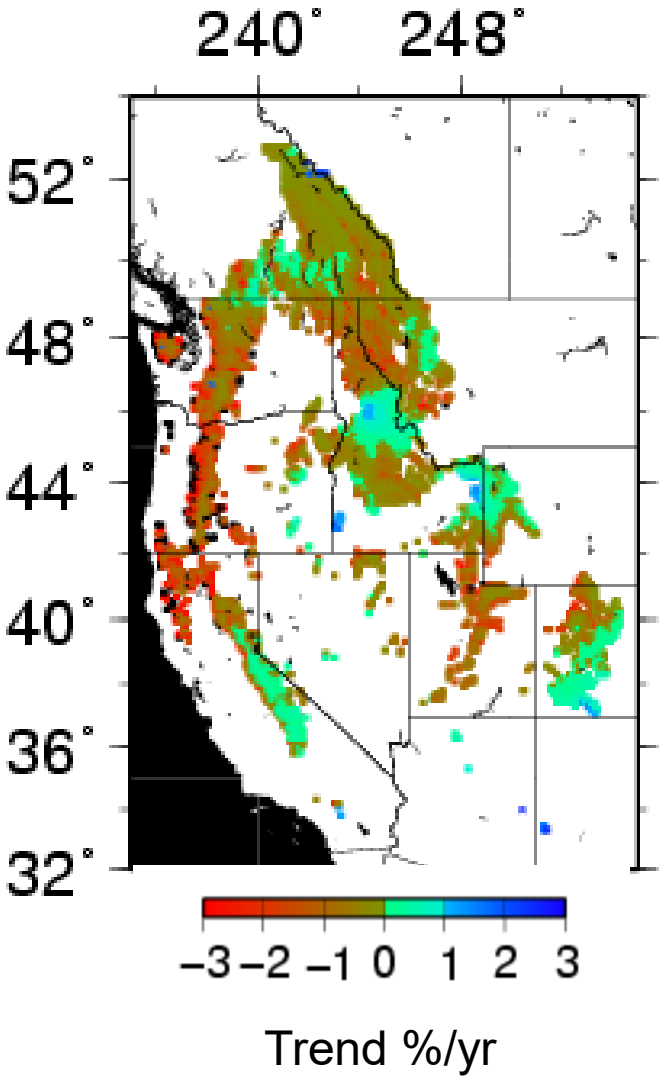
Snow Model

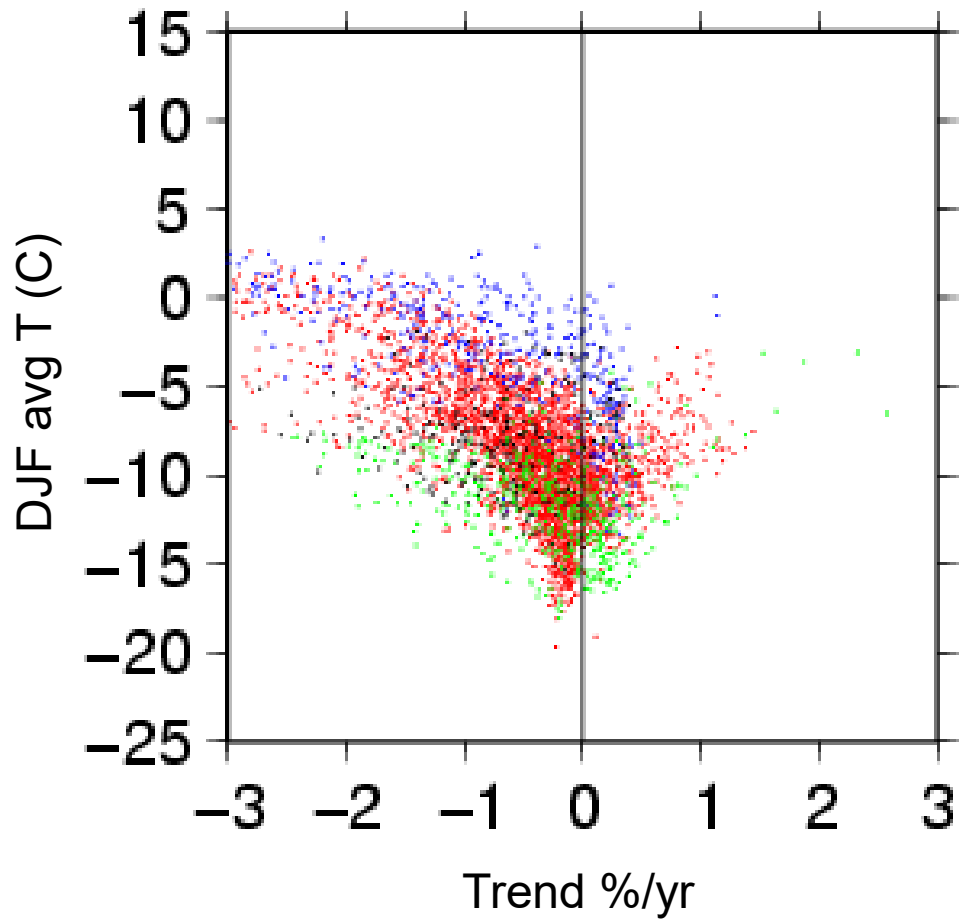
Trends in April 1 SWE 1950-1997



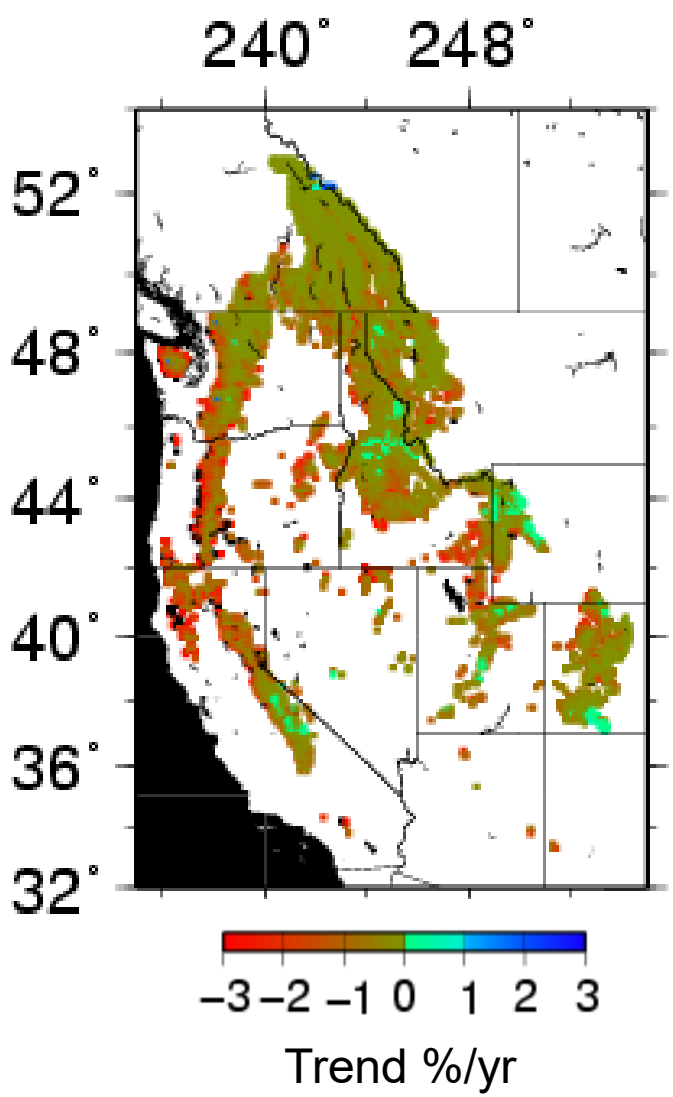
Mote P.W.,Hamlet A.F., Clark M.P., Lettenmaier D.P., 2005, Declining mountain snowpack in western North America, BAMS (in press)

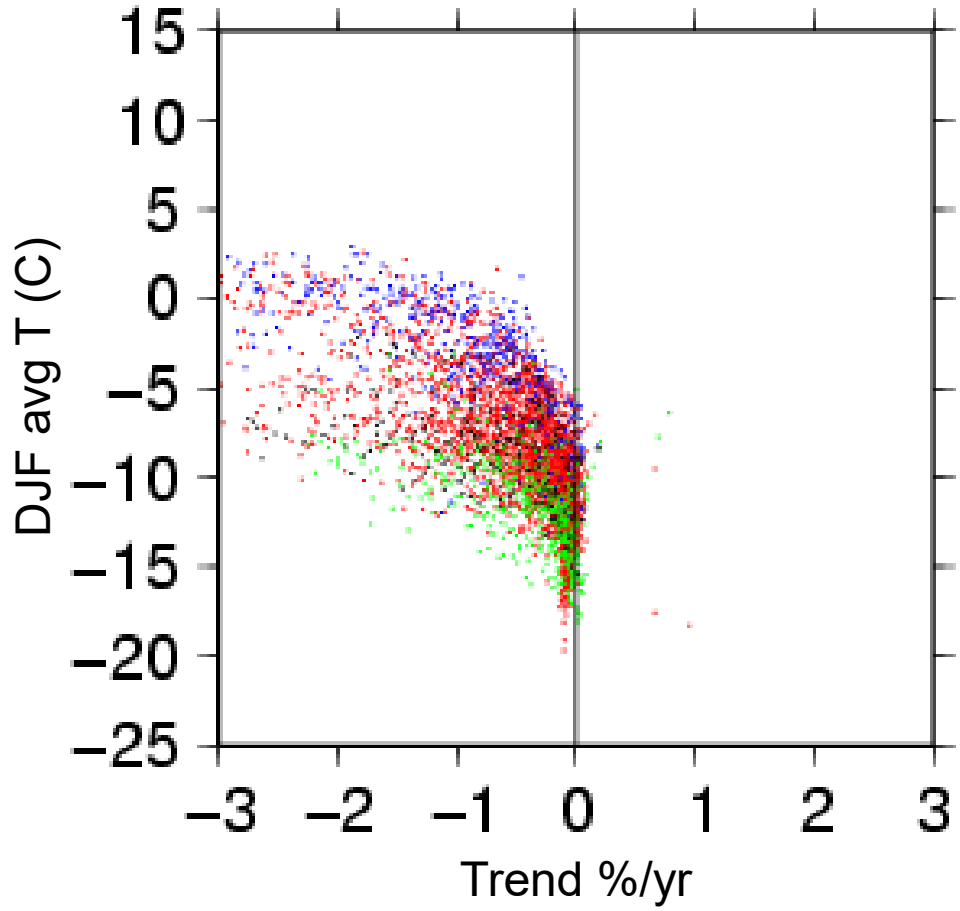
Overall Trends in April 1 SWE from 1947-2003



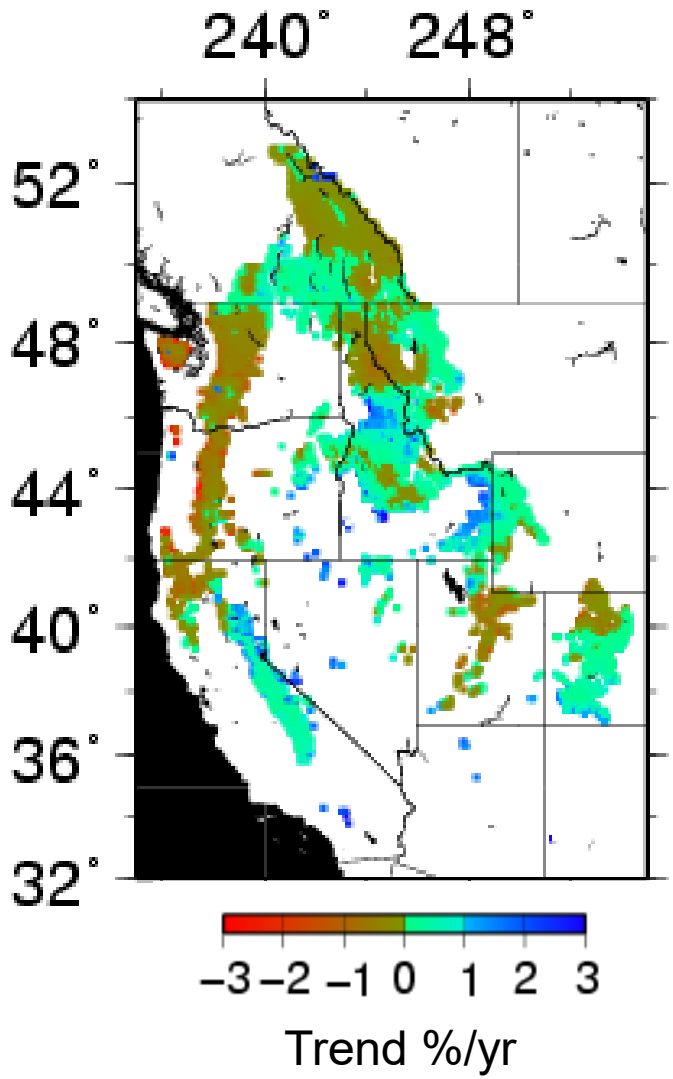


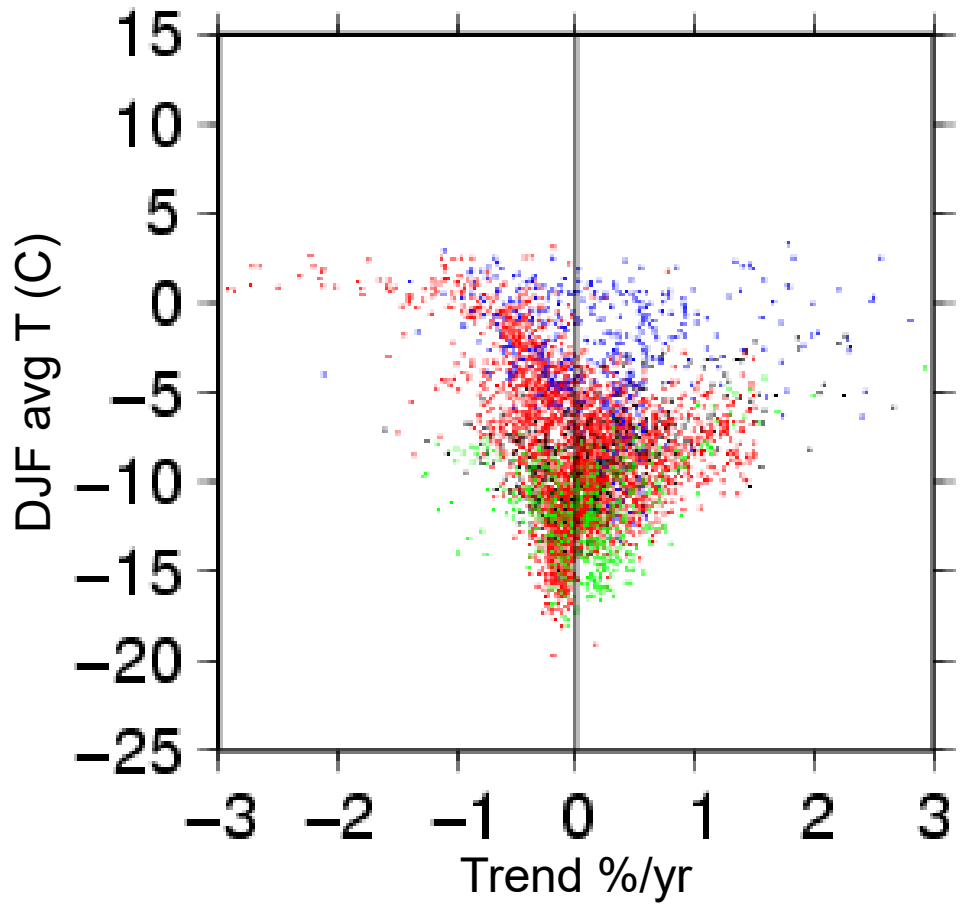
Temperature Related Trends in April 1 SWE from 1947-2003

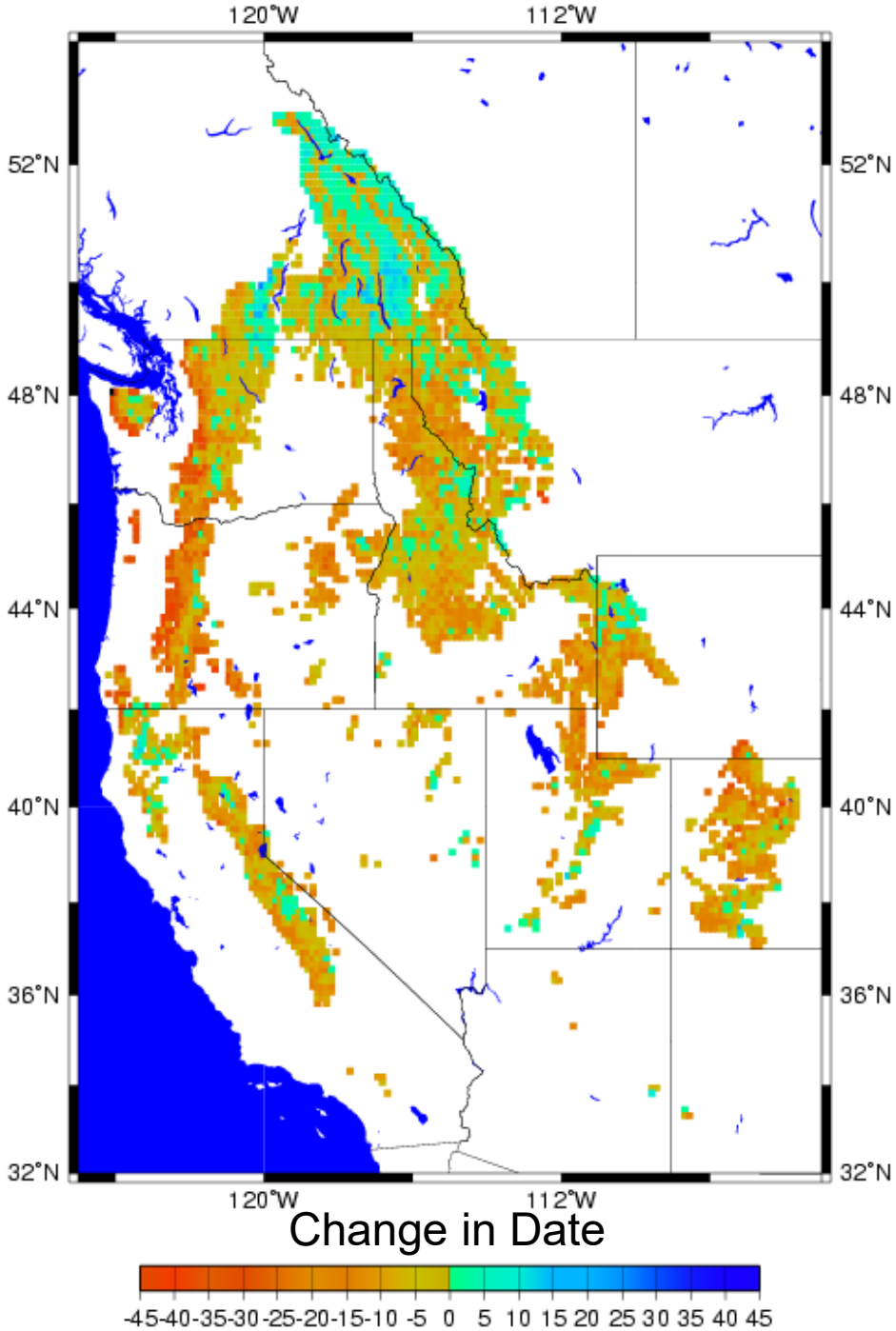




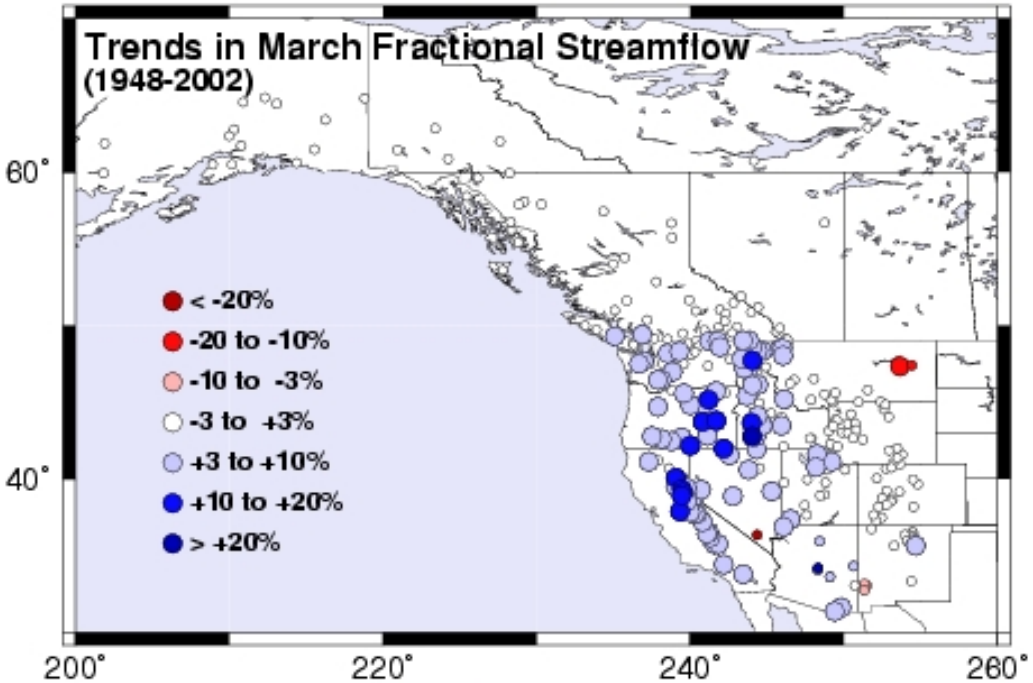
Precipitation Related Trends in April 1 SWE from 1947-2003

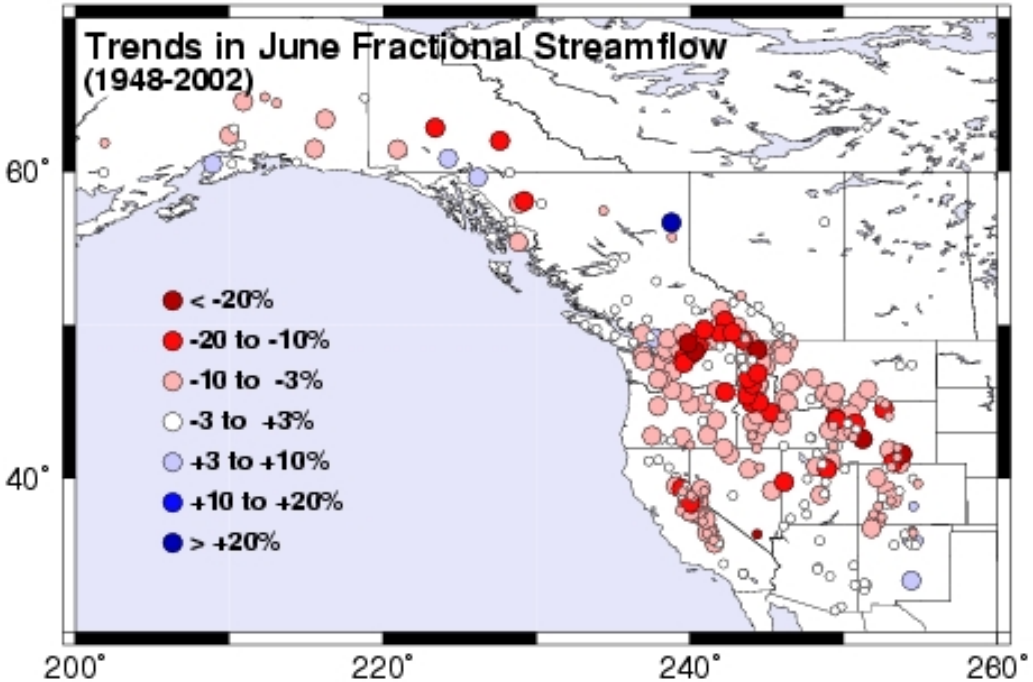






Trends in timing of peak snowpack are towards earlier calendar dates

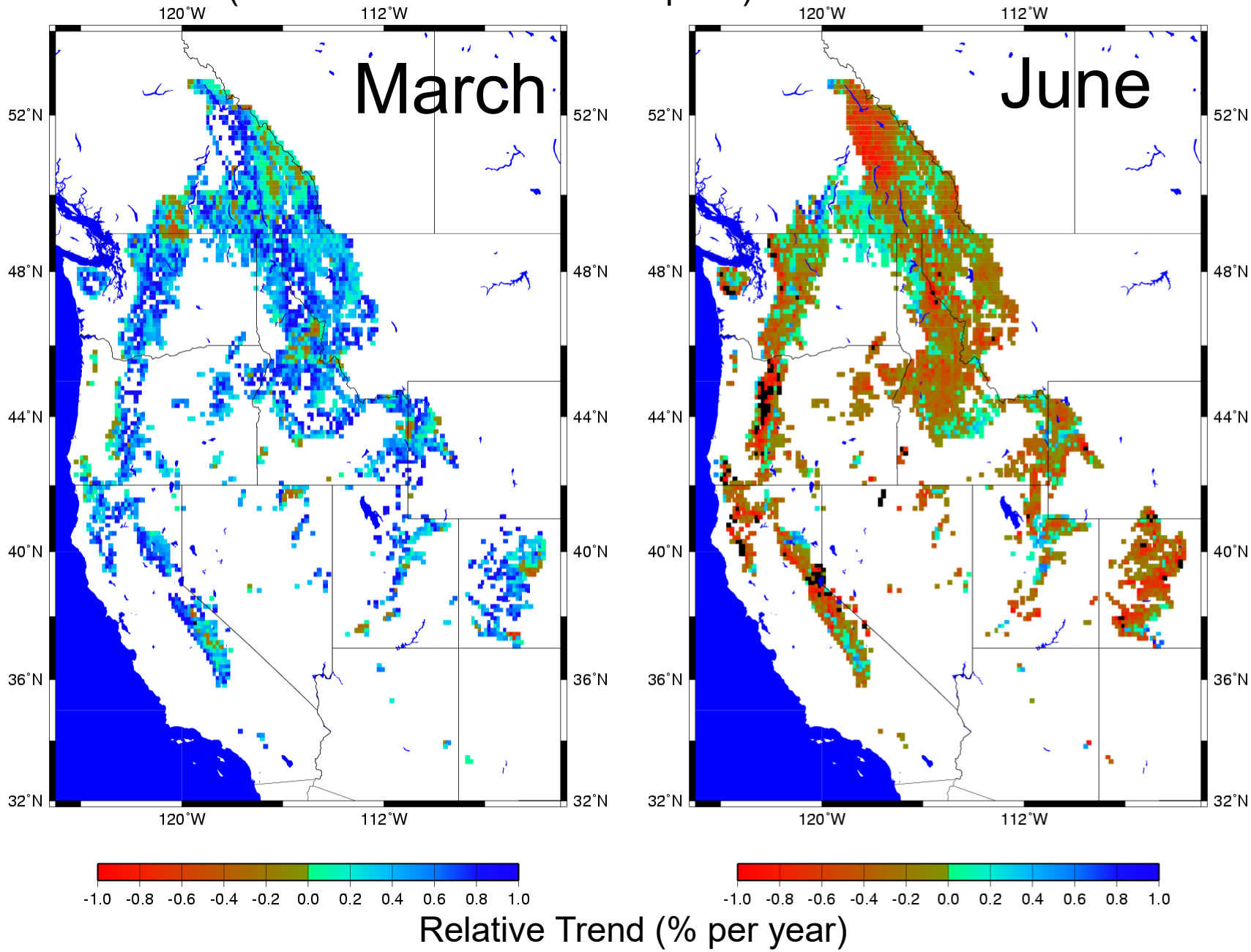


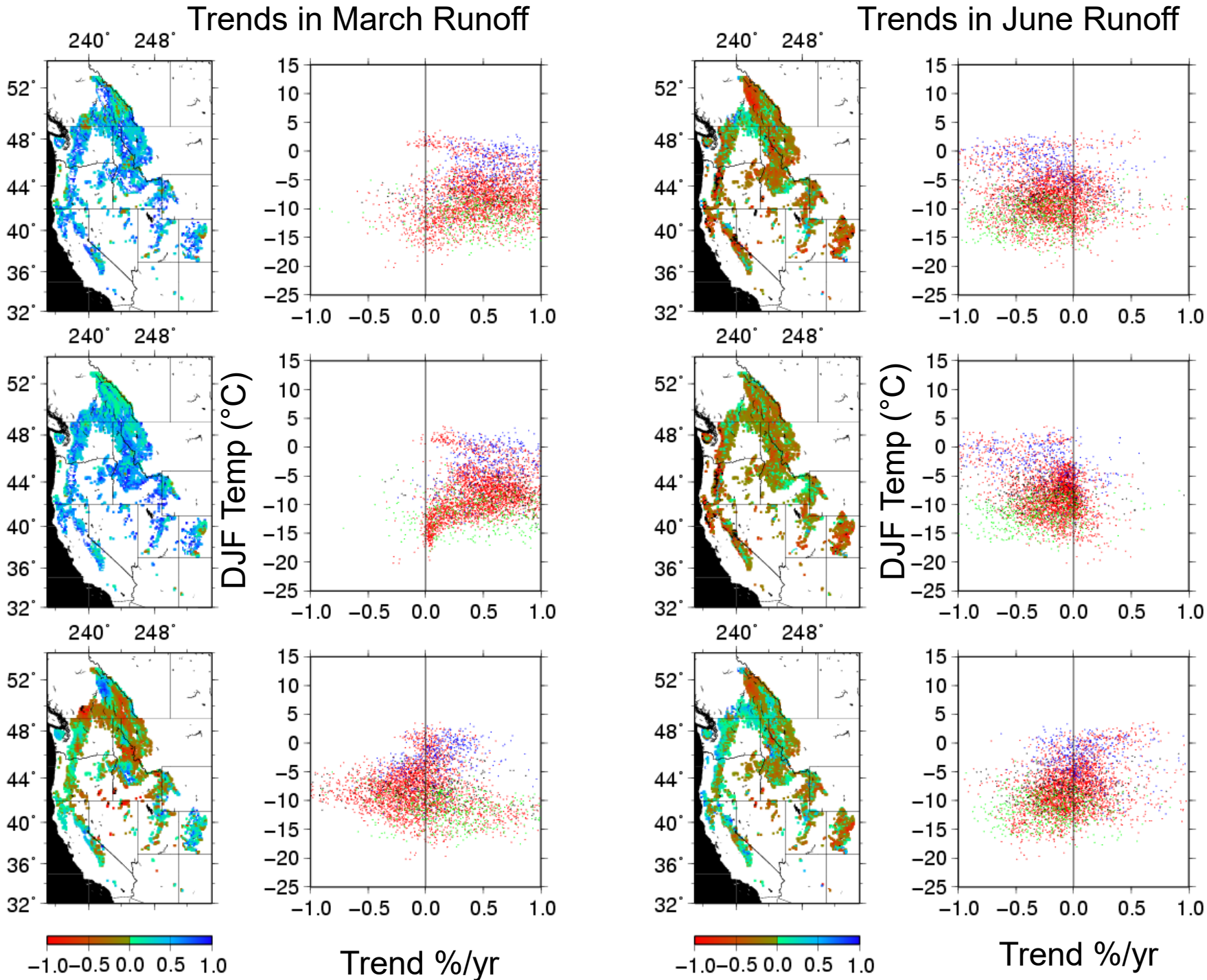


As the West warms, spring flows rise and summer flows drop

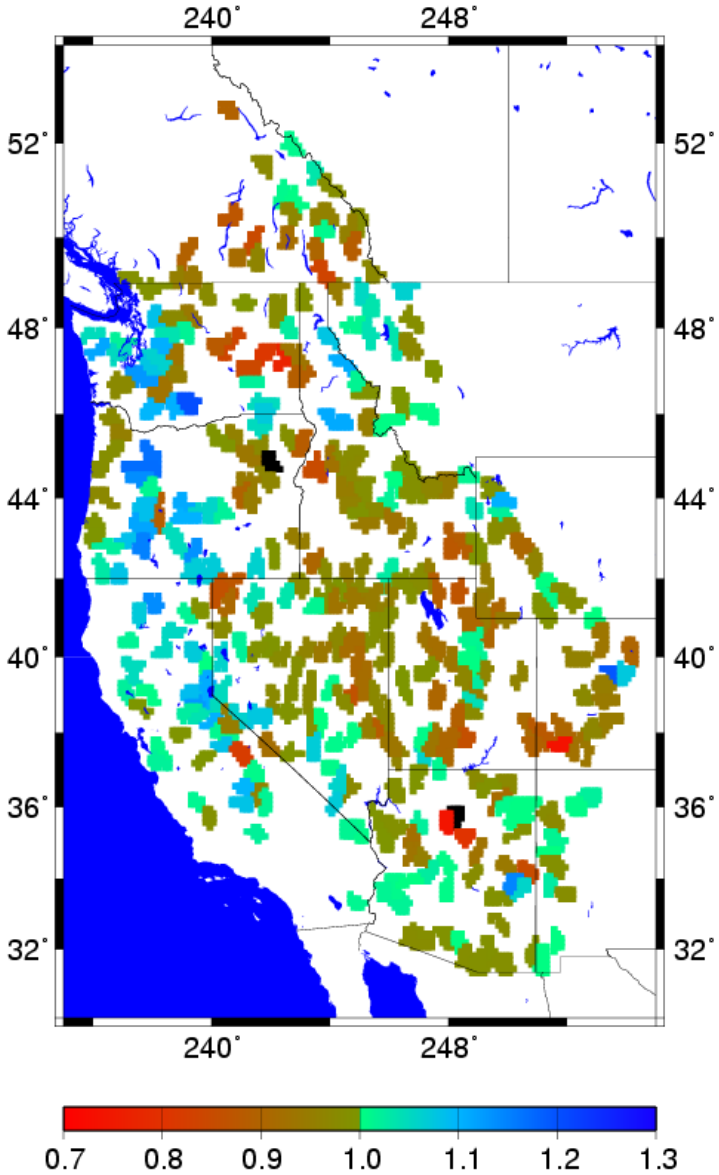
Stewart IT, Cayan DR, Dettinger MD, 2005: Changes toward earlier streamflow timing across western North America, J. Climate, 18 (8): 1136-1155

Trends in simulated fraction of annual runoff in each month from 1947-2003 (cells > 50 mm of SWE on April 1)



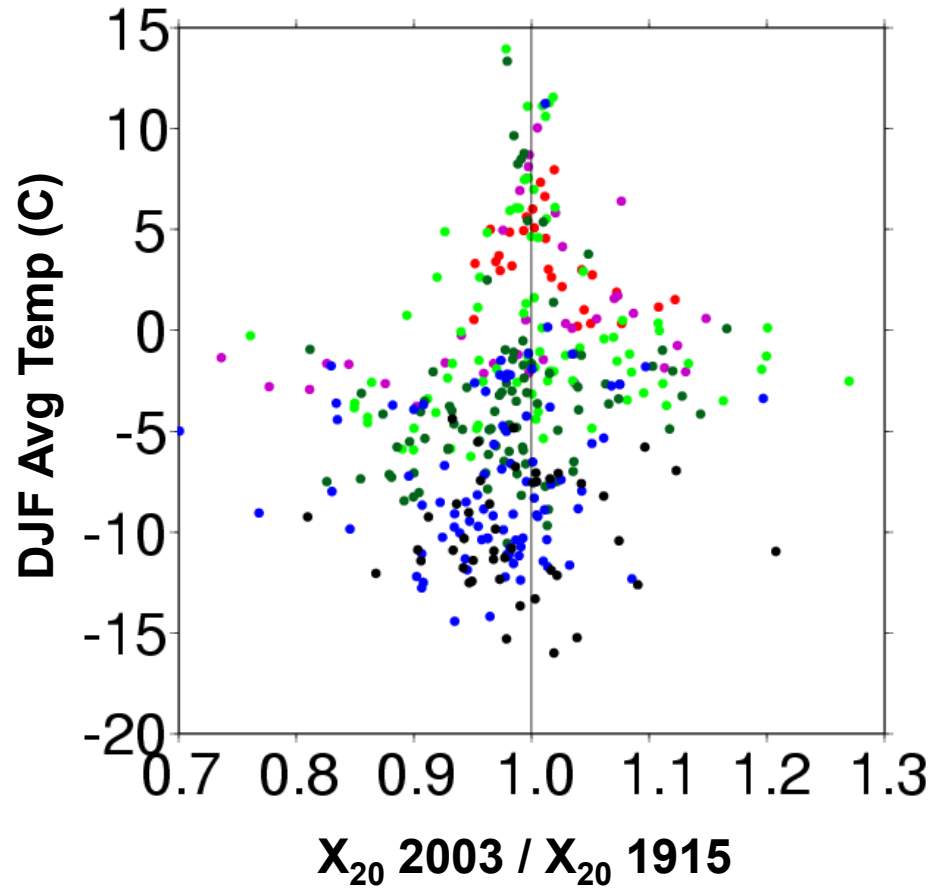

Trends in March Runoff
Trends in June Runoff
240˚ 248˚
52˚
48˚
44˚
40˚
36˚
32˚
15
10
5
0
−5
−10
−15
−20
−25
−1.0 −0.5 0.0 0.5 1.0
DJF Temp (°C)
−1.0−0.5 0.0 0.5 1.0
Trend %/yr

Flood risks have increased in many coastal areas with warm winter temperatures, whereas colder inland areas show decreases in flood risk.

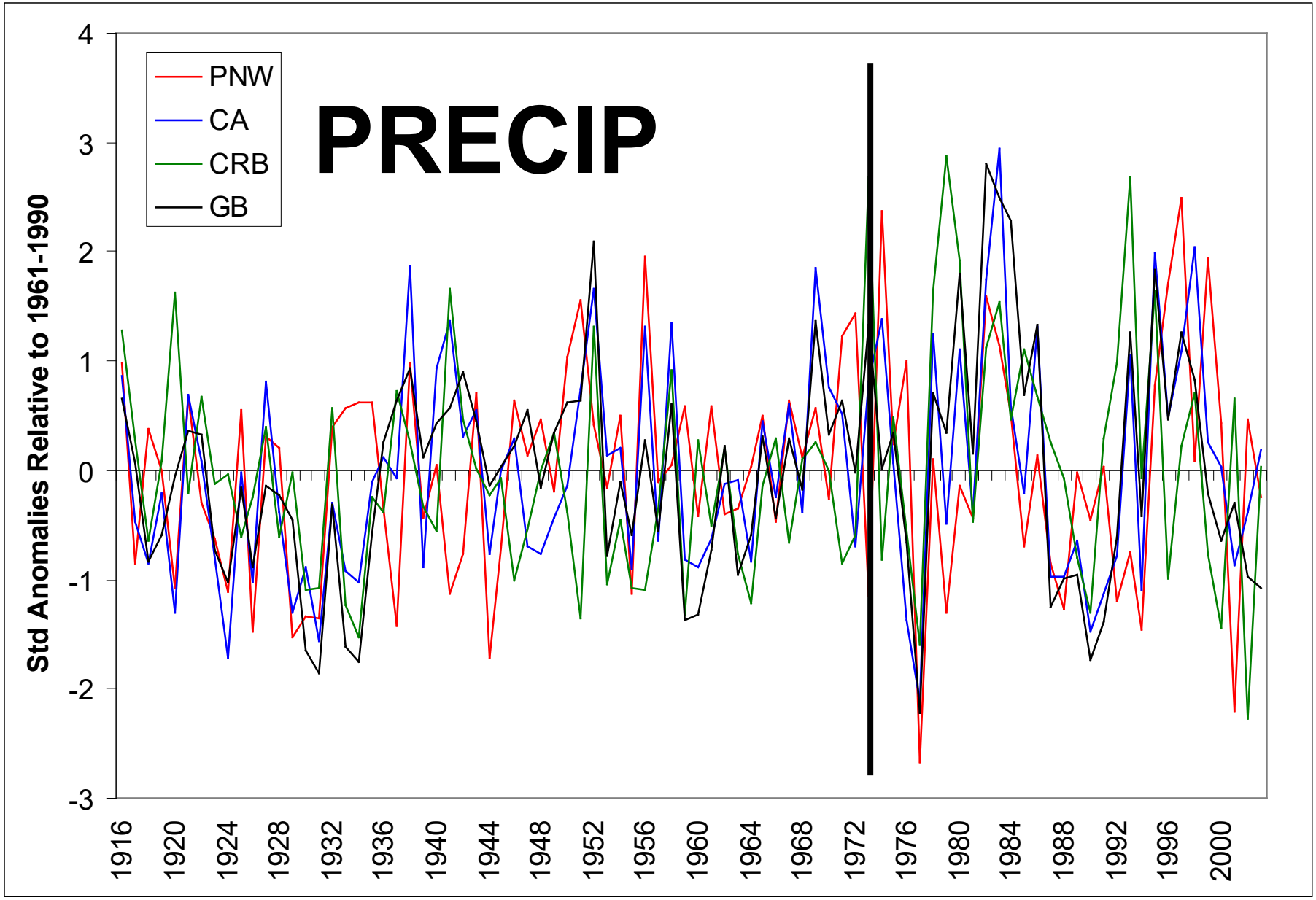


X_{20} 2003 / X_{20} 1915

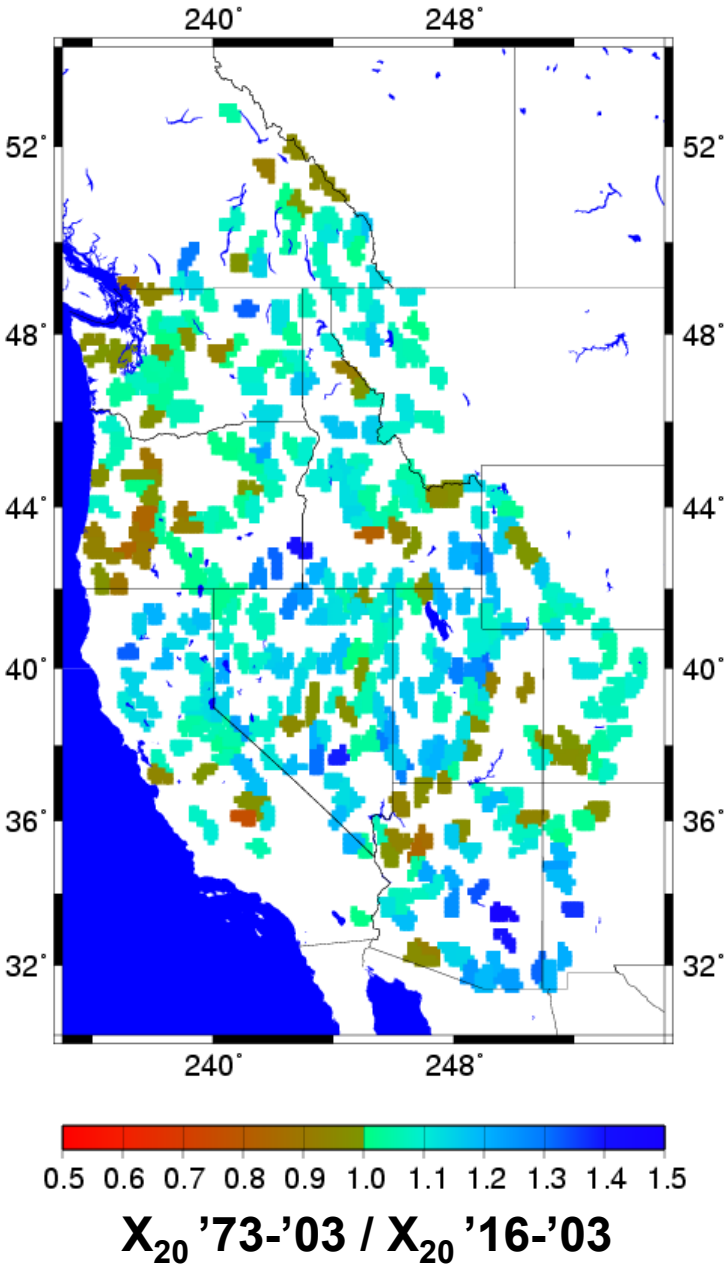
Simulated Changes in the 20-year Flood Associated with 20th Century Warming

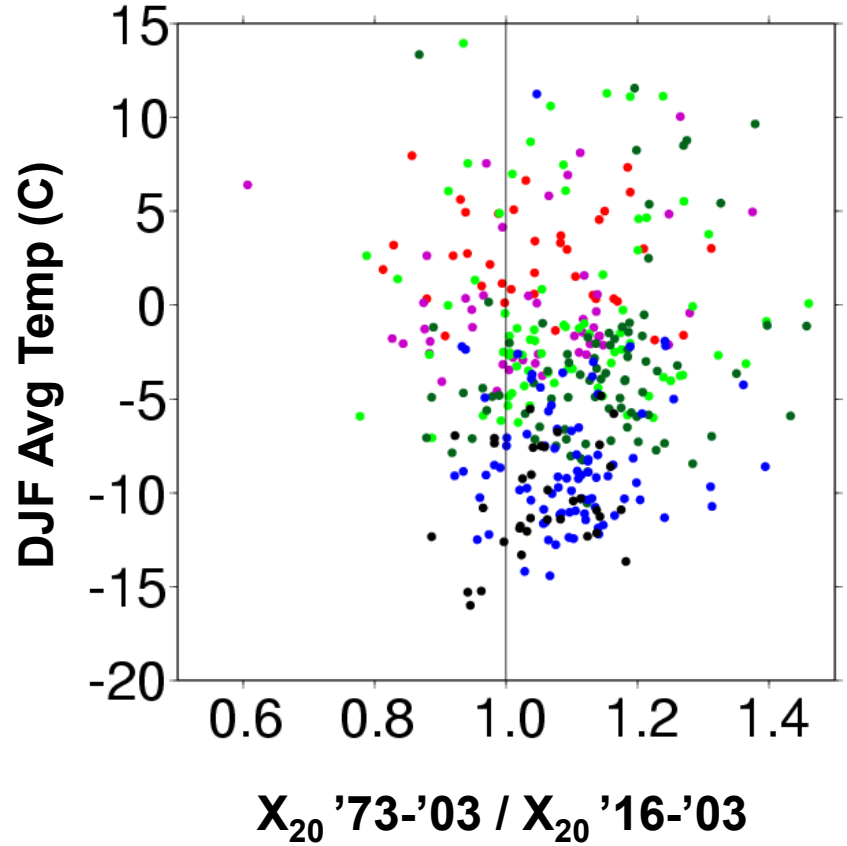


Regionally Averaged Cool Season Precipitation Anomalies



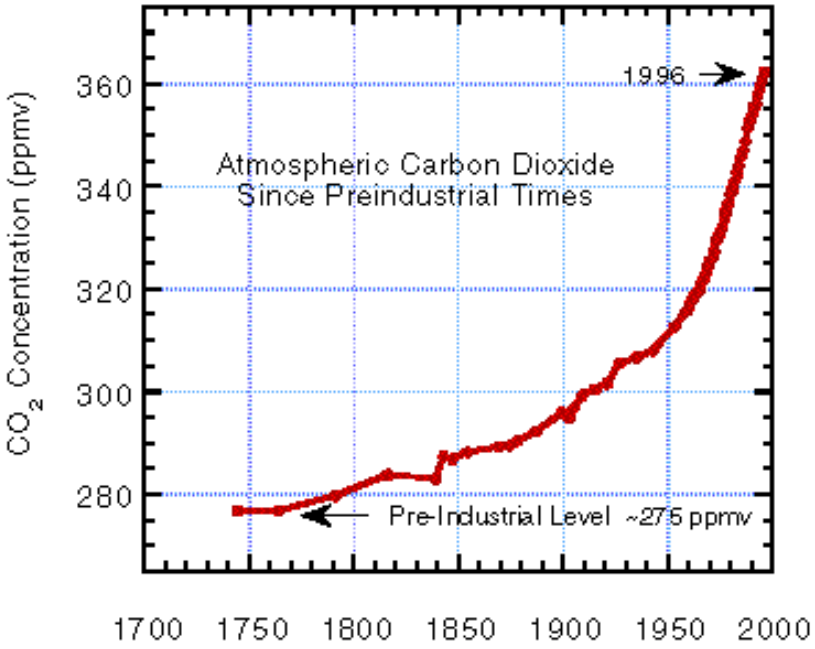
20-year Flood for “1973-2003” Compared to “1916-2003” for a Constant Late 20th Century Temperature Regime

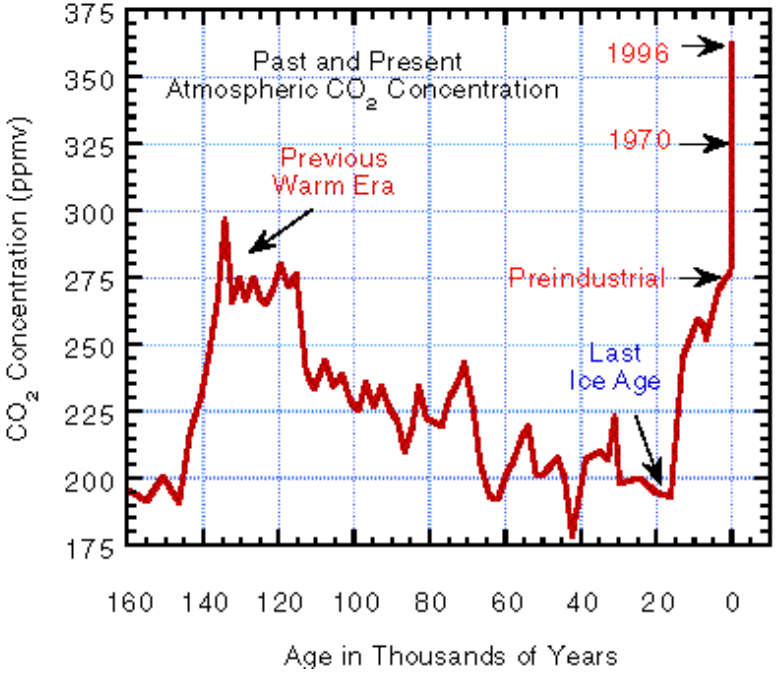




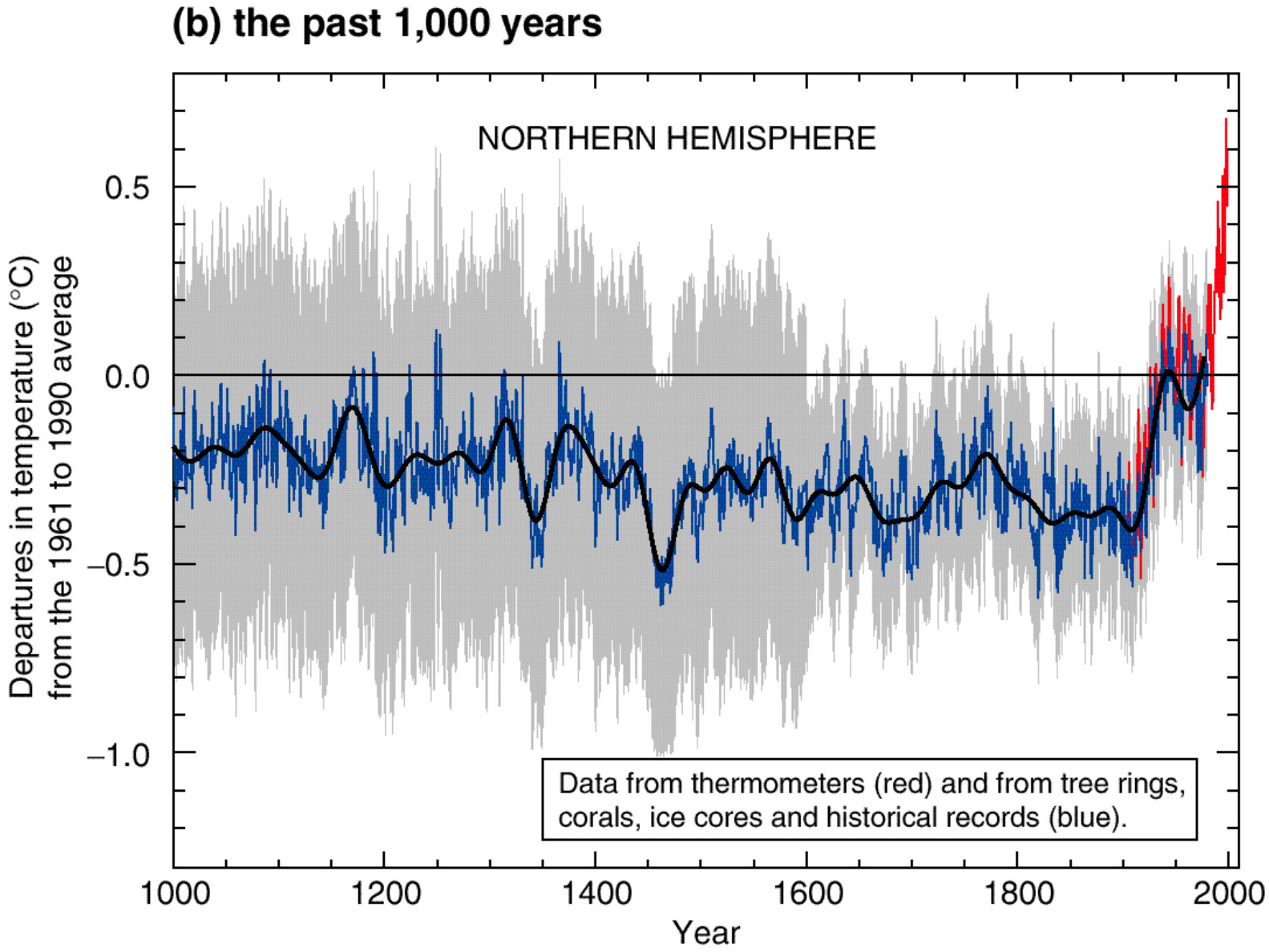
Global Climate Change Scenarios and Hydrologic Impacts for the PNW

Humans are altering atmospheric composition

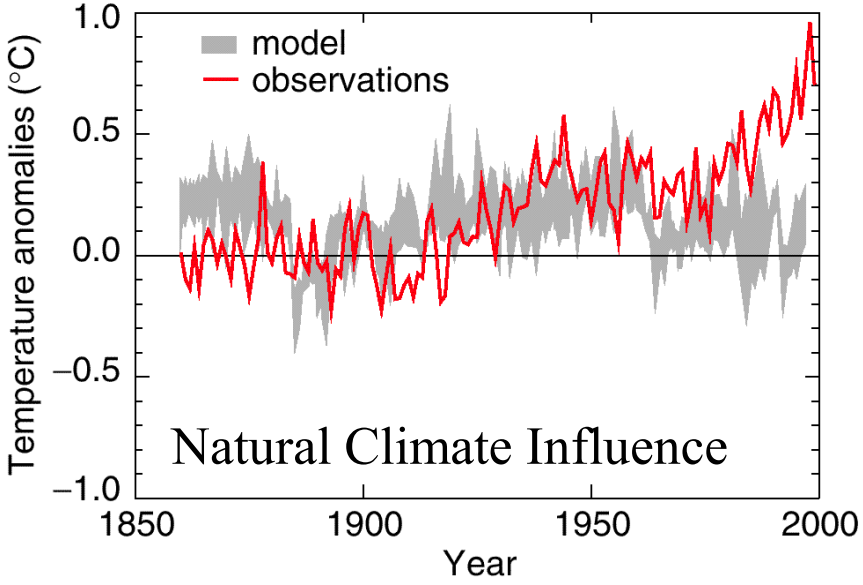


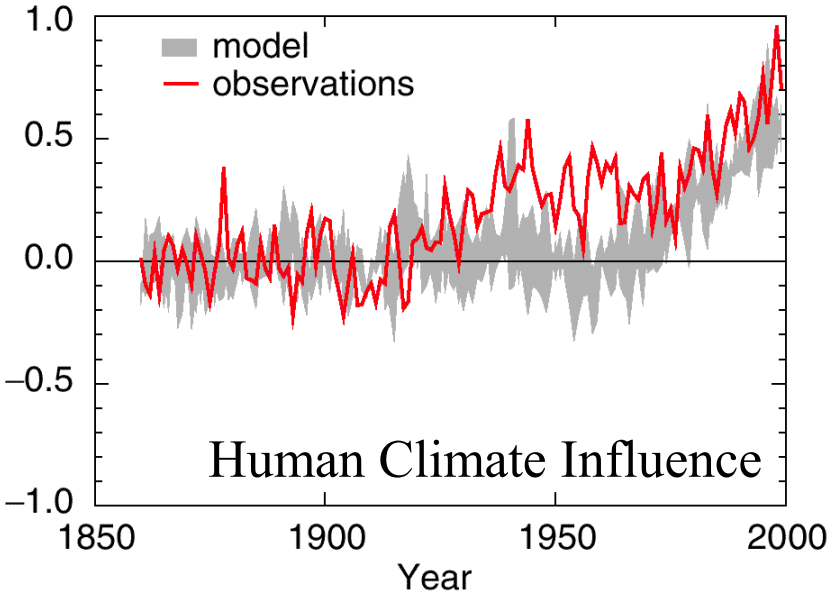


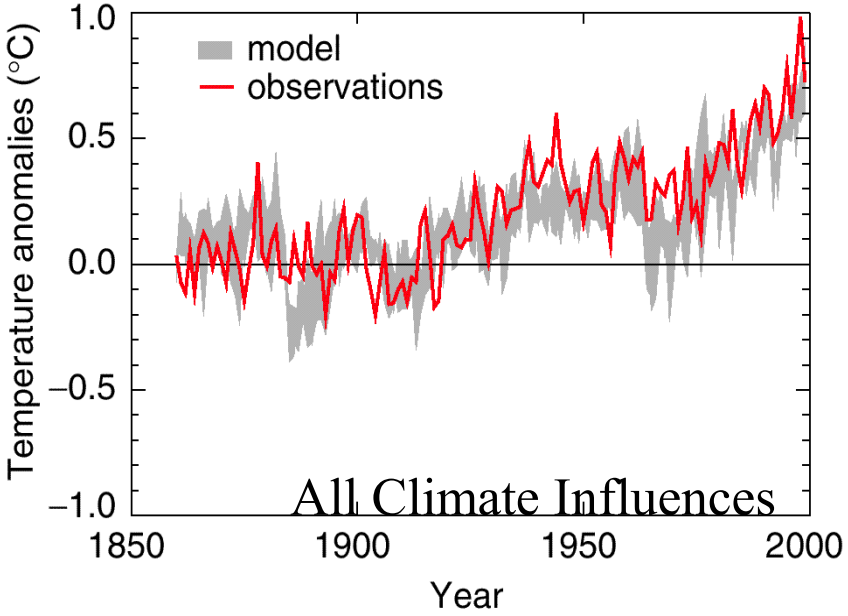
The earth is warming -- abruptly

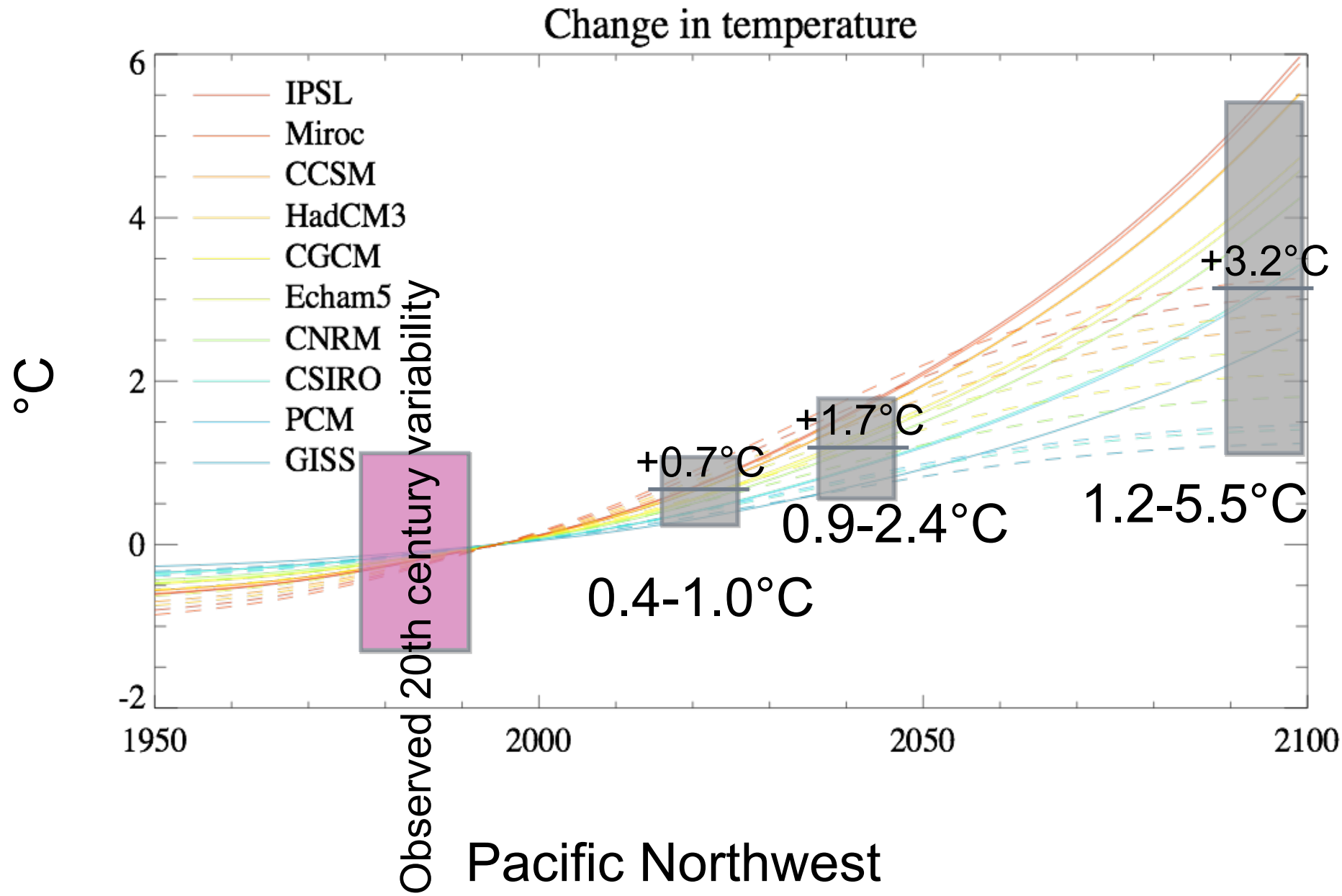


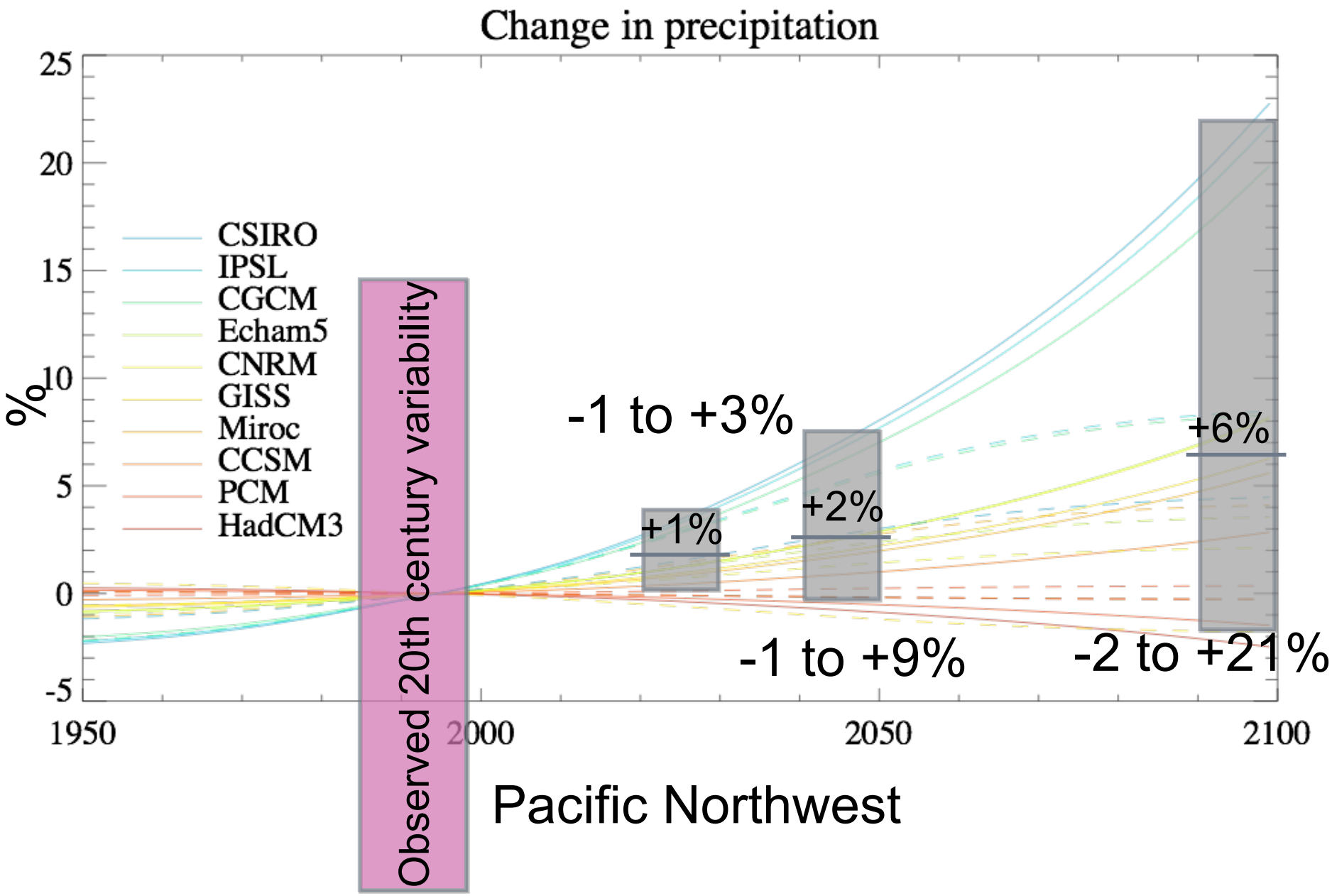
Natural AND human influences explain the observations best.





