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

Part I - Future Climate and Hydrology Datasets

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office
Boise, Idaho
Technical Service Center
Denver, Colorado

U.S. Army Corps of Engineers
Northwest Division
Portland District
Portland, Oregon

Bonneville Power Administration
Portland, Oregon

December 2010

Photographs on front cover from left to right: American Falls Dam on the Snake River, Idaho, operated by the Bureau of Reclamation; The Dalles Dam on the Columbia River, Oregon, operated by the Corps of Engineer; and Bonneville Lock and Dam on the Columbia River, Oregon, operated by the Bonneville Power Administration.

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

Part I - Future Climate and Hydrology Datasets

Authors:

Levi Brekke, Bureau of Reclamation

Brian Kuepper, Bonneville Power Administration

Seshagirir Vaddey, U.S. Army Corps of Engineers

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office
Boise, Idaho
Technical Service Center
Denver, Colorado

U.S. Army Corps of Engineers
Northwest Division
Portland District
Portland, Oregon

Bonneville Power Administration
Portland, Oregon

December 2010

RMJOC Sponsors:

- Patrick McGrane, Bureau of Reclamation, Pacific Northwest Region
- Rick Pendergrass, Bonneville Power Administration
- Jim Barton, U.S. Army Corps of Engineers, Northwestern Division

Authors:

- Levi Brekke, Bureau of Reclamation, Technical Service Center
- Brian Kuepper, Bonneville Power Administration
- Seshagirir Vaddey, U.S. Army Corps of Engineers, Portland District

RMJOC Agencies' Comments and Contributions from:

- Bureau of Reclamation, Pacific Northwest region: Patrick McGrane, Toni Turner, Chris Lynch, Ted Day, and Lori Postlethwait
- Bureau of Reclamation, Technical Service Center: Tom Pruitt and Nancy Parker
- Bonneville Power Administration: Rick Pendergrass, Nancy Stephan, Bruce Glabau, and Daniel Hua
- U.S. Army Corps of Engineers: Jim Barton, Peter Brooks, Malar Annamalai, Keith Duffy, Joel Fenolio, Patricia Low, Kristian Mickelson, John McCoskery, William Proctor, and Randal Wortman

Additional Comments and Contributions from:

- Northwest Power and Conservation Council
- Columbia River Inter Tribal Fish Commission
- BC-Hydro
- U.S. Fish & Wildlife Service
- NOAA Fisheries Service
- University of Washington Climate Impacts Group
- Oregon Climate Change Research Institute

Acknowledgments:

- University of Washington Climate Impacts Group (Alan Hamlet and Marketa M. Elsner) for providing climate and hydrologic information used in this effort, and for providing guidance on interpretation of this information and how may be used to support longer-term planning by RMJOC agencies.
- NRCS National Water and Climate Center (David Garen), National Weather Service Northwest River Forecast Center (Don Laurine), and National Weather Service Colorado Basin River Forecast Center (Kevin Werner) for providing assistance and guidance in the development of the water supply forecasting methodology under climate changed hydrologic conditions. This methodology was also developed through support from Reclamation's Research and Development Office and Reclamation's five regional offices.

Abbreviations and Acronyms

A1B	Medium emissions scenario
AMS	American Meteorological Society
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
B1	Low emissions scenario
BC	Bias-corrected
BCSD	Bias-Correction Spatial Disaggregation
BPA	Bonneville Power Administration
C	Central change scenario
C°	degrees Celsius
CDFs	Cumulative distribution functions
cfs	cubic feet per second
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
Council	Northwest Power and Conservation Council
CRITFC	Columbia River Inter-Tribal Fish Commission
CSRB	Columbia-Snake River Basin
DCP	downscaled climate projections
ET	Evapotranspiration
F°	degrees Fahrenheit
GCM	General Circulation Model
GHG	greenhouse gas
HB 2860	Washington State House Bill No. 2860
HD	Hybrid-Delta
hydro	hydropower
IPCC	Intergovernmental Panel on Climate Change
LW/D	Less warming and drier
LW/W	Less warming and wetter
MC	Minimal change

MW/D	More warming and drier
MW/W	More warming and wetter
NOAA Fisheries Service	National Oceanic and Atmospheric Administration, Fisheries Service
NRCS NWCC	Natural Resources Conservation Service, National Water and Climate Center
Obs	Observed weather
OBS	Observed hydrology
P	Precipitation
PCR	Component regression procedure
Prcp	Precipitation
RMJOC	Reservoir Management Joint Operating Committee
RMSE	Root-mean-squared-error
SAP	U.S. Climate Change Science Program Synthesis and Assessment Product
SRES	IPCC Special Report on Emissions Scenarios
SWE	Snow water equivalent
SWP	State Water Project
T	Temperature
TAF	Thousand acre-feet
T_{max}	Maximum temperature (typically used to refer to daily maximum temperature)
T_{min}	Minimum temperature (typically used to refer to daily minimum temperature)
USACE	U.S. Army Corps of Engineers
UW CIG	University of Washington Climate Impacts Group
VIC	Variable Infiltration Capacity model
WACCIA	Washington Climate Change Impacts Assessment
WCRP	World Climate Research Programme
ΔP	Mean-annual precipitation
ΔT	Mean-annual temperature

Table of Contents

List of Figures

List of Tables

Executive Summary

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (USACE), and Bureau of Reclamation (Reclamation) collaborated to adopt climate change and hydrology datasets for their longer-term planning activities in the Columbia-Snake River Basin (CSRB). This was coordinated through the River Management Joint Operating Committee (RMJOC), a sub-committee of the Joint Operating Committee which was established through direct funding Memorandum of Agreements between BPA, Reclamation, and the USACE. The RMJOC is specifically dedicated to reviewing the practices, procedures, and processes of each agency to identify changes that could improve the overall efficiency of the operation and management of the Federal Columbia River Power System projects.

In addition to creating these datasets, the RMJOC agencies worked together to adopt a set of methods for incorporating these data into those longer-term planning activities. Several goals framed this effort:

1. Arrive at consensus agreement on which available climate projection information should provide a range of future climate and hydrologic scenarios for use in RMJOC agencies' long-term planning, where the approach is flexible and can accommodate updates in climate projection information.

2. Demonstrate capability in using selected future climate and hydrology scenarios in the context of reservoir systems analyses typically conducted by RMJOC agencies.

3. Promote efficient use of each agency's limited resources in satisfying the first two objectives, avoiding redundancy where possible.

4. Collaborate with other stakeholders in the region to gain their support for this analysis and data.

Throughout this process, RMJOC agencies gathered input from several stakeholder groups, including BC-Hydro, Columbia River Inter-Tribal Fish Commission, NOAA Fisheries Service, Northwest Power and Conservation Council, Oregon Climate Change Research Institute, U.S. Fish and Wildlife Service, and the University of Washington Climate Impacts Group.

This report is the first of four documents to be produced in this effort titled *Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies*:

- Part I Report - Future Climate and Hydrology Datasets (this document)
- Part II Report - Reservoir Operations Assessment – Reclamation Tributary Basins (being issued Dec 2010)
- Part III Report - Reservoir Operations Assessment – Columbia Basin Flood Control and Hydropower (expected Spring 2011).
- Summary Report (expected Spring 2011)

Briefly stated, this report provides a detailed description of future climate and hydrology datasets that are meant to serve upcoming longer-term planning assessments conducted by RMJOC agencies. Part II and Part III reports are meant to complement this report by presenting demonstration operations analyses featuring the use of these future climate and hydrology datasets. The Summary Report will offer a non-technical description of key themes from the three technical reports along with discussions on lessons learned and potential next steps in this collaboration. On the assessments to be described in Part II and Part III reports, future climate change impacts on operations might be interpreted from study results; however, these results are not meant to be construed as findings on future operational vulnerability, which depends on stresses other than climate. Likewise, this effort was not scoped to consider potential alternative future operations strategies that might offset such impacts.

The remainder of this executive summary offers chapter capsules describing the contents of this report.

Introduction

This chapter summarizes motivations and key scoping considerations that framed this effort. One key scoping decision was to focus this effort on how future climate change could impact hydrology and water supplies, and how to represent such "supply-related" impacts in operations assessment. Potential adjustment to other types of operational assessment assumptions (e.g., water demands or operating constraints) was left to be the subject of follow-on collaboration, potentially taking advantage of ongoing research to develop methods for guiding such assumption adjustments. Another key scoping decision was to leverage future climate and hydrology information characterized over the Pacific Northwest by the University of Washington Climate Impacts Group (UW CIG) in response to Washington State House Bill 2860 (HB2860).

Literature review

This chapter provides a synthesis of peer-reviewed literature describing observed changes in climate and hydrology over the Pacific Northwest, projected changes in climate and hydrology, and associated impacts on water and environmental resources. This chapter also includes graphical descriptions of observed climate changes over the Columbia-Snake River Basin, as well as a summary of projected climate conditions over the region. For this depiction of projected climate conditions, the HB2860 information source was not used; rather, an alternative source was used that contained a larger set of downscaled climate projections over the Pacific Northwest, which is attractive for characterizing future projection uncertainty in this chapter. However, for other purposes of this effort, it has less desirable attributes compared to the HB2860 information (Chapter 3).

Selecting Future Climate Information

This chapter initially describes available sources of climate projection information spatially downscaled over the Pacific Northwest. The HB2860 information was used, given that (1) it featured the most spatially refined future climate information over the Columbia-Snake River Basin while representing an ample number of contemporary climate projections and, more significantly, and (2) it contained simulated Columbia-Snake River Basin hydrology under these downscaled climate projections. This latter aspect permitted the RMJOC effort to avoid considerable time and expense conducting the watershed hydrologic simulations required to develop such information.

After identifying the HB2860 information set as the candidate source of future climate scenarios, the chapter goes onto explain rationale for focusing on two types of HB2860 information:

- Hybrid-Delta (HD) Climate Change scenarios reflecting a step-change in climate from an historical period to a future period which is useful for studies on system operational sensitivity to a shift in climate

- Transient Climate scenarios that reflect time-developing climate conditions continuously through historical and future periods (i.e., climate projections) which are useful for studies where the onset of impacts matter (e.g., adaptation planning where there is interest in scheduling risk management interventions through time)

Three overarching goals framed the process of selecting HB2860 future climate scenarios for use in this effort:

1. Select a small set of scenarios for RMJOC purposes out of interest to keep the scenario set manageable in terms of both analysis and communication
2. Select scenarios to reflect the central estimates of future climate during the early and middle 21st Centuries
3. Select a set of scenarios to "bracket" a range of temperature and precipitation changes for both of these look-aheads

Stemming from these goals, selection consideration first focused on choosing HD Climate Change scenarios defined for two future periods, 2010-2039 and 2030-2059, labeled as the 2020s and 2040s scenarios, respectively. After selecting HD Climate Change scenarios, the underlying climate projections would be identified and accepted as the projections underlying Transient Climate scenarios.

Selection of HD Climate Change scenarios from the HB2860 information required subjective definition of "central estimate" of future climate change over the study area and uncertainty about this central estimate. This was done by defining climate change metrics, climate change location, and change-range of interest. Perspectives on these factors were gathered from RMJOC agencies and interested stakeholders. Collectively, these perspectives led to an approach where HD Climate Change scenarios were selected based on how they expressed joint changes in mean-annual temperature and precipitation, averaged over the entire Columbia-Snake River Basin, and with a goal that scenarios collectively bracket a span from the 10th to 90th percentile changes among HB2860 information. This approach was applied independently for candidate 2020s and 2040s HD Climate Change scenarios, leading to five qualitative scenarios selected for each period:

- central (C),
- more warming and wetter (MW/W)
- less warming and wetter (LW/W)
- more warming and drier (MW/D)
- Less warming and drier (LW/D).

Lastly, a sixth scenario was included in the set to reflect “minimal change” (MC), roughly targeting less warming and central precipitation change. These 12 HD Climate Change scenarios (six per period) were built from a collective of nine underlying climate projections, six of which were analyzed in the HB2860 effort for hydrologic conditions. Consequently, six HB2860 Transient Climate and Hydrology scenarios were selected for the RMJOC effort.

Finally, this chapter summarizes climate characteristics of selected HD Climate Change scenarios and Transient Climate scenarios. For HD Climate Change scenarios, emphasis is placed on the geographic and month-to-month complexity of change embedded within each scenario. For Transient Climate scenarios, emphasis is placed on how the ensemble of these scenarios tells a collective story though time.

Hydrologic Simulations Using Future Climate Scenarios

This chapter briefly describes the watershed hydrologic model used to characterize simulated future hydrology under each RMJOC future climate scenario. Discussion initially focuses on how daily weather sequences had to be generated to be compatible with both the daily time-step hydrology model and also the monthly climate characteristics of a given HD Climate Change scenario or Transient Climate scenario. The chapter then switches focus to how simulated runoff results and how the hydrology model tends to simulate biased runoff conditions at locations of interest, even after being developed to reproduce historical monthly runoff from various Columbia-Snake River subbasins. Noting this tendency to simulate biased runoff, the chapter explains a bias-correction procedure used to adjust simulated runoff time series so that they are statistically consistent with observed historical runoff at a given location (in a distributional sense, but not a sequencing sense).

After explaining runoff dataset development, the chapter describes runoff characteristics under future climate at key locations in the Columbia-Snake River Basin. Discussion focuses first on locations within the three Reclamation tributary basins featured in subsequent operations assessments (Report Part II): the Yakima River subbasin above its confluence with the Columbia River, the Deschutes River subbasin above Lake Billy Chinook, and the Snake River subbasin above Brownlee. Discussion then focuses a menu of locations within the remainder of the Columbia River Basin, located at major hydropower projects within the following subbasins: Upper Columbia River, Kootenay River, Pend Oreille River, Spokane River, Mid-Columbia River, Lower Snake River, and Lower Columbia River.

Review of runoff under RMJOC future climate scenarios reveals some several broad themes:

- Annual Runoff under HD Climate Change scenarios: For a subbasin of interest, the trend in historical to future mean-annual runoff generally follows the trend in mean annual precipitation. Such precipitation trends varied geographically within a given HD Climate Change scenario (Chapter 3). For example, considering the upper Snake River subbasin above Brownlee, four of the six HD Climate Change scenarios for both 2020s and 2040s featured "wetter than historical" conditions. Two of these four "wetter" scenarios varied in range from a "no change" condition to "slightly wetter" when viewed over the entire Columbia-Snake River Basin. A similar situation occurred over the upper Columbia River, where four of the six HD Climate Change scenarios were generally wetter in that part of the region. This led to increasing mean-annual runoff trends in four of the six HD Climate Change scenarios for both future periods in these four subbasins in particular and to a lesser degree, a wetter overall Columbia-Snake River Basin. For other subbasins, the distribution of mean-annual runoff changes tracked more closely with the basin-wide view (e.g., Yakima River subbasin, Deschutes River subbasin).

- Monthly Runoff under HD Climate Change scenarios: For most locations assessed, it was found that future monthly runoff patterns differ from historical, featuring reduced runoff during late spring to summer, and increased runoff during winter to early spring. This result appears to stem primarily from warming, which leads to increased winter rainfall as opposed to snowfall, increased winter rainfall-runoff rather than snowpack accumulation, and subsequently reduced snowmelt runoff volume. The degree to which this phenomenon occurs varies by location and varies with future climate period. More significant changes in runoff seasonality occur by the 2040s.

- Annual Runoff under Transient Climate scenarios: Viewing these runoff results through time suggests that for most subbasins any trend in annual runoff appears to be subtle relative to the envelope of potential annual variability through time. Focusing on the evolution of variability, it appears that the transient runoff envelopes at most locations are generally stable from the 20th Century through the 21st Century, suggesting that any changes in annual variability would likewise be subtle. After smoothing the runoff results to show moving 10-year and 30-year mean annual conditions, results more clearly reveal decadal to multi-decadal variability within the climate projections. The presence of such "low frequency" variability (e.g., decadal to multi-decadal variability) affects interpretation of the HD Climate Change scenarios and raises a question whether the latter scenarios reflect only climate change (as they have been sampled from climate projections having low-frequency variations) or some mix of climate change and low-frequency variability. Review of the results suggests that the latter may be a more accurate reflection.

Water Supply Forecasting under Hybrid-Delta Climates

The last subject addressed in this report is water supply forecasting under future climate. Interest in this subject stems from how traditional seasonal water supply forecasting is partially informed by snowpack monitoring, and that warming is expected to diminish snowpack and eventually diminish its prediction value within forecast models used to predict spring-summer runoff volumes. This was relevant when scoping the demonstration operations analyses featured in Parts II and III of this effort, where assumptions on system hydrology and water supplies were adjusted to reflect future climate. Such focus also meant considering the adjustment of operations assessment assumptions about water supply forecasts. To understand how climate change might impact water supply forecasting, and how such impacts could affect operations portrayal, the operations assessments of Part II and III were scoped to feature both *perfect* and *imperfect* water supply forecasting. This comparison was to be conducted in the context of HD Climate Change scenarios only to gage the significance of adjusting forecast assumptions for climate change.

This chapter describes the development of the *imperfect* water supply forecast time series consistent with each HD Climate Change scenario. The procedure used to develop forecast time series is generally consistent with real-world statistical forecast procedures used by various operational forecast providers within the Columbia-Snake River Basin. For each scenario, a menu of forecast situations was targeted, with each situation defined by location (e.g., Yakima River at Parker), forecast period (e.g., April through July runoff volume) and time of forecast issue (e.g., January). For each situation, a forecast model was developed within the hydrology and climate context of datasets selected from the HB2860 information set (i.e. historical, six HD 2020s Climate Change scenarios and six HD 2040s Climate Change scenarios). Each forecast model was similar to real-world forecast models in that it was informed by seasonal precipitation (October-to-date) and current snowpack (near time of issue) within the subbasin above the location of interest. Resultant forecast models were then applied to develop the imperfect water supply forecast series informing subsequent operations assessments.

Two key impressions were drawn from the resultant forecast models and series:

- The models developed under historical hydroclimate generally featured good skill, although they were generally less skillful than the models that inform real-world operations as developed by various forecast providers in the basin. This result stems from how model development in this effort was performed within the simulated hydroclimate context of a given HB2860 climate and hydrology dataset, and that the scheme for predictor types and locations was slightly limited relative to schemes considered in real-world forecast model development. With these limitations noted, the resultant models were judged to feature sufficient quality under historical climate for the purposes of operations assessments in Parts II and III of this effort.

- On the subject of forecast impact from historical to future climate, results broadly suggested that forecast skill should diminish for most locations as warming causes snowpack to diminish. For the look-aheads considered here (2020s and 2040s), skill decreases seem primarily confined to early and late issues (e.g., January and February issues of spring-summer runoff or June and July issues of remainder-of-summer runoff). Skill reductions varied by location, with some basins experiencing very little reduction (e.g., Columbia River at Keenleyside Dam, Columbia River at Mica Dam, and Snake River near Heise all showing less than 10 percent skill reduction for early and late issues) and others experiencing more significant reduction (e.g., Deschutes River above Cresent Lake, North Fork Clearwater at Dworshak Dam, and Yakima River at Parker all showing skill reductions exceeding 20 percent for early and late issues under some 2040s climate change scenarios). It is noted that any conclusions drawn from this result are limited given that this study did not exhaustively explore alternative predictors that might be used in the future to replace the predictive value currently offered by snowpack monitoring (or exploration of new snowpack monitoring sites at higher elevations). Nevertheless, like the historical forecast series listed above, the future forecast series were viewed to be reasonable depictions of potentially impacted water supply forecasting under future hydrology and climate conditions, and suitable for use in the operations assessments that followed.

1.0 INTRODUCTION

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (USACE), and Bureau of Reclamation (Reclamation) through their River Management Joint Operating Committee (RMJOC) collaborated to adopt a range of climate change and hydrology datasets and demonstrate how these data may be applied to support their longer-term planning activities in the Columbia-Snake River Basin (CSRB). This collaboration also included engagement with stakeholder agencies, including U.S. Fish and Wildlife Service (USFWS), NOAA Fisheries Service, Northwest Power and Conservation Council (Council), BC-Hydro, and Columbia River Inter-Tribal Fish Commission (CRITFC), to incorporate their perspectives during the scoping and application of methods featured in this effort. In this latter demonstration, the agencies also collaborated to develop a shared understanding on an appropriate set of methods for incorporating these data into such longer-term planning activities. The purpose of adopting such data and methods is to promote consistent incorporation of regional climate projection information in the agencies' planning efforts, and to promote efficient development of these data and methods by pooling agency resources.

This report serves as the first of four documents that will be produced in this effort titled *Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies*:

- Part I Report – Future Climate and Hydrology Datasets (this document)
- Part II Report – Reservoir Operations Assessment – Reclamation Tributary Basins (to be issued in December 2010)
- Part III Report – Reservoir Operations Assessment – Columbia Basin Flood Control and Hydropower (expected Spring 2011)
- Summary Report (expected Spring 2011)

This Part I Report focuses on RMJOC adoption of future climate and hydrology data from University of Washington's Climate Impacts Group (UW CIG), evaluation of those data, and development of associated water supply forecast series to reflect future hydrologic and climate conditions. The remainder of this introduction describes process motivation, key considerations, deliverables, and report organization.

1.1 Motivation

RMJOC agencies recognize the need to move toward incorporating climate projection information into their longer-term planning. Each agency regularly evaluates management or regional proposals that involve operational and/or infrastructure actions that would apply during some future period. Studying the benefits and effects of these proposals requires making future assumptions about possible water supplies, demands and operational constraints that would affect system operations under these proposals. As illustrated in Figure 1 (adapted from U.S. Geological Survey Circular 1331 [Brekke et al. 2009]), each of these assumptions has an assumed climate context. Traditionally this climate context has been provided by data from historical records. Proposals of interest are those that have planning periods distant enough in the future to be relevant on a "climate change time scale" (i.e., "longer-term" proposals having look-aheads of multiple decades and longer ([PCC 2007]).

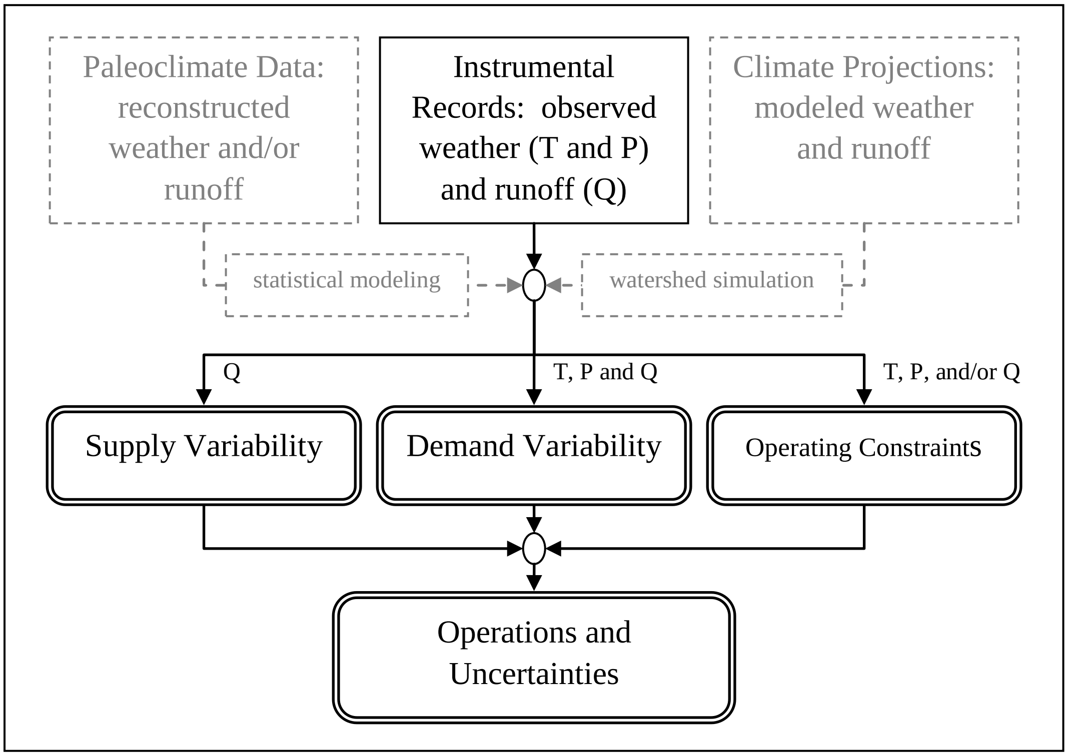

Figure 1. Climate-related assumptions in longer-term operations planning.

Several upcoming studies or planning processes involving RMJOC agencies might be classified as having "climate change relevant" planning periods. Notable studies include the Columbia River Treaty 2014/2024 Review, biological opinions on operational changes and actions within the Federal Columbia River Power System, BPA's capital investment scheduling and budgeting process, and Reclamation's suite of potential storage studies in the Boise, Yakima, Umatilla, and Columbia River basins. Given the prospective need for incorporating climate change information into such longer-term evaluations, the RMJOC agencies recognize that each agency would benefit from the use of a common Pacific Northwest climate change hydrologic dataset, and from collaboration on development of data and usage methods.

This recognition motivated several collaboration goals featured in this effort:

1. Arrive at consensus agreement on which available climate projection information should provide future climate and hydrologic scenarios for use in RMJOC agencies' long-term planning, where the approach is flexible and can accommodate updates in climate projection information.

2. Demonstrate capability in utilizing selected future climate and hydrology scenarios in the context of reservoir systems analyses typically conducted by RMJOC agencies.

3. Promote efficient use of each agency’s limited resources in satisfying the first two objectives, avoiding redundancy where possible.

4. Collaborate with other stakeholders in the region to gain their support for this analysis and data.

The process of incorporating climate projection information into a longer-term planning assessment leads to several method questions, each of which have been addressed in this collaborative effort.

1. (Figure 2, step 2.a) Should all available climate projections be regarded as suitable for planning purposes, or should only a portion of available projections be regarded as credible enough for planning while the others are discarded, or culled, from consideration? If yes on the latter, what rationale supports culling of projections?

2. (Figure 2, step 2.b) For the retained projections, should they be used to describe step-changes in climate based on their portrayal of historical period to future period conditions? Or should the time-developing nature of the projections be used for planning?

3. (Figure 2, step 3) Given the choice on how the retained information will be used, what steps follow on assessing natural and/or social systems responses that ultimately translate into planning assumptions for supplies, demands, and constraints?

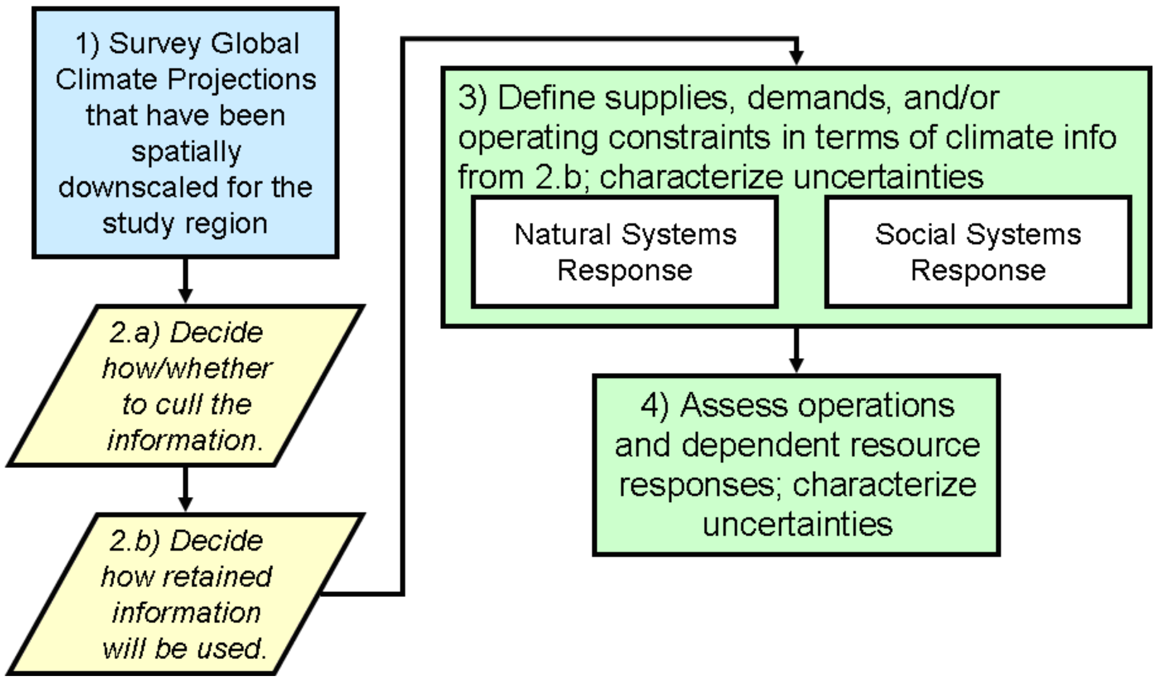

Figure 2. Framework for relating climate projection information to longer-term operations planning.

This Part I report explains how questions 1 and 2 were addressed (Section 3.0). On question 3, the following section explains several scoping considerations that led to a focus of assessing natural hydrologic response to certain selected future climate conditions and relating those hydrologic responses to supply-related assumptions in subsequent operations analyses.

1.2 Key Scoping Considerations

As stated, the primary goal of this effort was to develop (or adopt) an appropriate climate and hydrology dataset and set of usage methods for use in longer-term planning by RMJOC agencies and other stakeholders. Several scoping considerations framed this work effort.

1.2.1 Focus on Climate Change Implications for Hydrology and Water Supplies

Rather than consider adjusting all climate-relevant assumptions in long-range operations analyses for future climate conditions (Figure 2, supplies, demands, and operating constraints referenced in Step 3), it was decided to instead focus only on supply-related assumptions for which there were methods that are relatively better established through development and application in prior assessments. Methods to adjust assumptions related to water demands and operating constraints would ideally consider both socioeconomic and natural (climate) drivers. As a result, the assessment on how climate change may affect natural hydrology leads to a basis for adjusting hydrology-related inputs in RMJOC's operations analyses (i.e., reservoir inflows and seasonal water supply forecasts).

On the matter of adjusting demand-related assumptions, consideration was given toward adopting a simplified method to assess water demand response to changes in climate alone. However, it was eventually judged that it would be better to address these assumptions pending the outcomes of ongoing research (e.g., Washington State Department of Ecology's current effort with Washington State University). For example, consider climate change impacts on irrigation demands. It is clear that crop consumptive use models could be used to relate temperature and precipitation changes to changes in crop water needs. However, changes in atmospheric greenhouse gases (GHG) might also affect physical crop water requirements; how to assess such effects is less clear. It is also clear that while permissible growing season length would increase under warmer conditions, the necessary growing season for a given crop might in fact decrease if warming leads to crop biophysical responses that translate into a more rapid rate of maturation. Additionally, the operations analyses conducted by RMJOC agencies view water demands at the district-management level, within which there are the characteristics of crop-type distribution and irrigation technology. Future assumptions about these characteristics reflect not only climate, but also socioeconomics. Given these ambiguities, water demand responses to future climate change were not evaluated in this effort.[1] Potential changes to water demand assumptions might be explored in a subsequent effort. RMJOC agencies would be interested in scoping such an effort with potentially interested stakeholders.

Lastly, consideration was given toward multiple sets of management criteria that might be featured in the operations assessments (Part II through Part IV reports), meaning that current as well as potential alternative management strategies might be assessed in the context of future climate and hydrology conditions. In this case, it was judged that future studies would be required to formulate alternative management strategies and that this RMJOC effort will illustrate reservoir system performance under future climate and hydrology and current management criteria.

1.2.2 Focus on UW CIG Data Source

Another key scoping consideration was deciding which source of climate projection information would serve as the basis for future climate and hydrology scenarios featured in this effort. Based on several factors that will be highlighted in Section 3.0, the following scoping decisions were made:

[1] Note that although climate-driven variations in plant water needs and/or socioeconomic controls on district demand are not considered, some supply-related variations in demand are considered in the analysis. The supply-governed variations are embedded in the operations models introduced in the Part II report.

- Leverage future climate information developed through UW CIG's HB2860 effort, which includes bias correction and spatial downscaling (BCSD) of a large collection (or ensemble) of monthly global climate projections over the Pacific Northwest region.[2]

- Use two derived future climate scenario types issued in UW CIG's HB2860 effort, namely Hybrid-Delta (HD) Climate Change scenarios sampled from monthly BCSD climate projections over the region, and Transient Climate Projections which are essentially monthly-to-daily disaggregated versions of the same monthly BCSD climate projections.

- Select a subset of HD Climate Change scenarios and Transient Climate Projections to be featured in this effort and meant for use in subsequent RMJOC planning efforts.

- Adopt UW CIG's simulated hydrologic conditions under selected HD Climate Change scenarios and Transient Climate Projections.

The UW CIG climate information was viewed to be as good as other candidate information sources (see Section 3.1 for review of candidate climate data considered for this analysis). The fact that UW CIG was also prepared to provide associated hydrologic conditions over the Columbia-Snake River Basin was then seen as a significant advantage in using the UW CIG data source relative to others because the associated hydrologic modeling would not have to be scoped and included in this effort.

1.3 Report Organization

The remaining sections of this report are outlined as follows:

- Section 2.0 Literature Review – This section provides a brief summary on available literature summarizing current understanding on global climate change, Pacific Northwest climate change, and implications for water resources in Columbia-Snake River Basin.

- Section 3.0 Selecting Future Climate Scenarios – This section introduces optional future climate projection data sources considered in this effort, considerations on whether to cull available information, and rationale leading to the selection of future climate scenarios for this effort.

[2] More information can be found at http://www.hydro.washington.edu/2860/.

- Section 4.0 Selected Future Hydrologic Scenarios – This section is predicated on the selected UW CIG HB2860 HD Climate Change Scenarios and Transient Climate Projections presented in Section 3.0. Descriptions are provided on the development of simulated hydrologic conditions for each of these future climate scenarios, developed by UW CIG.

- Section 5.0 Water Supply Forecasting under Hybrid-Delta Climates – This section describes the method for developing seasonal runoff volume forecasts consistent with each selected HD climate change scenario, reflecting how climate change may affect hydroclimate relations traditionally relied upon to guide operational runoff volume forecasting (namely the interrelation of antecedent season precipitation, snowpack at the time of forecasting, and forecast period runoff volume).

2.0 LITERATURE REVIEW

2.1 Current Understanding on Global Climate Change

Assessments on climate change science and summaries of contemporary climate projections have been periodically updated by the Intergovernmental Panel on Climate Change (IPCC) since 1988. The IPCC was established by the World Meteorological Organization and the United Nations Environment Programme and its role is to assess on a comprehensive, objective, open, and transparent basis the latest scientific, technical and socioeconomic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts, and options for adaptation and mitigation.

The IPCC recently released its Fourth Assessment Report (AR4) (IPCC 2007). The AR4 offers statements and uncertainty estimates on recent trends, apparent human influence on those trends, and projections for various climate conditions. AR4 offers relatively more certain statements about warming-related events. For example, the AR4's report from Working Group I, Summary for Policymakers, Table SPM.2 states that it is "very likely" that global trends of "warmer and fewer cold days" and "warmer and more frequent hot days" occurred during the 20th Century and that it is "virtually certain" that these trends will continue based on 21st Century climate projections in response to future scenarios for GHG emissions (IPCC 2000). The AR4 synthesis report noted the major projected impacts on water resources to be "effects on water resources relying on snowmelt; effects on some water supplies," and goes on to state that over North America, "warming in western mountains is projected to cause decreased snowpack, more winter flooding and reduced summer flows, exacerbating competition for over-allocated water resources." Relatively less certain statements are offered about future precipitation-related events (e.g., phenomena like the areal extent of droughts, frequency of heavy precipitation events).

In addition to the findings reported in the IPCC AR4, several United States science groups have recently issued statements on climate change. The American Meteorological Society (AMS) issued a statement in February 2007 indicating that AMS views are "consistent with the vast weight of current scientific understanding as expressed in assessments and reports from the Intergovernmental Panel on Climate Change, the U. S. National Academy of Sciences, and the U. S. Climate Change Science Program." The American Geophysical Union adopted a revised climate change policy in December 2007, asserting that the Earth's climate is "now clearly out of balance and is warming. Many components of the climate system—including the temperatures of the atmosphere, land and ocean, the extent of sea ice and mountain glaciers, the sea level, the distribution of precipitation, and the length of seasons—are now changing at rates and in patterns that are not natural and are best explained by the increased atmospheric abundances of greenhouse gases and aerosols generated by human activity during the 20th Century." Additionally, the U.S. Global Change Research Program issued a series of Synthesis and Assessment Products during 2009[3] addressing various climate research elements, including those related to atmospheric composition, climate variability and change (including climate modeling), global water cycle, land-use and land-cover change, global carbon cycle, ecosystems, decision-support systems, climate monitoring systems, and communication.