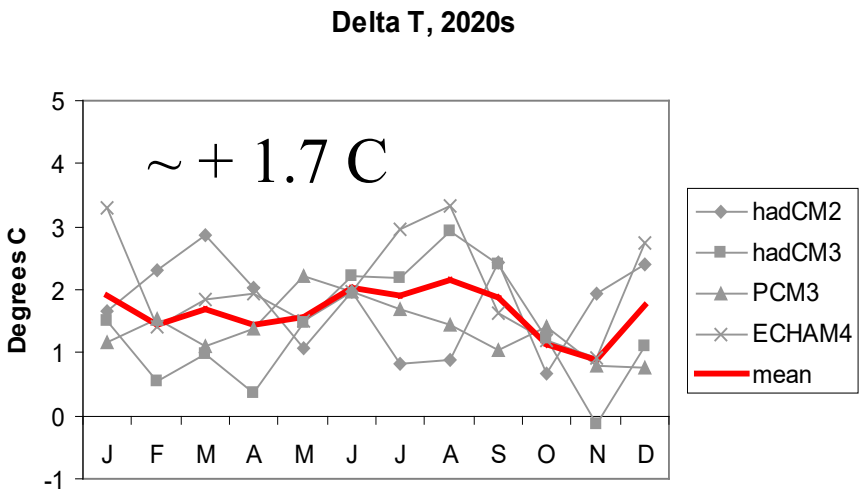


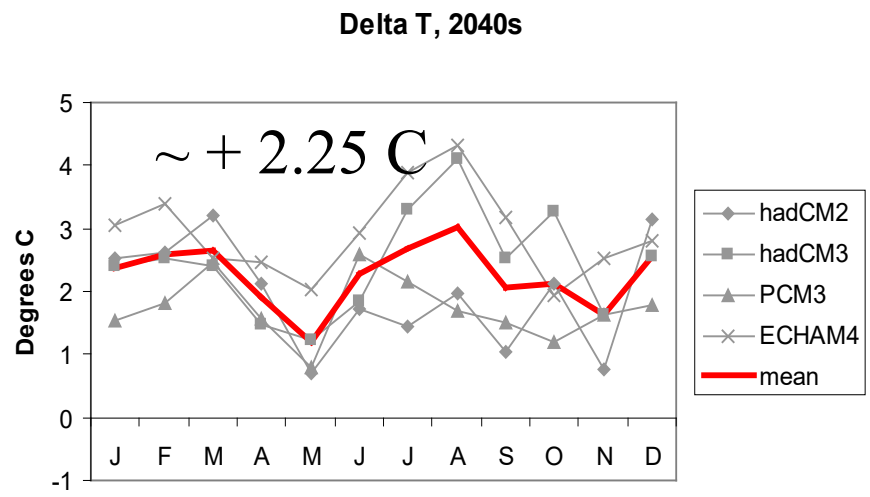

Change in temperature
°C
6
4
2
0
-2
1950
2000
2050
2100
IPSL
Miroc
CCSM
HadCM3
CGCM
Echam5
CNRM
CSIRO
PCM
GISS
Observed 20th century variability
+0.7°C
+1.7°C
+3.2°C
0.4-1.0°C
0.9-2.4°C
1.2-5.5°C
Pacific Northwest

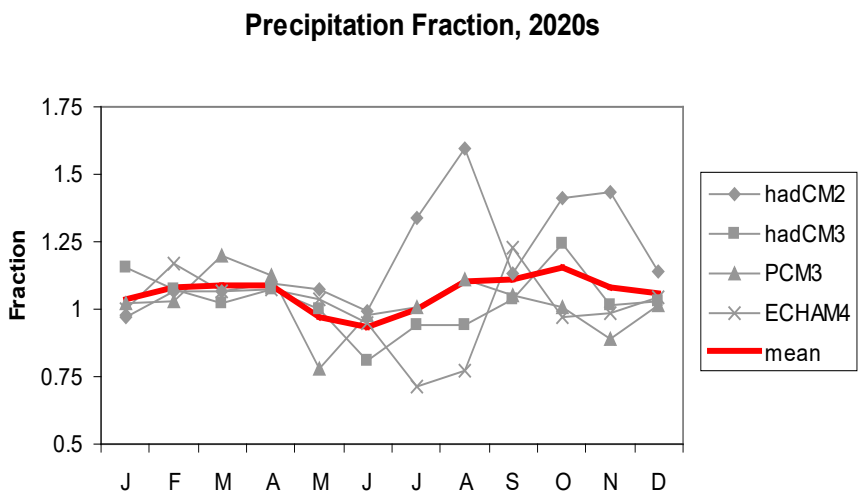


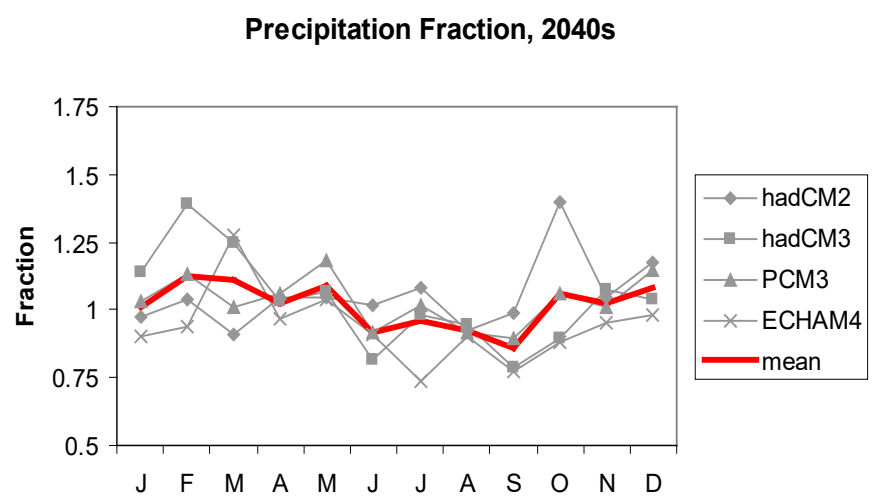
Pacific Northwest

Four Delta Method Climate Change Scenarios for the PNW



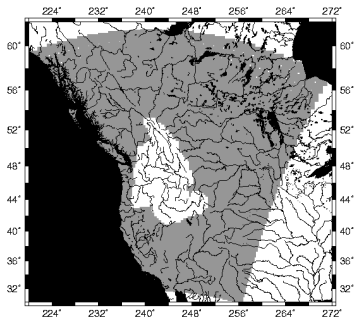




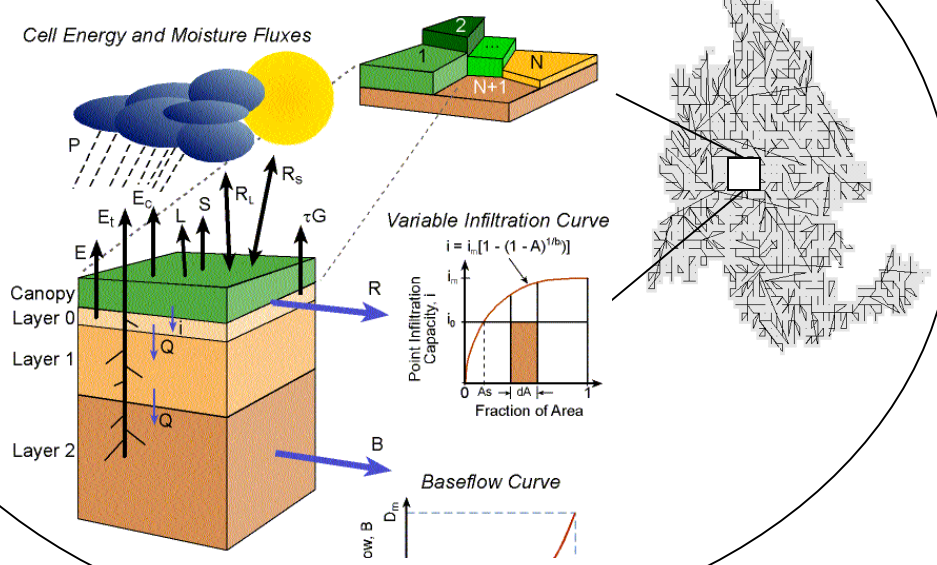


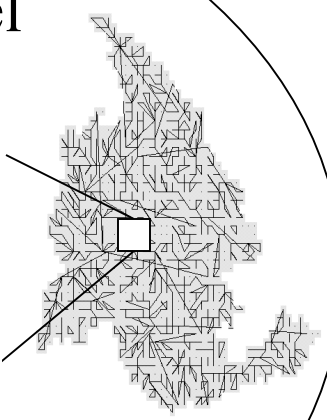
Somewhat wetter winters and perhaps somewhat dryer summers

Changes in Mean Temperature and Precipitation or Bias Corrected Output from GCMs

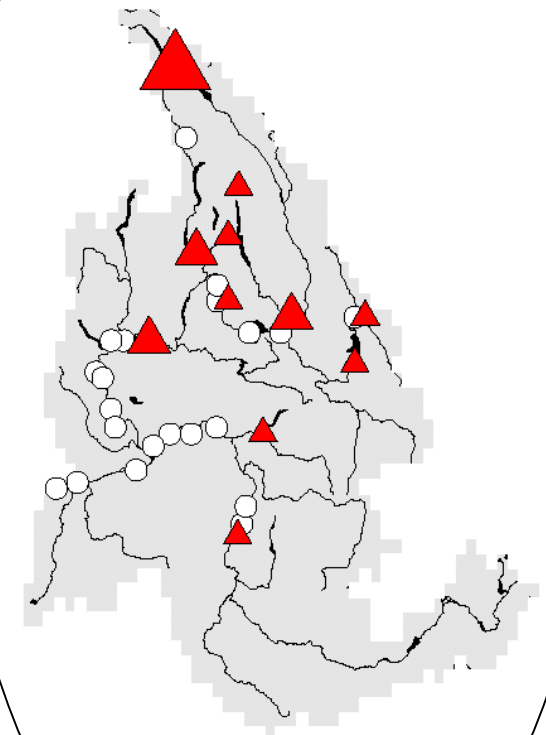


VIC
Hydrology Model

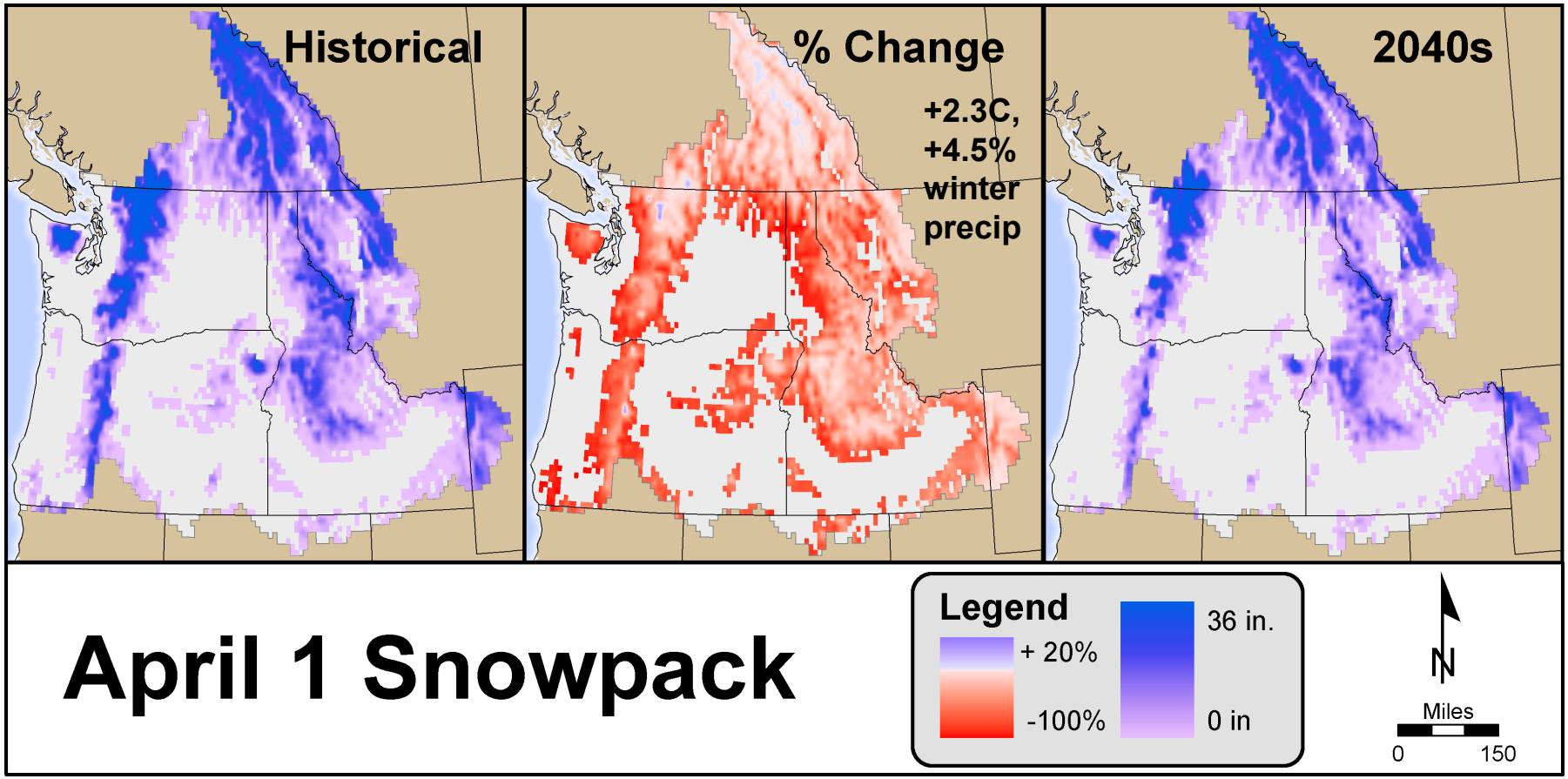




ColSim
Reservoir Model

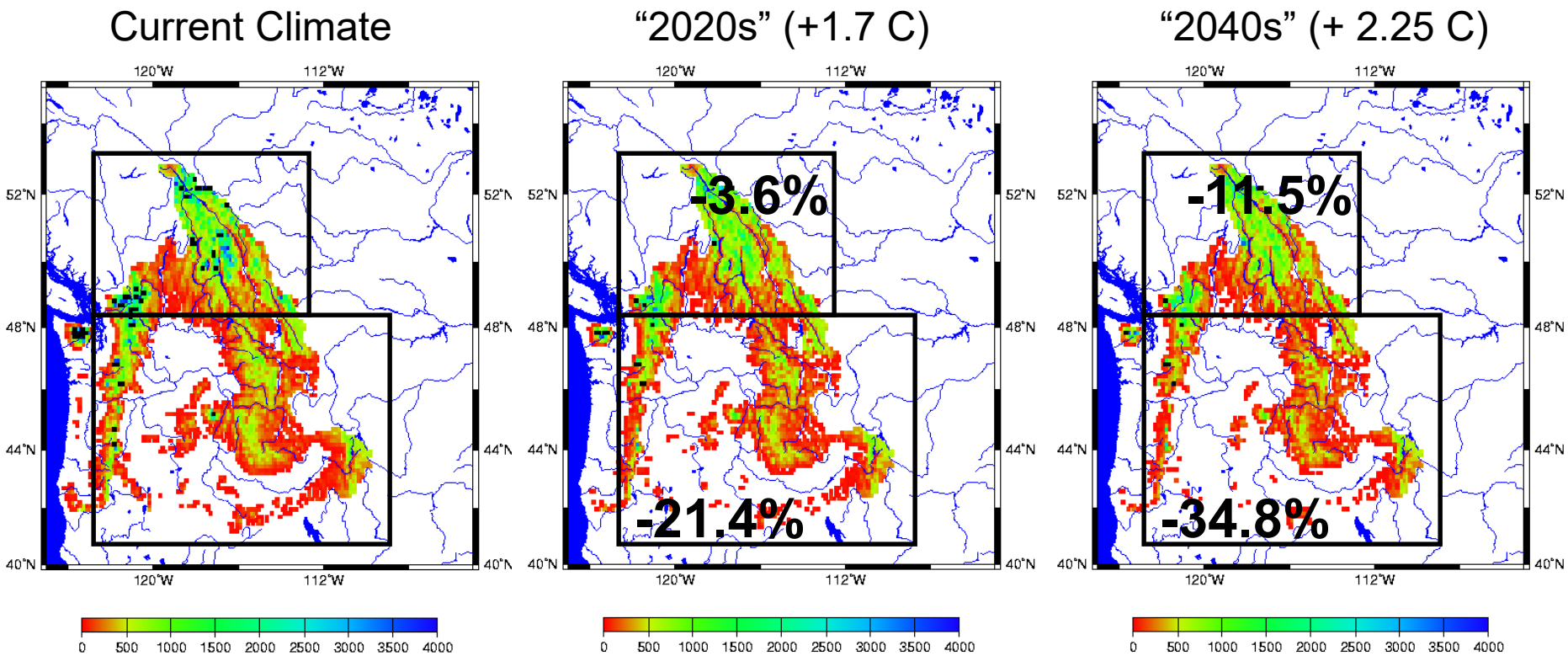


The warmest locations are most sensitive to warming

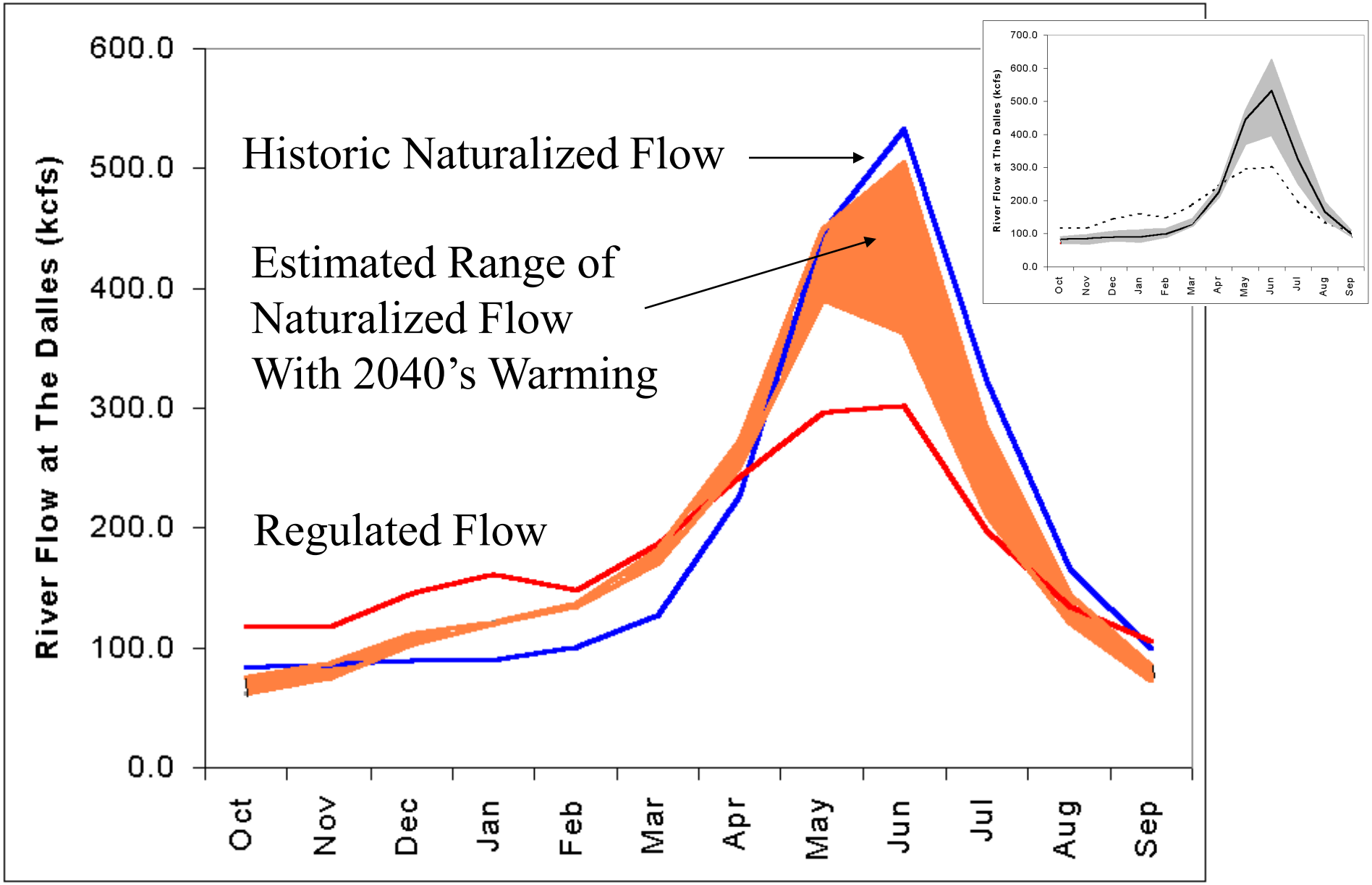


Changes in Simulated April 1 Snowpack for the Canadian and U.S. portions of the Columbia River basin

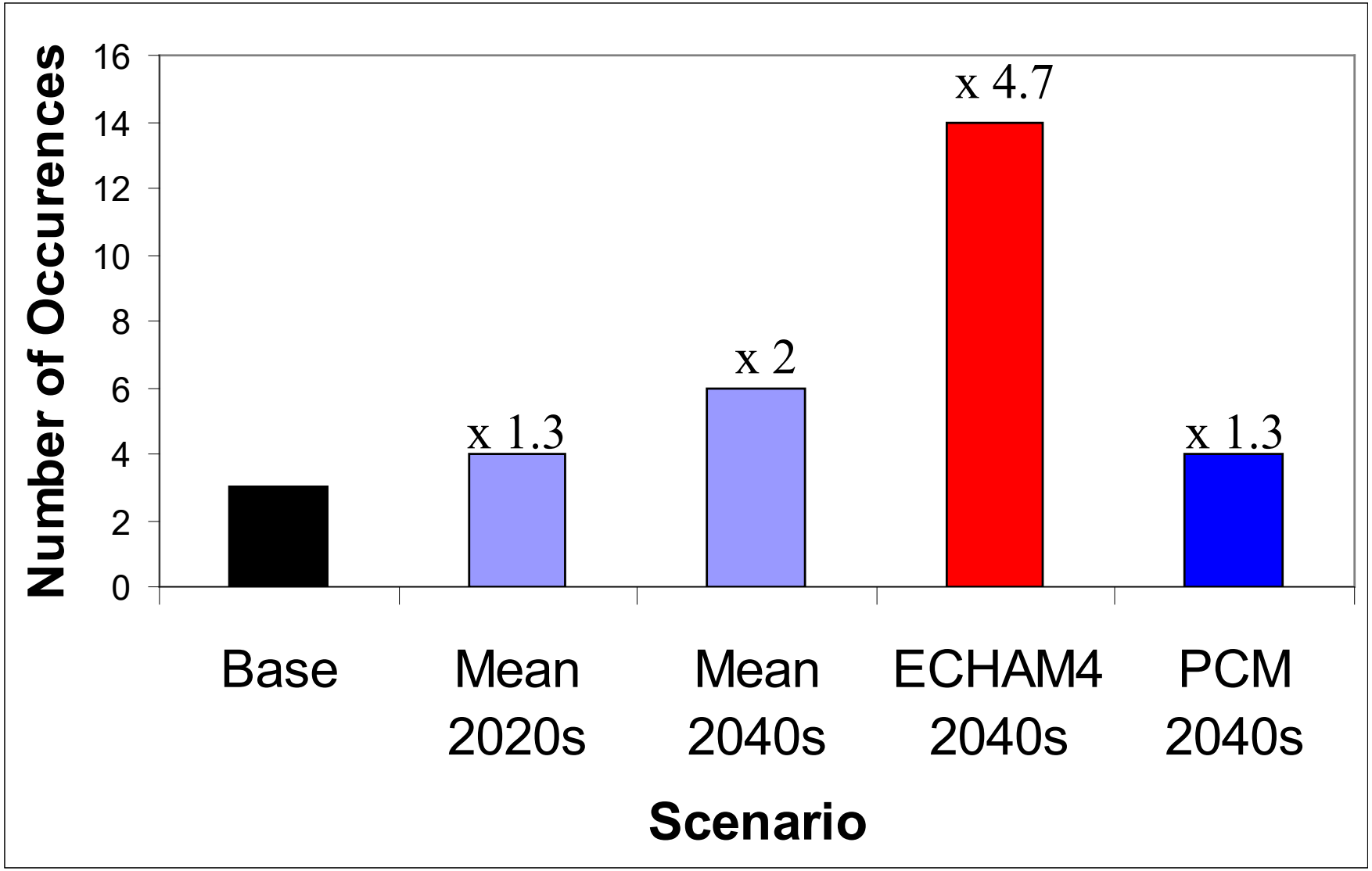
(% change relative to current climate)



Naturalized Flow for Historic and Global Warming Scenarios Compared to Effects of Regulation at 1990 Level Development



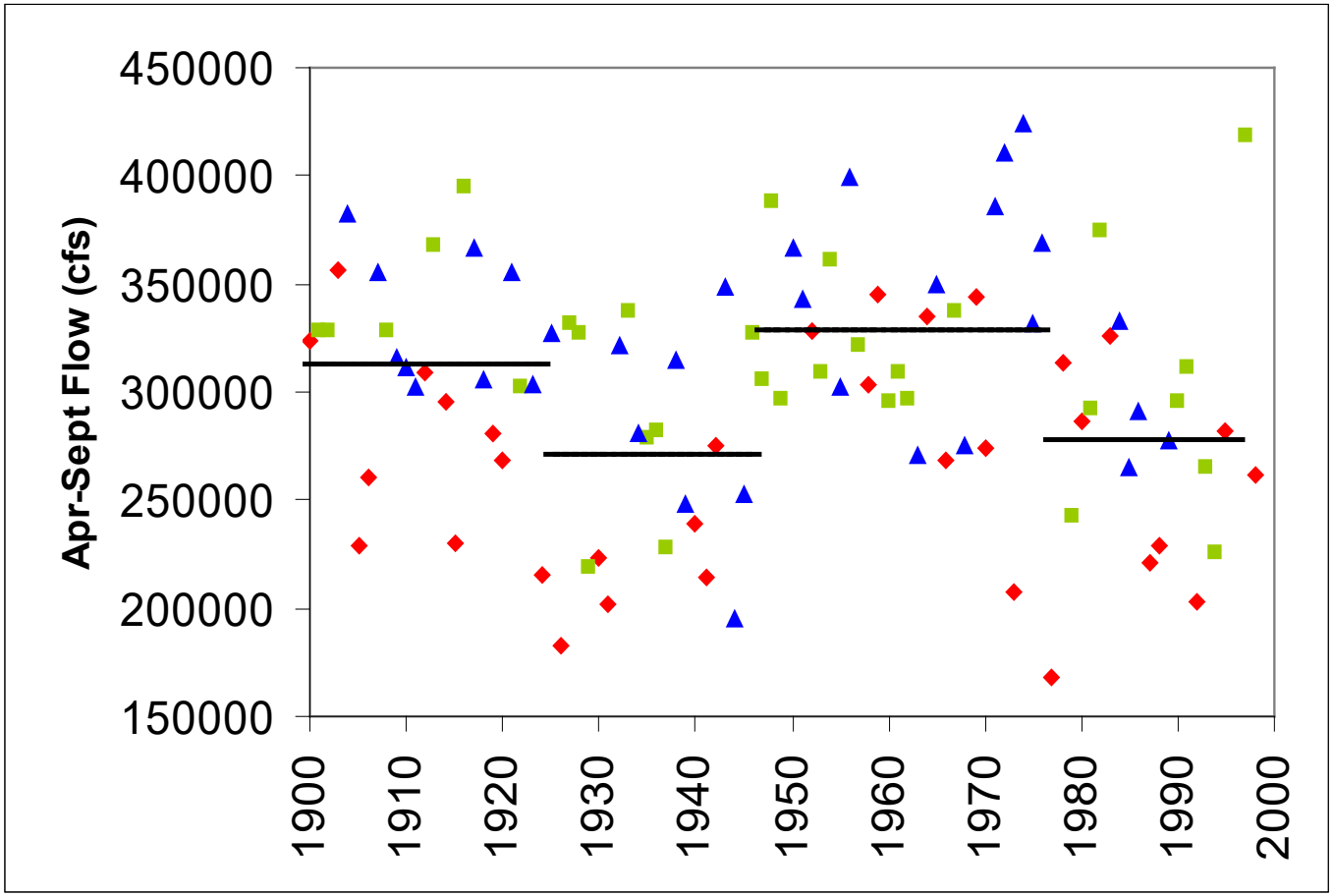
Frequency of Drought in the Columbia River Comparable to Water Year 1992 (data from 1962-1997)



Decadal Climate Variability and Climate Change

Will Global Warming be “Warm and Wet” or “Warm and Dry”?

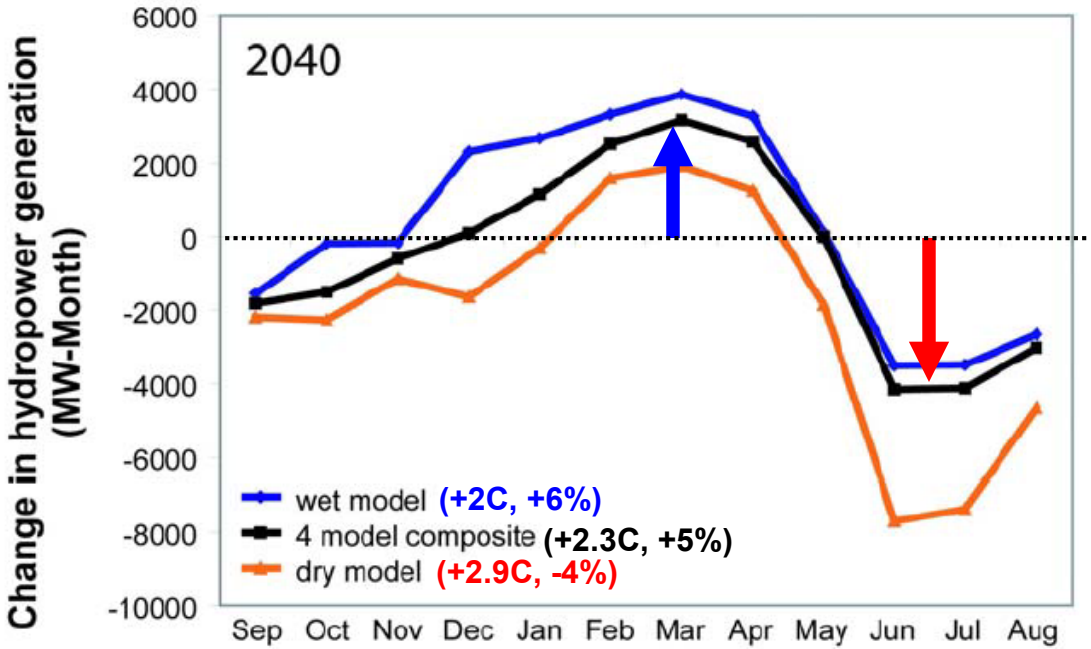
Answer: Probably BOTH!



Water Resources Implications for the Columbia River Basin

Impacts on Columbia Basin hydropower supplies

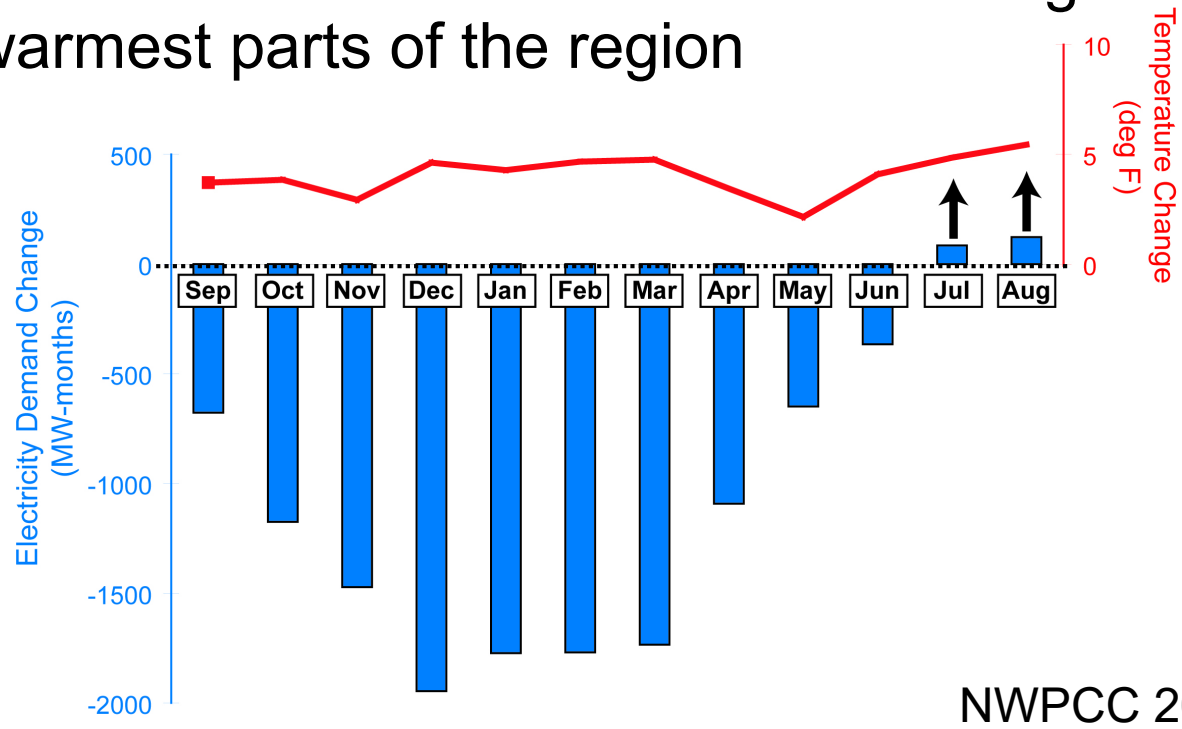
- **Winter and Spring:** increased generation
- **Summer:** decreased generation
- **Annual:** total production will depend primarily on annual precipitation



NWPCC (2005)

Warming climate impacts on electricity demand

- Reductions in winter heating demand
- Small increases in summer air conditioning demand in the warmest parts of the region



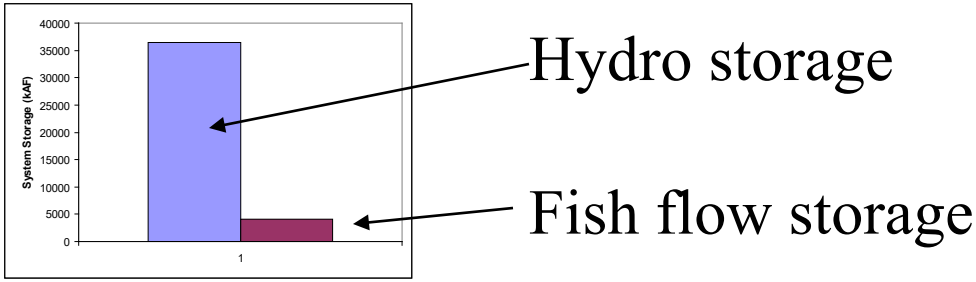
NWPCC 2005

Data source: NWPCC 5th Report Appendix N (2005)
Figure by: Climate Impacts Group, University of Washington

Managed Flow Augmentation

•The flow needed to provide acceptable flow velocity for juvenile transport is frequently higher than natural flow, particularly in late summer (I.e. use of storage is required). Climate change increases the amount of storage required to meet flow targets.

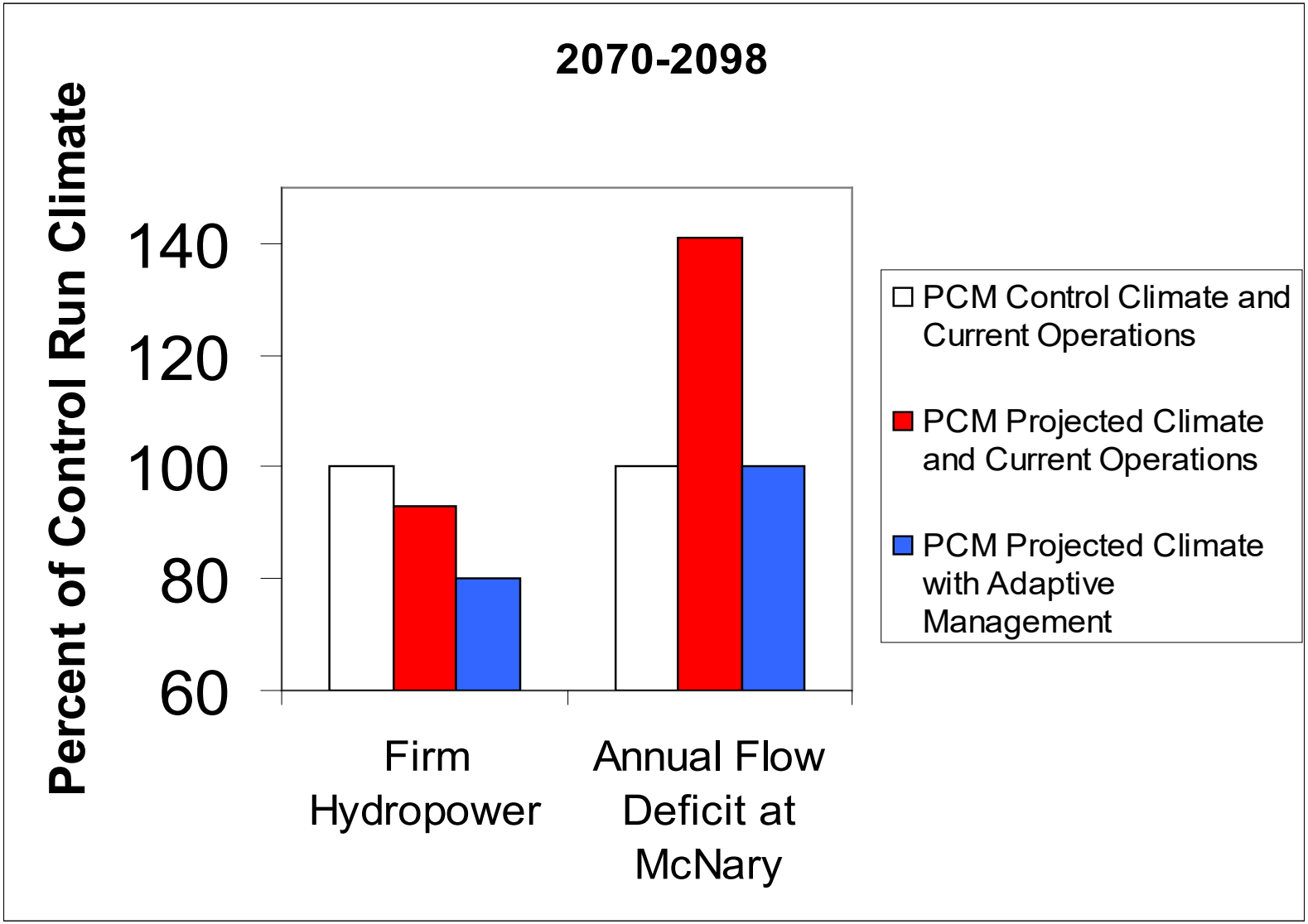
•Currently very little storage is allocated to fish in comparison with hydropower.



•In a conflict between hydro or irrigation and fish flow, the current reservoir operating policies are designed to protect hydro and irrigation (fish flow storage allocation for main stem and Snake River flow targets is at the top of a shared reservoir storage pool)

•The Columbia River Treaty does not provide explicitly for summer flow in the U.S. (transboundary issues). Compare with guaranteed winter releases associated with flood control.

Adaptation to climate change will require complex tradeoffs between ecosystem protection and hydropower operations



Source: Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier, 2004, Mitigating the effects of climate change on the water resources of the Columbia River basin, Climatic Change, Vol. 62, Issue 1-3, 233-256

Flood Control vs. Refill

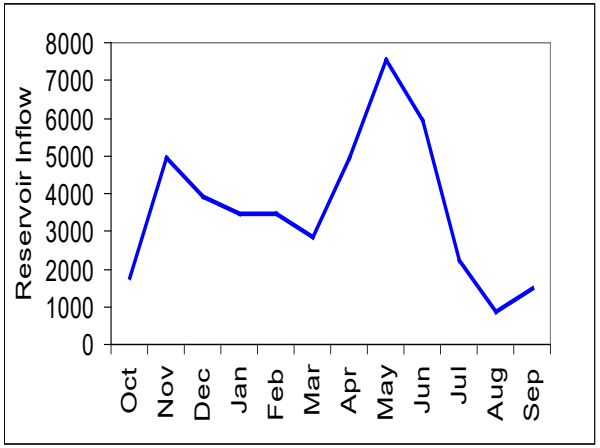
Maintaining an appropriate balance between flood protection and the reliability of reservoir refill is crucial to many water resources objectives in the Columbia Basin.

As streamflow timing shifts move peak flows earlier in the year, flood evacuation schedules may need to be revised both to protect against early season flooding and to begin refill earlier to capture the (smaller) spring freshet.

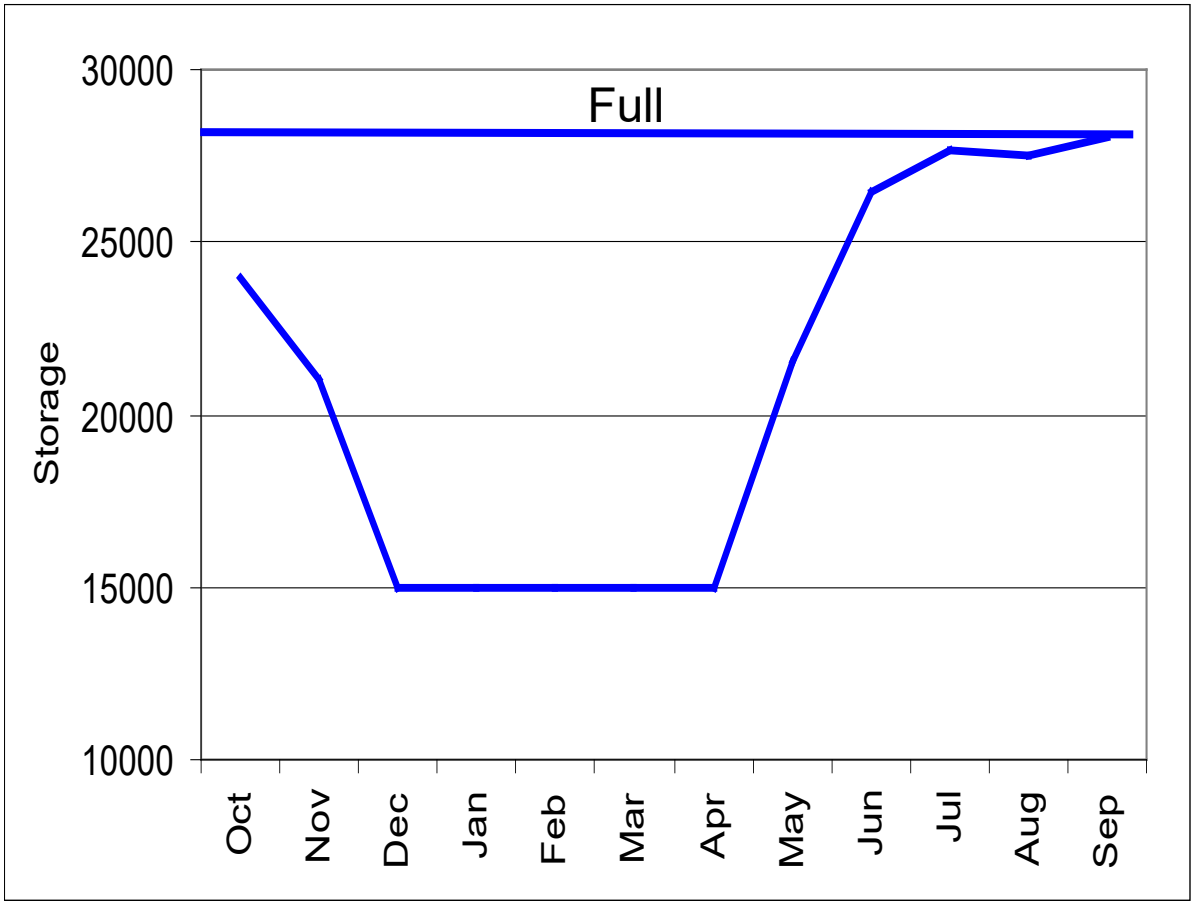
Model experiments (see Payne et al. 2004) have shown that moving flood evacuation two weeks to one month earlier in the year helps mitigate reductions in refill reliability associated with streamflow timing shifts.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier, 2004, Mitigating the effects of climate change on the water resources of the Columbia River basin, Climatic Change, Vol. 62, Issue 1-3, 233-256

Flood Control vs. Refill

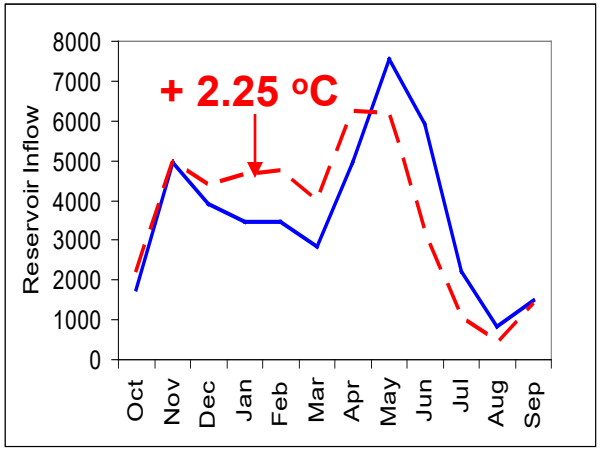


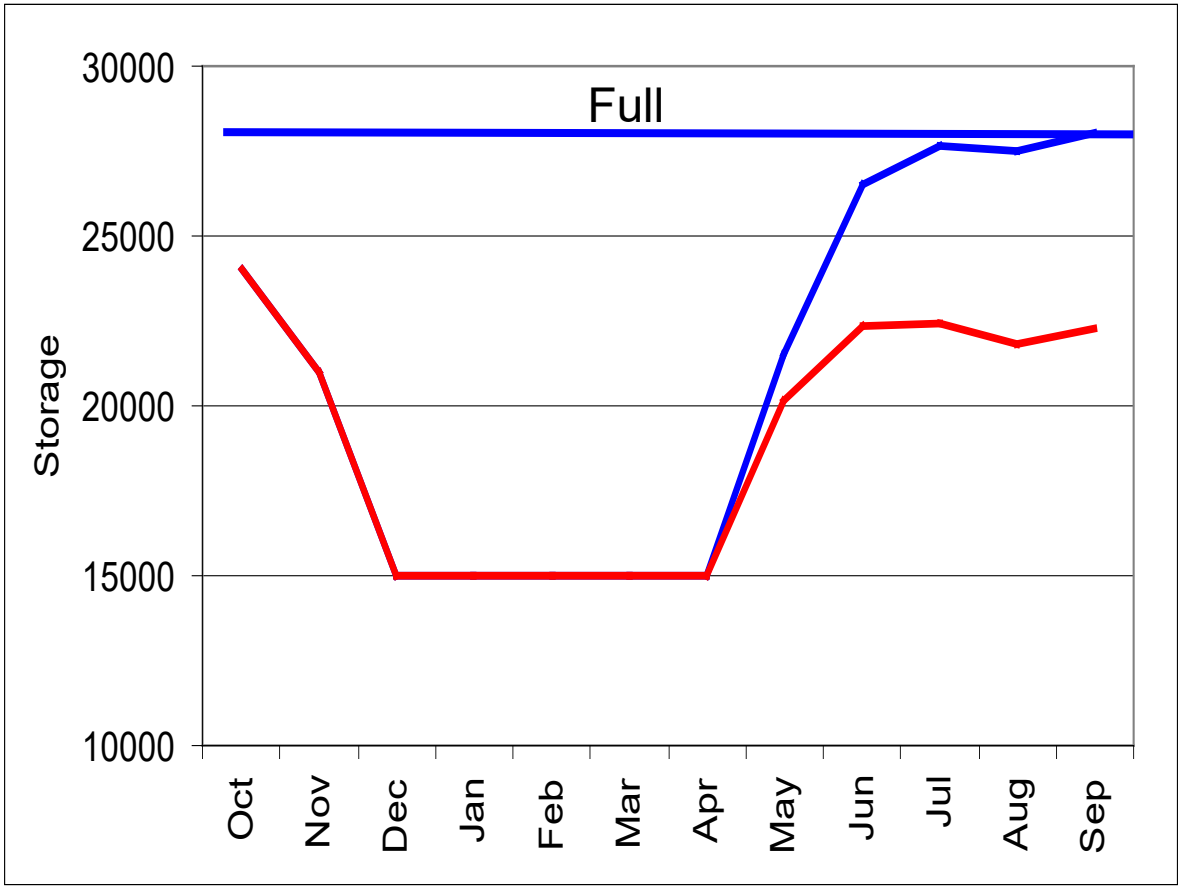
— : **Current Climate**



Flood Control vs. Refill

Streamflow timing shifts can reduce the reliability of reservoir refill



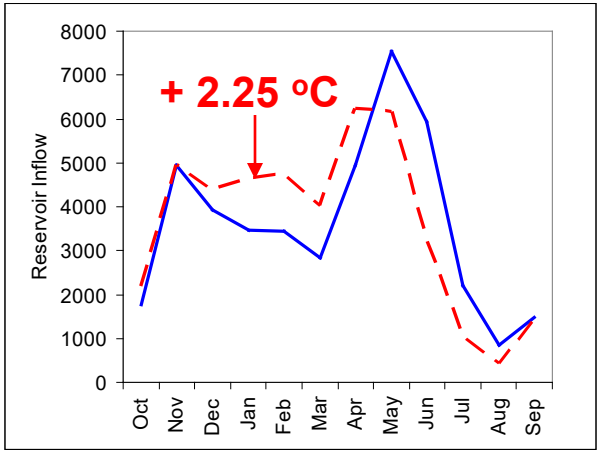


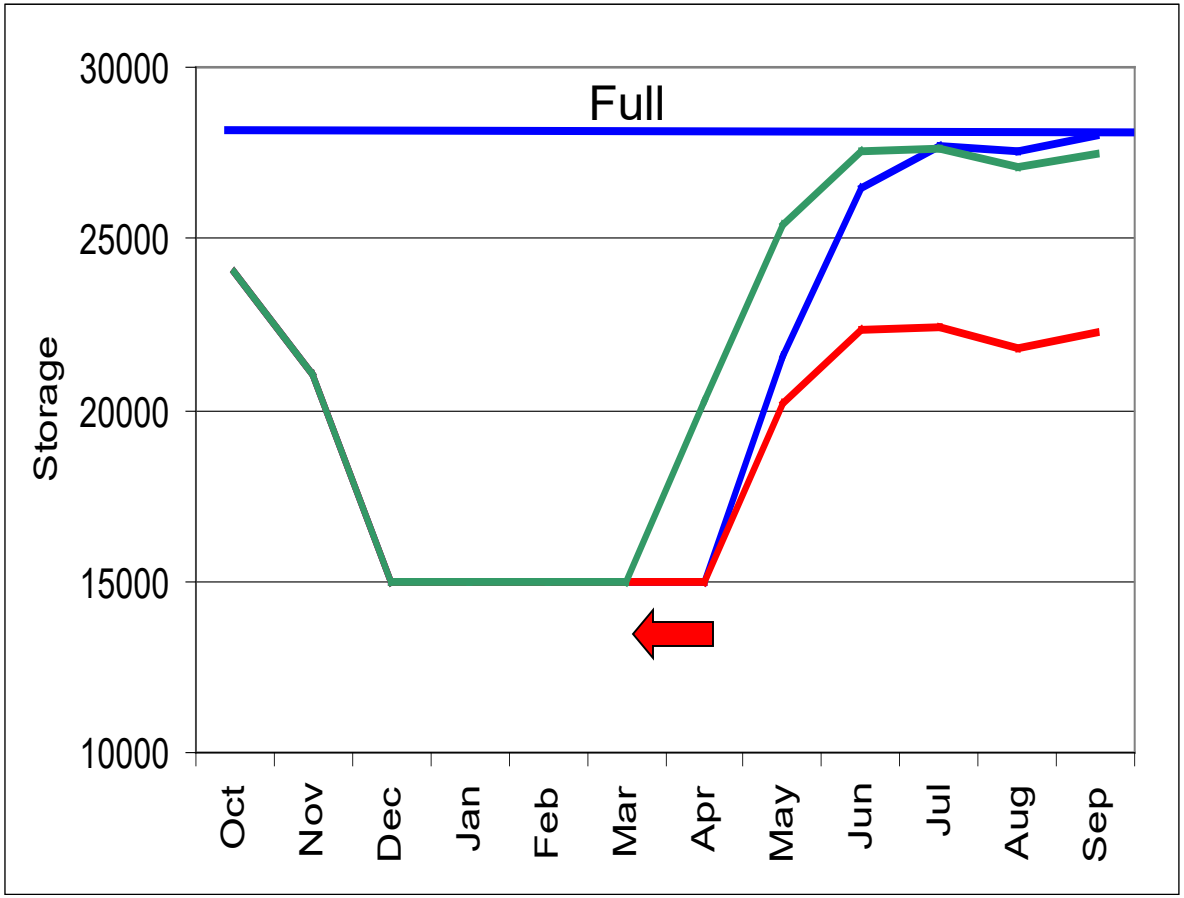
: Current Climate

: + 2.25 °C No adaption

Flood Control vs. Refill

Streamflow timing shifts can reduce the reliability of reservoir refill





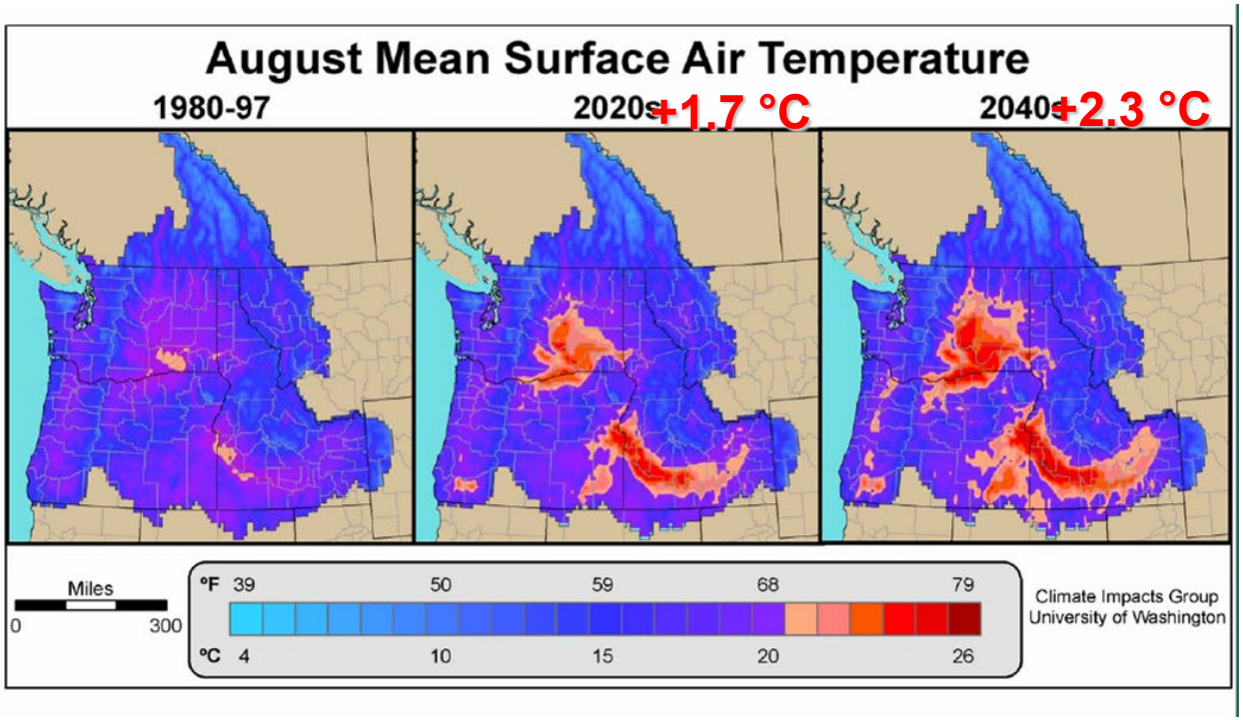
— : **Current Climate**

— : **+ 2.25 °C No adaption**

— : **+ 2.25 °C plus adaption**

Temperature thresholds for coldwater fish in freshwater

- **Warming temperatures will increasingly stress coldwater fish in the warmest parts of our region**
  - A monthly average temperature of 68ºF (20ºC) has been used as an upper limit for resident cold water fish habitat, and is known to stress Pacific salmon during periods of freshwater migration, spawning, and rearing



Implications for Transboundary Agreements

•Snowpack in the BC portion of the Columbia basin is much less sensitive to warming in comparison with portions of the basin in the U.S. and streamflow timing shifts will also be smaller in Canada.

•As warming progresses, Canada will have an increasing fraction of the snowpack contributing to summer streamflow volumes in the Columbia basin.

•These differing impacts in the two countries have the potential to “unbalance” the current coordination agreements, and will present serious challenges to meeting instream flows on the U.S. side.

•Changes in flood control, hydropower production, and instream flow augmentation will all be needed.

•Long-range planning is needed to address these issues.

Conclusions

•Climate change will result in significant hydrologic changes in the Columbia River and its tributaries.

•These changes will not be equally distributed throughout the region or between different water management objectives.

•With hydrologic changes, there will come a need to “rebalance” the system to compensate for these different impacts in each sector.

•This “rebalancing” will take time and will involve complex (and contentious) tradeoffs between different management objectives.

•We have the tools that we need to begin planning for a warmer future.

•We should begin to include climate information in planning now to reduce the severity of future impacts as much as possible.

Selected References and URL's

Climate Impacts Group Website

http://www.cses.washington.edu/cig/

White Papers, Agenda, Presentations for CIG 2001 Climate Change Workshop

http://jisao.washington.edu/PNWimpacts/Workshops/Skamania2001/WP01_agenda.htm

Climate Change Streamflow Scenarios for Water Planning Studies

http://www.ce.washington.edu/~hamleaf/climate_change_streamflows/CR_cc.htm

Northwest Power and Conservation Council Columbia Basin Hydropower Study

http://www.nwppc.org/energy/powerplan/plan/Default.htm

Refs on Climate Variability and Climate Change

http://www.ce.washington.edu/~hamleaf/hamlet/publications.html

A Comprehensive Hydrologic Data Base Incorporating IPCC Climate Change Scenarios to Support Long-Range Water Planning in the Columbia River Basin

Overview of Study Design, Downscaling Approaches, and Products

Alan F. Hamlet

•JISAO/CSES Climate Impacts Group
•Dept. of Civil and Environmental Engineering
University of Washington

Department of Civil and Environmental Engineering

Study Partnerships

Funding Partners:

WA Department of Ecology (via HB 2860)
Bonneville Power Administration
Northwest Power and Conservation Council
Oregon Water Resources Department
BC Ministry of the Environment

Collaborative Partners:

Montana Department of Natural Resources
Idaho Department of Water Resources
USBR, Boise Regional Office
USACE, Seattle and Portland Districts

Study Objectives:

Provide comprehensive hydrologic data bases to support water planning at a range of spatial and temporal scales in the Columbia River basin and PNW.

Increase spatial resolution of hydrologic models to capture smaller basins relevant to planning.

Conduct pilot studies using fine scale hydrologic simulation tools and compare to macro-scale tools that are currently being more widely implemented.

Improve range of products and services available, and construct tools and data processing methods to make future updates easier (and less expensive) to produce.

Key Deliverables:
This section lists key deliverables for the research project.

Deliverable 1	Hydrologic data base of water balance variables and streamflow scenarios (both natural and "regulated") for up to 200 Ecology selected streamflow locations for both historic and 21st century climate conditions. (See detailed description of these deliverables below.)	
Deliverable 2	Journal articles and/or technical reports	
Deliverable 3	Develop a user friendly web-based product for accessing and summarizing the VIC hydrologic and meteorological data bases. (See detailed description below.)	
Deliverable 4	Summary report describing the VIC data base and web server.	
Deliverable 5	Additional analysis in pilot watersheds comparing VIC and DHSVM results and associated technical reports or journal articles describing these studies. (See detailed description below.)	

Track I: Historic Driving Data, Downscaling Procedures, Climate Change Scenarios

Task 1	Develop historic driving data at 1/16th degree from 1915- 2005	
Task 2	Develop temperature and precipitation downscaling procedures suitable for both monthly water supply planning and subsequent flood analysis	
Task 3	Produce downscaled 1/16th degree driving data sets associated with each of 10 GCM scenarios for “2020” “2050” “2080” time periods	
Task 4	Produce a high resolution driving data set for four sub-watersheds at 150m resolution	
Task 5	Summary Reports	

Track II: Development of Hydrologic Models and Hydrologic Data Bases		
Task 1	Develop a 1/16th degree VIC model over the Columbia River basin.	
Task 2	Calibrate and develop statistical bias correction procedures for the 1/16th degree VIC model for up to 150 streamflow locations in the Columbia River Basin to be determined by Ecology.	
Task 3	Run the 1/16th degree VIC model for each of 10 GCM scenarios for the three time periods, and produce streamflow scenarios for up to 200 sites to be determined by Ecology.	
Task 4	Using available diversion and return data and typical patterns of regulation (to be provided by Ecology), adjust natural flow scenarios to estimate monthly "regulated" flows for up to 200 sites (as above).	
Task 5	Develop and archive a comprehensive hydrologic data base	
Task 6	Develop a high-resolution DHSVM implementation for four sub basins in the Columbia River basin at 150m resolution, and calibrate the model for both streamflow and water temperature.	
Task 7	Summary Reports	

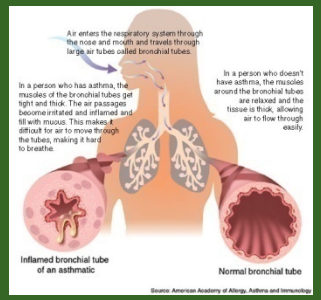
Track III: Preliminary User Interviews, Development of Web-Based Data Server, and Summary Report for the User Community.

Task 1	Conduct interviews with key stakeholders such that adequate feedback is obtained regarding deliverables desired.	
Task 2	Develop a user friendly web based product for accessing and summarizing hydrological and meteorological data.	
Task 3	Develop summary reports for the potential user communities.	