2.2 Current Understanding on Pacific Northwest Climate Change

Numerous studies have been conducted on the potential consequences of climate change for water resources in the Columbia-Snake River Basin. This section provides a brief summary of these studies, borrowing narrative from a regional literature synthesis presented in Reclamation (2010c). The synthesis reflects findings from recent studies (1994 through 2010) demonstrating evidence of regional climate change during the 20th Century, and exploring water resources impacts associated with various climate change scenarios.

2.2.1 Historical Climate Change and Effects on Water Resources

It appears that all areas of the Pacific Northwest region became warmer and some areas received more winter precipitation over the course of the 20th Century. Cayan et al. (2001) reports that western United States spring temperatures increased 1 to 3 degrees Celsius (ºC) (1.8 to 5.4 degrees Fahrenheit [ºF]) between 1970 and 1998. Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many western United States sites, including several in the Pacific Northwest, but a consistent region-wide trend is not apparent over this period.

Coincident with these trends, the western United States and Pacific Northwest region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid and late 20th Century. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 snow water equivalent (SWE) measurements at 173 western United States stations (Knowles et al. 2007). Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the western United States

[3] http://www.globalchange.gov/publications

system—including the temperatures of the atmosphere, land and ocean, the extent of sea ice and mountain glaciers, the sea level, the distribution of precipitation, and the length of seasons—are now changing at rates and in patterns that are not natural and are best explained by the increased atmospheric abundances of greenhouse gases and aerosols generated by human activity during the 20th Century." Additionally, the U.S. Global Change Research Program issued a series of Synthesis and Assessment Products during 2009[3] addressing various climate research elements, including those related to atmospheric composition, climate variability and change (including climate modeling), global water cycle, land-use and land-cover change, global carbon cycle, ecosystems, decision-support systems, climate monitoring systems, and communication.

2.2 Current Understanding on Pacific Northwest Climate Change

Numerous studies have been conducted on the potential consequences of climate change for water resources in the Columbia-Snake River Basin. This section provides a brief summary of these studies, borrowing narrative from a regional literature synthesis presented in Reclamation (2010c). The synthesis reflects findings from recent studies (1994 through 2010) demonstrating evidence of regional climate change during the 20th Century, and exploring water resources impacts associated with various climate change scenarios.

2.2.1 Historical Climate Change and Effects on Water Resources

It appears that all areas of the Pacific Northwest region became warmer and some areas received more winter precipitation over the course of the 20th Century. Cayan et al. (2001) reports that western United States spring temperatures increased 1 to 3 degrees Celsius (ºC) (1.8 to 5.4 degrees Fahrenheit [ºF]) between 1970 and 1998. Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many western United States sites, including several in the Pacific Northwest, but a consistent region-wide trend is not apparent over this period.

Coincident with these trends, the western United States and Pacific Northwest region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid and late 20th Century. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 snow water equivalent (SWE) measurements at 173 western United States stations (Knowles et al. 2007). Regonda et al. (2005) evaluated 1950–1999 data from 89 stream gauges in the western United States

[3] http://www.globalchange.gov/publications

and reports peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest. Luce and Holden (2009) report on distribution of streamflow reductions observed during 1948–2006 and significant trends in annual streamflow reductions during dry years.

It is important to note that linear trends in hydrologically important variables (including springtime SWE, indices of runoff timing, and surface air temperature) depend on the time period considered in the analysis. Mote et al. (2008), for instance, show that SWE trends for the Washington and Oregon Cascades computed with an end date of 2006 and a start date within a decade of 1955 are robust, while those computed through 2006 from later start dates differ dramatically, and are statistically insignificant because the shorter-term variability is much larger than the longer-term linear trends. This sensitivity to start date is a direct result of the combined influences of natural interdecadal time scale climate variations and longer-term anthropogenic trends that are part of many climate records for the 20th Century.

On explaining these historical trends, Chapter 4 of the U.S. Climate Change Science Program Synthesis and Assessment Product (SAP) 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted the question of detection and attribution of late 20th Century trends in hydrologically important variables in the western United States, aimed directly at better understanding the relative roles of anthropogenically forced versus natural origin climate variations in observed trends. Barnett et al. (2008) find that up to 60 percent of the climate-related trends of western United States river flow, winter air temperature, and snow pack from 1950 to 1999 are human-induced. Similar results are reported in related studies by Pierce et al. (2008) for springtime SWE, Bonfils et al. (2008) for temperature changes in the mountainous western United States, Hidalgo et al. (2009) for streamflow timing changes, and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and streamflow timing changes. An additional key finding of these studies is that the statistical significance of the anthropogenic signal is greatest at the scale of the entire western United States and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009).

While the trends in the river flow, winter air temperature, and snow pack in the western United States might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) shows that it remains difficult to attribute historical precipitation variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977 through 2006. They suggest that the relationship between sea temperatures and rainfall changes are generally not symptomatic of human-induced emissions of GHG and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability.

and reports peak runoff occurred earlier at most stations during the period and significant trends toward earlier runoff were found in the Pacific Northwest. Luce and Holden (2009) report on distribution of streamflow reductions observed during 1948–2006 and significant trends in annual streamflow reductions during dry years.

It is important to note that linear trends in hydrologically important variables (including springtime SWE, indices of runoff timing, and surface air temperature) depend on the time period considered in the analysis. Mote et al. (2008), for instance, show that SWE trends for the Washington and Oregon Cascades computed with an end date of 2006 and a start date within a decade of 1955 are robust, while those computed through 2006 from later start dates differ dramatically, and are statistically insignificant because the shorter-term variability is much larger than the longer-term linear trends. This sensitivity to start date is a direct result of the combined influences of natural interdecadal time scale climate variations and longer-term anthropogenic trends that are part of many climate records for the 20^{th} Century.

On explaining these historical trends, Chapter 4 of the U.S. Climate Change Science Program Synthesis and Assessment Product (SAP) 4.3 discusses several studies that indicate most observed trends for SWE, soil moisture, and runoff in the western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). This assertion is supported by a collection of journal articles that targeted the question of detection and attribution of late 20^{th} Century trends in hydrologically important variables in the western United States, aimed directly at better understanding the relative roles of anthropogenically forced versus natural origin climate variations in observed trends. Barnett et al. (2008) find that up to 60 percent of the climate-related trends of western United States river flow, winter air temperature, and snow pack from 1950 to 1999 are human-induced. Similar results are reported in related studies by Pierce et al. (2008) for springtime SWE, Bonfils et al. (2008) for temperature changes in the mountainous western United States, Hidalgo et al. (2009) for streamflow timing changes, and Das et al. (2009) for temperature, snow/rain days ratio, SWE, and streamflow timing changes. An additional key finding of these studies is that the statistical significance of the anthropogenic signal is greatest at the scale of the entire western United States and weak or absent at the scale of regional scale drainages with the exception of the Columbia River Basin (Hidalgo et al. 2009).

While the trends in the river flow, winter air temperature, and snow pack in the western United States might be partially explained by anthropogenic influences on climate, Hoerling et al. (2010) shows that it remains difficult to attribute historical precipitation variability to anthropogenic forcings. They evaluated regional precipitation data from around the world (observed and modeled) for 1977 through 2006. They suggest that the relationship between sea temperatures and rainfall changes are generally not symptomatic of human-induced emissions of GHG and aerosols. Rather, their results suggest that trends during this period are consistent with atmospheric response to observed sea surface temperature variability.

These findings are significant for regional water resources management and reservoir operations because snowpack has traditionally played a central role in determining the seasonality of natural runoff. In many Pacific Northwest headwater subbasins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs is that (with precipitation being equal) warmer temperatures in these watersheds cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

2.2.2 Future Climate Change and Effects on Water Resources

Several studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts. A recent paper by the Congressional Budget Office presents an overview of the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater at high latitudes and in the interiors of the United States, less precipitation will fall as snow and there will be earlier snowmelt runoff, and more intense and heavy rainfall will tend to be interspersed with longer relatively dry periods (CBO 2009). The CBO findings are qualitatively consistent with findings in the Washington Climate Change Impacts Assessment (WACCIA), developed and reported by the University of Washington Climate Impacts Group. The WACCIA reports on future climate change possibilities and associated impacts to hydrology, water resources, ecosystems, and other sectors. The WACCIA's report on future climate conditions over the greater Columbia River Basin (Mote and Salathé 2010) suggests increases in average annual Pacific Northwest temperature of 2.0°F by the 2020s, 3.2°F by the 2040s, and 5.3°F by the 2080s (compared to 1970–1999). Projected changes in average annual precipitation, averaged over all models, are small (+1 to +2 percent), but some models project an enhanced seasonal precipitation cycle with changes toward wetter autumns and winters and drier summers. These climate changes translate into impacts on hydrology, particularly regional snowpack and runoff seasonality (Elsner et al. 2010). For example, WACCIA findings suggest that April 1 snowpack is projected to decrease by 28 percent across Washington State by the 2020s, 40 percent by the 2040s, and 59 percent by the 2080s (relative to the 1916-2006 historical average). As a result, seasonal streamflow timing will likely shift significantly in sensitive watersheds.

SAP 3.3 discusses the effects of climate change on precipitation extremes (CCSP 2008). Chapter 3 of SAP 3.3 focuses on mechanisms for observed changes in extremes to better interpret projected future changes in extremes (Gutowski et al. 2008), and suggests that climate change will likely cause precipitation to be less frequent, but more intense in many areas, and suggests that precipitation extremes are very likely to increase.

These recent assessments on future climate and hydrology are consistent with earlier studies. Hamlet and Lettenmaier (1999) evaluated potential future changes to Pacific Northwest climate relative to the ability of the Columbia River reservoir system to meet regional resource objectives. The authors report decreased summer streamflows up to 26 percent relative to the historic average would create significant increased competition by water users. A subsequent study by Mote et al. (2003) included evaluations of impacts associated with climate change scenarios from numerous climate projections available at that time and reported findings suggesting that regional resources have a greater sensitivity to climate relative to what was previously understood. Mastin et al. (2008) predicted Yakima River subbasin runoff impacts under 1°C and 2°C increases temperature with no precipitation change scenarios. This study predicts modest decreases in annual runoff and significant late spring and summer runoff decreases under both scenarios. Rauscher et al. (2008) used a high-resolution nested climate model to investigate future changes in snowmelt-driven runoff over the western United States. Results include that runoff could occur as much as two months earlier than present, particularly in the Pacific Northwest and earlier runoff timing of at least 15 days in early-, middle-, and late-season flows is projected for almost all mountainous areas where runoff is snowmelt driven. On extreme hydrologic events, Raff et al. 2009 introduced a framework for estimating flood frequency in the context of climate projection information. The framework was applied to a set of four diverse subbasins in the western United States (i.e., the Boise River above Lucky Peak Dam, the San Joaquin River above Friant Dam, the James River above Jamestown Dam, and the Gunnison River above Blue Mesa Dam). Results for three of the four subbasins (Boise, San Joaquin, and James) showed that under current climate projection information, probability distributions of annual maximum discharge would feature greater flow rates at all quantiles. For the fourth subbasin (Gunnison), greater flow rates were projected for roughly the upper third of quantiles. Granted this study represents a preliminary effort focused on introducing a framework for estimating flood frequency in a changing climate. Results are limited by various uncertainties, including how the climate projection information used in the analysis did not reflect potential changes in storm frequency and duration, only changes in storm intensity relative to historical storm events.

Such future impacts on hydrology have been shown to have implications for water resources management. Chapter 4 of SAP 4.3 focuses on water resources effects and suggests that management of western United States reservoir systems is very likely to become more challenging as net annual runoff decreases and inter-annual patterns continue to change as the result of climate change (Lettenmaier et al. 2008). The WACCIA includes assessment of reservoir operations in the Yakima River subbasin (Vano et al. 2010) and suggests that impacts to snowpack and runoff seasonality translate into reduced ability (compared to 1970–2005) to supply water to all users, especially those with junior water rights. Without adaptation, their results suggest that shortages would likely occur 32 percent of years in the

2020s, 36 percent of years in the 2040s, and 77 percent of years in the 2080s (compared to 14 percent of years for the period 1916–2006). Focusing on the greater Columbia Basin, Payne et al. (2004) evaluated reservoir operations under projected hydrologic conditions and explored mitigation options that might become necessary to balance the needs of the various water users. Their findings included that increased winter runoff may necessitate earlier dates of winter flood control drawdown relative to current dates. The most significant operational result was an increased competition for water supply between demands associated with instream flows and hydropower production. In order to maintain current levels of instream flows, a 10 to 20 percent reduction in firm hydropower production would be required. Lee et al. (2009) performed a similar analysis on the Columbia River Basin system with findings consistent with Payne et al. (2004). Their results suggest that current Columbia River Basin reservoir systems could be operated to provide flood control and reservoir refill under climate change scenarios provided that current flood rule curves are updated.

2.2.3 Future Climate Change and Effects on Environmental Resources

Chapter 5 of SAP 4.3 discusses how biodiversity may be affected by climate change (Janetos et al. 2008) and indicates that many studies have been published on the impacts of climate change for individual species and ecosystems. Predicted impacts are primarily associated with projected increases in air and water temperatures and include species range shifts poleward, adjustment of migratory species arrival and departure, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change has also affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack (Ryan et al. 2008). Cayan et al. (2001) document earlier blooming of lilacs and honeysuckles correlated to increasing spring temperatures.

Chapter 2 of SAP 4.3 discusses the effects of climate change on agriculture and water resources (Hatfield et al. 2008). It addresses the many issues associated with future agricultural water demands and discusses that only a few studies have attempted to predict climate change impacts on irrigation demands. These limited study findings suggest significant irrigation requirement increases for corn and alfalfa due to increased temperatures and CO_2 and reduced precipitation. Further, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. On the other hand, agricultural water demand could increase if growing seasons grow longer. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th Century; and it is projected that, by the end of the 21st Century, it will be more than 2 weeks longer than typical of the late 20th Century (Gutowski et al. 2008)

The WACCIA (Mantua et al. 2009) reports that rising stream temperatures will likely reduce the quality and extent of freshwater salmon habitat. The WACCIA goes onto suggest that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double (low emissions scenario, B1) and perhaps quadruple (medium emissions scenario, A1B) by the 2080s for most analyzed streams and lakes; areas of greatest increases in thermal stress include the Interior Columbia River Basin. These findings are consistent with other studies in the region. Battin et al. (2007) focused on the impacts of climate change on the effectiveness of proposed salmon habitat restoration efforts in the Snohomish River subbasin of western Washington State. Based on climate model estimated mean air temperature increases of 0.7 to 1.0ºC (1.1ºF to 1.8ºF) by 2025 and 1.3ºC to 1.5ºC (2.3ºF to 2.7ºF) in 2050 relative to 2001 conditions, impacts on freshwater salmon habitat and productivity for Snohomish River subbasin Chinook salmon were found to be consistently negative. This study also found that scenarios for freshwater habitat restoration partially or completely could mitigate the projected negative impacts of anthropogenic climate change.[4]

In general, studies of climate change impacts on freshwater ecosystems are more straight-forward with streams and rivers, which are typically well mixed and track air temperature closely, as opposed to lakes and reservoirs, where thermal stratification and depth affect habitat (Allan et al. 2005). Ficke et al. (2007) presents an extensive synthesis and bibliography of literature on climate change impacts on freshwater fisheries. Fang et al. (2004a and 2004b) predicted changes to cold water fisheries habitat in terms of water temperature and dissolved oxygen under a doubled CO_2 climate change regional warming scenario for 27 lake types in the United States, including western United States lakes. Their findings suggest an overall decrease in the average length of good-growth periods and the area for which lakes cannot support cold-water fish would extend significantly further north. 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 (Lettenmaier et al. 2008; Ryan et al. 2008). Burkett and Kusler (2000) discuss potential impacts to wetlands caused by climate change. Potential impacts to five different types of wetlands are discussed as well how impacts may vary by region. Allan et al. (2005) suggest that although freshwater ecosystems will adapt to climate change as they have to land use changes, acid rain, habitat degradation, pollution, etc., but the adaptation will likely entail a diminishment of native biodiversity. Warmer water temperatures also could exacerbate invasive species issues (e.g., quagga mussel reproduction cycles responding favorably to

[4] Additional discussion on climate change implications for Columbia River Basin salmon fisheries(section "Climate Change and Ocean Conditions, pp. 37-62 of "Supplemental 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)(I)(A) Permit for Juvenile Fish Transportation Program," prepared by NOAA Fisheries, 20 May 2010).

warmer water temperatures); moreover, climate changes could decrease the effectiveness of chemical or biological agents used to control invasive species (Hellman et al. 2008). Warmer water temperatures could also spur the growth of algae, which could result in eutrophic conditions in lakes, declines in water quality (Lettenmaier et al. 2008), and changes in species composition.

Another potential effect of climate change impacts on ecosystems and watershed hydrology involves changes in vegetation disturbances due to wildfires and forest dieback. Warm season temperatures, which have increased in the western United States, attenuate snow melt and soil and fuel moistures. This, in turn, will affect wildland fire activity. These effects are discussed in chapter 3 of SAP 4.3 (Ryan et al. 2008). Because of observed warmer and drier climate in the western United States in the past two decades, forest fires have grown larger and more frequent. Both the frequency of large wildfires and fire season length increased substantially since 1985 and these changes were closely linked with advances in the timing of spring snowmelt. Hot and dry weather also allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008). Ryan et al. (2008) goes on to report that several insect outbreaks have recently occurred or are occurring in the United States and increased temperature and drought likely influenced these outbreaks. Climate change has affected forest insect species range and abundance through changes in insect survival rates, increases in life cycle development rates, facilitation of range expansion, and effect on host plant capacity to resist attack. The WACCIA reports similar potential impacts (Littell et al. 2009), suggesting that due to increased summer temperature and decreased summer precipitation, the area burned by fire regionally is projected to double by the 2040s and triple by the 2080s (relative to 1916–2006). The WACCIA also reports that in areas primarily east of the Cascades, mountain pine beetles will likely reach higher elevations and pine trees will likely be more vulnerable to attack by beetles.

Other studies on forest impacts under climate change include Westerling et al. (2006), which documents large increases in fire season duration and fire frequency, especially at mid-elevations, in the western United States. Hot and dry weather allows fires to grow exponentially, covering more acreage (Lettenmaier et al. 2008). Brown et al. (2004) predict future (2006–2099) western United States wildfire potential based on the General Circulation Model (GCM) output relative to current conditions that were based on a historical (1870-1998) GCM run with wildfire potential quantification using the Forest Service National Fire Rating System. The study predicts increased potential for large wildfires throughout most of the western United States with the exception of the Pacific Northwest and with the greatest increase in the northern Rockies, Great Basin, and the southwestern United States. McKenzie et al. (2004) project increases in numbers of days with high fire danger and acres burned, respectively, as a result of increasing temperatures and related climate changes. These authors also discuss how some plant and animal species that are sensitive to fire may decline, whereas the distribution and abundance of species favored by fire may be enhanced due to increased wildfires resulting from climate change. Beukema et al. (2007) discuss the potential for increased fire risk and insect and pathogen impacts to East Cascades ponderosa pine forest ecosystems resulting from climate change. Robinson et al. (2008) describes and compares several ecological models that estimate vegetation development (productivity or vegetation type) under climate change conditions. Climate changes can also trigger synergistic effects in ecosystems through triggering multiple nonlinear or threshold-like processes that interact in complex ways (Allen 2007). For example, increasing temperatures and their affects on soil moisture are a key factor in conifer species die-off in western North America (Breshears et al. 2005). Increased temperatures are also a key factor in the spread and abundance of the forest insect pests that also have been implicated in conifer mortality (Logan et al. 2003; Williams et al. 2008). The one-two punch of temperature-driven moisture stress on trees and the enhanced life cycles and ranges of insect pests kill large swaths of forest, triggering changes in ecosystem composition and flammability, hence a cascading series of impacts such as decreased soil retention and increased aeolian and fluvial erosion. Lastly, Ansu and McCarney (2008) offer a categorized bibliography of articles related to climate change and environmental resources impacts. Readers are encouraged to review this bibliography for additional articles relevant to their specific interests.

2.3 Observed Climate Conditions over the Columbia-Snake River Basin

As indicated in the preceding literature summary, observations suggest that all areas of the Pacific Northwest region became warmer, and some areas received more winter precipitation over the course of the 20th Century. This is shown in Figure 3 for the subbasins listed in Table 1, where results reflect historical weather conditions over the Columbia-Snake River Basin spatially averaged basin-wide. [5] The first and third panels of Figure 3 show annual total precipitation and annual mean temperature from 1916-2006. Each panel has text indicating trend information (i.e., change per decade). Decadal trends by subbasin are then shown on the second and fourth panels, corresponding to subbasins shown on Figure 4. Figure 3 shows that during 1916-2006, all subbasins appear to have become warmer and that most subbasins have experienced a minor trend toward wetter conditions.

[5] http://www.hydro.washington.edu/2860/report/ Chapter 3 – Historical Meteorological Driving Data Set

Table 1. Columbia River subbasins identifiers used in the HB2860 effort and by RMJOC agencies.

HB 2860 #	HB 2860 label	RMJOC label	Subbasin Outlet Location	River	Lat	Long
Columbia Basin (Interior Basin) Locations						
1015	MICAA	MCD	Columbia River at Mica Dam	Columbia	52.08	-118.57
1019	ARROW	ARD	Columbia River at Keenleyside Dam	Columbia	49.34	-117.77
3002	LIBBY	LIB	Kootenai River at Libby Dam	Kootenai	48.41	-115.31
1025	CORRA	COR	Kootenay River at Corra Linn Dam	Kootenay	49.47	-117.47
3027	FLATW	HGH	SF of Flathead River above Twin Ck near Hungry Horse	Flathead	47.98	-113.56
2005	ALBEN	ALB	Pend Oreille River at Albeni Falls Dam	Pend Oreille	48.18	-117.03
6031	LLAKE	LLK	Spokane River at Long Lake Dam	Spokane	47.84	-117.84
6034	GCOUL	GCL	COLUMBIA RIVER AT GRAND COULEE DAM	Columbia	47.97	-118.98
6073	LGRAN	TDA	Snake River at Litle Goose Dam	Snake	46.67	-117.44
2008	PFALL	PFL	Spokane River near Post Falls	Spokane	47.70	-116.98
2038	DWORS	DWR	N. Fork Clearwater at Dworshak Dam	NF Clearwater	46.52	-116.30

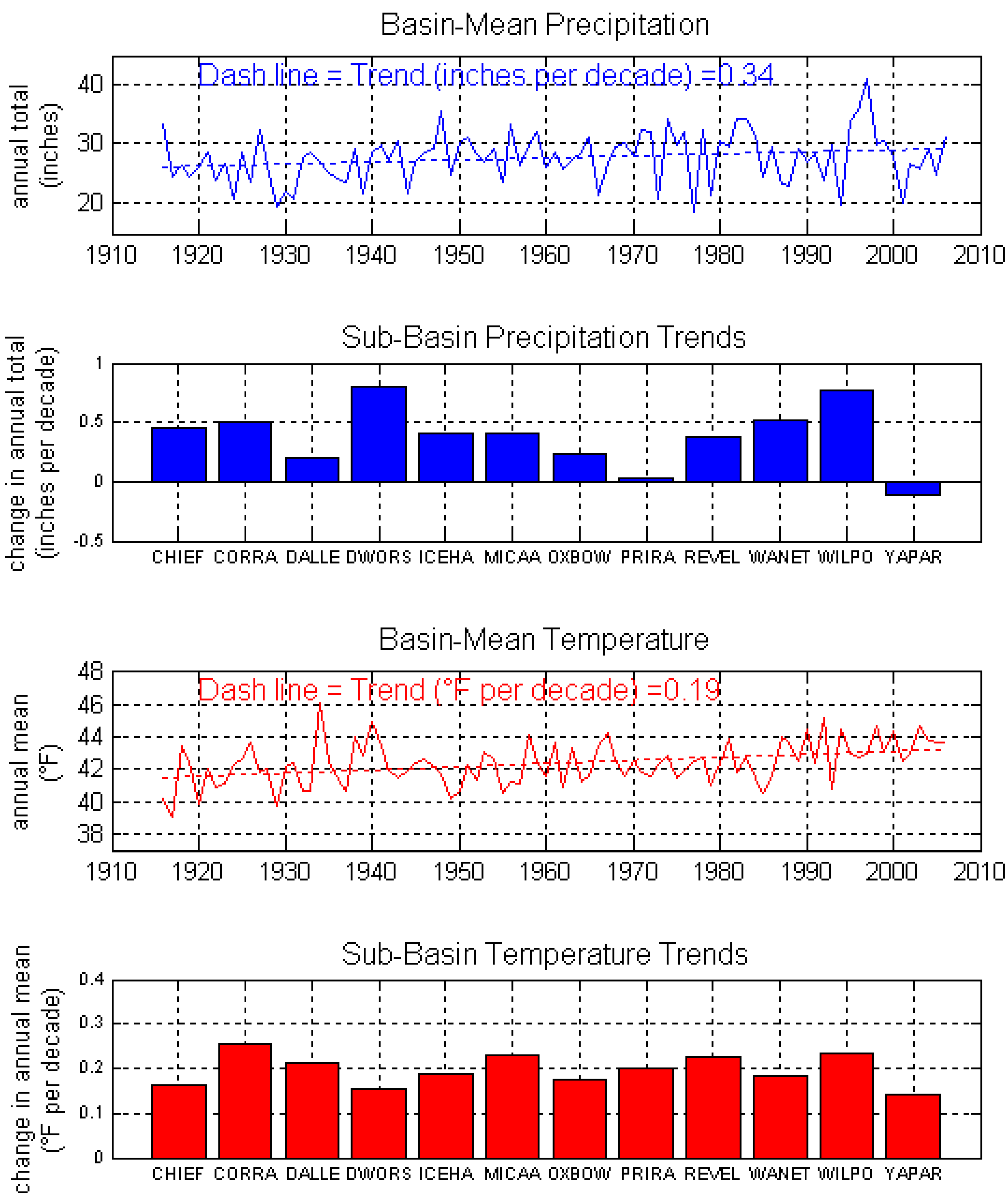

Figure 3. Observed historical climate over the Columbia-Snake River Basin for Water Years 1916-2006.

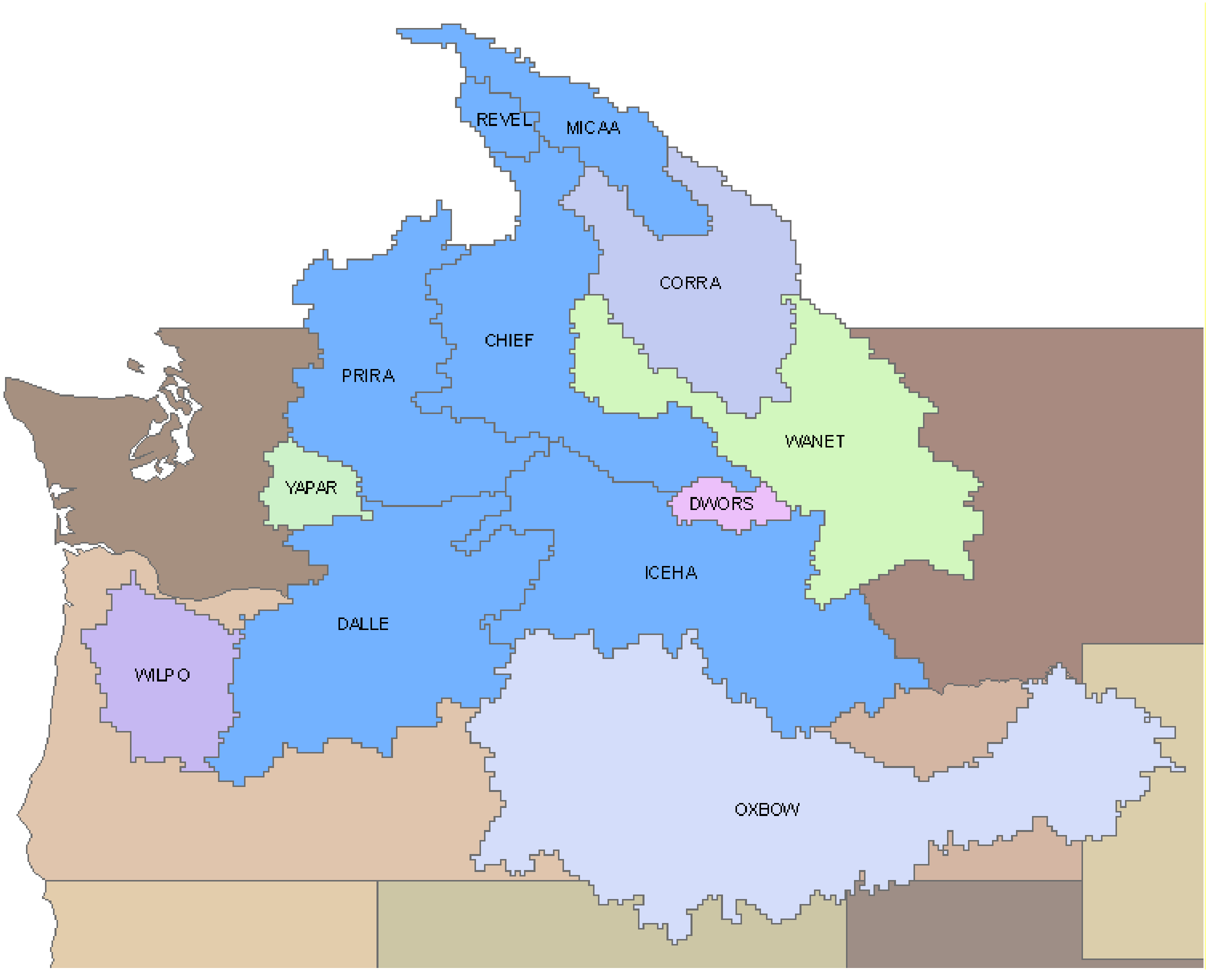

Figure 4. Columbia-Snake subbasins corresponding to Figure 3.

2.4 Future Climate Conditions over the Columbia-Snake River Basin

During the past decade, climate projections have been made available through efforts of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP). This project has advanced in three phases (CMIP1 [Meehl et al. 2000], CMIP2 [Covey et al. 2003], and CMIP3 [Meehl et al. 2007]). WCRP CMIP3 efforts were fundamental to completion of IPCC AR4 (IPCC 2007). The CMIP3 dataset was produced using climate models that include coupled atmosphere and ocean general circulation models. These were used to simulate global climate response to various future GHG emissions paths (IPCC 2000) from end-of-twentieth Century climate conditions. The emission paths vary from lower to higher rates, depending on assumptions about global technological and economic developments during the twenty-first Century.

One limitation with the CMIP3 dataset and climate models projections, in general, is the climate model spatial scale output is too coarse for regional studies on water resources response (Maurer et al. 2007). A large collection of bias-corrected and spatially downscaled translations of CMIP3 projections have been made available to address this limitation.[6] The projections in this archive (downscaled climate projections [DCP] archive) were collectively produced by 16 of the 23 different CMIP3 models simulating three different emissions pathways (e.g., B1 [low], A1b [middle], A2 [high]) from different end-of-20th-Century climate conditions (i.e., for some combinations of model and emissions scenarios, there are multiple projections, or "runs," associated with multiple initial climate system conditions). The methodology used to develop DCP archive data is consistent with the methodology featured in the UW CIG HB2860 effort to initially generate monthly BCSD projections (discussed further in Section 3.0). For the purposes of describing projected climate uncertainty over the broader Columbia-Snake River Basin, DCP archive data are referenced here given that they represent a larger portion of the CMIP3 ensemble relative to what is represented in the UW CIG HB2860 information set albeit at a coarser spatial resolution (i.e., 112 versus 19 projections, but at a 1/8º spatial resolution versus 1/16º spatial resolution, as will be discussed furthering in Section 3.1).

Focusing on historical and future climate periods that will drive discussions in Section 3.0, the DCP archive data were sampled for percentile period-mean changes in annual precipitation and temperature, spatially distributed throughout the Columbia-Snake River Basin. Precipitation changes are shown on Figure 5 and Figure 6 for two future periods (respectively, 2010-2039 and 2030-2059) and three percentiles (panels A through C corresponding to 10th, 50th and 90th percentiles). In similar fashion, temperature changes are shown on Figure 7 and Figure 8.

[6] http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/

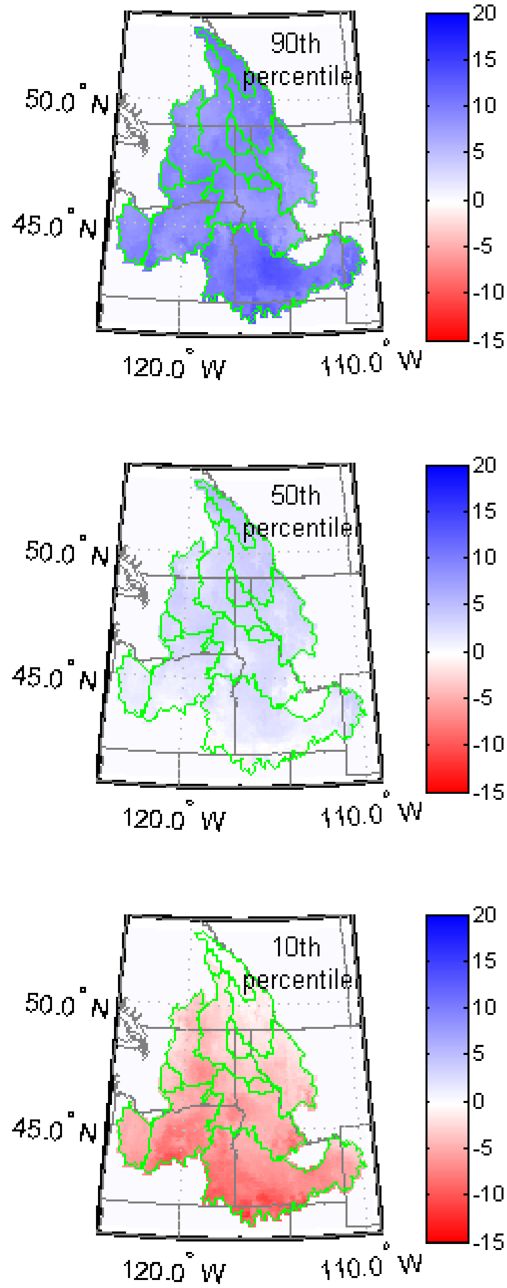

Figure 5. Projected change in mean annual precipitation (%) over the Columbia-Snake River Basin, from 1970-1999 to 2010-2039.

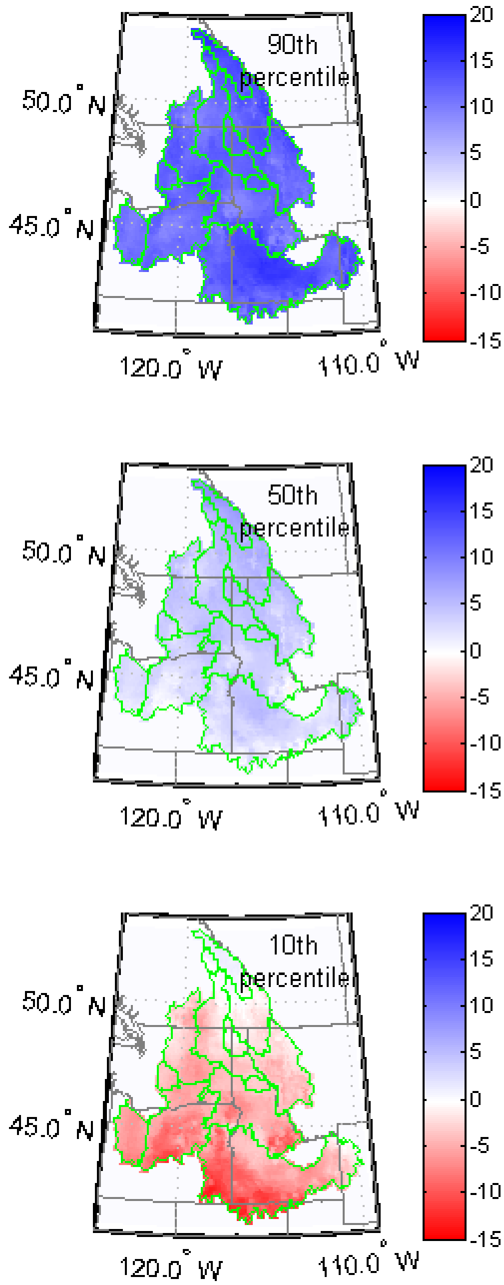

Figure 6. Projected change in mean annual precipitation (%) over the Columbia-Snake River Basin, from 1970-1999 to 2030-2059.