Overlap with the Washington State Climate Impacts Assessment (HB 1303)

A comprehensive climate change impacts assessment for Washington State

Human Health



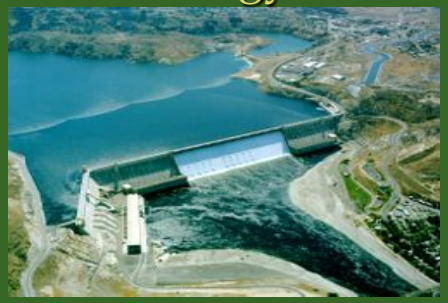
Infrastructure

Agriculture/Economics

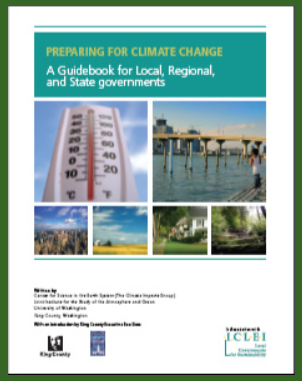
Water Resources

Coasts

Energy



Forest Resources



Adaptation

Salmon

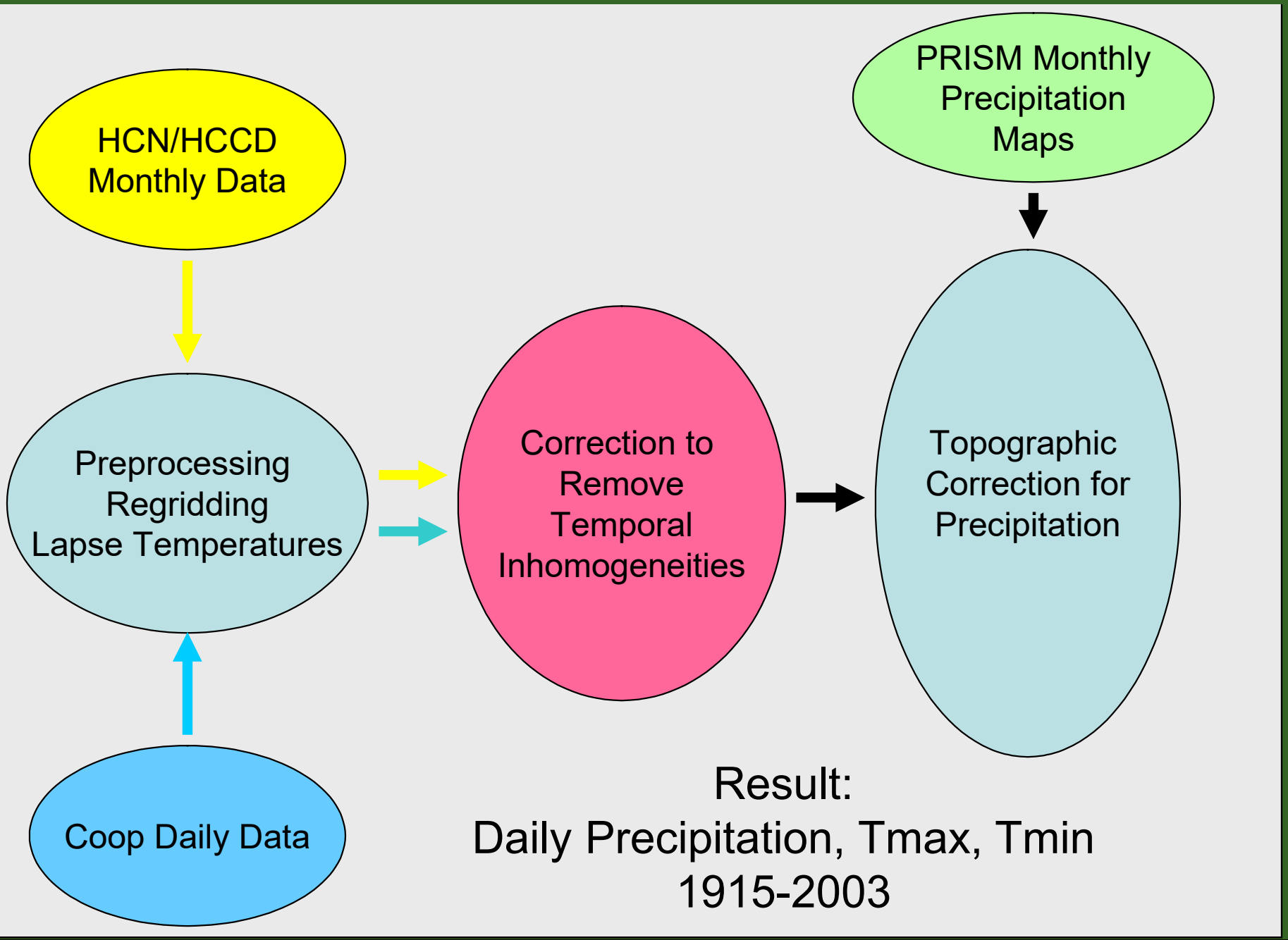
Project Domain: WA and the PNW

To assess impacts in water and other sectors, the analysis must include all of the PNW = **wide range of data available for all the PNW!**

Detailed case studies for water supply are being done for the Puget Sound Region and Yakima Basin

Overview of Meteorological Data and Downscaling Approaches

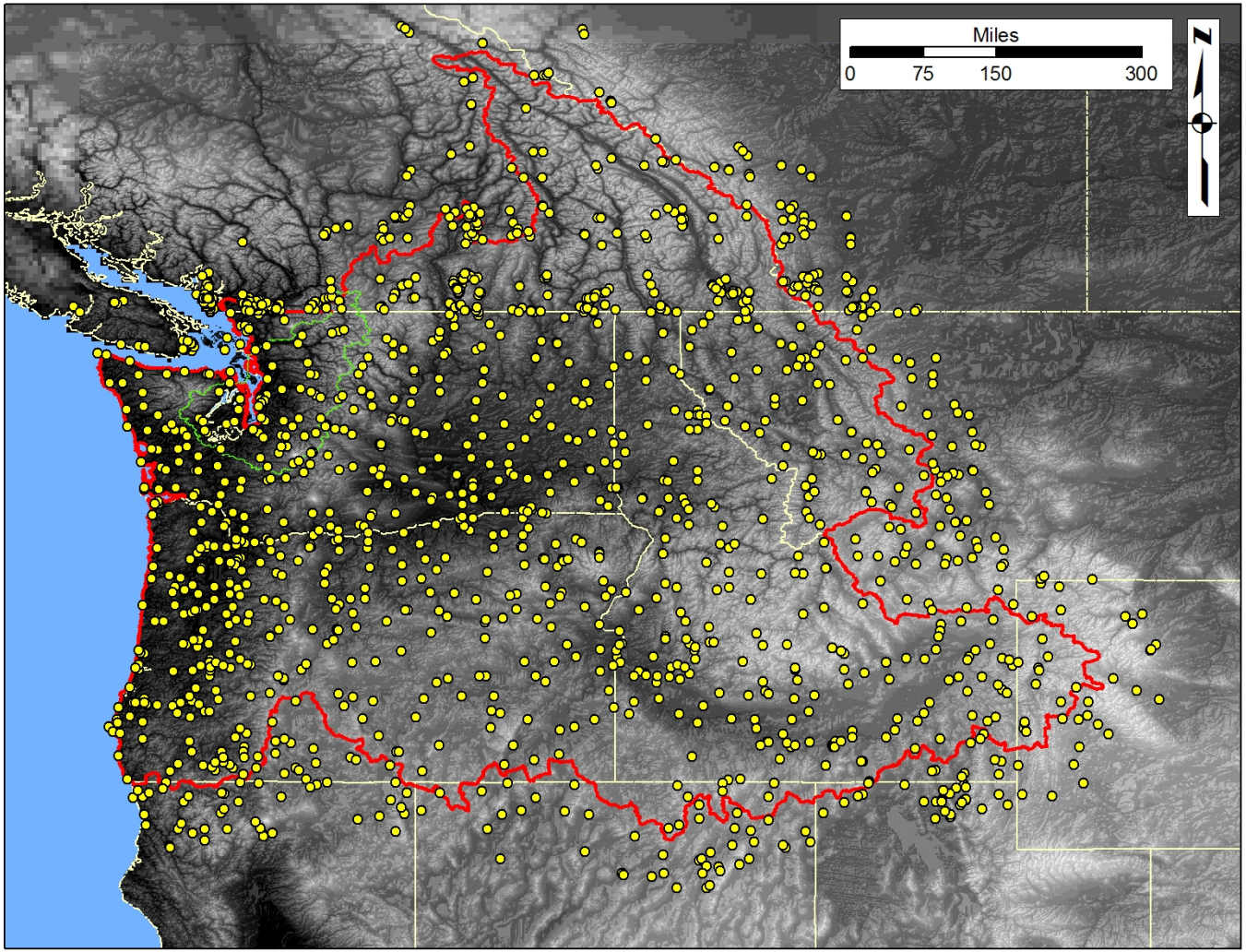
Existing Methods Used to Produce 1/8th Degree MET Products



Key Objectives for 2860 Project:

- Increase spatial resolution to 1/16th degree
- Extend data through 2006
- Select stations to include in gridding exercise more carefully
- Incorporate more data from Canada and improve quality control
- Resolve data processing issues identified in past efforts related to temporal corrections (tighter coupling to HCN data)
- Update to incorporate 1971-2000 PRISM means at 30 arc second resolution
- Incorporate the PRISM temperature maps and explore their utility in improving temperature lapse rates.
- Explore the use of different station lists in some parts of the domain (mainly effects the Puget Sound drainages)
- Create and archive derived meteorological data bases using the VIC model as a preprocessor.

Primary Meteorological Stations Used to Create Gridded Product (1915-2006)



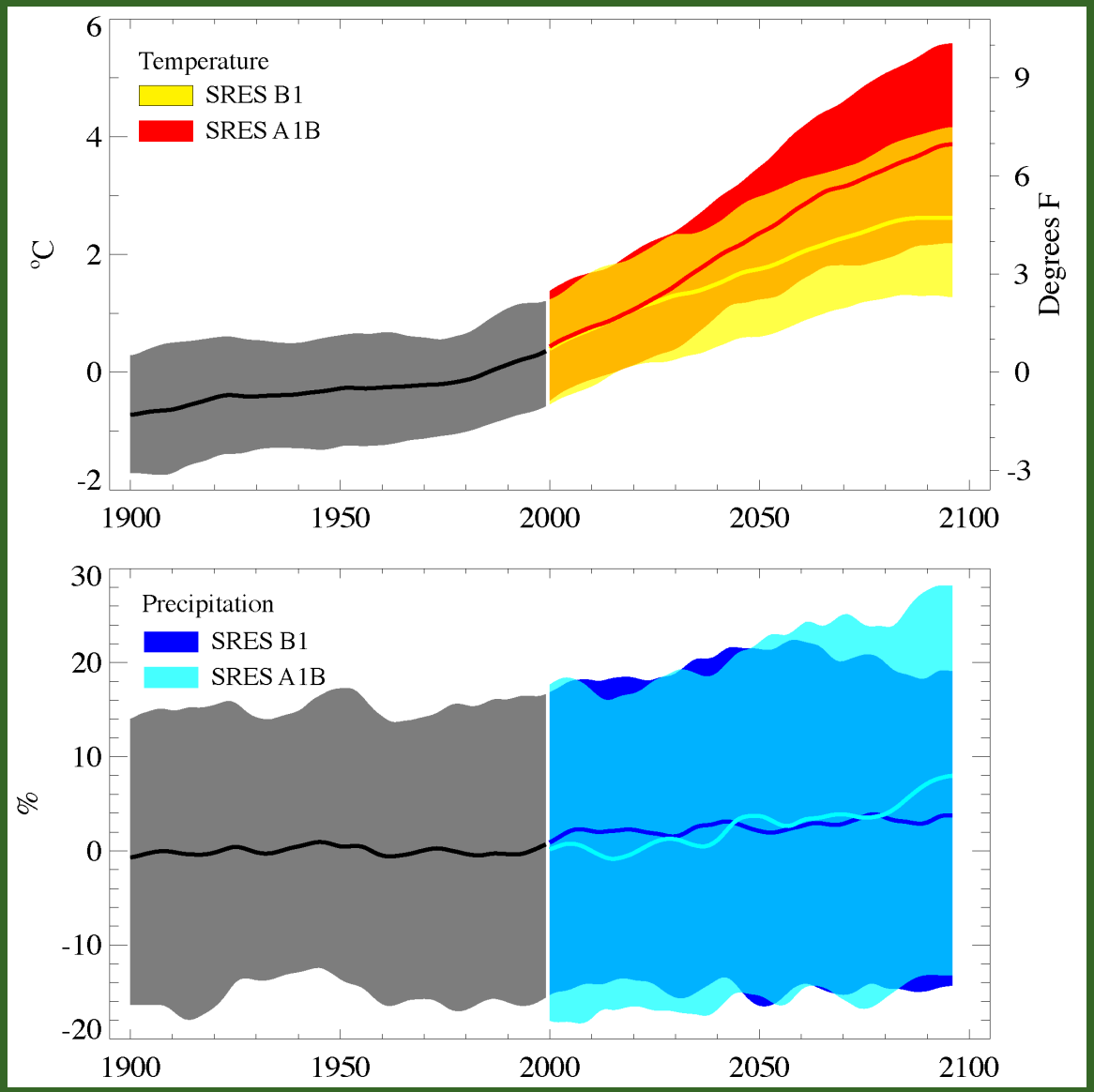
Status of Met Data Sets:

Data set has been completed, and has been thoroughly exercised in preliminary VIC simulations and the 1303 assessment.

Journal article is in progress, and will include comparisons with past data sets at 1/8th degree.

Downscaling Global Climate Change Scenarios for the PNW

21st Century Climate Impacts for the Pacific Northwest Region



Mote, P.W. and E. P. Salathe Jr., 2009: Future climate in the Pacific Northwest (in review)

Overview of Downscaling Approaches:

Delta Method

•Realistic daily time series and spatial variability.

•91 years of variability associated with each time frame and emissions scenario.

•Only incorporates changes in mean T and P.

Bias Corrected and Statistically Downscaled GCM Data (BCSD)

•Incorporates more information from the GCMs, but as a result may also inherit undesirable aspects of GCMs as well.

•Facilitates trend analysis, examination of potentially altered variability.

Hybrid Methods

•Takes time series and spatial behavior from the observed record, but incorporates more detailed statistical changes from the GCMs.

Dynamic Downscaling

•Uses meso-scale climate models. (Not proposed for this study.)

Typical Applications of Each Downscaling Approach:

Delta Method

•Sensitivity studies

•Summary of all GCM projections in one run (limited runs to identify the central tendency

Bias Corrected and Statistically Downscaled GCM Data (BCSD)

•Trend Analysis of Hydrologic Variables

•Ensemble uncertainty analysis for 30-year windows at any time in the 21st century (flexible time period of analysis)

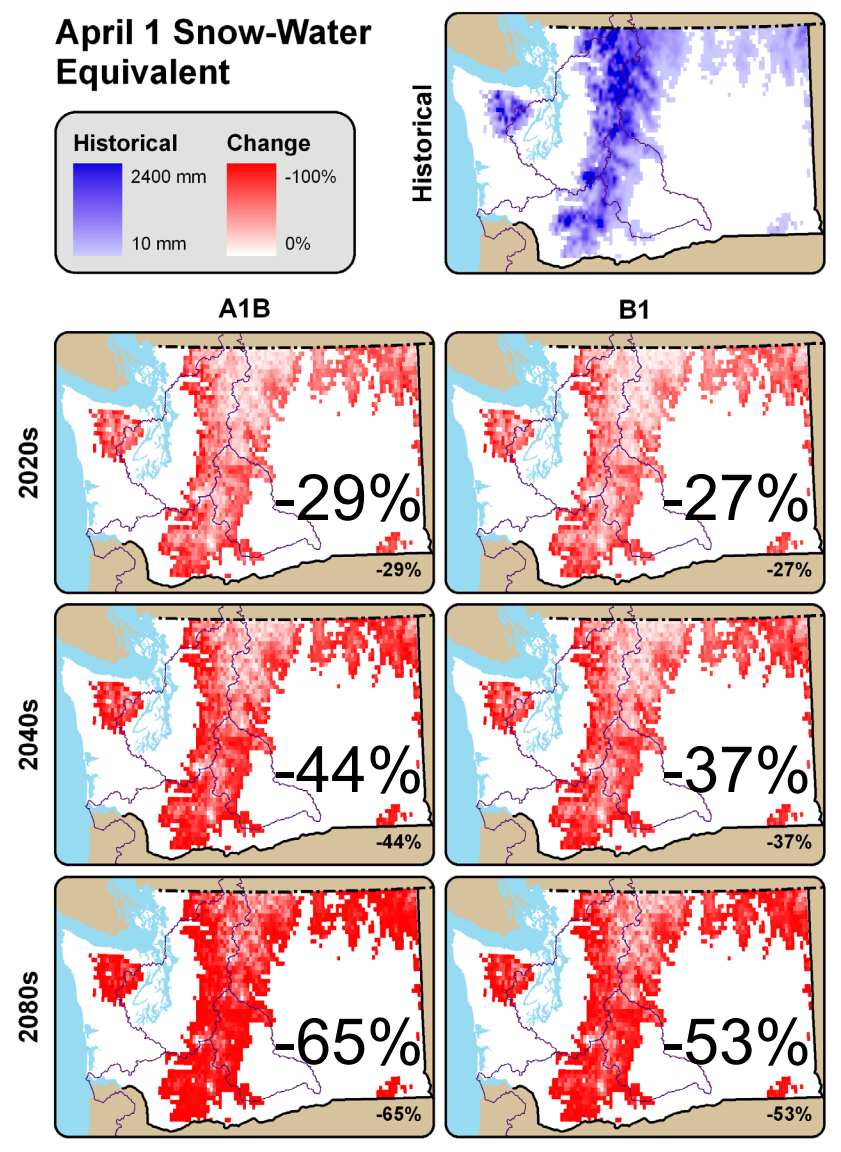
Hybrid Methods

•Ensemble analysis of water systems over 90 years of variability.

•Flood and low flow analysis

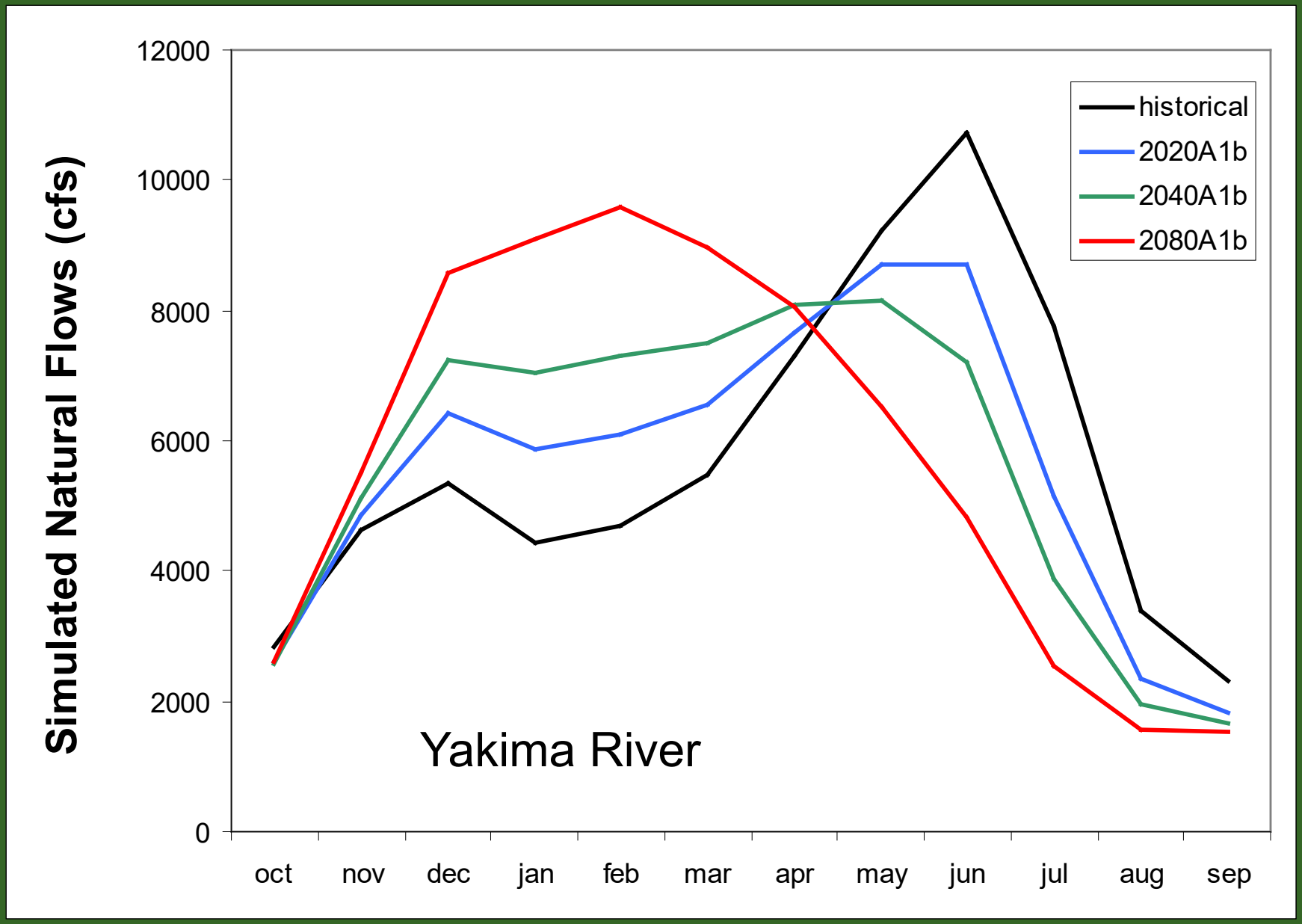
•Any application that needs very realistic time series behavior, spatial extent of storms, etc.

Change in Long-Term Mean April 1 SWE in WA

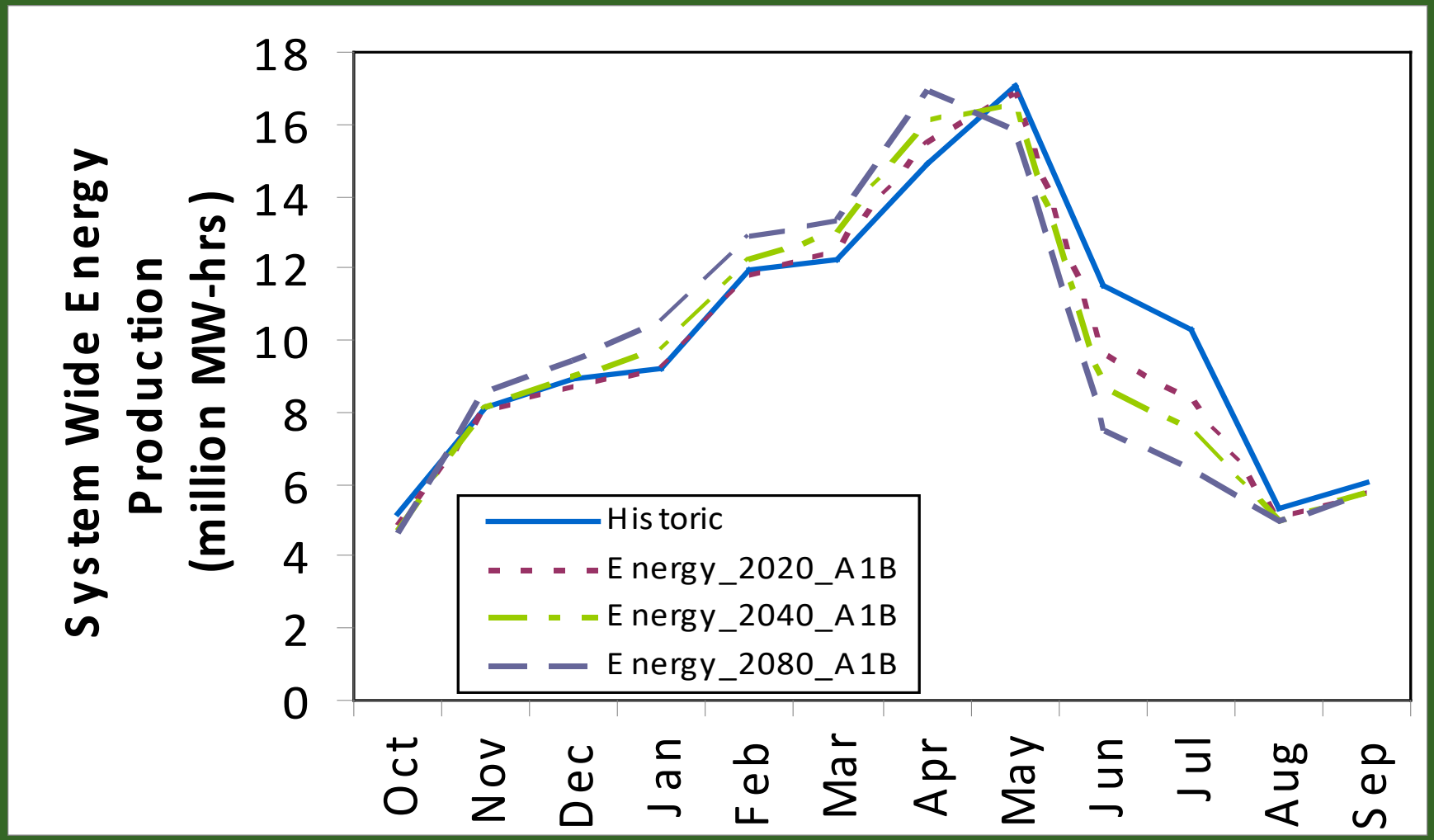


Elsner et al., 2009: Implications of 21st Century climate change for the hydrology of Washington State (in review)

Historical and Projected 21st Century Flows for the A1b Scenario

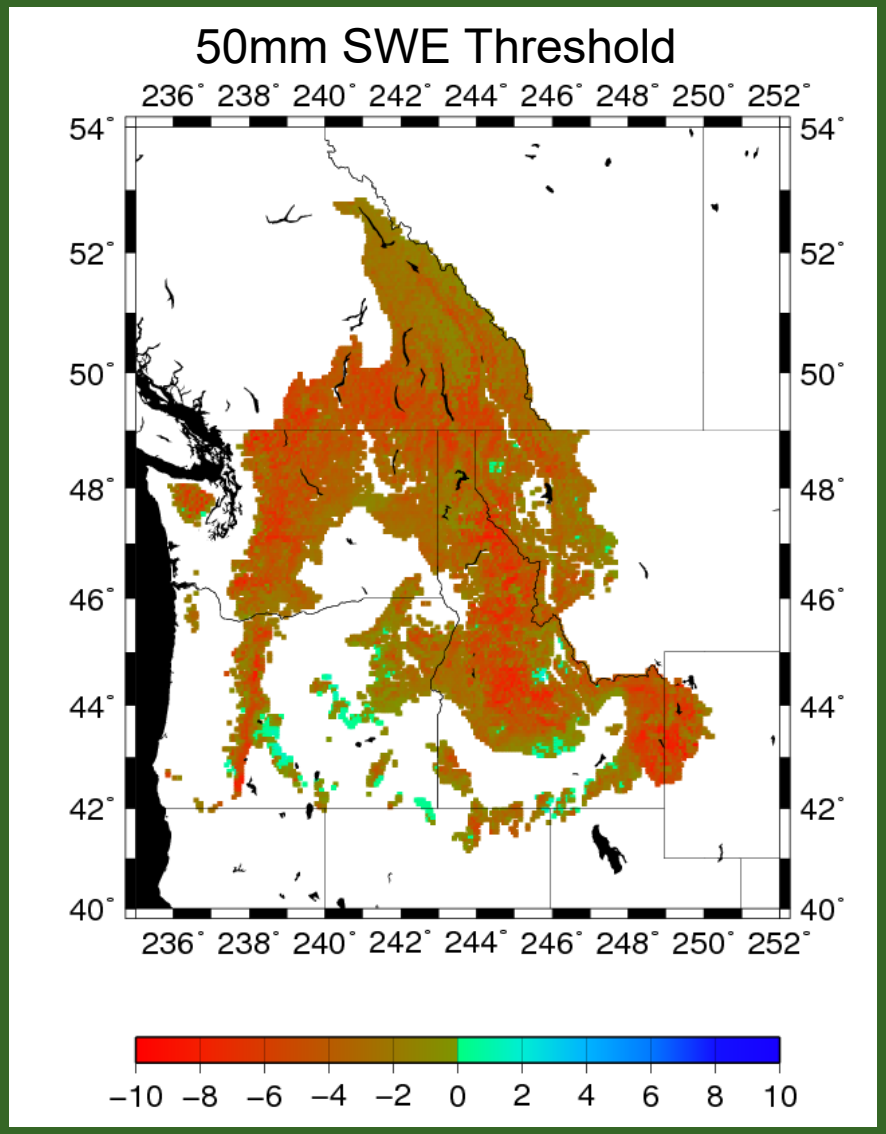


Streamflow Timing Shifts in the Columbia River Will Impact Regional Electrical Energy Production

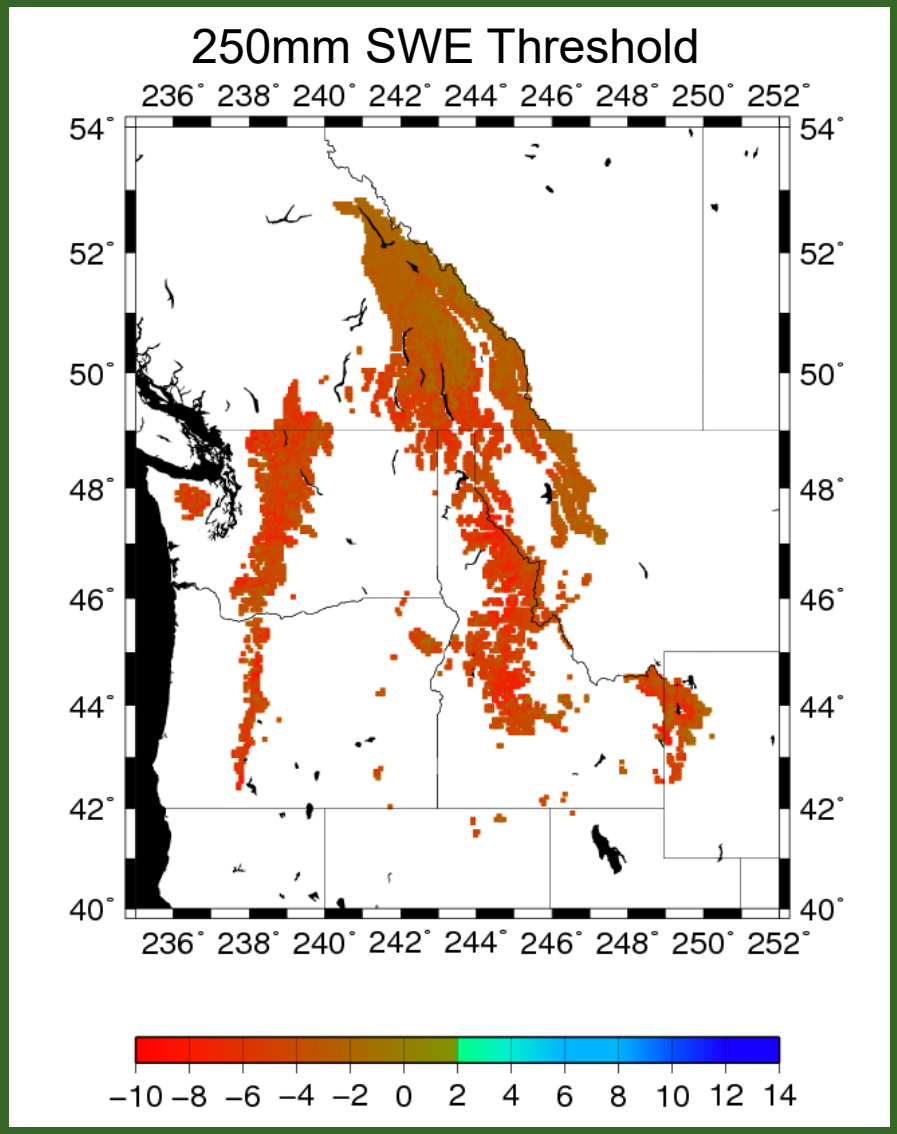


Hamlet et al., 2009: Effects of Projected Climate Change on Energy Supply and Demand in the Pacific Northwest and Washington State

21st Century Trends in the Calendar Date of Peak SWE (Transient ECHAM5 A1b)

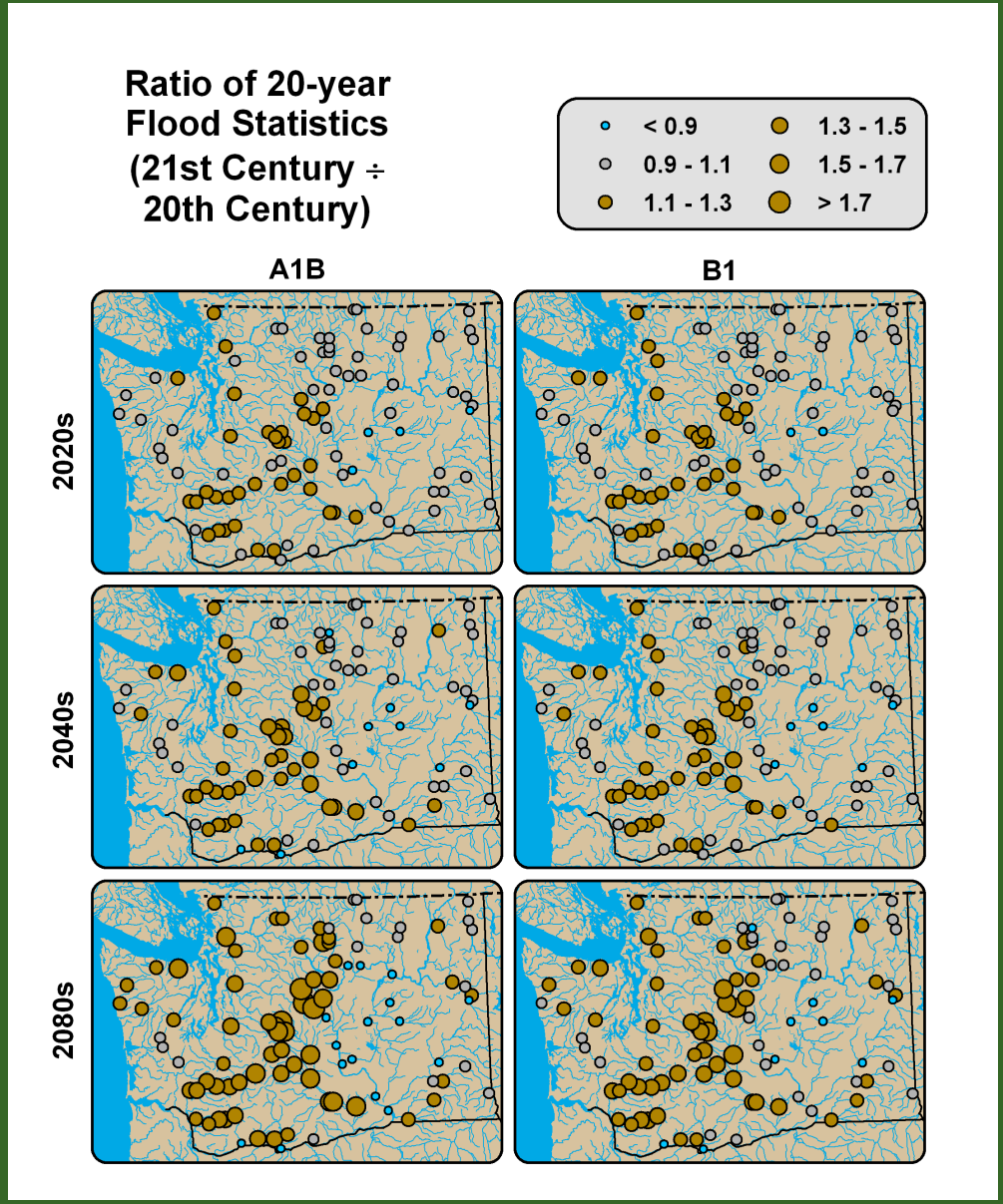


Trend (Days per Decade)



Trend (Days per Decade)

Future Projections of Flood Risk in Washington



- Floods in western WA are expected to increase in magnitude due to the combined effects of warming and increasingly intense winter storms.

- In other parts of the State, changes in flooding are smaller, and in eastern WA projected *reductions* in flood risk are common due to loss of spring snow cover.

Mantua, N., I. Tohver, A.F. Hamlet, 2009: Impacts of climate change on key aspects of freshwater salmon habitat in Washington State, (in review)

Status:

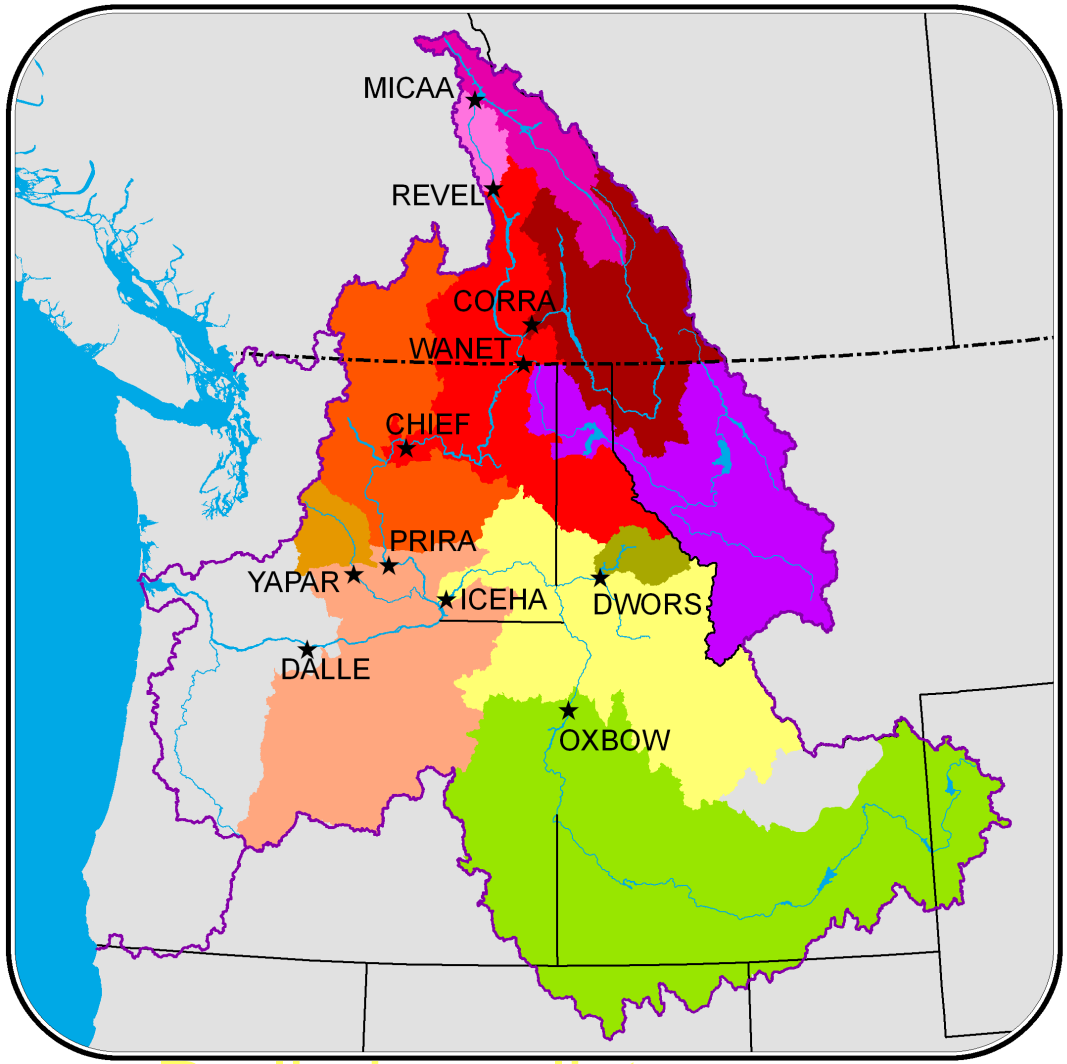
A number of delta method runs were made for the entire Columbia basin for the 1303 effort, including a full ensemble of runs for the 2020s over the Yakima basin, and results have generally been very encouraging. (6 updated future runs planned)

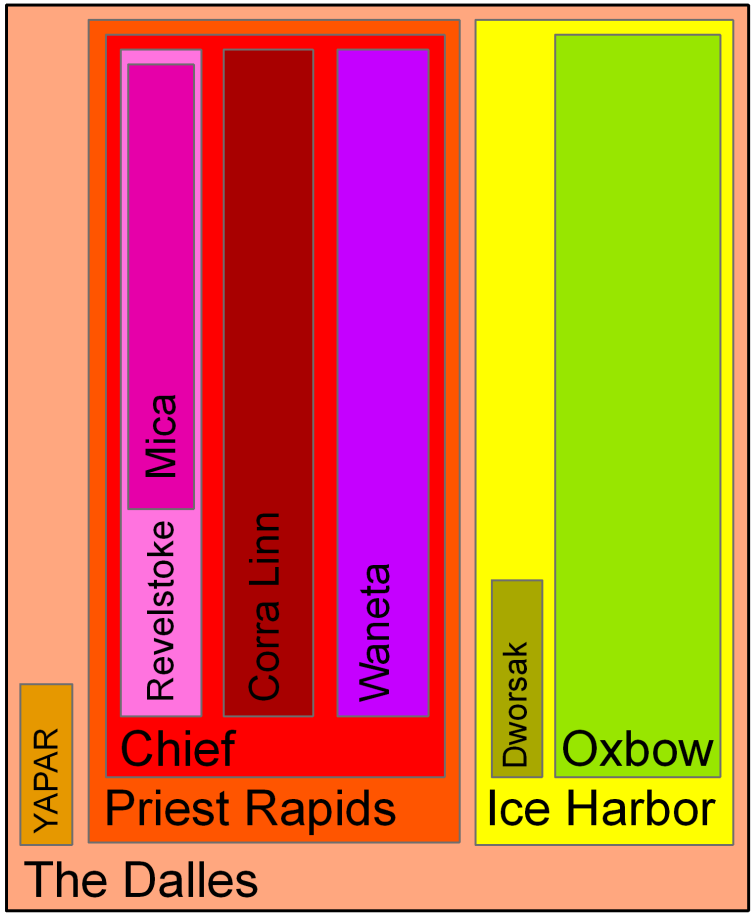
Initial transient downscaling results showed many undesirable artifacts at daily time scales in smaller basins. Further work on the downscaling method this spring has largely resolved these issues. (10 future runs planned)

Hybrid methods have been implemented and testing phase is nearly completed. (60 future runs planned)

Model Calibration

Calibration Watersheds





- Preliminary list
- Snake and Willamette sites will be added

VIC Model Calibration Procedure

- Calibrate model to simulated streamflow by changing soil parameters (uncertainty in subsurface processes)
- Compare simulated and historical streamflow using summary statistics
  - e.g. R^2, Nash-Sutcliffe Efficiency, annual volume error
- Use split sample calibration/validation approach
- Utilize auto-calibration tool developed by U. of AZ

Status:

- Testing of auto-calibration routine is essentially complete
- Model calibration for 10-15 Columbia River sub-watersheds is expected to be complete in July.

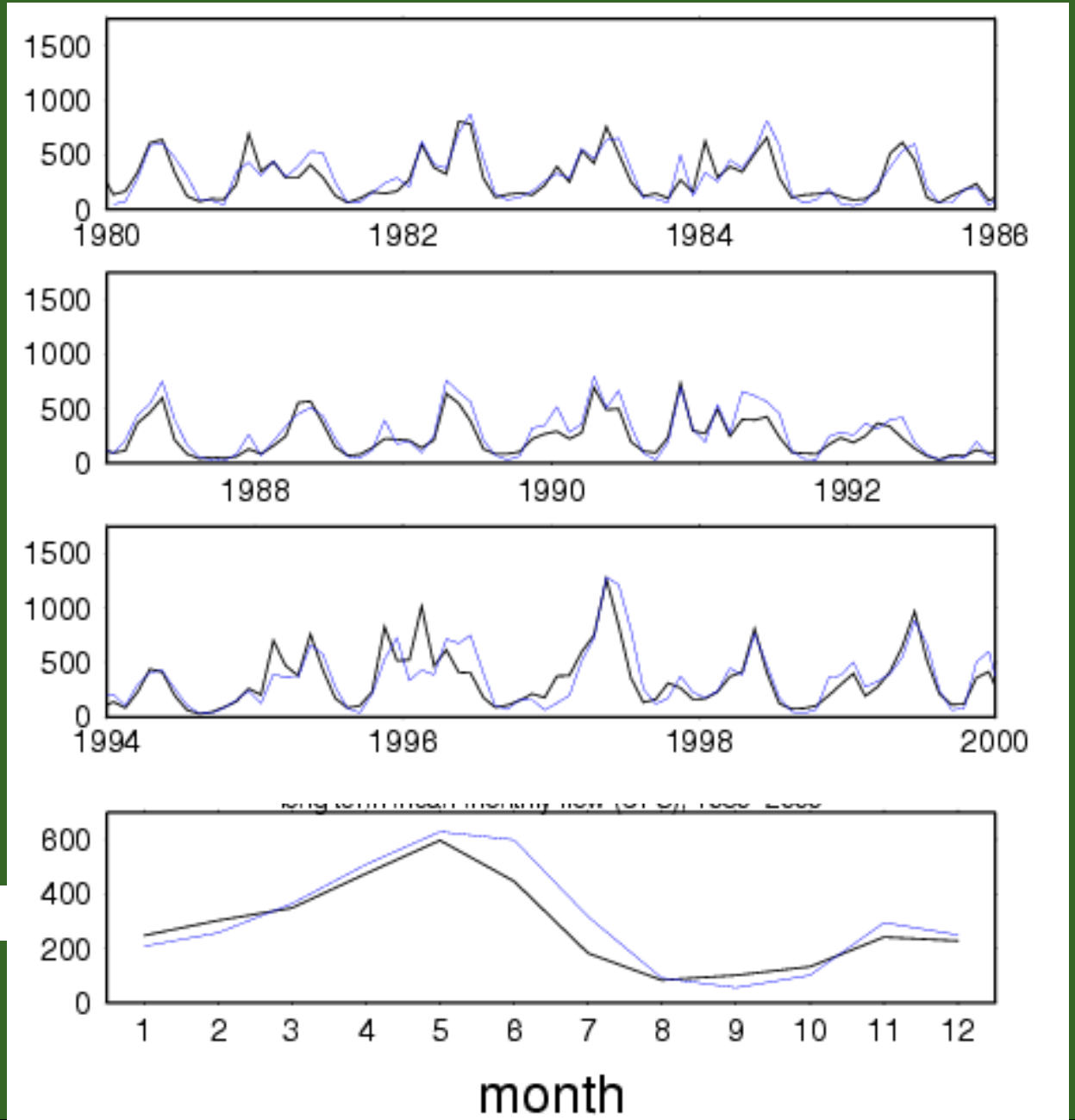
Yakima River at Parker
Net Monthly Mean Flow (units of 1000AF)

Naturalized Flow

Simulated Flow

Summary Statistics

R^2: 0.88
N-S Efficiency: 0.71
Avg. Ann. Flow,
Sim/Nat: 1.08



Long-term Monthly Mean (1980-2000)

Overview of Products

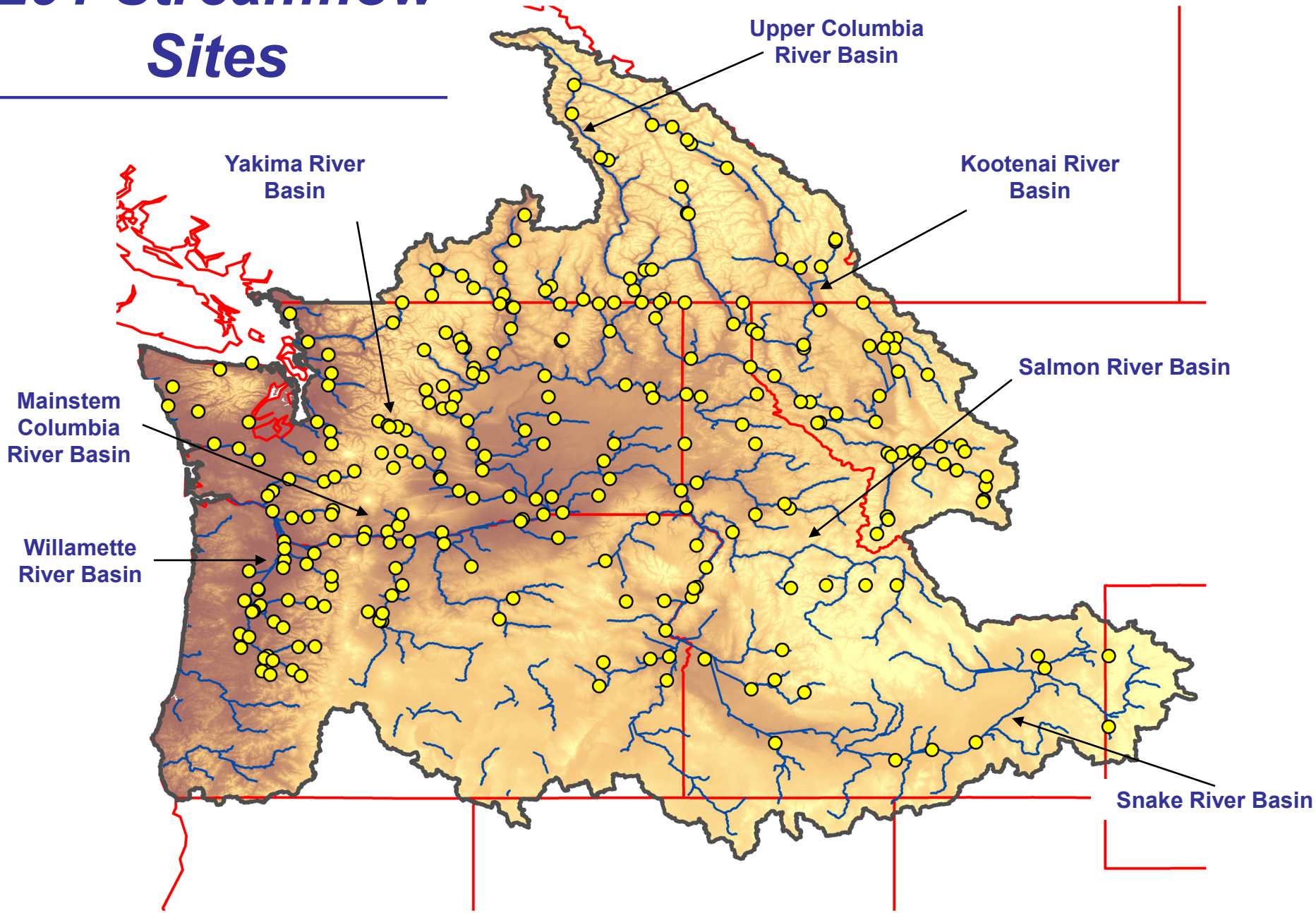
Criteria for Streamflow Site Selection:

We requested prioritized site selection suggestions from all stakeholder groups (50 from each).

Contractually we were only required to produce data for 200 sites, but we made the decision to include all sites suggested by our stakeholders. (note that calibration may not be equally good across all sites)

Additional naturalized data and diversion/return information was provided for a specific group of sites in Washington, and a special set of products for these sites will produced.

291 Streamflow Sites



VIC Model Output Variables

- Daily time step
- Spatial maps of data anomalies/patterns of mean changes
- Excel or ASCII (text) data format

Data Variable
291 Sites
Naturalized streamflow
Regulated streamflow
Changes is flood frequency (100 yr flood)
Changes in low flow (7Q10)
Drought frequency, severity, duration analysis
Analysis of streamflow timing shifts
Gridded Data (16th degree)
Min/Max temperature
Precipitation
Soil Moisture
Potential evapotranspiration
Snowpack (SWE, depth)
Date of peak SWE
Date of 90% SWE melt
Fraction of precipitation as rain

Specific bias adjusted products to support the following reservoir simulation models will be produced under funding for this project:

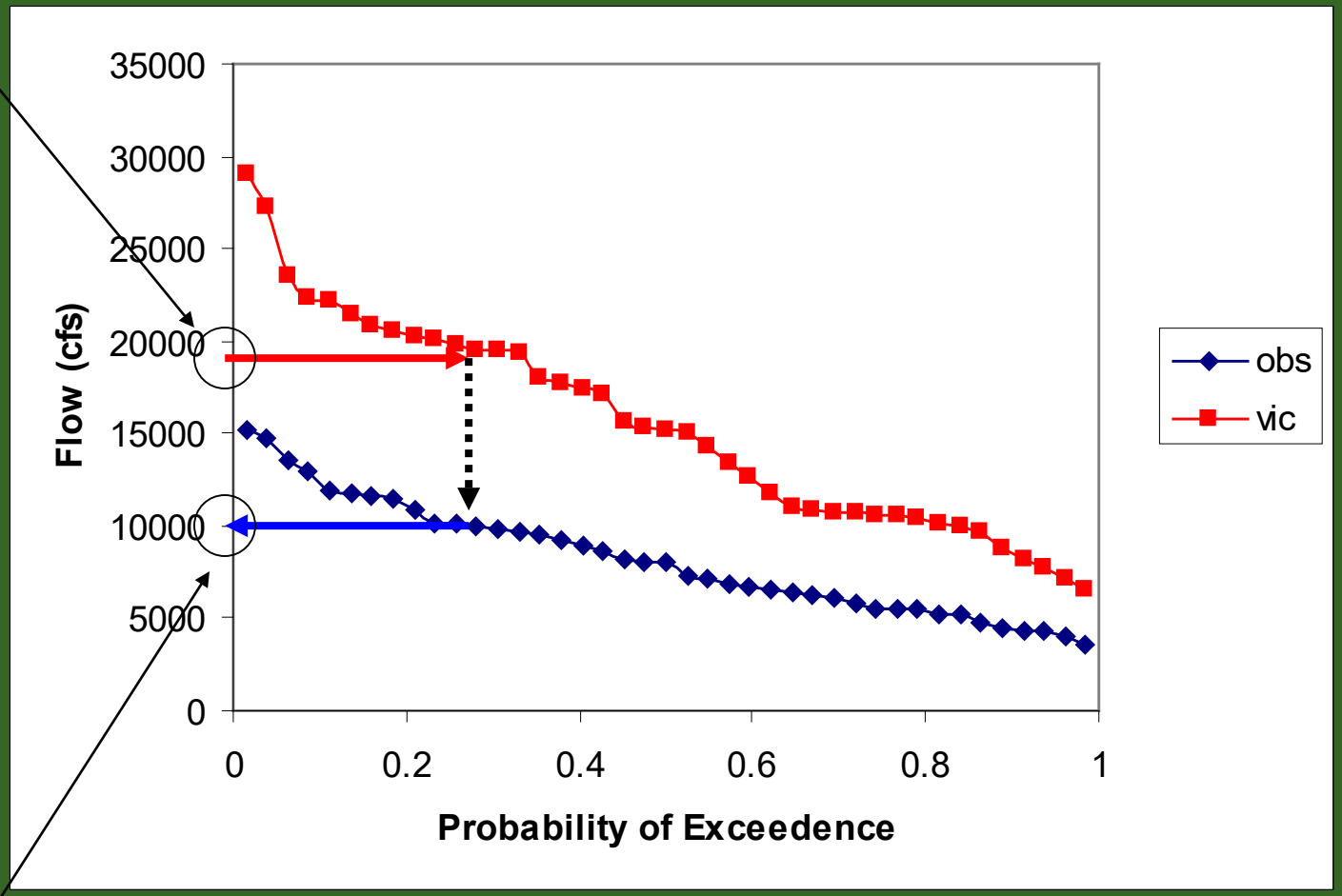
- GENESYS (VIC)
- Snake River basin simulation models (VIC)

Additional simulation products supported by HB 1303:

- USBR Riverware model for the Yakima basin (VIC)
- Seattle, Everett and Tacoma water supply systems (DHSVM)
- ColSim model for the Columbia Mainstem (VIC)

Quantile-Based Bias Correction (Snover et al. 2003)

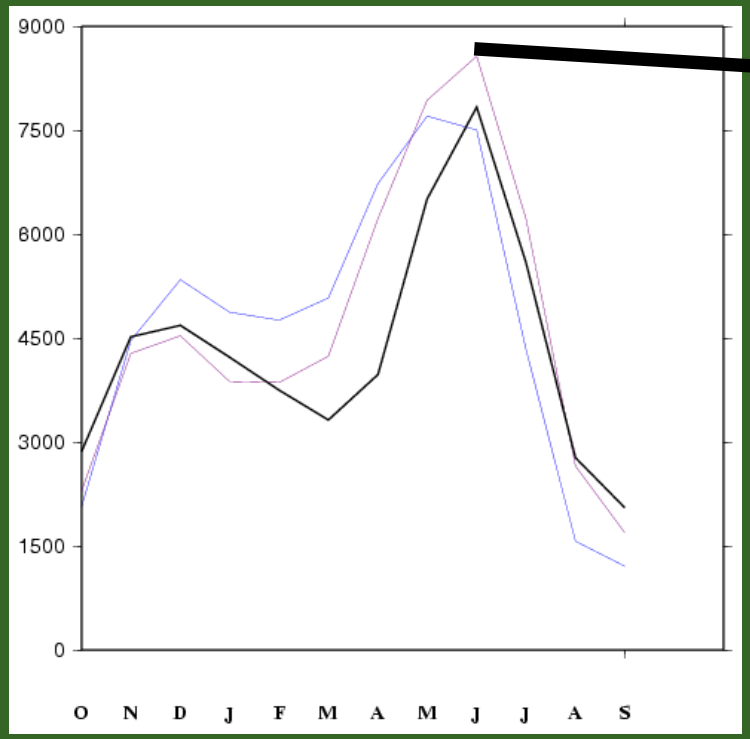
VIC Input = 19000



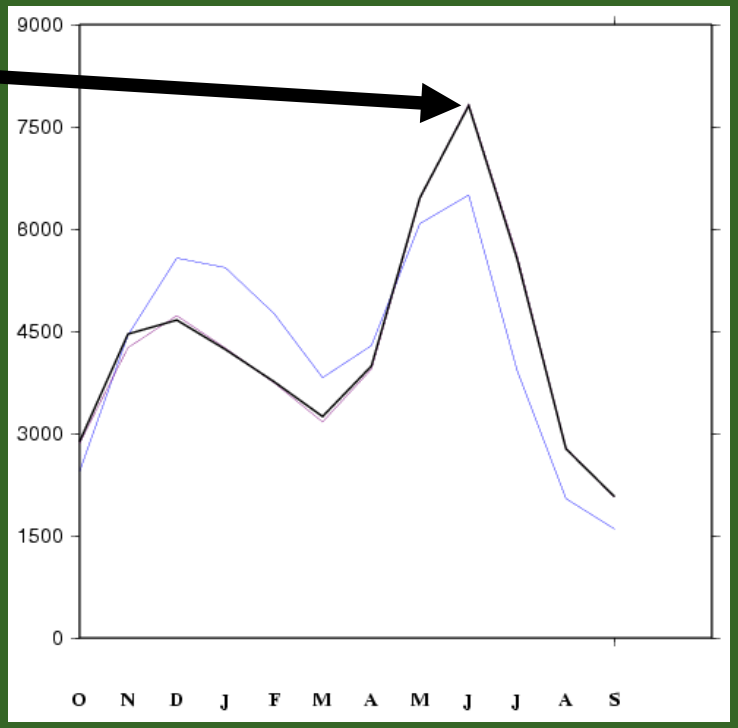
Bias Corrected Output = 10000

Bias Correction Results:

Raw



Bias Corrected



Legend

Observed — VIC — 2020's

Result: Bias Corrected Hydrologic Simulations are Consistent with Observed Streamflows in Absolute Value and Climate Change Signals are Translated Without Significant Distortion.

Project Timelines

Project Completion for Primary Study Outcomes is Anticipated in Sept, 2009

Five Parallel Efforts:

- Downscaling
- VIC development and runs
- Website Development
- DHSVM pilot projects
- Reporting Obligations and Journal Submissions

VIC Time Line

Web Site Time Line

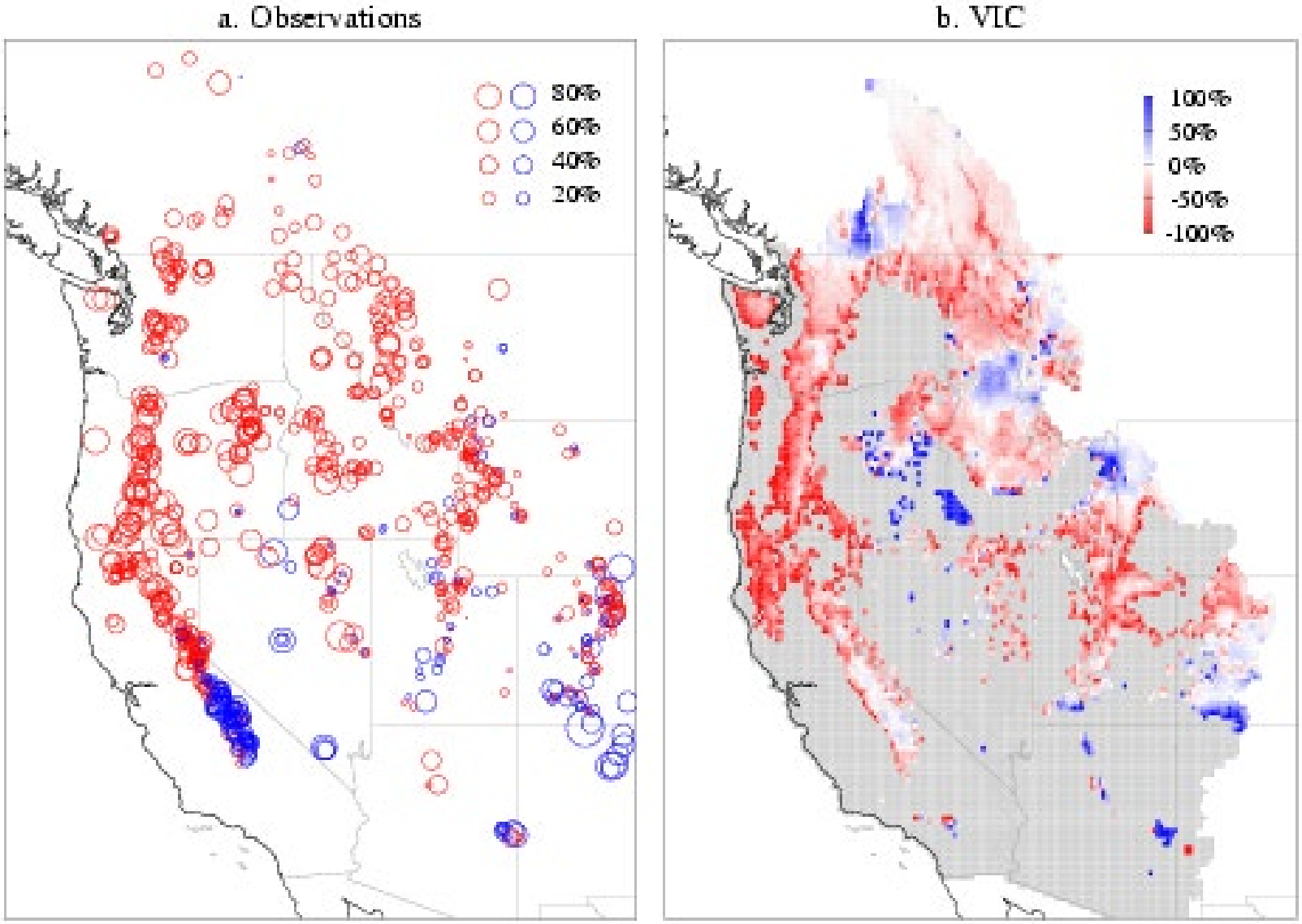
Transboundary Implications of Climate Change for the Columbia River Basin

Richard N.Palmer, Alan F. Hamlet,
Philip W. Mote, Nate Mantua,
Dennis P. Lettenmaier

•JISAO/CSES Climate Impacts Group
•Dept. of Civil and Environmental Engineering
University of Washington

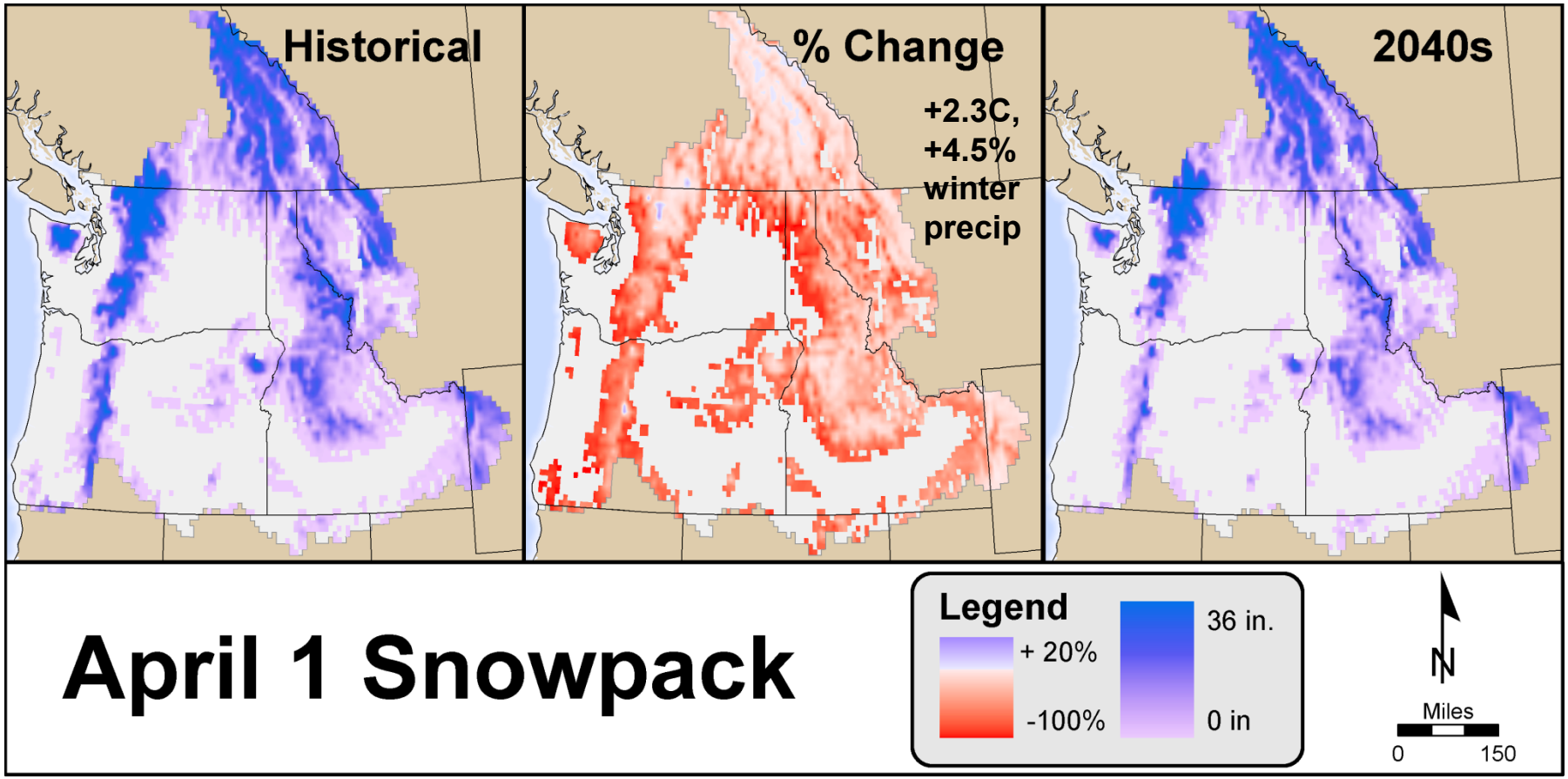
Department of Civil and Environmental Engineering

Trends in April 1 SWE 1950-1997



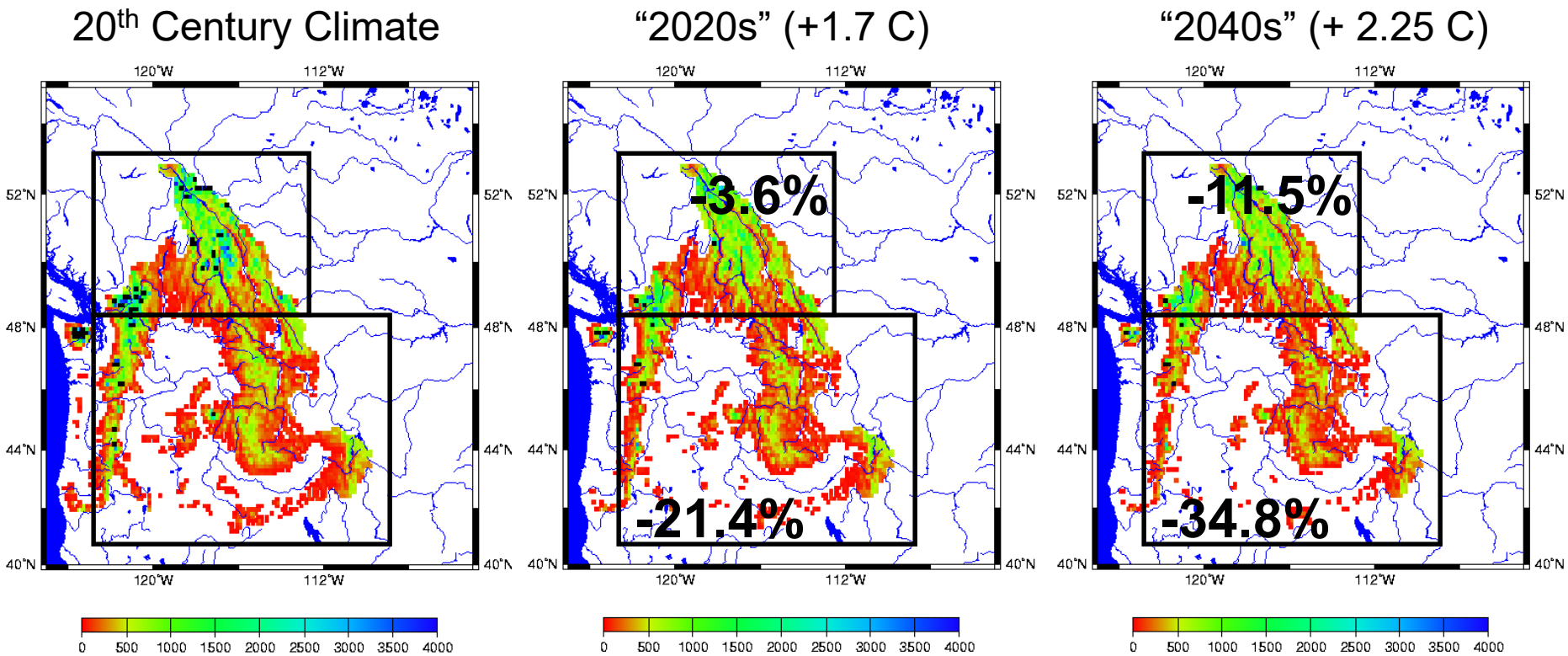
Mote P.W.,Hamlet A.F., Clark M.P., Lettenmaier D.P., 2005, Declining mountain snowpack in western North America, BAMS, 86 (1): 39-49

The warmest locations are most sensitive to warming

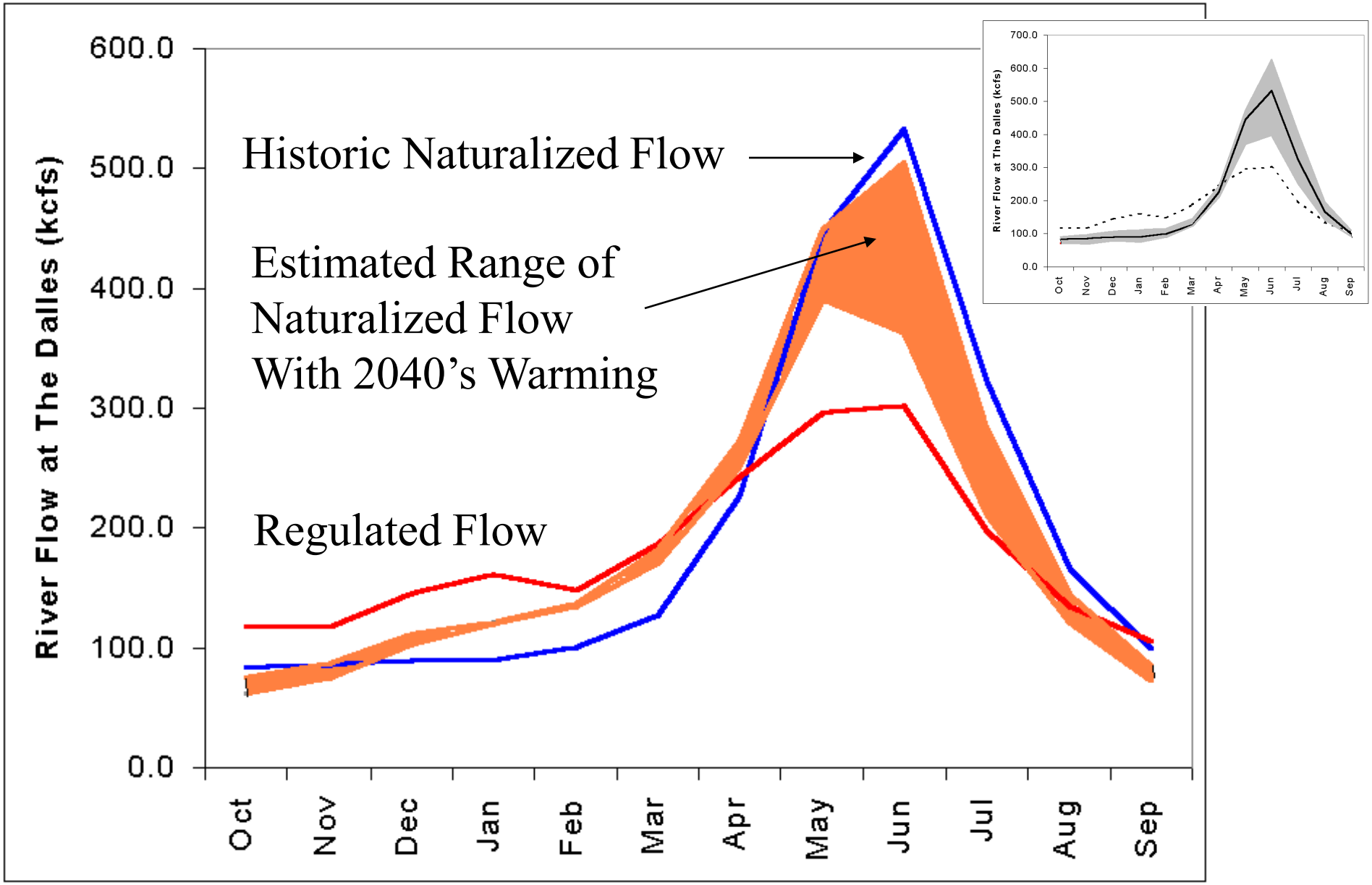


Changes in Simulated April 1 Snowpack for the Canadian and U.S. portions of the Columbia River basin

(% change relative to current climate)



Naturalized Flow for Historic and Global Warming Scenarios Compared to Effects of Regulation at 1990 Level Development



Implications for Transboundary Agreements in the Columbia Basin

•Climate change will result in significant hydrologic changes in the Columbia River and its tributaries.

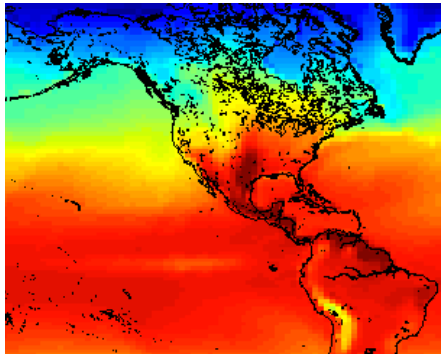
•Snowpack in the BC portion of the Columbia basin is much less sensitive to warming in comparison with portions of the basin in the U.S. and streamflow timing shifts will also be smaller in Canada.

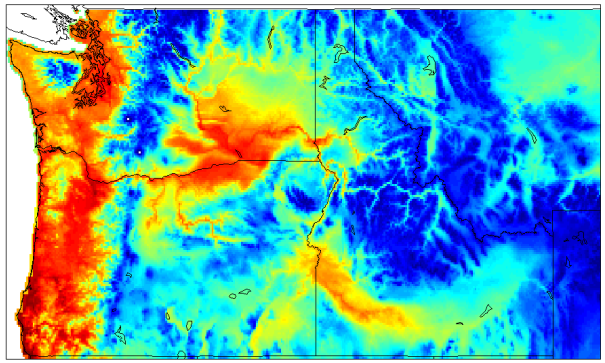
•As warming progresses, Canada will have an increasing fraction of the snowpack contributing to summer streamflow volumes in the Columbia basin.

•These differing impacts in the two countries have the potential to “unbalance” the current coordination agreements, and will present serious challenges to meeting instream flows on the U.S. side.

•Changes in flood control, hydropower production, and instream flow augmentation will all be needed as the flow regime changes.

MACA Statistical Downscaling





John Abatzoglou, Katherine Hegewisch

University of Idaho

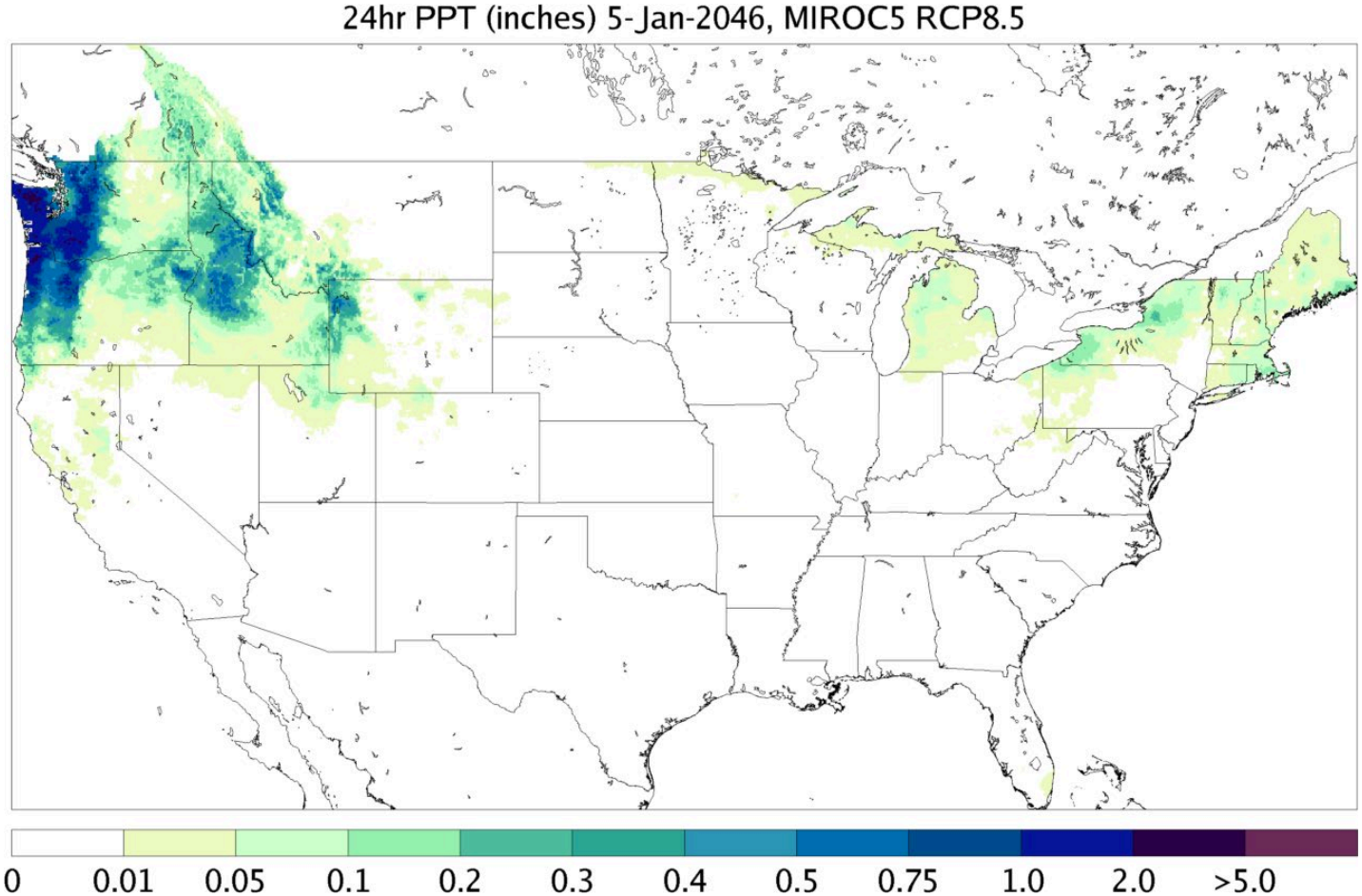
CIRC
Climate Impacts Research Consortium

REACCH
Regional Approaches to Climate Change – PACIFIC NORTHWEST AGRICULTURE

DEPARTMENT of the INTERIOR
SE CLIMATE SCIENCE CENTER

NW CSC
Northwest Climate Science Center

Multivariate **A**daptive **C**onstructed **A**nalogs Downscaling



- Directly uses daily weather as simulated by climate models
- Preserves changes in statistical moments under future climate
- Extends to variables other than temperature & precipitation

Multivariate **A**daptive **C**onstructed **A**nalogs Downscaling

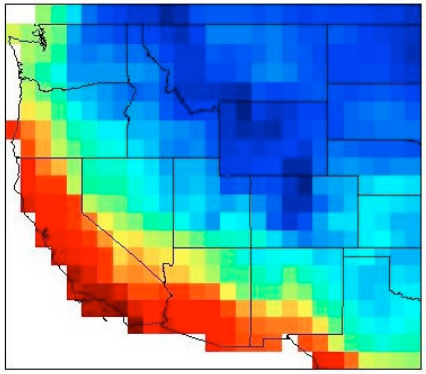
Statistical method

1. Epoch adjustment (31-yr moving averages, 21-d windows)
2. Non-parametric bias correction
3. Joint bias correction for T & P
4. Multiple Variable Constructed Analogs %
5. Non-parametric bias correction *
6. Epoch adjustment *

* Indicates performed on fine-scale grid
% 10 patterns with residual term included

Constructed Analogues
Joint Search Across Variables*

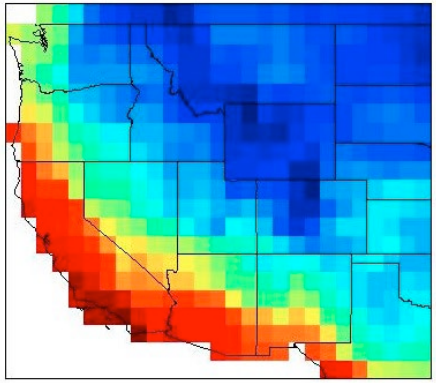
Bias Corrected Target Fields (GCM)
e.g., May 14, 2048

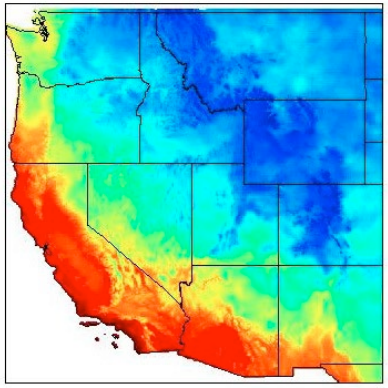


$$\sum_{n=100} \alpha_n Z_n$$

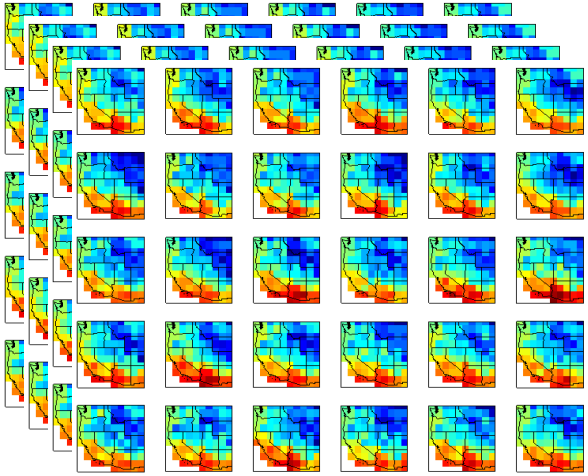
$$\sum_{n=100} \alpha_n Y_n$$

CA Coarse Res.





Library of
Potential Analogs



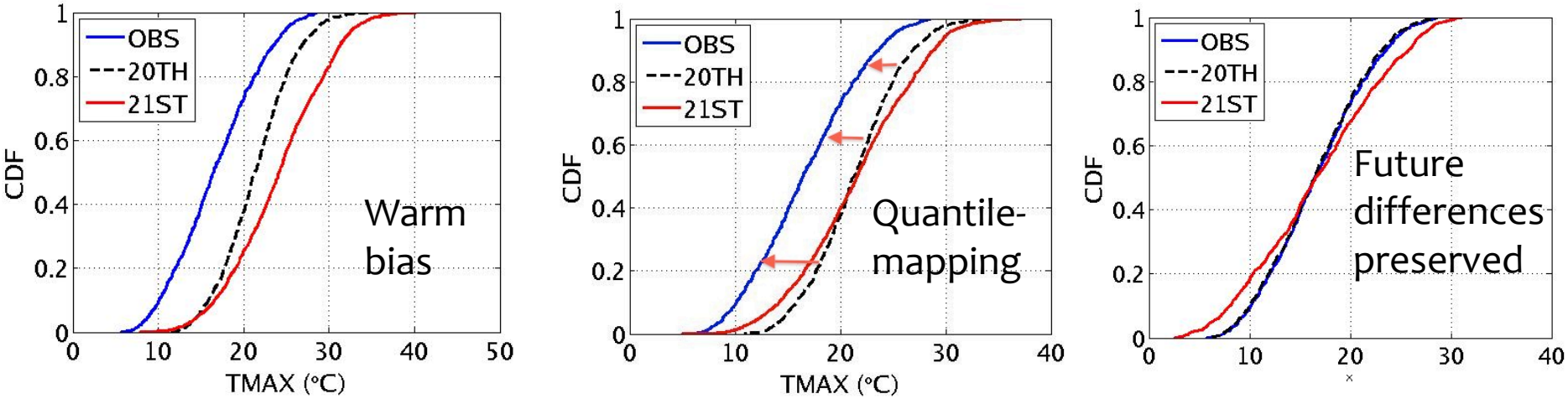
Minimize RMSE

10 "Best" Analogs + Residual

Hidalgo et al., 2008; Abatzoglou and Brown, 2012

Equidistant Quantile Mapping Bias Correction

i.e., Maximum Temperature (30 day period, all years)



Raw GCM Data | After Epoch Adjustment | After Bias Correction

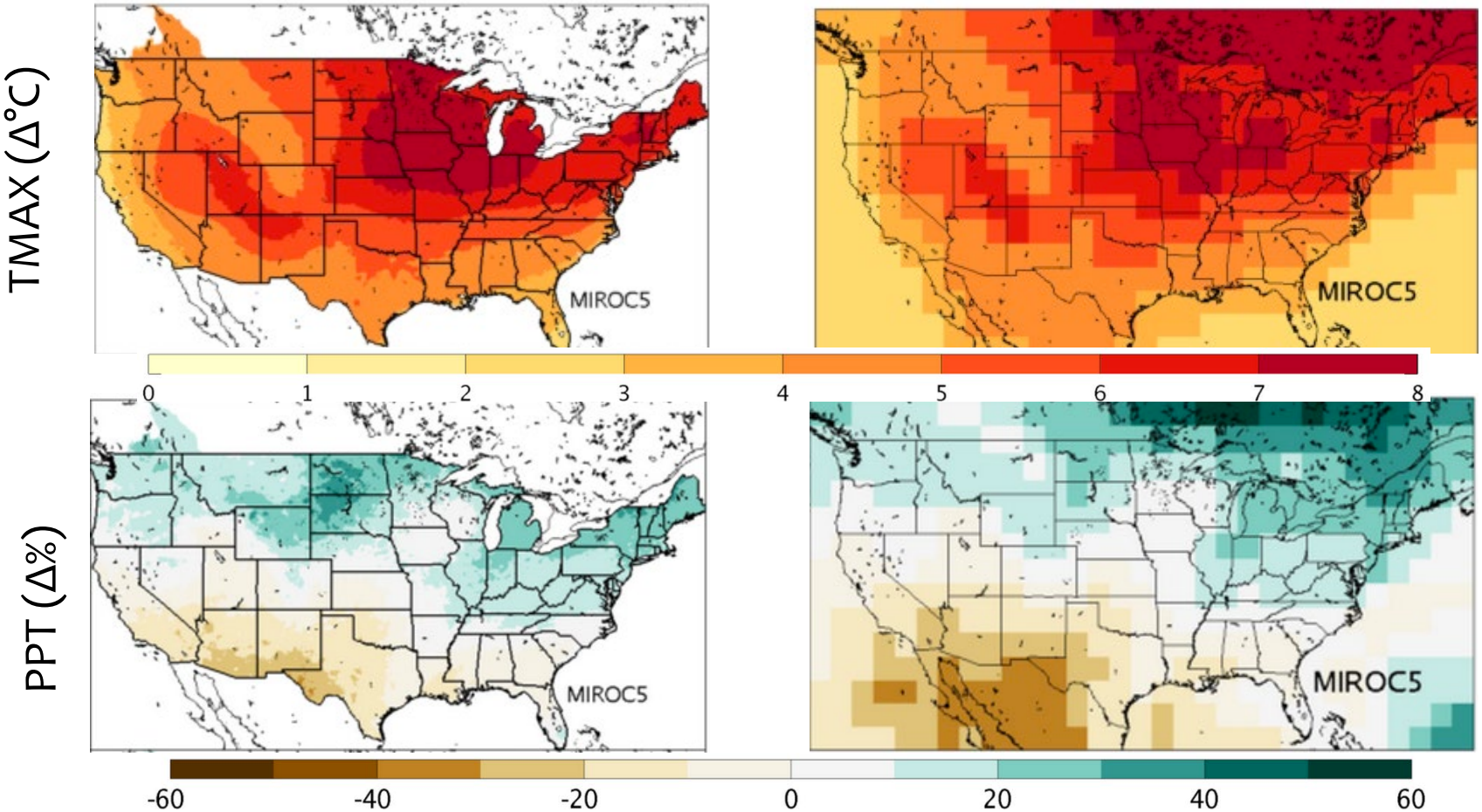
- Removes biases in mean and higher-order statistics, but preserves change in quantiles across time.
- Non-parametric approach; conservative extreme value tail fitting
- Additional PresRat correction applied for precipitation

Pierce et al., submitted

Forced to preserve:

Downscaling preserves modeled change

Dec-Feb 2070-2099 (RCP85) vs. 1950-2005 (HIST) for MIROC5



Trend preserving bias correction ensures GCM change captured in downscaled change for 30-day moving window; while also allowing for distributions to change.

Pierce et al., submitted

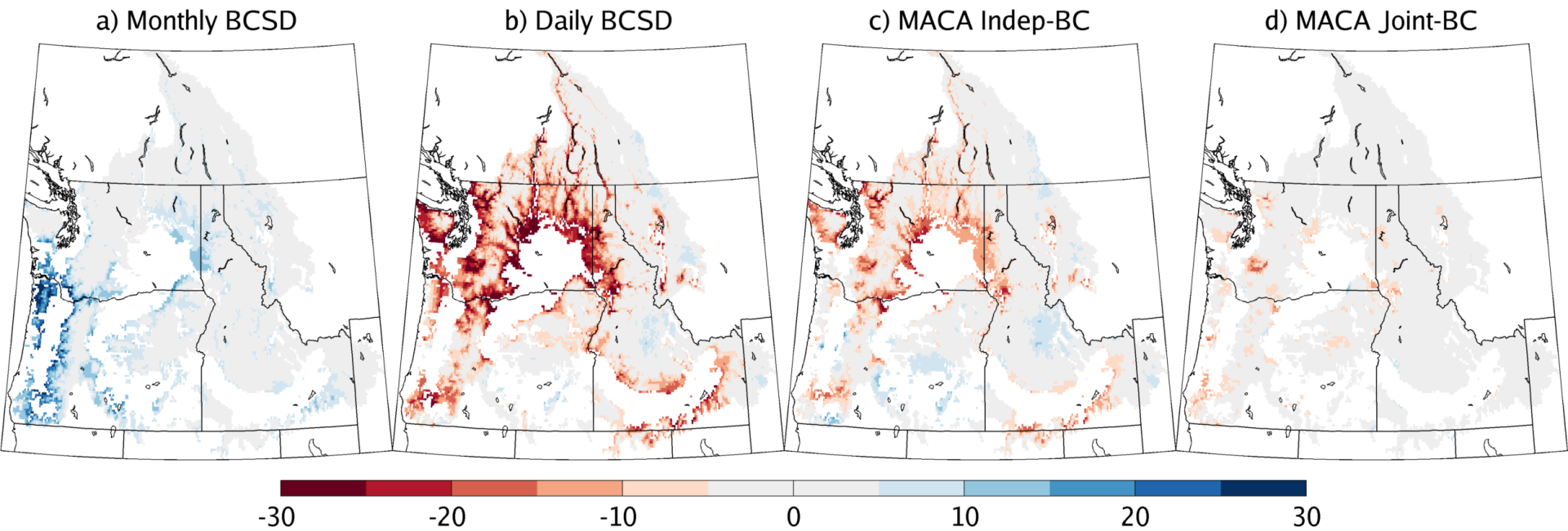
Whack A Bias

Problems:

(1) Biases in GCM simulated temperature on wet days in winter that will alter hydrologic sensitivity

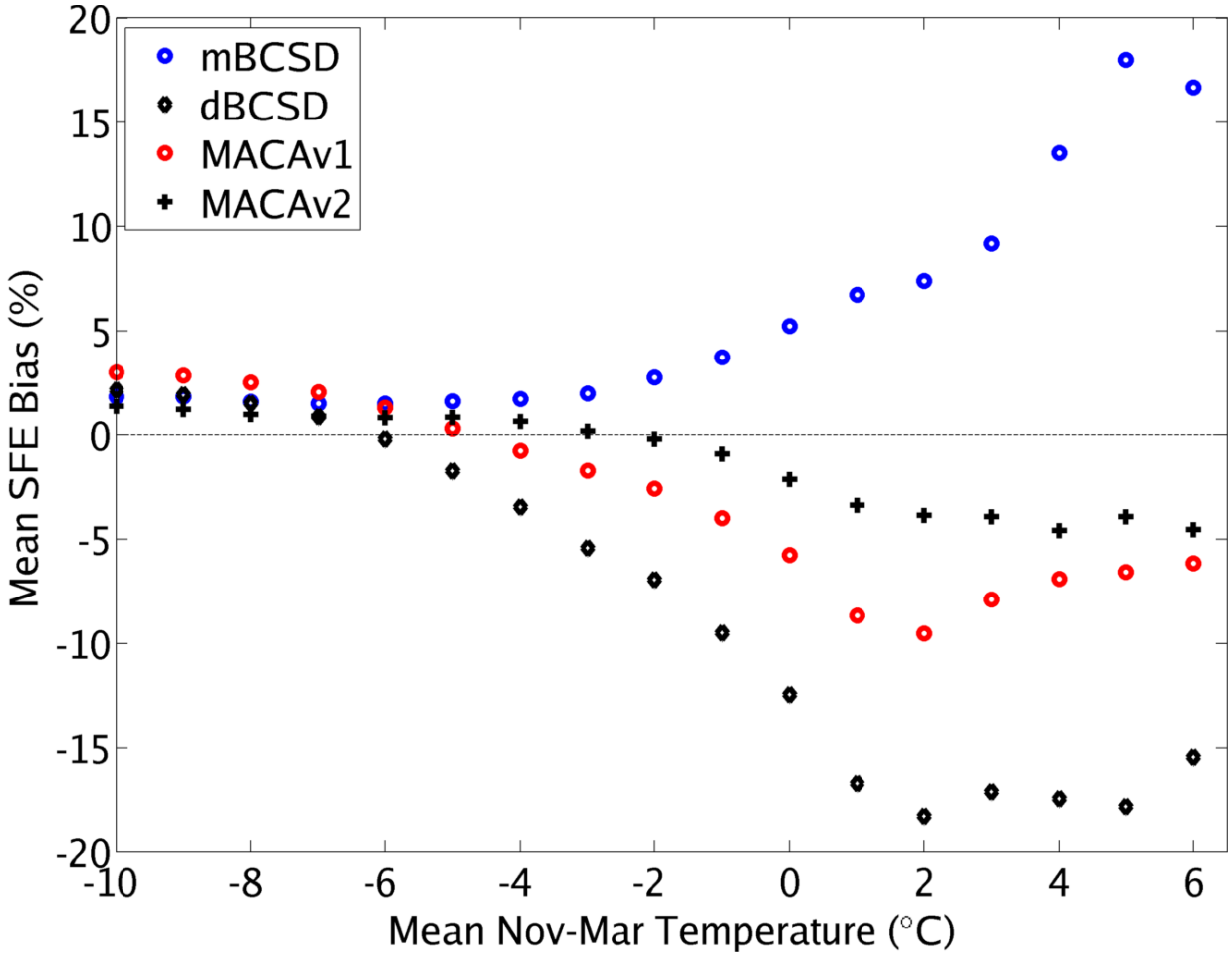
(2) Univariate bias correction will not eliminate these biases

Solution: joint equidistant quantile BC of temperature/precip



Snowfall water equivalent bias: Downscaled historical/Observed Historical

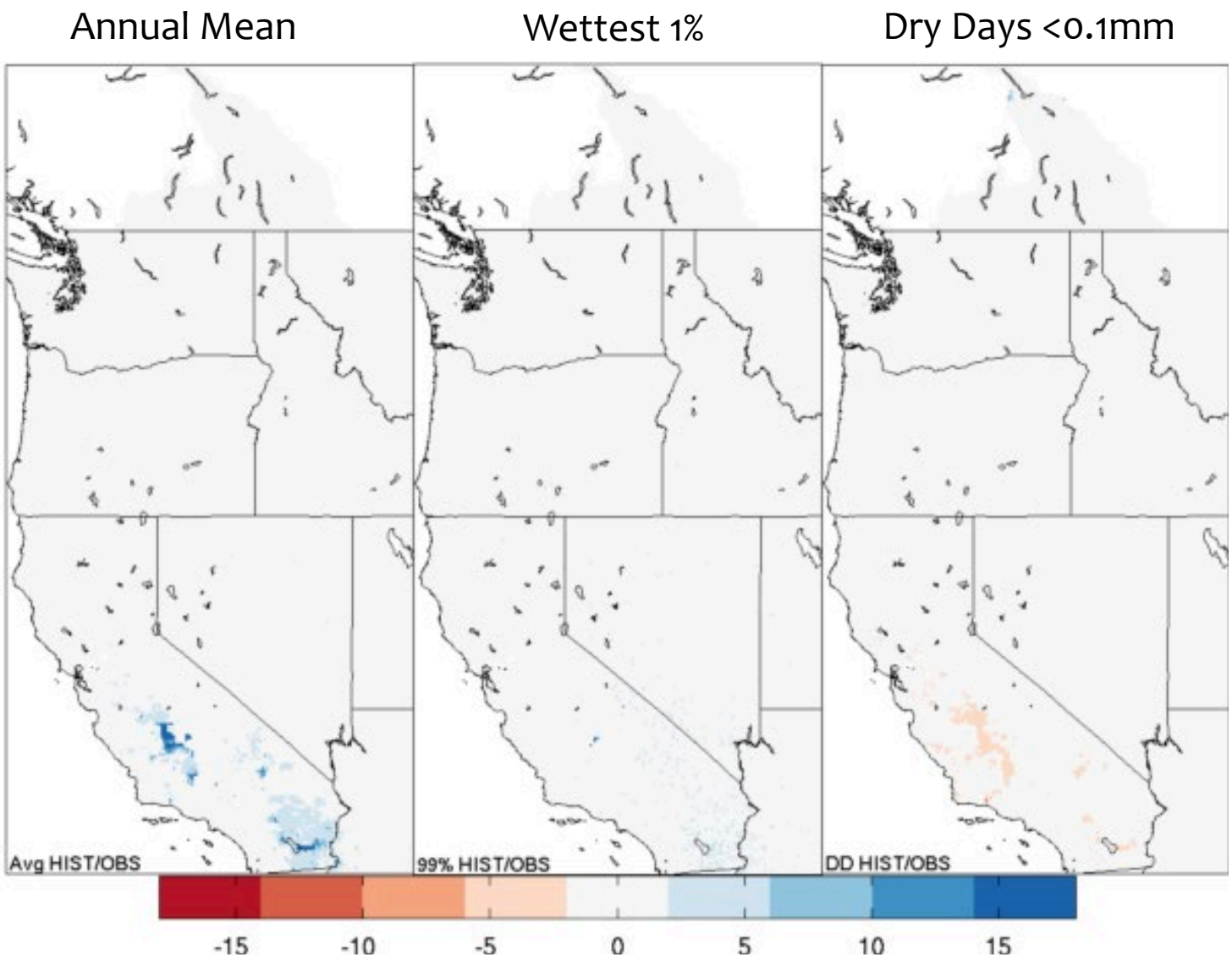
Whack A Bias



Snowfall water equivalent bias: Downscaled historical/Observed Historical

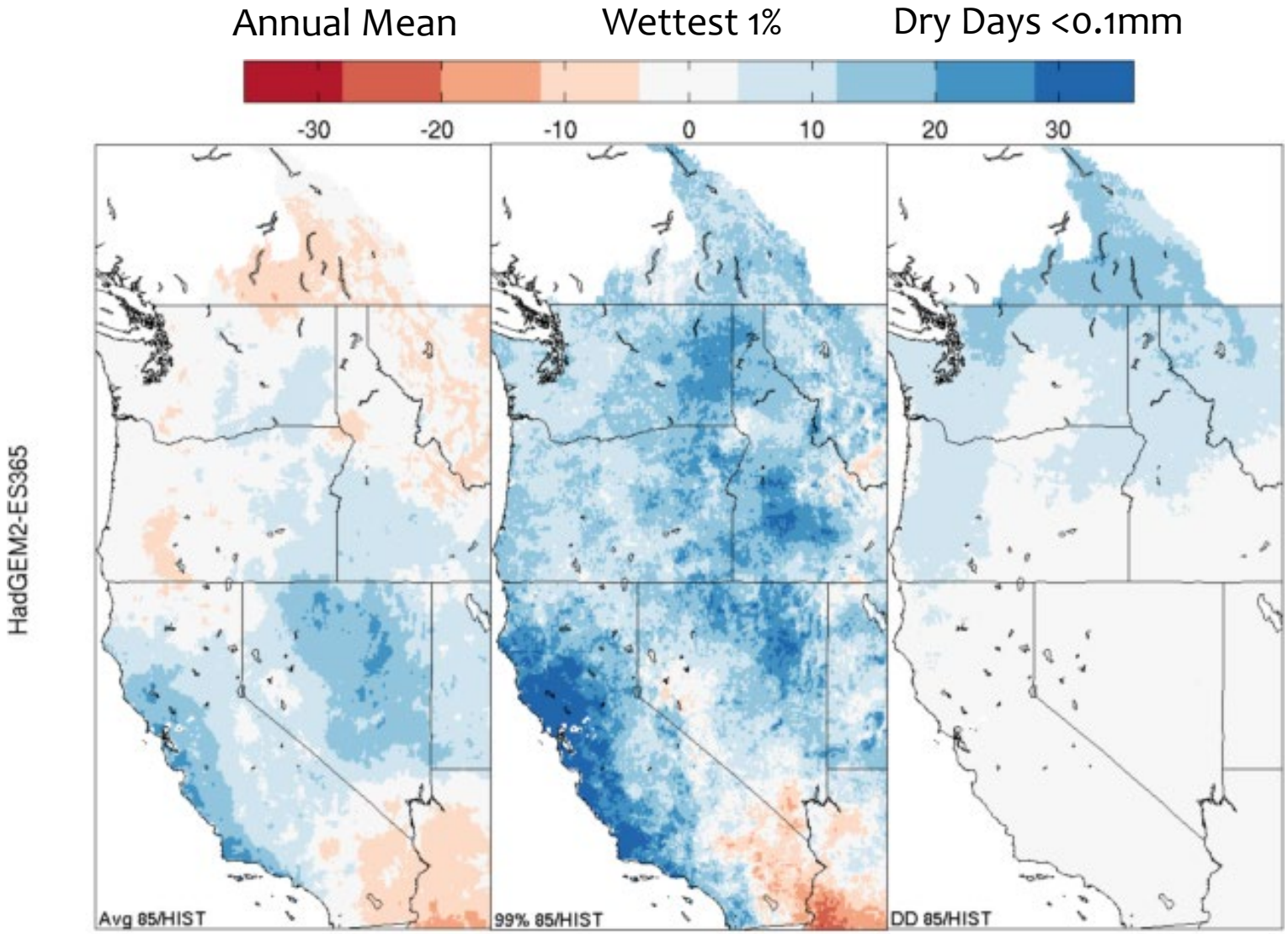
MACA Biases?

Observations (1950-2011) vs. 1950-2005 (HIST) for MIROC5



Statistical view of changing extremes

2070-2099 (RCP8.5) vs. 1950-2005 (HIST) for HadGEM2-ES



Data Products

Variables	Resolution	Scenarios
• T_{max} T_{min} • Precipitation • Specific Humidity • 10-m wind speed • Downward shortwave radiation • RH_{max} RH_{min} • wind velocity	6-km grid (1/16th dg.) US+Canadian CRB Daily time scales 4-km grid (1/24th dg.) US Daily time scales	Historic Forcing: 1950-2005 RCP45 and RCP85: 2006-2100 20 models

Training data: Livneh et al (2013) L1.1 US, L1.2 Canada (1950-2011)

Training data: Abatzoglou (2013) NLDAS2-PRISM (1979-2012)

Uncertainties

Large-scale climate simulations

- Contingent on GCM to simulate meteorology & climate change
- Will not correct for serial correlation biases (sequences)
- Skill of downscaling contingent on GCM skill for regional climate
- You can only bias correct so much

Statistical limitations

- Will not capture/simulate dynamic feedbacks

Not a panacea for downscaling, but error << model uncertainty

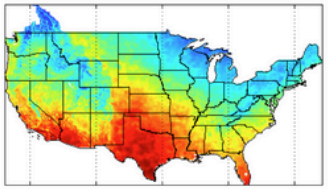
What we've learned

1. Joint bias correction of temperature and precipitation important in reducing snowfall biases

2. Some biases will persist

3. Downscaling with daily data important for capturing higher-order changes in climate (e.g., temperature extremes)

4. Statistical methods can't capture changes in mesoscale phenomena and localized climate change signals



Multivariate Adaptive Constructed Analogs(MACA) Statistical Downscaling Method

University of Idaho

MACA Home | ABOUT THE DATA | VISUALIZATIONS | GET THE DATA | GUIDANCE | CONTACT

CMIP5 Statistically Downscaled for Coterminous USA (CONUS)

The Multivariate Adaptive Constructed Analogs(MACA)(Abatzoglou, Brown, 2011) method is a statistical downscaling method which utilizes a training dataset (i.e. a meteorological observation dataset) to remove historical biases and match spatial patterns in climate model output.

We have used MACA to downscale the model output from 20 global climate models (GCMs) of the Coupled Model Inter-Comparison Project 5 (CMIP5) for the historical GCM forcings (1950-2005) and the future Representative Concentration Pathways (RCPs) RCP 4.5 and RCP8.5 scenarios (2006-2100) from the native resolution of the GCMS to either 4-km or ~6-km.

The MACA dataset is unique in that it downscales a large set of variables making it ideal for different kinds of modeling of future climate (i.e. hydrology, ecology, vegetation, fire, wind). We currently have data for the following variables:

- tasmax - Maximum daily temperature near surface
- tasmin - Minimum daily temperature near surface
- rhsmax - Maximum daily relative humidity near surface
- rhsmin - Minimum daily relative humdity near surface
- huss - Average daily specific humidity near surface
- pr - Average daily precipitation amount at surface
- rsds- Average daily downward shortwave radiation at surface
- was - Average daily wind speed near surface
- uas - Average daily eastward component of wind near surface
- vas - Average daily northward component of wind near surface

We are currently dispensing 3 data products: MACAv1-METDATA, MACAv2-METDATA and MACAv2-LIVNEH.

- MACAv1-METDATA is available for the Western USA, while MACAv2-LIVNEH/MACAv2-METDATA are available over the entire coterminous USA.
- MACAv2-LIVNEH/MACAv2-METDATA both use the newest version of the MACA method (version 2), while MACAv1-METDATA uses version 1. Both methods are very similar to that described by Abatzoglou and Brown, 2011. MACAv2-METDATA is only being dispersed directly from UofI.

http://climate.northwestknowledge.net/MACA

University of Idaho | REACCH Regional Approaches to Climate Change – Pacific Northwest Agriculture | CIRC Climate Impacts Research Consortium | NKN Northwest Knowledge Network | NW CSC Northwest Climate Science Center | Department of the Interior SE Climate Science Center

Extras

Guidelines on Using Climate Information

"Think" projections, not predictions

Don't use to query the weather on Apr 17, 2050, or 2050 or 2050s

Suggest using a 30-yr time period for analysis

Don't limit your model selection

Model "A" says it will be wetter in Portland

General Rule is that 10-12 models should be used to make most confident decisions (Mote et al., 2011)

Compare apples to apples

Consider differences between your "station" and training data

Near term regional climate projections may be less useful

FAQ page for further suggestions

How to Use This Information

Best to compare modeled futures to modeled historic

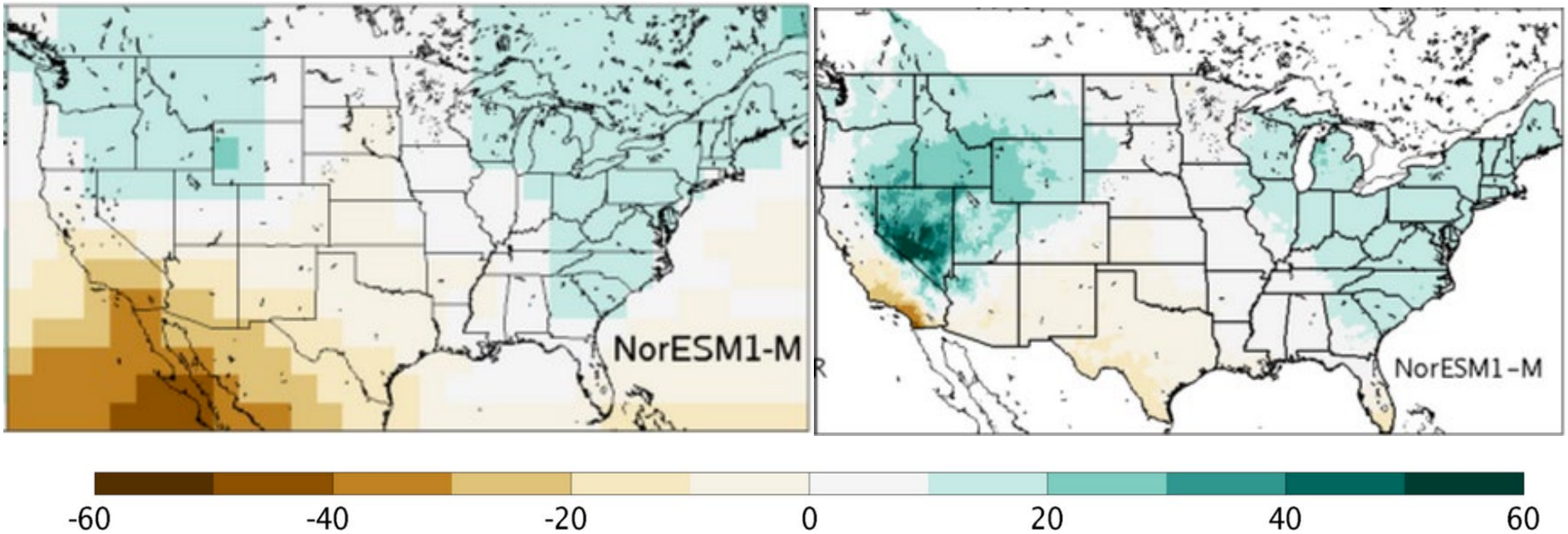
- Downscaling uses training data, not your "station" or your climate dataset
- Use projections in context to historical modeled runs, and historical runs relative to observations.

Establish Confidence Level of Climate Projections

- General Rule is that 10-12 GCMs should be used to make most confident decisions (Mote et al., 2011)
- Selection of "best" models useful for some applications

Disagreement?

Annual Precipitation Change (%)
2070-2099 RCP85 vs. 1950-2005



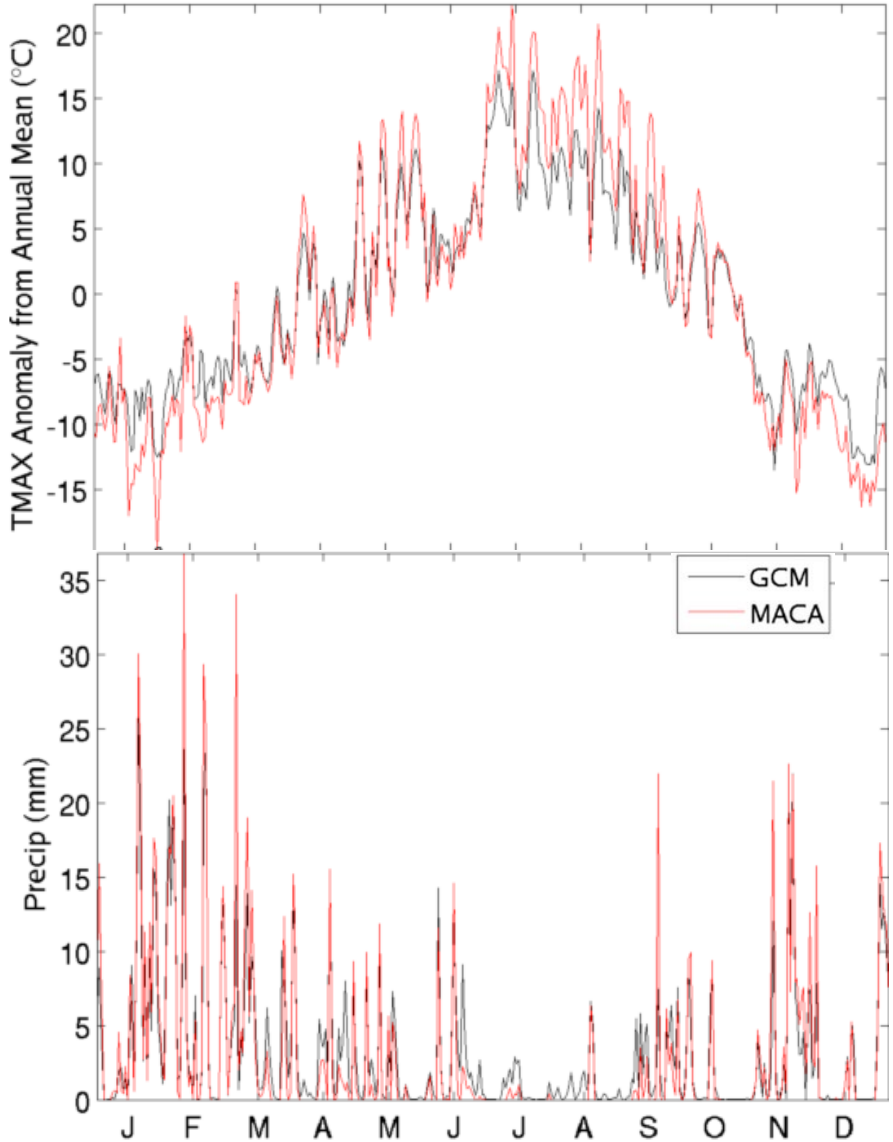
- Downscaled data shows PPT increase in Nevada; GCM does not
- MACA preserves changes at timescales ~ 30-days

Wonderful World of Metadata IV:

Daily Sequences at 45.85N, 121.5W, MIROC5

Downscaled data

GCM data



RECLAMATION

Managing Water in the West

Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies

Review of Draft Outcomes, Tasks 1-2

Levi Brekke (Reclamation, Denver, CO)

U.S. Department of the Interior
Bureau of Reclamation

19 April 2009, Portland, OR

Purpose Today…

- Start assembling Work Plan progress into project briefing (*this is only draft…*)
- Goal is to highlight Work Plan outline, choice points, task decisions, key results
- Eventual audience includes RMJOC sponsors and interested parties

RECLAMATION

Begin draft briefing…

RECLAMATION

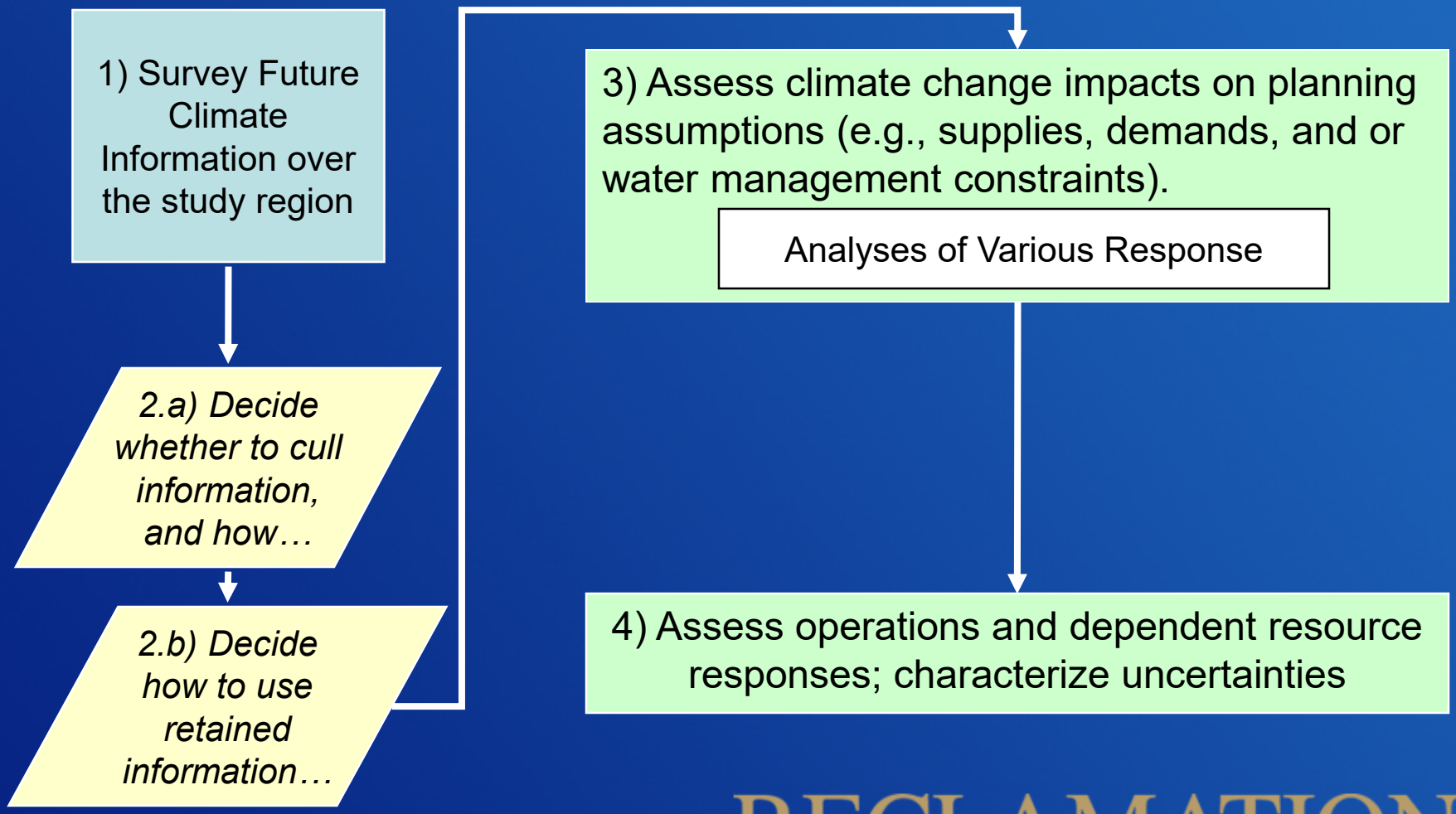
RMJOC Motive and Need

- Motive
  - consistent incorporation of climate projection information into Agencies' longer-term planning studies
- Need
  - adopt common dataset (climate and hydrology)
  - establish consensus methods for data use
  - efficiently use limited resources through coordinated development of data and methods

Potential Applications

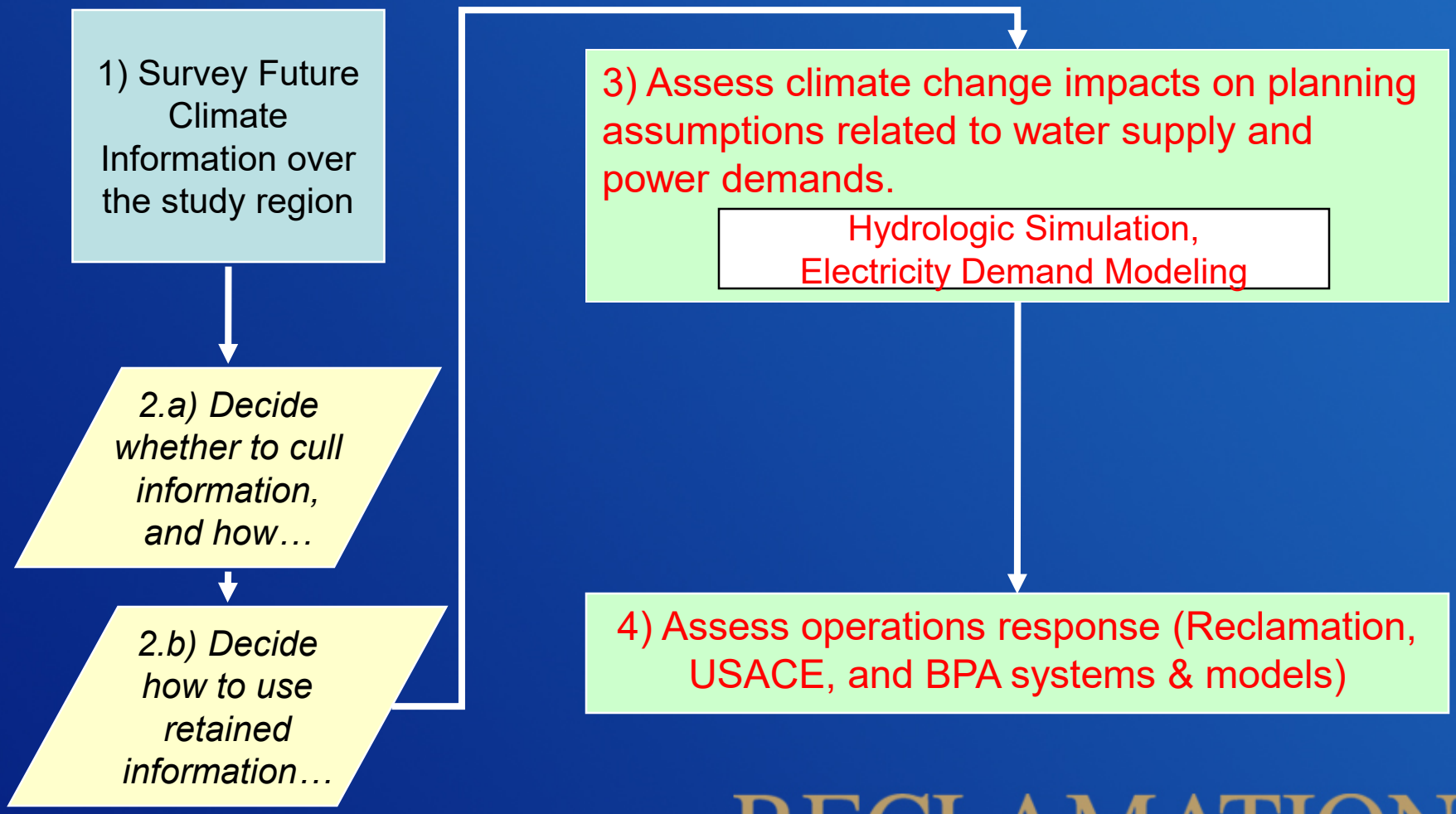
- 2014/2024 Columbia River Treaty Review
- Bi-Op assessments
- ESA/NEPA
- Reliability Studies
- Council's 6th Power Plan
- Flood Risk Management
- Rates/Revenues
- Infrastructure Studies

Flow of Information: General View



RECLAMATION

Flow of Information: RMJOC collaboration with CIG



RECLAMATION

Flow of Information: Key CIG Decisions…

Considered 100+ current projections…

ure

ver

on

2.a) Decide whether to cull

Decided to focus on 19 projections…

retained information…

Made two types of Columbia Basin weather and hydrology

Hydrologic Simulation, Electricity Demand Modeling

4) Assess operations response (Reclamation, USACE, and BPA systems & models)

RECLAMATION

Flow of Information: Key RMJOC decisions…

Considered CIG's 19 projections…

2.a) Decide whether to cull

Decided to focus on smaller set…

retained information…

Decided to use both types of Columbia Basin weather and hydrology…

Assessing operations under both types of information… insights for planning applications

RECLAMATION

Work Plan Deliverables

- Reviewed Data from CIG
  - (#1) Future Climate Information
    - "Climate Change" (Hybrid-Delta)
    - Climate Projections (Transient)
  - (#2) Columbia Basin weather (both types)
  - (#3) Columbia Basin hydrology (both types)

- Developed Data by RMJOC agencies (extending from both types)
  - (#4) Bias-Corrected Streamflows for reservoir operations modeling
  - (#5) Seasonal Runoff Volume Forecasts
  - (#6) Develop Flood Control and Operating Rule Curves

- (#7) Demonstration Studies by RMJOC agencies' staff
  - Use both data types (Hybrid-Delta, Transient)
  - Comparison of Results – implications for planning applications

Work Plan Status
Tasks 1.1 – 2.3

RECLAMATION

TASK 1 - CLIMATE PROJECTIONS SURVEY AND SELECTION

- Task 1.1 - Review of Regional Climate Projection Information available from UW CIG
- Task 1.2 - Select Subset of UW CIG Regional Climate Projection Information (Deliverable #1)
- Task 1.3 - Documentation and Internal Review

Start with future climate forcings (mulitple scenarios!)

Future Global Econ/Tech Scenario (e.g., IPCC 2000)

↓

GHG Emissions Scenario (e.g., energy portfolios)

↓

Atmospheric GHG Concentrations (fate of emissions)

↓

Climate modeled response (lots of models!)

NCAR CCSM | UKMO-HadCM3 | GFDL CM2.0 | … 22 models from 16 centers

Run1 … Run 4 ← Different initial conditions!

Courtesy: Barsugli

RECLAMATION

CIG's Two Types of Information

- "Climate Change" Hydrology
  - RMJOC Label: Hybrid-Delta
  - Retains more sense of historical variability (in space and time), but shifted for future climate

- Climate and Hydrologic Projections
  - RMJOC Label: Transient
  - Reflects monthly evolving nature of climate, as reflected in climate projections

RECLAMATION

About these Information Types

- Hybrid-Delta (HD) Scenario
  - Involves two data sequences: Observed Historical and Adjusted Historical reflecting "Climate Change", both having duration same as Observed Historical (1915-2006)
  - Weather: gridded 1/16º, daily
  - Hydrology:
    - gridded 1/16º, daily runoff & snow water equivalent
    - routed runoff to RMJOC locations of interest, daily/monthly/annual

RECLAMATION

About these Information Types

- Transient Projections
  - Involves one data sequence: from GCM-simulated historical to simulated future (1950-2099)
  - Weather: gridded 1/16º, daily
  - Hydrology:
    - gridded 1/16º, daily runoff & snow water equivalent
    - routed runoff to RMJOC locations of interest, daily/monthly/annual

RECLAMATION

CIG Options: 19 HD Scenarios for both 2020s and 2040s, 14 Transient Projections

Climate Projections			"Climate Change" Hydrology (Hybrid-Delta Scenarios)						Hydrologic Projections (Transient) (x = selected, o = not selected)
			2020s			2040s			
Number	Climate Model	Emissions Scenario	Selected (RMJOC Labels) [1]	Change in P (in) [2]	Change in T (°C) [2]	Selected (RMJOC Labels) [1]	Change in P (in) [2]	Change in T (°C) [2]	
1	ccsm3	B1		-1.2	1.4		-0.8	1.8	
2	cgcm3.1 t47	B1		7.9	1.1		11.5	1.3	
3	cnrm cm3	B1		7.5	1.2		5.3	1.2	
4	echam5	B1		1.3	0.7		5.9	1.2	
5	echo g	B1		-4.2	1.2		-7.9	1.8	
6	hadcm	B1		3.8	1.0		3.7	1.7	
7	ipsl cm4	B1		3.8	1.4		6.9	2.1	
8	miroc 3.2	B1		8.1	1.3		10.4	2.3	
9	pcm1	B1		1.5	0.6		3.6	0.8	
10	ccsm3	A1b		4.6	1.4		2.0	2.4	
11	cgcm3.1 t47	A1b		8.8	1.2		13.4	1.8	
12	cnrm cm3	A1b		0.8	1.0		4.1	1.6	
13	echam5	A1b		3.7	0.7		3.7	1.5	
14	echo g	A1b		-4.7	1.1		0.9	1.9	
15	hadcm	A1b		3.0	1.5		6.7	2.2	
16	ipsl cm4	A1b		7.4	1.6		11.2	2.6	
17	miroc 3.2	A1b		4.2	1.6		14.2	2.7	
18	pcm1	A1b		-1.5	1.0		-0.2	1.8	
19	hadgem1	A1b		-1.5	1.3		-2.5	2.8	

Notes

[1] RMJOC Labels: MW = More Warming, LW = Less Warming, W = Wetter, D = Drier, MC = Minor Change, C = Central Change

[2] P = precipitation, T = average daily temperature, "Change in" means change in 92-year period-mean annual condition. For assessing change, the reference is Observed Climate Variability, 1916-2006. The changed condition is the 92-year Observed Climate Variability sequence adjusted to reflect change in 30-year climate characteristics from observed 1970-1999 to a projected 30-year period (2020s = 2010-2039 and 2040s = 2030-2059) sampled from the given underlying climate projection (see Number).

TASK 1 - CLIMATE PROJECTIONS SURVEY AND SELECTION

- Task 1.1 - Review of Regional Climate Projection Information available from UW CIG
- Task 1.2 - Select Subset of UW CIG Regional Climate Projection Information (Deliverable #1)
- Task 1.3 - Documentation and Internal Review

Selection Preliminaries

- We can't say any selections are right or wrong.
- We could have randomly chosen subsets from CIG scenarios; instead we tried to apply some rationale (as discussed).
- Each RMJOC participant has a different perspective in applying the rationale.
- We attempted to balance perspectives… but there's no "one size fits all"

RECLAMATION

Oct 16 Tech Team Meeting #1: Summary of Discussion

- "Keep it simple. Keep it manageable."
  - Identify small scenario-set to support RMJOC agencies' planning, representative of CIG information.
  - Larger scenario sets are possible as follow-on efforts.

- Proceed with Small Subset identification
  - First select HD 2020s subset & HD 2040s subset
  - …then select associated Transient Projections.

RECLAMATION

Dec 7 Tech Team Meeting #2: Selecting HD Subsets

- Guiding philosophy:
  - Reflect the “spread” of climate change information from CIG
  - Reflect the central tendency of this information also (e.g., centrally estimated “climate change” increment)

- Selection considerations also discussed on Oct 16

- HD Scenario Selection Factors (repeated for 2020s, 2040s)
  - Climate change periods (already decided by CIG)
  - Climate change metrics (Tech Team choice)
  - Climate change location (Tech Team choice)
  - Climate change range of interest (Tech Team choice)

RECLAMATION

Dec 7 Tech Team Meeting #2: Selecting HD Subsets

- Which Climate Change Metrics?
- …over which part of the basin?
- …for what percentile range of change?
- Notes:
  - Climate period choices already made by CIG

RECLAMATION

Dec 7 Tech Team Meeting #2: HD Selection Factor Decisions

- Climate Change Metrics:
  - Decided to focus on period-mean annual T and P, which broadly relates to a host of resources managed in the basin (environmental , flood control, water supply, hydropower).
- Climate Change Location:
  - Decided to focus on basin-mean; caviat is that documentation should illustrate how projection selections for bracketing spread based on basin-mean may end up not bracketing spread so-well on a sub-basin basis.
- Climate Change Range of Interest:
  - Decided to focus on10- to 90-percentile, noting that while this may be extreme (USFWS), we're already starting with a scenario-limited set given that CIG limited their considerations to 38 projections from the 100+ CMIP3 projections available.
  - Decided to include sixth selection: "minimum change" (i.e. close to no precipitation change and minimum warming), which happened to coincide with one of the transient projection recommendations from BC-Hydro.