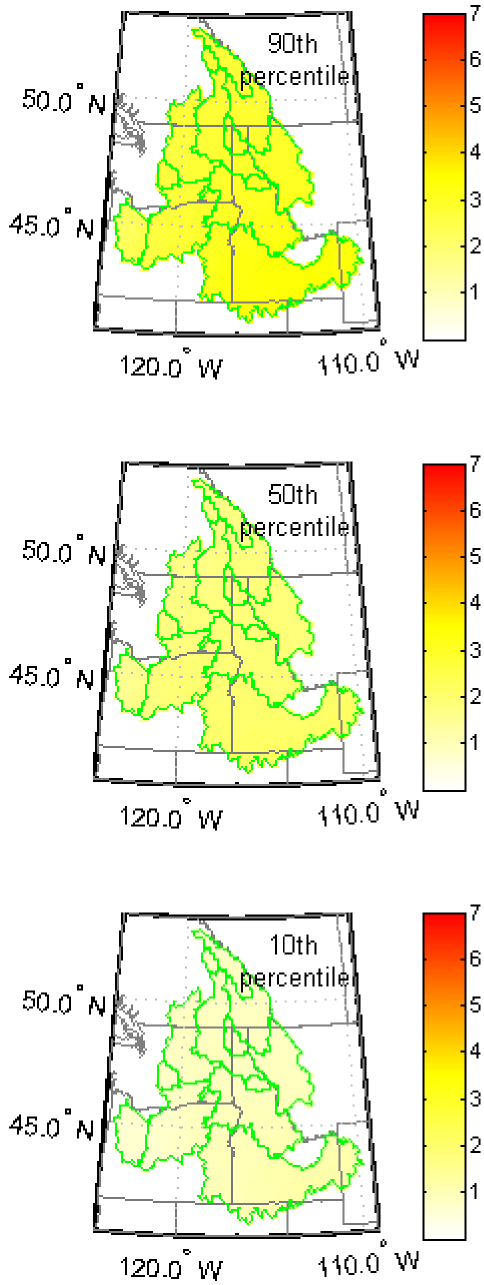

Figure 7. Projected change in mean annual temperature (ºF) over the Columbia-Snake River Basin, from 1970-1999 to 2010-2039.

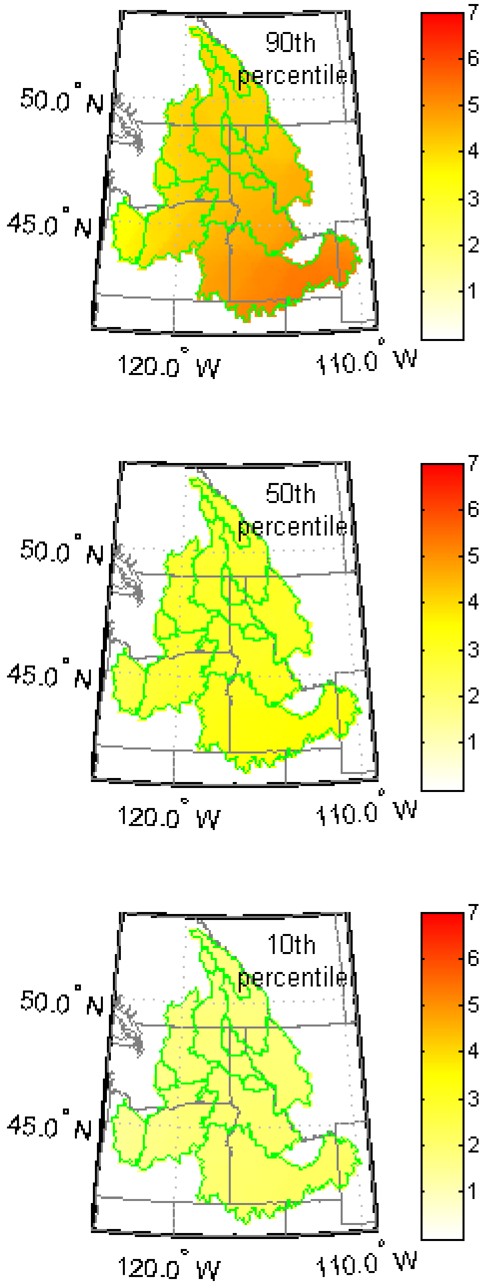

Figure 8. Projected change in mean annual temperature (ºF) over the Columbia-Snake River Basin, from 1970-1999 to 2030-2059.

Central change expectations can be interpreted by focusing on the middle panels on each figure (panel B). These panels indicate spatially distributed “median” period-change among DCP archive projections. The mapped results illustrate that the majority of the DCP archive’s 112 projections suggest a future change toward warmer and wetter conditions throughout the basin. For precipitation, the maps suggest that median change in mean-annual precipitation may be greater over the northern half of the basin.

Uncertainty about projected changes in mean-annual precipitation and temperature can be interpreted by jointly focusing on the top and bottom panels of each figure (panels A and C). Focusing on temperature (Figure 7 and Figure 8), it appears that by the 2010-2039 period (measuring change from the 1970-1999 period), the centrally expected change is generally 2 ºF throughout much of the basin and that the 10 to 90 percentile range spans roughly 1 to 3 ºF. By 2030-2059, these values increase to a central change of generally 3 ºF and a 10 to 90 percentile range spanning roughly 2 to 4 ºF. Focusing on precipitation (Figure 5 and Figure 6), the central changes in mean-annual precipitation are generally a few percent by 2010-2039 and 2030-2059. However, the range of 10 to 90 percentile changes is rather broad, varying by location, ranging roughly from -10 percent to +10 percent by 2010-2039 and roughly from -15 percent to +15 percent by 2030-2059, with the lower limit occurring primarily in the southern part of the basin and the upper limit occurring primarily in the northern part.

3.0 SELECTING FUTURE CLIMATE INFORMATION

This section provides a review of different climate projection information sources that could have been used in this RMJOC effort. Subsequently, rationale is introduced for using the UW CIG's HB2860 information source and for selecting two types of information from this information source (i.e., Hybrid-Delta (HD) Climate Change scenarios and Transient Climate Projections). The section concludes with a summary description of selected future climate information.

3.1 Optional Sources of Downscaled Climate Projections

Attention was given to information sources that provided spatially downscaled climate projection information over the Pacific Northwest region. By definition, spatial downscaling is the process of taking global climate model output on a coarse scale, and translating that to a finer spatial scale that is more meaningful for analyzing local and regional climate conditions. Many downscaling methods have been developed, all of which have strengths and weaknesses. Several reports offer discussion on the various methodologies, notably the AR4 (Wigley 2004, IPCC 2007 - Chapter 11, Regional Climate Projections, Salathé et al. 2007; Fowler et al. 2007; Brekke et al. 2009).

3.1.1 Downscaled Climate Projections (DCP) Archive

DCP archive data are based on an empirical downscaling technique that has been applied to support numerous hydrologic impacts investigations (e.g., Reclamation 2008, LCRA SAWS 2008, Reclamation 2009, CWCB 2010, and Reclamation 2010a). The technique involves processing CMIP3 data in two ways. First, the CMIP3 data are "bias-corrected," which means that they are adjusted to account for climate model tendencies to simulate past conditions that statistically differ from observations (e.g., too warm, cool, wet, or dry). Second, the data are "spatially downscaled," which involves interpolating spatially coarse resolution changes in the bias-corrected CMIP3 data to a finer-resolution spatial grid, and applying the finer-resolution grid of changes to a historical spatial climatology on the same grid, leading to a "disaggregated" version of the coarse-resolution CMIP3 data. For this reason, the technique is referred to as Bias Correction Spatial Disaggregation, or BCSD (Wood et al. 2004). Procedures for accomplishing both BCSD steps are described and illustrated at the DCP archive website and were initially introduced by Wood et al. 2002 and Wood et al. 2004. The BCSD technique also underlies data in the UW CIG HB2860 dataset discussed in the next section.

Relative to more sophisticated methods such as dynamical downscaling, BCSD is computationally more efficient, enough so that it may be applied to many CMIP3 projections at a feasible computational cost (Brekke et al. 2009). Given a motive of characterizing climate projection uncertainty and ensuring that a given planning application under climate change is well representative of the breadth of climate projection information available, it is desirable to develop downscaled climate projections datasets that represent a large portion of available global projections. These thoughts led to the scoping of the DCP archive, which represents 112 CMIP3 projections and offers the most comprehensive downscaled CMIP3 projections dataset available (surveyed as of August 2010).

Compared to dynamical downscaling approaches, the BCSD method has been shown to provide downscaling capabilities comparable to other statistical and dynamical methods in the context of hydrologic impacts (Wood et al. 2004). However, dynamical downscaling has also been shown to identify some local climate effects and land-surface feedbacks that BCSD cannot readily identify (Salathé et al. 2007). Another potential limitation of BCSD, like any non-dynamical downscaling method, is the assumption of some stationarity in the relationship between large-scale precipitation and temperature and fine-scale precipitation and temperature. For example, it is assumed that there will be no change (historical to future) in the processes governing how precipitation and temperature changes averaged spatially for a global climate model grid-box translate into finer spatial resolution changes within the grid-box. A second assumption included in the bias-correction step of the BCSD method is that any biases exhibited by a GCM for the historical period will also be exhibited in future simulations. Tests of these assumptions, using historic data, show that they appear to be reasonable, inasmuch as the BCSD method compares favorably to other downscaling methods (Wood et al. 2004).

Thinking about applying DCP archive data for the RMJOC effort, one advantage is that the archive has the largest set of available downscaled climate projections that were developed using a consistent methodology over the Pacific Northwest region. A disadvantage is that the RMJOC technical team would have to conduct watershed simulation analysis to translate these downscaled climate projections into Columbia-Snake River Basin hydrologic conditions. This disadvantage stood out relative to the next information source, which features both future climate and hydrology information over the basin and at finer spatial resolution.

3.1.2 UW CIG HB2860 Future Climate Scenarios (Delta, Hybrid-Delta and Transient)

This information source features hydrologic climate change scenarios for the Pacific Northwest Columbia River Basin and coastal drainages.[7] Many of these same motivations underlying the development of the DCP archive also underlie development of this source, namely the desire to represent a breadth of available climate projection information downscaled in a consistent fashion, and in this case, specifically over the Pacific Northwest. There are several features that distinguish the HB2860 information source from the DCP archive:

- Reference Historical Weather: The HB2860 information source uses a new gridded "observed historical" meteorological dataset[8] to guide application of BCSD over the Pacific Northwest. It is comparable to the dataset underlying DCP archive development (Maurer et al. 2002), but has the advantages of a longer historical reference period (1916-2006 versus 1950-1999) and a finer spatial resolution (1/16º versus 1/8º).

- Associated Hydrology: The HB 2860 information source features paired information on future climate and future hydrology. The latter is generated by applying a watershed hydrologic simulation model (Section 4.0) to translate future climate information into associated hydrologic conditions.

- Multiple Versions of Future Climate and Hydrology: The HB 2860 information source was scoped with the intent to display various kinds of hydrologic information and data, and to facilitate the downloading of these products to a broad user community ranging in technical sophistication. As the website states, the information source is meant to serve an audience ranging from "the general public needing summary information about impacts to specific watersheds of interest to highly technical users who require access to primary data resources needed to conduct their own analyses."[9] Consequently, the source features different types of future climate scenarios (Table 2) having unique temporal downscaling (from monthly BCSD climate projections to daily weather forcings driving hydrologic simulation) and as a result different hydrology. The information types are labeled as Hybrid-Delta, Transient BCSD, and Delta Method.

---

[7] http://www.hydro.washington.edu/2860/

[8] http://www.hydro.washington.edu/2860/report/, *Chapter 3 – Historical Meteorological Driving Data Set*

[9] http://www.hydro.washington.edu/2860/new_users/

Table 2. Menu of HB2860 future climate and hydrology scenarios.

Downscaling Approach		A1B Emissions Scenario	B1 Emissions Scenario
Hybrid Delta	2020s	10	9
	2040s	10	9
	2080s	10	9
Transient BCSD*	1950-2099	7	7
Delta Method	2020s	1	1
	2040s	1	1
	2080s	1	1

Hybrid-Delta and Delta method reflect period-changes in climate (e.g., change in 30-year monthly conditions). Both information types require defining a reference historical climate period. UW CIG adopted 1970-1999 to serve as this reference historical climate period, sampled within the Reference Historical Weather dataset described above.[10] Both information types then require specifying a future period within a climate projection during which future conditions are surveyed and measured relative to the reference historical climate period. UW CIG used three future periods in constructing both Hybrid-Delta and Delta scenarios: 2010-2039 (2020s scenarios), 2030-2059 (2040s scenarios), and 2070-2099 (2080s scenarios). Change in 30-year climate conditions are then used to adjust the complete period of Reference Historical Weather (1916-2006) in order to reflect a unique "climate change" version of this weather sequence for each scenario.

There are 20 Hybrid-Delta scenarios for each future period. This arises from applying the method to 19 individual climate projections during that period, 10 projections generated by 10 different GCMs simulating the A1B future greenhouse gas emission scenario (IPCC 2000) and 9 more projections generated by 9 of the 10 GCMs simulating the B1 SRES emissions scenario.[11] In contrast, the Delta scenarios for each future period are actually "composite" scenarios reflecting 10-member ensemble-mean changes in climate, averaged across the 10 underlying projections for each emission group.[12]

[10] Note, the climate of 1970-1999 may differ from the climate of other 30-year periods in the 20th Century. This affects interpretation of CIG Hybrid-Delta "climate changes" if the interest is to associate them with other periods in the 20th Century.

[11] UW CIG's choice of 10 GCMs to inform the HB2860 dataset was based on how these 10 were found to feature relatively less bias in simulating 20th Century climate (i.e., annual mean and monthly mean temperature and precipitation) over the Columbia-Snake River Basin (*personal communication, M. McGuire-Elsner, University of Washington, November 2010*).

[12] http://www.hydro.washington.edu/2860/report/, *Chapter 4 - Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies*

There are two other notable differences between the HB2860 Hybrid-Delta and Delta scenarios. Spatial resolution of application differs between the two, as the Hybrid-Delta changes are assessed at each 1/16º spatially downscaled grid cell over the region, whereas Delta scenarios reflect period-changes in regionally averaged temperature and precipitation over the Pacific Northwest (i.e., not spatially downscaled conditions via BCSD). Also, the Hybrid-Delta scenarios reflect a change in 30-year monthly-distributions of temperature or precipitation conditions where as the composite Delta scenarios reflect a change in 30-year monthly means. Thus, the Hybrid-Delta scenarios permit portrayal of expansion or contraction of the envelope of climate variability experienced during the reference historical climate period. The expansion or contraction is indicated by underlying global climate projections over the Pacific Northwest. Frequency information from the reference climate is preserved (i.e., reoccurrence of relatively wet or dry, or warm or cool, conditions), but intensities are adjusted in a way that permits expanded or contracted envelope of variability (discussed further in Section 4.0). This contrasts from composite Delta scenarios that only portray translation of historical envelopes of climate variability based on change in mean conditions.

Transient BCSD contrasts sharply with Hybrid-Delta and Delta information types. Hybrid-Delta and Delta methods feature a familiar sequence of monthly temperature and precipitation conditions adjusted to reflect future period-climate statistics. Transient BCSD features a time-evolving (statistically non-stationary) sequence reflecting the gradual influence of global warming on regional weather conditions. The time-evolving sequence maps to the monthly sequence simulated by GCMs over the region and modified via BCSD. Initially this product is only a monthly gridded BCSD dataset (i.e., like data served at the DCP archive). UW CIG translates this into what they call "Transient BCSD" by implementing a time-disaggregation procedure (Wood et al. 2004), effectively converting monthly gridded climate data to daily gridded weather data (summarized in Section 4.0). As a result, the monthly to lower frequency aspects of temperature and precipitation sequences in the Transient BCSD products may differ from historical experience (e.g., timing of a drought or below-normal runoff conditions during the historical part of the Transient BCSD period differing from experience, or duration-frequency aspects of climatic excursions on monthly to longer time scales differing from experience).

A potential advantage of the Transient BCSD information relative to Hybrid-Delta information is that it is more time-flexible and permits portrayal of a time-evolving system view that may be useful for adaptation planning purposes (e.g., how do evolving climate conditions map to evolving managed system conditions, and when do system conditions cross a performance threshold requiring action?). The Transient BCSD information also permits portrayal of climatic sequences not experienced, which might be useful in testing system robustness. A disadvantage of the Transient BCSD information is that the time-disaggregation procedure to convert monthly BCSD climate to daily BCSD weather (necessary for hydrologic modeling) can produce undesirable weather artifacts at very local scales, which may be a concern for local impacts studies. Another issue with Transient BCSD is that in order to portray future climate uncertainty at any point in time, it is necessary to consider an ensemble of transient projections and view them to collectively to show an evolving envelop of climate variability (from historical to future). To get a well-characterized evolving envelope, it is best to have many climate projections in the ensemble. Comparatively, the HB2860 information source only has 10 BCSD projections available, which may be somewhat sparse for characterizing an evolving envelope of future climate conditions.

Thinking about applying HB2860 data for the RMJOC effort, there was interest in the Hybrid-Delta and Transient information types because both types feature an ensemble of scenarios and permit portrayal of climate uncertainty during a given future period. There was also interest in exploring the use of both types. Hybrid-Delta scenarios were attractive because they permitted portrayal of expanded or contracted envelopes of climate variability, but without departure from familiar climatic sequences (i.e., historical occurrence of dry or wet periods, warm or cool periods). Transient scenarios were attractive because they permit portrayal of drifting system performance which might be useful for adaptation planning. Application of Transient scenarios within this RMJOC effort would also move the agencies towards having greater flexibility in types of hydrologic sequences featured in their planning analysis frameworks, forcing departure from input hydrology tied to observed hydroclimate sequences.

3.2 Selection of UW CIG Data for use in this RMJOC Study

The RMJOC work group decided to utilize the UW CIG HB2860 information source, and to utilize two of the three information types at this source: Hybrid-Delta and Transient. Two factors drove this decision:

- The HB2860 source is built on an ensemble of global climate projections representative of available information on future climate over the Pacific Northwest.
- The HB2860 source provides corresponding hydrologic information and the effort required to generate such information is considerable (Section 4.0).

This decision included focusing on Hybrid-Delta scenarios for the 2020s and 2040s periods, noting these periods to be more relevant for RMJOC long-term planning purposes compared to the 2080s period. Lastly, a decision was made to focus on Transient BCSD scenarios derived from underlying climate projections that also support definition of selected Hybrid-Delta scenarios for this effort.

Moving forward, the following scenario selection questions were addressed during initial stages of this effort, vetted at meetings involving the RMJOC technical team and stakeholders (October 16, 2009 and December 7, 2009[13]). Two primary questions were addressed in HB2860 scenario selection, which are addressed in the following sub-sections:

- Should some of the HB2860 information be culled from consideration?
- Of the retained information, should all Hybrid-Delta and Transient scenarios be used in this effort and subsequent planning applications conducted by RMJOC agencies, or should we rationalize selection and a scenarios subset for RMJOC agencies' planning purposes?

3.2.1 Decision whether to cull UW CIG Data before making Selections

In this effort, consideration was given toward the notion that some of the HB2860 Hybrid-Delta or Transient scenarios might be relatively more credible to support RMJOC planning purposes given relative regard for the global climate projections that underlie these scenarios. It might be possible to establish some basis for judging relative credibility of the climate projections underlying Hybrid-Delta and Transient scenarios and then to use that relative credibility to rationalize the culling of projections from consideration. Relative credibility might be based on views about the likelihood of the future emissions scenario underlying the given climate projection, or views about the skill of the GCM used to simulate the given climate projection. For the most part, the basis for establishing such rationale was found to be unclear and all HB2860 Hybrid-Delta and Transient scenarios were retained for selection consideration as this section explains.

On determining relative likelihood for emissions paths, there is limited guidance on which path is more probable (IPCC 2007) because the distribution of CMIP3 climate projections presented in AR4 show that the expected range of climate possibilities does not become dependent on IPCC Special Report on Emissions Scenarios (SRES) paths (IPCC 2000) until about the middle 21st Century (IPCC 2007). Consequently, for defining regional climate change scenarios in this study, the RMJOC work group decided to consider scenarios reflecting either A1B emissions or B1 emissions in the HB2860 information source. According to IPCC (2000), the A1 scenarios are of a more integrated world characterized by rapid economic growth; a global population that reaches 9 billion by 2050 and then gradually declines; quick spread of new and efficient technologies; and a convergent world with extensive social and cultural interactions worldwide. A1B is a subset scenario with balanced

[13] Meeting materials are at: http://www.usbr.gov/pmts/rivers/awards/Nm2/tp/rmjoc/

emphasis on all energy sources, contrasting from fossil-intensive A1FI and non-fossil A1T. The B1 scenarios are a more integrated and ecologically-friendly world, characterized by economic growth similar to A1 but with rapid changes towards a service and information global economy; population growth similar to A1; reductions in material intensity and the introduction of clean and resource efficient technologies; and an emphasis on global solutions to economic, social, and environmental stability.

The A1B emissions pathway leads to a greater rate of GHG accumulation in the atmosphere than the B1 pathway, which leads to more warming with time. Granted, there are other SRES scenarios that lead to greater warming over time (e.g., A1FI). However, as stated, this effort is focused on climate possibilities through the 2040s, and it has been shown that future climate response to emissions pathway does not appear to significantly vary between the A1B and B1 pathways until after the mid-21st Century (IPCC 2007).

On determining relative credibility of climate models, there has been more research activity (e.g., Dettinger 2005, Tebaldi et al. 2005, Brekke et al. 2008, Reichler and Kim 2008, Gleckler et al. 2008, Mote and Salathé 2010). The general approach has been to evaluate climate models' relative skill in simulating historical conditions relative to observed historical conditions. Models found to have a closer match to observations (for the climatic variables and statistical metrics considered) are regarded as having relatively better skill. A philosophical bridge is then made, saying that the relatively more credible models based on historical simulation skill should offer more reliable climate simulations during the future. To date, there still remains limited evidence to support such a philosophical statement (Reichler and Kim 2008, Santer et al. 2009, Pierce et al. 2009). It has been shown that when such skill assessments are based on a few climate metrics (e.g., Tebaldi et al. 2005, Mote and Salathé 2010), the clarity of "better" versus "worse" climate models is more obvious than when the assessment is based on a larger collection of metrics (Brekke et al. 2008, Reichler and Kim 2008, Gleckler et al. 2008). However, even when the historical skill assessment results have been used to rank and cull climate models, thereby conditioning the assessments of future climate uncertainty (Brekke et al. 2008) or detection and attribution of causes for trends in historical atmospheric water vapor over large spatial scales (Santer et al. 2009), the effect of model culling has been minor to indistinguishable. Instead, it appears that there are other factors driving spread and rank of projected climate changes within an ensemble, including emissions pathway and the interplay between a GCM's "natural variability." The latter is important because sequences of simulated regional climate variability depend on initial global climate state (i.e., distributed ocean heat content, phase-state of ocean cycles like the Pacific Decadal Oscillation (Mantua et al. 1997), and CMIP3 projections do not exhibit consistent initial global climate states. The factor has been shown to be significant on interpreting climate projection uncertainty at a spatial scale of the British Isles, which is similar in scale to the Columbia-Snake region (Hawkins and Sutton 2009).

In summary, given the lack of evidence demonstrating the utility of culling projections based on relative GCM skill or evidence suggesting greater likelihood of one GHG emissions path over another, a preliminary decision was made for this effort to not cull any projections from the chosen data source. That means that all Hybrid-Delta scenarios from the HB2860 information source were included in the subsequent deliberations on selecting a scenario subset for application interests of simplicity and manageability. However, feedback was provided during the process by BC Hydro that in their view, some of the GCMs used to generate HB2860 global climate projections exhibit desirable simulation skills over the Pacific Northwest and British Columbia region (Mote and Salathé 2010). Consequently, a subjective decision was made to choose Hybrid-Delta and Transient scenarios from one such GCM preferred by BC-Hydro, as will be explained in the next section.

3.2.2 Selecting a Subset of UW CIG Data for RMJOC Applications

In holding discussions with technical team members and stakeholders, the RMJOC work group decided to select a smaller, representative set of Hybrid-Delta 2020s scenarios (relative to the 20 available), Hybrid-Delta 2040s scenarios (relative to the 20 available), and associated Transient scenarios. This decision stemmed from discussions on the advantages and disadvantages of using all available HB2860 scenarios for RMJOC planning purposes. It was apparent that use of all scenarios would be advantageous for portraying future climate and system uncertainties; however, the matter of applying the RMJOC agencies' current operations modeling and assessment procedures to handle many future hydroclimate scenarios was seen as a very challenging and time consuming undertaking and disadvantageous in the near-term (relative to focusing on a few scenarios). The present paradigm features a portrayal of future hydrologic and water supply possibilities indicated by a single scenario of historical hydrologic experience. System hydrologic and operational statistics are then assessed and communicated within this historical context. Such practice is commonplace in water resources planning throughout the United States and incorporation of climate projection information within this paradigm introduces challenges (Brekke et al. 2009).

In order for RMJOC agencies to broaden from a single hydrologic scenario to many scenarios reflecting future climates, both analytical and communication challenges would have to be addressed. On analytical challenges, in order to feasibly analyze many hydrologic scenarios (multiplied by however many planning alternatives), some aspects of RMJOC agencies' current operations analysis procedures would have to be converted from a process featuring manual interaction under each scenario (e.g., inspecting preliminary model results, making judgments about model settings given hydrologic inputs, adjusting model settings, and repeating until results are judged to be reasonable) to an automated process where such manual interaction is replaced by additional model logic that is developed to adequately approximate results that would have occurred via the manual interaction. On communication challenges, any communication of results for a given planning alternative that is assessed within the context of many hydroclimate scenarios would likely require aggregating results across scenarios. This would probably require orienting RMJOC decision-makers and stakeholders on probabilistic approaches to viewing the information that differ from modes of communication they have grown accustomed. It is possible for RMJOC agencies to address both of these challenges; however, doing so was beyond the scope of this effort.

Based on these considerations, the RMJOC work group decided that this effort should put RMJOC agencies in a position to consistently incorporate climate change into planning efforts, but not force significant departures from analytical and communication practices at this time. This leads to focus on a smaller, more manageable set of future hydroclimate scenarios; however, it is recognized that there are advantages to being able to assess larger scenario sets and communicate such information to decision-makers. Follow-on RMJOC collaborations may be scoped to address this potential goal. There may be motivation to scope such an effort upon the release of CMIP5 (expected 2012), where there will be interest to understand what updated global climate projections imply for the region and perhaps to advance analytical and communication capacities in the process.

Proceeding with the objective of selecting small, representative scenario sets, potential rationale were discussed at initial technical team and stakeholder meetings. Ultimately, a decision was made to select enough Hybrid-Delta scenarios per future period (2020s and 2040s) to indicate central change possibility and to portray change uncertainty ranging from less to more warming and from less to more precipitation. At minimum, this suggests selection of five Hybrid-Delta scenarios for each period. As summarized below, discussions at the second meeting led to selection of a sixth scenario. This will be explained after summarizing rationale for selecting the minimum five scenarios per period.

Four factors were used to guide selection of five Hybrid-Delta scenarios per period.

- Factor 1 - Future look-ahead periods considered in various RMJOC planning efforts that we expect this dataset to serve.

- Factor 2 - Climate metrics that might be used to diagnose spread of climate changes within the collection of HB8260 Hybrid-Delta scenarios, with interest in metrics that broadly relate to different types of climate-related planning inputs (e.g., hydrologic conditions, environmental conditions, water supplies, water demands, power demands, operating constraints). For example, climate metrics might focus on mean annual or seasonal climate or range of annual or seasonal climate variations. It is understood that focus on certain metrics may lead to removal of scenarios that suggest more pronounced changes in other metrics. For example, scenario selection may arrive at different scenario choices if the selection is meant to describe range of changes in mean climate rather than range of changes in climate variability.

- Factor 3 **–** Geographic focus of climate changes for metric and future periods indicated in Factors 1 and 2.

- Factor 4 **–** Projected "Change Range" of interest, given Factors 1 through 3 applied to all HB2860 Hybrid-Delta scenarios of a given look-ahead period. A motive for setting a broader range of interest would be to represent the breadth of possible future climates indicated by available climate projection information. It is also motivated by recognition that the collective of CMIP3 climate projections represents a limited range of future climate possibilities that probably does not fully reflect all uncertainties. A motive for setting narrower range of interest would be a concern about misinterpreting change in 30-year climate as "climate change only" rather than a blend of "climate change and natural variability" given that CMIP3 global projections do not originate from a common global climate state, which may cause interpretation uncertainties at the regional scale (Hawkins and Sutton 2009). The concern is that 30-year changes may be sampled from a climate projection and be misinterpreted as climate change, when in fact such changes may be sampled low-frequency climate variations. This challenge is particularly relevant when sampling and interpreting 30-year regional precipitation changes from global projections (Giorgi 2005).

The first three factors might be abbreviated to reflect questions of climate change by when, for what climatic aspect, and over what region. The last factor speaks to risk attitudes of planners, namely how much climate change uncertainty do they wish to reflect in planning efforts. Application of Factors 1 through 4 helps identify four bracketing climate change scenarios among the possibilities considered and has been featured in recent planning applications (Reclamation 2008, LCRA SAWS 2008, Reclamation 2009, CWCB 2010, Reclamation 2010a). Identifying a fifth, or central, climate change scenario can be done by modifying Factor 4 to be concerned with "change range" and "central tendency" among candidate change scenarios considered.

Application of the four factors required decisions by RMJOC technical team and stakeholder members. It was predetermined that Factor 1 would be the first two Hybrid-Delta periods and likewise change in 30-year climate conditions. This led to group focus on specifying Factors 2 through 4. Given that each RMJOC agency and participating stakeholder implements different types of long-term planning studies within the region, it is understandable that there was a diversity of views on how to specify these factors for application in this effort.

- *Reclamation*: Suggested Factor 2 focus might be placed on two metrics, mean-annual temperature and mean-annual precipitation, noting that these two metrics broadly relate to a variety of hydrologic and environmental conditions underlying many planning assumptions. Suggested Factor 3 focus on the spatially averaged Factor 2 metric conditions over the Columbia-Snake River Basin (basin-wide), noting that this setting would best serve a geographically dispersed set of planning interests among RMJOC agencies and stakeholders if the goal is to adopt a common scenario set. On Factor 4, suggested that the change range of interest might be defined by the intersection of Hybrid-Delta Scenarios' spread of scenario-specific climate change coordinates. To define the spread, first consider each Factor 2 metric individually and identify a desirable percentile range reflecting risk attitudes (e.g., 25th to 75th percentile range, or 10th to 90th percentile range), then intersect the range of changes within chosen percentile limits for each Factor 2 metric and subjectively select scenarios expressing "climate change coordinates" closest to the vertices of this intersected range (i.e., scenario-specific changes in mean-annual temperature (ΔT) and mean-annual precipitation (ΔP) closest to target paired percentile coordinates: $\Delta T_{10\%\text{-tile}}$ vs. $\Delta P_{10\%\text{-tile}}$; $\Delta T_{10\%\text{-tile}}$ vs. $\Delta P_{90\%\text{-tile}}$; $\Delta T_{90\%\text{-tile}}$ vs. $\Delta P_{10\%\text{-tile}}$; $\Delta T_{90\%\text{-tile}}$ vs. $\Delta P_{90\%\text{-tile}}$; and $\Delta T_{50\%\text{-tile}}$ vs. $\Delta P_{50\%\text{-tile}}$. Similar logic would be used to identify the central change scenario, targeting proximity to $\Delta T_{50\%\text{-tile}}$ vs. $\Delta P_{50\%\text{-tile}}$.

- *NPCC*: Suggested Factors 2 and 3 should respectively be mean-annual temperature and precipitation spatially averaged over the Columbia-Snake River Basin (basin-wide). On Factor 4, given the two change ranges suggested by Reclamation, they specified no preference.

- *USFWS*: Suggested Factors 2 and 3 should be mean-annual temperature and precipitation spatially averaged basin-wide. On Factor 4, given two change range options suggested by Reclamation, they suggested it might be better to focus on the smaller range (25th to 75th percentiles), questioning whether the broader range might be too extreme.

- *BC-Hydro*: Did not offer specific suggestions on Factors 2 through 4, but provided a memorandum offering general support for the RMJOC work group's rationale for the selection of GCMs for hydrologic impact studies (i.e., selection factors discussed above). However, they did express concern about limiting the number of Hybrid-Delta scenarios selected for 2020s and 2040s periods and asserted that it would be preferable to characterize future hydrology and operations using a larger collection of the HB2860 scenarios (or all of them). On the matter of emission scenarios, they recommended that the A1B, A2, and B1 emissions scenarios should be used in the study even though recent updates on the trajectory of global greenhouse gas emissions and the current direction of economic development might be interpreted to suggest that the B1 scenario seems to be less likely (Mote and Salathé 2010).

- *USACE*: Suggested Factor 2 might be rationalized for several different climatic metrics (mean-annual, mean-seasonal, extreme conditions, etc.) or for hydrologic metrics simulated under associated climate conditions (Section 4.0). Suggested Factor

3 might be specified to reflect basin-wide conditions (as suggested by the Council and USFWS) and/or on a combined subset of Columbia River headwater subbasins more "relevant" to USACE operations concerning flood control (i.e., from Figure 4, REVEL, MICAA, CORRA, WANET, and DWORS). On Factor 4, given the options indicated above, no preference was specified. However, given a chosen change range and target percentile coordinates, they suggested that objective methods might be used to select scenarios proximate to target climate change coordinates. They also suggested applying such a scheme for multiple settings of Factor 2 and 3 and then selecting scenarios that are most frequently selected to bracket spread candidate scenarios.

Based on discussion and consensus among participants, the four selection factors were set as:

- Factor 1: Future periods of 2010-2039 and 2030-2059 (i.e., HB2860s Hybrid-Delta 2020s and 2040s scenarios)
- Factor 2: Climate metric of 30-year mean-annual temperature and precipitation.
- Factor 3: Spatially averaged change in Factor 2 metric over the entire Columbia-Snake River Basin.
- Factor 4:
    - For identifying four "bracketing" scenarios, consider all B1 and A1b scenarios from CIG's HB2860 collection of Hybrid-Delta scenarios for a given future period and choose four that best approximate "climate change coordinates" describing a change range of interest bounding 10th percentile to 90th percentile changes in basin-average mean-annual temperature and mean-annual precipitation.
    - For identifying the fifth "central" scenario, apply similar logic, but identify Hybrid-Delta scenario closest to the intersection of 50th percentile temperature and 50th percentile precipitation changes.

Figure 9 illustrates the application of these factors to identify four bracketing scenarios (blue highlighted scenario numbers) and a central scenario (yellow highlighted number). Scenario numbers correspond to those listed in Table 3,[14] which also indicates selected scenarios.

[14] Note that the table lists only 19 Hybrid-Delta scenarios per period whereas the HB2860 website indicates that 20 per period are now available. At the time of scenario selection, only these 19 were available for consideration.

Figure 9 also illustrates that a sixth scenario was selected for both Hybrid-Delta 2020s and 2040s periods (pink highlighted numbers). One motivator was offered by stakeholders from U.S. Fish and Wildlife Service to include scenarios that feature relatively less warming and minimal precipitation change relative to the spread of changes portrayed in the HB2860 scenario ensembles, particularly for the 2020s period. Another motivator was to include scenarios from one of BC Hydro's preferred GCMs. Balancing both motives, the sixth scenarios were selected and conveniently arise from a common underlying climate projection generated by one of BC Hydro's preferred GCMs.

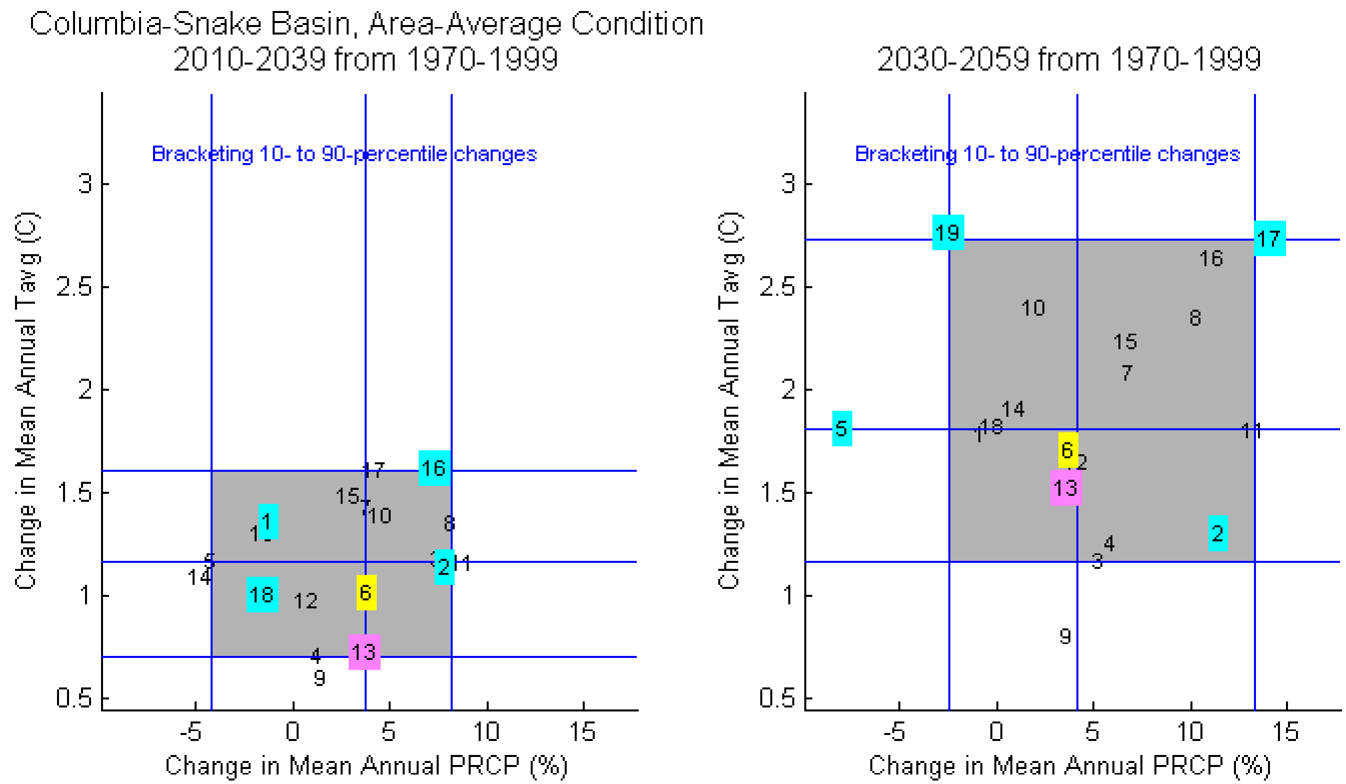

Figure 9. Selected UW CIG HB2860 Hybrid-Delta climate change scenarios.

Figure Explanation: The left panel shows the 19 2020s Hybrid-Delta (HD) Scenarios from Table 3. *The right panel shows the 19 2040s HD scenarios from Table 3. The three vertical blue lines on each panel are the 10, 50 and 90 percentile changes in ΔP among the 19 scenarios for the given period. The three horizontal blue lines are similar, but for change in ΔT. The gray shaded region is the change range of interest (selection Factor 4). The resultant six HD scenarios selected per period are color-highlighted.*

Table 3. List of UW CIG HB2860 climate projections and Hybrid-Delta climate change scenarios and Transient Hydrologic projections.

Climate Projections [1]			"Climate Change" Hydrology (Hybrid-Delta Scenarios)						Hydrologic Projections (Transient) (x = selected, o = not selected)
			2020s			2040s			
Number	Climate Model	Emissions Scenario	Selected (RMJOC Labels) [2]	Change in P (%) [3]	Change in T (°C) [3]	Selected (RMJOC Labels) [2]	Change in P (%) [3]	Change in T (°C) [3]	
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] CMIP3 climate projections are referenced by climate model, emissions scenario, and initial condition (i.e. run #). All CMIP3 climate projections are "run 1" for the given combination of climate model and emissions scenario, except for projection number 1 (run 5) and number 9 (run 2).

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

[3] Change in mean precipitation (P) or temperature (T) spatially averaged over the Columbia-Snake River Basin. 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).

There were other minor considerations driving scenario selections not highlighted here, including discussion on how this effort was limited by CIG's decision to only include B1 and A1b emissions-scenarios in their information set and not include "higher" emissions paths like A2 and A1Fi (IPCC 2000). It was judged that this effort was largely unaffected by this decision given that the focus is generally on climate change during the first half of the 21st Century and that it has been shown that projected climate change uncertainty is largely insensitive to the variations in these emissions pathways until the latter half of the 21st Century (IPCC 2007). For additional information, the reader is invited to review meeting materials for the December 7, 2009, technical team and stakeholders' workshop.[15]

3.3 Summary of Selected Future Climate Scenarios

In summary, six Hybrid-Delta 2020s and six Hybrid-Delta 2040s climate change scenarios were selected for RMJOC purposes (Table 3). Summary changes in mean-annual temperature and precipitation are listed for these scenarios. The table also indicates that six HB2860 Transient scenarios were selected for RMJOC purposes to support comparative operations assessments under both the Hybrid-Delta and Transient information types (addressed in subsequent reports). Table 3 indicates that 14 Transient scenarios were available for consideration ("o"),[16] and six of the 14 were selected here ("x").

3.3.1 Hybrid-Delta Scenarios

The Hybrid-Delta scenarios of each period-set were given qualitative labels for discussion purposes:

- The four bracketing scenarios were labeled less warming and wetter (LW/W), more warming and wetter (MW/W), less warming and drier (LW/D), and more warming and drier (MW/D).
- The central change scenario was labeled as such (C).
- The sixth scenario was labeled "minimal change" (MC).

[15] http://www.usbr.gov/pmts/rivers/awards/Nm2/tp/rmjoc/Meeting_091207/, RMJOC_Meeting_091207_Brekke_Task1.2-2.2.ppt.

[16] At the time of selection, 14 scenarios were available. UW CIG has since opted to serve only 10 of the 14 at their HB2860 website.

The remainder of this section offers a more detailed characterization of the selected scenarios, pointing out several issues relevant for planning application:

(a) How the set does or does not well-represent change range of interest on a subbasin view

(b) How individual scenarios have geographically complex patterns of change

(c) How the geographic complex patterns of change vary by month.

To preface, each of these issues speaks to how the scenario labels can be misleading (e.g., wetter or “W” versus drier or “D”) as these scenarios actually feature complex differences over the Columbia-Snake River Basin that vary geographically and on a month-to-month basis.

On issue (a), if attention is placed on subbasin climate changes for each selected scenario, review will show that these qualitative change labels may not apply as well for the subbasin view as they did for the basin-wide view. To illustrate, consider the Columbia-Snake River subbasins that were referenced in earlier discussion (Figure 4). Scatter of candidate HB2860 scenarios are assessed with the same selection factors 1 through 4, but with Factor 3 adjusted to be change by subbasin. Scatter is then plotted with RMJOC scenario selections highlighted as before (Figure 10 shows the spread of subbasin 2020s changes and Figure 11 shows the spread of 2040s changes). Some of the subbasin plots show that the selected scenarios reasonably bracket change range of interest for some subbasins. For others, the scenarios do not bracket the change range of interest as reasonably well (e.g., note how the set of selected scenarios are collectively “wetter” over OXBOW under both future periods relative to the basin-wide view [Figure 9]).

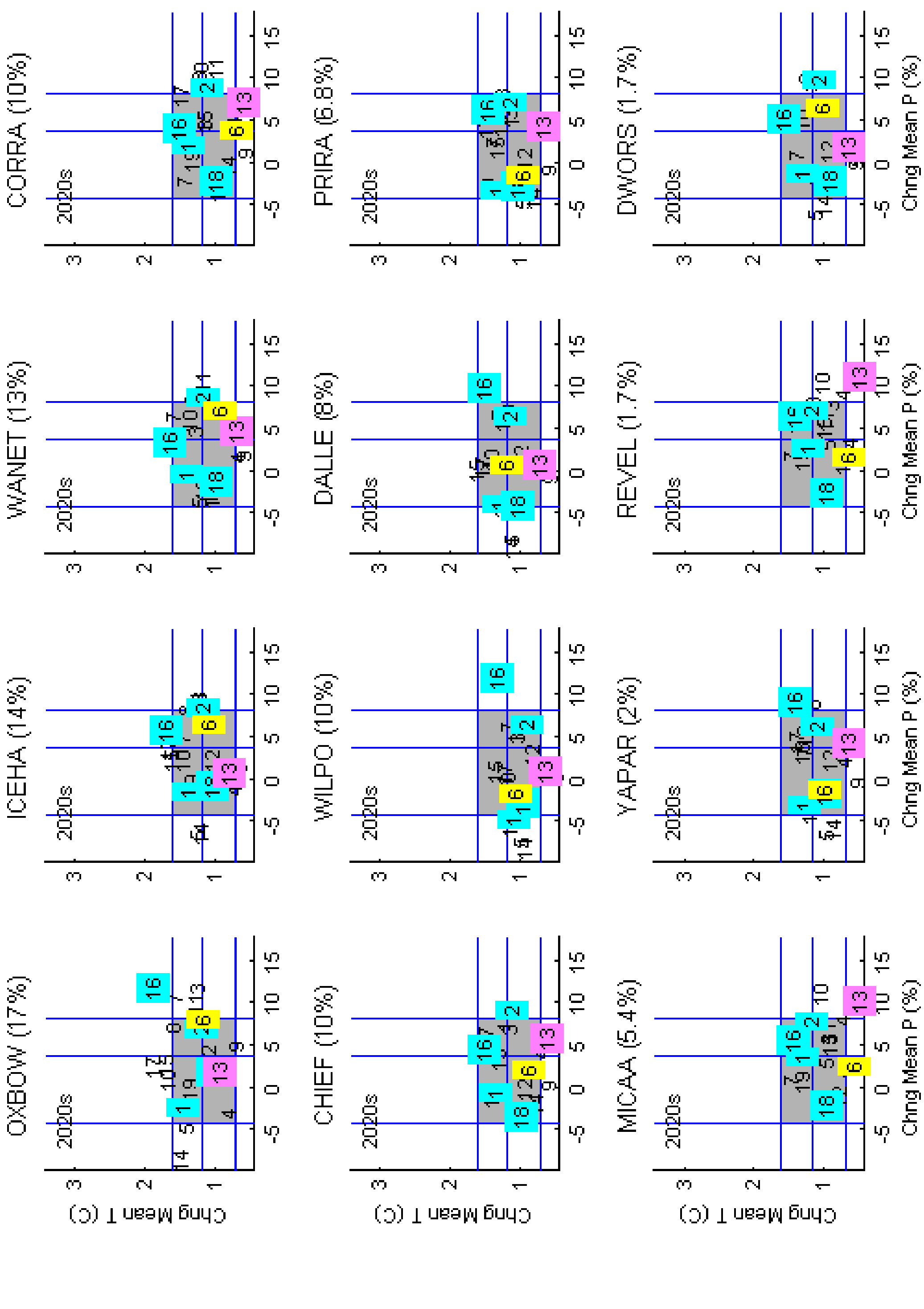

Figure 10. Similar to Figure 9, but showing spread of Hybrid-Delta 2020s changes by subbasin (Figure 4).

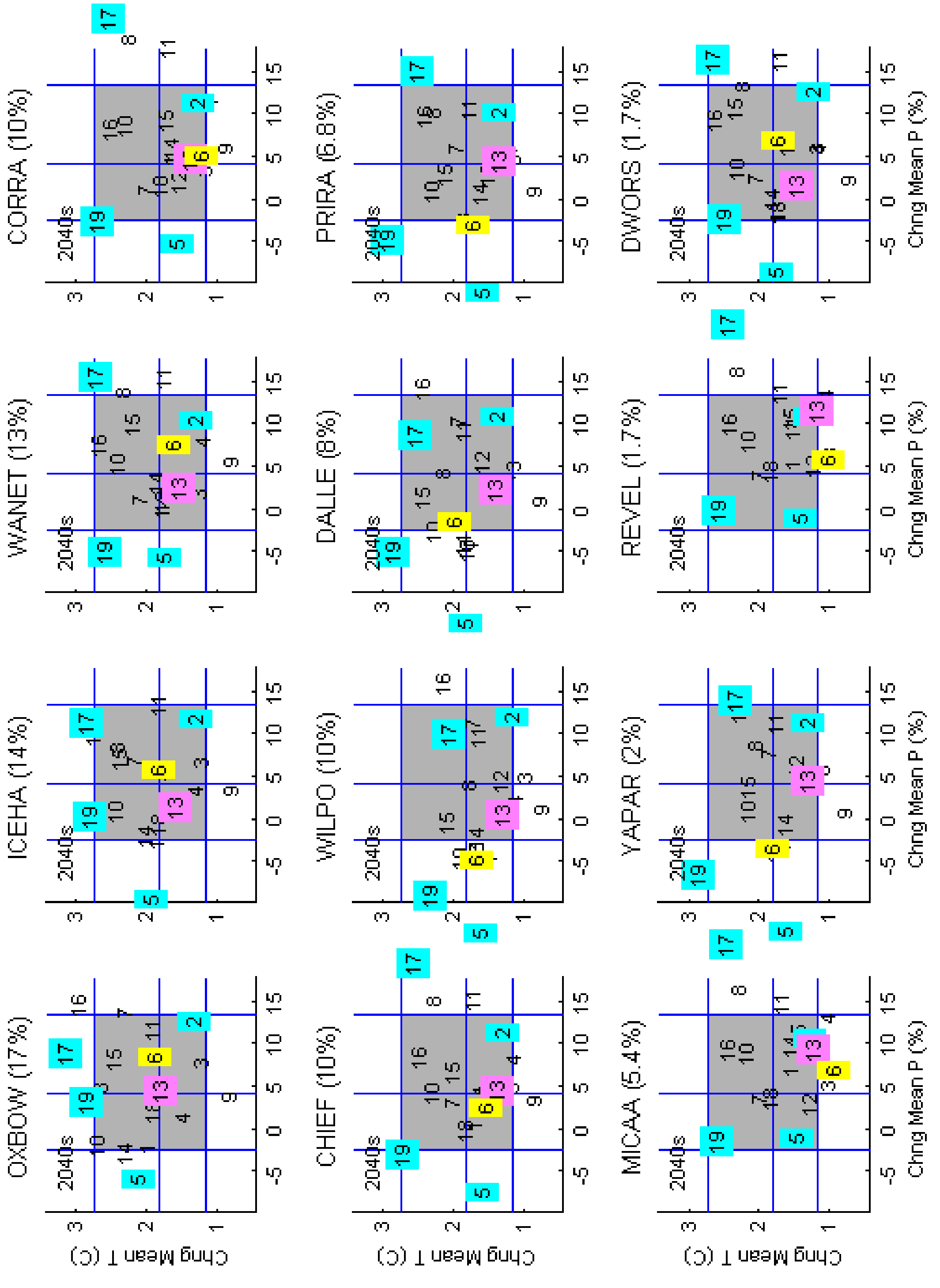

Figure 11. Similar to Figure 9 but showing spread of Hybrid-Delta 2040s changes by subbasin (Figure 4).

On issue (b), focusing on individual scenarios shows that although a scenario may be qualitatively labeled as one type of climate change (e.g., more warming and wetter), this does not necessarily mean that change for that scenario is spatially uniform across the basin. This is illustrated on Figure 12 through Figure 20.

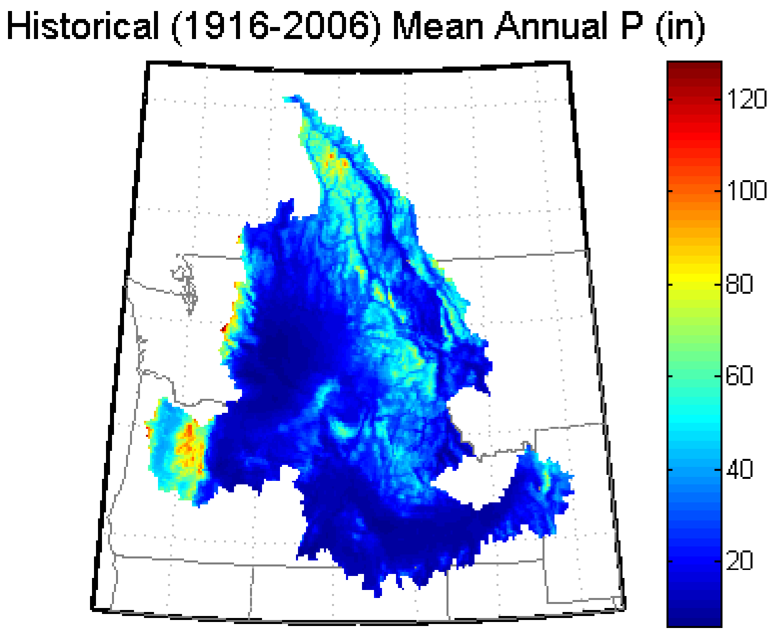

Figure 12. Observed mean-annual precipitation, 1916-2006.

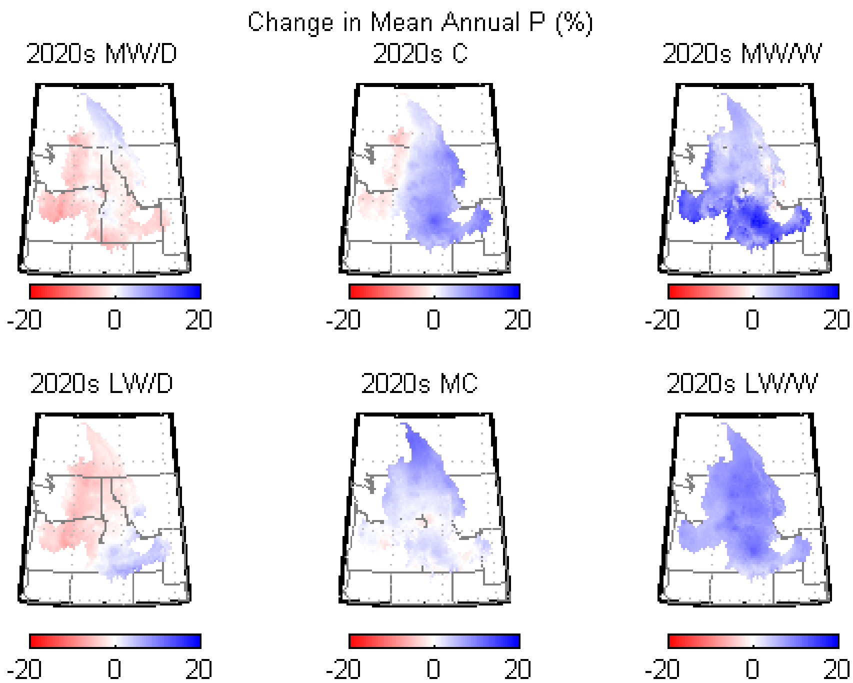

Figure 13. Changes in mean-annual precipitation (%) for Hybrid-Delta 2020s scenarios (Table 3) relative to observed historical.

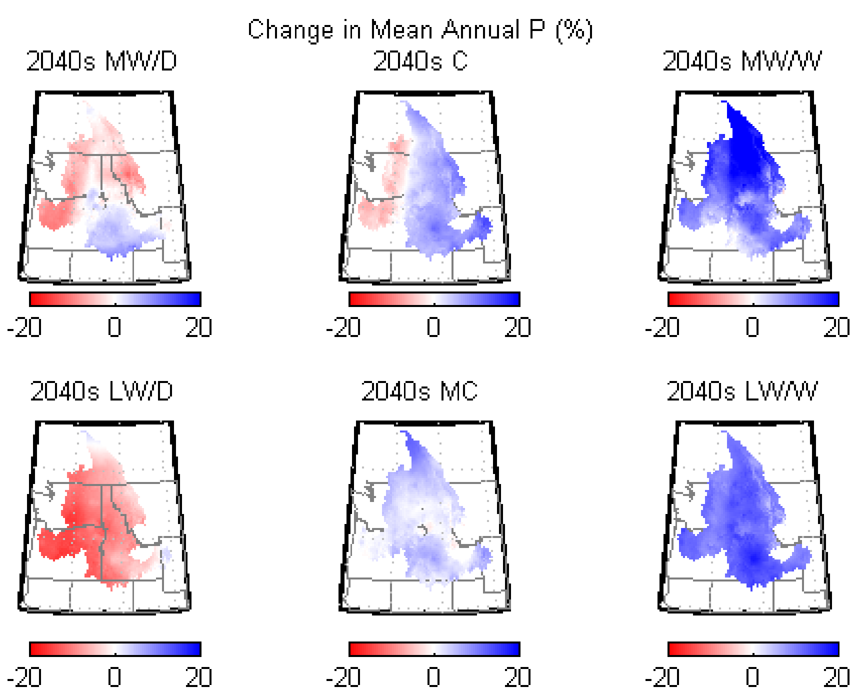

Figure 14. Changes in mean-annual precipitation (%) for Hybrid-Delta 2040s scenarios (Table 3) relative to observed historical.

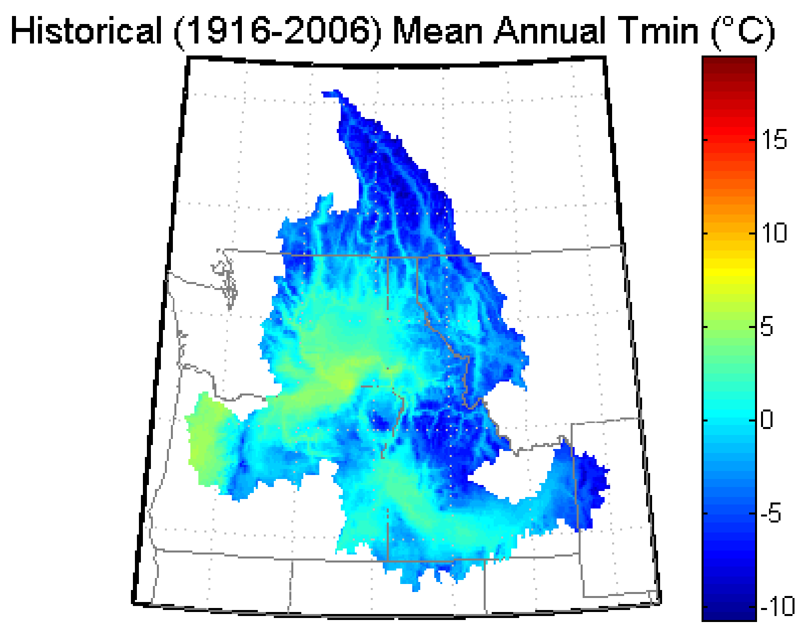

Figure 15. Observed mean-annual "daily minimum" temperature, 1916-2006.

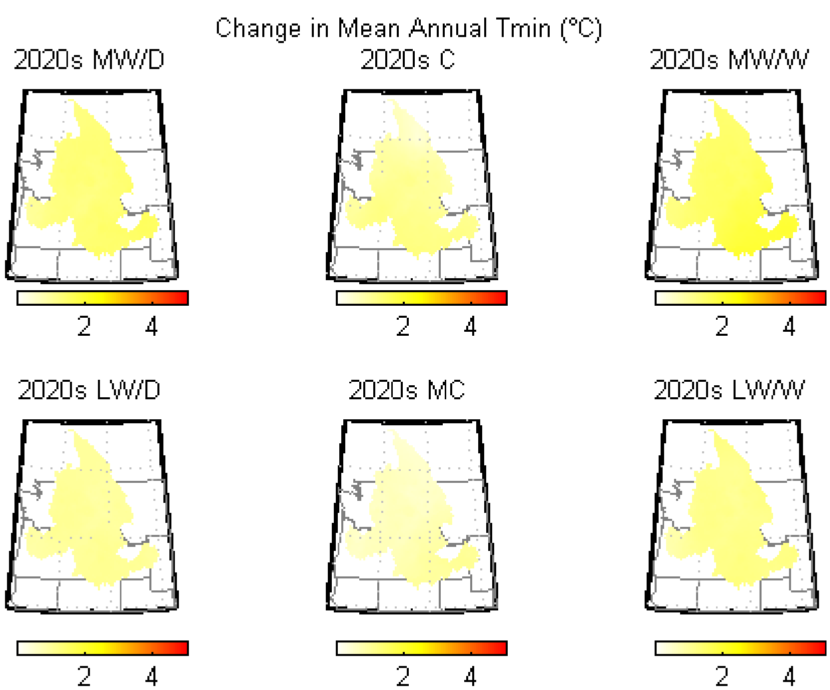

Figure 16. Changes in mean-annual "daily minimum" temperature for Hybrid-Delta 2020s scenarios (Table 3) relative to observed historical.

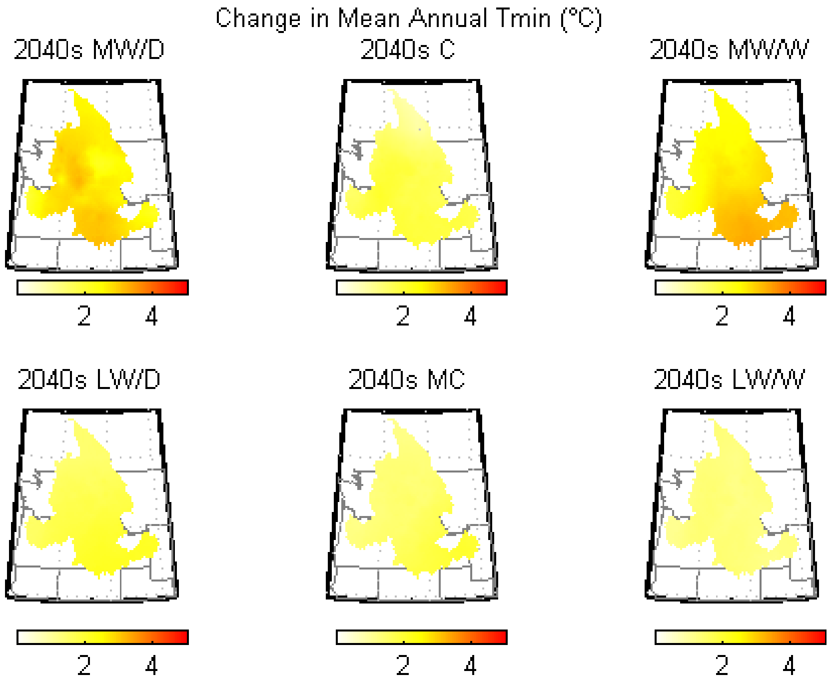

Figure 17. Changes in mean-annual "daily minimum" temperature for Hybrid-Delta 2040s scenarios relative to observed historical.

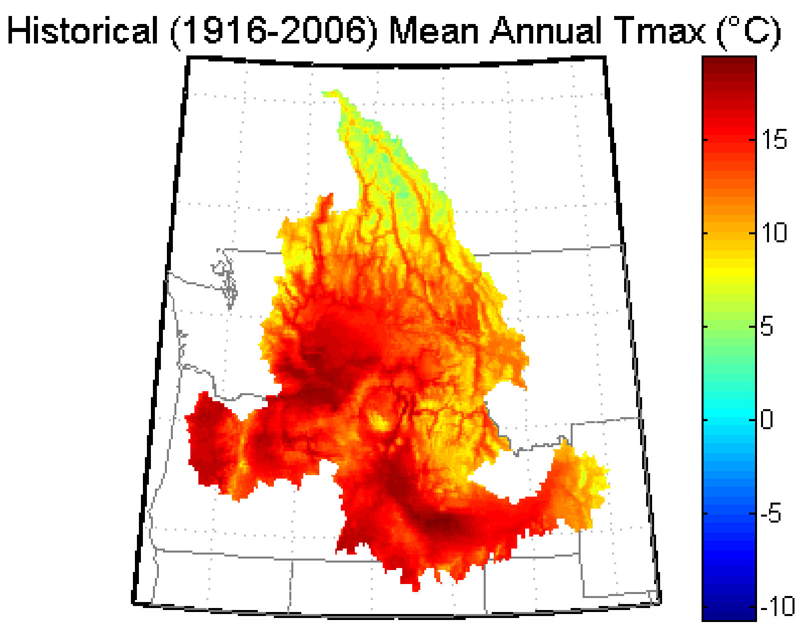

Figure 18. Observed mean-annual "daily maximum" temperature, 1916-2006.

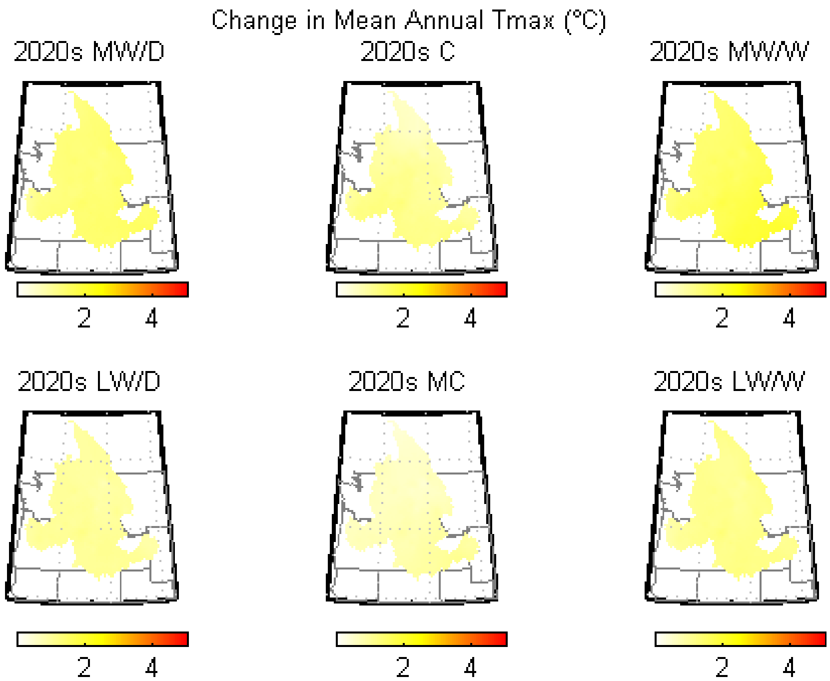

Figure 19. Changes in mean-annual "daily maximum" temperature for Hybrid-Delta 2020s scenarios (Table 3) relative to observed historical.

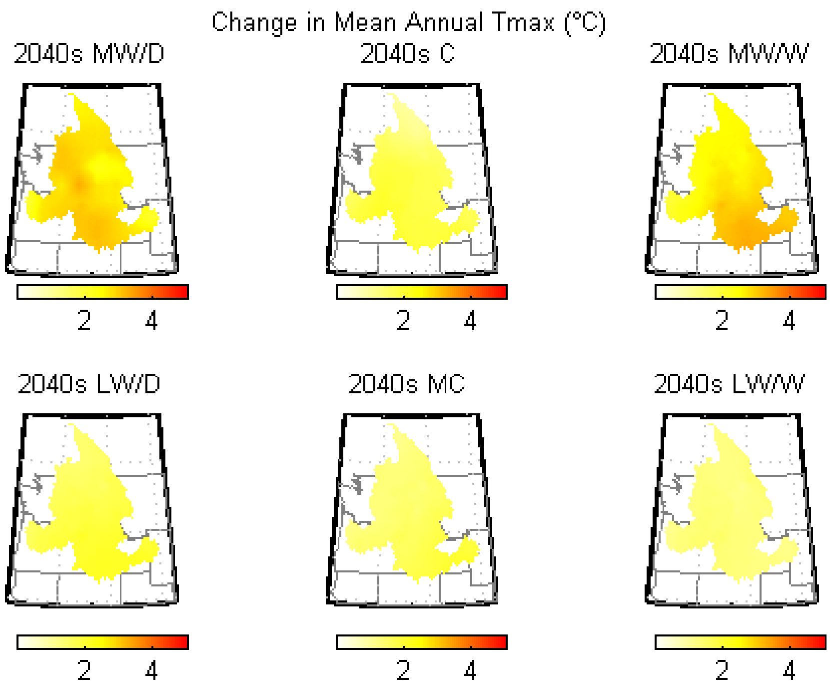

Figure 20. Changes in mean-annual "daily maximum" temperature for Hybrid-Delta 2040s scenarios (Table 3) relative to observed historical.

First consider the annual spatial climatologies on Figure 12, Figure 15, and Figure 18, respectively, for 1916-2006 mean-annual precipitation (P), "daily minimum" temperature (T_{min}), and "daily maximum" temperature (T_{max}) specified at each 1/16º grid cell within CIG's HB2860 Reference Historical Weather data. These maps illustrate how climatological precipitation and temperature conditions vary by location in the basin. Next consider changes in annual spatial climatology for each Hybrid-Delta scenario. This is generated by mapping changes in mean-annual conditions at each grid cell (i.e., a Hybrid-Delta scenario's mean 91-year condition departing from that of the Reference Historical Weather data, where the Hybrid-Delta's 91-year weather sequence is generated using a technique summarized in Section 4.0). The following observations might be made from these maps:

- For P, Figure 13 and Figure 14 show that change in mean-annual total precipitation (percent) is spatially distributed for both 2020s and 2040s scenarios. For example, the 2020s C scenario may feature a central "few percent" increase in mean-annual precipitation basin-wide (Table 3), but this masks how the scenario portrays drier changes over the western part of the basin and more substantial wetter changes over the eastern part. Similarly, the 2020s LW/D scenario is drier basin-wide, but spatially distributed view shows that the scenario is actually wetter over the Snake River portion.

- For T_{min} and T_{max}, the spatial change maps are the same given that Reference Historical T_{min} and T_{max} are adjusted by the same increments to reflect change in average daily temperature (Section 4.0). Nevertheless, change maps are shown for both variables and both future periods (Figure 16 and Figure 17 for T_{min} and Figure 19 and Figure 20 for T_{max}). Unlike for P, the sign of temperature change for T_{min} and T_{max} is spatially consistent for each Hybrid-Delta scenario over the basin. However, scenario-specific maps do show that increment of warming does vary spatially over the basin.

The maps on Figure 12 through Figure 20 might lead to questions about whether global climate change might trigger such geographically complex patterns over the region. Such complex regional change is not ruled out, but it is proposed that the scenario-specific change patterns actually exhibit climate change spatial variability, or "noise," that arises from considering individual underlying climate projections per scenario. Had a collection of underlying projections informed each scenario, then it is assumed that more consensus change information might be exhibited and that changes would be spatially more uniform, which is illustrated in the summary of DCP archive climate change information presented in Section 2.0 (Figure 5 through Figure 8) where ensemble percentile changes are spatially mapped rather than mapping changes from individual projections.

On issue (c), the focus switches from changes in mean-annual to changes in mean-monthly conditions. Considering how changes evolve from month to month, it is apparent that each Hybrid-Delta scenario also exhibits both geographically and serially complex change, especially for P. This is illustrated on Figure 21 which shows monthly maps of spatially distributed P changes for the 2040s MW/D scenario, and on Figure 22 which shows similar information for T_{min} (T_{max} maps are not shown, but are the same as T_{min} maps). For example in the single "drier" scenario shown (2040s MW/D scenario), much of the Columbia-Snake River Basin experiences wetter conditions during the months of March, April, and October. Focusing in on the Snake River tributary, wetter conditions are featured in this "drier" scenario for the months of January, April, May, and July through October. It would be hasty to interpret from a single projection that climate change should lead to wetter summers over the Upper Snake River subbasin and month-to-month oscillations in drier to wetter to drier changes over the whole basin. This is also not necessarily the case when many climate projections are considered. As with the discussion on mean-annual changes, it is noted that the geographic complexity of mean-monthly changes is introduced by building each Hybrid-Delta scenario from a single underlying climate projection, which also introduces month-to-month change complexity that varies geographically. If a collection of underlying projections were used to inform each Hybrid-Delta scenario, then month-to-month change factors would be more serially consistent over given locations. This has been shown in a recent study of climate change impacts on hydrology in Oklahoma, where Delta, Hybrid-Delta, and ensemble-informed Hybrid-Delta applications are compared (Reclamation 2010a).