RECLAMATION

Overview of RMJOC Selections

Climate Projections			"Climate Change" Hydrology (Hybrid-Delta Scenarios)						Hydrologic Projections (Transient) (x = selected, o = not selected)
			2020s			2040s			
Number	Climate Model	Emissions Scenario	Selected (RMJOC Labels) [1]	Change in P (in) [2]	Change in T (°C) [2]	Selected (RMJOC Labels) [1]	Change in P (in) [2]	Change in T (°C) [2]	
1	ccsm3	B1	MW/D	-1.2	1.4		-0.8	1.8	x
2	cgcm3.1 t47	B1	LW/W	7.9	1.1	LW/W	11.5	1.3	x
3	cnrm cm3	B1		7.5	1.2		5.3	1.2	o
4	echam5	B1		1.3	0.7		5.9	1.2	o
5	echo g	B1		-4.2	1.2	LW/D	-7.9	1.8	x
6	hadcm	B1	C	3.8	1.0	C	3.7	1.7	x
7	ipsl cm4	B1		3.8	1.4		6.9	2.1	
8	miroc 3.2	B1		8.1	1.3		10.4	2.3	
9	pcm1	B1		1.5	0.6		3.6	0.8	o
10	ccsm3	A1b		4.6	1.4		2.0	2.4	o
11	cgcm3.1 t47	A1b		8.8	1.2		13.4	1.8	o
12	cnrm cm3	A1b		0.8	1.0		4.1	1.6	o
13	echam5	A1b	MC	3.7	0.7	MC	3.7	1.5	x
14	echo g	A1b		-4.7	1.1		0.9	1.9	o
15	hadcm	A1b		3.0	1.5		6.7	2.2	o
16	ipsl cm4	A1b	MW/W	7.4	1.6		11.2	2.6	
17	miroc 3.2	A1b		4.2	1.6	MW/W	14.2	2.7	
18	pcm1	A1b	LW/D	-1.5	1.0		-0.2	1.8	x
19	hadgem1	A1b		-1.5	1.3	MW/D	-2.5	2.8	

Notes

[1] RMJOC Labels: MW = More Warming, LW = Less Warming, W = Wetter, D = Drier, MC = Minor Change, C = Central Change

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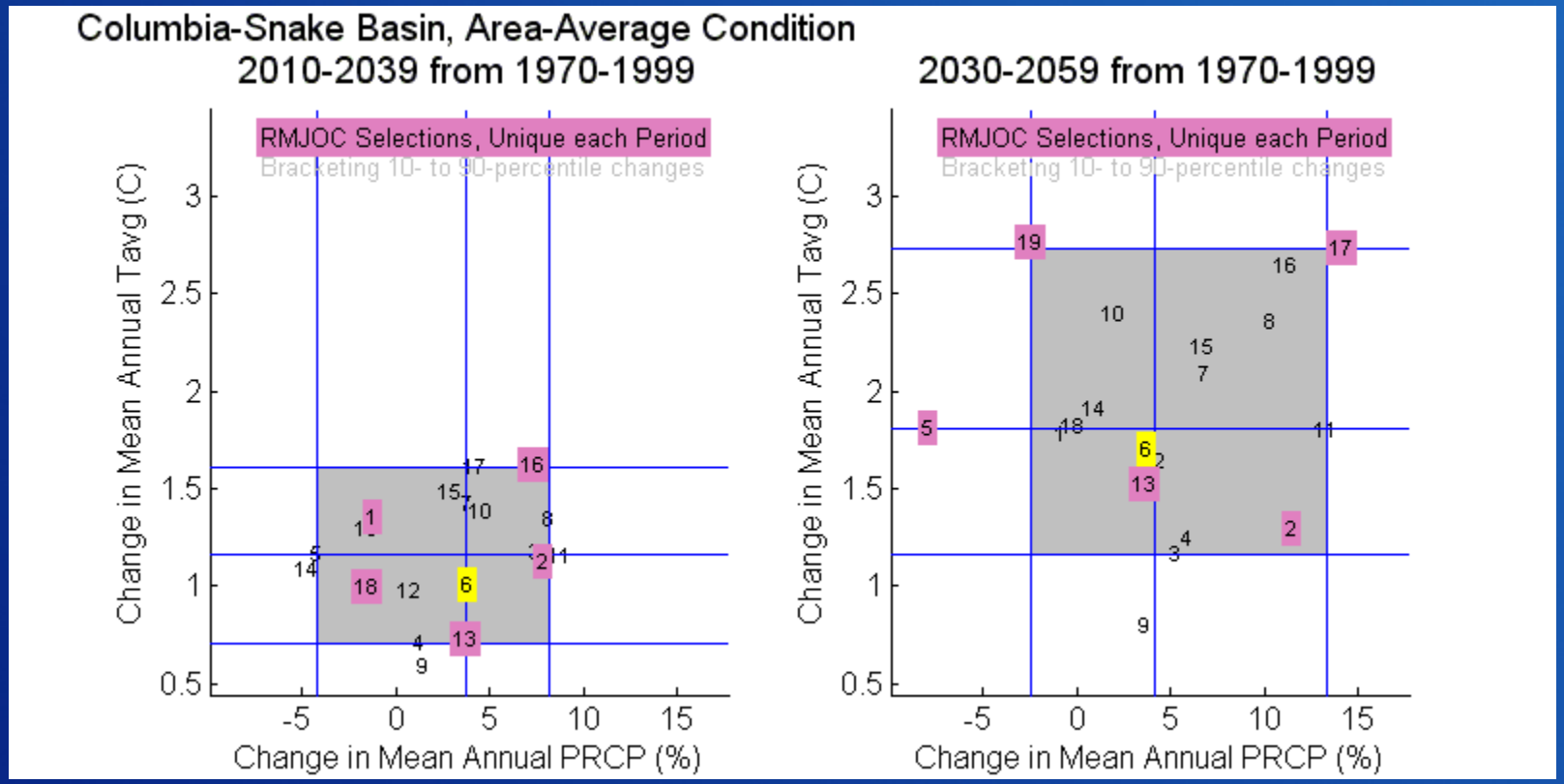
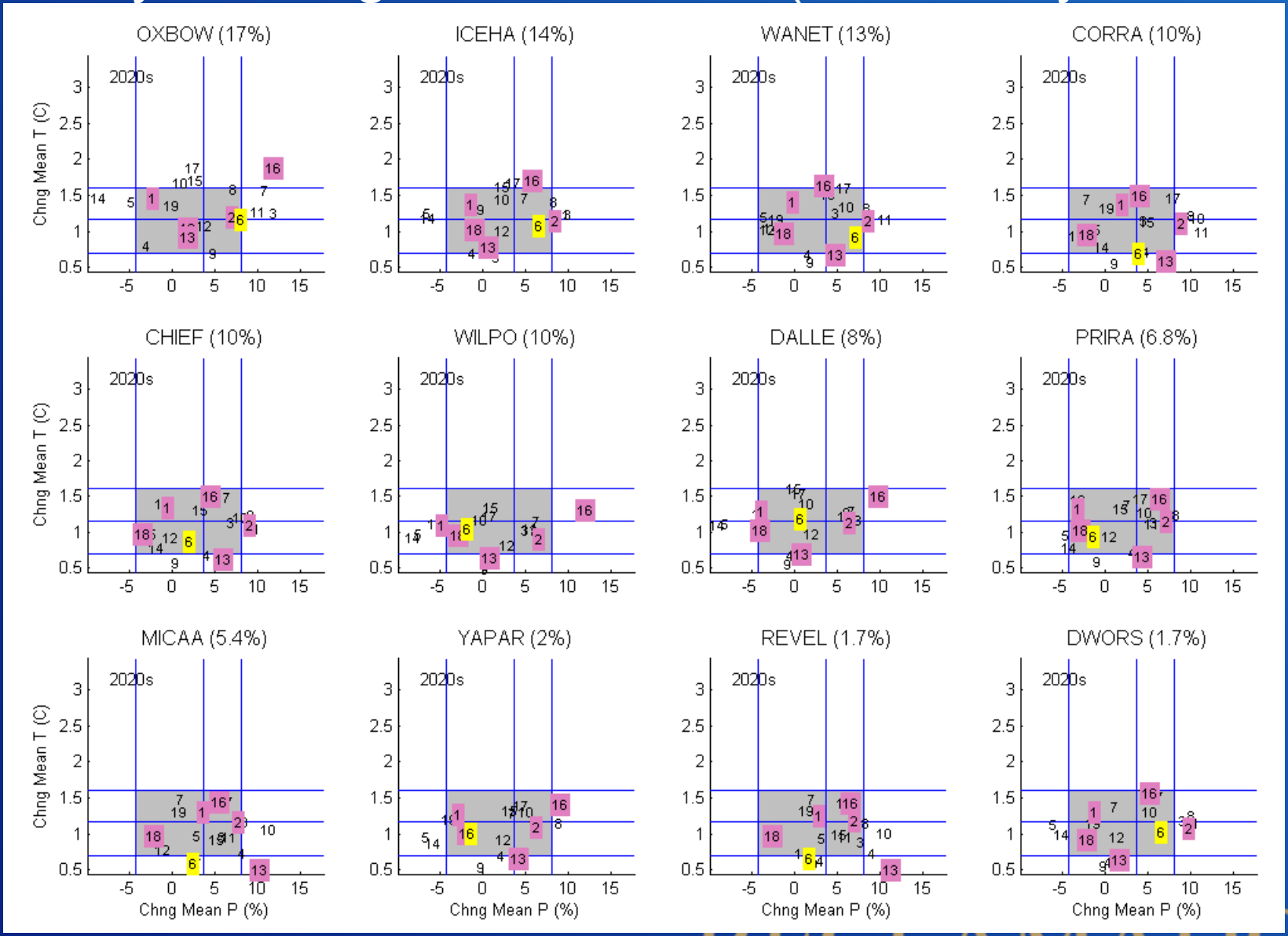
HD Scenario Selections



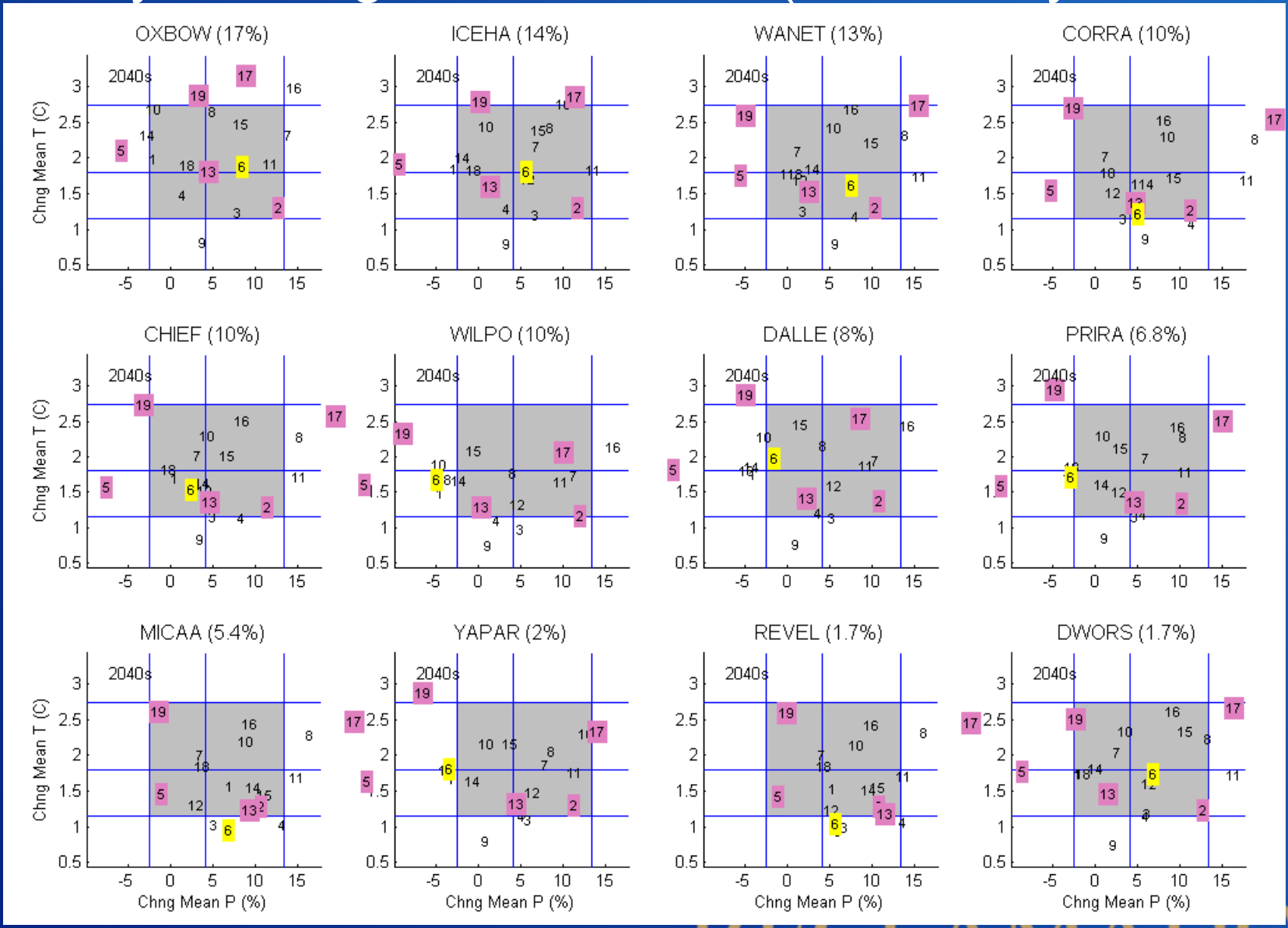
RECLAMATION

… showing how 2020s HD Scenarios bracket spread differently over a given sub-basin (ordered by P volume)



RECLAMATION

… showing how 2040s HD Scenarios bracket spread differently over a given sub-basin (ordered by P volume)



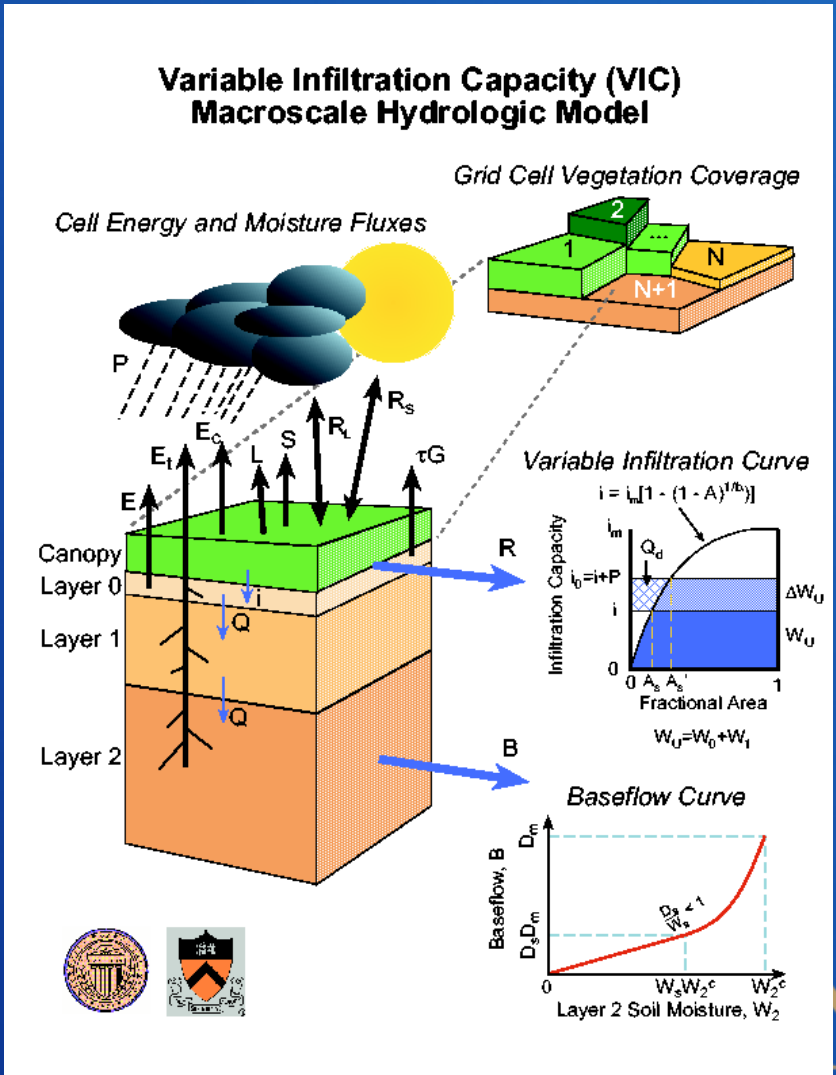
RECLAMATION

TASK 2 - HYDROLOGIC DATA SELECTION AND VERIFICATION

- Task 2.1 – Obtain and Review Hydrologic Model
- Task 2.2 – Obtain and Review Daily Weather Inputs (Deliverable #2)
- Task 2.3 - Obtain and Review Simulated Water Balance and Streamflow (Deliverable #3)
- Task 2.4 - Independently Verify Datasets #1, #2, and #3
- Task 2.5 - Internal Review, Revised Documentation

About VIC Hydrology Model

- Model Structure: Liang et al. 1994
  - http://www.hydro.washington.edu/Lettenmaier/Models/VIC/
- VIC Inputs (water balance mode):
  - gridded time series of precipitation, min/max daily temperature, & wind speed



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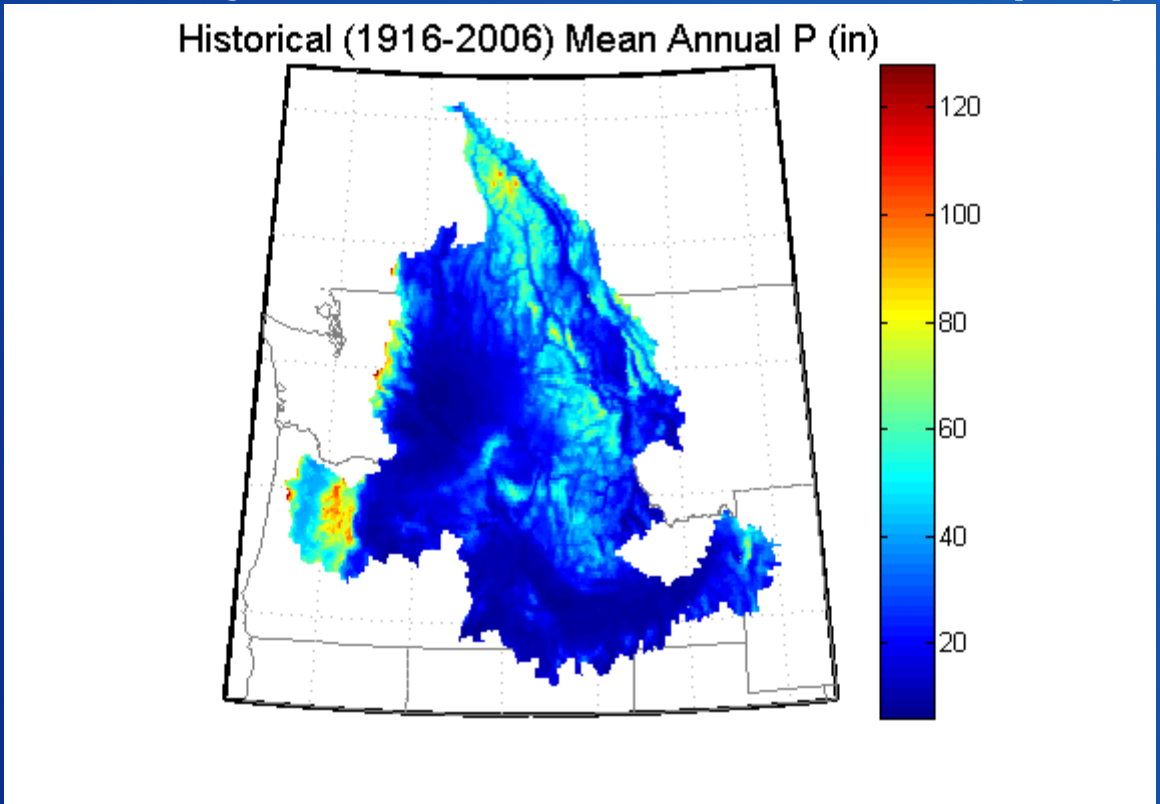
VIC Weather Inputs: Hybrid-Delta Scenario

- From Task 1.1, HD Scenarios…
  - two data sequences:
    - Observed Historical
    - Adjusted Historical
      - *Sequence*: follows 1915-2006
      - *Monthly Distributions*: adjusted, grid-cell specific, to reflect change in 30-year monthly climate from observed 1970-2099 to simulated HD Scenario's future period
  - attributes:
    - gridded data, 1/16º resolution
    - time series, daily

RECLAMATION

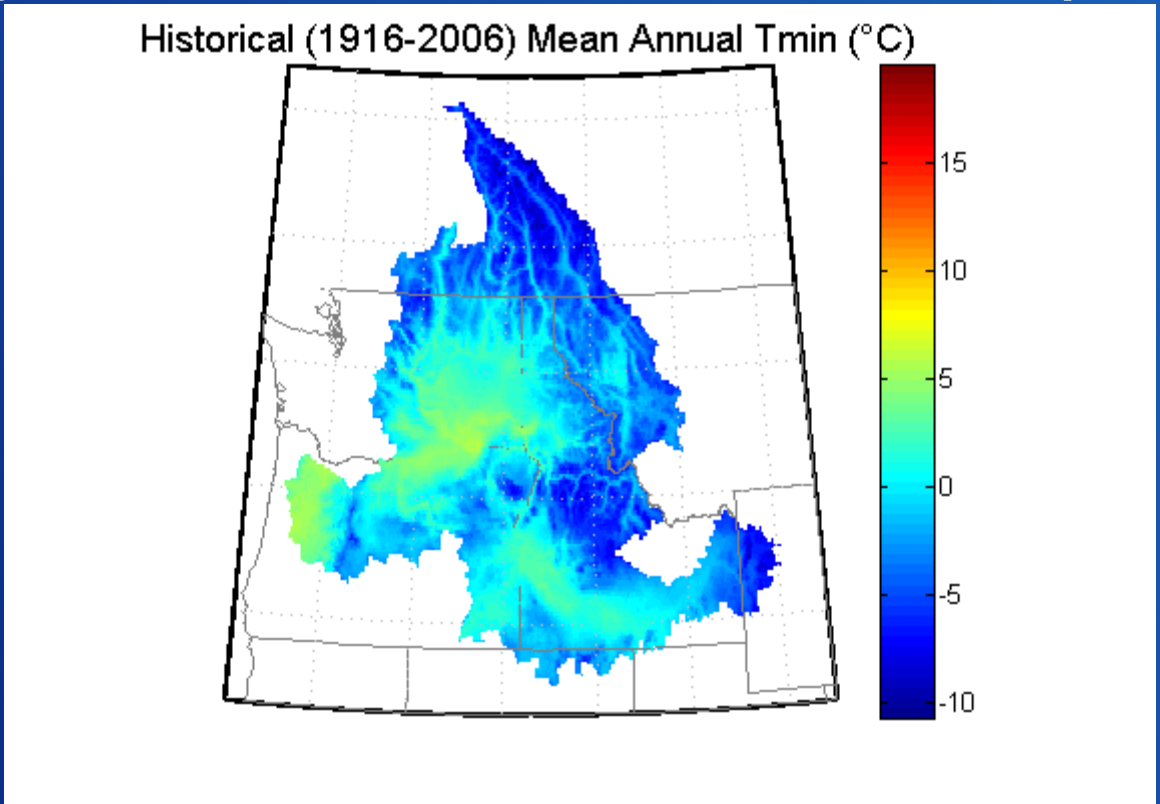
Observed Historical Daily Precipitation (P)



Showing period-mean for water years 1916-2006

RECLAMATION

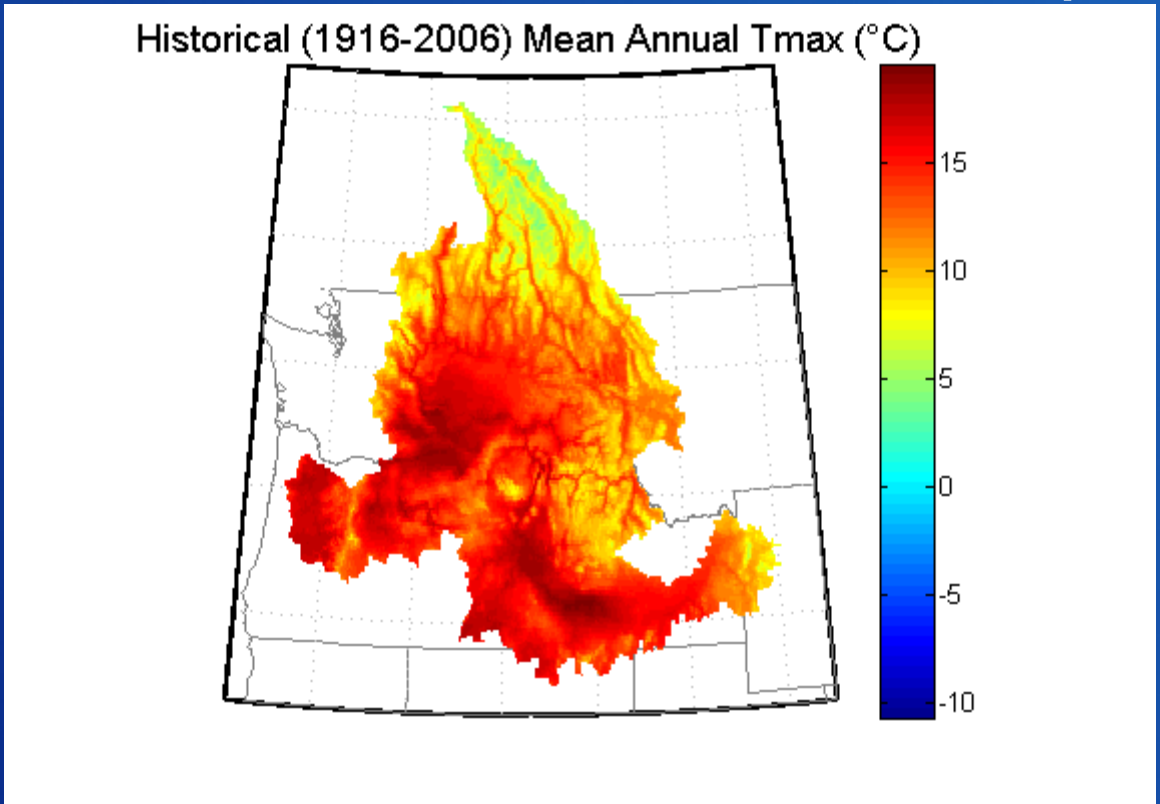
Observed Historical Daily Min. Temperature (Tmin)



Showing period-mean for water years 1916-2006

RECLAMATION

Observed Historical Daily Max. Temperature (Tmax)



Showing period-mean for water years 1916-2006

RECLAMATION

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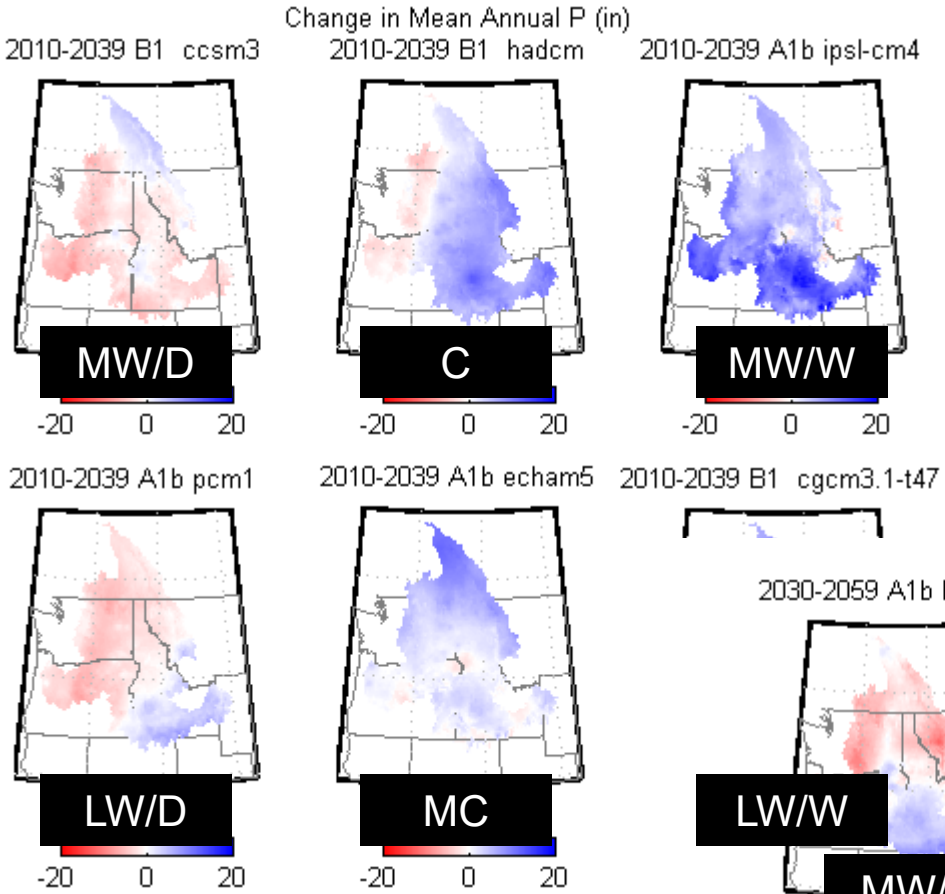
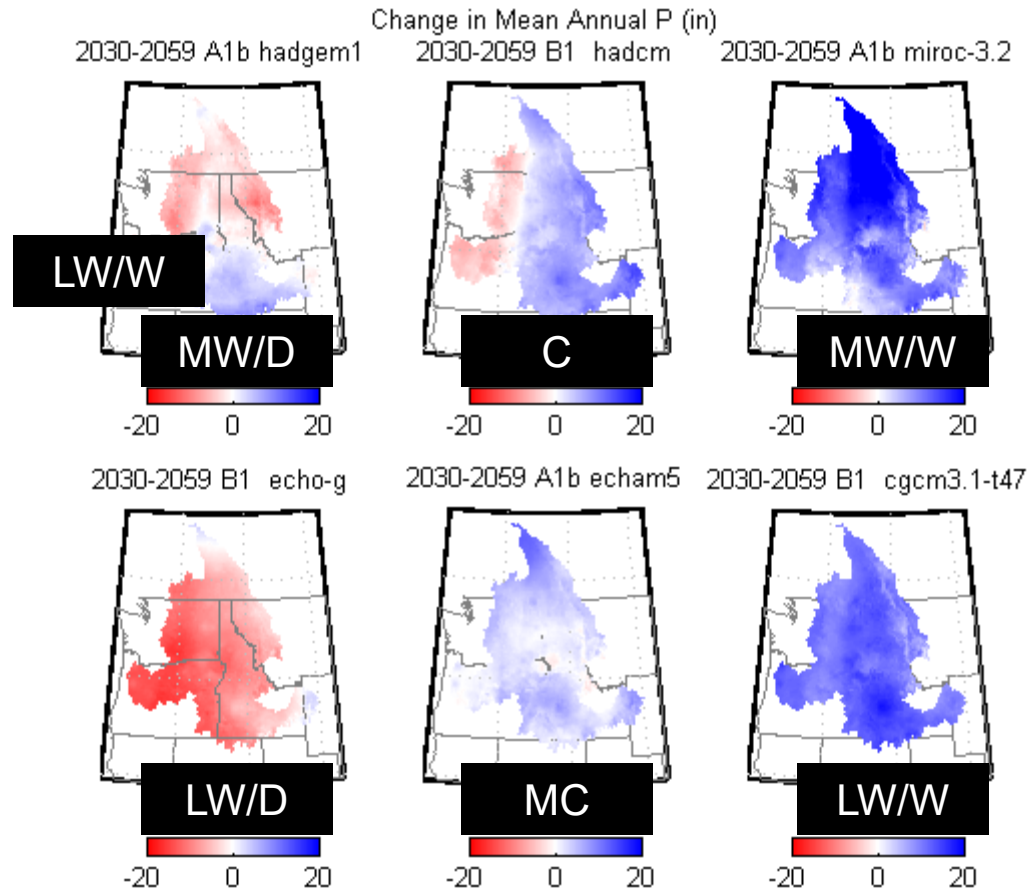
RECLAMATION

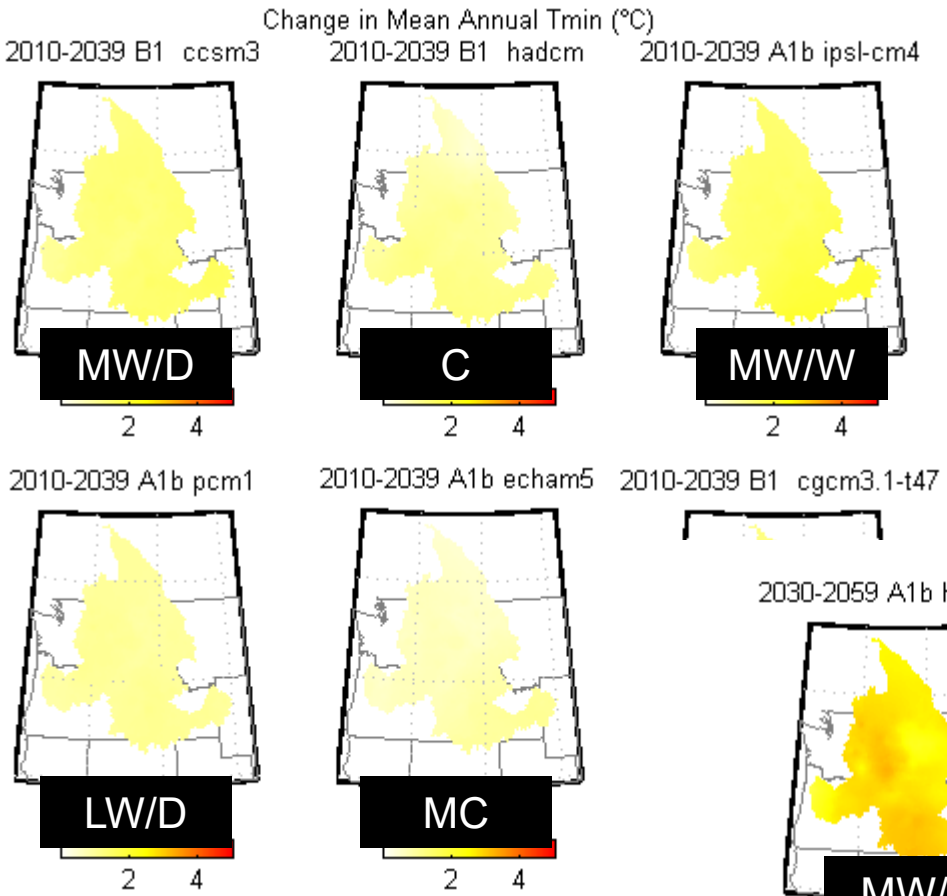
P: Selected HD 2020s Scenarios



P: Selected HD 2040s Scenarios



Tmin: Selected HD 2020s Scenarios



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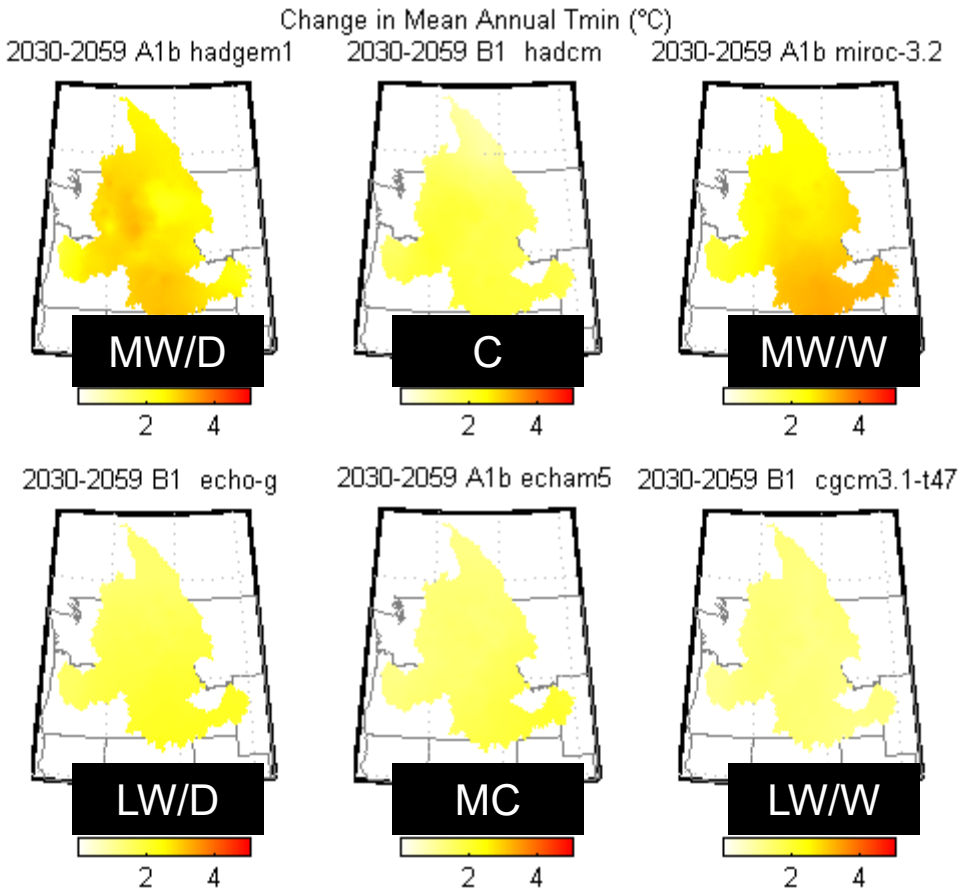
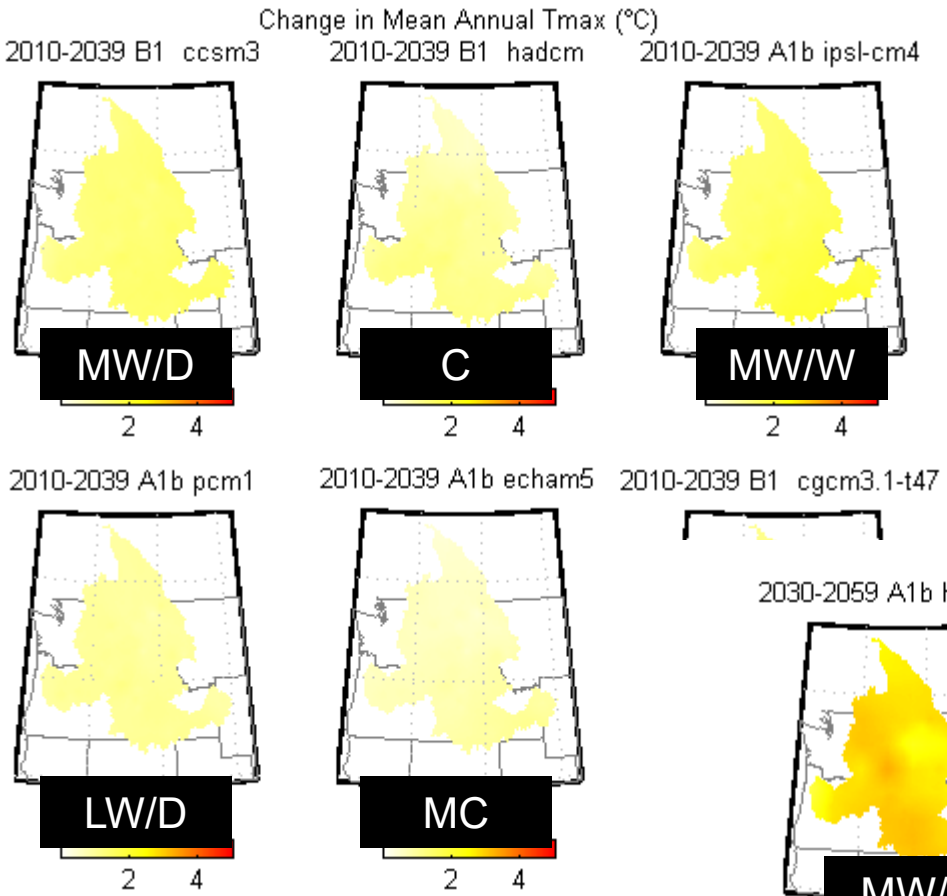


Tmax: Selected HD 2020s Scenarios



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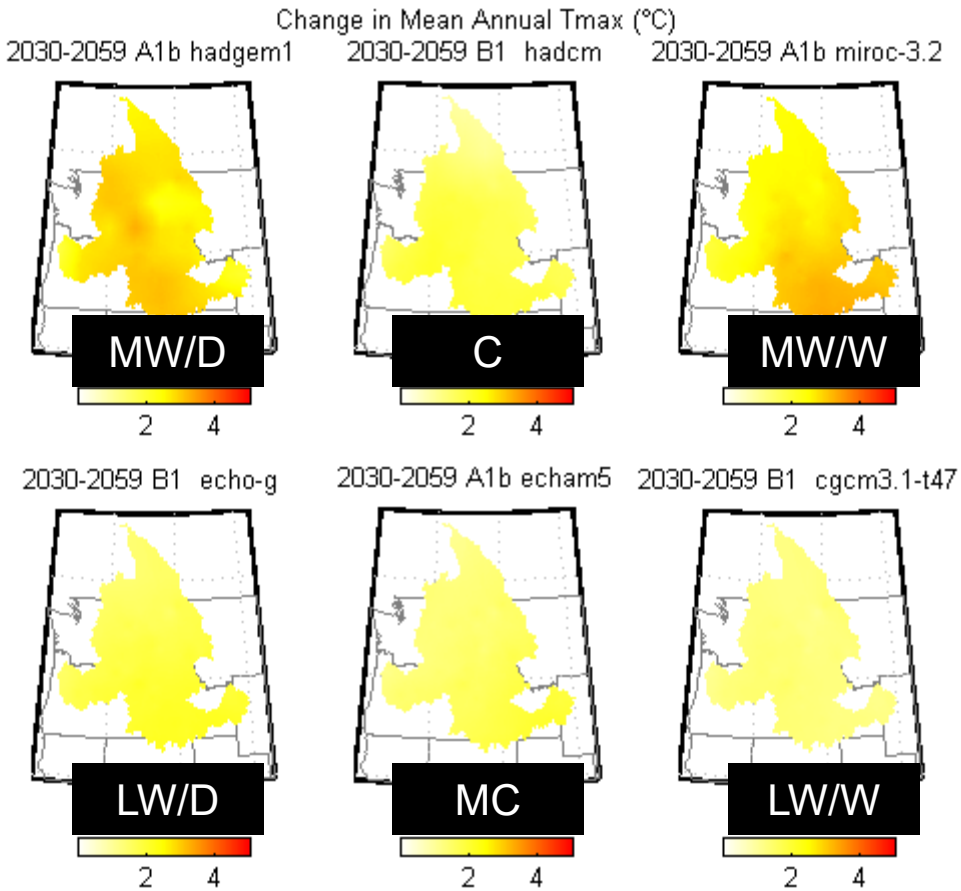


Notes:

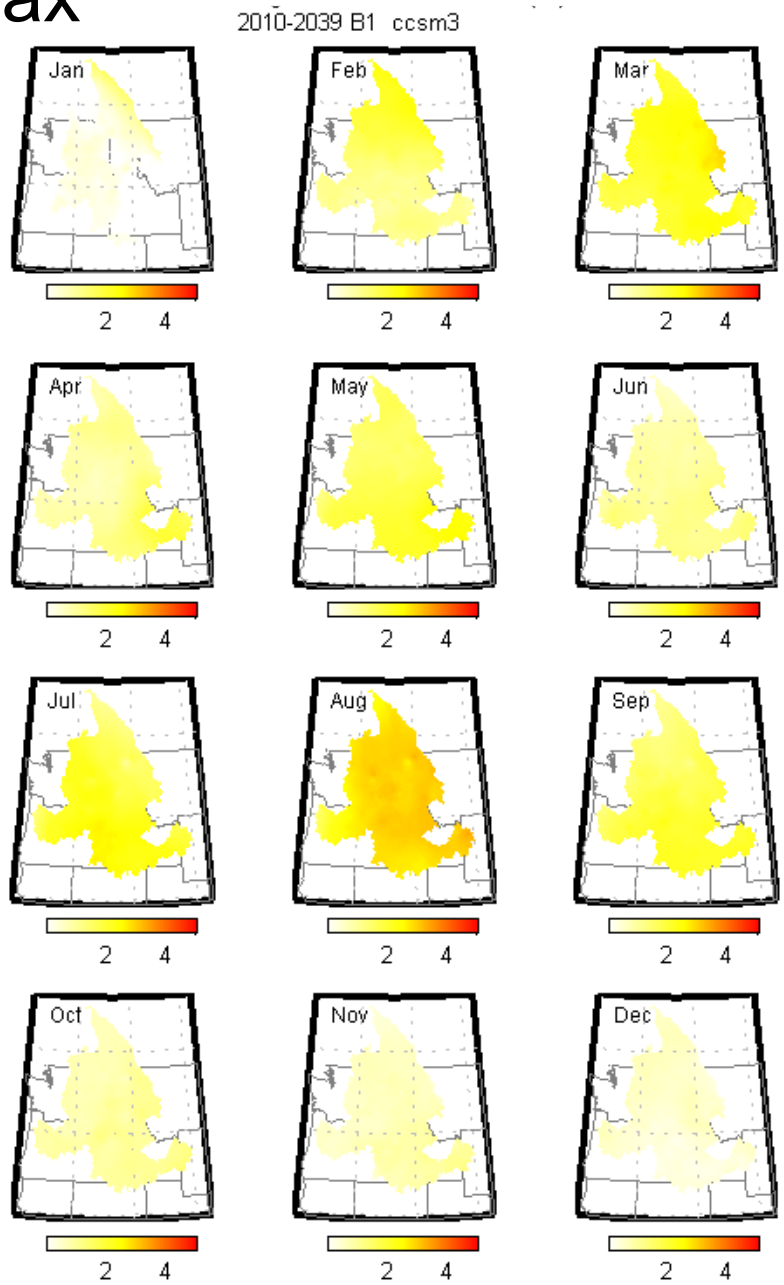
(1) HD Scenarios were selected for how they represent “change in mean-annual” over “whole basin”

(2) Previous maps show that change in mean-annual varies *geographically*

(3) These maps (for HD 2020s MW/D Scenario) show that sign of change also varies by *month* …

(4) Amount of month change may be affected by projection-specific multi-decadal variability (noise, not “change” signal?); next effort might consider HD Scenarios informed by ensemble of projections

Tmax



To be added to Task 2.2 Summary…

Basin-mean time series, T & P, for HD 2020s, HD 2040s, and Transient Projections

Other graphics? Tables?

RECLAMATION

TASK 2 - HYDROLOGIC DATA SELECTION AND VERIFICATION

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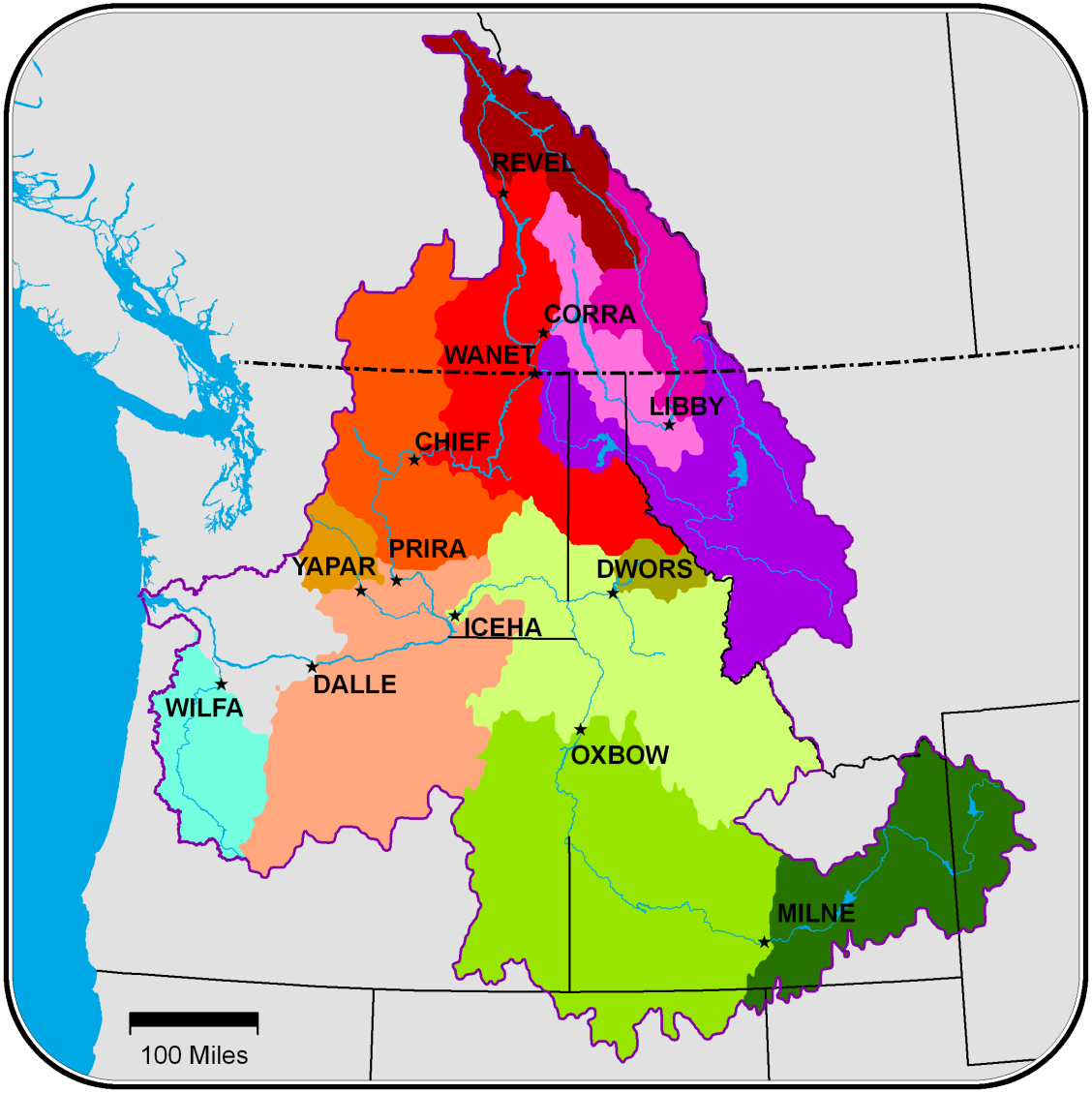
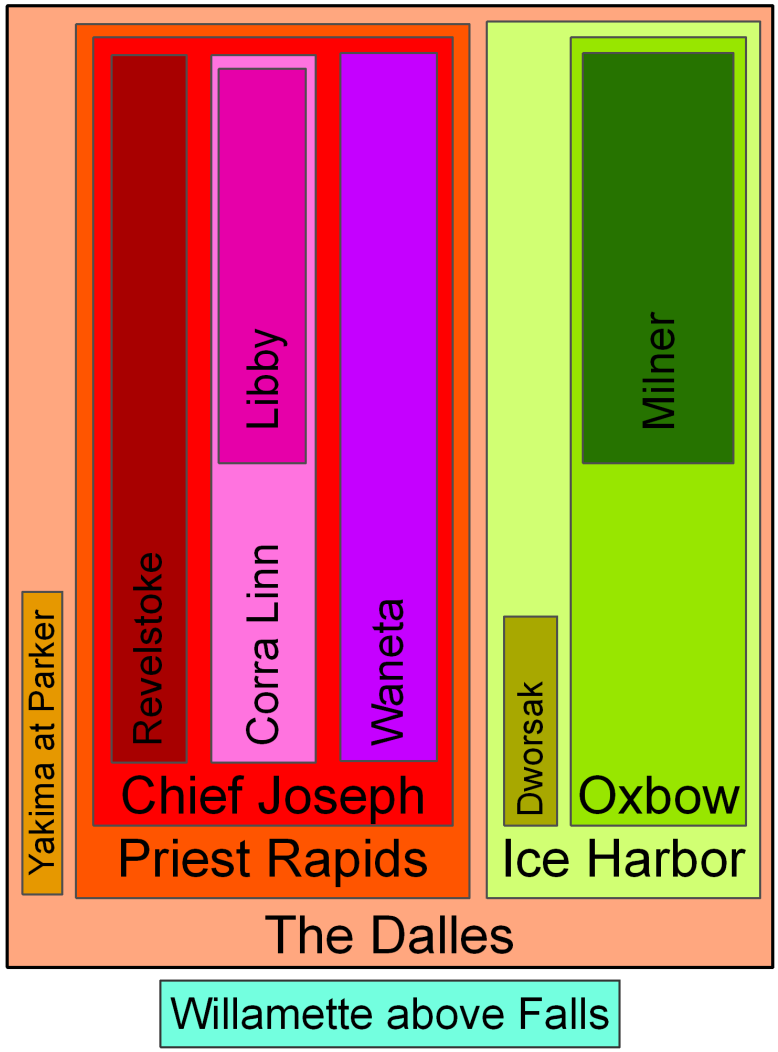
VIC Gridded & Routed Runoff

- CIG's Columbia Basin VIC application produces 1/16d gridded runoff, daily
- VIC model has been calibrated to large sub-basin areas, but RMJOC agencies required routed runoff at other locations
- Bias-correction is performed to account for VIC simulation tendencies at these locations

RECLAMATION

CIG's Calibration Watersheds





Bias-Correction Procedure

- Discussed at Dec 7 and Feb 16 Tech Team meetings
- Identify Bias-Correction Targets
  - we have “raw” VIC historical simulation…
  - we need corresponding “observed” data that we accept as the target, and what we would expect VIC to ~reproduce
  - Identify common overlap period

- Step 1: Correction Basis, Monthly Volumes
  - month-specific historical quantile maps, common overlap period
- Step 2: Correction Basis, Annual Volumes
  - annual historical quantile map, common overlap period
- Step 3: Apply Corrections to HD and Transient results

RECLAMATION

Two Bias-Correction Examples

“Minor Correction” Boise River

“Major Correction” Wickiup Inflow

RECLAMATION

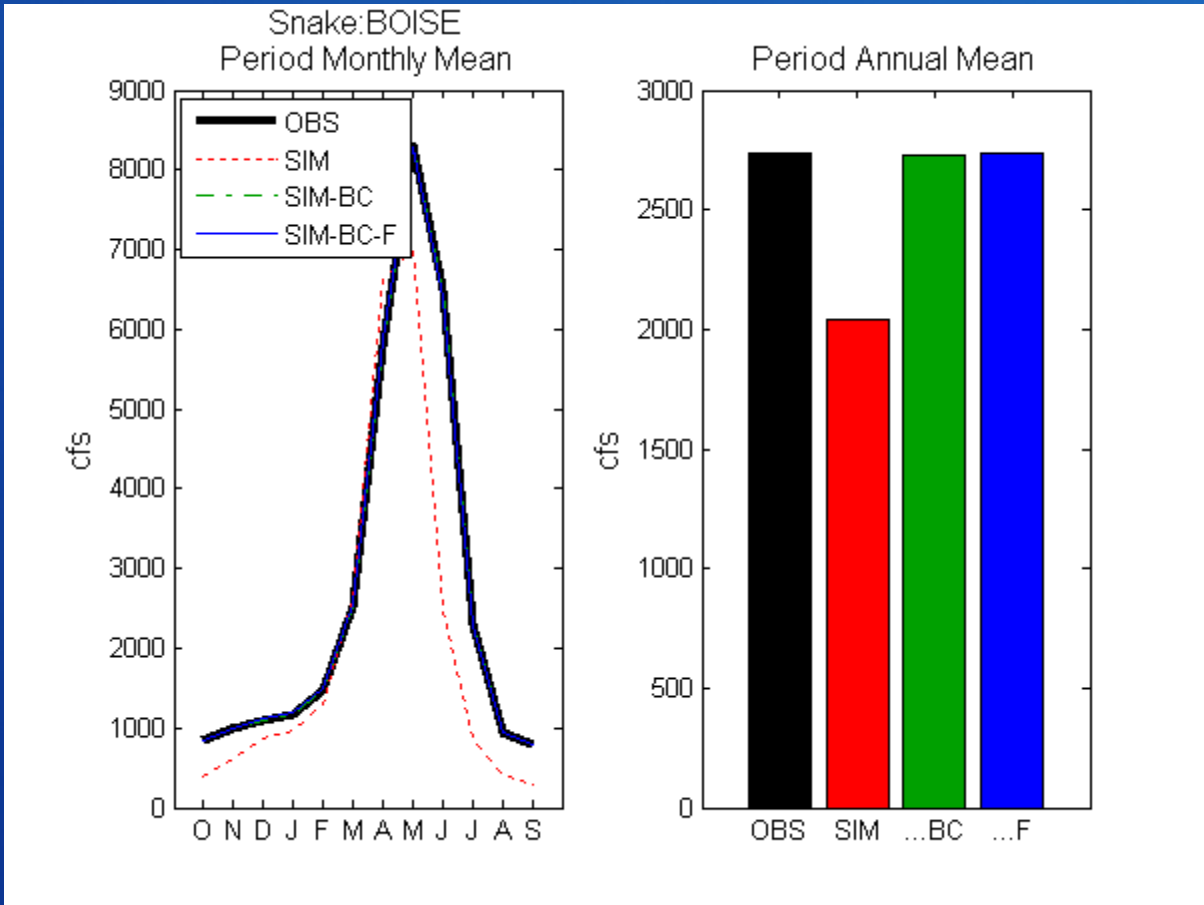
Example #1: Boise River at Lucky Peak (Snake Basin)

OBS = target

SIM = raw VIC

SIM-BC = first correction based on month-specific quantile maps

SIM-BC-F = final correction based on annual quantile map



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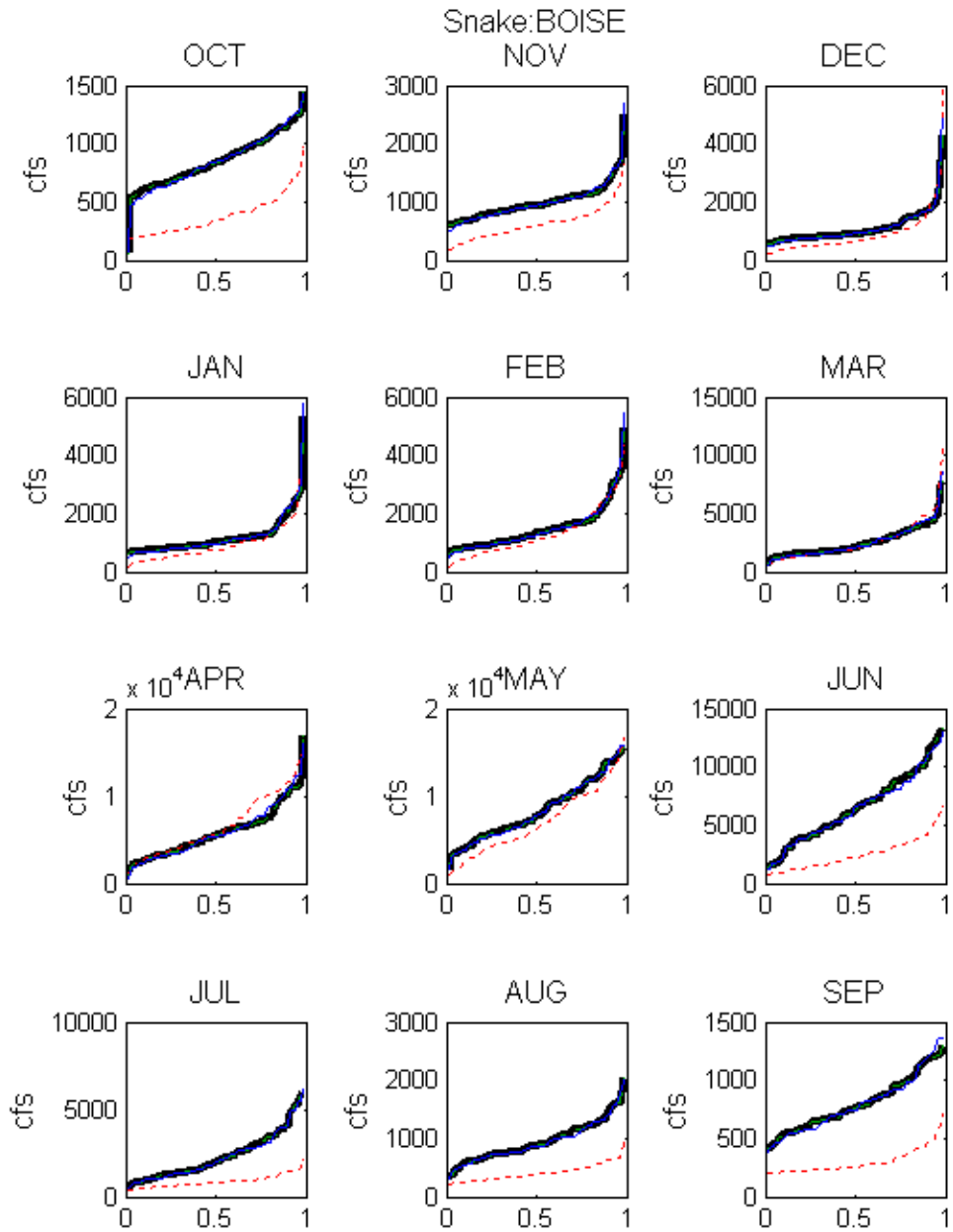

black, red, green, and blue = OBS, SIM, SIM-BC, and SIM-BC-F, respectively

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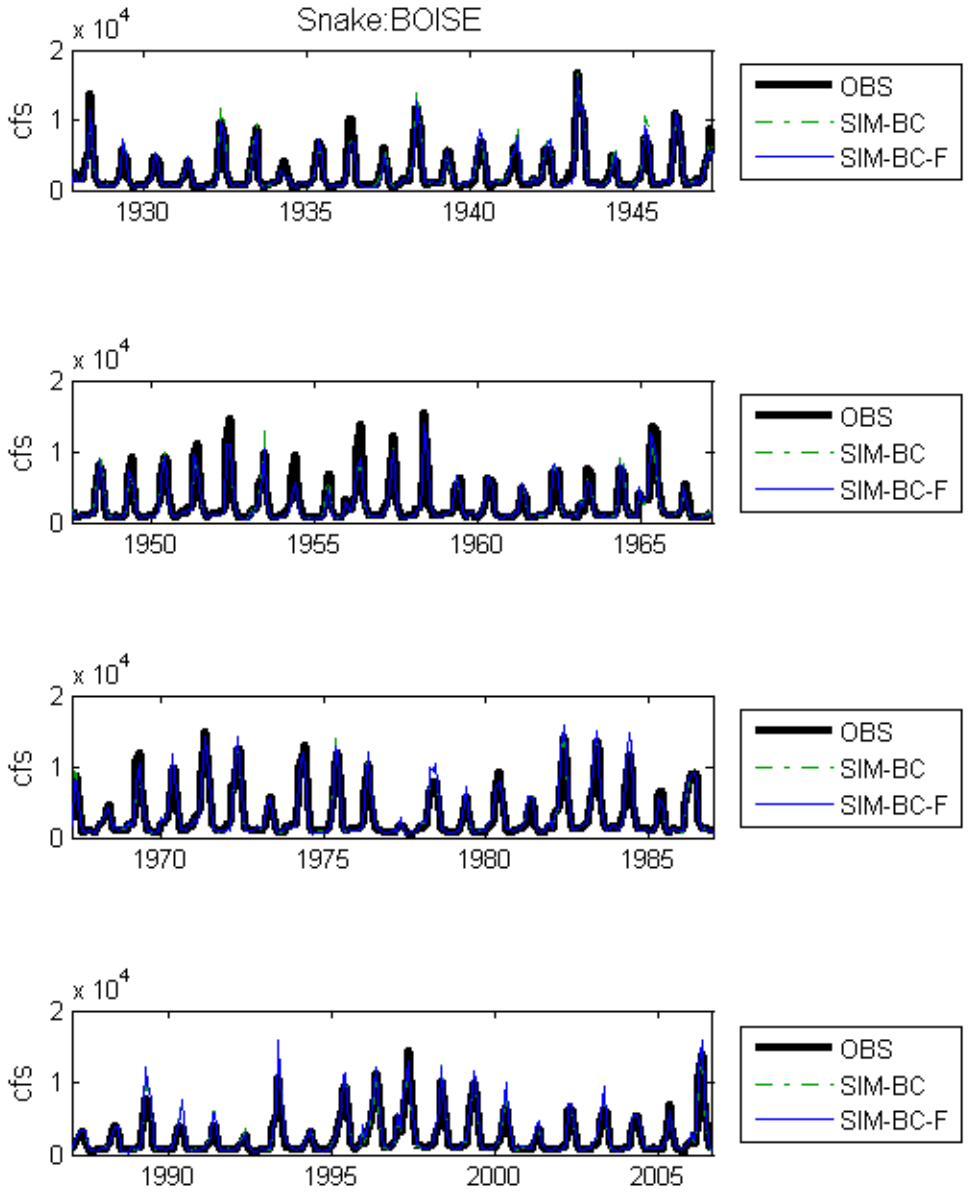

Example #2: Wickiup Reservoir Inflow (Deschutes Basin)