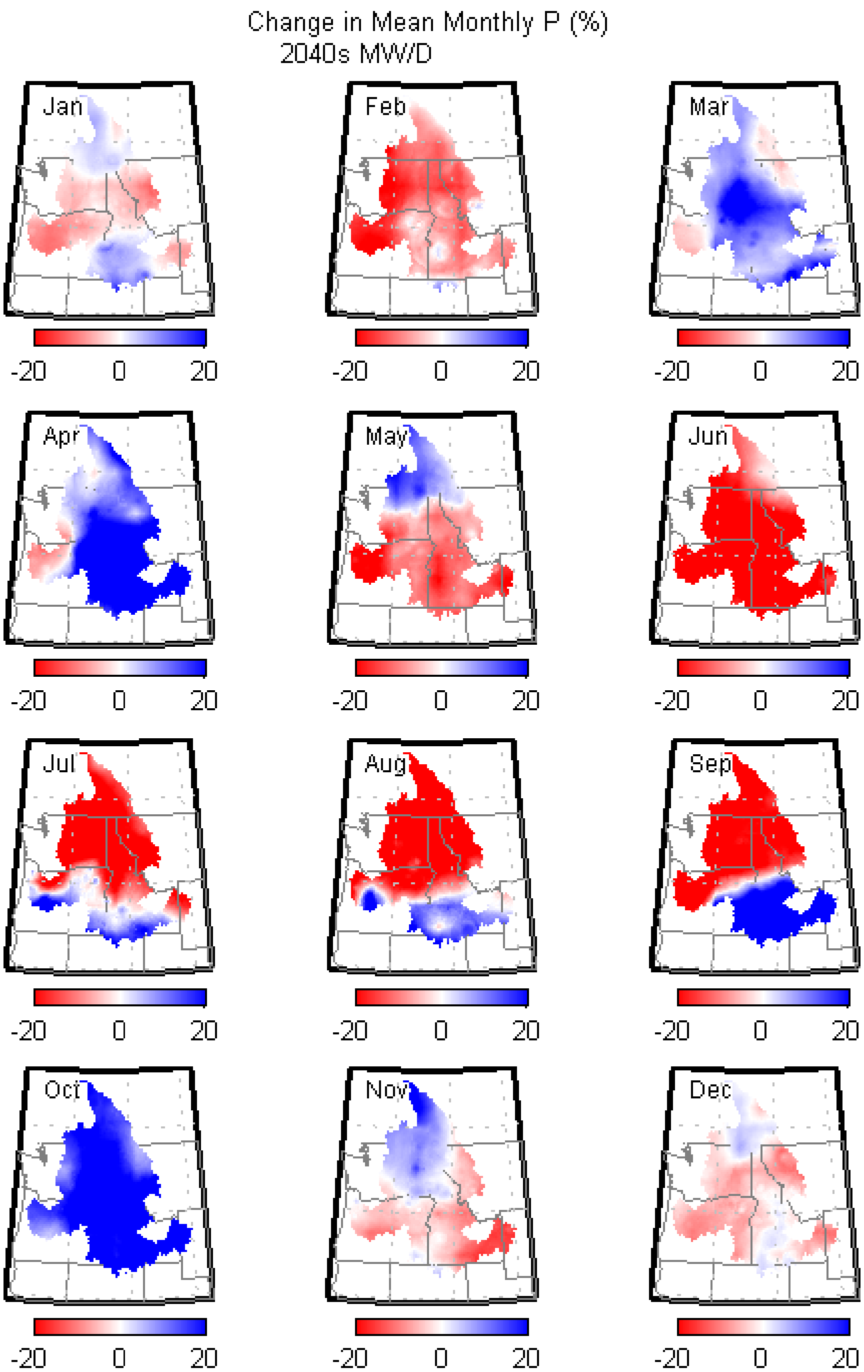

Figure 21. Changes in mean-monthly precipitation for HD 2040s MW/D scenario relative to historical.

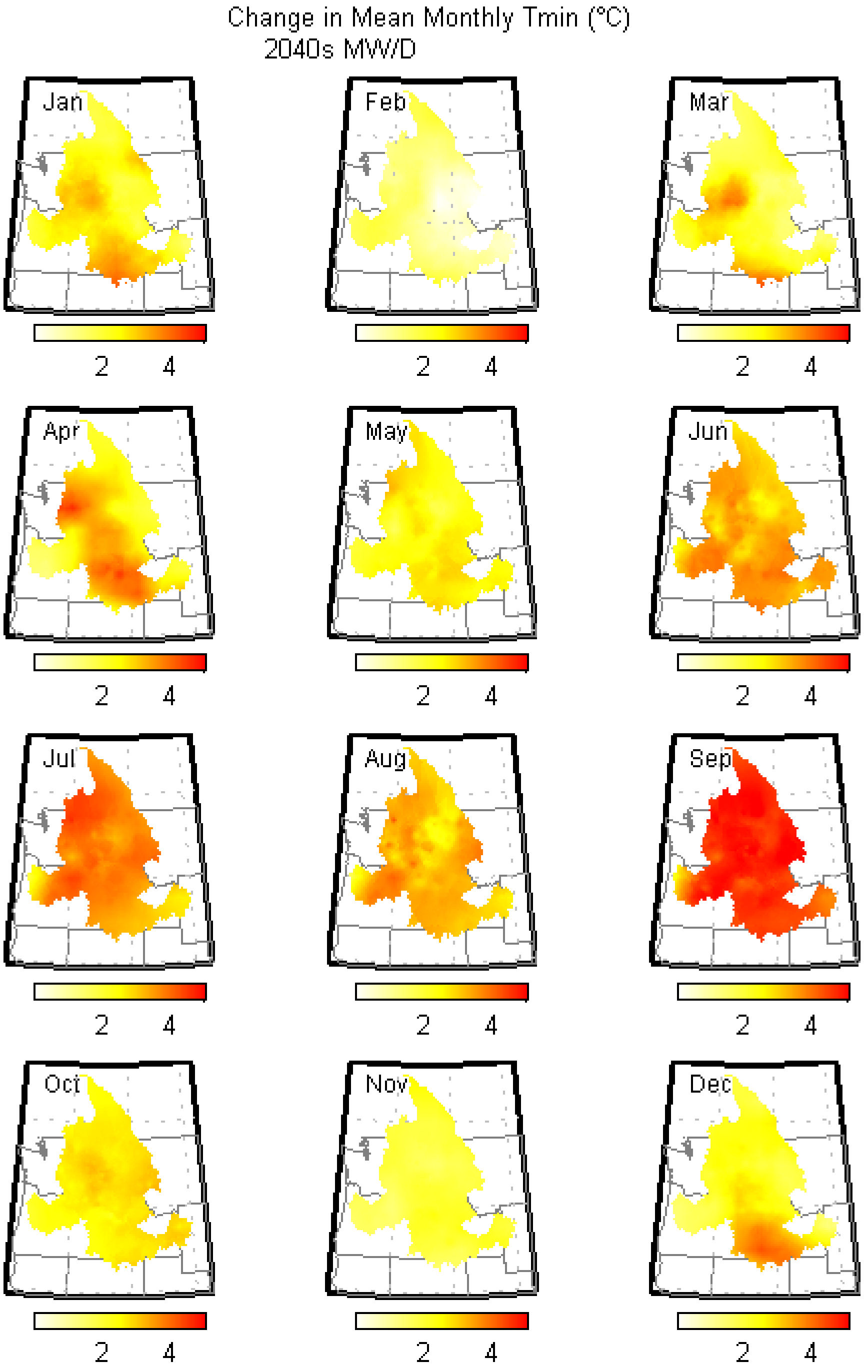

Figure 22. Changes in mean-monthly "daily minimum" temperature for HD 2040s MW/D scenario relative to historical.

3.3.2 Transient Climate Projections

The six HB2860 Transient scenarios from Table 3 are not qualitatively labeled like the Hybrid-Delta scenarios. Instead, the six Transient scenarios are each viewed as equally possible climatic sequences over the region. Further, the historical portion of the Transient scenario period (1950-present) does not map to the observed historical climatic sequence over the region; instead, it maps to the simulated climatic sequence expressed in the underlying global climate projection. However, the monthly BCSD processing used to develop each Transient climate scenario adjusts the underlying global climate projection so that it has consistent 50-year statistics with observed historical during a 1950-1999 common overlap period, where statistics includes all 50-year statistical moments. So although the historical sequencing may not be consistent with experience, the Transient scenarios' envelope of historical variability originates from a common envelope as what was experienced during 1950-1999. The scenarios then express evolving change in climate from this reference period.

The selected Transient climate scenarios are meant to be considered together as a group, or ensemble. Assessing the ensemble through time is meant to portray an envelope of climatic possibility through time. This is illustrated on Figure 23, where each panel shows the candidate 14 Transient basin-average ensembles of annual T_{min}, T_{max}, and P (gray lines), the 14-member ensemble median through time (heavy black line), and overlay of the RMJOC selected six Transient projections (yellow, red, and blue ensembles for T_{min}, T_{max}, and P, respectively). Tracking the ensemble-median suggests the central tendency of the given climatic condition through time. Tracking the ensemble spread suggests the drift in climate variability and prediction uncertainty through time. It is cautioned that a larger ensemble of projections informing Figure 23 would likely smooth out year-to-year variations in the ensemble median and ensemble envelope.

Comparing Hybrid-Delta and Transient information, it is evident that change in mean-annual conditions projected by the "central" Hybrid-Delta scenarios (2020s or 2040s) are similar to those implied by the ensemble-median of Transient scenarios (sampled during respectively the same periods). For example, consider the 2020s, the HD 2020s "C" scenario (Table 3) implies a change in basin-wide mean-annual temperature of roughly 1.0 ºC (1.8 ºF). Inspection of Figure 23 left or middle panels shows a similar change (about 2 ºF) in 30-year average "ensemble-median" from 1970-1999 to 2010-2039 (which are the 30-year periods used to define HD 2020s climate changes). Looking beyond the periods considered with the Hybrid-Delta information, the Transient information suggests that mean-annual temperature should continue to increase through the 21^{st} Century and that mean-precipitation might experience a slightly increasing trend.

The six Transient climate scenarios can be assessed for the same subbasins considered in assessing the Hybrid-Delta climate change scenarios (Figure 4). Figure 24 and Figure 25 show annual temperature and precipitation projection ensembles by subbasin, shown in similar fashion as Figure 23, but with annual mean T_{min} and annual mean T_{max} conditions simply averaged to estimate annual mean temperature as shown. Figure 24 shows that warming trends are expected in all subbasins during the course of the 21st Century. Figure 25 shows that precipitation trends are less pronounced, with some subbasins exhibiting slightly increasing trends in annual precipitation.

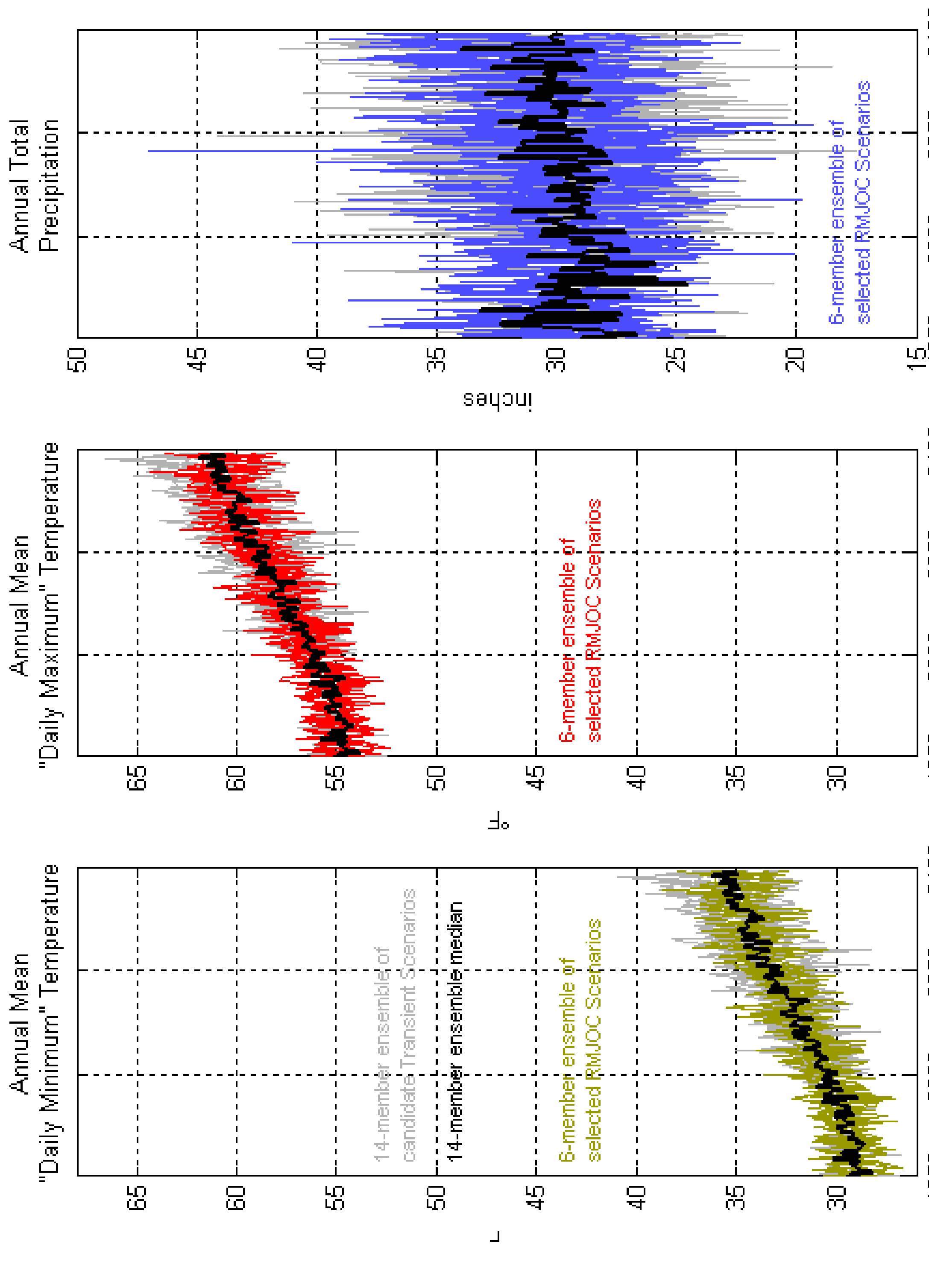

Figure 23. Selected UW CIG HB2860 Transient climate scenarios describing Columbia-Snake River Basin average climate conditions.

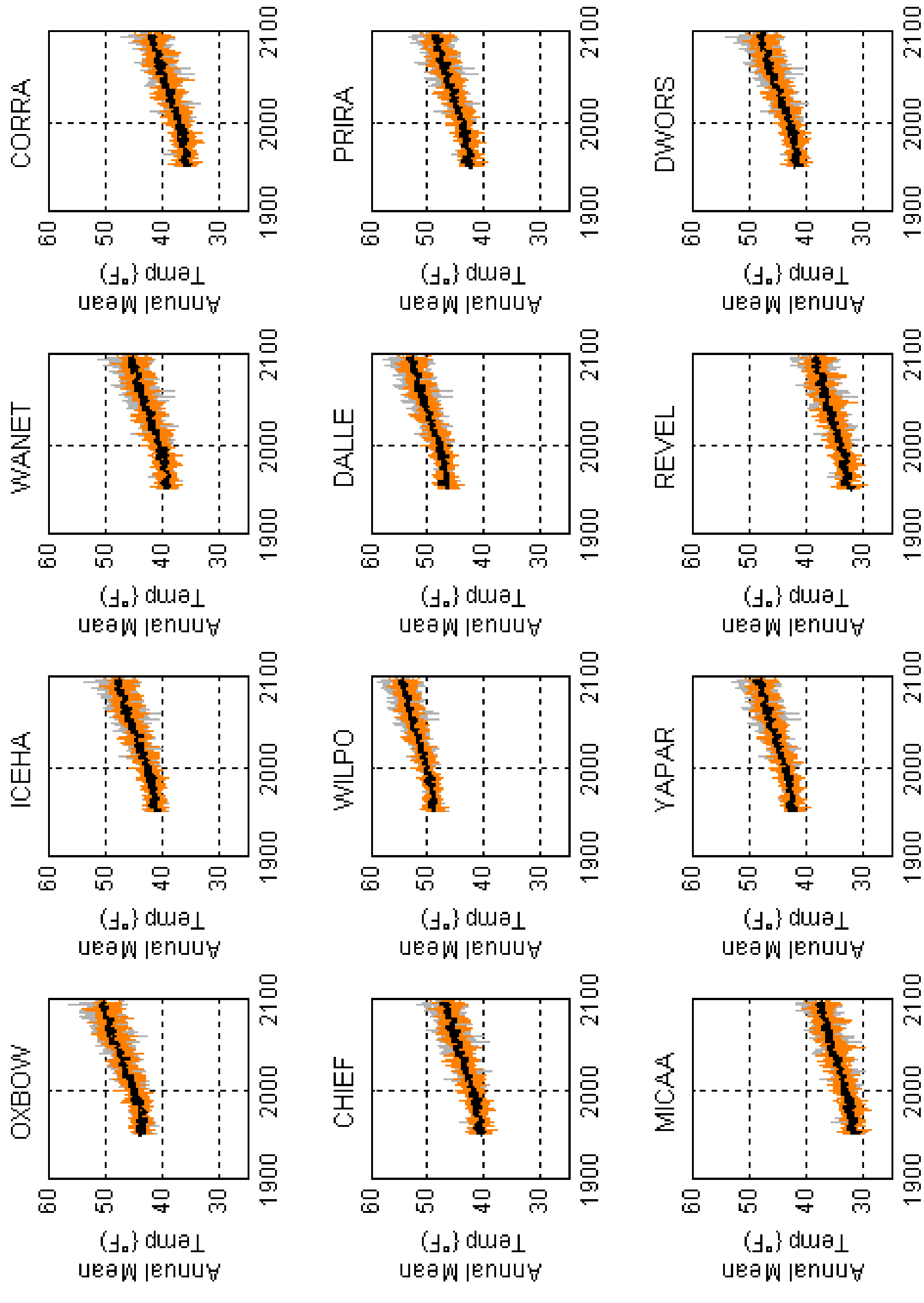

Figure 24. Selected UW CIG HB2860 Transient climate scenarios describing subbasin average temperature conditions.

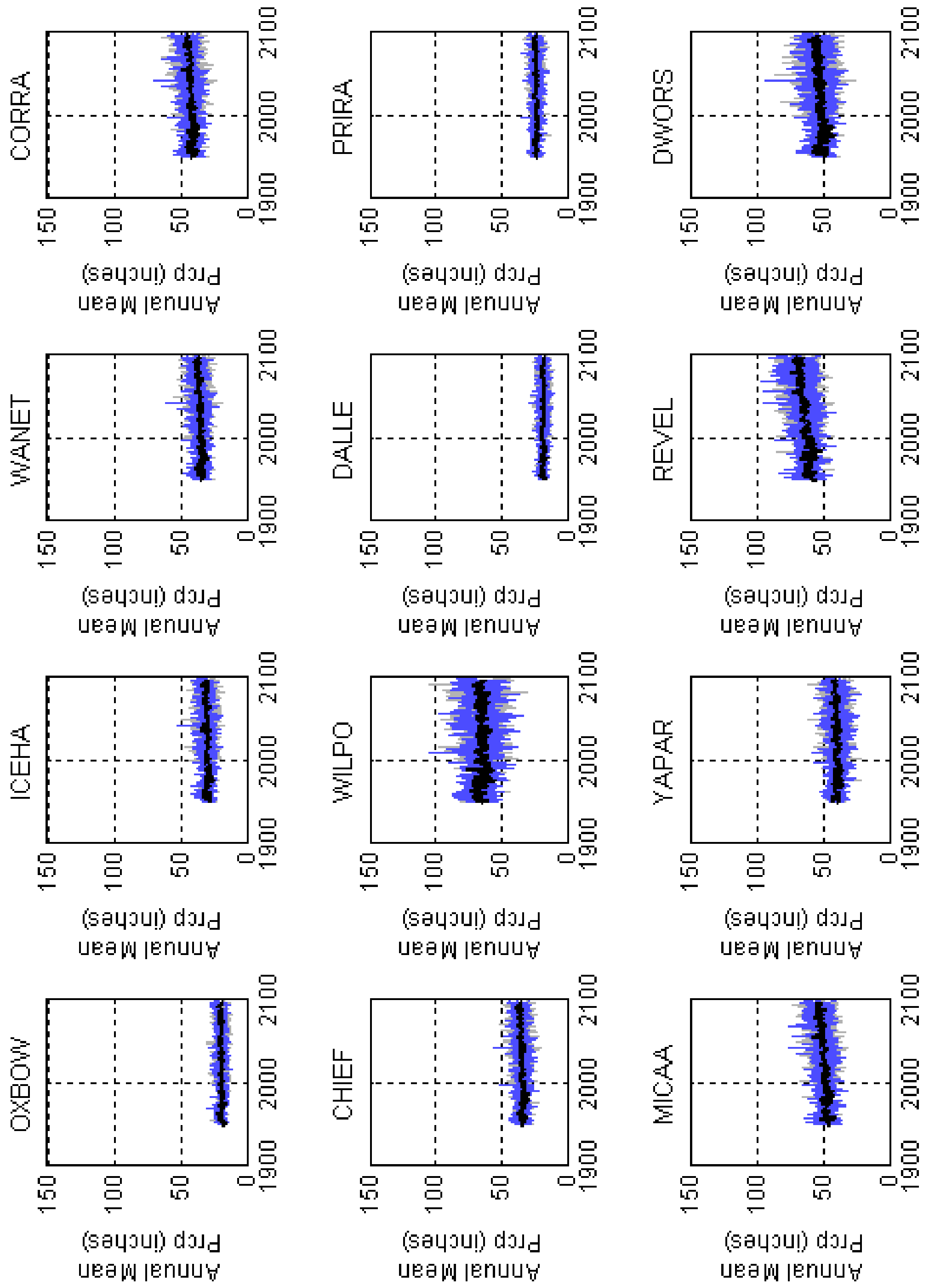

Figure 25. Selected UW CIG HB2860 Transient climate scenarios describing subbasin average precipitation conditions.

4.0 HYDROLOGIC SIMULATIONS USING FUTURE CLIMATE SCENARIOS

Focus now proceeds to the hydrologic analysis under each of the selected Hybrid-Delta climate change and Transient climate scenarios selected in Section 3.0. Such analysis requires:

- Selection of a hydrologic simulation model
- Preparation of weather forcing compatible with the hydrologic simulation model's input expectations (time step, spatial scale) and also consistent with the given climate scenario
- Simulation of hydrologic conditions under each scenario, assessing scenario output for gridded water balance conditions throughout the Columbia-Snake River Basin and routed runoff at specified locations
- Adjustment of routed runoff to account for Hydrologic Model's error tendencies (i.e., bias during historical simulation, varying by location)

4.1 UW CIG's Hydrologic Simulation Model

Hydrologic conditions under each HB2860 future climate scenario were simulated using a Columbia-Snake River Basin application of the Variable Infiltration Capacity (VIC) model (Liang et al. 1994).[17] VIC is similar to other surface water hydrologic models (e.g., PRMS, SacSMA/Snow17) in that surface water balance conditions are simulated through time, driven by specified input meteorology.

A schematic of the surface water hydrologic processes represented in VIC is shown on Figure 26. The VIC outputs include basin stored water states through time (i.e., soil moisture, snowpack) and water leaving the basin either as evapotranspiration or runoff, where the latter represents the combination of faster-response near-surface runoff and slower-response baseflow. VIC models are typically applied like other surface water hydrologic models such that the fate of precipitation is ultimately runoff or evapotranspiration and not the potential fate of percolation to deep aquifer systems.

[17] For information on the VIC model structure, see http://www.hydro.washington.edu/Lettenmaier/Models/VIC/ .

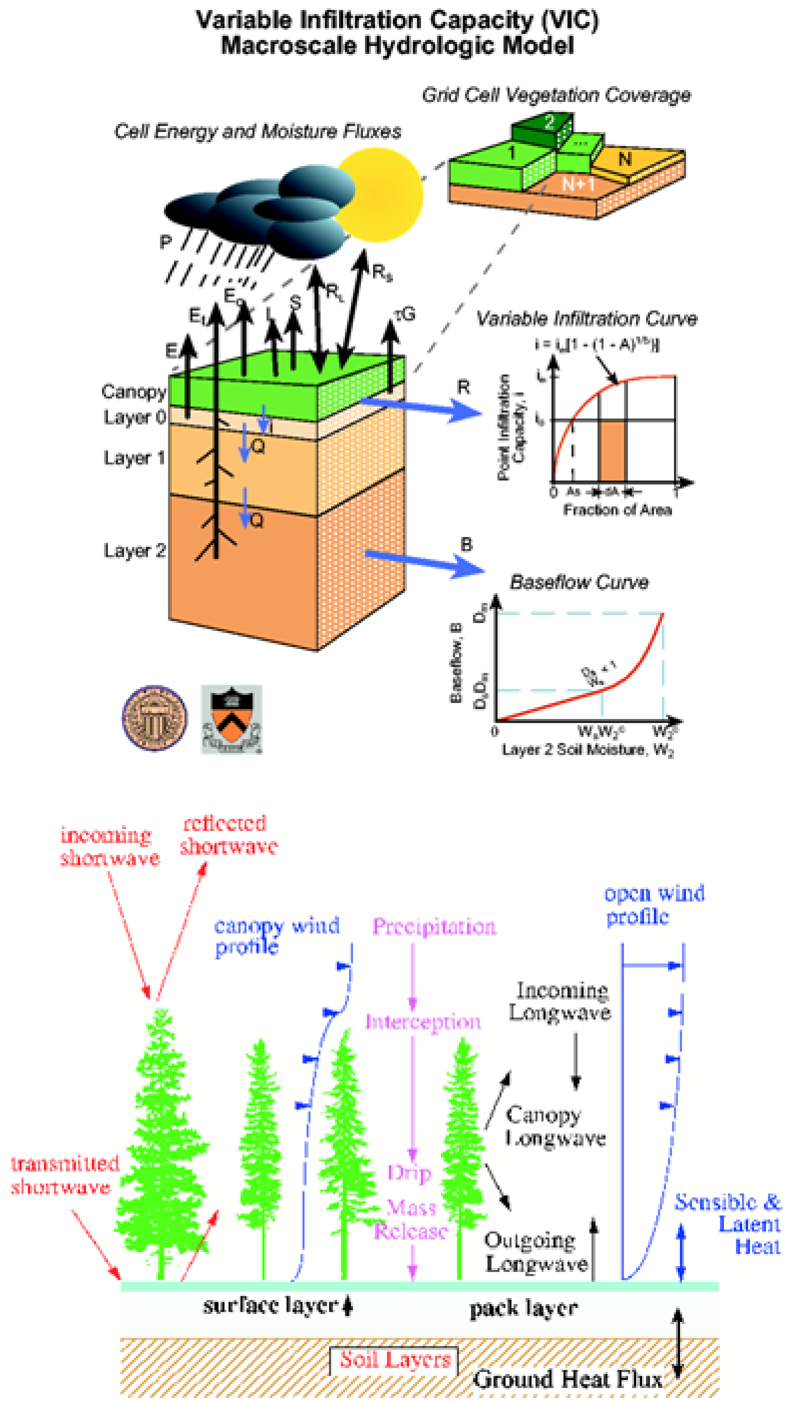

Figure 26. Schematic of VIC hydrologic model and energy balance snow model. *(Acknowledgment: Figure from Alan Hamlet, University of Washington Climate Impacts Group)*

For HB2860 work, UW CIG refined a 1/16º daily time-step VIC application in the Columbia-Snake River Basin previously applied for the Washington State Climate Change Impacts Assessment (Elsner et al. 2010).[18] The refinement focused on improving the application parameters so that monthly to annual characteristics of historical runoff simulations more closely match historical unregulated observations. The calibration exercise focused on matching runoff characteristics from 12 subbasins in the Columbia-Snake River Basin, indicated on Figure 27.

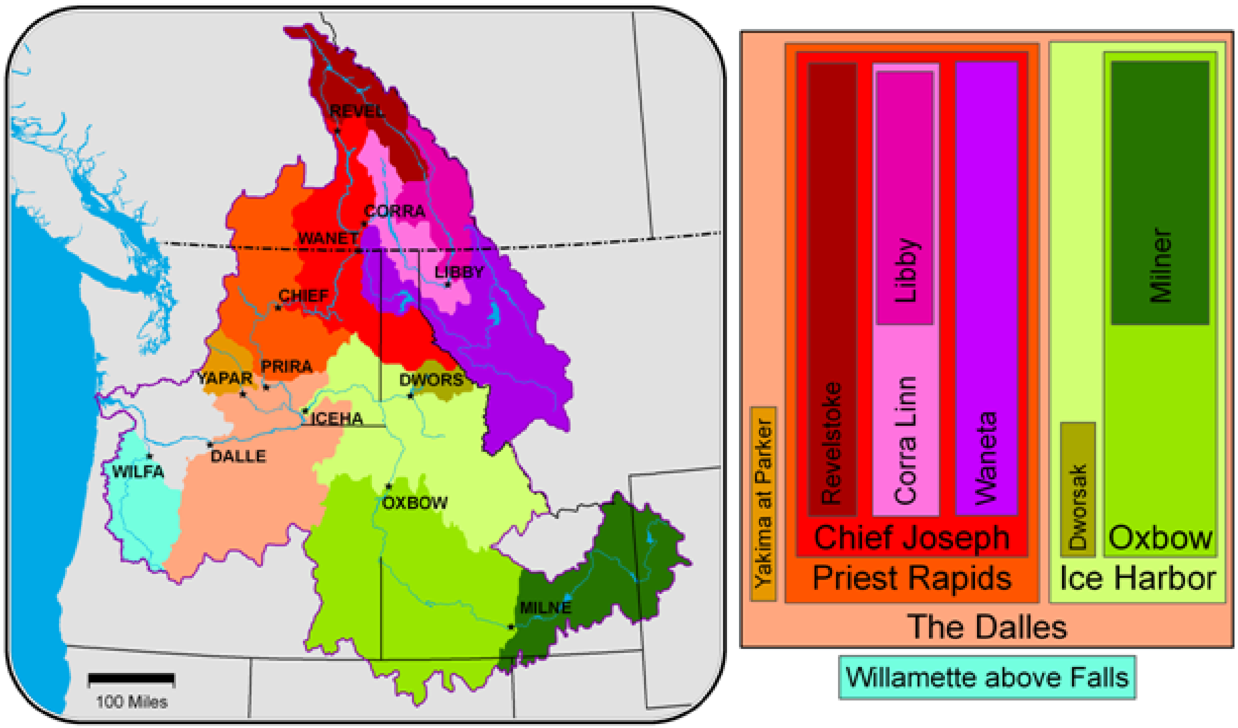

Figure 27. VIC model calibration watersheds (left panel) and order of calibration (right panel).
(Acknowledgment: Figure from Alan Hamlet, University of Washington Climate Impacts Group)

The calibration procedure geographically progressed from upstream subbasins to downstream subbasins (Figure 27). In a given subbasin, the VIC application's soil parameters were adjusted to refine simulation of monthly to annual runoff characteristics from the basin. Parameter adjustments were guided by an automated procedure (Shuffled Complex Evolution developed at The University of Arizona [Duan et al. 1993]), which uses various metrics to characterize runoff statistical matching during the automated calibration process (e.g., r^2, Nash-Sutcliffe Efficiency, annual volume error).

[18] http://www.hydro.washington.edu/2860/report/ Chapter 5 – Macro-Scale Hydrologic Model Implementation

4.2 Developing Future Climate Driving Meteorology for VIC Simulation

This section summarizes the methodologies used to generate gridded driving meteorology for VIC simulations corresponding to Hybrid-Delta and Transient climate scenarios. For each scenario situation, it was necessary to specify a daily gridded time series of four variables required for surface water balance simulation in VIC: precipitation, minimum temperature, maximum temperature, and wind speed. By construct, the spatial grid of each future climate scenario (Hybrid-Delta and Transient) is consistent with that of the 1/16º VIC Columbia-Snake River Basin. This means that no spatial reconciliation of downscaled climate scenarios with hydrologic model input structure had to be performed, and only monthly-to-daily translation of future climate information had to be accomplished. Details of these procedures are described in the HB2860 report, and briefly summarized in the following sections.

4.2.1 Hybrid-Delta Climate Change Scenarios

As referenced in earlier discussion, Hybrid-Delta climate change scenarios may portray expansion or contraction of climate variability. This is accomplished in how a Future Climate set of driving meteorology are constructed relative to a Reference Historical set of driving meteorology. The technique (referenced in this section as HD) involves identifying adjustment factors for temperature and precipitation (i.e., change in 30-year monthly condition, by grid location in the VIC domain) relative to a reference historical conditions (i.e., the Reference Historical Weather data previously referenced[19]). The adjustment factor is then imposed on Reference Historical weather in order to generate Future Climate weather. Like preceding scaling methods, the HD technique is applied on a month-by-month basis. The novelty of HD is that the adjustment is unique for each quantile condition of a given variable and given month. In other words, the adjustment differs for relatively drier to wetter precipitation conditions and for relatively cooler to warmer temperature conditions. This contrasts from simple Delta techniques (Reclamation 2010a) where the adjustment is the same for all year-types (e.g., adjusting base historical weather to reflect change in monthly period-mean T and P conditions). Implementation of the HD is illustrated in Figure 28 and involves four steps:

[19] Hybrid-Delta scenario wind speed values are kept the same as Reference Historical Weather values.

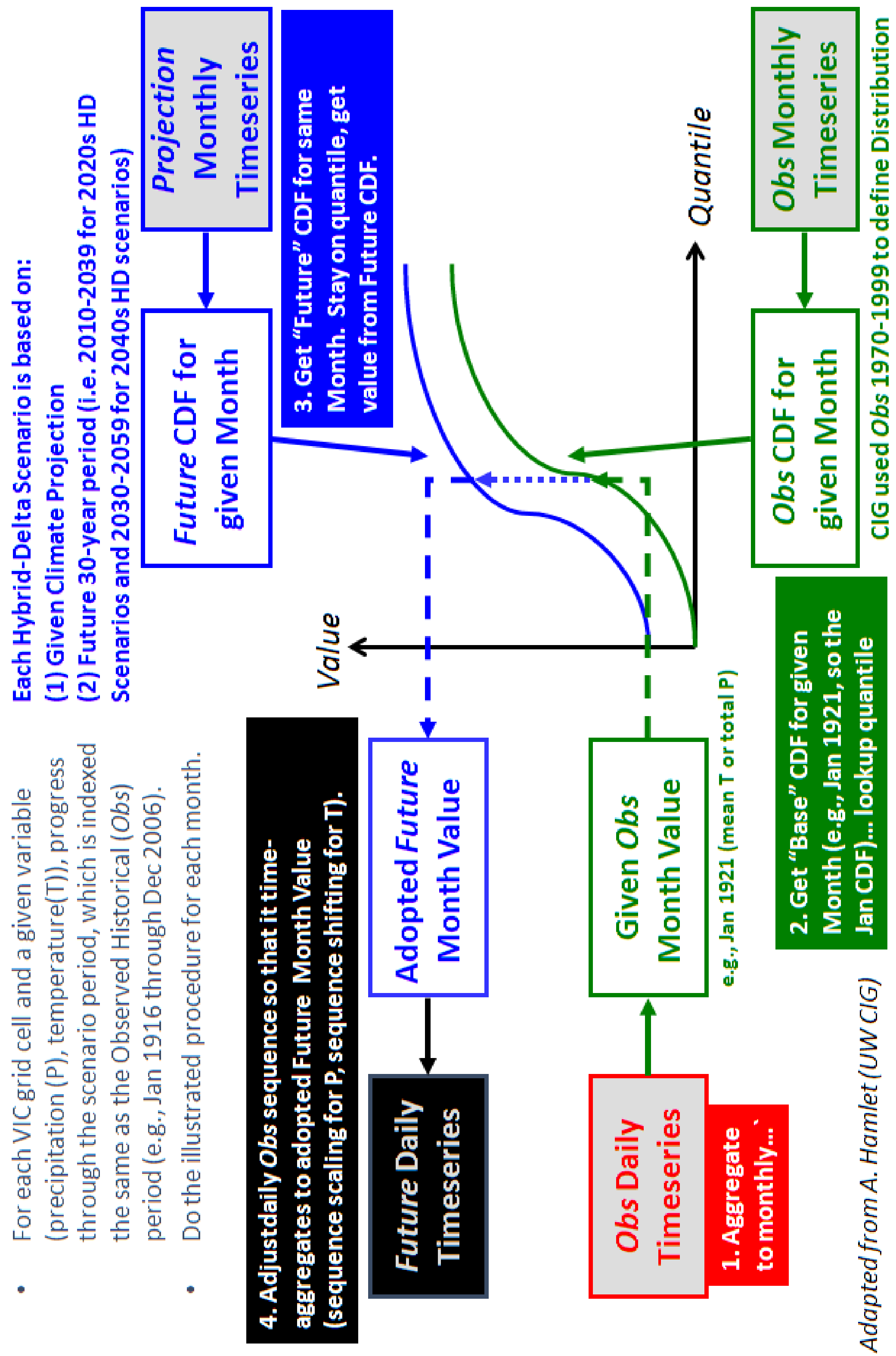

Figure 28. VIC Weather Generation Schematic for Hybrid-Delta Climate Change Scenarios.

- Step 1: Choose Observed Historical Daily Data, aggregate to Monthly Data, and make Base Climate Monthly Cumulative Distribution Functions (CDFs). For UW CIG's HB2860 effort, the 1916-2006 Reference Historical Weather data are used, with the 1970-1999 period providing the reference historical 30-year climate and associated monthly CDFs (Obs on Figure 28). This leads to a set of 12 month-specific empirical CDFs for each grid cell for monthly total precipitation (P) and mean temperature (taken as the average of mean "daily minimum" and "daily maximum" temperature).

- The next part of the procedure involves progressing monthly through the Obs period of record (1916-2006), implementing three steps for each month, variable, and grid cell.

  - Step 2: Get the given month's Obs Month Value and look up its Base Climate Quantile. For example, say that the variable is precipitation and the month is January 1921. Look up Obs January 1921 precipitation and then look up this value's quantile position within the 1970-1999 January Obs CDF. Let the quantile position be the 40 percentile.

  - Step 3: For the Quantile from Step 2, look up and adopt the corresponding value from the given month's Future CDF. Following the example and assuming that we are considering a 2020s HD scenario from projection "A," look up the 40 percentile value from the 2010-2039 CDF of January precipitation values from projection "A."

  - Step 4: Adjust the Daily ObsSequence for the given variable and month so that it time-aggregates to the adopted Future Month Value. Say that the adopted Future Month Value (i.e., 40 percentile value during observed 2010-2039) is 10 percent greater than the Obs Month Value (i.e., 40 percentile value during projected 1970-1999). In this case, scale the daily precipitation sequence of the Obs Month by 10 percent to serve as the daily precipitation sequence within the adopted Future Month Value. If the variable was temperature, then the Obs sequence is incrementally shifted rather than scaled and applied the same to both VIC's input minimum and maximum temperatures.

Variants of the HD technique have been implemented in other recent studies (LCRA SAWS 2008, Reclamation 2010a, and Reclamation 2010b). The technique may also be implemented with three distributions, as shown in Reclamation 2010a: Observed Historical, Simulated Historical, and Simulated Future. Using three distributions, adjustments are computed by comparing Simulated Historical and Future conditions and then applied to adjust Observed Historical conditions.

4.2.2 Transient Climate Projections

In order to generate VIC weather inputs under Transient climate conditions, UW CIG applied and refined a procedure that translates monthly BCSD projections into corresponding daily driving meteorology following a historical sampling and scaling procedure introduced in Wood et al. 2004. The procedure involves proceeding month by month through a monthly BCSD projection and doing the following three-step procedure:

- Step 1. Get the monthly total precipitation and mean temperature at every grid cell of the VIC domain for the projection month.
- Step 2. Randomly select an historical observed month from the Reference Historical Weather data (in this case from the period of 1950-1999) with sampling constraints (discussed below).
- Step 3. Preserving the daily sequence of the month selected in Step 2 at every location; adjust each grid cell's historical observed daily sequence so that the adjusted historical month value matches the projection month value. For precipitation, apply a scaling ratio to the sequence. For temperature, apply an incremental adjustment to the sequence.

As an example, consider making synthetic daily weather for a single month in a given climate projection at a given grid cell. Step 1 involves recognizing the projection month for which we are developing synthetic weather (e.g., January 2031 of the given climate projection). Step 2 involves randomly sampling a historical month (e.g., January 1979). The observed January 1979 provides a realistic daily sequence of weather variability (e.g., occurrence of precipitation, spells of warmer to cooler days). Step 3 involves scaling for precipitation or shifting for temperature, such that the adjusted daily precipitation or temperature series matches the monthly value for the projection month (January 2031).

There are some cautions when applying this monthly-to-daily translation scheme. The cautions primarily focus on precipitation scaling issues. For example, if sampling constraints are not imposed (e.g., to match relative month "types," wetter or drier), then it is possible to sample an historical "dry" observed month and match it with a projection "wet" month, which would require questionably large scaling of the observed "dry" month's daily precipitation to make it aggregate to the projection "wet" month's value. Conversely, if sampling constraints are imposed and rigid (e.g., forcing close alignment of relative month "types"), then the same historical observed months may get repetitiously sampled. In the end, UW CIG struck a balance between these precipitation scaling concerns. Final sampling criteria for generating Transient VIC driving meteorology are summarized in the HB2860 report.

4.3 Menu of Hydrologic Simulations

The following menu highlights the HB2860 hydrologic simulations associated with the selected future climate scenarios for this RMJOC effort.

- One Historical simulation generating daily water balance conditions during water years 1916-2006 and meant to reflect observed historical hydroclimate conditions over the basin during 1916-2006.
- Six Hybrid-Delta 2020s simulations similar to Historical, also generating daily water balance indexed during water years 1916-2006, but reflecting driving meteorology consistent with the climate of a given Hybrid-Delta 2020s scenario.
- Six Hybrid-Delta 2040s simulations similar to Historical, also generating daily water balance indexed during water years 1916-2006, but reflecting driving meteorology consistent with the climate of a given Hybrid-Delta 2040s scenario.
- Six Transient Climate simulations generating daily water balance conditions indexed during water years 1951-2099, reflecting observed historical sub-monthly weather patterns from 1950-1999, but sampled and scaled in a way to reflect monthly climatic sequencing characteristics from an underlying global climate projection over the region.

In preparing for operations analyses under Historical and Hybrid-Delta climate conditions, input and/or output VIC information is used in the following ways.

1. VIC simulated runoff is used to provide a basis for adjusting system inflows in each RMJOC agency's operations analyses (Part II through IV reports).
2. VIC simulated runoff and snow water equivalent as well as VIC driving precipitation, collectively to provide a basis for specifying water supply forecast used in each RMJOC agency's operations analyses (Section 5.0 of this report).
3. VIC driving temperature at point locations to provide a basis for adjusting electricity demands in BPA's hydropower operations analyses (Part IV report).

In preparing for operations analysis under Transient climate conditions, only the first and third way of utilizing VIC input and output information are featured.

4.4 Adjusting Simulated Runoff to Account for the Simulation Biases in the HB2860 VIC Application

As indicated in Snover et al. (2003), even after calibrating a given hydrologic model application to reproduce runoff characteristics at a menu of locations in a given basin (e.g., the 12 subbasins implied on Figure 27), the resultant model-application will still likely exhibit tendency to incorrectly simulate runoff. This is partially due to how the calibration scheme is set up to balance objectives in reproducing different aspects of runoff at calibration locations and not being able to identify a model parameter that results in perfectly reproducing each aspect. Another reason is that model calibration is not constrained to reproduce runoff at other locations in this system domain that may be important for reproducing runoff at the targeting calibration locations. The extent to which the model-application still incorrectly simulates runoff at calibration and other locations is defined here as simulation bias. There are several potential sources for these remaining biases:

- Biases in the model (structure)
- Biases in the forcing data (weather)
- Biases in the model parameters (calibration not tailored for a given location or output aspect)

As an alternative to applying calibration procedures at all runoff locations of interest in the HB2860 effort, CIG instead applied a post-simulation bias correction introduced in Snover et al. (2003) that is designed to adjust simulated runoff results to be consistent with monthly to annual aspects of runoff from observed datasets. This section provides a brief summary on how the bias-correction procedure is implemented at a given location.

4.4.1 Bias Identification

The first step involves focusing on the VIC historical runoff simulation (under Historical climate, Section 4.3) and identifying a reference historical runoff dataset that VIC's historical runoff simulation is expected to resemble (selection of the reference historical dataset is addressed later). After choosing the reference dataset, choose a period of historical overlap during which runoff statistics are expected to match (VIC simulation vs. reference historical) and call this the "bias-identification" period. In HB2860 implementation, the bias-identification period for the VIC historical runoff simulation is the period of maximum overlap between the VIC simulation (1916-2006) and a given reference historical dataset (e.g., if the reference historical dataset is from 1950-2009, then the bias-identification would focus on comparing VIC's 1950-2006 simulation to the 1950-2006 values in the reference dataset).

Next, within the bias-identification period, characterize bias in a user-specified manner. The HB2860 characterizes bias following the procedure outlined in Snover et al. (2003), Elsner et al. (2010), and Vano et al. (2010, where bias is first characterized for monthly mean flow and then for annual mean flow, and in a way that reveals bias that may vary under relatively greater or lesser runoff conditions. This is accomplished by preparing empirical CDFs, one fit to the period runoff values from the VIC historical simulation and the other fit to the period values from the reference historical dataset. For example, say the bias-identification period is 1950-2006 at location A. Focusing on January, one CDF will be fit to the 57 VIC-simulated January mean-flow values and the other will be fit to the 57 reference historical January mean-flow values during the 1950-2006 period.

4.4.2 Bias Correction

The paired CDFs serve as a quantile map describing bias by flow quantile. The CDFs are constructed at a given runoff location, first on month-specific basis to characterize bias in monthly mean flows and then on an annual basis to characterize bias in the annual mean flow. Once generated, these quantile maps are interpreted to reveal VIC runoff simulation bias for a given simulated runoff magnitude. For example, consider a VIC runoff location where the simulated January 2021 runoff magnitude happens to equal the 10th percentile magnitude within the VIC simulated-historical January CDF, fit to simulated 1950-2006 January runoff values. Switching from simulated- to observed-historical CDF and keeping the view on the 10th percentile, the observed-historical 10th percentile value is identified. This latter value is accepted as the new "bias-corrected" magnitude for January 2021. Because the bias-correction is magnitude-based, the correction can be viewed as ignorant of climate condition and permits the maps to be applied to correct runoff from any climate-specific VIC simulation (Historical l, Hybrid-Delta, or Transient).[20]

The HB2860 runoff data used in this RMJOC effort have undergone a two-step bias-correction, first to correct monthly flow aspects and second to correct annual flow aspects. Given that the annual correction happens second, it can be viewed that higher priority is placed on matching the historical annual flow distribution at the expense of some mismatch with the historical month-specific distributions.[21] In other words, for the historical condition,

[20] Runoff conditions under future climate conditions may fall outside the envelope of runoff magnitudes in the VIC historical simulation. In these cases, the extremes of the CDFs must be extrapolated to guide bias-correction of runoff magnitudes outside the range of historical magnitudes.

[21] It should be noted that the HB2860 effort includes bias-corrected runoff generated from the two-step procedure above and also a three-step procedure. The third step follows the same first two steps (Snover et al.

the resultant bias-corrected (BC) runoff features annual period-statistics and CDFs that exactly match those from the reference runoff dataset, and monthly period-statistics and CDFs that closely match those from the reference dataset. For future climate conditions, the resultant BC runoff reflect a blend of future climate impact on runoff (relative to historical) and bias-correction for VIC's historical simulation tendencies.

4.4.3 Bias-Correction Notes for this RMJOC Effort – Reclamation Basins

For this RMJOC effort, the CIG computation scripts for implementing the bias-correction procedure were obtained and applied to produce BC runoff data at locations within Reclamation's tributary basins (i.e., the Yakima, Deschutes, and Snake). The need for tailoring the bias-correction procedure for Reclamation purposes is based on three issues:

- For HB2860 work, UW CIG considered multiple reference runoff datasets supplied by different stakeholders. This inevitably led to some locations receiving multiple candidate datasets for guiding bias-identification. A prominent example relevant to RMJOC purposes is that both Reclamation and Idaho Department of Water Resources supplied estimates of historical natural monthly flows in the Snake River subbasin above Brownlee and these estimates differed in some respects. Given that the RMJOC future climate and hydrology scenarios will be applied to serve Reclamation planning needs in the Snake River subbasin, and given that UW CIG indicated intention to use IDWR's estimate of Snake River subbasin natural flows to develop the BC runoff data served at the HB 2860 website, the RMJOC work group decided that UW CIG's bias-correction procedure would be independently applied in this effort to generate VIC BC runoff in the Upper Snake River subbasin consistent with Reclamation estimates of historical natural flows. The implications of doing this are that there will be better comparability between Reclamation operations simulations forced by the VIC-simulated BC runoff under historical climate and simulations forced by Reclamation-estimated historical natural flows.

- During the course of identifying HB2860 VIC runoff reporting locations corresponding to system inflow locations required for Deschutes River subbasin operations analysis, it was recognized that several critical runoff reporting locations

---

2003) and involves a final basin-wide correction that is coordinated across runoff locations. It was noted that this third step had minor effect on final bias-corrected runoff (personal communication, Alan Hamlet, December 2009). Given that this effort involved redoing the runoff bias-correction in the Yakima, Deschutes, and Snake River basins (Section 4.4.3), and given this redo could proceed more easily if correction could just focus on locations in these tributaries rather than the whole basin, a decision was made to implement the two-step procedure in these tributaries. This led to a decision to also use two-step bias-corrected runoff for the Interior Columbia River Basin.

had not been provided to the HB2860 effort (i.e., inflow at Crescent Lake, Crane Prairie Reservoir, and Wickiup Reservoir and Deschutes River flow above Lake Billy Chinook).

- Updated estimates of “no regulation, no irrigation” historical monthly flows within the Yakima River subbasin became available during December 2009, which was roughly the same time when the Snake and Deschutes River subbasins issues were being contemplated.

Given these issues and based on a general interest in being able to implement the procedure should improved historical natural runoff datasets be issued for these subbasins in the future, a decision was made to apply the UW CIG bias-correction procedure for various locations in Reclamation tributary basins, addressing Reclamation preferred reference runoff datasets in the Snake and Yakima River subbasins, and addressing some new runoff locations in the Deschutes River subbasin. Runoff bias-correction locations by tributary basins are listed in Table 4 through Table 6. Bias-identification periods were water years (WY) October-September 1929-2005 for the Deschutes River subbasin, WY 1926-2006 for the Yakima River subbasin, and WY1928-2006 for the Snake River subbasin.

Table 4. Yakima River subbasin locations where VIC simulated runoff was bias-corrected.

Site Number	Site I.D.	Site Description	State	Lat	Lon	Historical Correlation (OBS, SIM-BC-F)
6105	BUMPI	Bumping River near Nile	WA	46.87	-121.29	0.83
6062	CLERO	Cle Elum River below Cle Elum Lake near Roslyn	WA	47.24	-121.07	0.93
6104	KACHE	Kachess River near Easton	WA	47.26	-121.20	0.88
6103	KEEMA	Yakima River near Martin	WA	47.32	-121.34	0.88
6065	NACCL	Naches River at Cottonwood Campground near Cliffdell	WA	46.91	-121.03	0.88
6003	NACTI	Naches River below Tieton River near Naches	WA	46.75	-120.77	0.88
6106	RIMRO	Tieton River at Tieton Dam	WA	46.66	-121.12	0.91
6109	TIECH	Tieton River at Canal Headworks near Naches	WA	46.67	-121.00	0.82
6063	YACLE	Yakima River at Cle Elum	WA	47.19	-120.95	0.92
6068	YAEUC	Yakima River at Euclide Bridge at River Mile 55 near Grandview	WA	46.22	-119.92	0.91
6099	YAKEA	Yakima River at Easton	WA	47.24	-121.18	0.87
6069	YAKKI	Yakima River at Kiona	WA	46.25	-119.48	0.92
6064	YAKUM	Yakima River at Umtanum	WA	46.86	-120.48	0.92
6066	YAPAR	Yakima River near Parker	WA	46.50	-120.44	0.92

Site Number ant I.D. reference runoff locations at UW CIG's HB2860 website (http://www.hydro.washington.edu/2860/).

Historical correlation is computed between reference historical monthly runoff (OBS) and HB2860 simulated-historical and bias-corrected monthly runoff (SIM-BC-F) during the bias-identification period.

Table 5. Deschutes River subbasin simulated runoff locations subjected to adjustment for VIC biases.

Site Number	Site I.D.	Site Description	State	Lat	Lon	Historical Correlation (OBS, SIM-BC-F)
added	ABILL	Deschutes River above Lake Billy Chinook	OR	44.60	-121.28	0.74
added	CRANE	Deschutes River at Crane Prarie Dam	OR	43.76	-121.79	0.34
added	CRESC	Crescent Creek at Crescent Lake	OR	43.50	-121.97	0.59
4023	CROOK	Crooked River below Opal Springs near Culver	OR	44.49	-121.28	0.77
4022	DESCH	Deschutes River above Lake Billy Chinook	OR	44.50	-121.32	0.69
4024	METOL	Metolius River near Grandview	OR	44.63	-121.48	0.68
4026	PELTO	Deschutes River at Pelton Dam	OR	44.73	-121.26	0.74
4029	REREG	Deschutes River at Moody, near Biggs	OR	45.62	-120.90	0.79
4025	RNDBB	Round Butte (Lake Billy Chinook near Metolius)	OR	44.60	-121.28	0.77
4027	WARMS	Warm Springs River near Kahneeta Hot Springs	OR	44.86	-121.15	0.85
4028	WHITE	White River below Tygh Valley	OR	45.24	-121.09	0.75
added	WICKI	Deschutes River at Wickiup Dam	OR	43.68	-121.69	0.48

Site Number ant I.D. reference runoff locations at UW CIG's HB2860 website (http://www.hydro.washington.edu/2860/).

"added" denotes runoff routing sites not included in UW CIG H2860, but added for this RMJOC effort.

Historical correlation is computed between reference historical monthly runoff (OBS) and HB2860 simulated-historical and bias-corrected monthly runoff (SIM-BC-F) during the bias-identification period.

Table 6. Snake River subbasin simulated runoff locations subjected to adjustment for VIC biases.

Site Number	Site I.D.	Site Description	State	Lat	Lon	Historical Correlation (OBS, SIM-BC-F)
2015	AMERI	Snake River at American Falls Dam	ID	42.77	-112.88	0.90
2045	BLADA	Blackfoot River at Blackfoot Dam	ID	42.82	-111.51	0.55
2021	BOAND	South Fork Boise River at Anderson Ranch Dam	ID	43.34	-115.48	0.81
2022	BOARK	Arrowrock Reservroir Inflow at Arrowrock Dam	ID	43.59	-115.92	0.82
2023	BOISE	Boise River near Boise	ID	43.53	-116.06	0.85
2019	BOTWI	Boise River near Twin Springs	ID	43.66	-115.73	0.81
2027	BROWN	Snake River at Brownlee Dam (ID-OR state line)	ID	44.84	-116.90	0.93
2018	BRUNE	Bruneau River near Hot Springs	ID	42.77	-115.72	0.81
4006	BURNT	Burnt River at Huntington	OR	44.36	-117.27	0.79
2044	CJSTR	Snake River at CJ Strike Dam	ID	42.95	-115.98	0.88
2039	DEADR	Deadwood River below Deadwood Reservoir near Lowman	ID	44.29	-115.64	0.68
2040	HENRY	Henrys Fork River near Lake	ID	44.59	-111.35	0.42
2012	HFORK	Henrys Fork Rivernear Rexburg	ID	43.83	-111.91	0.93
2043	IPARK	Henrys Fork River at Island Park Dam	ID	44.42	-111.39	0.86
5001	JLAKE	Jackson Lake near Moran	WY	43.86	-110.59	0.77
2042	LBOIS	Boise River near Parma	ID	43.78	-116.97	0.85
4005	MALHE	Malheur River at Nevada Dam	OR	43.99	-117.22	0.63
2017	MILNE	Snake River at Milner	ID	42.53	-114.02	0.89
2016	MINAD	Snake River at Minidoka Dam	ID	42.67	-113.50	0.89
2025	NPCSC	North Fork Payette River at Cascade	ID	44.53	-116.05	0.87
4001	OWYHE	Owyhee River below Owyhee Dam	OR	43.65	-117.26	0.75
2010	PALIS	Snake River near Irwin	ID	43.35	-111.22	0.92
2026	PAYET	Payette River near Payette	ID	44.04	-116.93	0.87
2024	PAYLO	South Fork Payette River at Lowman	ID	44.09	-115.62	0.57
4008	POWDE	Powder River near Richland	OR	44.78	-117.29	0.81
2013	RIRDM	Willow Creek at Ririe Dam	ID	43.58	-111.74	0.74
2011	SNKHE	Snake River near Heise	ID	43.61	-111.66	0.92
2014	SNSHY	Snake River near Shelley	ID	43.41	-112.14	0.91

Site Number ant I.D. reference runoff locations at UW CIG's HB2860 website (http://www.hydro.washington.edu/2860/).

Historical correlation is computed between reference historical monthly runoff (OBS) and HB2860 simulated-historical and bias-corrected monthly runoff (SIM-BC-F) during the bias-identification period.

Review of BC runoff data in Reclamation tributary basins revealed that the significance of bias-correction varied from location to location. Relatively speaking, less correction was required for Yakima and Snake River headwater locations and more correction was required for Deschutes River locations. For locations requiring more correction, the period-statistics of VIC BC historical runoff were still found to match those of the reference historical runoff dataset (by design of the bias-correction procedure), but forcing such a match has consequences on runoff sequence. This is apparent when focusing on the historical bias-correction period and comparing observed and bias-corrected runoff (e.g., correlation values shown in Table 4 though Table 6). To understand this consequence, it is helpful to view the bias-correction during the historical period as essentially resampling observed-historical magnitudes to replace raw simulated magnitudes and serve as new bias-corrected magnitudes. This sampling is not constrained in time, so the sampled-observed magnitudes (i.e., "bias-corrected" magnitudes) do not necessarily end up being in the same time-sequence as observed magnitudes. This leads to imperfect time-correlation between observed and bias-corrected flows. Put another way, the quantile maps generated to guide runoff bias-correction feature a CDF of VIC simulated runoff magnitudes and a CDF of observed historical runoff magnitudes. The time order of occurrence for quantile magnitudes in each CDF does not have to match. For example, for a bias-identification period of WY1928-2006 used in the Snake River subbasin, the 40th percentile observed January runoff may have occurred in 1940 whereas in the VIC simulation of WY1928-2006, the 40th percentile January runoff may have occurred in 1950. Bias-correction (as implemented) would force the VIC simulated January 1950 value (being 40th percentile within the simulated distribution) to be the observed 40th percentile value (or the observed January 1940 value). This would then force the observed January 1950 value to be assigned to some other VIC simulated January.

Based on evaluation of results, it appears that locations requiring a greater degree of bias-correction experienced a greater degree of sequencing impact and ended up featuring lower time-correlation between observed and bias-corrected runoff. To illustrate, consider a location where bias-identification and correction were both somewhat minimal compared to other Reclamation locations: Snake River subbasin, Boise River above Lucky Peak (BOISE). Figure 29 shows:

- Mean monthly and mean annual historical runoff during the bias-identification period for the reference data set (black, labeled OBS)
- VIC simulation before bias-correction (red, labeled SIM)
- VIC simulation after correcting for monthly biases (green, labeled SIM-BC)
- Subsequently after correcting for annual biases (blue, labeled SIM-BC-F)

Inspection of simulated runoff statistics through each step (red, green, blue) shows that the procedure forces the simulated annual mean to match the reference's annual mean (comparing black and blue lines). The procedure forces the monthly means to nearly match also (comparing black and green lines), which shows that much of the bias-correction is accomplished during the first step which is month-specific, and that only minor additional adjustments are made during the second step that forces annual distributions to match.

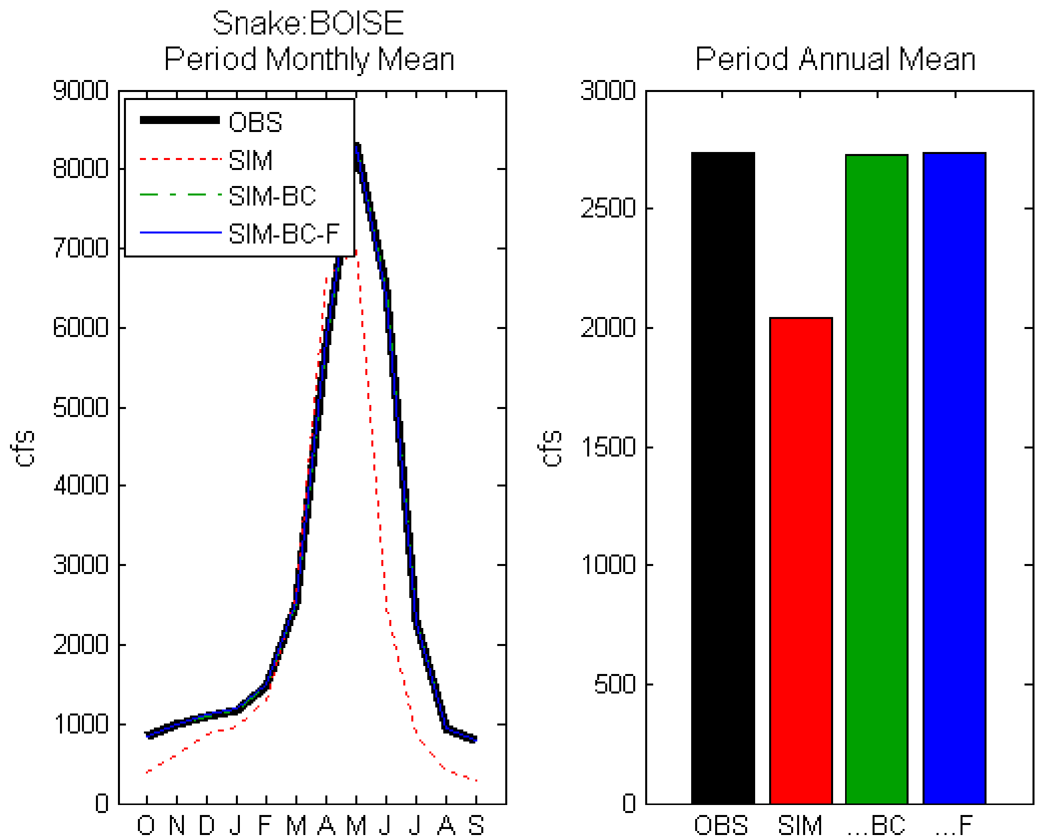

Figure 29. VIC-BC runoff example: Boise River at Lucky Peak, period means.

Figure 30 expands the view from period monthly-mean to period monthly-distributions. The same color schemes apply and the similar storyline is apparent: after bias-correction, the BC historical runoff magnitudes generally feature the same range of runoff conditions, month by month, as the reference historical dataset. However, switching from the period monthly-distribution view to the monthly time series view, some artifacts begin to emerge (Figure 31). Notice how VIC BC runoff magnitudes (blue) depart from reference magnitudes for some time steps. This stems from how time order of quantile magnitudes does not constrain the bias-correction procedure.

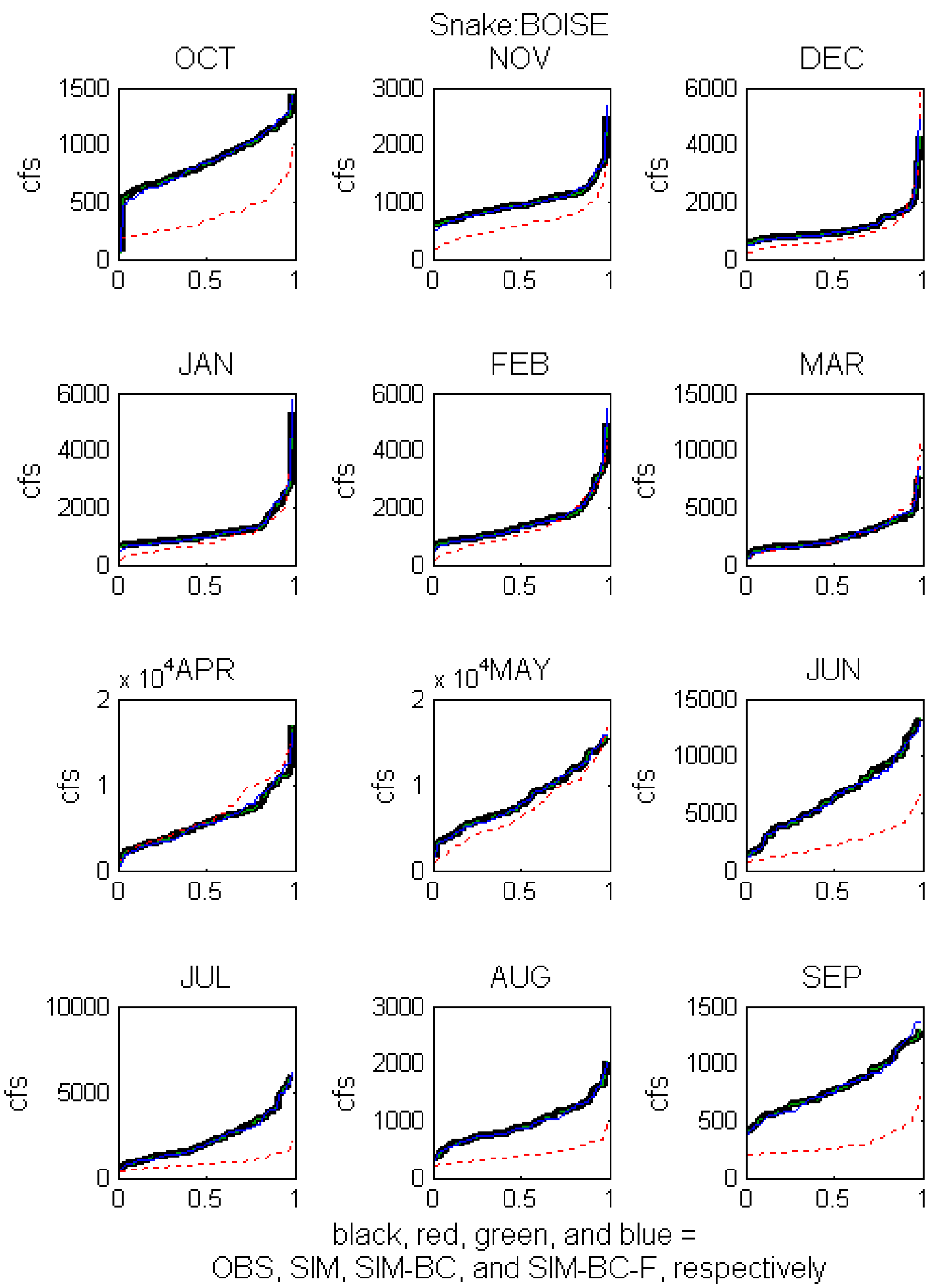

Figure 30. VIC-BC runoff example: Boise River at Lucky Peak, period monthly distributions.

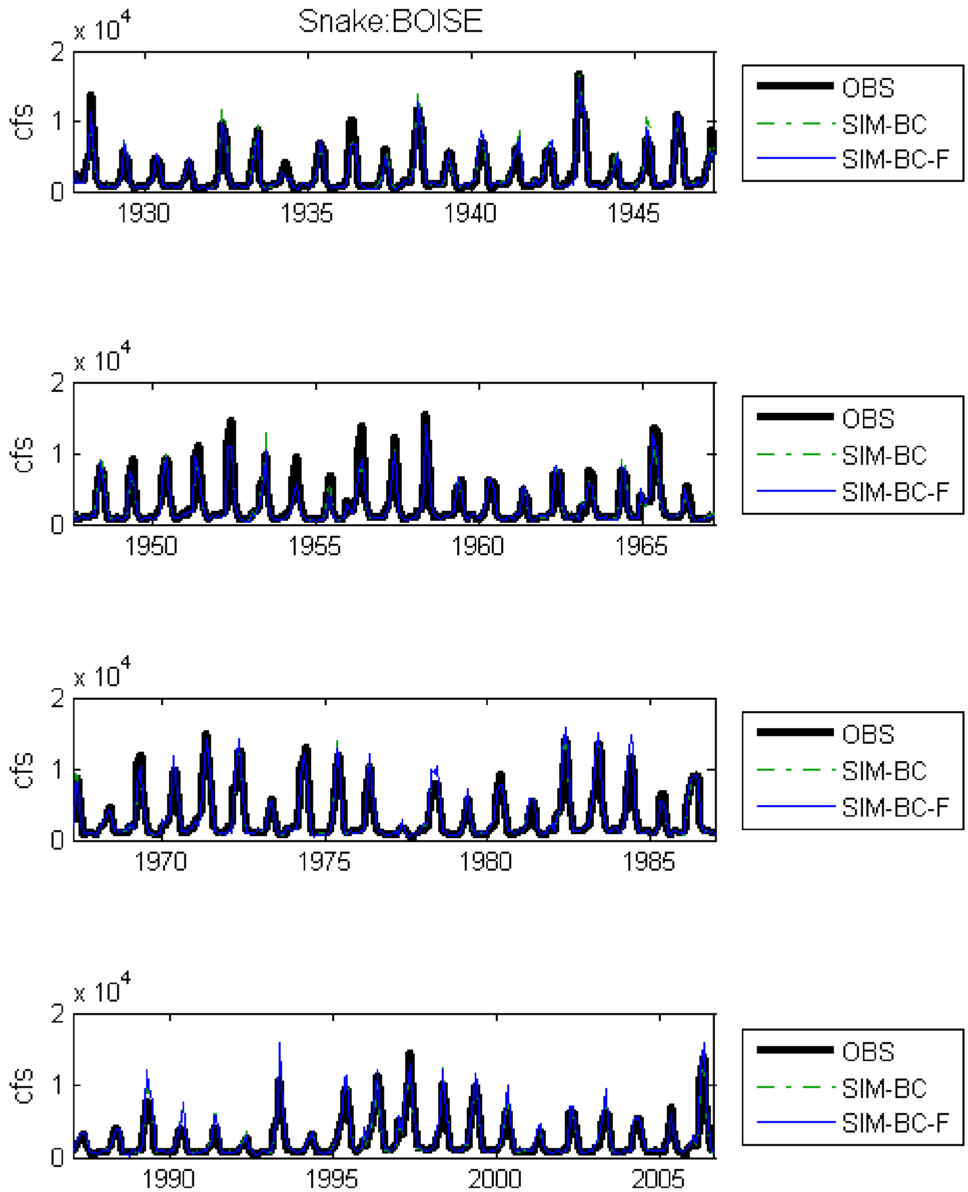

Figure 31. VIC-BC runoff example: Boise River at Lucky Peak, monthly time series.

For BOISE, this matter of quantile time-order not constraining bias-correction only had minor effects on resultant runoff. For other Reclamation locations, this was not the case, particularly for locations in the Deschutes River subbasin. Focusing on inflow to Wickiup Reservoir (WICKI) as an example, Figure 32 and Figure 33 show that even with much more significant runoff simulation biases and the bias-correction procedure successfully adjusts the VIC simulated runoff to statistically match reference runoff conditions at this location. However, the time reordering of these magnitudes is significant (Figure 34), leading to a resultant VIC BC runoff sequence that looks very different than that from the reference historical dataset. On why there are such significant biases at WICKI and other Deschutes River subbasin locations (not shown), it is suspected that the VIC application's shallow-soil portrayal of watershed hydrology may be incongruent with the actual Deschutes River subbasin setting where groundwater and surface water interactions are prominent in defining runoff conditions (Gannett et al. 2001).

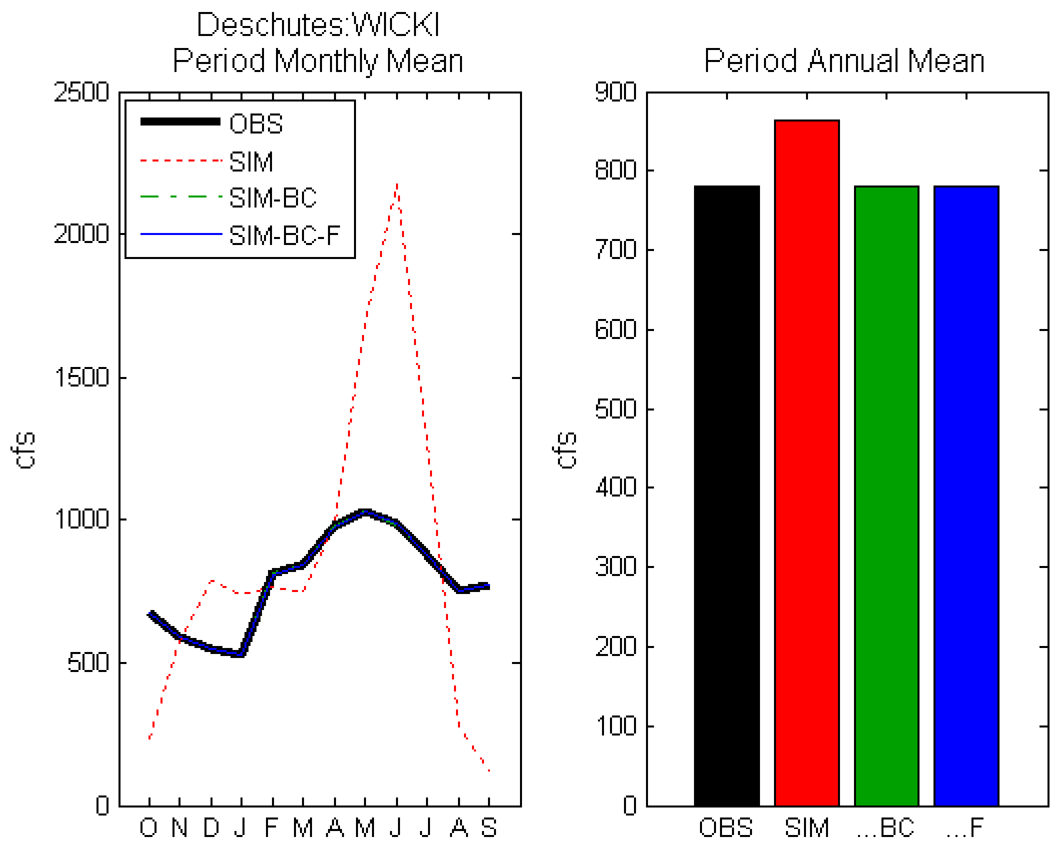

Figure 32. VIC-BC Runoff Example: Deschutes River inflow to Wickiup Reservoir (WICKI), Period Means.