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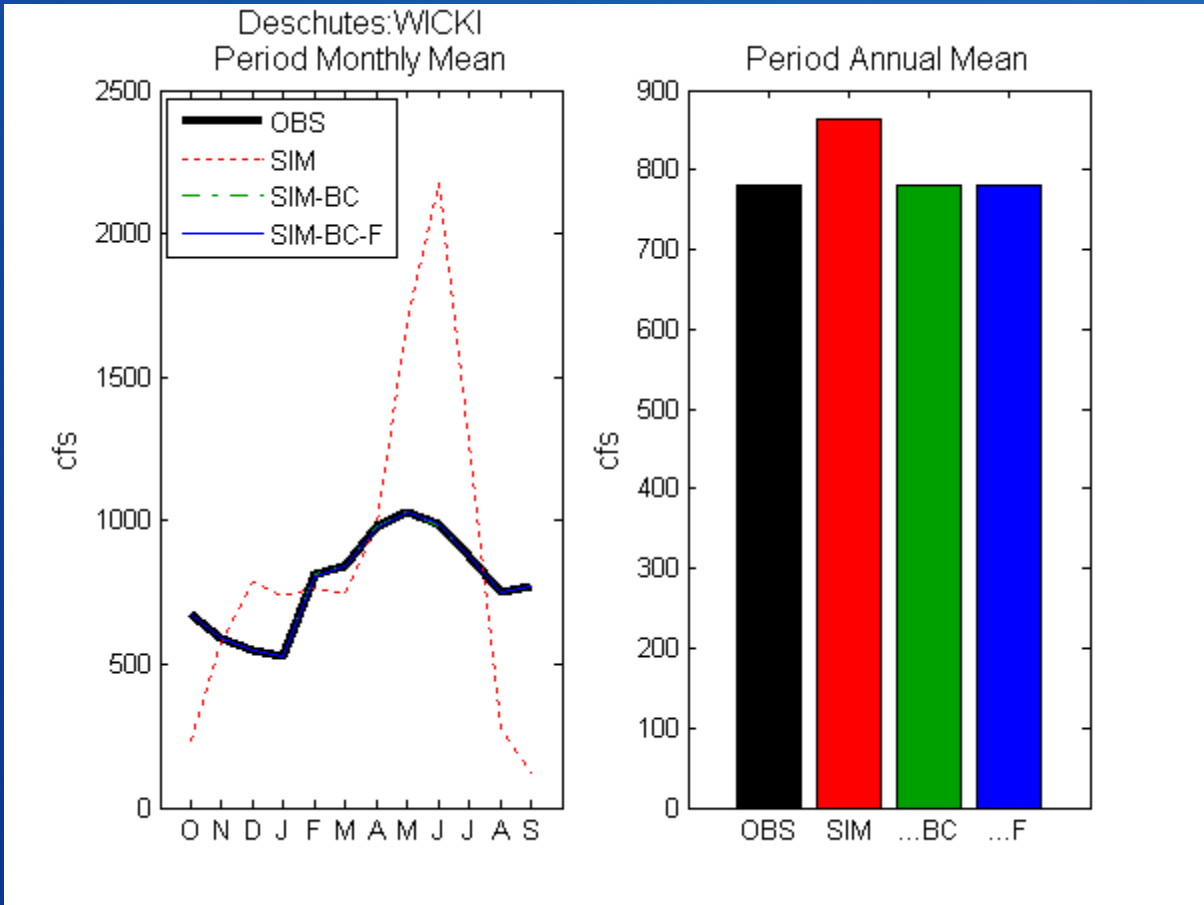

RECLAMATION

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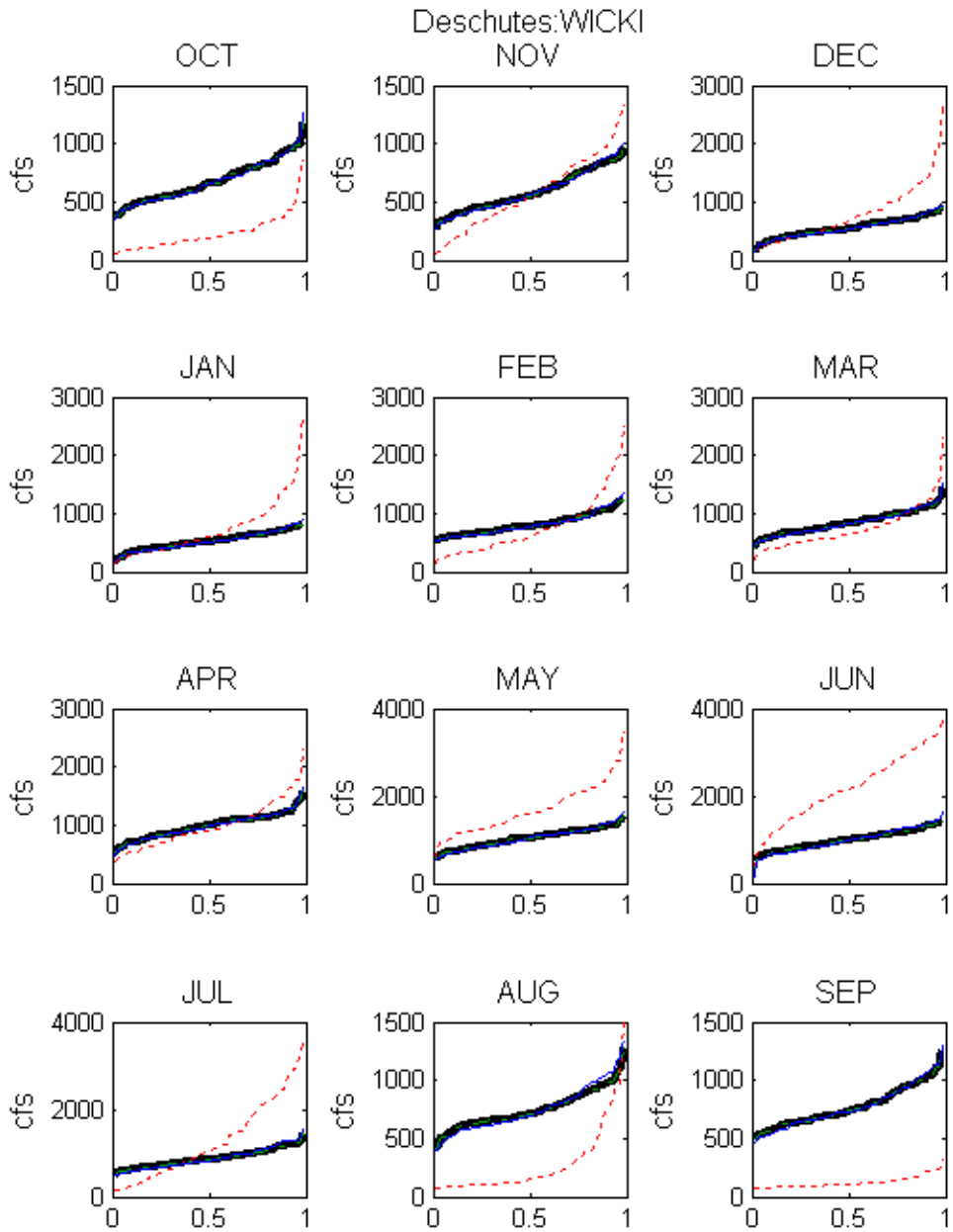

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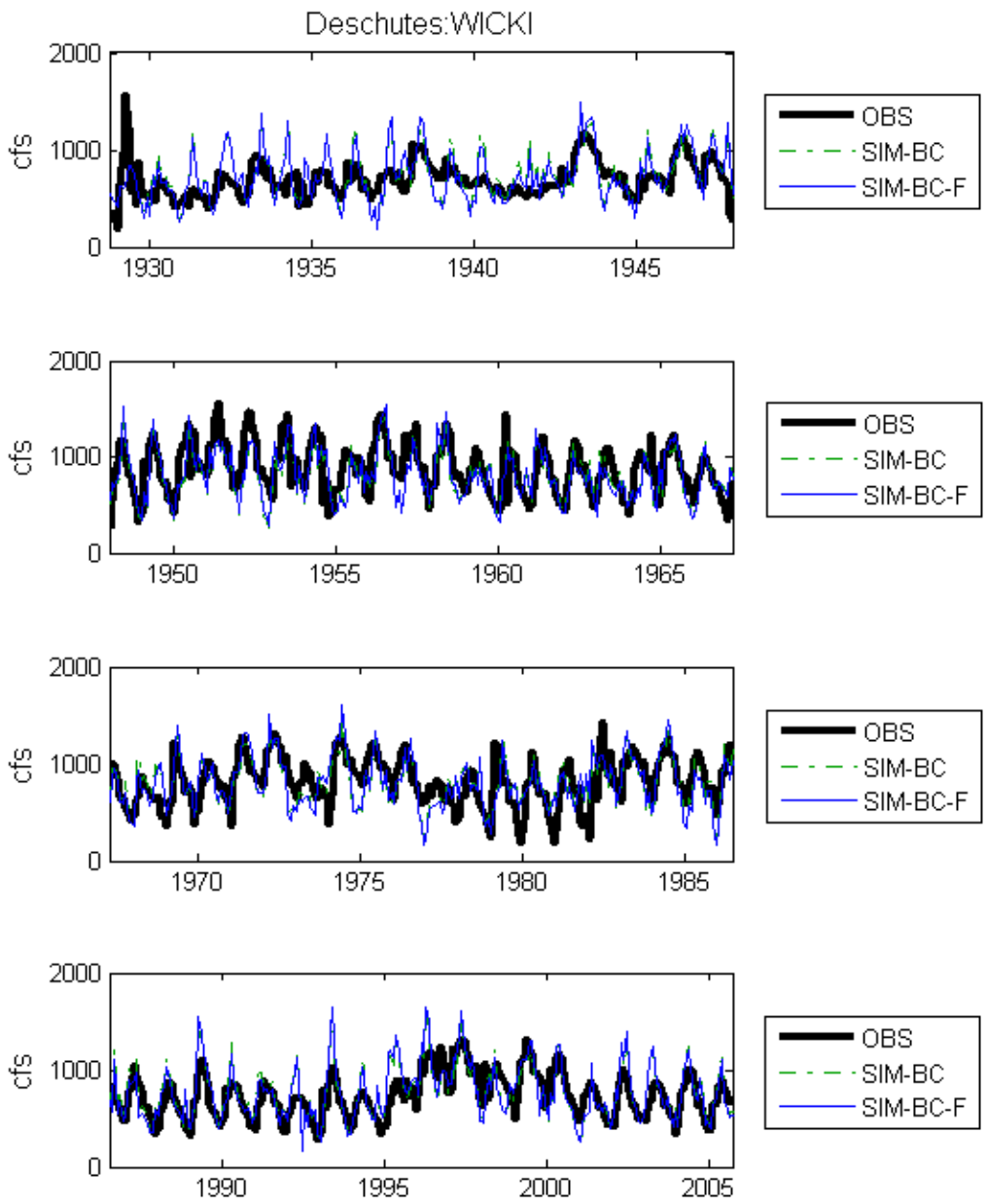


To be added to Task 2.3 Summary…

Tables classifying locations with major or minor bias-correction?

Tables & Graphics summarizing statistical and time series changes – HD scenarios & Transient Projections

RECLAMATION

RECLAMATION

Managing Water in the West

Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies

Tasks 3.2 – Seasonal Runoff Volume Forecasts – Finalization

Levi Brekke (Reclamation, Denver, CO)

U.S. Department of the Interior
Bureau of Reclamation

19 April 2009, Portland, OR

Context

- Climate change with warming is expected to eventually lead to reductions in water supply predictability
  - Loss of snow
- Regardless of *timing* in loss of predictability, as climate change affects hydrology (SWE, Runoff), water supply prediction models should also change
  - perhaps with similar “relative error” on the near term
- Task 3.2 Objectives
  - Construct Seasonal Runoff Volume Forecast series consistent with HD Scenarios and Transient Projections

RECLAMATION

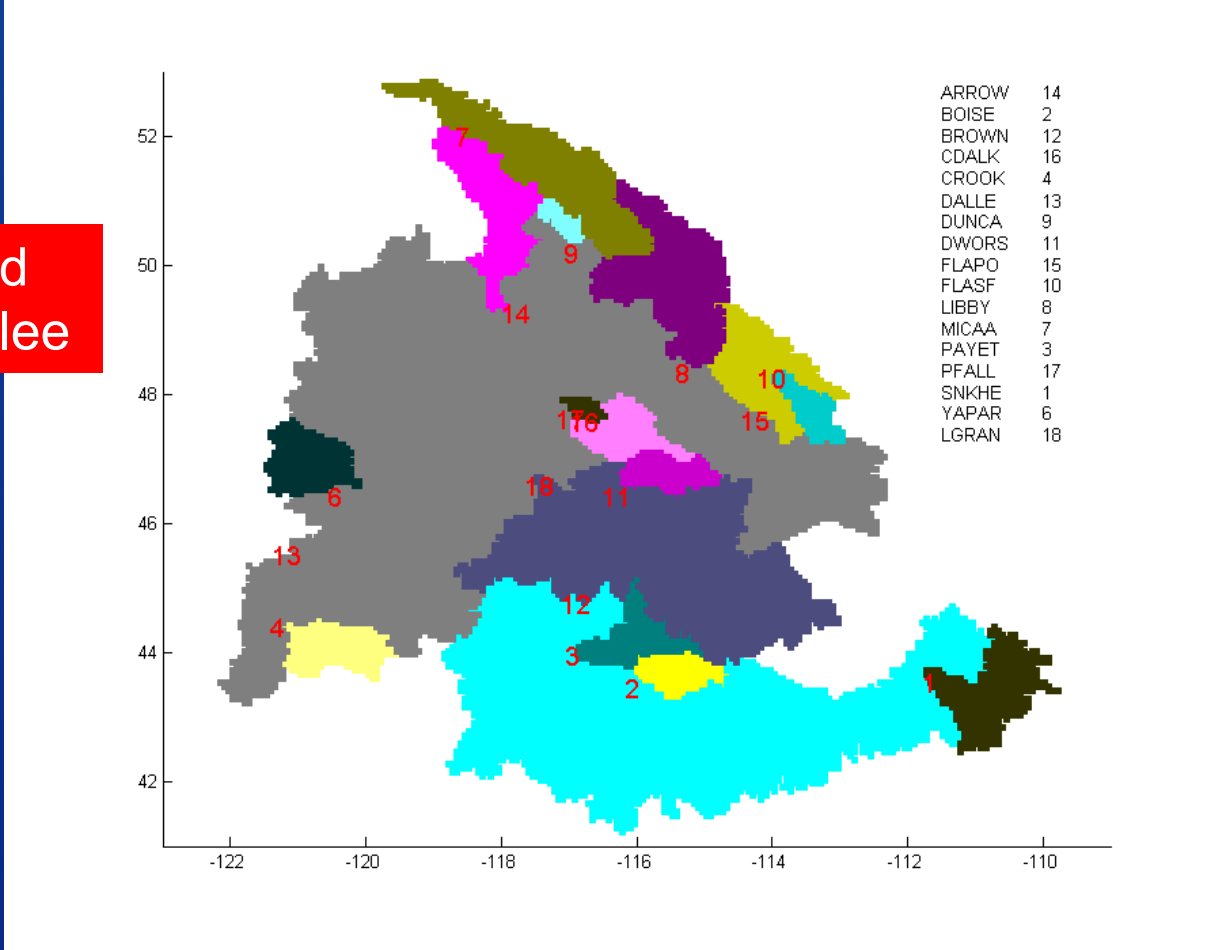
Progress since Feb 16 meeting

- March 23: Draft forecast series developed…
  - Forwarded data and forecast graphics to selected Tech Team members (R. Wortman, D. Garen, F. Weber, K. Dittmer, N. Stephan, S. Vaddey, T. Turner, R. Tama, T. Day)
- Follow-up Meetings:
  - March 26: T. Day
  - March 29: R. Wortman, F. Weber
- Finalization
  - Add predictor “grid” stations for some basins
  - Finish

RECLAMATION

Forecast Basins

Need to add Grand Coulee



RECLAMATION

Forecast Situations

- See LocationsMenu_NoMaps.xlsx.
- Forecast Situations defined by: basin runoff location, forecast period, time of issue)
- Forecast Situations correspond to those featured in RMJOC agencies' reservoir systems simulation models (and not necessarily to operational forecasting situations).

RECLAMATION

Procedure

- Build regression model for each situation
- Build model using the pc-regression technique
- Predictand = VIC routed runoff, bias-corrected (Qbc)
- Predictors = VIC “grid-cell station” P and SWE (for historical or given HD Scenario future climate)
  - Decision from Feb 16

RECLAMATION

Procedure

- Location of Predictors within and near the Basin:
  - For any forecast situation and climate, constrain spatial sampling to VIC grid cells near P and SWE observation stations used in real-world forecasting
  - Consulted forecastors from Reclamation, NRCS, USACE, and BPA/BC-Hydro for these station lists
  - These sampling points are “candidate” P and SWE stations for pc-regression modeling that follows.
  - Reviewed menu of stations on Mar 26 & 29 calls with Day, Wortman and Weber.

Procedure

- Mix of Predictors and best P-season
  - Permit grid-cell antecedent P-season and mix of grid-cell P and SWE “stations” to differ from specifications in real-world forecasting.
  - Try all combinations of P-season and station combinations to identify station combination and P-season that yields the best regression calibration r^2.

RECLAMATION

Approach for Transie

1. Get Climate Projection, WY195
2. Get Simulated Hydrology Proje
   - Monthly, gridded P, gridded SWE,
3. Decadally-Moving Analysis Wi followed by 10-year Valid
   - Repeat Steps 3-5 from Hybrid-De window
   - Calibrate regression model on firs
   - Apply model to next 10 years

Not discussing this today, but moving- implementation was tested in FY0

Decision after Feb 16:

Implement Task 3 HD Scenario operations analyses with perfect and imperfect forecasts.

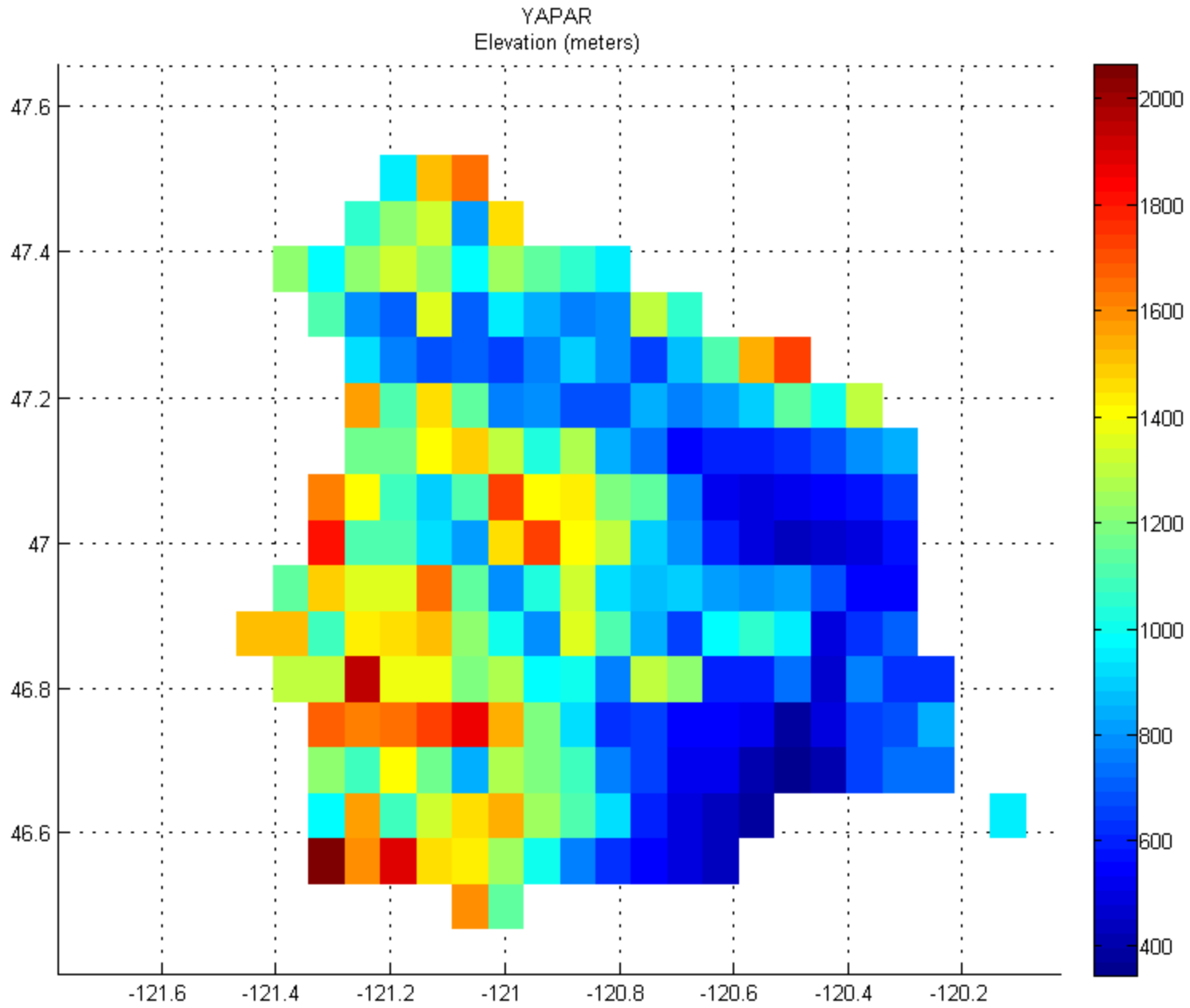
Implement Task 3 Transient operations anlayses with perfect forecasts only.

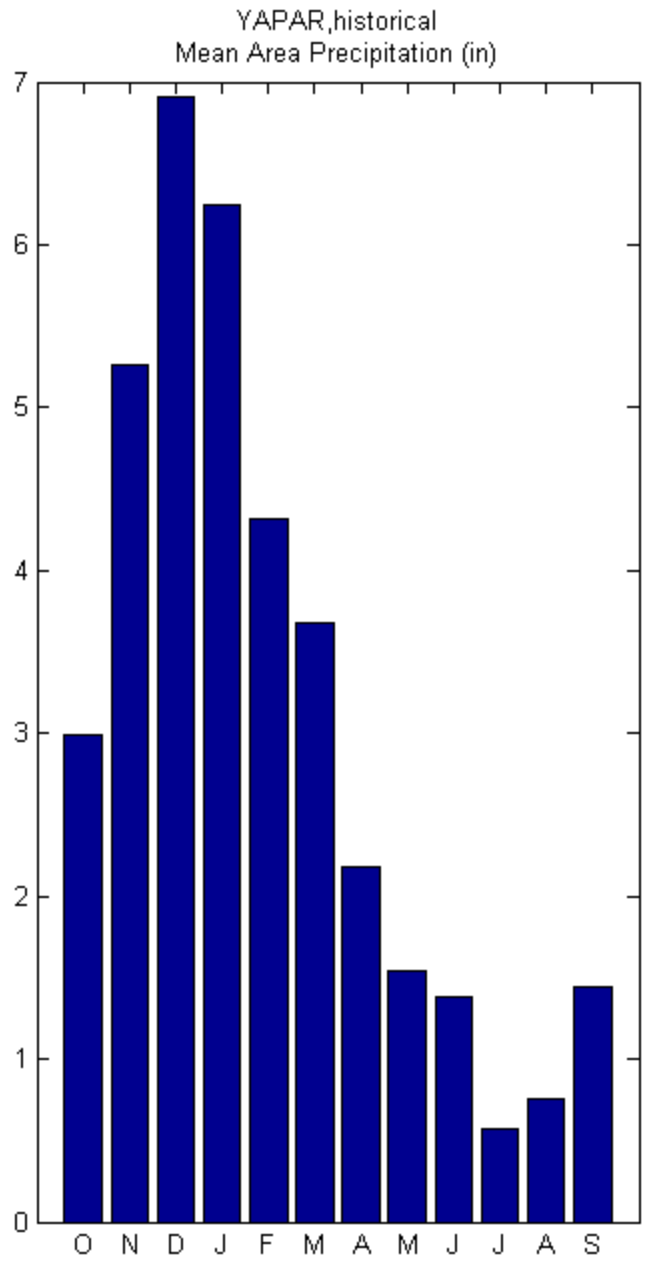
RECLAMATION

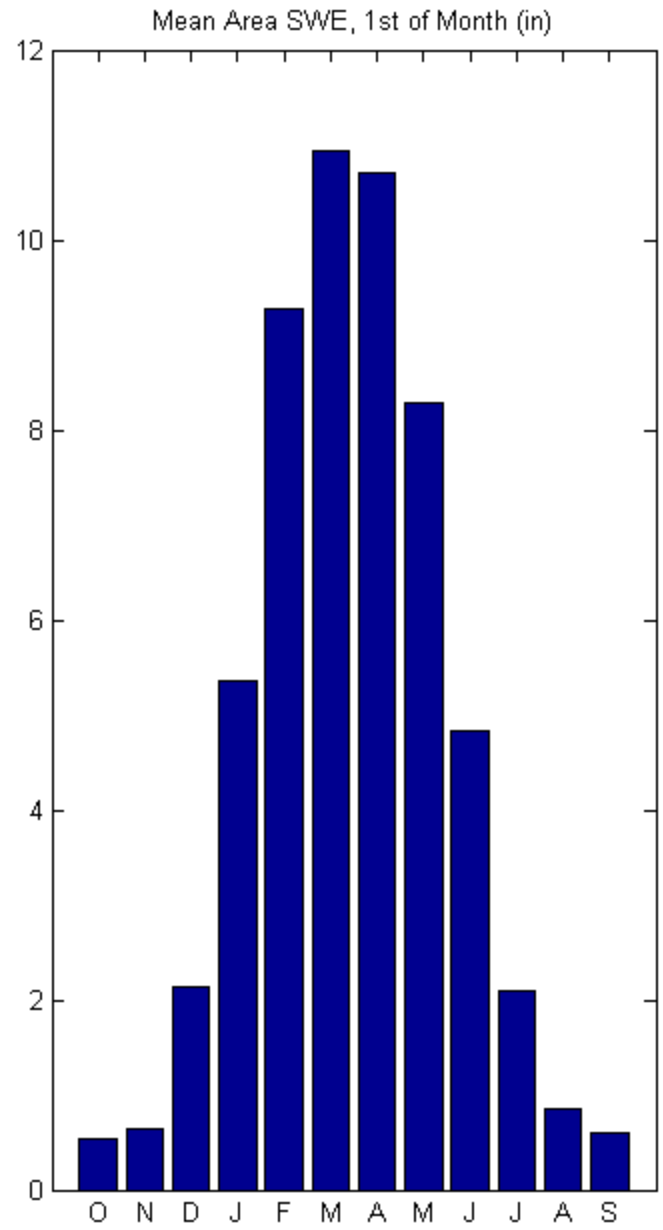
Pre-Regression Figures: Assessing “Historical” P-SWE-Qbc Data

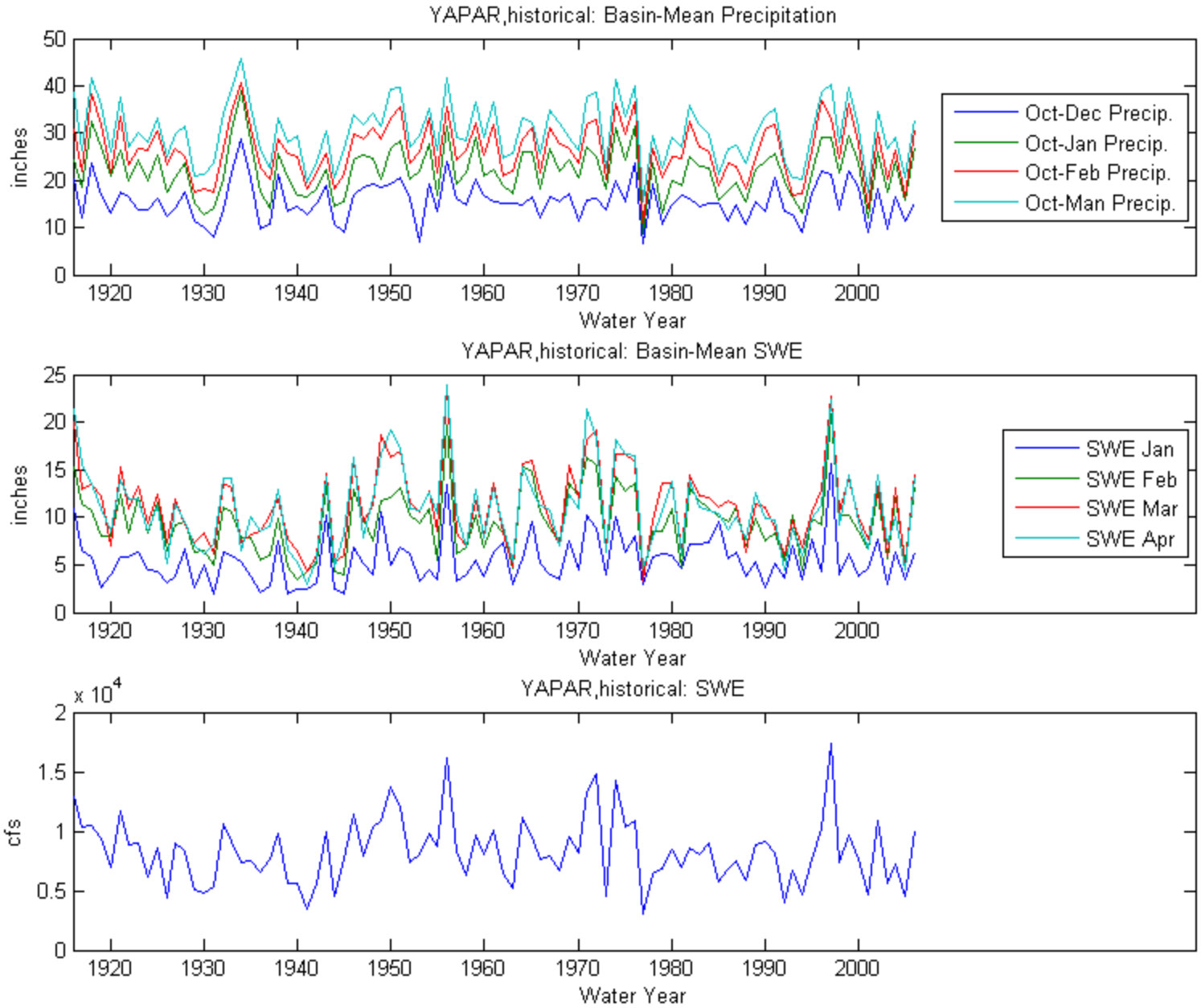
Example: Snake at Heise

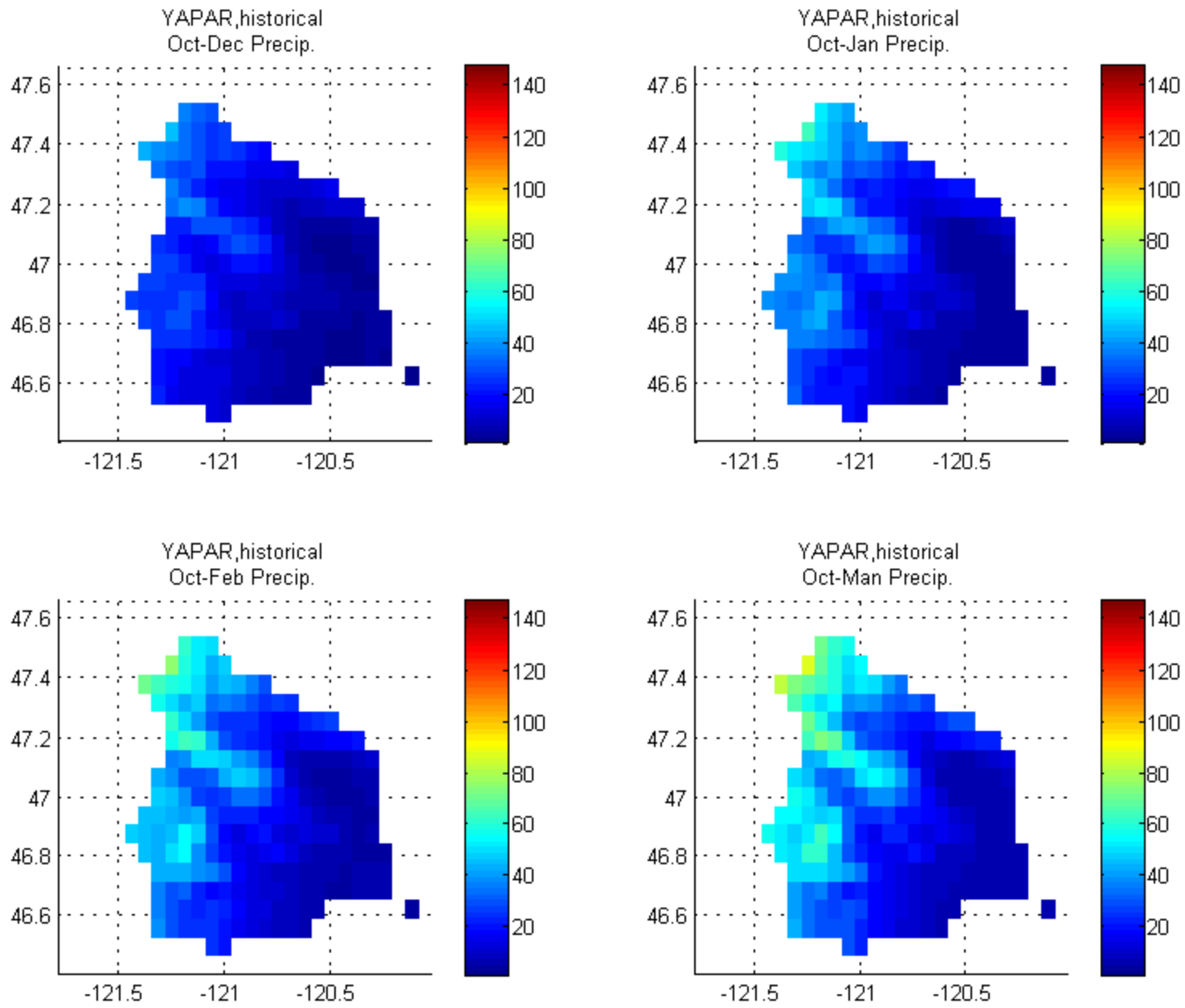
RECLAMATION

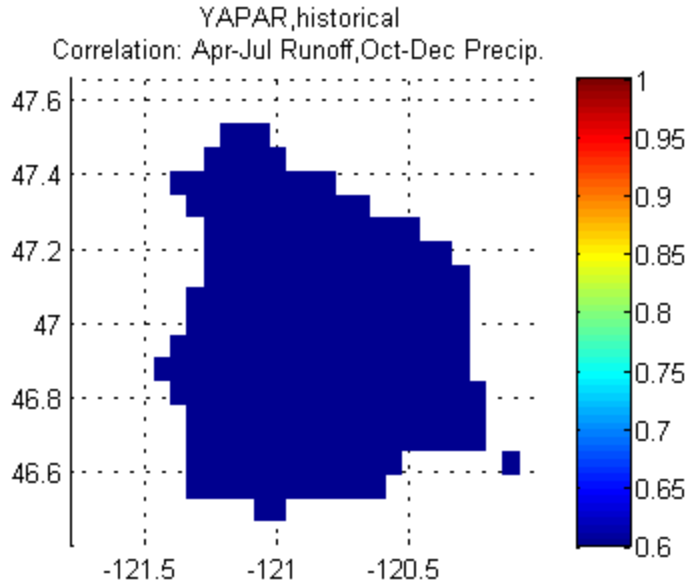

YAPAR
Elevation (meters)
47.6
47.4
47.2
47
46.8
46.6
-121.6
-121.4
-121.2
-121
-120.8
-120.6
-120.4
-120.2
2000
1800
1600
1400
1200
1000
800
600
400

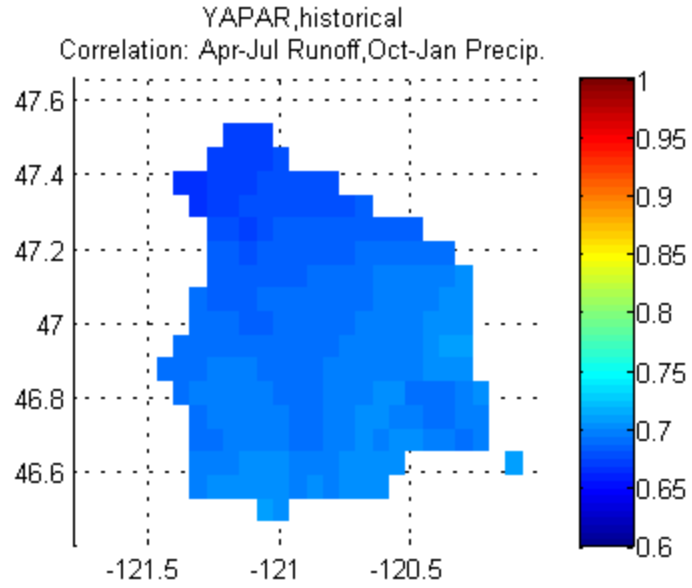

YAPAR,historical
Mean Area Precipitation (in)
0
1
2
3
4
5
6
7
O N D J F M A M J J A S

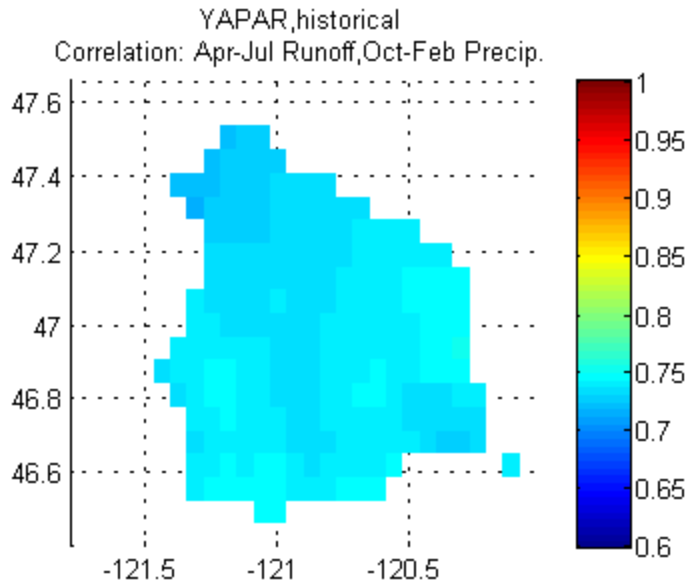

Mean Area SWE, 1st of Month (in)
0
2
4
6
8
10
12
O N D J F M A M J J A S

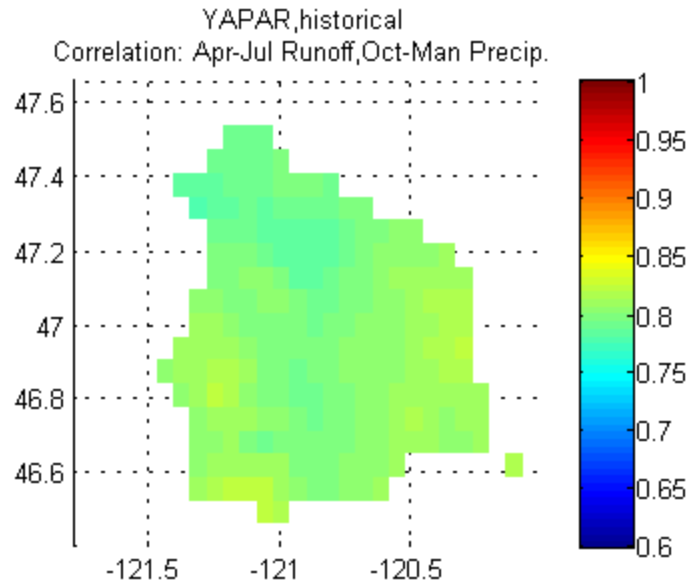

YAPAR,historical: Basin-Mean Precipitation
inches
Water Year
Oct-Dec Precip.
Oct-Jan Precip.
Oct-Feb Precip.
Oct-Man Precip.
YAPAR,historical: Basin-Mean SWE
inches
Water Year
SWE Jan
SWE Feb
SWE Mar
SWE Apr
YAPAR,historical: SWE
x 10^4
cfs
Water Year

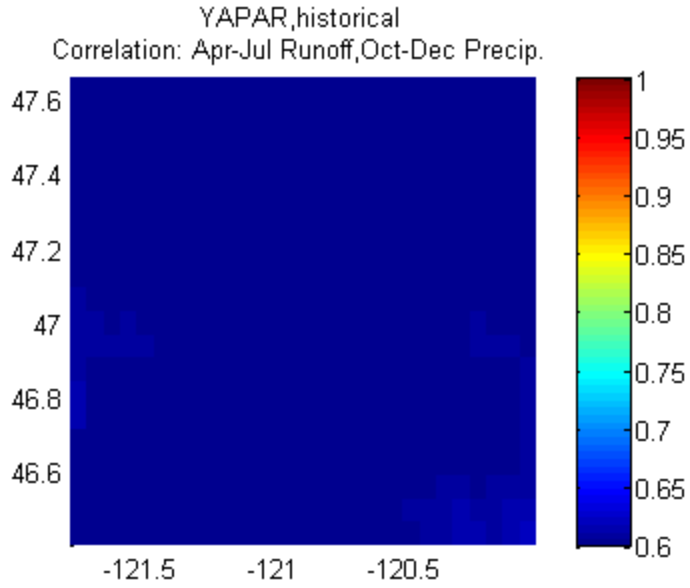

YAPAR,historical
Oct-Dec Precip.
YAPAR,historical
Oct-Jan Precip.
YAPAR,historical
Oct-Feb Precip.
YAPAR,historical
Oct-Man Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
140
120
100
80
60
40
20

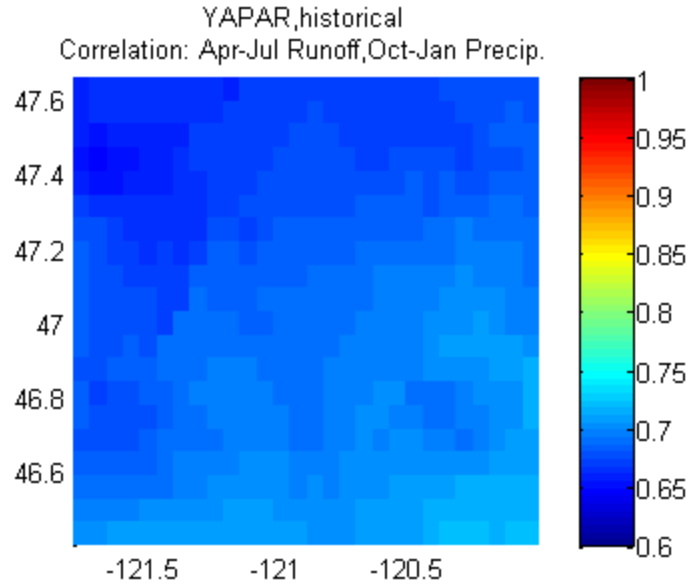

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Dec Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

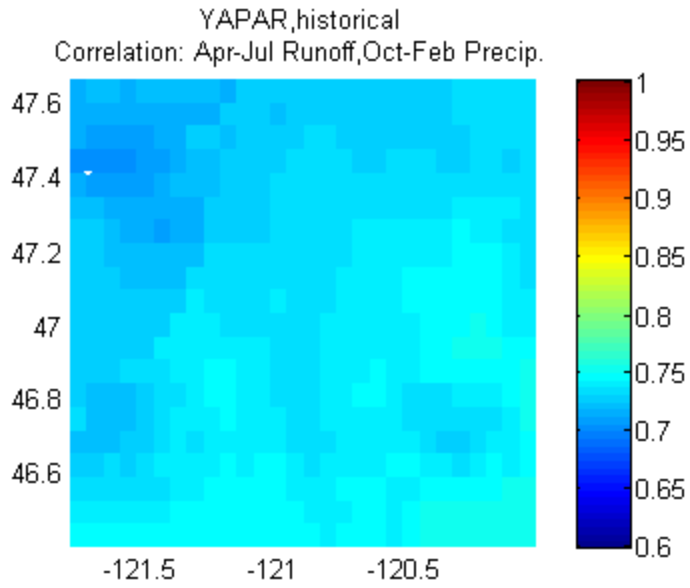

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Jan Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

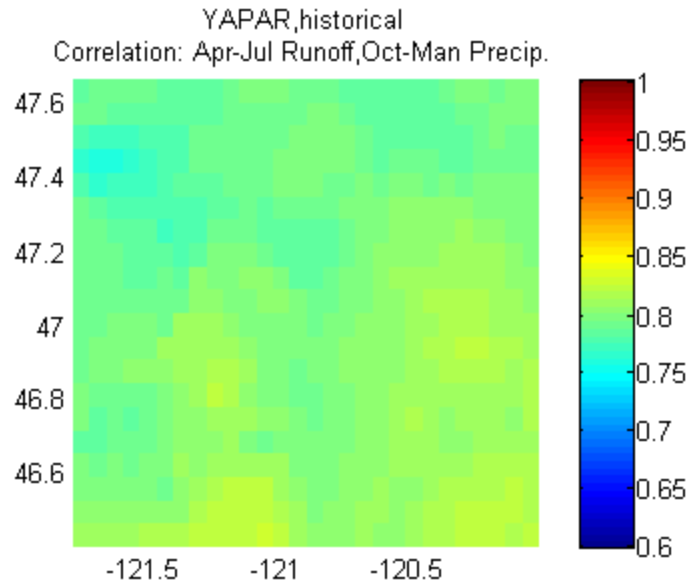

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Feb Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

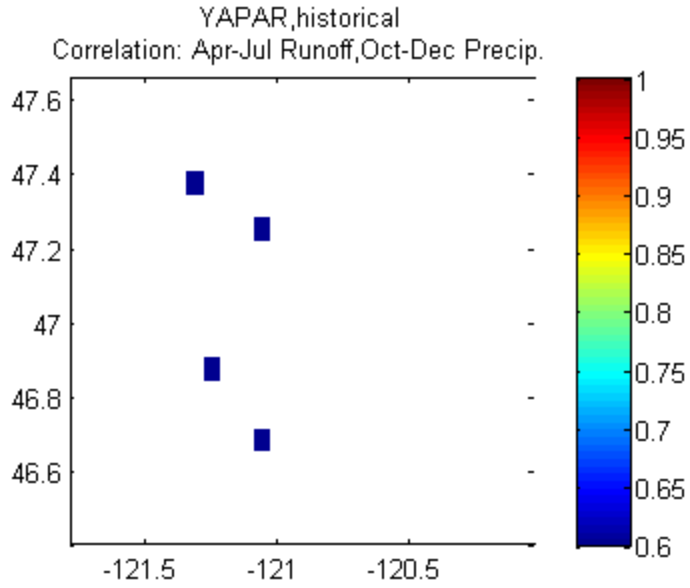

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Man Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

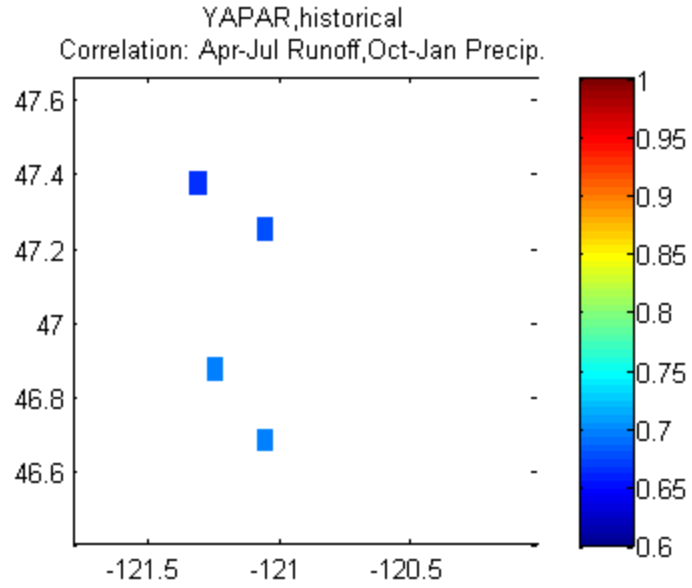

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Dec Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

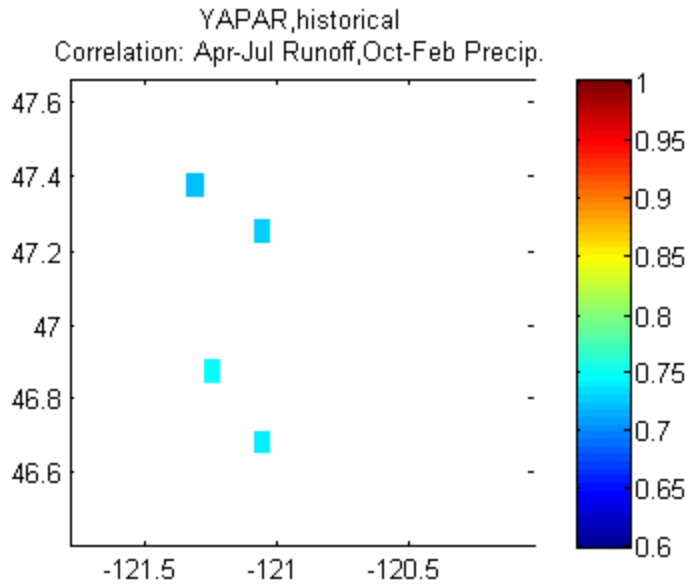

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Jan Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

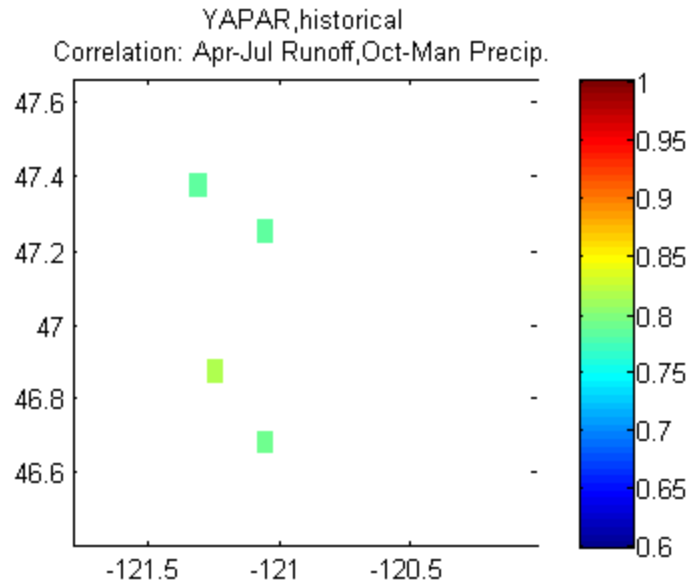

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Feb Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

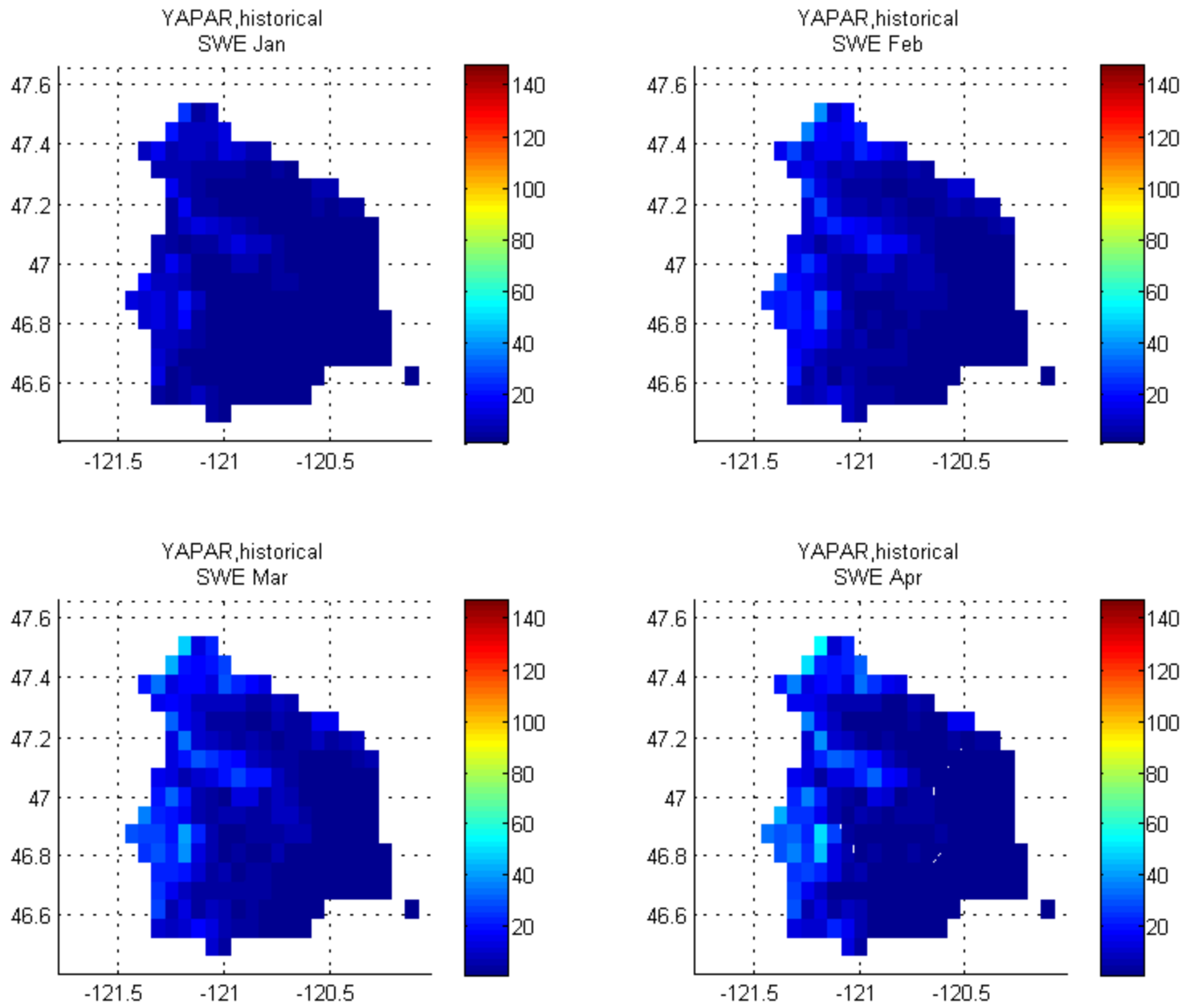

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Man Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

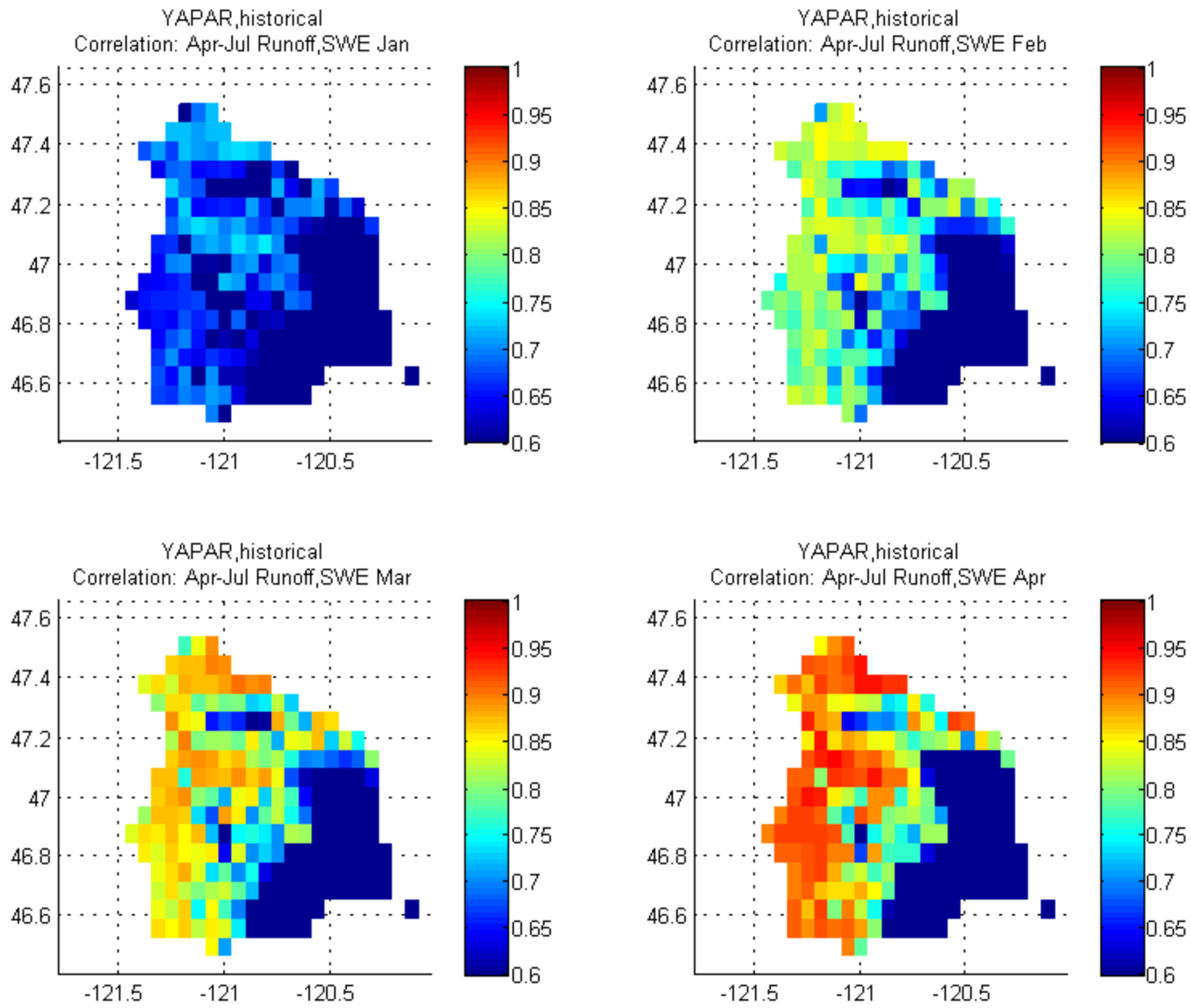

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Dec Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

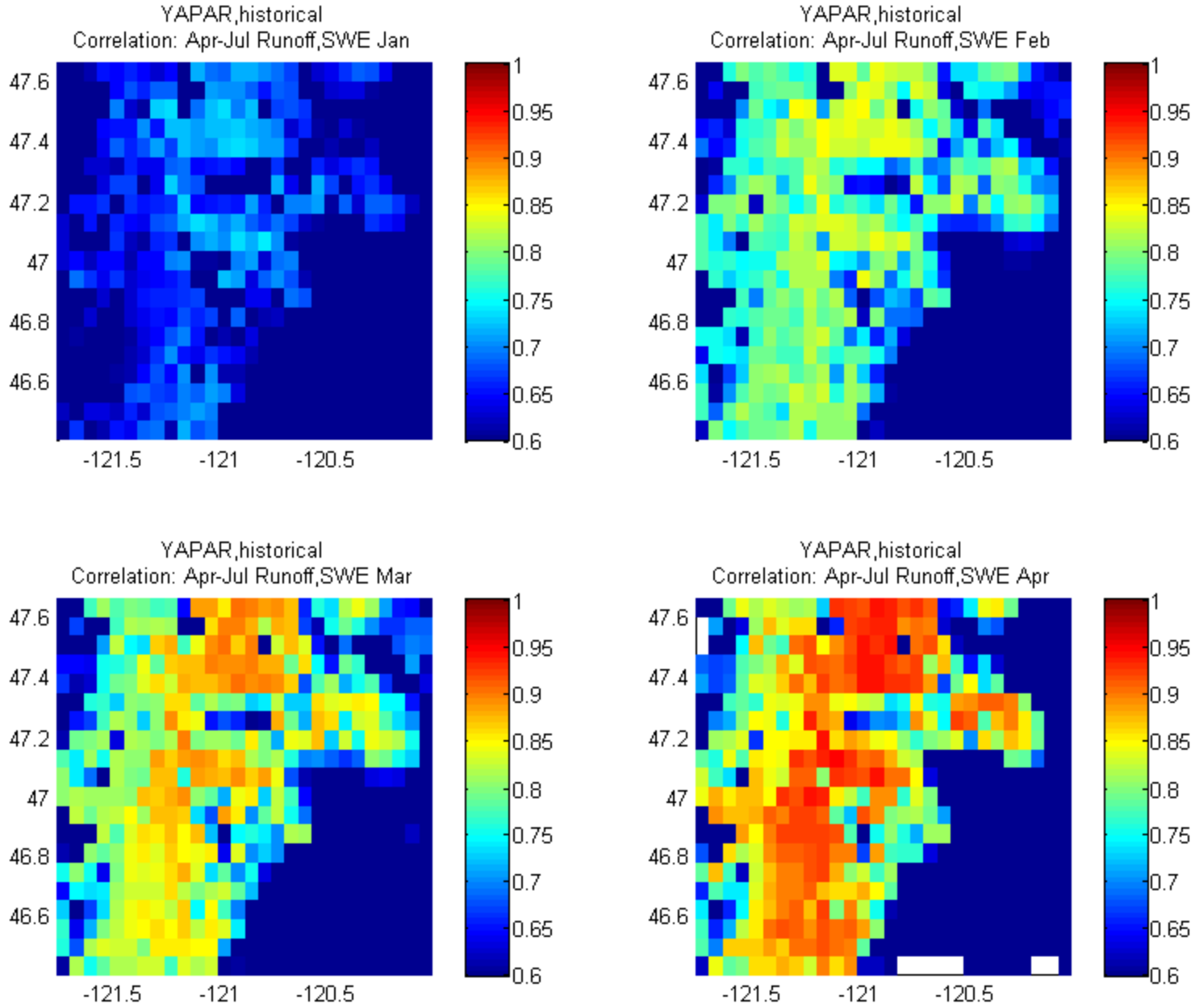

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Jan Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

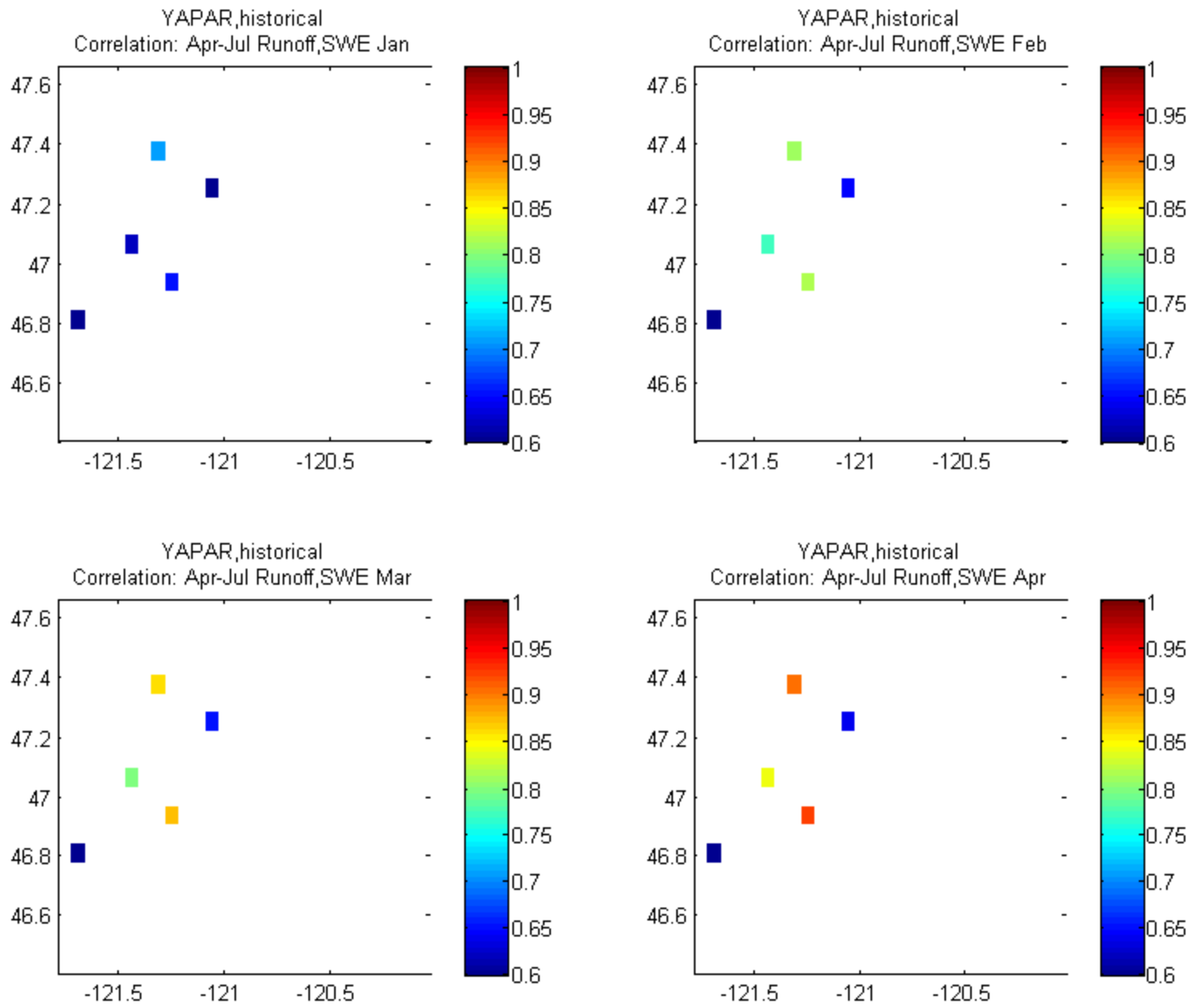

YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Feb Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6


YAPAR,historical
Correlation: Apr-Jul Runoff,Oct-Man Precip.
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6


YAPAR,historical
SWE Jan
YAPAR,historical
SWE Feb
YAPAR,historical
SWE Mar
YAPAR,historical
SWE Apr
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
140
120
100
80
60
40
20


YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Jan
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Feb
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Mar
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Apr
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