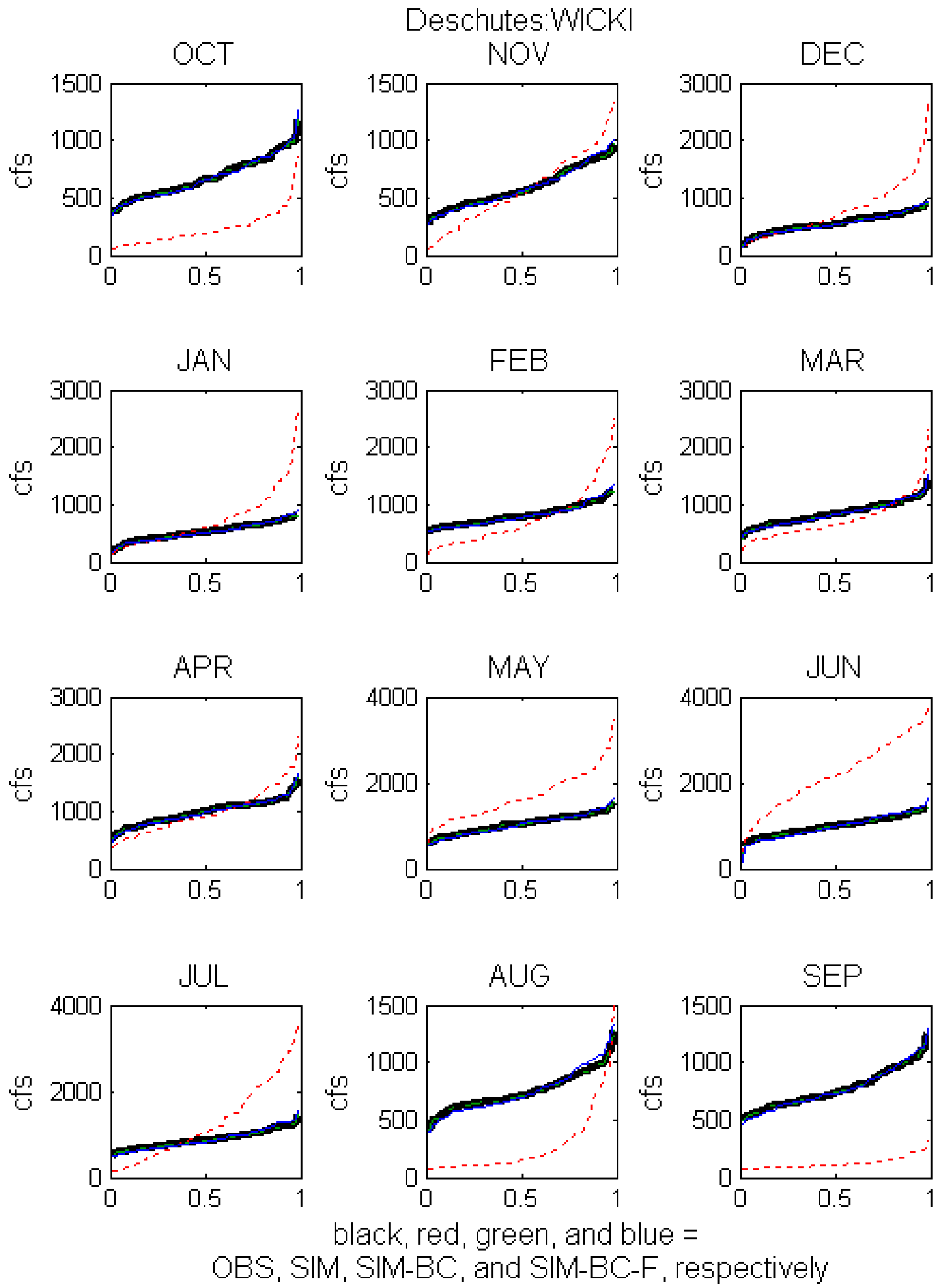

Figure 33. VIC-BC Runoff Example: Deschutes River inflow to Wickiup Reservoir (WICKI), Period Monthly Distributions.

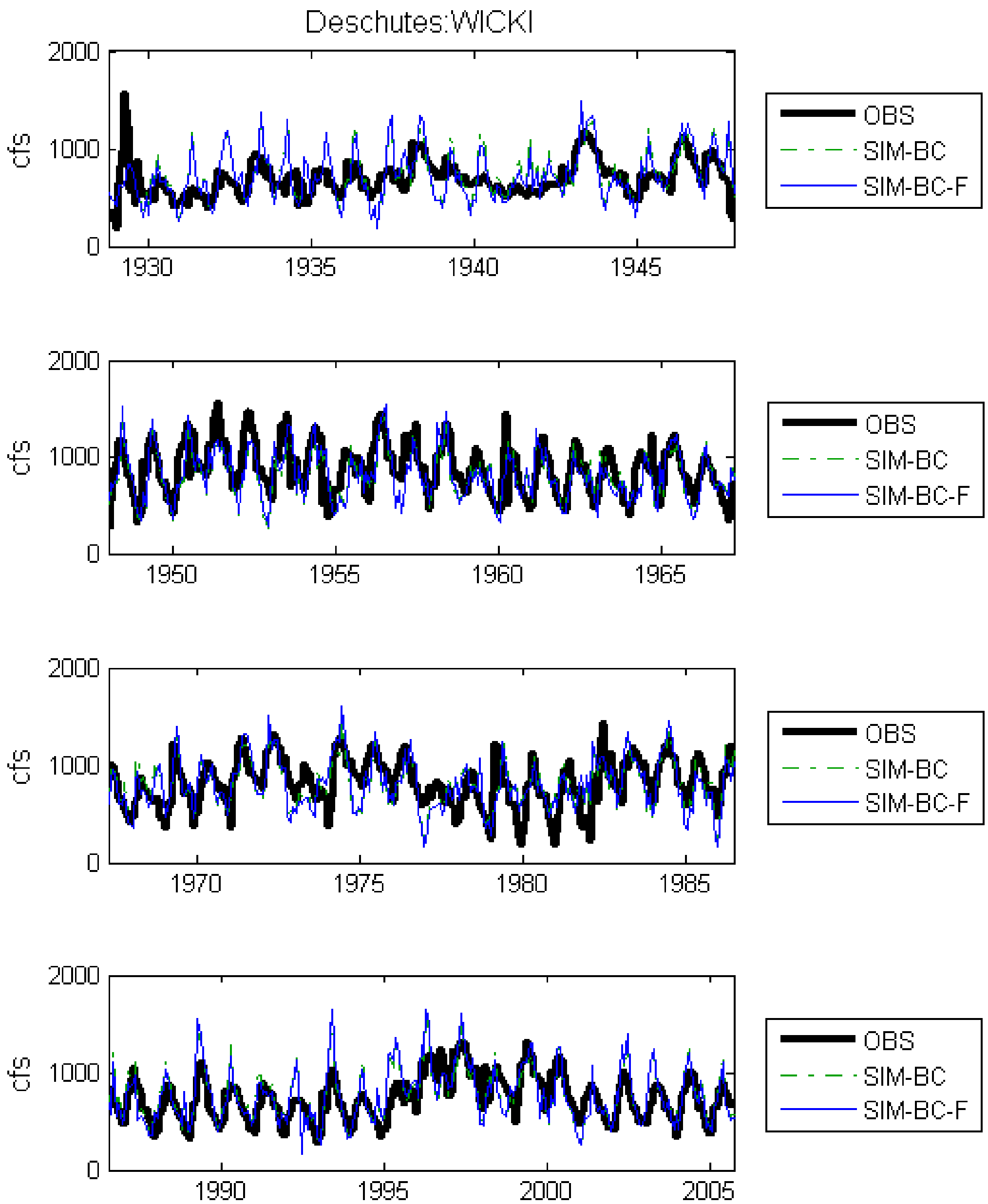

Figure 34. VIC-BC Runoff Example: Deschutes River inflow to Wickiup Reservoir (WICKI), Monthly Time Series.

4.4.4 Bias-Correction notes for this RMJOC effort – Columbia River Basin

For interpreting BC runoff data for the broader Columbia River Basin there are two issues that are discussed in this section. The first involves the time period of data used. The second involves the reference data used to produce bias-corrected flows.

On the first issue, both BPA and the Council utilize datasets that cover 14-periods per year. The typical monthly data required to run their model systems is adequate for most months of the year; however, in April and August when shifts in streamflow can be more dramatic over a monthly time step, they found the need to partition those two months into two datasets. Thus, a 14-period dataset that covers the full year of streamflow data was used. BPA and the Council specifically had a contract with UW CIG to deliver bias adjusted runoff data using their 14-period data (developed in the Modified Flows program) as the reference data. USACE utilizes daily streamflow data to feed their model simulation systems. This daily data was delivered by UW CIG using the standard 12-period reference data used per Snover et al. (2003), Elsner et al. (2010), and Vano et al. (2010). The daily data was then generated from the monthly sequence of bias adjusted data. Though differences are not expected to be significant, there is a difference between the daily data generated in this way and the 14-period data used as the basis for BPA and Council analysis.

On the second issue, as already discussed, the bias correction process requires reference data of natural flows, or flows with any sort of human-directed regulation removed from them. Within the Columbia River Basin, there are a variety of different datasets produced as "naturalized" flows by different stakeholder groups, similar to what was discussed earlier for the Snake River subbasin. One set of data is known as the Modified Flows dataset which removes any regulation from dams except for the upper Snake River upstream of Brownlee, in the Yakima River at the mouth, and Deschutes River into Lake Billy Chinook, but maintains diversions for irrigation and other uses at current level of development. Techniques have been developed that can take the Modified Flow datasets and remove the effects of irrigation diversions. Other stakeholder groups have actually done work to develop naturalized flowsets. As a result the UW CIG had a variety of reference data at their disposal to use. The model systems and analytical approaches used by USACE, BPA, and the Council are built around the Modified Flows dataset.

For the first issue above, a complicating factor is that USACE model systems that operate on daily time-steps are not currently viable for running the volume of climate change data available. There is a significant amount of human interaction required to operate the current models and as such, the time required to run simulations is prohibitively long. New model systems are in development that will be able to fully utilize the climate change data, but were not ready in time to support demonstration modeling as part of this work effort. The alternative modeling approach utilized by USACE (discussed in the Part III Report to be issued spring 2011) required monthly volumes as inputs, rather than daily streamflows. With this limitation for daily data removed, a solution was much easier to arrive at given BPA's need to operate with 14-period data. The decision was made to utilize BPA's 14-period data (and the corresponding bias-corrections applied to it) as the underlying data for model simulations. The RMJOC work group recognizes that this issue will need to be revisited later, once USACE model system development is complete and the RMJOC undertakes a climate change impacts study in the future.

Figure 35 provides a graphic illustration of the available data and their corresponding reference data for bias correction. The points of interest illustrated with a red star reflect locations for which modified and naturalized flow datasets are available, but the UW CIG naturalized flow data was used as the reference data for bias correction. Concerns arose during the rule curve development for the regulation studies that inconsistencies existed with a streamflow dataset that combined both naturalized and modified bias adjustments. The concern is not whether the flow at a single point is using modified or naturalized flows, but rather that a consistent set of reference data is used within a given subbasin or watershed. The main use of the interior subbasin streamflow locations is the generation of local flows (ungaged runoff between two gaged locations). If the bias corrected streamflows have different underlying reference data, the resulting difference in flows will calculate incorrect local flows.

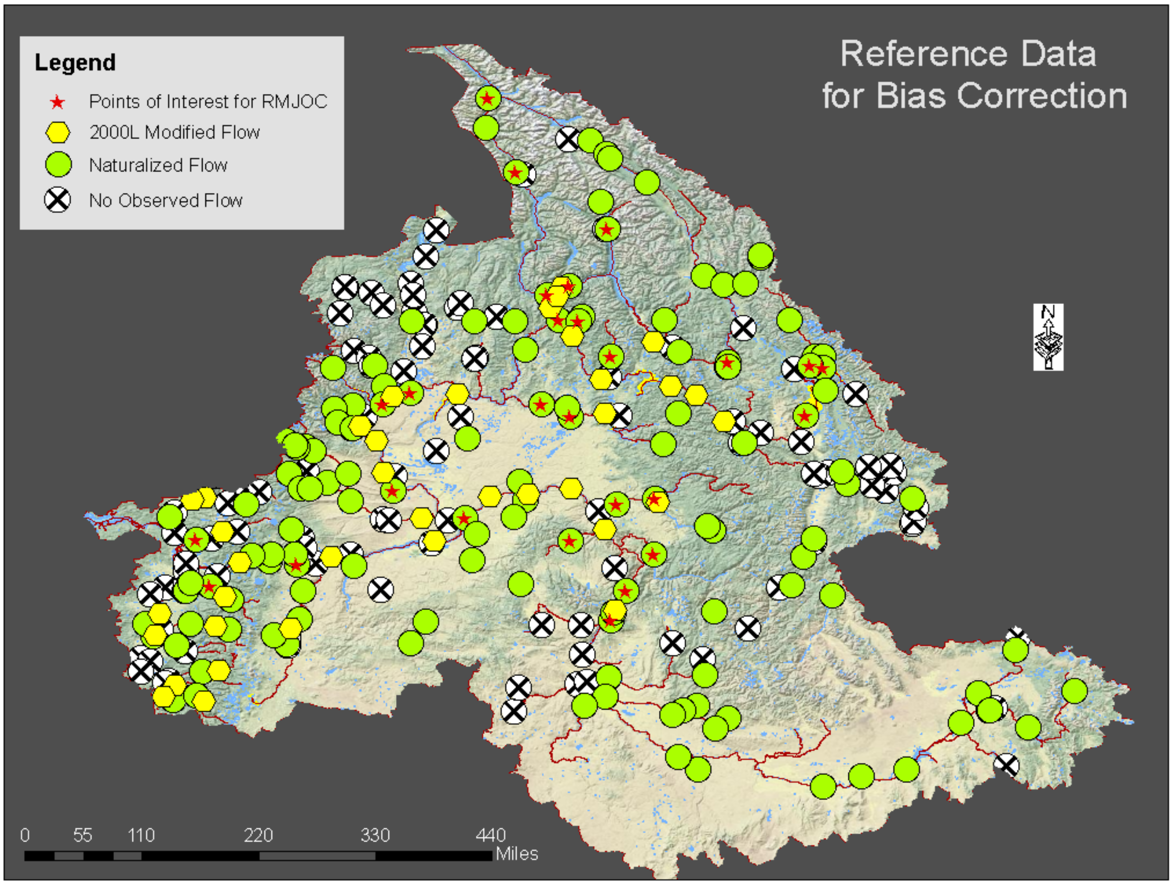

Figure 35. Reference data for bias correction.

To illustrate the last point, consider three locations in the lower Snake River subbasin as shown in Figure 36: Ice Harbor Dam (ICEHA) which uses naturalized flow for reference data, and Lower Monumental (LMONU) and Lower Granite dams (LGRAN) which both used modified flows as their reference data. Figure 37 through Figure 39 show the results of bias correction process for three of the lower Snake River dam locations. These three locations are in line with each other and have relatively small local inflow. The first figure at Ice Harbor Dam uses a naturalized flow dataset as the reference data and shows where the bias correction process is actually introducing error into the streamflow. The raw VIC simulation results are closer to the observed data than after bias correction. Average annual flows after bias correction are close to 60 thousand cubic feet per second (kcfs). For the locations just upstream at Lower Monumental and Lower Granite dams, the bias correction process yields very different results. Much better correlation between observed and bias corrected flows is seen, with average annual flows after bias correction closer to 50 kcfs. The gain of 10 kcfs between Lower Monumental and Ice Harbor dams is fairly large (over 20 percent) given there are no tributaries between these projects and is not consistent with the smaller difference between Lower Monumental and Lower Granite dams.

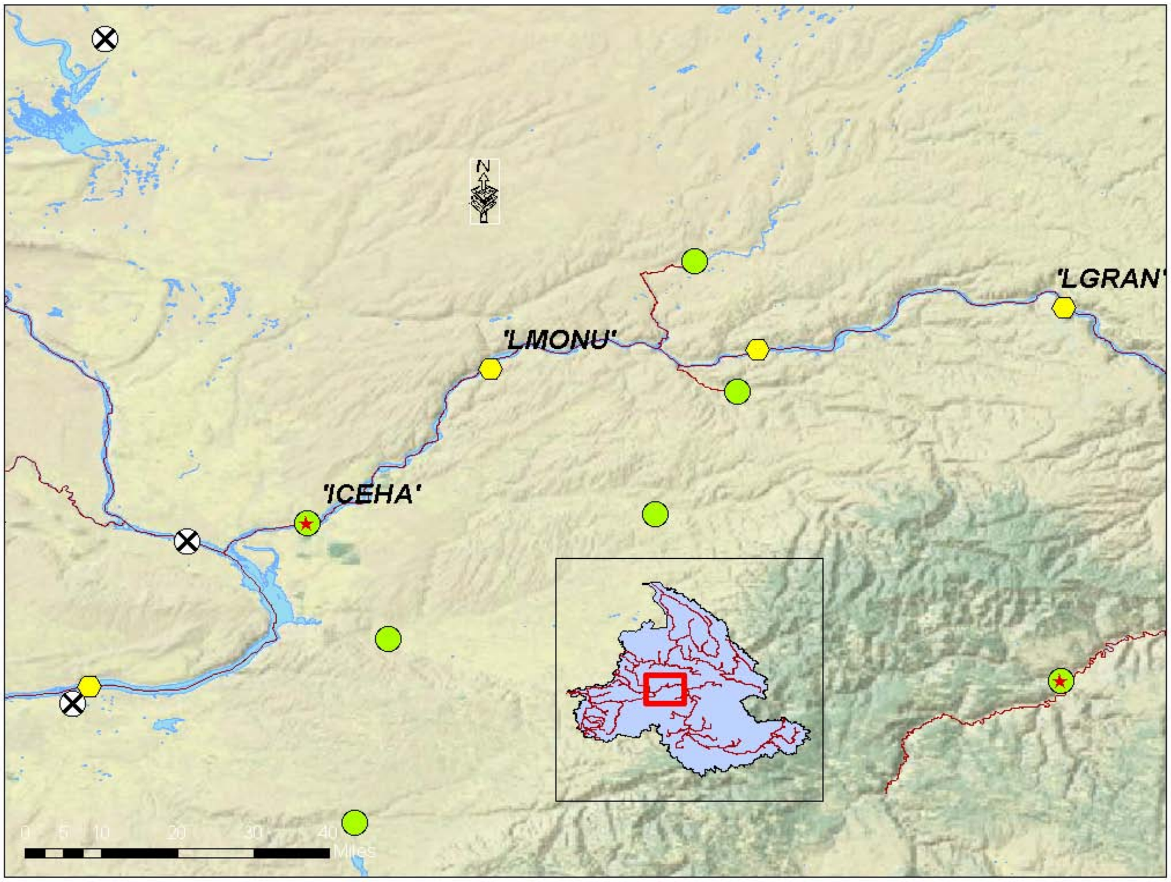

Figure 36. Locations within a watershed with different bias correction reference data.

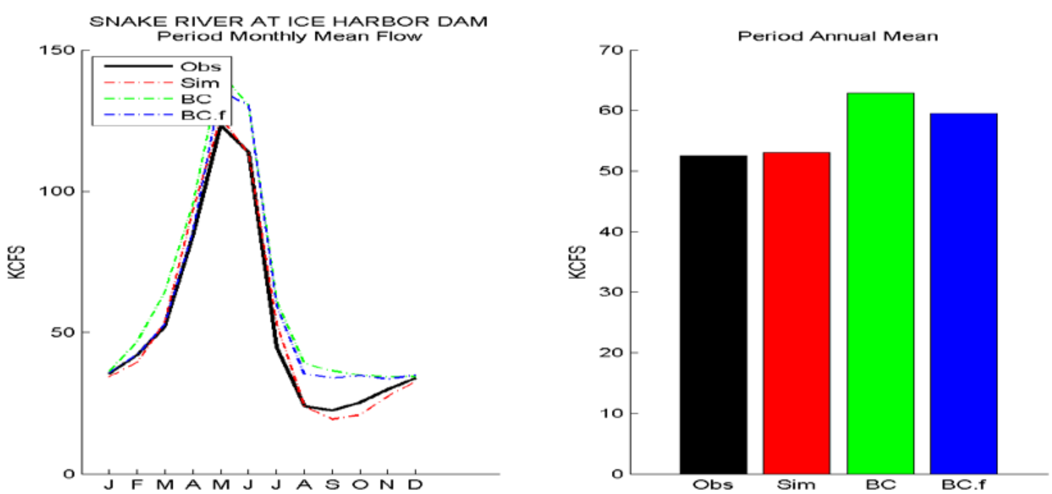

Figure 37. VIC-BC runoff example: Ice Harbor Dam, period means.

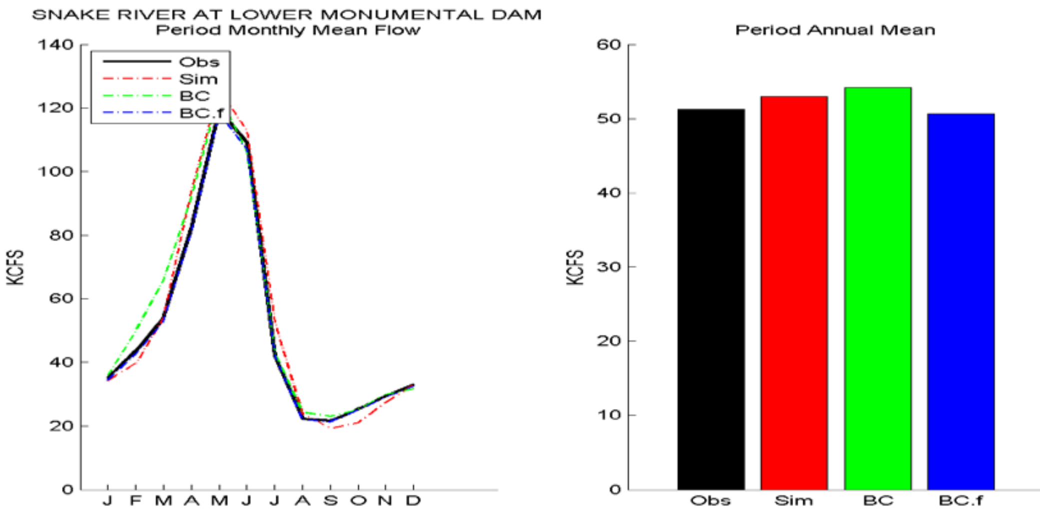

Figure 38. VIC-BC runoff example: Lower Monumental Dam, period means.

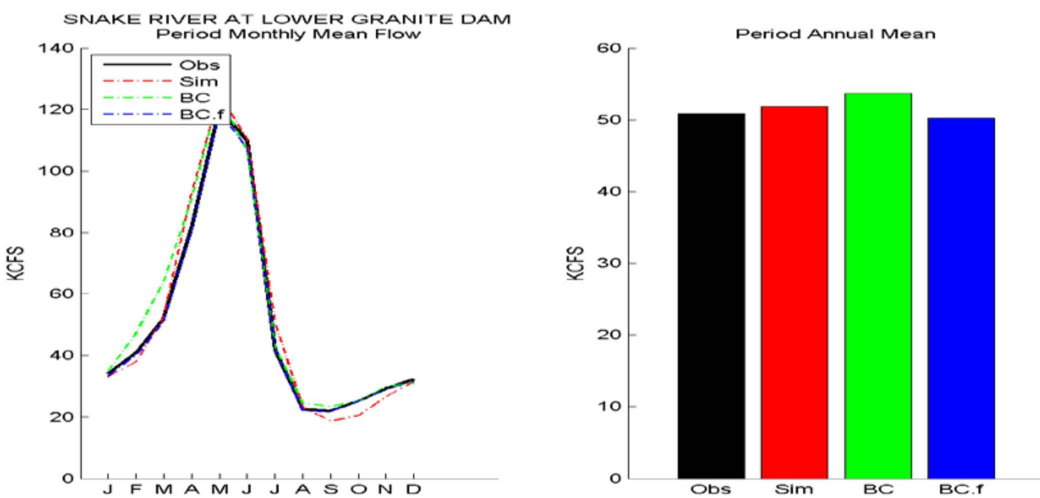

Figure 39. VIC-BC runoff example: Lower Granite Dam, period means.

Again, the demonstration modeling performed as part of this work effort was based upon monthly data only and did not require daily data for flood control purposes. As a result, it was acceptable to use the dataset delivered to the BPA that used a 14-period bias correction that was completely based upon the Modified Flow dataset. However, it is recognized that when USACE is ready to perform model runs with their new model system, some work will be required at that time to re-run the bias correction scripts with reference datasets that will be consistent throughout the Columbia-Snake River Basin for points needed as inputs into their model system.

Figure 40 through Figure 42 show similar results for effect of bias-correction on mean monthly and mean annual runoff at other Columbia River Basin locations. For most locations within the Columbia River Basin, the amount of correction required was relatively small with the final bias correction well correlated to the reference data. The resulting impact on monthly sequencing of flow data appears to be minimal also compared with issues identified within Reclamation tributary basins. Figure 43 and Figure 44 represent the monthly streamflow probability distribution for Mica and Libby dams.

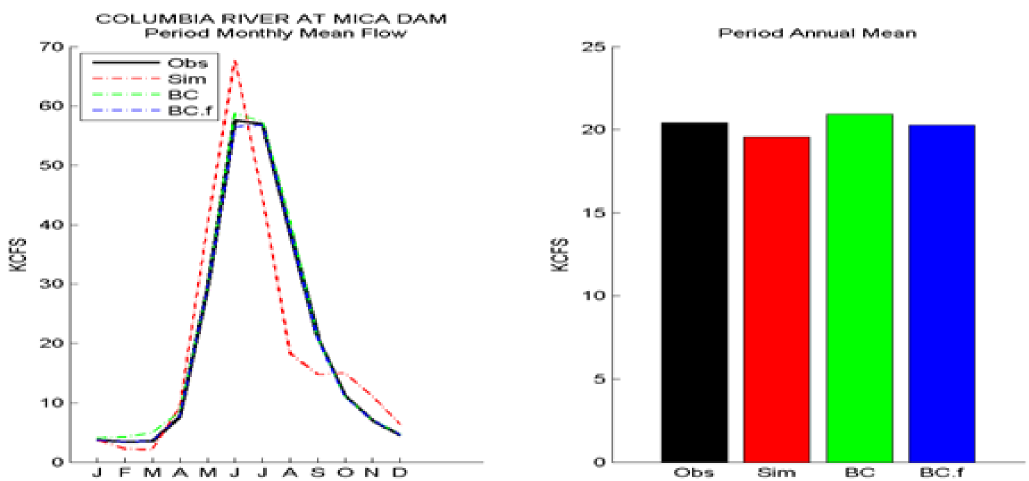

Figure 40. VIC-BC runoff example: Mica Dam, period means.

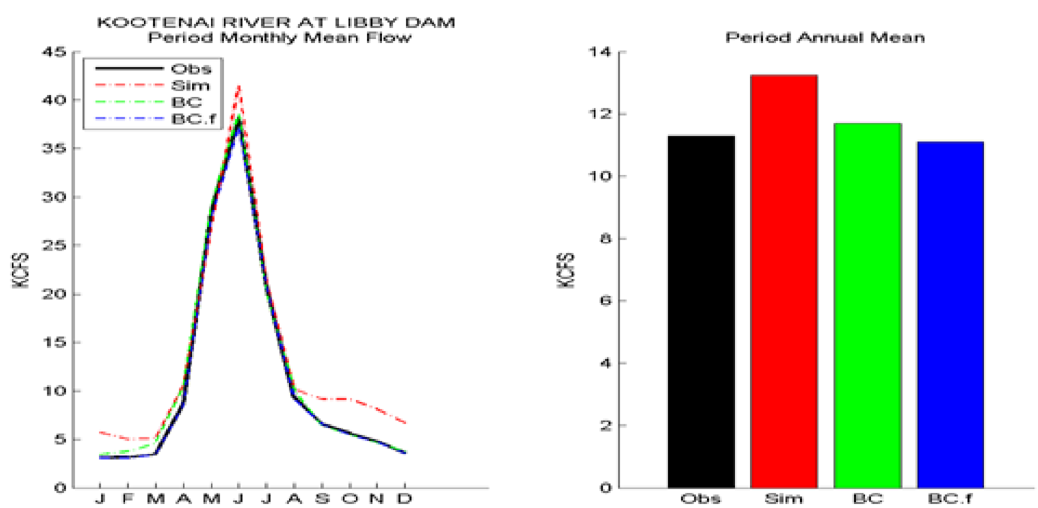

Figure 41. VIC-BC runoff example: Libby Dam, period means.

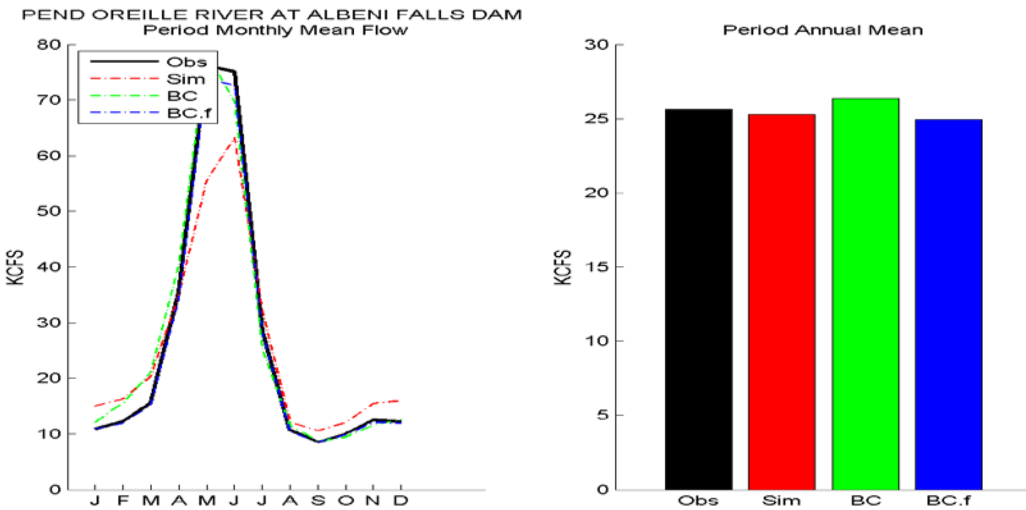

Figure 42. VIC-BC runoff example: Albeni Falls Dam, period means.

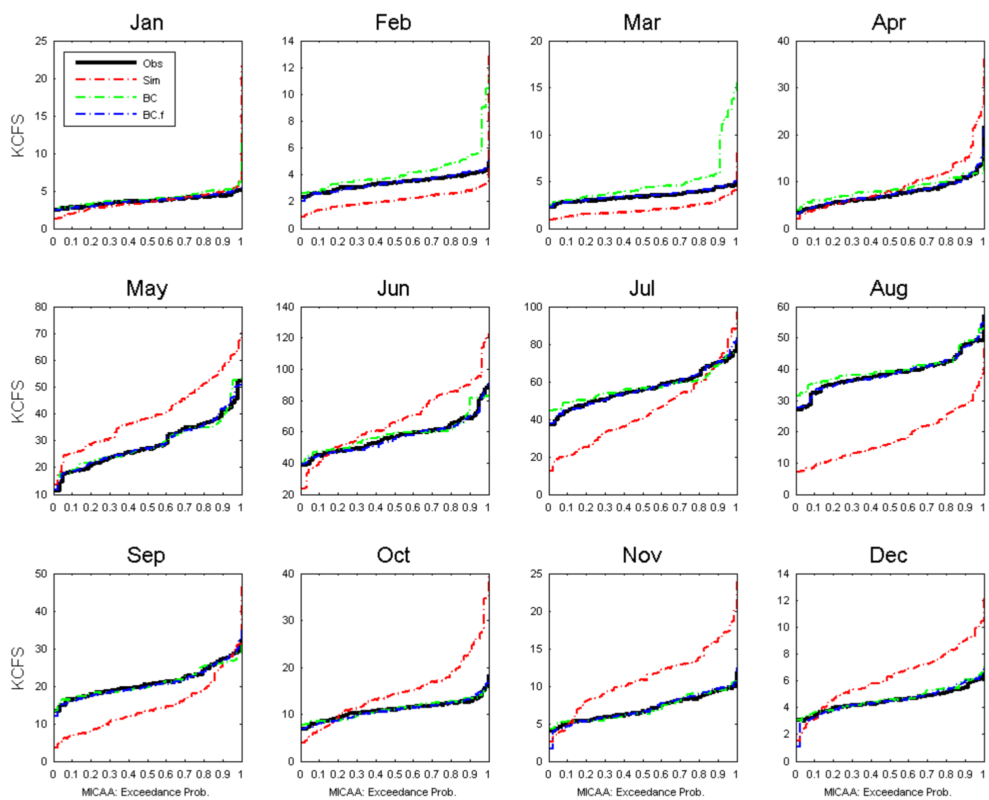

Figure 43. VIC-BC runoff example: Mica Dam, period monthly distributions.

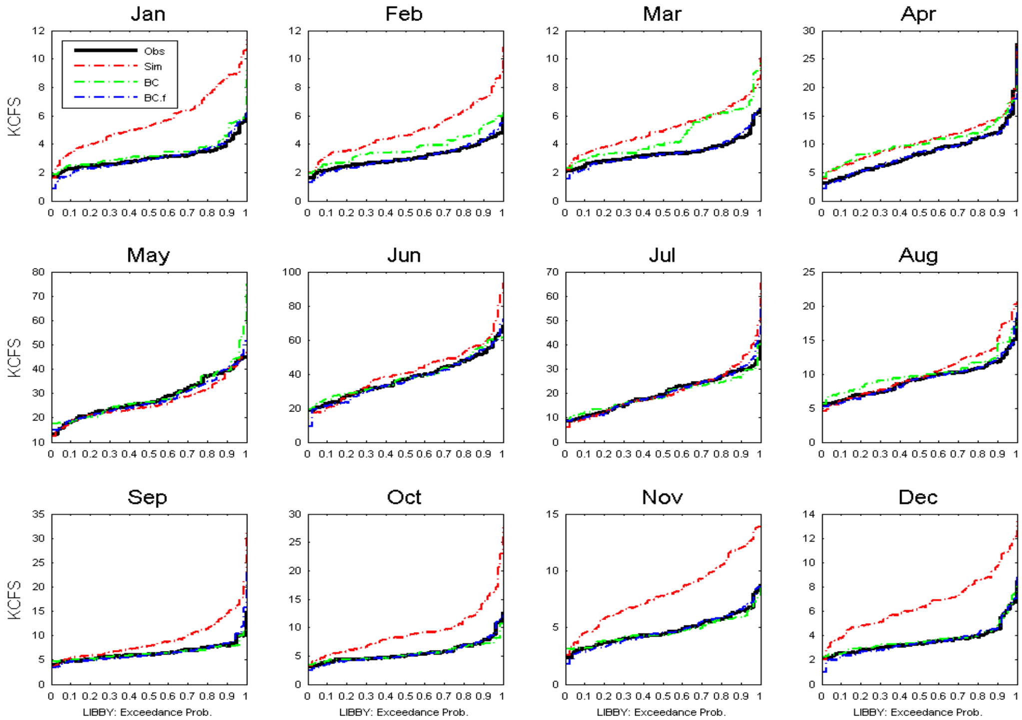

Figure 44. VIC-BC runoff example: Libby Dam, period monthly distributions.

4.5 Assessment of Runoff Conditions under Future Climate

To conclude description of selected future hydrologic scenarios for this RMJOC effort, summary discussions are provided on runoff conditions associated with selected future climates. Focus is on summarizing the VIC BC runoff data just discussed. A summary is first provided for runoff conditions in Reclamation tributary basins, followed by a summary of future runoff conditions representing the remainder of the Columbia River Basin.

4.5.1 Columbia River Tributaries (Yakima, Snake, Deschutes)

This section first presents a representative summary of runoff conditions under Hybrid-Delta 2020s and 2040s climates and runoff changes relative to historical conditions. The summary focused on change in period-mean monthly and mean annual runoff conditions, choosing representative locations in the Yakima (YAPAR, [Table 4]), Deschutes (CROOK and REREG [Table 5]), and Snake subbasins (HEISE, PAYET, and BROWN [Table 6]).