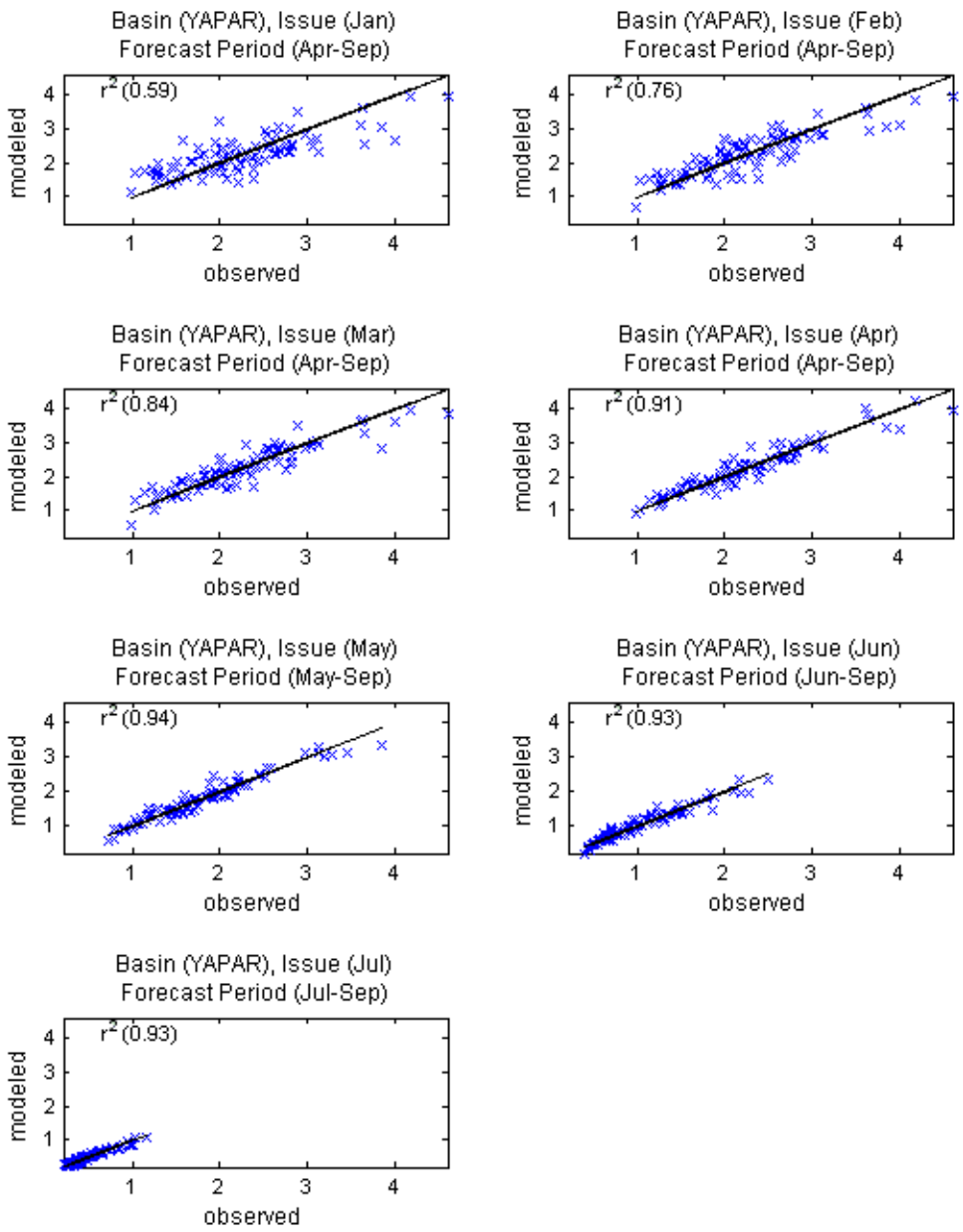

YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Jan
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Feb
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Mar
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Apr
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

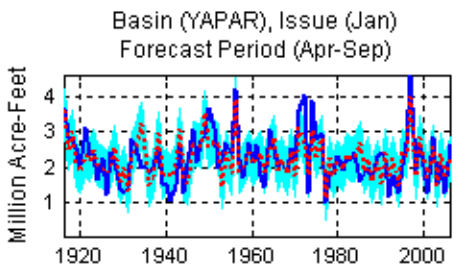

YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Jan
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Feb
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Mar
YAPAR,historical
Correlation: Apr-Jul Runoff,SWE Apr
47.6
47.4
47.2
47
46.8
46.6
-121.5
-121
-120.5
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

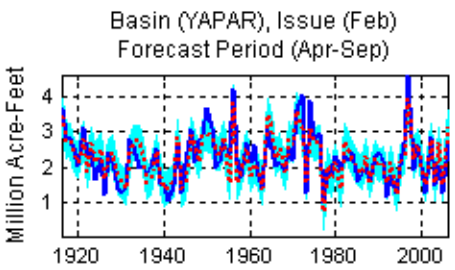
Regression Figures: Climate-Specific

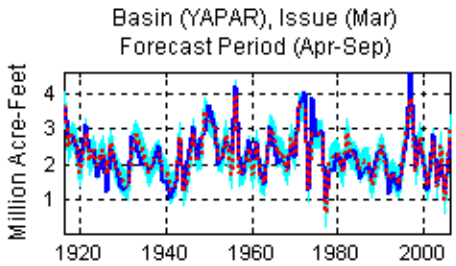
Example: Yakima at Parker… Historical & HD 2040s MW/D

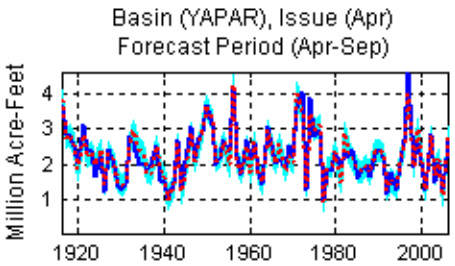
RECLAMATION

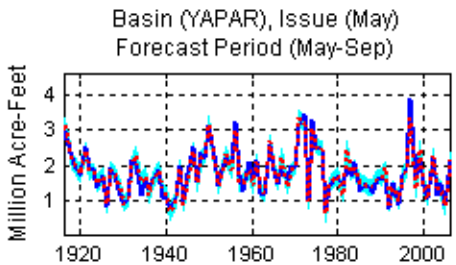

Basin (YAPAR), Issue (Jan)
Forecast Period (Apr-Sep)
r2 (0.59)
Basin (YAPAR), Issue (Feb)
Forecast Period (Apr-Sep)
r2 (0.76)
Basin (YAPAR), Issue (Mar)
Forecast Period (Apr-Sep)
r2 (0.84)
Basin (YAPAR), Issue (Apr)
Forecast Period (Apr-Sep)
r2 (0.91)
Basin (YAPAR), Issue (May)
Forecast Period (May-Sep)
r2 (0.94)
Basin (YAPAR), Issue (Jun)
Forecast Period (Jun-Sep)
r2 (0.93)
Basin (YAPAR), Issue (Jul)
Forecast Period (Jul-Sep)
r2 (0.93)
modeled
observed

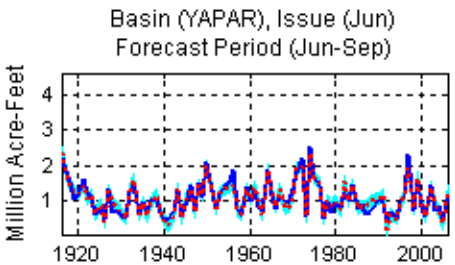

Basin (YAPAR), Issue (Jan)
Forecast Period (Apr-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

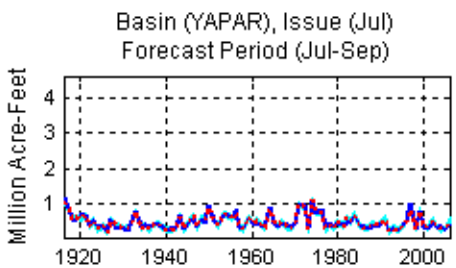

Basin (YAPAR), Issue (Feb)
Forecast Period (Apr-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

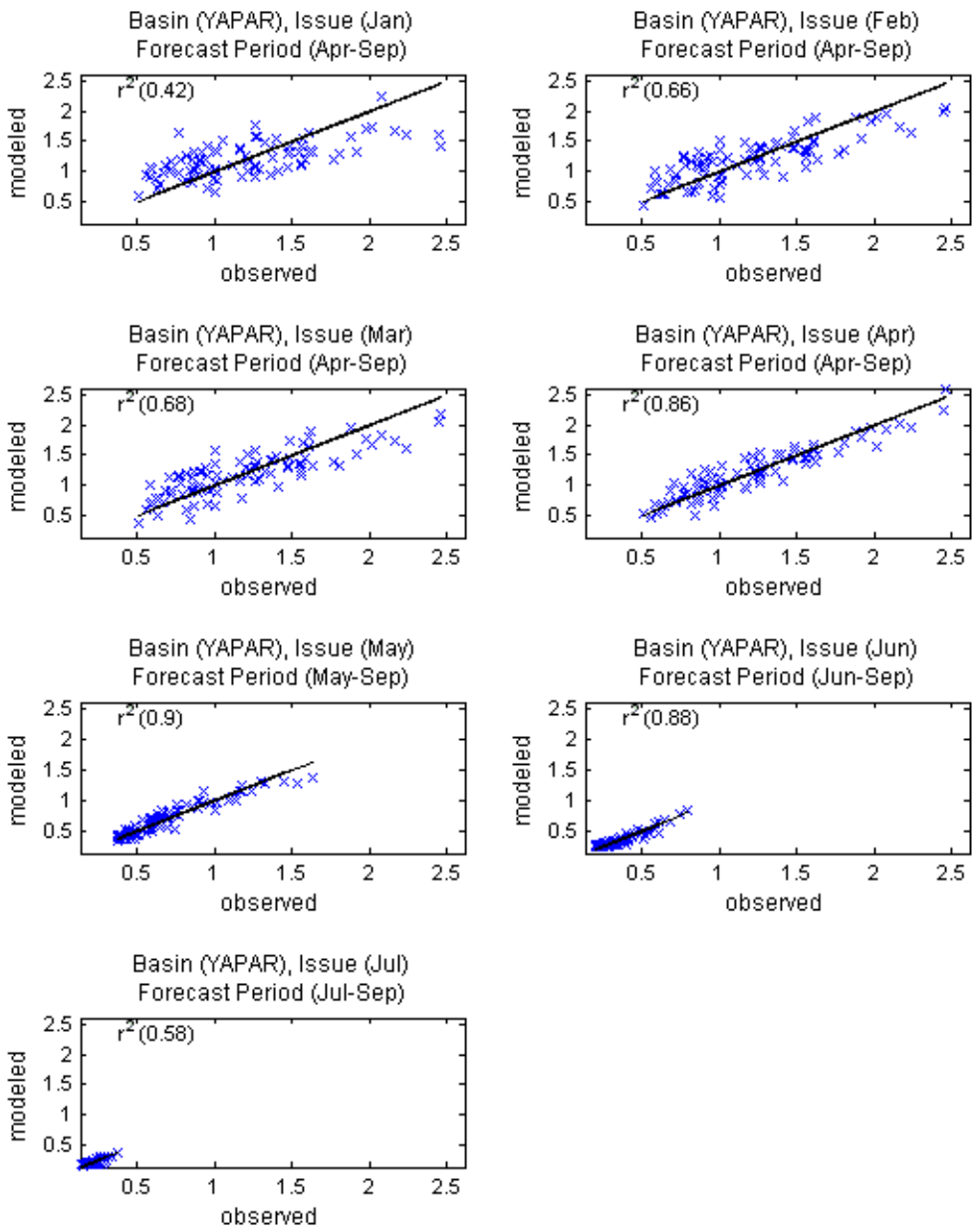

Basin (YAPAR), Issue (Mar)
Forecast Period (Apr-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

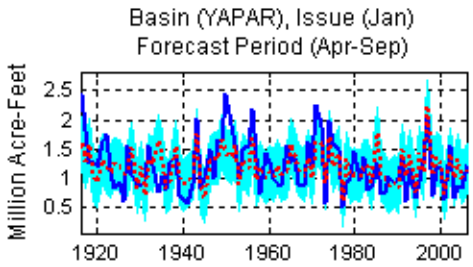

Basin (YAPAR), Issue (Apr)
Forecast Period (Apr-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

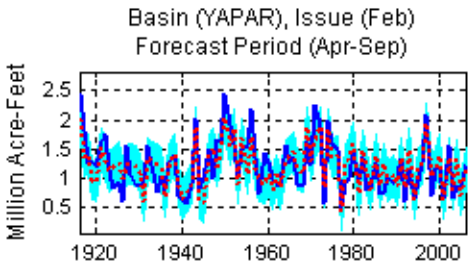

Basin (YAPAR), Issue (May)
Forecast Period (May-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

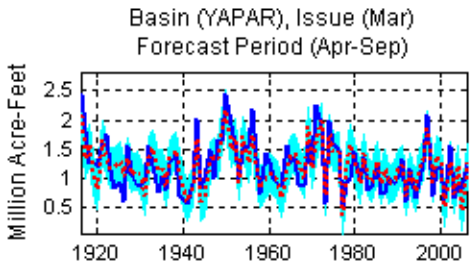

Basin (YAPAR), Issue (Jun)
Forecast Period (Jun-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000

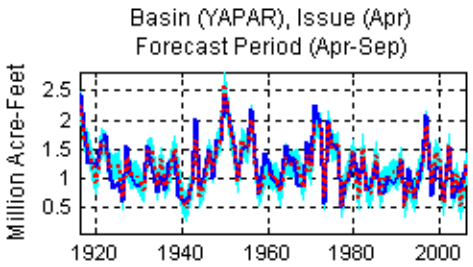

Basin (YAPAR), Issue (Jul)
Forecast Period (Jul-Sep)
Million Acre-Feet
1
2
3
4
1920
1940
1960
1980
2000


Basin (YAPAR), Issue (Jan)
Forecast Period (Apr-Sep)
r2 (0.42)
Basin (YAPAR), Issue (Feb)
Forecast Period (Apr-Sep)
r2 (0.66)
Basin (YAPAR), Issue (Mar)
Forecast Period (Apr-Sep)
r2 (0.68)
Basin (YAPAR), Issue (Apr)
Forecast Period (Apr-Sep)
r2 (0.86)
Basin (YAPAR), Issue (May)
Forecast Period (May-Sep)
r2 (0.9)
Basin (YAPAR), Issue (Jun)
Forecast Period (Jun-Sep)
r2 (0.88)
Basin (YAPAR), Issue (Jul)
Forecast Period (Jul-Sep)
r2 (0.58)
modeled
observed
0.5
1
1.5
2
2.5


Basin (YAPAR), Issue (Jan)
Forecast Period (Apr-Sep)
Million Acre-Feet
2.5
2
1.5
1
0.5
1920
1940
1960
1980
2000


Basin (YAPAR), Issue (Feb)
Forecast Period (Apr-Sep)
Million Acre-Feet
2.5
2
1.5
1
0.5
1920
1940
1960
1980
2000


Basin (YAPAR), Issue (Mar)
Forecast Period (Apr-Sep)
Million Acre-Feet
2.5
2
1.5
1
0.5
1920
1940
1960
1980
2000


Basin (YAPAR), Issue (Apr)
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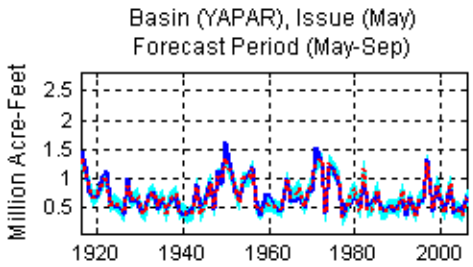
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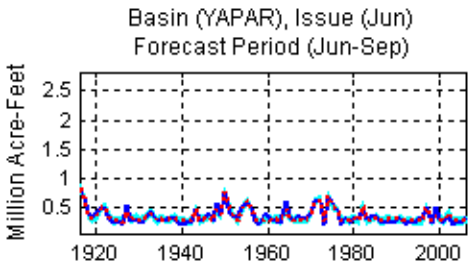
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Forecast Period (Jun-Sep)
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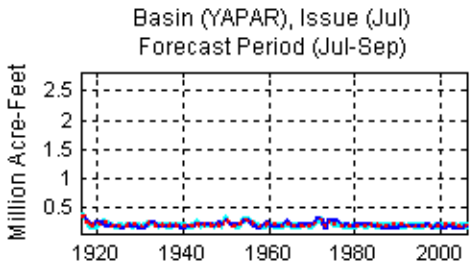
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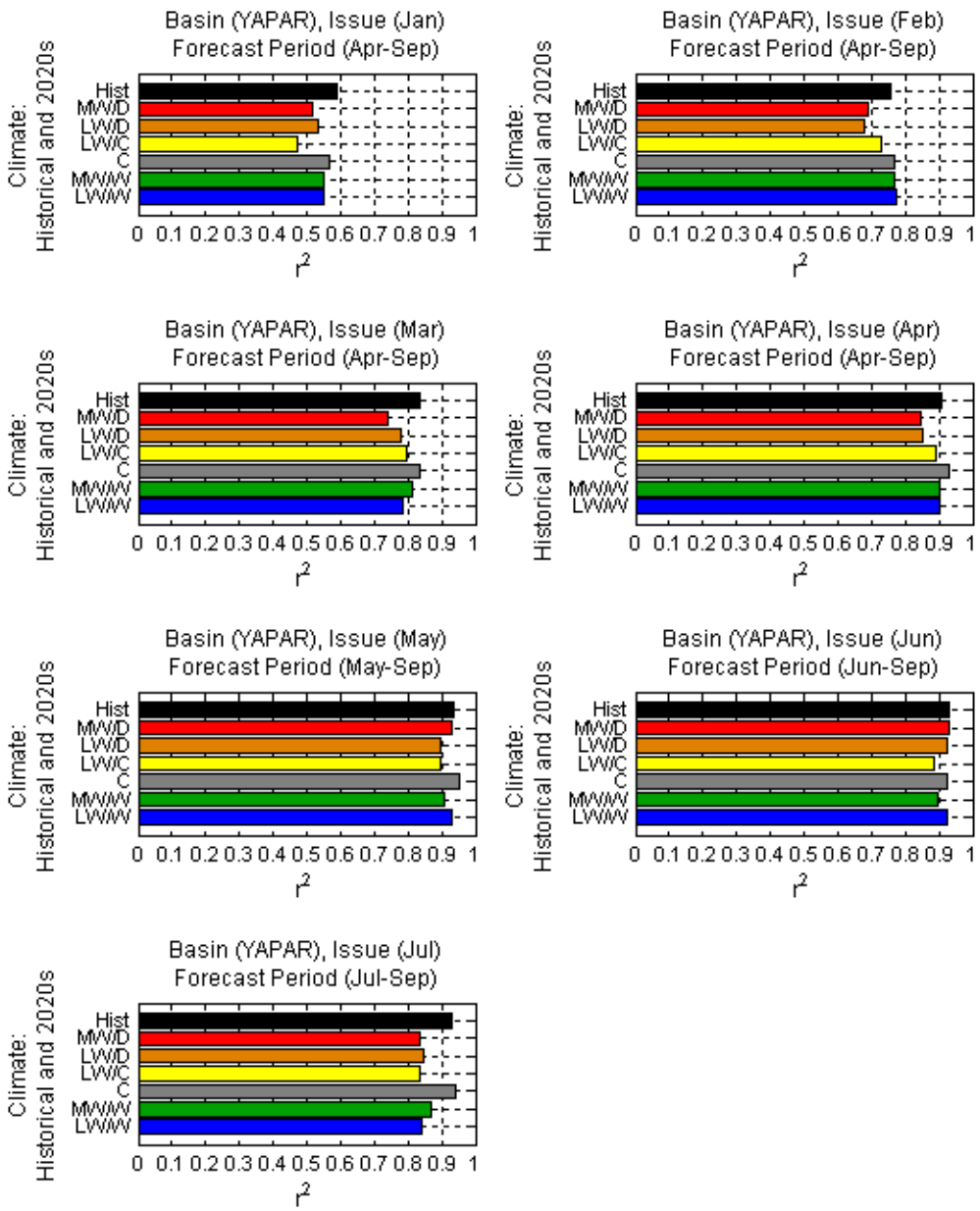
Regression Figures: Climate-Compare

Example: Yakima at Parker…

RECLAMATION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Basin (YAPAR), Issue (Jul)
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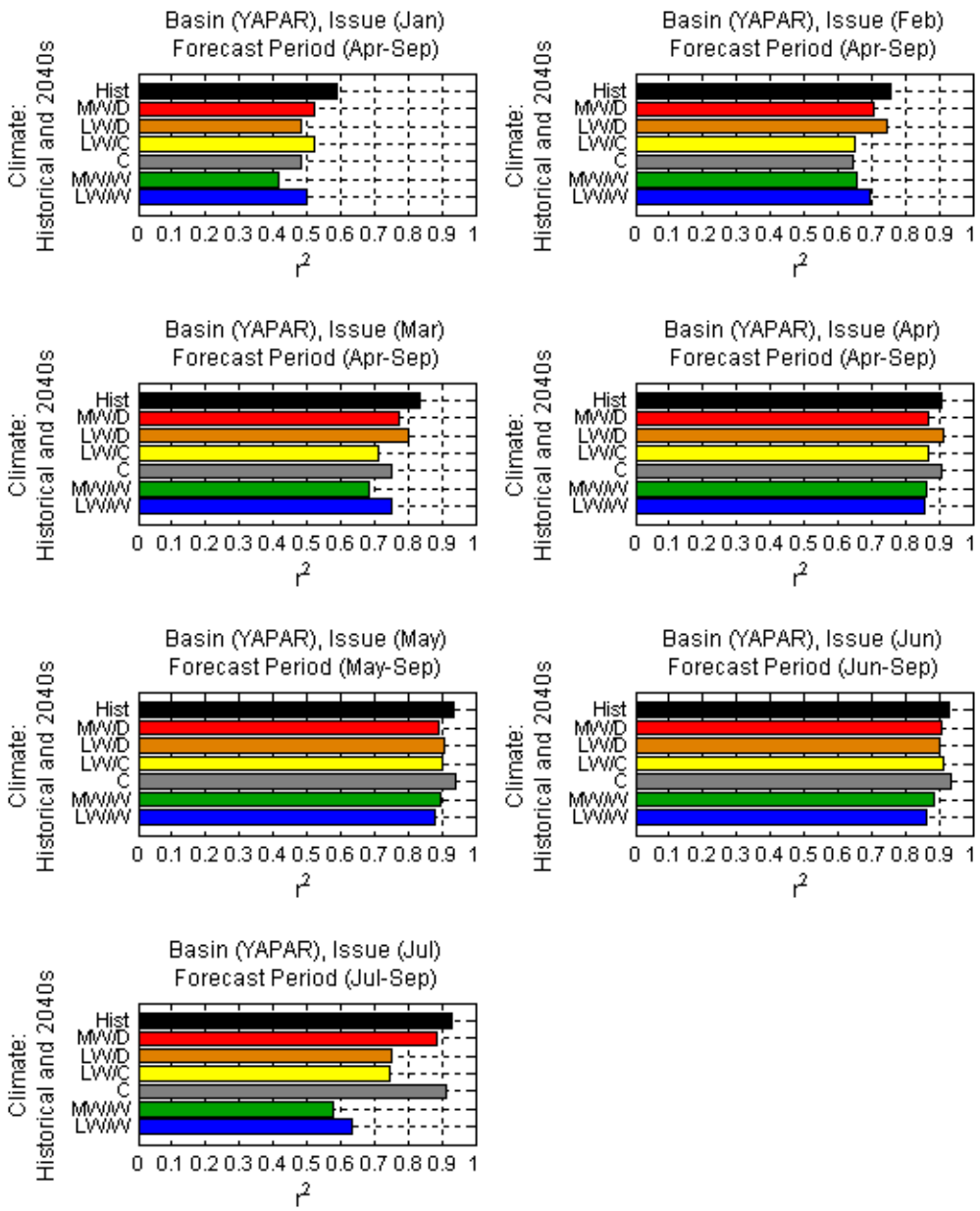
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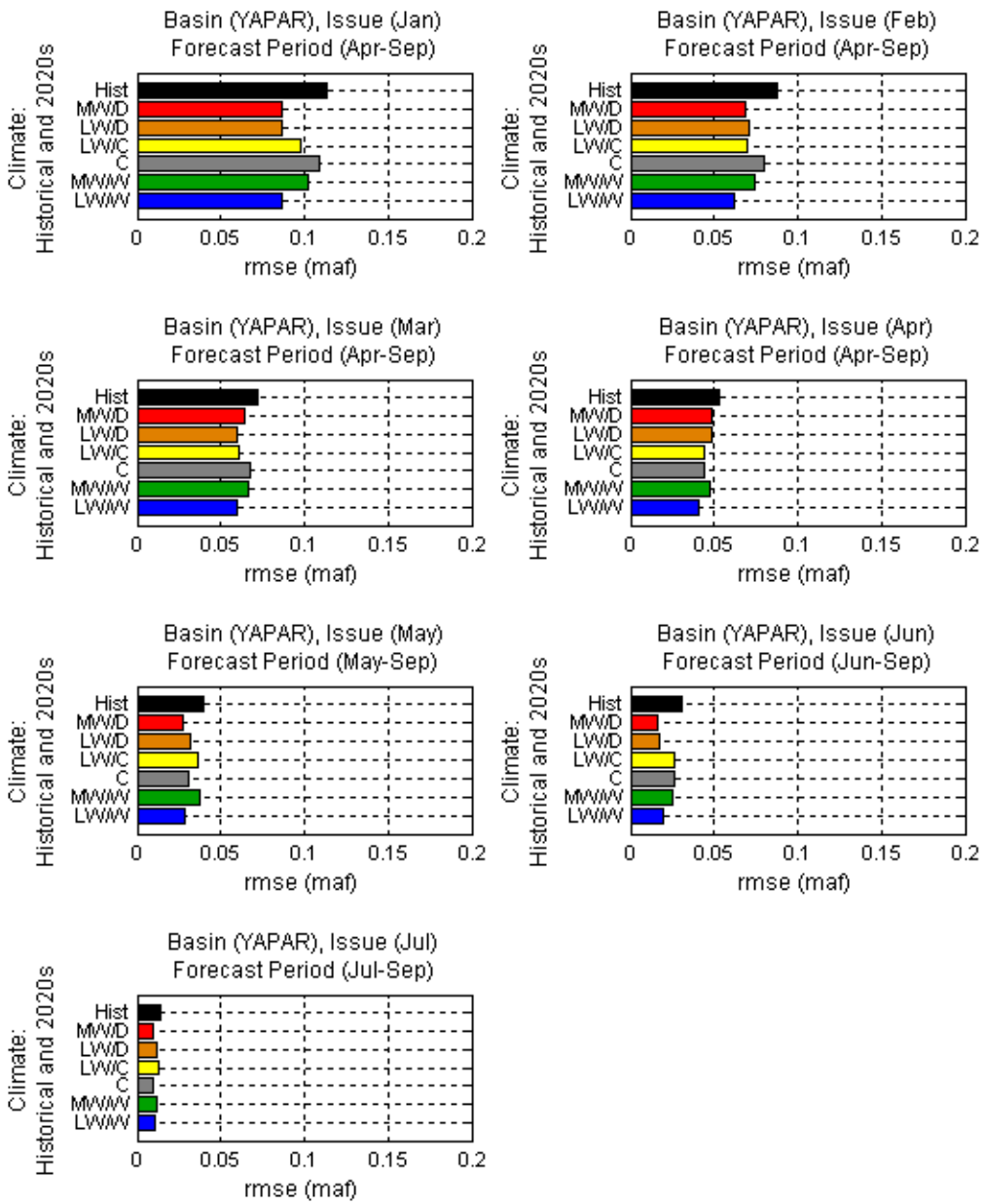
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Forecast Period (Apr-Sep)
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Basin (YAPAR), Issue (Jul)
Forecast Period (Jul-Sep)
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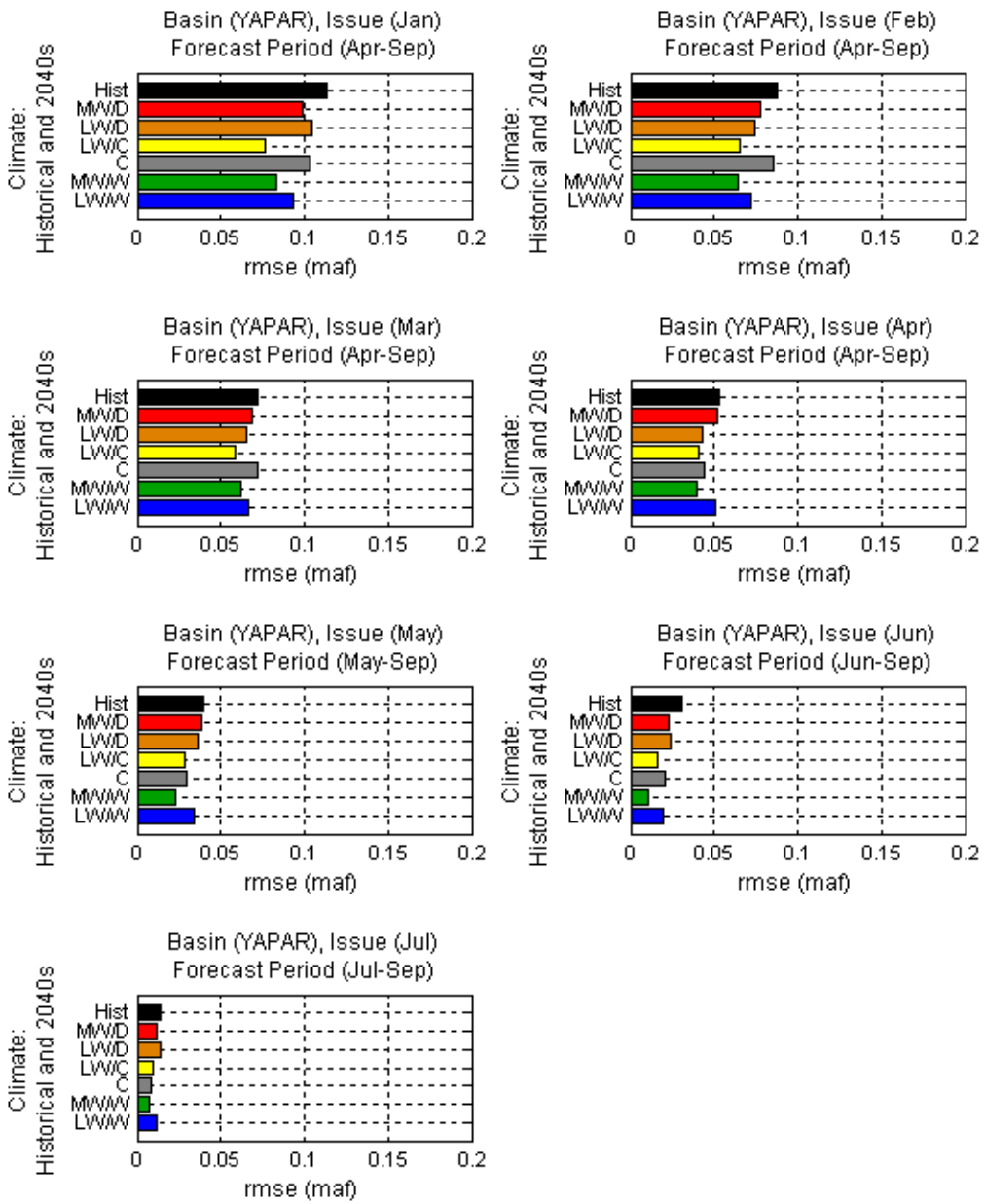
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Historical and 2040s
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For other basins, switch to figures directory…

RECLAMATION

Reactions

- Focusing only on historical regression models:
  - Models are generally good quality, though not as good as real-world regressions.
  - Some of this is due to calibration period and predictor selection. Some of this may also be due to characteristics of VIC's P-SWE-Qbc relationship.
  - Some of the poorer quality may also be due to our use of Qbc as the prediction rather than VIC's raw-routed runoff (Q) which is more clearly associated with P-SWE.
    - The reason I used Qbc rather than Q is because we're using the Qbc series as inflows in our system models.
    - For the water supply forecast series to be consistent with input inflow series during Task 3.4, the water supply forecast series must be of Qbc volumes, not Q volumes.

Reactions

- Re: VIC-based regression models being more error-prone than Real-World regression models
  - Does this significantly affects reservoir systems simulation results?
  - Depends on how forecasts are used in reservoir systems simulation. Regression estimate is 50% exceedence value. Regression "standard error of the estimate" can be used to compute X% exceedence forecasts
  - If model is more error-prone, concern is that a model with wider error bars will produce more conservative forecasts and cause more conservative reservoir simulation.
    - On the flip-side, we already do reservoir systems simulation in "observed" model, which is unrealistic in it's own right.
    - Also, we're still doing HD Scenarios with "perfect foresight", for comparison.
  - Significance of concern depends on forecast error use…

RECLAMATION

Reactions

- Forecast model error trends
  - There only appear to be minor trends from 2020s to 2040s climates.
  - For some basins, trends seem to be apparent for early and late forecast situations (e.g., January issues of spring-summer volume, or June issue for summer volume)…
    - This seems physically intuitive (i.e., warming leading to less mature snowpack negatively affecting early season forecasting, or warming leading to less late-season snowpack and negative forecast effects)

To-Do Items, Decisions

- Finish Model Development
  - Natural Volumes: CDALK, FLAPO, PFALL, and CROOK
  - Regulated Volume: BROWN
    - after MODSIM-Snake is complete, Task 3.4)
- Decide on Model Development Method
  - GCOUL: Natural Volume – routed approach?
  - LGRAN, DALLE: Nat/Reg Volume – routed approach?
- Address F. Weber information requests…
- Decide on X% exceedence needs (*check the following*)
  - Reclamation Task 3.4 analyses based on 50%exc volumes
  - USACE Task 3.4 analyses based on 50% exc volumes
  - BPA Task 3.4 analyses based on 95%exc volumes

RECLAMATION

RECLAMATION
Managing Water in the West

SECURE Water Act Section 9503(c) 2016 Technical Report

Columbia River Basin Summary Report

[Add appropriate graphic]

U.S. Department of the Interior
Bureau of Reclamation
Policy and Administration
Denver, Colorado

March 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

SECURE Water Act Section 9503(c) 2016 Technical Report

Columbia River Basin

Prepared for

United States Congress

Prepared by

U.S. Department of the Interior
Bureau of Reclamation

[Citations, Contributors, or whatever]

U.S. Department of the Interior
Bureau of Reclamation
Policy and Administration
Denver, Colorado

March 2016

Acronyms and Abbreviations

BA	Biological Assessment
BiOp	Biological Opinion
BPA	Bonneville Power Administration
cfs	cubic feet per second
Corps	U.S. Army Corps of Engineers
CRBIA	Columbia River Basin Impact Assessment
ENSO	El Niño/Southern Oscillation
ESA	Endangered Species Act
ESU	Evolutionarily Significant Units
FCRPS	Federal Columbia River Power System
FWS	U.S. Fish and Wildlife Service
GWh/year	Gigawatt hours per year
kWh	kilowatt hours
MW	Megawatt
NMFS	National Oceanic and Atmospheric Administration National Marine Fisheries Service
PDO	Pacific Decadal Oscillation
PN	Pacific Northwest
Reclamation	U.S. Bureau of Reclamation
RMJOC	River Management Joint Operating Committee
RPA	Reasonable and Prudent Alternatives
TDG	Total dissolved gas
TMT	Technical Management Team
WACCIA	Washington Climate Change Impacts Assessment

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About this Report

This *Columbia River Basin Summary Report* provides basin-specific discussions of the Columbia River Basin; a major Reclamation river basin identified within the SECURE Water Act. This Report includes information on the basin setting, historical climate and hydrology, projected future climate and hydrology, implications for various water and environmental resources, adaptation strategies, and coordination activities.

Columbia River Basin Setting
States: Idaho, Montana, Nevada, Oregon, Utah, Washington, Wyoming
Major U.S. Cities: Boise, Columbia Falls, Yakima, Portland, Spokane
International: Canada
River Length: 1,243 miles
River Basin Area: 258,000 square miles
Major River Uses: Municipal (8 million people), Agricultural (7.8 million acres of land), Hydropower (400 dams provide up to 80% of the electrical needs in the northwest, with 31 major federal dams comprising the Federal Power System), Recreation, Flood Control (39.7 million acre-feet of flood storage), Navigation, Fish and Wildlife including anadromous salmon and steelhead

Reclamation's 2016 SECURE Water Act Report[1] identifies the following challenges in climate and hydrology in the Columbia River Basin:

- Projections show that temperatures throughout the Columbia River Basin above The Dalles Dam may increase steadily by 6 to 7° F during the 21st century.
- Average annual precipitation, including subbasins such as the Yakima and Snake, are projected to increase from 3.9 percent to 6.2 percent over the basin by 2050. Mean annual runoff is projected to increase by from 1.2 to 3.7 percent by the year 2050.
- The projected temperatures changes will cause a decreased snowpack for many of the subbasins. Decreased snowpack could result in decreased groundwater infiltration, runoff, and ultimately lower base flows in the rivers during the summer.
- Moisture falling as rain instead of snow at lower elevations will increase the wintertime runoff with decreased runoff during the summer.

This report is based on synthesizing available literature and summarizing key findings from peer-reviewed studies. The key studies referenced in this report include the Yakima River Basin Study - Proposed Integrated Water Resource Management Plan, Henrys Fork of the Snake River Basin Study, Hood River Basin Study, Upper Deschutes Basin Study, and Columbia River Basin Impact Assessment.

[1] Note: Complimentary reports included in the SECURE Report to Congress package include the Overview Report, West-Wide Summary Report and River Basin Summary Reports.

1 Basin Setting

The Columbia River Basin is located in the Pacific Northwest region of the United States, extending over seven U.S. states and parts of southern British Columbia, Canada (Figure CRB-1). The Columbia River is the largest river in the Pacific Northwest, traveling more than 1,240 miles and draining roughly 260,000 square miles. Beginning at its headwaters in the Rocky Mountains of British Columbia, the river first flows northwest before heading south into the State of Washington. It then continues west along the boundary between Oregon and Washington until it drains into the Pacific Ocean. Where the river meets the coast, saltwater intrusion from the Pacific Ocean extends approximately 23 river miles upstream from the mouth; tidal effects can be experienced up to Bonneville Dam, located 146 river miles inland.

The Columbia River has an annual average runoff of approximately 200 million acre-feet (AF) (275,000 cubic feet per second (cfs)), with roughly 25 percent of that flow originating in the Canadian portion of the basin (Bonneville Power Administration, 2001). Major tributaries to the Columbia River include:

- The Snake River, which originates in Wyoming and flows primarily through Idaho;
- The Yakima, Spokane, and Methow Rivers in Washington;
- The Kootenai River, which originates in Canada and flows through Montana and Idaho;
- The Pend Oreille, Clark Fork, and Flathead Rivers, which originate in Montana and flow through Idaho and Washington; and
- The Willamette, Deschutes, and John Day Rivers in Oregon

Commented [bdg1]: Since these tribs are mentioned, suggest showing on the final map.

Reclamation manages more than 54 dams and reservoirs in the Pacific Northwest (PN) region, with a combined active capacity of more than 18 million AF. Some of these dams are operated as a system in coordination with the U.S. Army Corps of Engineers (Corps) and non-Federal dams. These dams are collaboratively managed to provide flood control and supply water to help satisfy irrigation, hydropower, and ecosystem requirements. Nearly 80 percent of Pacific Northwest energy supplies come from hydropower in the Columbia River Basin, including both Federal and non-Federal hydropower facilities. The Federal portion alone, referred to as the Federal Columbia River Power System (FCRPS), generates almost 76.4 million megawatts of energy annually.

Commented [bdg2]: Replace with "about 75.7"

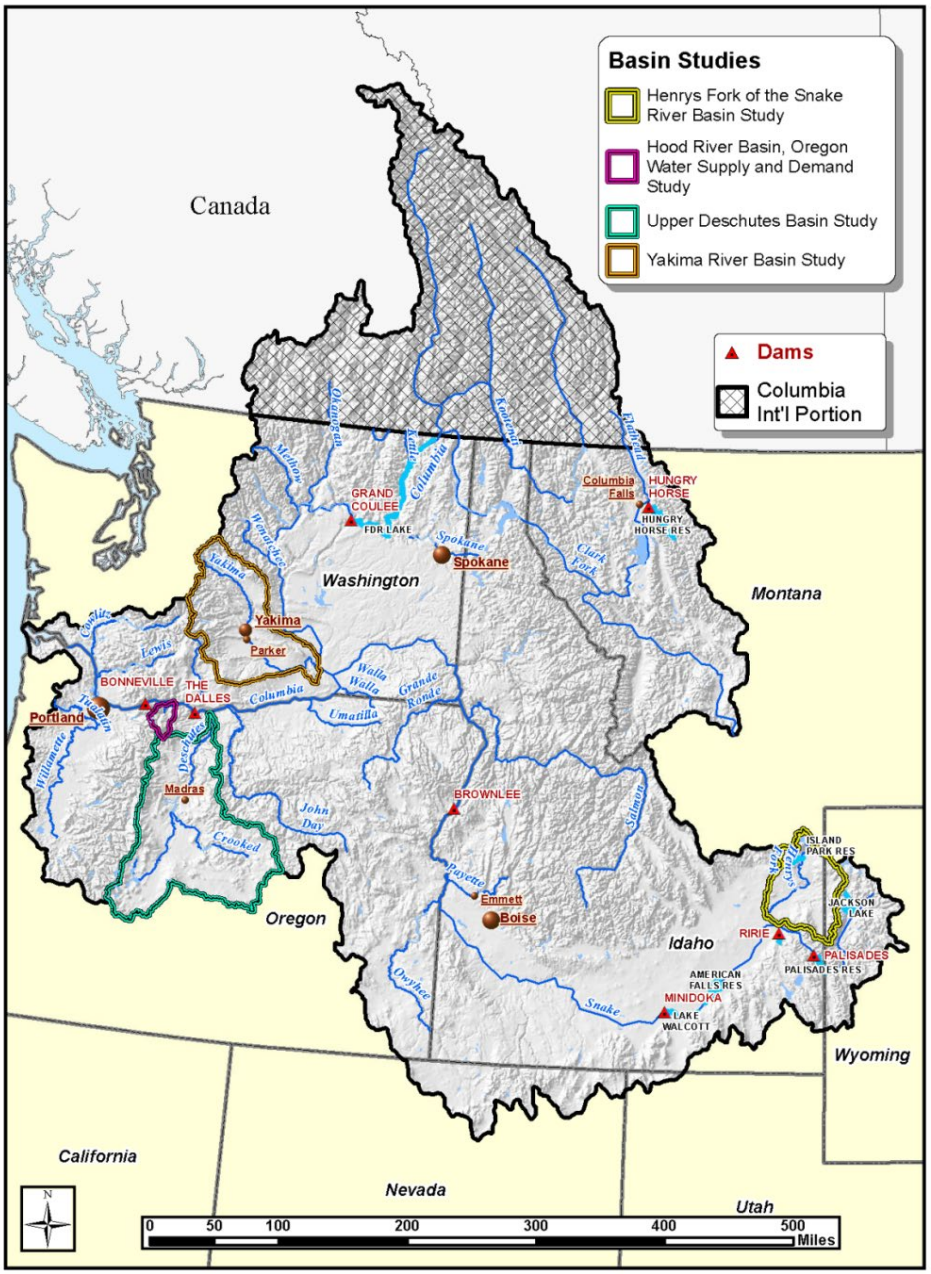


Figure CRB-1. Columbia River Basin Map (Placeholder Map).

Within the Columbia River Basin, Reclamation actively collaborates with other Federal agencies; the water resource departments of Oregon, Montana, and Idaho; the State of Washington's Department of Ecology; the Montana Department of Fish, Wildlife and Parks; Native American tribes; local entities; and water users on a variety of water-resource planning activities in the Columbia River Basin. Such activities include water supply analysis, water quality assessments, renewable energy production, and water conservation activities.

1.1 Columbia River Basin Studies Overview

The challenges and complexities of ensuring a sustainable water supply and meeting future demand in a complex and highly variable system such as the Columbia River have been recognized and documented in several studies conducted by the Bureau of Reclamation (Reclamation) and the Basin states over the past several decades. Looking ahead, concerns regarding the reliability of the Columbia River system to meet future Basin resource[2] needs are even more apparent, given the likelihood of increasing demand for water throughout the Basin, coupled with projections of changing supply due to climate change.

Since 2009, five climate impact and basin studies in the Columbia River Basin (see Figure CRB-1) have been completed or are ongoing:

Columbia River Basin Impact Assessment – Reclamation is conducting the Columbia River Basin Impact Assessment to evaluate the potential effects of future climate change on flows at more than 300 locations across the Basin. This assessment will determine baseline risks to water supplies and demands to establish a foundation for more in-depth analyses and the development of adaptation strategies.

Yakima River Basin Study – Reclamation collaborated with the Washington Department of Ecology - Office of Columbia River to fund the study. The study area is located in south-central Washington.

Henrys Fork of the Snake River Basin Study – Reclamation collaborated with the Idaho Water Resource Board to fund the study. The study area is located upstream of the confluence of the Henrys Fork and the Snake River in central Idaho.

Hood River Basin Study – Reclamation collaborated with the Hood River County Water Planning Group to fund the study. The study area encompasses a 339-square-mile region in Hood River County in north-central Oregon.

[2] Resources include water allocations and deliveries for municipal, industrial, and agricultural use; hydroelectric power generation; recreation; fish, wildlife, and their habitats (including candidate, threatened, and endangered species); water quality including temperature and dissolved gas; flow- and water-dependent ecological systems; and flood control.

Upper Deschutes Basin Study – Reclamation collaborated with the Deschutes Basin Board of Control to fund this study. The study area includes surface water and groundwater upstream of the confluence of the Deschutes, Crooked, and Metolius river systems in Oregon's Deschutes Basin.

The Impact Assessment and Basin Studies are funded and conducted by Reclamation through the Basin Study Program under the Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program. The Basin Studies are conducted in coordination with stakeholders in the Columbia River Basin. The purpose of the Basin Studies is to define current and future imbalances in water supply and demand in the Basin and sub-basins over a long-term planning horizon, and to develop and analyze adaptation and mitigation strategies to resolve those imbalances.

Additionally, Reclamation is a chair of the River Management Joint Operating Committee (RMJOC). The RMJOC comprises of representatives from the Bonneville Power Administration (BPA), Corps, and Reclamation and functions as a forum for the coordination of FCRPS dam operations and other river management activities within the Columbia River Basin. With respect to addressing climate change impacts in the Columbia River Basin, Reclamation is working with the RMJOC on the continued development of up-to-date climate change projections in support of long-range planning activities performed by Federal agencies, States, tribes, local governments, and nonprofits.

2 Historical Climate and Hydrology

Climate varies considerably over the Columbia River Basin, both temporally (year-to-year) and spatially (geographically). The El Niño/Southern Oscillation (ENSO) has a strong influence on the Columbia River Basin and drives much of the year-to-year variability, causing drier conditions in the basin, typically on a 4-year cycle. The Pacific Decadal Oscillation (PDO) also influences conditions across the basin. Warm-phase PDO winters tend to be warmer and drier than average, while cool-phase PDO winters tend to be cooler and wetter than average (Climate Impacts Group 2014). When the two events are in-phase, or occurring at the same time (El Niño and warm-phase PDO or La Niña and cool-phase PDO), the potential for temperature and precipitation extremes increases. Such conditions translate into significant shifts in the distribution of January-through-July volume runoff at The Dalles Dam (Barton & Ramirez, 2004).

Commented [bdg3]: I hadn't heard of a 4 yr dry ENSO cycle before. I suggest noting a reference here unless it is the one at the bottom of the paragraph.

Geographically, the Columbia River Basin climate is strongly influenced by the north-south Cascade Mountain Range and the Blue-Wallowa Mountains of northeast Oregon. These geographic features play an important role in creating the cooler and wetter climate that is characteristic of the western, or windward, side of these mountain ranges and the warmer and drier climate that is more characteristic of the eastern, or leeward, side (Oregon Climate Change Research

Commented [bdg4]: This paragraph does not seem to capture the entire basin geography that effects the weather and hydrology of the Columbia Basin. For example, there is no mention of the effect of the Rocky Mnt range capturing the snow.

Institute, 2010). The variation in precipitation from one year to the next and the complexity of the basin result in highly variable Columbia River flows year to year (Figure CRB-2).

Commented [bdg5]: I suggest adding the concept of snowmelt here too. Precipitation matters but snow melt and temperature are the major player in determining the current distribution of Columbia River flows that you show in your chart.

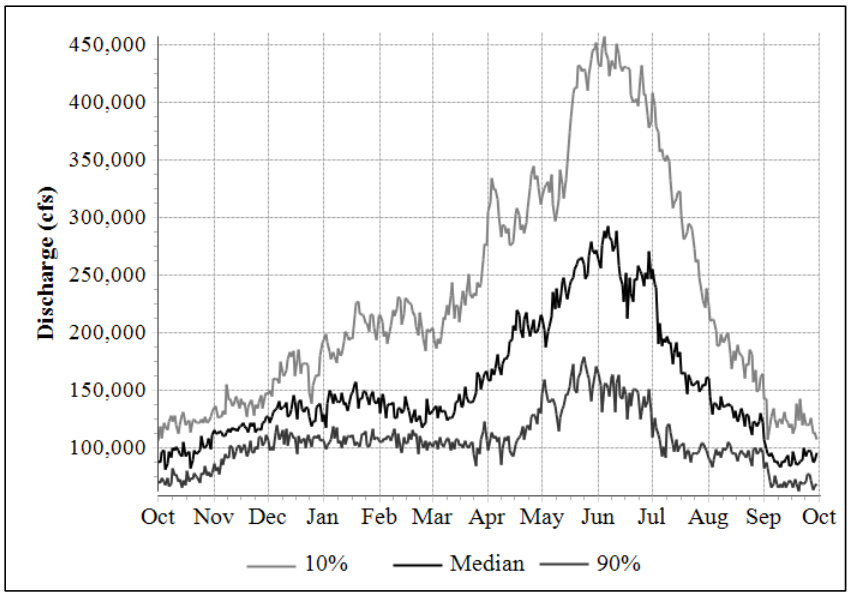


Figure CRB-2. Daily summary of historical discharge data from the USGS gage 14105700 Columbia River at The Dalles for water years 1916-2015 showing 10 percent, median, and 90 percent exceedence values.

Despite the large variability in observed temperature changes across the region, warming has been prevalent over the course of the 20th century, and some areas have experienced increased winter precipitation (Brekke, Kuepper, & Vaddey, 2011). Temperature observations since the late 1800s indicate that the average annual temperature has increased by approximately 2° F. Precipitation trends are less consistent across the region; however, several locations across the Pacific Northwest have experienced increasing precipitation trends during the period 1950-1999 (Regonda, Rajagopalan, Clark, & Pitlick, 2005). Figure CRB-3 illustrates the observed changes in precipitation and temperature from 1916 to 2006, both in terms of basin-wide observations over time and in terms of change per decade by sub-basin. While there does not appear to be an obvious trend in precipitation, temperatures have increased, particularly over the latter half of the century.

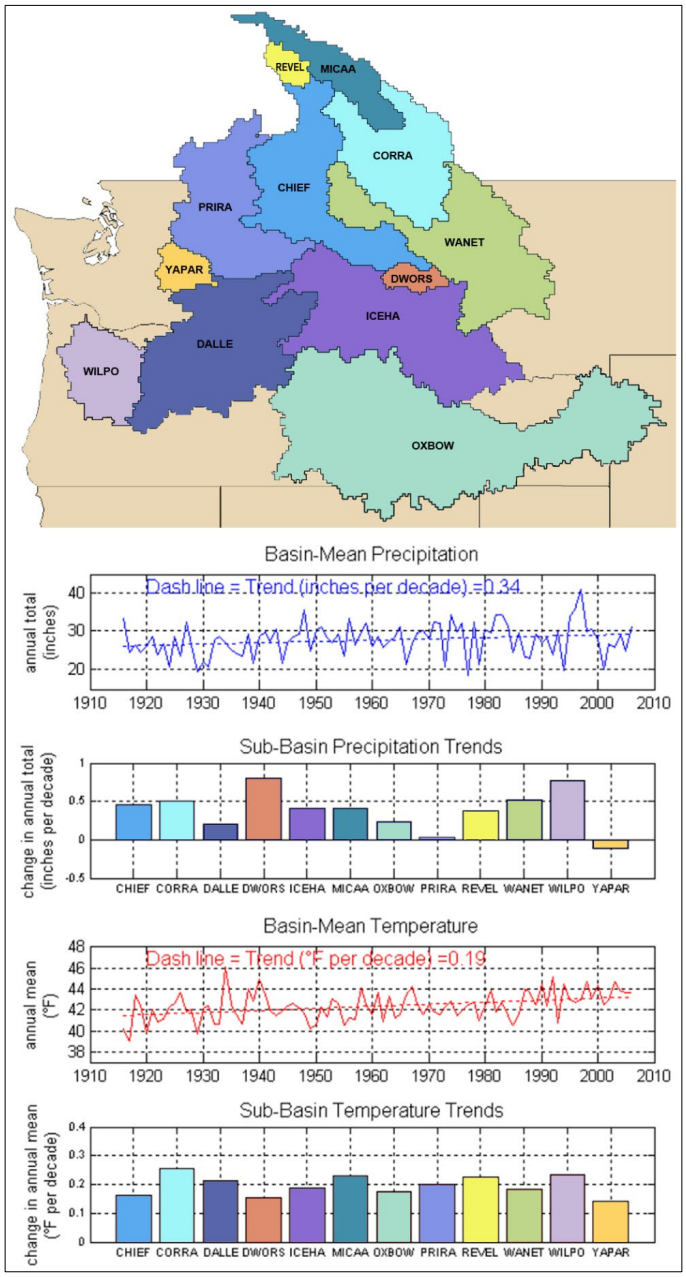


Figure CRB-3. Observed historical climate over the Columbia-Snake River Basin and sub-basins for water years 1916-2006 (Brekke, Kuepper, & Vaddey, 2011)

Studies have also revealed increasing trends in heavy precipitation events. The U.S. Climate Change Science Program Synthesis and Assessment Product 3.3 (SAP 3.3) (Karl, et al., 2008) reported that heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski, et al., 2008). An increasing trend in the frequency of such events was also documented by other studies, including one by Kunkel (2003), which evaluated changes since the 1920s/1930s, and another by Madsen and Figdor (2007), which evaluated the occurrence of events between 1948 and 2006.

Commented [JG6]: I know we're trying to keep this section succinct, but I think it would benefit from including a couple of key data points or specific information to illustrate these points. For example, for the heavy precipitation trend, maybe give the start and end dates for the data and the highest and lowest precipitation observed during that period, and/or the number of heavy precipitation events per year over the period (whichever best illustrates the point made, which should be clarified, as well).

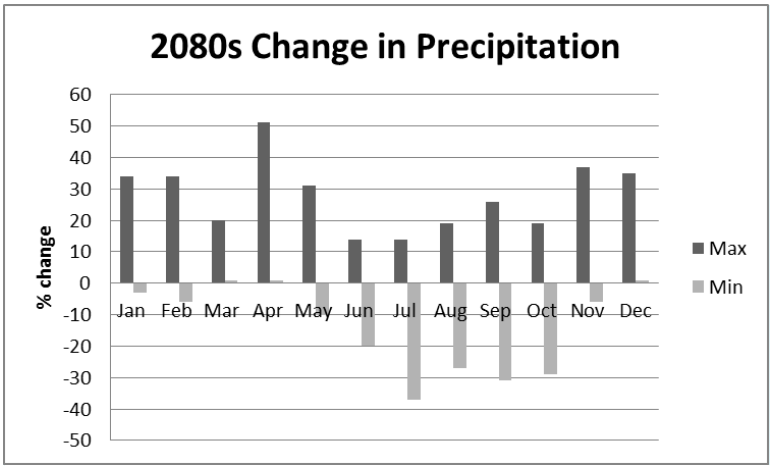
Coincident with these trends in temperature and precipitation, the Columbia River Basin has also experienced a general decline in spring snowpack, a reduction in the amount of precipitation falling as snow in the winter, and a shift toward earlier snowmelt runoff between the mid- and late-20th century ((Knowles, Dettinger, & Cayan, 2006); (Regonda, Rajagopalan, Clark, & Pitlick, 2005)). Meanwhile, a study by Luce and Holden (2009), which evaluated the distribution of streamflow reductions from 1948-2006, revealed significant trends in annual streamflow reductions during dry years and suggests that dry years have been getting increasingly dry (Figure CRB-4).

Commented [JC7]: Good suggestion. This text was ported straight over from SECURE 2011, so I don't have anything on hand to elaborate on this. I will see if I can dig up more information. If not, I think we should just move forward with this as-is.

3 Projected Climate and Hydrology

Add information on research into climate change impacts into extreme events and variability. Reclamation studies summarized here have not used models that are capable of evaluating extreme events.
Update entire section to incorporate results from the CRBIA (when available). Interesting to note that CRBIA used CMIP5, while RMJOC1 used CMIP3.

Recent studies by Reclamation (including the Henrys Fork River Basin Study, the Hood River Basin Study, the Yakima Integrated Plan, the Columbia River Basin Impacts Assessment, and the RMJOC-1) provide more detailed insight into the range of impacts that are expected across the region. These studies illustrate that climate change impacts across the Columbia River Basin vary not only spatially (geographically) but also temporally. Figure CRB-4 illustrates the monthly minimum and maximum projected changes in temperature and precipitation for the 2080s, while Figure CRB-5 illustrates the change in mean annual temperature and precipitation over time (Reclamation, 2015a).



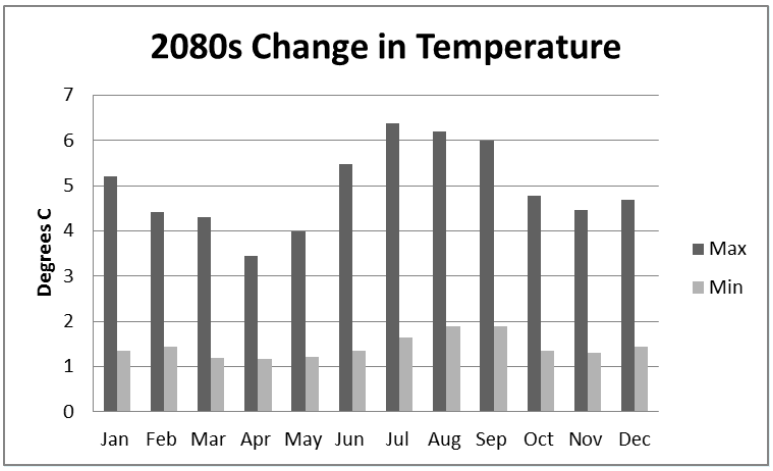
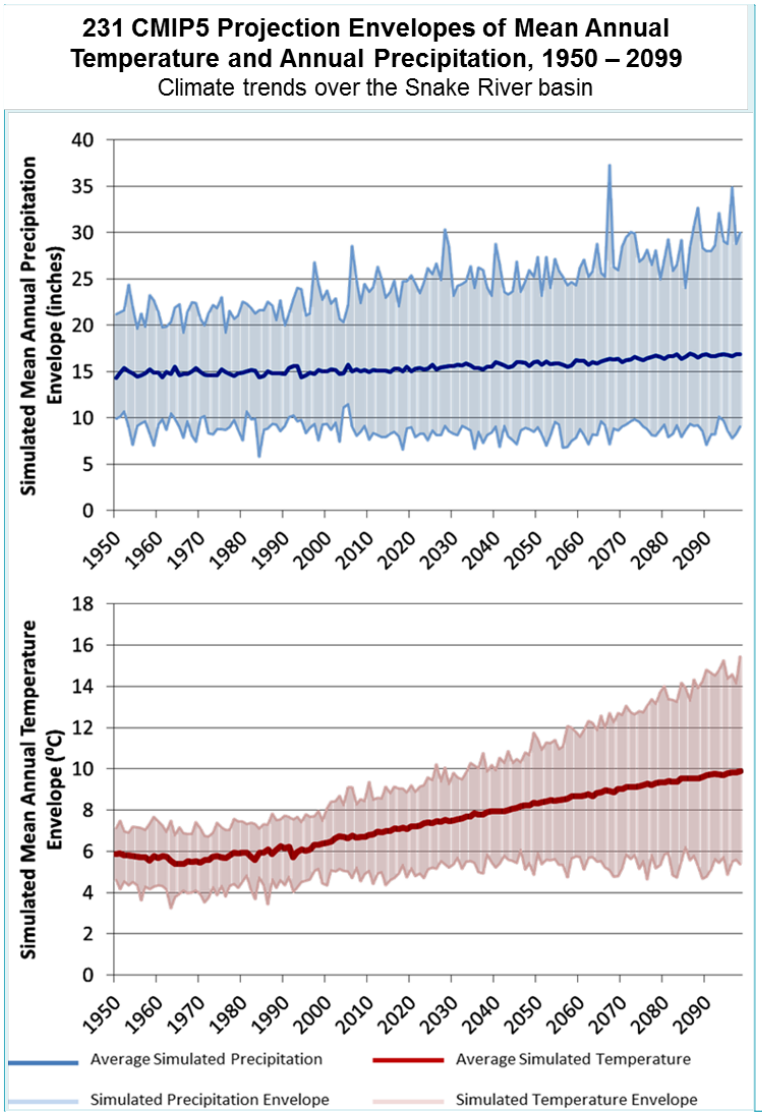


Figure CRB-4.

Commented [JC8]: Data is still being reviewed and revised and is subject to change.

3.1 Temperatures

Climate models indicate that temperatures in the Northwest will continue to increase over the next century (Table CRB-1). As illustrated in the top-left panels of Figure CRB-5 and [Figure CRB-6], which depict the spatial distribution of annual maximum and annual minimum temperatures, conditions are generally cooler in the north and along the mountainous rims, while warmer temperatures are observed in the lower-lying areas of the Columbia River Basin interior and throughout the Snake River plain of southern Idaho.



[Figure CRB-5 PLACEHOLDER] CMIP5 231-member ensemble envelopes of mean annual temperature and precipitation

Commented [JC9]: Update figure with basin wide projections (not just Snake River Basin).

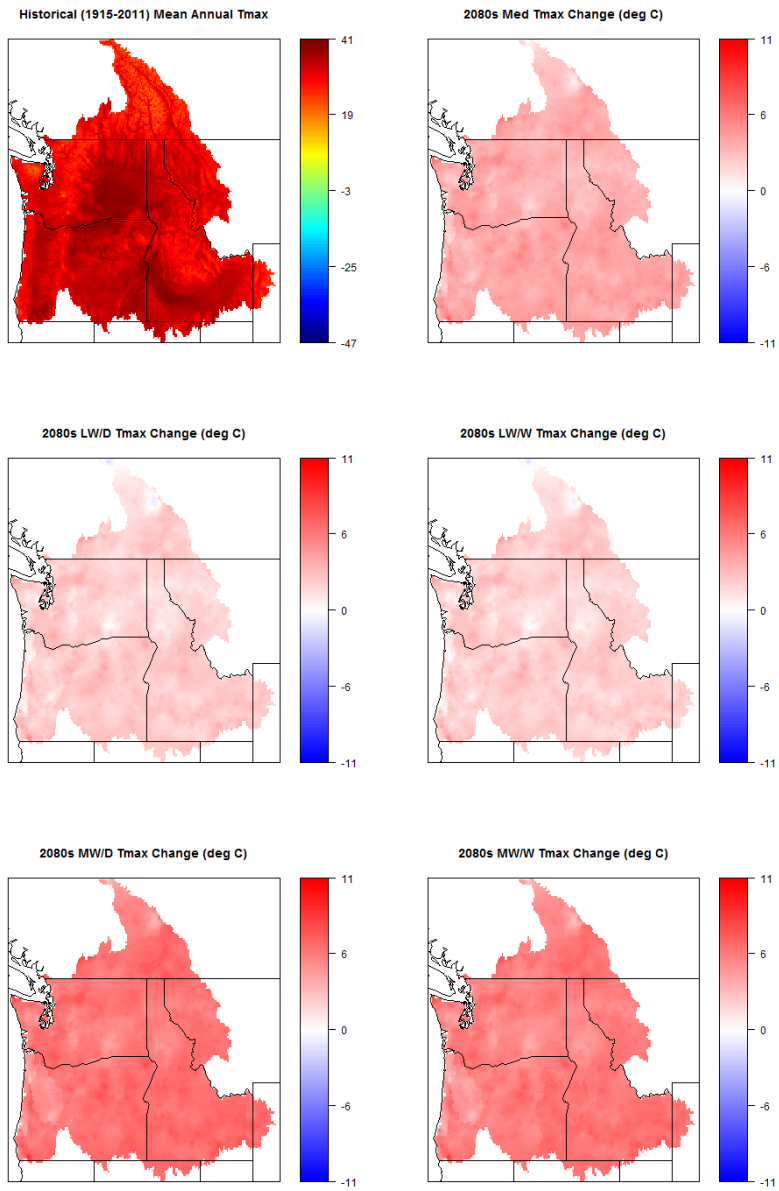


Figure CRB-6. Mean annual maximum temperature for the period of January 1915 through December 2011 (from (Livneh, et al., 2013)) and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario.

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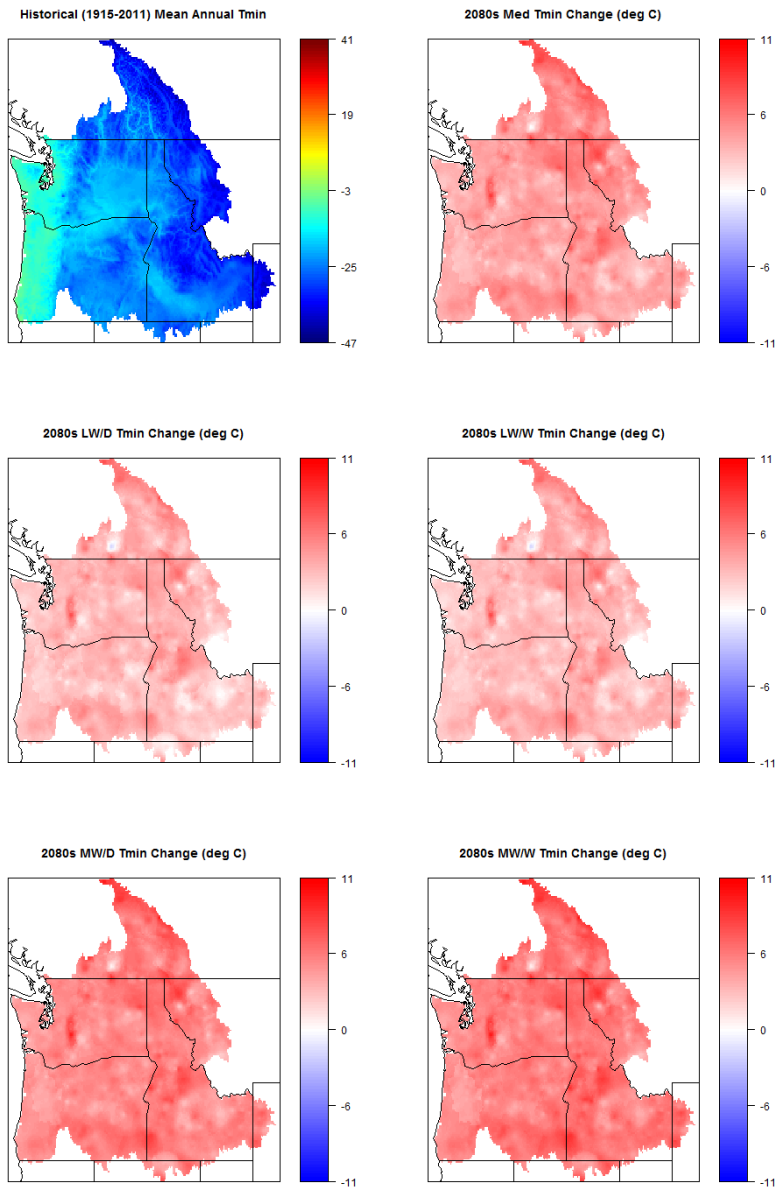

Figure CRB-7 Mean annual minimum temperature for the period of January 1915 through December 2011 (from (Livneh, et al., 2013)) and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario.

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3.2 Precipitation

The effects of climate change on precipitation are less certain, but models generally agree in their prediction of wetter autumns and winters and drier summers (Brekke, Kuepper, & Vaddey, 2011), (Melillo, Richmond, & Yohe, 2014). These studies also identify some of the complexities of climate change effects that become apparent througout the Columbia River Basin when climate projections are inspected by location, particularly with respect to changes in precipitation. Precipitation levels are generally greater in the north and at higher elevations (Figure CRB-9, top left panel), and lower in lower-lying areas and across the Snake River plain. Precipitation events are expected to occur less frequently, however they are also projected to occur with greater intensity in many areas, and precipitation extremes are likely to increase (Brekke, Kuepper, & Vaddey, 2011).

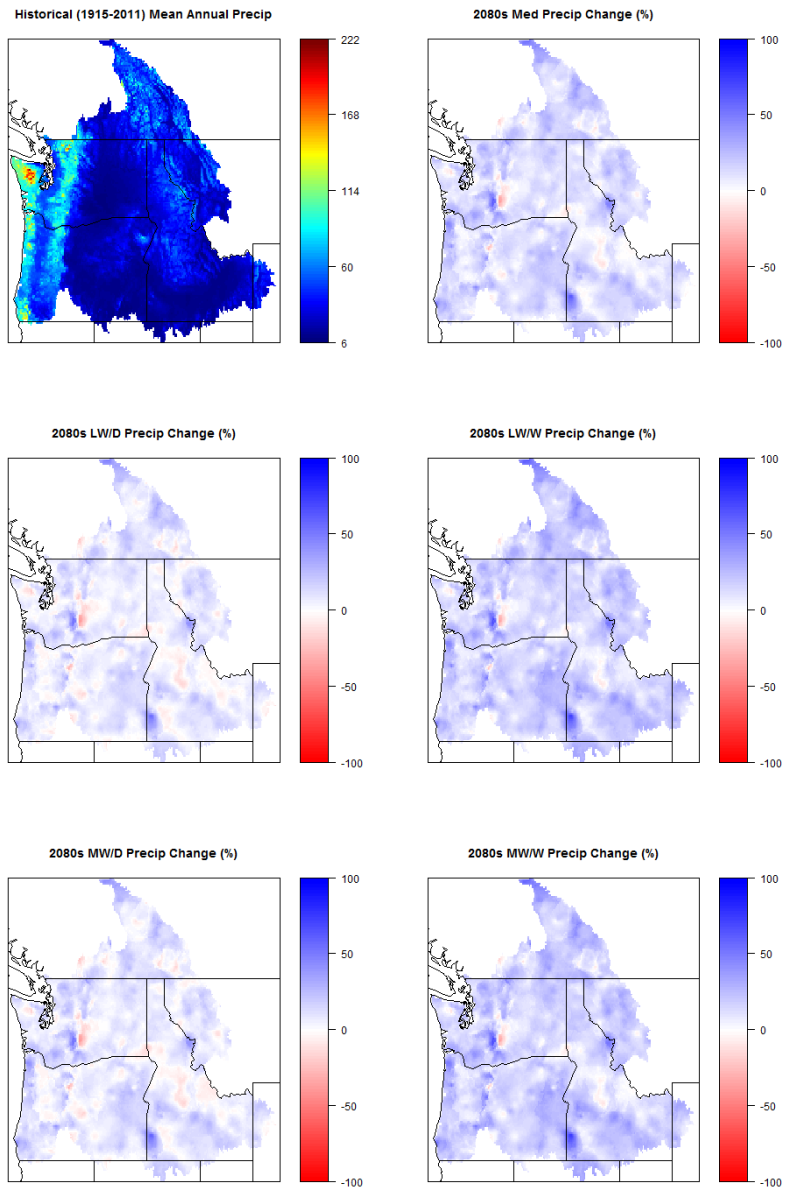

Figure CRB-8. Mean annual precipitation for the period of January 1915 through December 2011 (Livneh, et al., 2013) and maps of percent change between historical and 2080 period averages for each Hybrid-Delta climate scenario.

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3.3 Snowpack

Changes in temperature and precipitation will have important and varied consequences for water resources across the region, with hydrologic response depending upon the dominant form of precipitation in the basin and other local characteristics such as elevation, aspect, geology, vegetation, and changing land use (Melillo, Richmond, & Yohe, 2014). As previously discussed, climate change studies for the Columbia River Basin expect temperatures to continue to increase above historical levels. Some of the Columbia River sub-basins, depending on elevation, will experience decreases in snowpack accumulation due to projected increases in temperature. As illustrated by Figure WW-1 in the West-Wide Overview, most of the basin area will experience a net decrease in snowpack accumulation by the 2070s.

In the Yakima River basin, studies have found snowpack to be highly sensitive to even modest warming. A 2008 study on the sensitivity of snowpack to warming in the Yakima River basin showed a 12 percent and 27 percent decrease in snowmelt for +1° C and +2° C warming scenarios, respectively (Mastin, 2008). With decreased snowpack and increases in the amount of precipitation that falls as rain rather than snow, peak streamflow in the Yakima River basin is expected to shift to earlier in the year, and warm-season flows are expected to decrease.

Commented [JC13]: Update this paragraph to include results from CRBIA when available.

Change in snowpack accumulation, timing, and quantity will have important consequences for seasonal water supply and runoff forecasting. For many reservoir systems in the Columbia River Basin, snowpack is an important predictor variable for late-spring and early-summer forecasting. These forecasts, which are relied upon for flood-control operations, are expected to deteriorate in skill as snowpack (a major predictor variable in the models) diminishes going into the future (Brekke, Kuepper, & Vaddey, 2011). With less predictability in volume runoff and rain events, projects may need to operate more conservatively to account for this uncertainty (Brekke, Kuepper, & Vaddey, 2011).

3.4 Runoff

The shift to rain instead of snow accumulation will result in increases in winter flows, advances in the timing of spring melt, and reductions in the availability of snowmelt to sustain runoff during the warm season (Melillo, Richmond, & Yohe, 2014). Decreased snowpack volumes may also result in decreased groundwater infiltration and ultimately decreased contribution to summer base flow in rivers. Columbia River Basin climate studies ((Brekke, Kuepper, & Vaddey, 2011), (Reclamation, 2015a), (Melillo, Richmond, & Yohe, 2014)) simulated the effects of changes in temperature and precipitation on runoff at locations throughout the Columbia River Basin. Climate-change scenarios exhibited a seasonal shift of higher flows in the winter and lower flows in the summer. These studies also show the varying degrees of response that can be expected across the basin, depending upon baseline climate and projected changes in temperature and precipitation.

This seasonal shift is due in part to more winter precipitation in the form of rain instead of snow and increased snowmelt earlier in the year due to warmer temperatures. Such impacts are illustrated in Figure CRB-10, which shows the projected monthly average stream flows for the 2020s, 2040s, 2060s, and 2080s at ## locations throughout the Columbia River Basin.

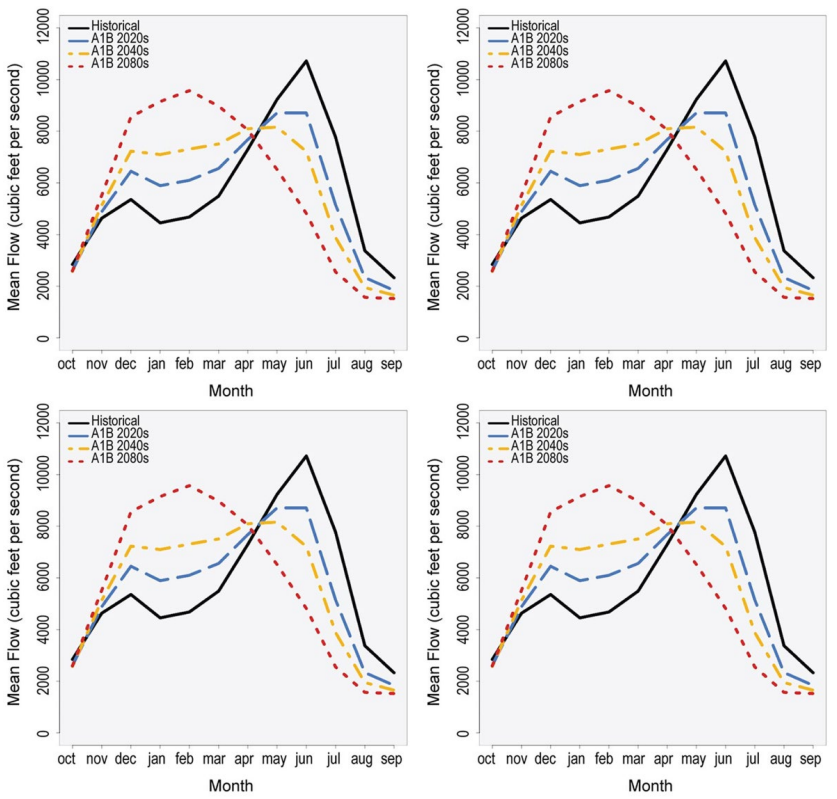


Figure CRB-9. Future shift in stream-flow timing at select locations throughout the Columbia River Basin (Reclamation, 2015a)

Commented [JC14]: Update this figure with CRBIA results when available. Which climate change scenario should be used? Median?

Tohver et al. (Tohver, Hamlet, & Lee, 2014) found that mixed-rain-and-snow basins (basins that receive a mixture of rain and snow as their primary water source) with average winter temperatures near freezing show the greatest increase in flood risk due to a combination of warming (increasing the functional contributing area) and more winter precipitation. Climate change impacts to maximum and minimum runoff events, which are of particular interest with respect to flood control and ecosystem management, are considerably less certain compared to the projected impacts to annual or seasonal runoff. Climate models typically are not capable of simulating acute weather events. Additional analysis is needed in order to identify trends in the freqency and magnitude of extreme

weather events (link to future research need in the congressional and west-wide reports find references).

Table CRB-1 summarizes the climate and hydrologic changes that have been projected by the RMJOC1 study at three important locations within the Columbia River Basin: the Columbia River at The Dalles, the Snake River at Brownlee Dam, and the Yakima River at Parker. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

Insert table of Temp and Precip projections from CRBIA. Maybe follow with a table of april 1 SWE and runoff %

Table CRB-1. Summary of Simulated Changes in Decade-Mean Hydroclimate for Several Subbasins in the Columbia River Basin[3]

Commented [ER15]: Update with CRBIA data

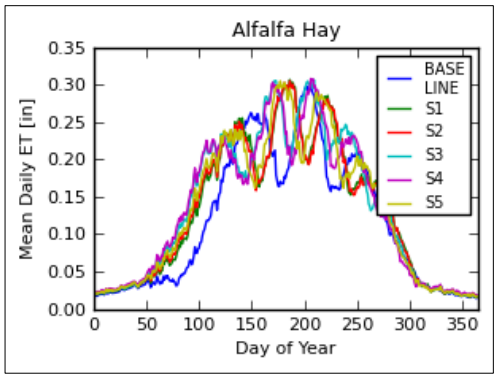
Hydroclimate Metric (Change from 1990s)	2030s-2060s	2070s-2080s
Columbia River at The Dalles		
Mean April 1st Snow Water Equivalent (%)	-39.3	-47.2
Mean Annual Runoff (%)	3.7	7.5
Mean December–March Runoff (%)	18.5	27.3
Mean April–July Runoff (%)	4.1	2.4
Snake River at Brownlee Dam		
Mean April 1st Snow Water Equivalent (%)	-57.6	-67.2
Mean Annual Runoff (%)	1.2	3.4
Mean December–March Runoff (%)	13.7	21.0
Mean April–July Runoff (%)	-2.0	-0.9
Henrys Fork of the Snake River		
Mean Annual Temperature (°F)		
Mean Annual Precipitation (%)		
Mean April 1st Snow Water Equivalent (%)		
Mean Annual Runoff (%)		
Mean December–March Runoff (%)		
Mean April–July Runoff (%)		
Hood River		
Mean Annual Temperature (°F)	0.5 to 2.2	
Mean Annual Precipitation (%)	-10 to 20	
Mean April 1st Snow Water Equivalent (%)		
Mean Annual Runoff (%)		
Mean December–March Runoff (%)		
Mean April–July Runoff (%)		
Yakima River at Parker		
Mean Annual Temperature (°F)	1.57 to 2.9	2.49 to 4.2
Mean Annual Precipitation (%)	2.1 to 5.7	3.4 to 7.7
Mean April 1st Snow Water Equivalent (%)	-37.6	-50.7
Mean Annual Runoff (%)	3.7	5.6
Mean December–March Runoff (%)	39.9	56.9
Mean April–July Runoff (%)	-9.5	-17.0

[3] Sources of data for this table include (Melillo, Richmond, & Yohe, 2014), Basin studies for Hood River and Yakima, Henry's.

4 Projected Changes in Water Demand

The complex nature and the multitude of processes that play into agricultural, municipal, industrial, and in-stream water demands make it difficult to quantify the impacts of climate change on water demands from these sectors. However, changes are likely to occur due to increased air temperatures, increased atmospheric carbon dioxide levels, and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. In addition to these natural system changes, socioeconomic changes (including those related to infrastructure, land use, technology, and human behavior) will also affect future water demands.

The atmosphere's moisture-holding capacity increases with increasing air temperature, leading to less precipitation and less water available for agricultural and hydropower use. Agricultural demands associated with plant water consumption and surface water evaporation are likely to increase in a warming climate. By 2080, average annual evapotranspiration is expected to increase by 1.1 percent across the Columbia River Basin (Reclamation, 2015b). Increasing growing-season length due to climate change is also likely to result in increased irrigation demands. Studies have indicated that the average North American growing-season length increased by about 1 week during the 20th century and may increase by another 2 weeks by the end of the 21st century (Gutowski, et al., 2008). Livestock water demands are also projected to increase substantially, as is the amount of agricultural land requiring irrigation, with the latter projected to increase by up to 40 percent due to climate change (Pacific Institute, 2009).



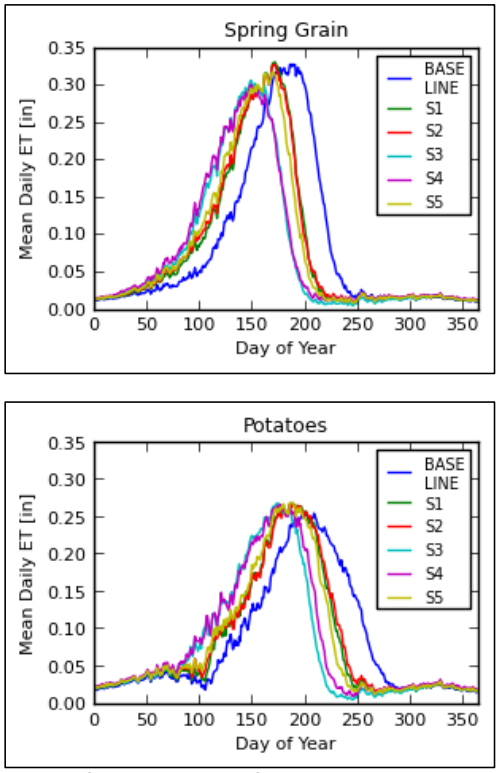


Figure CRB-10. These figures show the Baseline and projected mean daily evaporation for time periods 2080 at the Columbia River Basin – COOP station ID9303 (Twin Falls 6E). The blue line shows baseline evapotranspiration (Reclamation, 2015b).

Conversely, other studies suggest that increased atmospheric carbon dioxide may increase plant water-use efficiency (Melillo, Richmond, & Yohe, 2014). Meanwhile, crop failures associated with changes in plant diseases, pests, weeds, heat stress, and extreme wet and dry events will also act to reduce irrigation demand (Melillo, Richmond, & Yohe, 2014); (Baldocchi & Wong, 2008); (Bloom, 2010).

In-stream water demands, including those associated with ecosystem requirements, hydropower and thermoelectric power production, industrial cooling, navigation, and recreation, could increase due to climate change. Diversions for thermoelectric power production and industrial cooling facilities are predicted to increase as warmer air and water temperatures cause these processes to function less efficiently. Demand for hydropower during the warm season is also expected to increase over the next century, in part due to increased use of air conditioners as people adapt to higher temperatures and increased cooling degree-days (number of days over 65° F). Increases in energy demand

are also expected to occur in response to increased groundwater pumping for irrigated agriculture and the pumping and treatment of water for municipal uses (Department of Energy, 2012).

The efficiency of water-supply infrastructure is also subject to impacts from climate change. Losses associated with reservoir evaporation, water conveyance, and on-farm application can be significant and may increase as warming temperatures result in increased evaporation rates (Reclamation, 2015b). However, delivery and application efficiency may increase as more-efficient irrigation methods are implemented and improvements are made to conveyance systems over time.

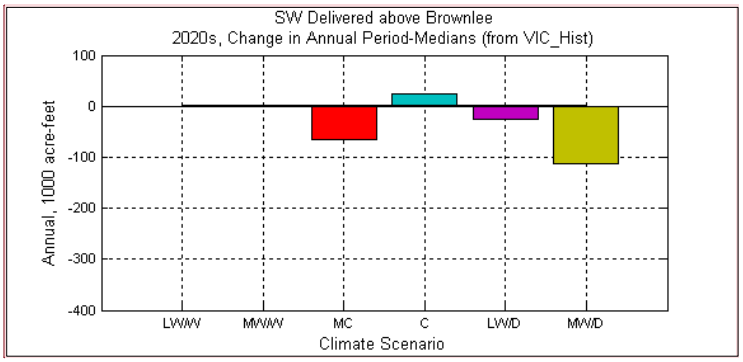
5 Analysis of Impacts to Water Resources

Columbia River Basin reservoir systems have multiple, often competing, objectives, including irrigation, municipal and industrial use, hydropower production, flood control, and preservation of habitat for aquatic species. These systems were designed under the assumption that snowpack would act as an additional reservoir, holding water (in the form of snow) during the cool season and gradually releasing it into the summer months. Similarly, ecosystems have evolved to depend on specific hydrologic regimes to support important life-cycle events. Climate change impacts, such as increased winter flows and decreased summer flows, will stress these systems and likely require more tradeoffs among reservoir management objectives.

5.1 Water Delivery

Climate change impacts to water delivery are likely to vary throughout the Columbia River Basin. Climate change conditions are expected to worsen deficits throughout the study area due to changes in the phase of precipitation, shifts in runoff timing, a lengthening of the growing season, and greater reliance on storage water. Recent Reclamation water resource studies have examined the projected hydrologic regimes, reservoir operational constraints, and ecological requirements. These studies have found that overall water supply, and specifically supply late in the irrigation season, will decrease, increasing the reliance on water storage where available and increased use of other supplies, such as groundwater. Irrigators with junior natural-flow water rights or those without storage contracts are likely to be more adversely affected. In many places, water-supply shortages will be more frequent.

For the Snake River Basin above Brownlee Reservoir, slight decreases in the amount of surface water delivered during July and August, as well as significant decreases in September, are expected in 2020s and 2040 projections (see Figure CRB-12).



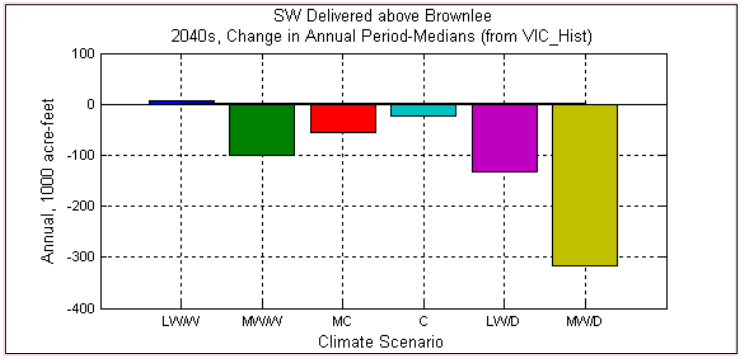


Figure CRB-11. Annual median change in surface water delivered in the HD 2020 and HD 2040 scenarios above Brownlee Reservoir on the Snake River.

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While changes in the total amount of water delivered may be relatively small, simulations revealed a shift toward increased dependence on storage water within the basin. Figure CRB-13 and Figure CRB-14 illustrate the change in the amount of storage flow and natural flow delivered to the Northside Canal Company for the 2020s and 2040s. Northside holds senior natural-flow water rights and contracts for storage from reservoirs in the Upper Snake River Basin. Irrigators with junior natural-flow water rights or those without storage contracts are likely to be more adversely affected.

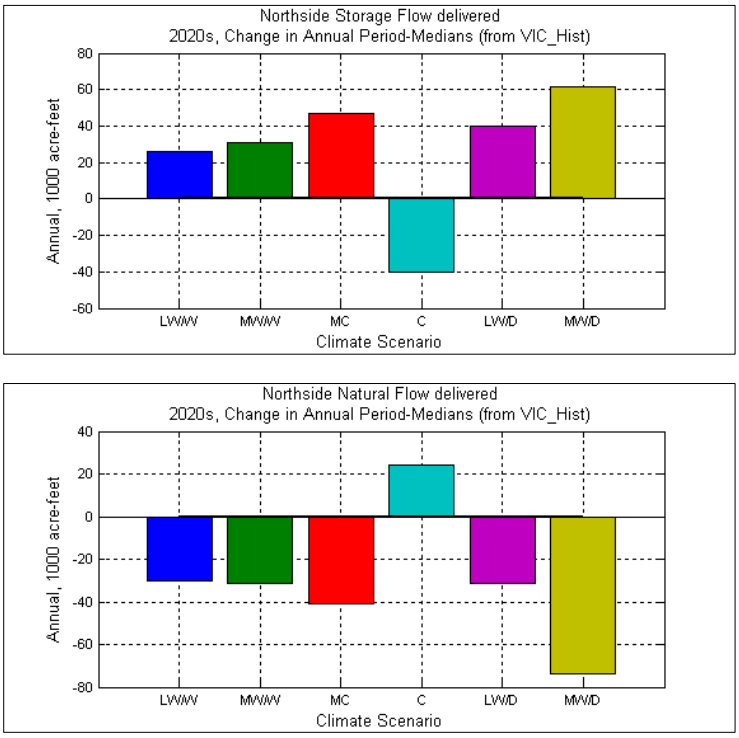
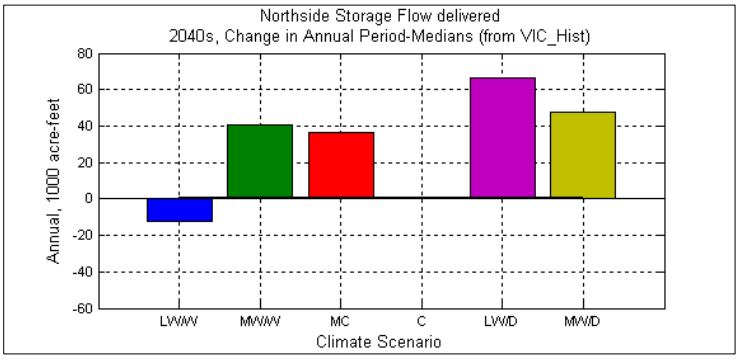


Figure CRB-12. Change in Northside storage (top) and natural flow (bottom) delivered in the 2020s for six climate scenarios when compared to VIC Simulated Historical delivery (Low, Kuepper, Nielsen, & Hua, 2011)



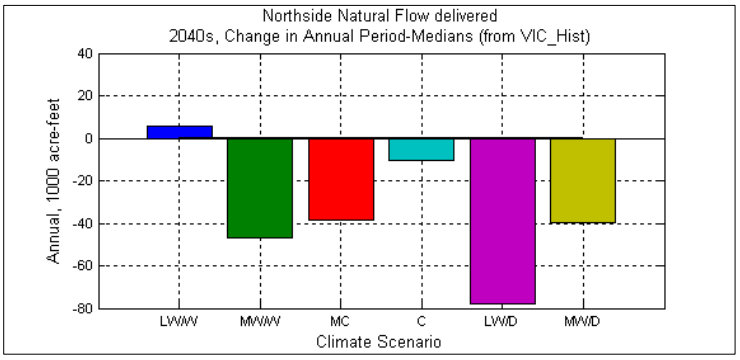


Figure CRB-13. Change in Northside storage (top) and natural flow (bottom) delivered in the 2040s for six climate scenarios when compared to VIC Simulated Historical delivery (Low, Kuepper, Nielsen, & Hua, 2011)

The Henrys Fork River Basin Study also points out the increased reliance on storage water in the future. According to the study, lower flows that are projected in future summer months may result in less water in the rivers and creeks to fulfill natural-flow water rights, subsequently increasing the use of stored water by those who hold storage contracts. Such increased use of storage water may also affect reservoir carryover during particularly long-term drier periods. Some parts of the Henrys Fork River basin are already experiencing stressed water supplies. This is particularly the case in the North Fremont and Teton Valley irrigated regions, which already experience significant deficits under current conditions. Other areas, like the Lower Watershed and the Egin Bench regions, experience deficits during consecutive drought years. Climate change conditions are expected to worsen deficits throughout the study area due to changes in the phase of precipitation, shifts in runoff timing, a lengthening of the growing season, and greater reliance on storage water.

Meanwhile, modeling results for the Yakima River basin showed similar trends for future water delivery and indicated that the water supply available for delivery to junior water users will be reduced in the future (Brekke, Kuepper, & Vaddey, 2011). The study notes an increase in cool-season storage and decreases in warm-season and end-of-season storage, an indication of less-manageable water in the subbasin. The Yakima Basin Study revealed a similar trend, with projected shifts in runoff quantity and timing likely to cause significant risks to water supply. While fall and winter inflow was projected to increase, the study notes that reservoir systems may not have sufficient capacity to capture and hold winter and spring flows for later delivery during the high-demand and lower-inflow summer period. Decreases in flow during the irrigation season will increase the rate at which stored water is used to meet demands, decreasing the overall supply during the high-demand period.

In the Deschutes River Basin (evaluated in the RMJOC1 study), impacts to surface water deliveries varied by climate-change scenario. Simulations of the 2020s showed significant decreases in delivery for the driest climates in May and June, with deliveries rebounding to historical levels by the end of the summer. Projections for the 2040s showed less surface water delivered than historical levels for the entire irrigation season. Modeling results also suggest that under extremely dry conditions, increased drafts from the reservoirs during the summer and fall may be so significant that refill the following year may not be possible.

The Hood River Basin Study evaluated water delivery effects to potable water districts and major irrigation districts within the basin. Simulations of the increased-warming/dry scenario revealed greater shortages for both potable and irrigation water demands. As for irrigation water deliveries in the basin, three of the five major irrigation districts are projected to experience greater water-delivery shortages (compared to historical shortages) under the increased-warming/dry scenario. The East Fork of the Hood River, having significant diversion demands and no storage supply, is particularly susceptible to climate change impacts and projected reductions in flow during the late summer. The study also points out that most irrigation districts in the basin are already operating at very high efficiencies, meaning there are limited opportunities for conservation in terms of water delivery.

5.2 Hydropower

Hydropower supplies approximately 60 to 70 percent of the electricity in the Northwest (Bonneville Power Administration, 2001). Storage reservoirs can be operated to correct, at least partially, the discrepancy between seasonal runoff and power demand. Currently, customers in the Northwest use more electricity in the winter than in the summer, so projected changes to increased winter and spring flows should not negatively affect generation to meet demand during those periods. However, decreases to summer flows may be problematic, as future demand for hydropower during the warm season is also expected to increase over the next century, in part due to increased use of air conditioners as people adapt to higher temperatures and increased cooling degree-days (number of days over 65° F) (Hamlet, Lee, Mickelson, & Elsner, 2010).

BPA, the Corps, and Reclamation collaborate on the operations of the Federal Columbia River Power System (FCRPS[4]), as defined by the National Marine Fisheries Service (NMFS) FCRPS Biological Opinion (BiOp) (in addition to other biological opinions discussed further in Sections 5.5 and 5.6 below) to balance operations for hydropower, fish and wildlife, irrigation, navigation, cultural resources, and flood-risk management. Historically, the Columbia River Treaty

[4] The FCRPS as defined here only refers to 14 Federal projects: Bonneville, The Dalles, John Day, McNary, Ice Harbor, Little Goose, Lower Monumental, Lower Granite, Dworshak, Chief Joseph, Grand Coulee, Albeni Falls, Hungry Horse and Libby.

(Treaty) with Canada is a primary influence of system operations, but it currently only recognizes navigation, power production, and flood control. Power operations are constrained by the listing of several species of salmonids under the Endangered Species Act (ESA). The NMFS and U.S. Fish and Wildlife Service (FWS) have conducted a series of consultations, resulting in BiOps, which BPA, Reclamation, and the Corps use to guide operations in ways that protect endangered and threatened species. The current strategy requires the operation of reservoirs to meet the demand of ESA-listed fish, increased storage in the fall and winter, and increased flows and spill during the spring and summer, which can be in direct conflict with hydropower demand (Bonneville Power Administration, 2001).

Commented [bdg17]: The CR Treaty only deals with power and flood control.

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In 2011, Reclamation, the Corps, and BPA developed climate and hydrology datasets for the Columbia and Snake River basins to conduct reservoir operational assessments, including an assessment of hydro-regulations focusing on changing hydrology and power loads (Low, Kuepper, Nielsen, & Hua, 2011). The analysis on energy capabilities included the Columbia River Treaty; fish, wildlife, and recreation objectives; and flood control and provided summary results for Federal projects and non-Federal projects referred to as Regional projects. The Federal projects include storage and run-of-river dams operated by the Corps or Reclamation. The Regional projects include all non-federal public utility district projects on the Columbia, including Wells, Rocky Reach, Rock Island Wanapum, and Priest Rapids.

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The modeling found that the general timing of generation would be similar under climate change scenarios (Figure CRB-15), with more generation during the winter and early-spring months and reduced generation during the late-summer period, assuming 2012 loads. The climate-change effects to generation in May and June are not substantial, as the peak of the natural runoff occurs during this 2-month period, and the natural flows are high enough to operate the projects at or near maximum turbine capacity. In contrast to the expected winter generation increases, the late-summer period will experience a decrease in generation, with annual Regional generation decreases expected to be between 600 to 1800 average megawatts (aMW) and 400 to 1500 aMW for Federal generation.

Two USBR projects, Hungry Horse and Grand Coulee, were examined in detail in the RMJOC1 reports (Turner & Brekke, 2011).

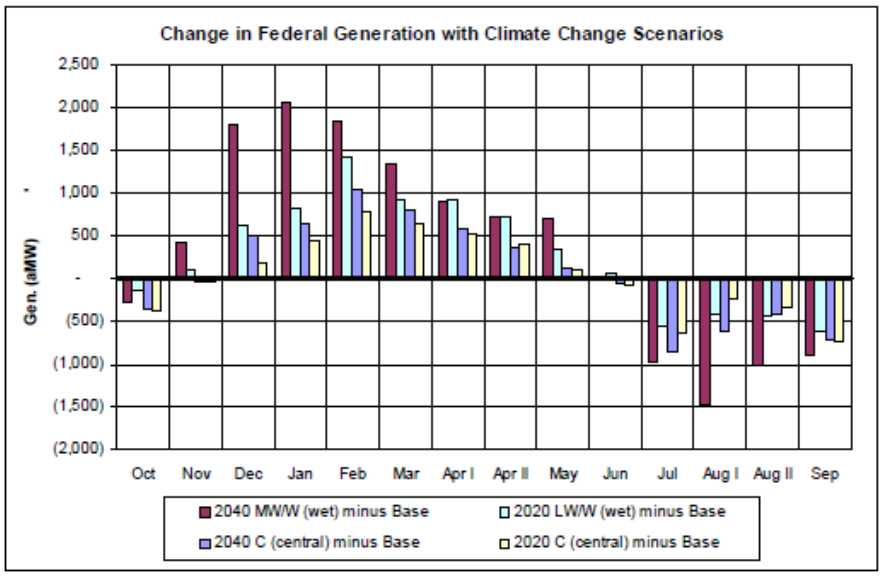

Figure CRB-14. Climate change average changes in Federal generation (Low, Kuepper, Nielsen, & Hua, 2011). Where Apr I and Aug I are the first half of each respective month and Apr II and Aug II are the second half of those months.

Similar to the regional assessment, the Hungry Horse Reservoir modeling indicates that in the climate change scenarios, inflow increases November through May, and more significant increases occur in March and April. Conversely, June through October inflows are expected to decrease, with the biggest reduction occurring in June. Currently, Hungry Horse power generation is more limited by transmission constraints and FWS Biological Opinion flow requirements than by hydrologic conditions, but the projected increased spring flows are high enough to operate the project at or near maximum turbine capacity. However, the decreased summer flows will decrease summer generation. Grand Coulee natural inflows from November to May are expected to increase, resulting in higher discharges sufficient to operate the projects at or near maximum turbine capacity. However, this may increase spill. Spill is any discharge from the dam that does not pass through the turbines (i.e., discharge over the spillway or through the outlet tubes). Spill is of concern because spilled water does not generate power, and spill at hydroelectric dams causes elevated total dissolved gas (TDG), which may cause gas-bubble trauma to some species of fish. Conversely, lower inflows during the summer-fall period result in lower summer discharge and generation.

Climate change will also have indirect effects on generation due to changes in air temperatures, humidity, or wind patterns (Bull, Bilello, Ekmann, Sale, & Schmalzer, 2007). Some studies have focused on how hydropower generation in the Columbia River Basin would be affected in the context of managing impacts

to multiple reservoir operations objectives. Payne et al. (2004) reported that, under the future climate and hydrology scenarios considered in their study, there could be increased competition for maintaining reservoir storage in the interest of satisfying firm hydropower objectives versus drafting reservoir storage to satisfying in-stream flow targets developed pursuant to the Endangered Species Act listing of Columbia River salmonids. In a more recent study (Lee, Hamlet, Fitzgerald, & Burges, 2009), a comparison of operations was conducted under existing and alternative operating criteria and under both 20th century climate and a future climate reflecting the 20th century warming by 2° C (3.6° F). Results showed that under existing operating criteria, satisfaction of flood-risk management objectives would be prioritized and lead to decreased storage trends and hydropower production.

5.3 Flood Control Management

Reclamation reservoirs in the PN Region range from coastal, fed primarily from rainfall, to alpine, primarily fed from snowmelt but most of Reclamation's reservoirs are located in the transitional zone. These projects are the most susceptible to the effects of climate change, as the historical balance between rain and snow changes over time. Mixed rain and snow basins (basins that receive a mixture of rain and snow as their primary water source) with average winter temperatures near freezing show the largest increase in flood risk (Figure CRB-16) due to a combination of warming (increasing the functional contributing area) and more winter precipitation (Tohver, Hamlet, & Lee, 2014).

For example, the Upper Snake River flow is expected to increase in the cool season and decrease in the summer, with a peak flow occurring earlier in the spring. Current flood-control requirements and the change in runoff timing will increase the probability of passing floodwaters downstream. Similarly, in the Yakima River Basin Study, the projected higher air temperatures would cause runoff from snowpack to begin earlier, shifting the peak runoff period to earlier in the season. Currently, runoff is derived from rainfall and, more important to irrigation, from mountain snowpack each spring and summer. Snowpack in the unregulated portions of the basin is referred to locally as the "sixth reservoir" of the system and is crucial to providing adequate irrigation supplies. Spring and summer runoff is projected to decrease (ranging from 12 to 71 percent of existing runoff), which would increase reliance on stored water. Fall and winter runoff is projected to increase (ranging from an increase of 4 to 74 percent of existing runoff) and the reservoir system may not be able to capture and hold the increased flow, exacerbating the conflicting operations for flood control and reservoir refill.

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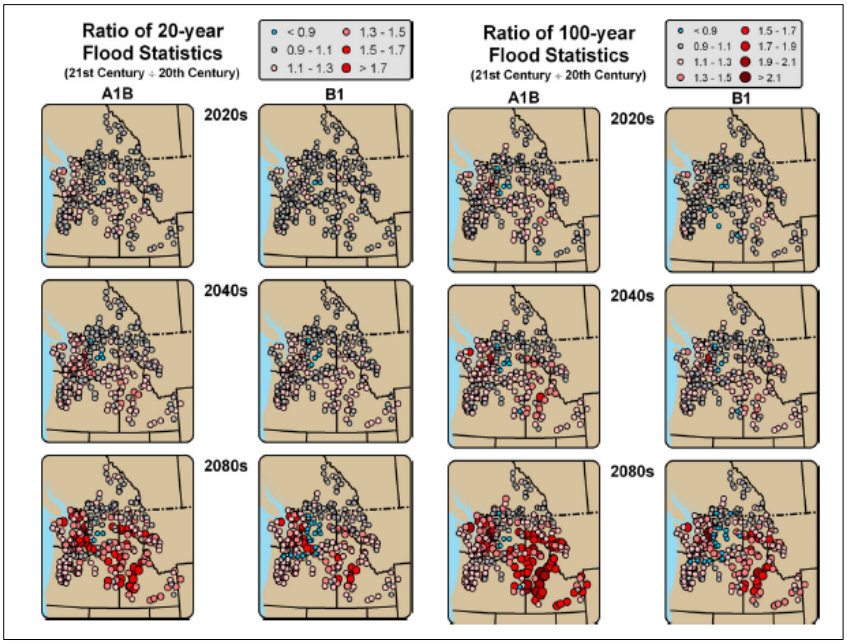

Figure CRB-15. Maps of the Ratio of the 20-year and 100-year flood magnitude (future/historical) from (Tohver, Hamlet, & Lee, 2014)

Flood-control requirements are unique to each project or reservoir system and were developed using individual historical datasets, risk assumptions, flood-protection criteria, and rule-curve development techniques. While many of the reservoirs' operating criteria were developed to account for a wide range of natural variability, operating rules will need to be examined and potentially modified to ensure their adequacy for any changes brought by climate change.

Commented [bdg21]: Corps prefers the term "flood risk management" now.

5.4 Recreation at Reclamation Facilities

The Columbia River Basin offers a number of water-dependent recreational activities (Figure CRB-16) that are likely to be affected by climatic changes that affect the system hydrology. The reservoirs and rivers in the Columbia River Basin provide recreational opportunities such as camping, boating, swimming, fishing, nature study, and hunting. Increased summer and winter temperatures may increase the popularity of these water-based activities. Changes in the hydrologic regime and project operations may also alter the timing of boat ramp availability and flows associated with floating rivers. This is in addition to the impacts to fish and wildlife discussed in previous sections, which will affect associated recreational hunting, fishing, and wildlife viewing.

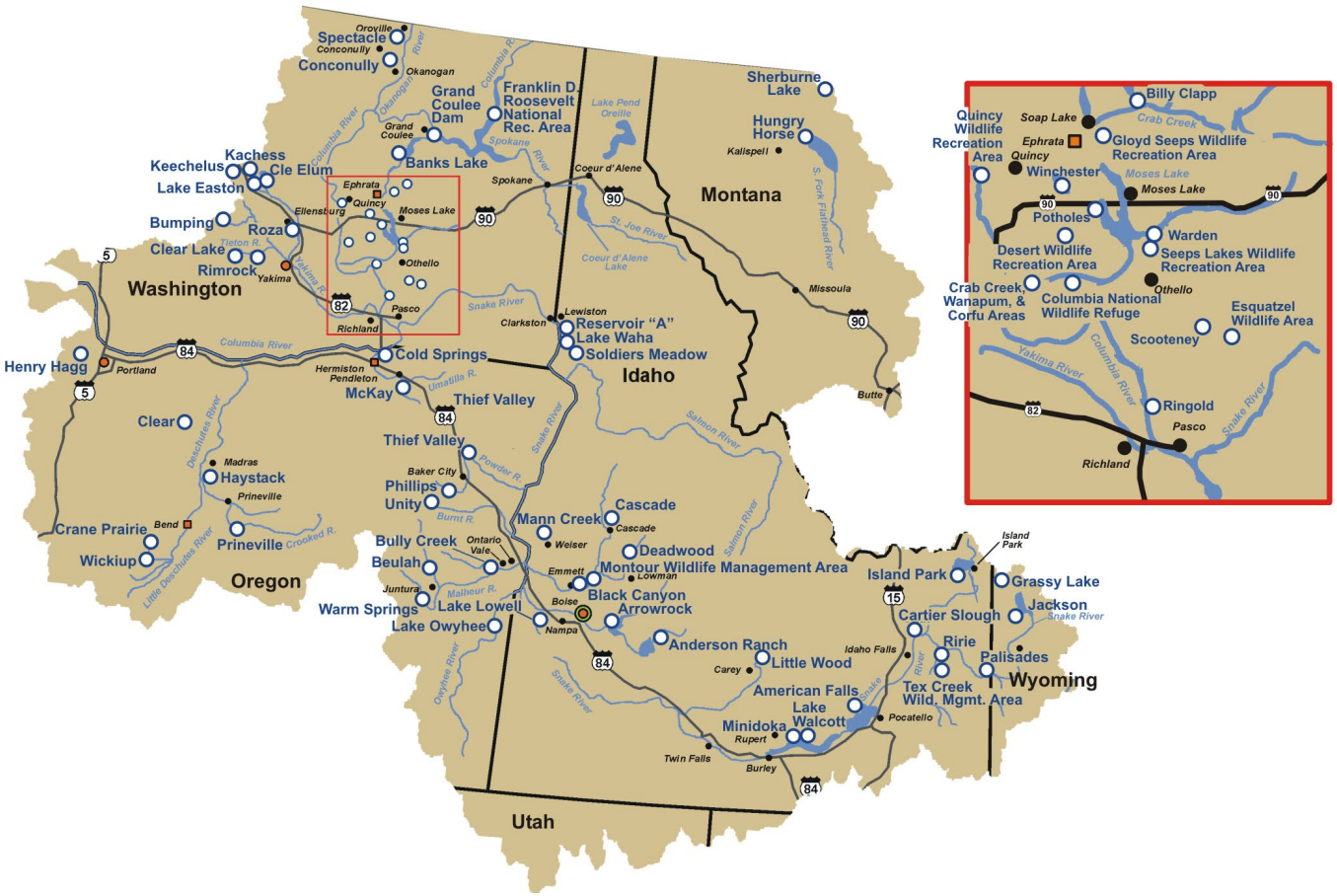

Figure CRB-16. Maps of Recreation Locations in the Columbia River Basin

Climate change may also cause fluctuations in water depth and surface acreage, which may affect recreation use and economic value in a variety of ways. For instance, extended periods of low reservoir levels may decrease overall visitor numbers. Water-based recreation is also susceptible to impacts of cascading changes, such as from debris flows caused by rainstorms over fire scars. Such impacts may become more common as the climate becomes hotter and drier. Overall, reduced supplies, altered timing of flows, and increased variability will change the availability and nature of recreational opportunities.

5.5 Fish and Wildlife Habitat

Major tributaries feeding the Columbia include the Kootenai, Flathead/Clark Fork/Pend Oreille, Kettle, Okanogan, Methow, Spokane, Wenatchee, Yakima, Snake/Clearwater/Salmon, Owyhee, Grande Ronde, Walla Walla, Umatilla, John Day, Deschutes, Hood, Willamette, Klickitat, Lewis, and Cowlitz Rivers. The Columbia River is home to six species of anadromous Pacific salmonids: Chinook, Coho, sockeye, chum, pink salmon, and steelhead[5]. The basin's salmon and steelhead runs were once among the largest in the world, with an estimated average of 10 to 16 million fish returning to the basin annually. In addition to anadromous fish, the Columbia River and its tributaries are home to sturgeon, lamprey, whitefish, and rainbow, cutthroat, and bull trout (char), among other species. Many animals, including bald eagles, osprey, and bears, also rely on fish from the Columbia River and its tributaries to survive and feed their young.

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts, with feedbacks to runoff volume, water quality, evapotranspiration, and erosion ((Janetos, et al., 2008); (Lettenmaier, Major, Poff, & Running, 2008); (Ryan, et al., 2008)). At present, most projected impacts are primarily associated with increases in air and water temperatures and include:

- increased stress on fisheries that are sensitive to a warming aquatic habitat,
- increased risk of watershed vegetation disturbances due to increased fire potential,
- shifts in the geographic range of various species (Isaak, Wollrab, Horan, & Chandler, 2012),
- impacts on migration timing, and
- effects on pests and pathogens in ecosystems.

There have also been instances of extreme events during which hundreds or thousands of adult salmon die when their thermal tolerances are exceeded (Isaak, Wollrab, Horan, & Chandler, 2012). Both migration delays and mortality events

[5] Pink salmon are not listed and are not part of the FCRPS biological opinion (BiOp).

are more likely with increased water temperatures. The Washington Climate Change Impacts Assessment (WACCIA) (Mantua, Tohver, & Hamlet, 2009) reports that rising stream temperatures likely will reduce the quality and extent of freshwater salmon habitat. WACCIA also suggests that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double by the 2080s, consistent with other studies in the region (e.g., (Battin, et al., 2007)). For example, in the Yakima River basin, elevated stream temperatures would increase the number and severity of thermal barriers to migration.

Another impact to aquatic ecosystems is the potential for increases to winter flood frequency and intensity. Increase in winter flooding would affect incubating eggs and juvenile Coho, Chinook, and steelhead survival (Hatten, Batt, Connolly, & Maule, 2014). In addition, decreases in summer flows will reduce the availability of rearing habitat, result in shallower and less suitable habitat, and not utilize from riparian cover. Climate change can also trigger synergistic effects in ecosystems and exacerbate invasive species problems. Allan et al. (2005) suggest that although freshwater ecosystems will adapt to climate change, native biodiversity in these ecosystems could diminish.

5.6 Endangered, Threatened, or Candidate Species

There are 13 Evolutionarily Significant Units (ESU) of salmonids listed as threatened or endangered under the Endangered Species Act (ESA) in the Columbia River Basin. The Columbia River Basin salmonids were first listed in the 1990s; listed salmonids and char include Chinook, chum, Coho, sockeye, steelhead, and bull trout.

ESA listed species with habitat in the Columbia River Basin include the following:

Commented [BOR22]: Consider a table to reduce length.

Amphibians

- Oregon spotted frog

Birds

- Marbled Murrelet (CH[6])
- Northern spotted owl (CH)
- Red knot
- Streaked horned lark (CH)
- Western snowy plover

[6] CH = Critical Habitat has been designated for the species.

Population = A group of individuals that are more or less alike, and that are able to breed and produce fertile offspring under natural conditions. (http://www.fws.gov/Midwest/endangered/glossary/index.html)

- Yellow-billed cuckoo

Fish

- Bull trout (CH)
- Chinook Salmon (CH; 5 populations)
- Chum salmon (CH)
- Coho salmon (CH)
- Eulachon
- Green sturgeon (CH)
- Lahnontan cutthroat trout
- Sockeye salmon (CH)
- Steelhead (CH; 5 populations)
- White sturgeon (CH)

Mammals

- Canada Lynx
- Columbian White Tailed Deer
- Gray Wolf
- Grizzly Bear
- Northern Idaho ground squirrel
- Orca
- Pygmy Rabbit
- Woodland caribou (CH)

Plants

- Applegate's Milk-vetch
- Bradshaw's desert parsley
- Golden paintbrush
- Howell's Spectacular Thelypody
- Kincaid's lupine (CH)
- Macfarlane's four-o'clock
- Nelson's checkermallow
- Showy stickseed
- Spalding's catchfly
- Umtanum Desert Buckwheat (CH)
- Ute Ladies'-tresses
- Water Howellia
- Wenatchee Mountains Checkermallow (CH)
- White bluffs bladderpod (CH)
- Willamette Daisy (CH)

Insects

- Fender's blue butterfly (CH)
- Taylor's Checkerspot (CH)

Snails

- Banbury springs limpet
- Bliss Rapids snail
- Bruneau hot springsnail
- Snake River physa snail

Reptiles

- Leatherback turtle

The impact from a changing climate on these listed species has the potential to be detrimental, as these species, and ESUs, are already at risk. The ESA requires the action agencies (Reclamation, BPA, and Corps) to ensure that their actions are not likely to jeopardize the continued existence of a listed species, and that they do not result in the destruction or adverse modification of habitat designated as critical to its conservation.

Reclamation currently operates according to several biological opinions, including opinions on the FCRPS, the Upper Snake, Deschutes, and Umatilla Rivers, and the Lewiston Orchards Irrigation District, to protect the continued existence of anadromous species (NMFS Opinions[7]) and bull trout (FWS Opinion[8]). The mainstem effects from Reclamation projects in the Deschutes, Umatilla, Okanogan, and Yakima basins, as well as diversions directly from the Columbia River, are integrated into the FCRPS biological assessment (BA) and biological opinion (BiOp). The FCRPS BiOp guides the agencies in operating the FCRPS and requires a series of mitigation measures, called Reasonable and Prudent Alternatives (RPA). The FCRPS RPAs includes an aggressive program

[7] NMFS 2008 Upper Snake Biologic Opinion, "Consultation for the Operation and Maintenance of 10 U.S. Bureau of Reclamation Projects and 2 Related Actions in the Upper Snake River above Brownlee Reservoir"; NMFS 2008/2010/2014 FCRPS Biologic Opinion, "Consultation on Remand for Operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a)(1)(A) Permit Juvenile Fish Transportation Program"; NMFS 2010, "Consultation for the Operation and Maintenance of the Lewiston Orchards Project (17060306 (Clearwater River), 17060103 (Lower Snake River - Asotin), 170601 (Lower Snake River), 170701 (Middle Columbia River) and 170800 (Lower Columbia River), Nez Perce County, Idaho (One Project)".

[8] USFWS 2000 FCRPS Biological Opinion, "Effects to Listed Species from Operation of the Federal Columbia River Power System", this opinion evaluates the effects of operating the FCRPS on threatened Columbia Basin bull trout in areas downstream of Hells Canyon Dam and in the Upper Columbia Basin, and on endangered Kootenai River white sturgeon.; USFWS 2005. Biological Opinion for Bureau of Reclamation Operations and Maintenance in the Snake River Basin above Brownlee Reservoir.; USFWS 2014 Continued operation and maintenance (O&M) of Reclamation projects in the Snake River basin above Brownlee Reservoir

of actions to improve tributary habitat and survival through system operations. Tributary habitat actions are typically geared toward improving spawning and rearing habitat, providing habitat access, and enhancing in-stream flows. Since 1992, consultations between Reclamation and NMFS under Section 7(a)(2) of the ESA have included the consideration of flow augmentation from Reclamation's Upper Snake projects to increase flows in the Lower Snake and Columbia Rivers. In the reservoirs that require minimum pools or flows, it may be more difficult to meet these augmentation objectives in some of the reservoirs in the driest conditions.

5.7 Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables, including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier, Major, Poff, & Running, 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well-understood (Lettenmaier, Major, Poff, & Running, 2008).

Increased fire potential and changes to watershed vegetation will affect water quality attributes in many watersheds, specifically stream temperatures and sedimentation. Forested watersheds reduce storm runoff, stabilize streambanks, shade surface water, cycle nutrients, and filter pollutants. Altered streamflow, stream networks (USFS, 2010), and erosion regimes, as well as higher air temperatures, will affect water quality and aquatic ecosystems.

5.8 Flow- and Water-Dependent Ecological Resiliency

The impacts to fish populations from the previously discussed climate change impacts on aquatic habitats and ecosystems, and on endangered and threatened species, will largely depend on the resiliency of the aquatic ecosystems and specific species. Schindler and Rogers (Schindler & Rogers, 2009) state that the effects of changing climate on salmon populations depend on the species and life history of interest, local expressions of climate change, characteristics of habitat, and the adaptation of specific populations to geographic variation in habitat characteristics. In addition to the potential for mortality and thermal barriers, another impact to freshwater from warming is a growth response in juveniles, although this will vary substantially with latitude (Schindler & Rogers, 2009). The effects of changes in thermal conditions on salmon populations throughout their range will likely show substantial variation both among and within climatic regions, and among species, populations, and life history strategies. Schindler and Rogers identify the protection of the life history variability, or biocomplexity, of viable habitats and stock diversity as keys to maintaining the resiliency of aquatic ecosystems in the face of a changing climate (Schindler & Rogers, 2009).

A stock characterized by a high diversity of populations and their associated dynamics is less sensitive to the variation in an individual population, compared to a stock with low diversity (Schindler & Rogers, 2009). Several studies have shown the importance of biocomplexity to the resilience of salmonids in dynamic environments (Rieman & Dunham, 2000). Evidence from this work suggests three important elements are necessary for resilience of Pacific salmon in fresh water: (1) the capacity to recover, (2) the diversity of habitats necessary to support the range of salmon life histories, and (3) habitat connectivity. Additionally, Beechie et al (2013) found that restoring floodplain connectivity, restoring stream flow regimes, and re-aggrading incised channels are most likely to ameliorate stream flow and temperature changes and increase habitat diversity and population resilience.

Reclamation's tributary habitat actions are directed toward improving salmonid spawning and rearing habitat, providing habitat access, and enhancing in-stream flows. These efforts should improve spawning and rearing habitat, including providing improved fish passage, refuge from predators, and thermal refugia, all of which could be affected by, or in some cases help reduce the impacts of, the projected changes to climate and the hydrologic regime.

6 Adaptation Strategies Considered to address Potential Impacts

The DOI's Climate Change Adaptation Policy requires Reclamation to effectively and efficiently adapt to the challenges posed by climate change using Best Available Science to increase understanding of climate change impacts, inform decision-making, and coordinate an appropriate response to impacts on land, water, wildlife, cultural and tribal resources, and other assets. Reclamation's Climate Change Adaptation Strategy identifies increasing flexibility in reservoir operations to respond to climate change as a core strategy goal to increase water management flexibility.

6.1 Reservoir Operations and Modifications

Reclamation's Policy and Administration Office has convened a Reclamation-wide team of regional reservoir operations experts, planners, climate scientists, and hydrologists to develop a process for evaluating reservoir-operating criteria to determine whether adjustments are needed in response to climate change. Increased water management flexibility is identified as a core strategy in the Bureau of Reclamation's Climate Change Adaptation Strategy. As climate change alters the hydrologic regime, reservoir operations may need to be adjusted in order to maintain reliable water deliveries, power generation, support for environmental needs and flood control management. Some general operational changes that may provide resiliency to projects in the Pacific Northwest Region,

including modifications to the refill schedules, flood-control rule curves, flood operating criteria, and changes to acceptable flood risk. The Pacific Northwest Region of Reclamation will initiate a pilot operations study examining a river basin in 2016-2018 as part of this effort.

The State of Idaho is also addressing the need to adapt to potential water shortages in the Upper Snake River basin by conducting an ongoing investigation on the potential for a pool raise at Island Park Reservoir. The Henrys Fork Basin Study recommended a pool raise, among other alternatives, to increase water-delivery reliability with a changing climate. This modification received the most favorable stakeholder response, environmental impacts were low or beneficial, and it required the lowest cost for water. Upon completion of the Henrys Fork Basin Study, the Idaho Water Resource Board secured state funding to advance the study on the pool raise at Island Park Reservoir.

6.2 Hydropower Modernization

As discussed in Section 5, the impacts of climate change on hydropower will reduce hydropower generation capacity in the region during summer months. Although not identified specifically as a reaction to climate change, the Pacific Northwest Region is undergoing modernization efforts on aging infrastructure to provide increased reliability and efficiency that may provide resilience to some impacts from climate change.

As the largest hydroelectric facility in the U.S., the 6,809-MW Grand Coulee Project on the Columbia River is integral to power generation in the Pacific Northwest. Rehabilitation and potential uprating of generating units at Grand Coulee will ensure continued reliable operation of this valuable asset and provide an additional 510 MW in generating capacity.

The turbines at Palisades Dam and Reservoir, on the Upper Snake River, have been in service since 1957 and have experienced a 1.6 percent decrease in efficiency. Due to the winter minimum flow requirements and the rough-zone characteristics of the original turbines, two units are required to operate at low efficiency from October through March, which decreases power generation. The new turbines will have a 4.5 to 6.0 percent efficiency improvement and a 30 percent efficiency improvement during winter operations, which translates to approximately 44 gigawatt hours per year (GWh/year) in additional generation. After all work is completed, the four hydroelectric generating units will operate with optimized efficiencies and increased generation capacity, and will have a life expectancy of at least 50 years.

Similarly, at Hungry Horse Dam on the Flathead River in Montana, modernization efforts will improve the reliability and efficiency for power generation. The entire powertrain of the four generating units will be replaced and/or overhauled during the 10-year modernization program. The capstone

project of the modernization effort is the replacement of the turbines with a new design that improves efficiency and reduces cavitation. Because of this effort, there will be improved reliability and less need for maintenance.

On the Payette River, a tributary of the Snake River, Reclamation is planning the construction of a third hydroelectric generating unit at Black Canyon Diversion Dam. The proposed 12.5 MW hydroelectric unit will expand the capacity of the two existing 5 MW units to generate 105 million kilowatt-hours (kWh) – enough to power 9,359 homes a year. The additional generating unit will take advantage of water that is currently being bypassed and turn it into hydroelectric power.

6.3 Aquatic Ecosystem Restoration

In addition to these modernization efforts, the Pacific Northwest Region is a leader in aquatic ecosystem restoration, specifically targeting critical habitat improvements for anadromous salmon and steelhead, which have benefits to resident species as well. The Federal Columbia River Power System (FCRPS) Biological Opinion guides the agencies in a series of mitigation measures, called Reasonable and Prudent Alternatives (RPA). The FCRPS RPAs include an aggressive program of actions to improve tributary habitat limiting factors and attain targets for improving population survival. Tributary habitat actions are typically geared toward improving spawning and rearing habitat, providing habitat access, and enhancing in-stream flows. These rehabilitation efforts should improve spawning and rearing habitat, including providing increased fish passage, refuge from predators, and thermal refugia, all of which could be affected by, or in some cases, help reduce the impacts of, the projected changes to climate and the hydrologic regime.

Two examples of ongoing habitat rehabilitation efforts can be seen in the Methow Basin in Washington and the Salmon River drainage in Idaho. Reclamation removes barriers like diversion structures, installs large wood material, and restores channels to a more natural and complex state. All habitat restoration projects require a high level of coordination and collaboration during the planning, construction, and post-construction monitoring among all the stakeholders, including landowners, local government entities, Federal agencies, interested parties, and environmental groups. On the Methow River, Reclamation worked with partners to reconnect a side channel and provide cover to provide salmon and steelhead thermal refuge and rearing habitat.

The Lewiston Orchards Project in Idaho is an existing system that diverts water from streams on the Nez Perce Indian Reservation that are occupied by ESA-listed steelhead. Warming climate trends have shifted the water supply from a snowpack-driven system to a system dependent primarily on rainfall. Earlier runoff, lower stream base flows in winter, and warmer stream temperatures are expected in the future. Minimum stream flows established in a Biological Opinion for the Lewiston Orchards Project to limit the take of the steelhead and

avoid impacts to critical habitat are expected to mitigate for impacts due to climate change. The Appraisal Investigation of the Lewiston Clearwater Exchange Project is a Rural Water Supply Program study of options for removing the Lewiston Orchards Project from the watershed and developing alternative water supplies, namely groundwater, while maintaining minimum stream flows necessary for the Nez Perce Tribe to manage steelhead recovery efforts.

7 Coordination Activities

Since 2010, Reclamation has led multiple efforts to address climate change impacts in the Columbia River Basin. These include studies and coordination discussed below.

Operations of the Federal Columbia River Power System are reviewed by the River Management Joint Operating Committee (RMJOC). The RMJOC comprises representatives from BPA, Corps, and Reclamation and functions as a forum for the coordination of FCRPS dam operations and other river management activities within the Columbia River Basin. With respect to addressing climate change impacts in the Columbia River Basin, Reclamation is working with the RMJOC on the continued development of up-to-date climate change projections in support of long-range planning activities performed by Federal agencies, States, tribes, local governments, and nonprofits. The information from the RMJOC1 study (Brekke, Kuepper, & Vaddey, 2011) was used in the three completed Basin Studies in the Pacific Northwest Region to assist local entities to address water imbalances and the potential impacts from climate change.

Reclamation is an active member of the Columbia River Technical Management Team (TMT). The TMT is an interagency group responsible for making in-season recommendations on dam and reservoir operations to optimize passage conditions for juvenile and adult anadromous fish. In addition to Reclamation, the TMT comprises representatives from BPA, the Corps, NOAA Fisheries, FWS, and various other State and Tribal entities. The TMT was established to implement RPAs under the NOAA Fisheries FCRPS BiOp for anadromous salmonids, starting with the 1995 BiOp. The FCRPS is currently operating under the 2014 NOAA Fisheries FCRPS BiOp.

The basin studies and the Columbia River Basin Impacts Assessment, mentioned in Section 1, are good examples of past and ongoing efforts that involve multiple stakeholder groups. One of the purposes of the basin studies is to enable stakeholders to look at potential mitigation actions by providing relevant climate and hydrologic analysis.

For example, the Henrys Fork Basin Study identified alternative actions to help mitigate for a changing climate, including a pool raise at Island Park Reservoir (see Section 6.1). While the Idaho Water Resource Board will lead this effort to

complete the pool raise, Reclamation will continue coordination, as Island Park is a Reclamation facility.

The Hood River is another location where minimum flows may become more frequent and cause additional stresses to aquatic ecosystems. The Reclamation basin study of the Hood River found that shortages to the established minimum flow requirements are projected to increase under the simulated climate change conditions. These shortages are most severe in the summer months and are a direct impact of changes in the basin's hydrologic regime, where spring runoff is projected to peak earlier in the season. Reclamation has made basin study results and water recourse models available to study partners to assist better-informed decision-making.

Another example of coordination is occurring in the Yakima River Basin. The State of Washington identified strategies to cope with current and future stresses on water resources (Adelsman & Ekrem, 2012). Some of these strategies were directly related to the Reclamation Yakima River Basin Study, which identified that snowpack, the "sixth reservoir", is in jeopardy due to current and projected temperature increases and changes in precipitation timing and form. In 2009, Washington Department of Ecology and Reclamation brought representatives from the Yakama Nation, irrigation districts, environmental organizations, other Federal, state, and local stakeholders to develop a consensus-based solution to the current and future water issues. The group agreed upon a proposed approach to improving water management, an Integrated Water Resources Management plan. The Yakima River Basin Study further investigated strategies identified in the Yakima Integrated Water Resources Management Plan. With partners, Reclamation is evaluating project to better manage water in the basin and provide proper flows for endangered species during the necessary life stage.

Reclamation has also been working collaboratively with a diverse group of stakeholders to initiate the Upper Deschutes River Basin Study in central Oregon. Reclamation and its non-Federal cost-share study partners finalized a Plan of Study in May 2015, and a comprehensive analysis of water supply and demand that addresses the impacts of climate change is now underway. The study will use integrated surface water and groundwater models to apply climate change projections to future in-stream and out-of-stream water demands. Outcomes will include a tradeoff analysis of options identified to address agricultural, environmental, and municipal water supply interests.

Reclamation is generating reconnaissance-level hydrologic data and analysis on the potential effects of climate change in the Columbia River Basin and how those effects relate to water supply and demand in the Columbia River Basin Climate Impact Assessment (CRBIA). Results from the CRBIA will provide important information to the water management community in the Columbia River Basin on the scale of the challenges that climate change is likely to pose in this basin. The CRBIA will establish a foundation for stakeholders to develop more in-depth

analyses and adaptation strategies through Basin Studies; operations planning; feasibility level analyses; or any other activity that can benefit from the results.

Reclamation also coordinates with and provides technical review and information to the Columbia Basin Development League. The Columbia Basin Development League is a 501(C)(6) nonprofit organization incorporated in 1964 with the mission to provide support for the Columbia Basin Irrigation Project and its future development, protect its water rights, and educate the public on renewable resource and multi-purpose benefits of the project. Reclamation is a member of the Columbia River Water Resources Program Policy Advisory Group, formed in 2006 to provide a forum for communication among stakeholders and the State of Washington's Department of Ecology with respect to key water-resource management issues in the Columbia River Basin. Reclamation and the Columbia River Water Resources Program Policy Advisory Group work with the State of Washington to identify policy issues associated with implementing water-resource management programs for the Columbia River and assist in setting criteria for funding of storage and conservation projects.

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