In terms of annual runoff conditions, it is clear that mean annual runoff follows the trend of mean annual precipitation of a given Hybrid-Delta climate scenario over a given location. This can be interpreted by inspecting the geographic precipitation change patterns for each Hybrid-Delta scenario over a given location. For example, consider the changes in mean-annual runoff at YAPAR in the Yakima River subbasin (Figure 45) and compare the relative changes by Hybrid-Delta scenario (2020s or 2040s) to relative changes in mean-annual precipitation over the Yakima River subbasin (i.e., inspect scenario-specific precipitation change maps on Figure 13 and Figure 14, or consider YAPAR subbasin-mean precipitation changes indicated on Figure 10 and Figure 11). In the case of YAPAR, the spread of mean-annual runoff changes aligns fairly well with the qualitative descriptions of the Hybrid-Delta climate change scenarios, even though the latter were labeled with basin-wide climate change in mind.

Switching focus to the Deschutes River subbasin and focusing on results at CROOK and REREG (Figure 46 and Figure 47), a similar story is apparent; however, it is interesting to note that within the mix of the 2020s Hybrid-Delta scenarios, the MW/W scenario yields more mean-annual runoff than the LW/W scenario. This may seem counter-intuitive since “more warming” should lead to greater evapotranspiration and greater reduction in annual runoff. What is misleading is that the degree of “wetter” over the Deschutes River subbasin is not the same for the MW/W and LW/W scenarios. Inspection of those two scenarios’ 2020s precipitation change maps (Figure 13) shows that the MW/W scenario happens to be significantly wetter over the Deschutes River subbasin than the LW/W scenario.

Lastly, consider the three locations over the Snake River subbasin (SNKHE, PAYET, and BROWN on Figure 48 through Figure 50, respectively). The preceding themes also apply, but there is one result that becomes apparent for the Snake River subbasin that did not appear to be the case for the Yakima and Deschutes River subbasins. The basin-wide Hybrid-Delta scenario selections qualitatively describe similar types of climate changes in the Yakima and Deschutes River subbasins (e.g., basin-wide LW/W and MW/W scenarios are generally also “wetter” over the subbasin, or basin-wide LW/D and MW/D are generally also “drier” over the subbasin). This is not the case for the Snake River subbasin, where four of the six selected Hybrid-Delta scenarios for both 2020s and 2040s happen to be “wetter than historical” over the Snake River subbasin. In particular, the MC and C scenarios are wetter over the Snake River subbasin than they are when averaged over the Columbia-Snake River Basin. This appears to be a geographic artifact of the selected mix of Hybrid-Delta scenarios (as discussed in Section 3.0). These findings are not interpreted to suggest that the Snake River subbasin should be relatively wetter than the remainder of the Columbia River Basin. In fact, the consensus view of changes from a larger collection of projections suggests the Snake River subbasin precipitation changes should be comparable to those in northern portions of the Columbia River Basin and possible slightly less (Figure 5 and Figure 6, discussed in Section 2.0).

Moving forward, it is understood that while the selected Hybrid-Delta scenarios may well-represent the breadth of climate change possibilities from a basin-wide view, they may represent a relatively wet sampling of available change information over the Snake River subbasin. The outcome in the Snake River subbasin highlights limitations of the climate scenario selection process (Section 3.2.2) due to (1) how any individual climate projection underlying a Hybrid-Delta climate change scenario may portray spatially non-uniform climate change over a given region, and (2) how the underlying climate projections were classified based on how they described mean changes in precipitation and temperature over the Columbia-Snake River Basin. On (1), given the intent to select a small set of scenarios and the desire to reflect a range of mean climate changes, an outcome like that in the Snake River subbasin is generally unavoidable. On (2), it is questioned whether use of a runoff criterion might have led to Hybrid-Delta scenario selections that avoided this Snake River subbasin outcome. Such a result seems unlikely if the basin-wide view is maintained (i.e., selecting Hybrid-Delta scenarios that reflect a range of runoff changes at The Dalles), noting that upstream runoff changes would follow climate change conditions and be spatially non-uniform.

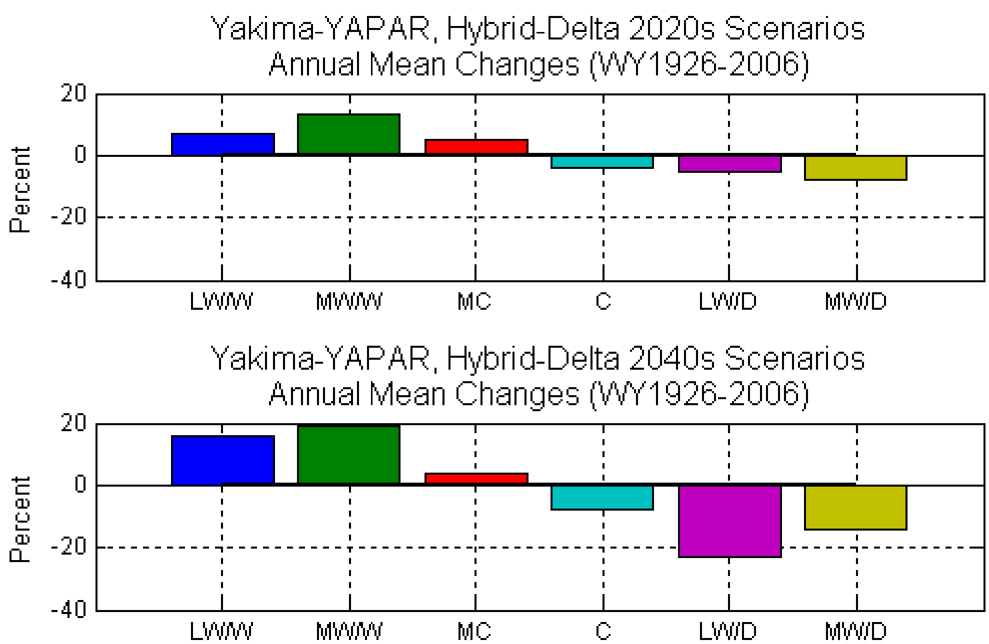

Figure 45. Yakima River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

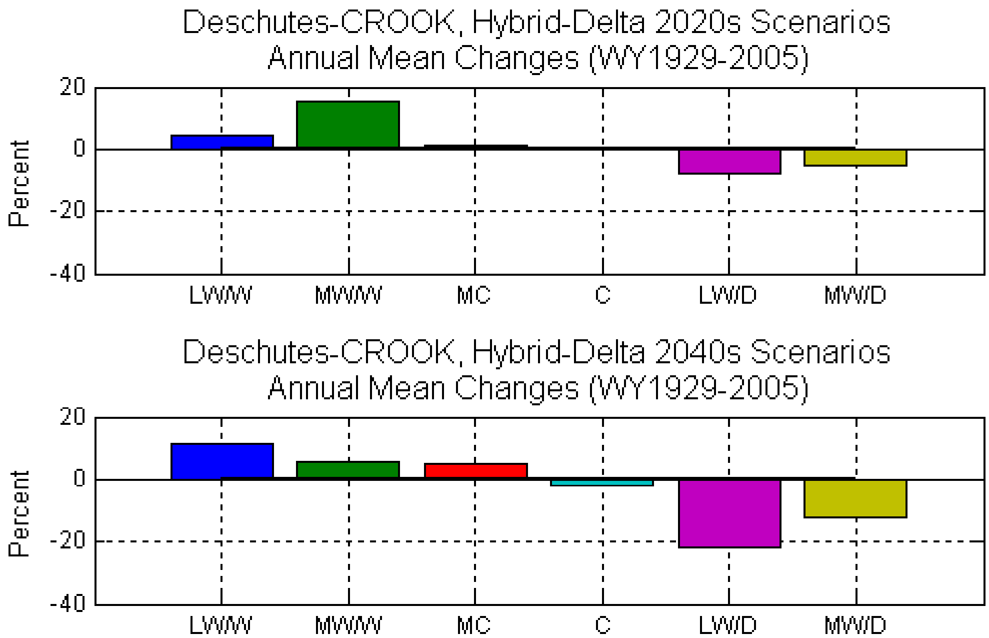

Figure 46. Deschutes River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

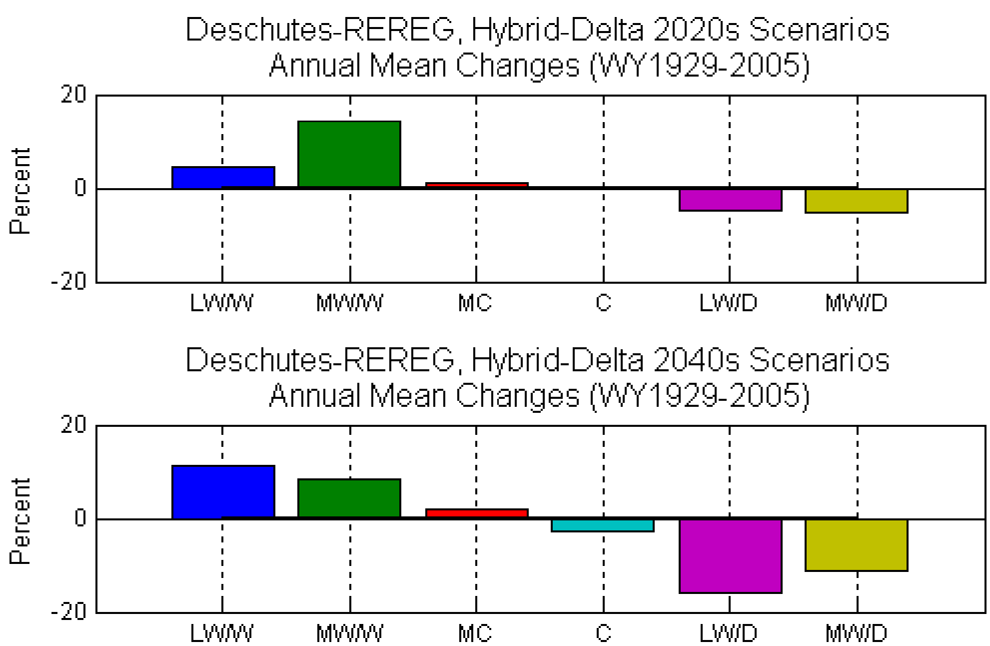

Figure 47. Deschutes River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

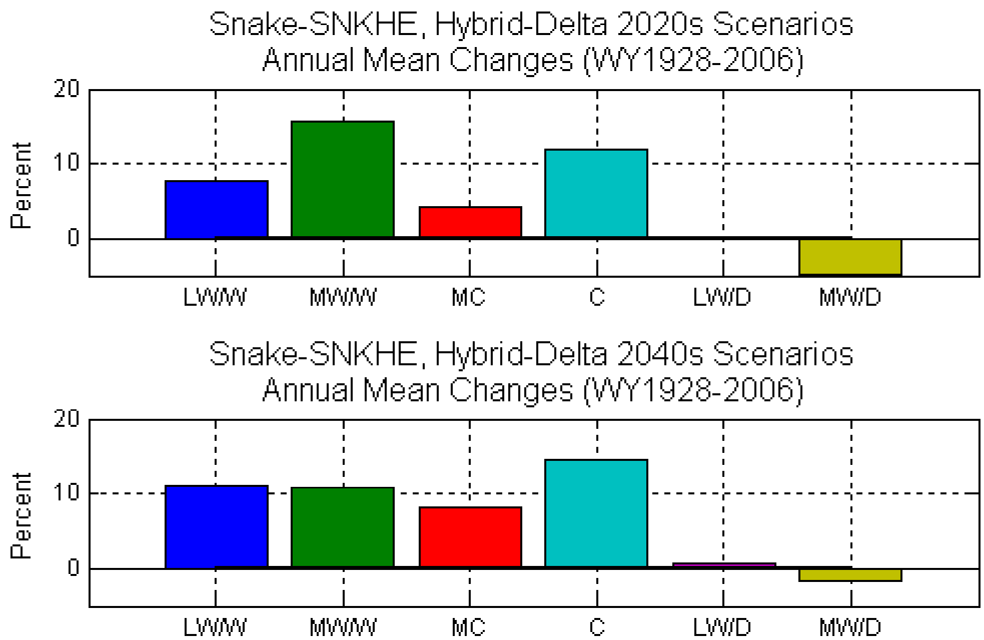

Figure 48. Snake River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

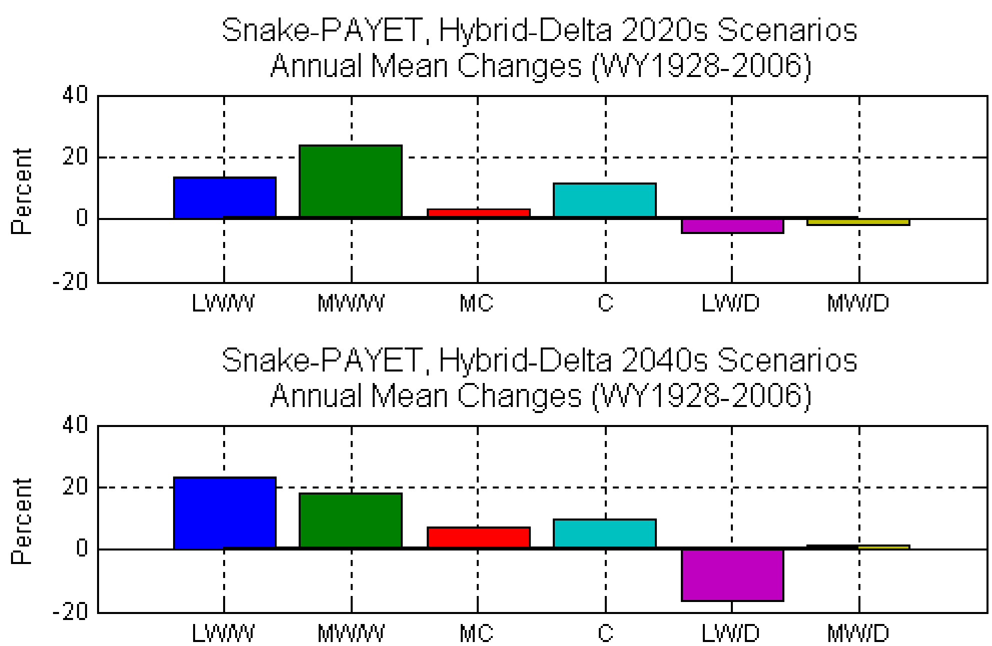

Figure 49. Snake River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

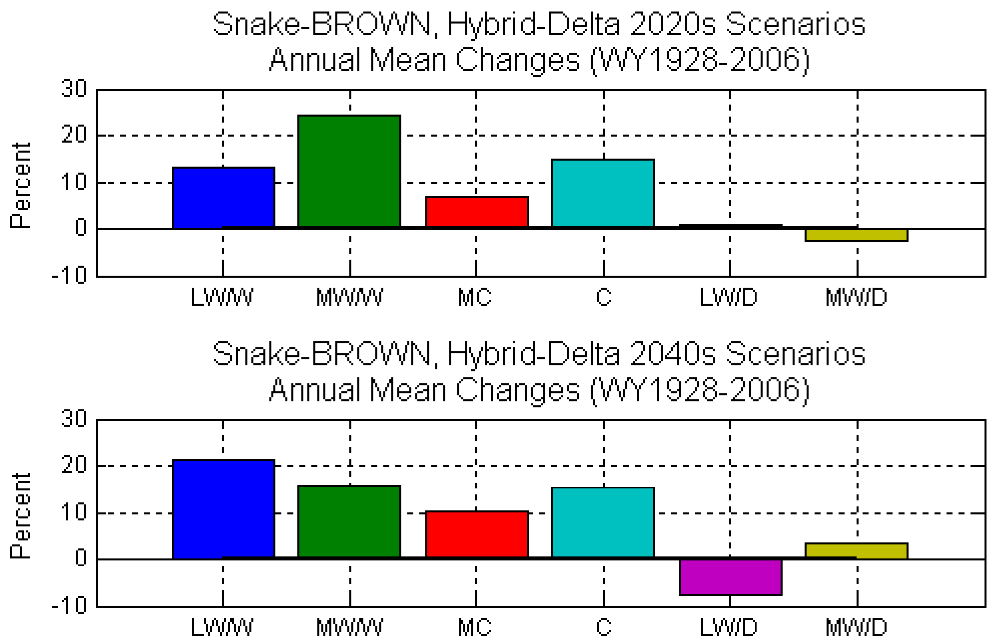

Figure 50. Snake River subbasin runoff under Hybrid-Delta climate scenarios: change in mean-annual.

Switching from annual to monthly view, Figure 51 through Figure 56 show mean monthly runoff for Historical and Hybrid-Delta climates for the same six locations just discussed. These figures also show change in mean-monthly runoff. Review of results shows that monthly runoff patterns are expected to change under Hybrid-Delta climates relative to Historical climate, with warming leading to reduced spring-summer runoff and increased winter-spring runoff, stemming from the impacts of warming (e. g., increased winter rainfall and runoff, reduced coincident snowfall leading to reduced snowpack accumulation, and reduced snowmelt volume during spring-summer)

The degree to which this phenomenon occurs varies by location and varies with future climate period, with more significant changes in runoff seasonality occurring by the 2040s. One potential exception to the rule is shown at the Deschutes CROOK location (Figure 52), which happened to be a location where VIC simulated runoff results was more significantly bias-corrected, perhaps leading to a distorted portrayal of monthly runoff impacts. Another change artifact is seen for the PAYET location (Figure 55), where a large percentage runoff increase is shown for the month of August for the 2020s and 2040s C scenarios. The reasons for this are not discussed here, but the effect of this August PAYET flow increase appears to be minor in the sense of how it affects BROWN runoff further downstream (Figure 56).

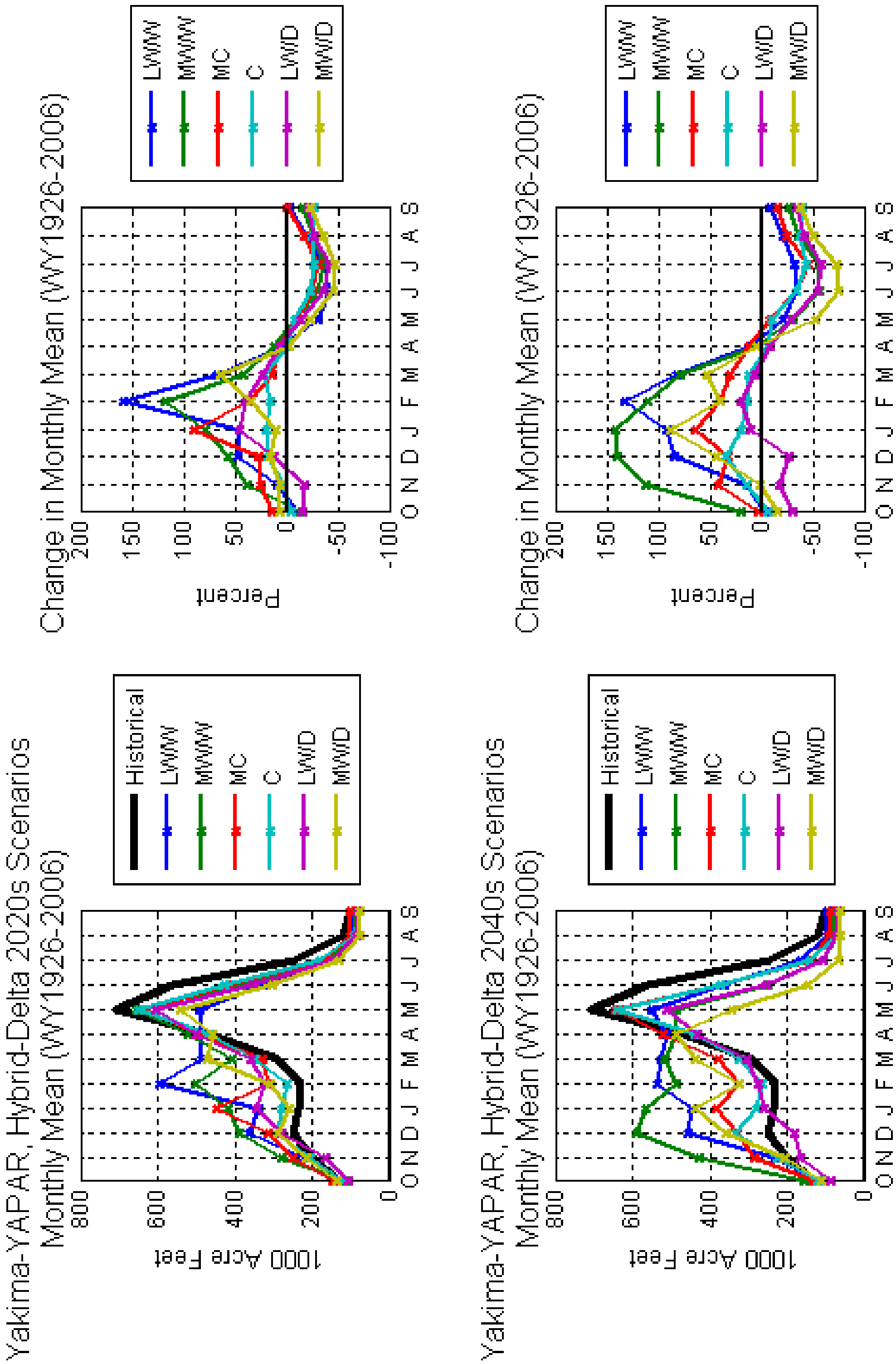

Figure 51. Yakima River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

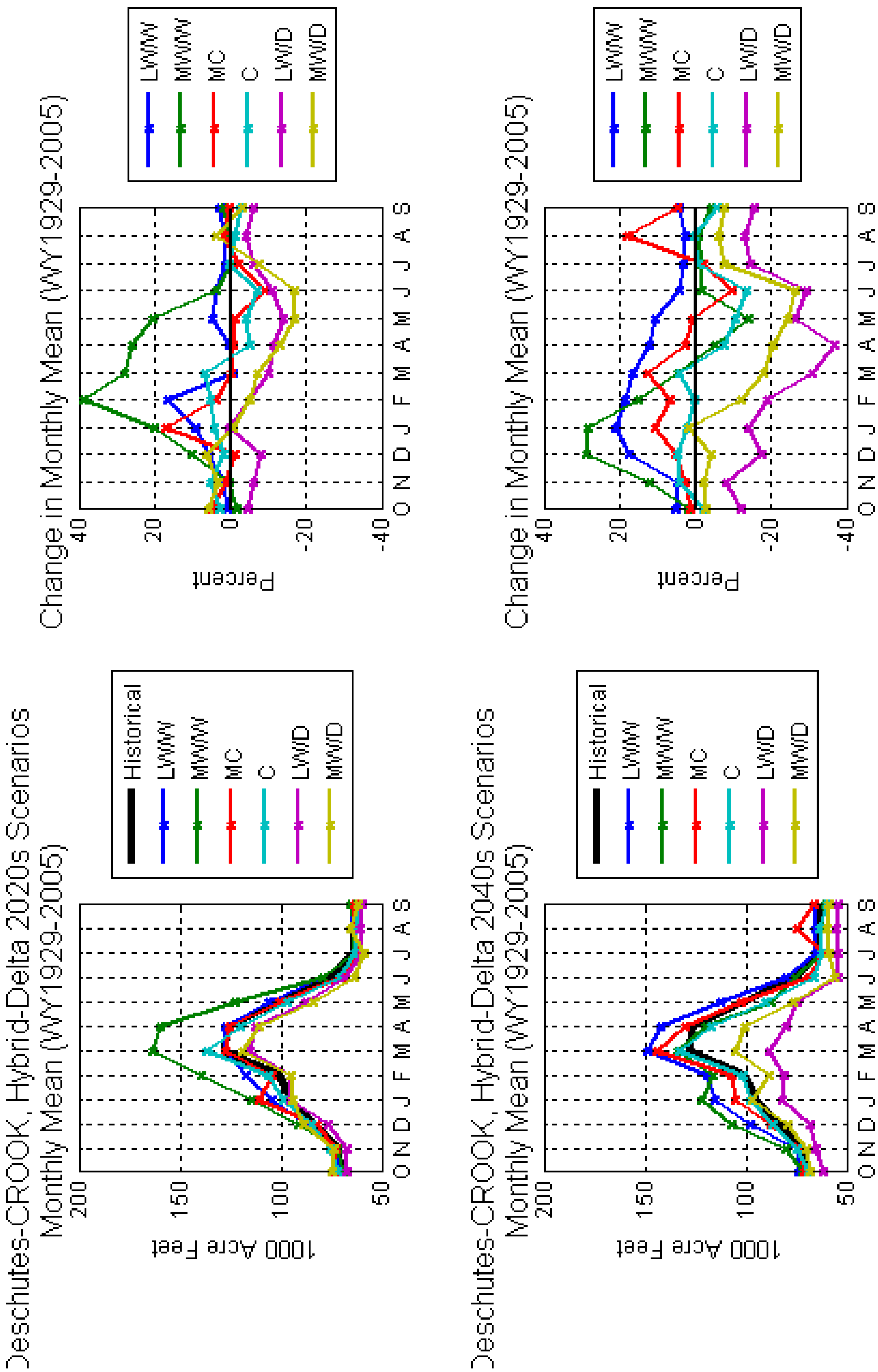

Figure 52. Deschutes River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

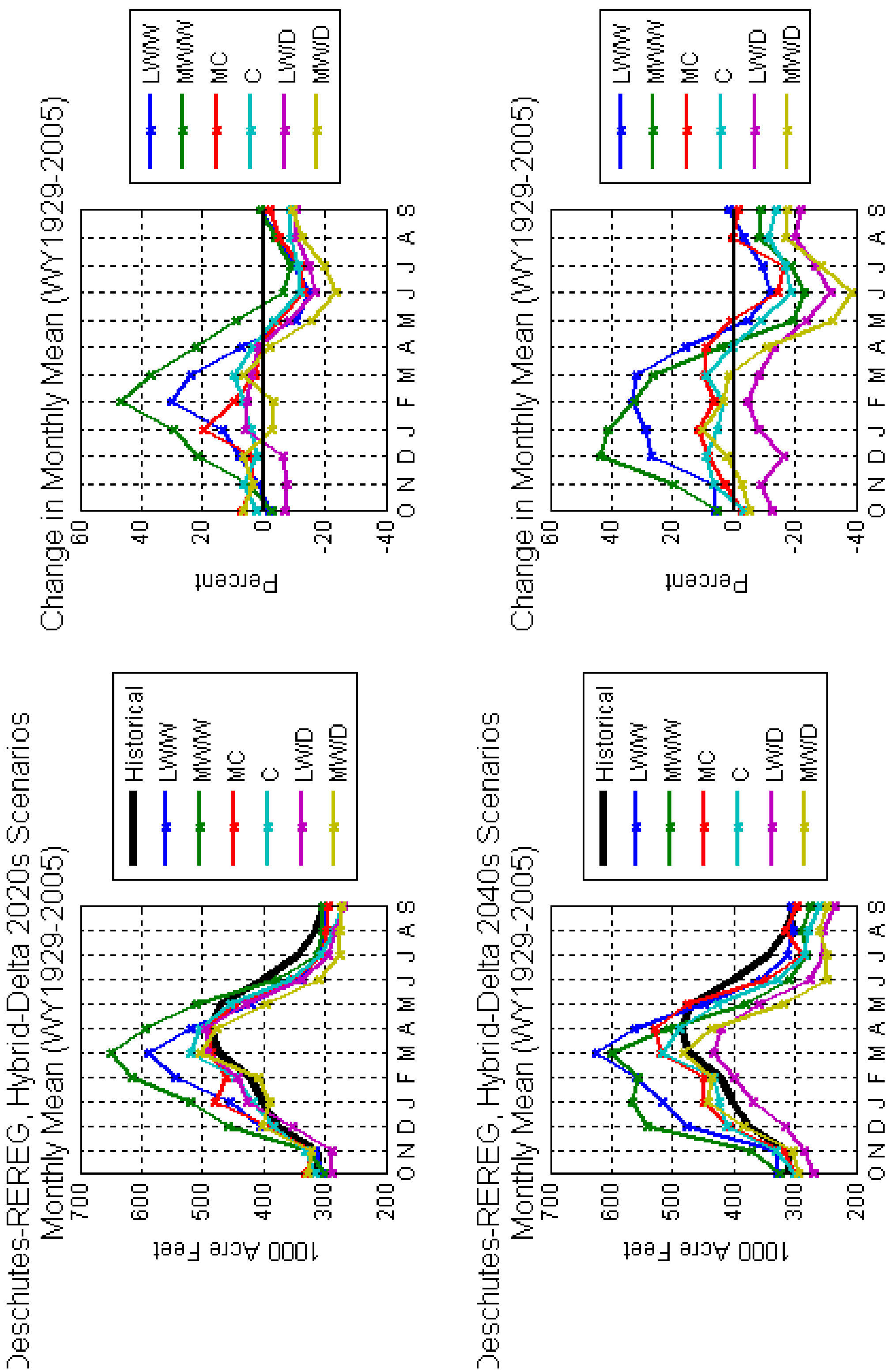

Figure 53. Deschutes River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

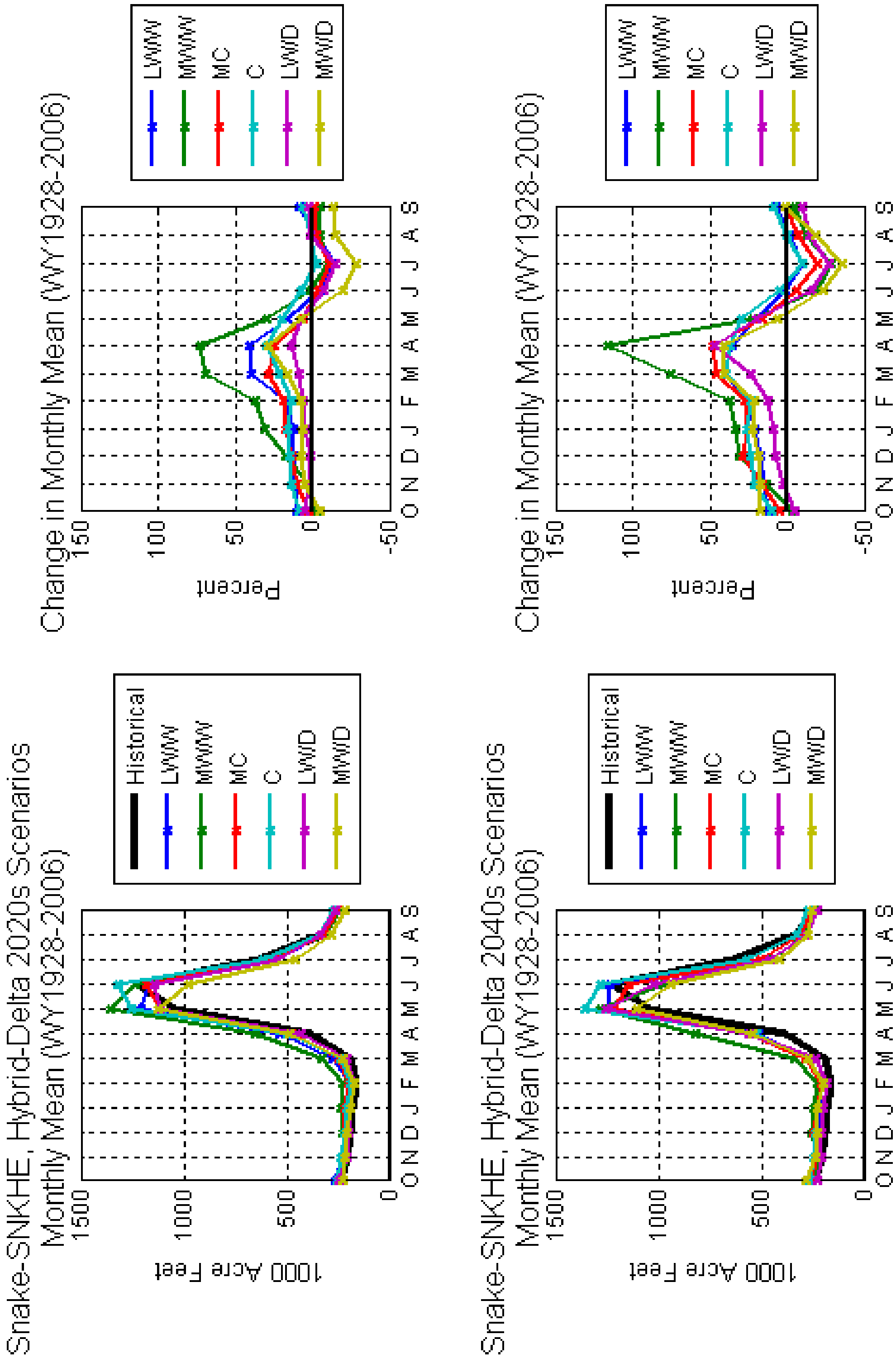

Figure 54. Snake River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

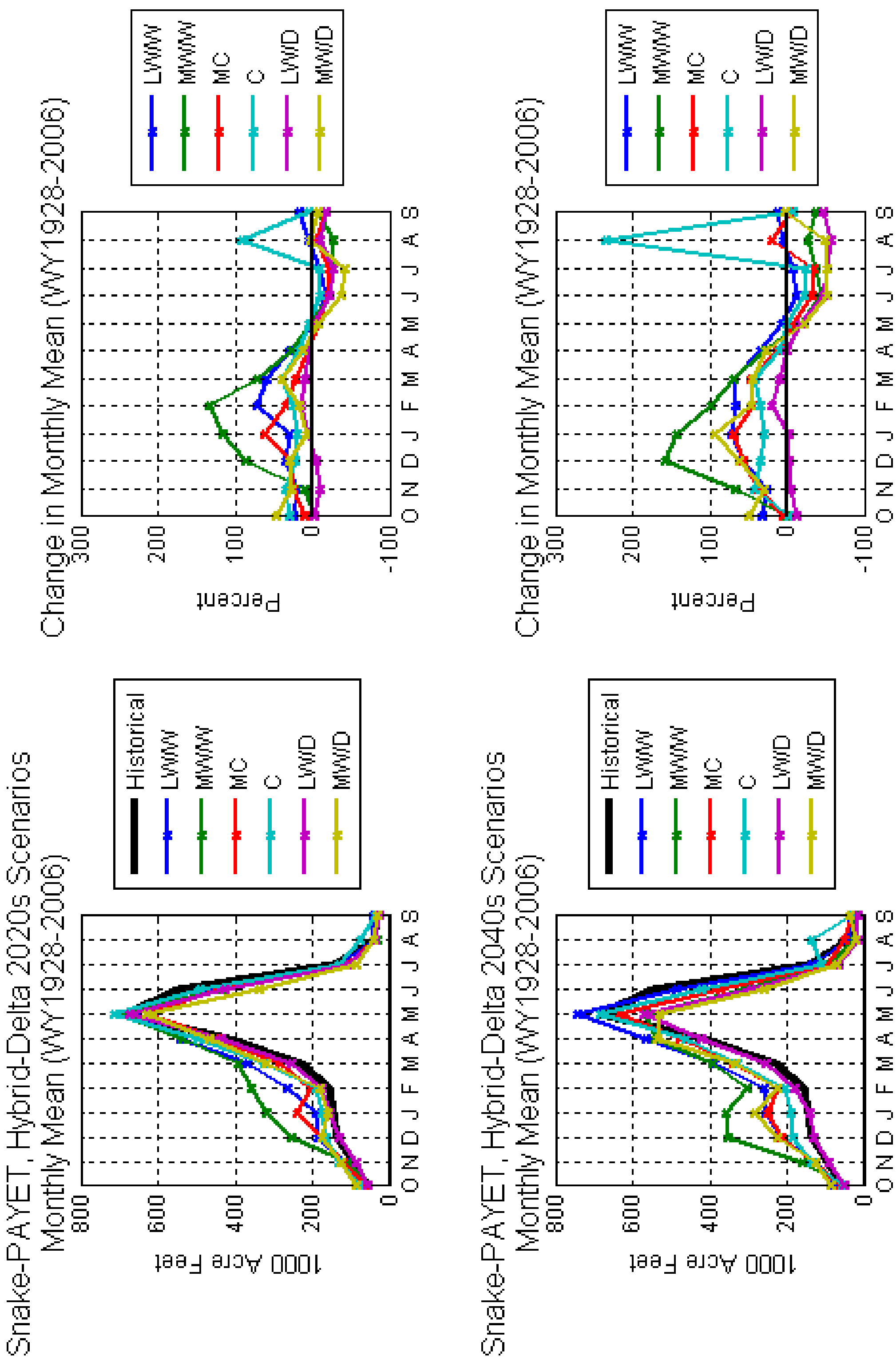

Figure 55. Snake River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

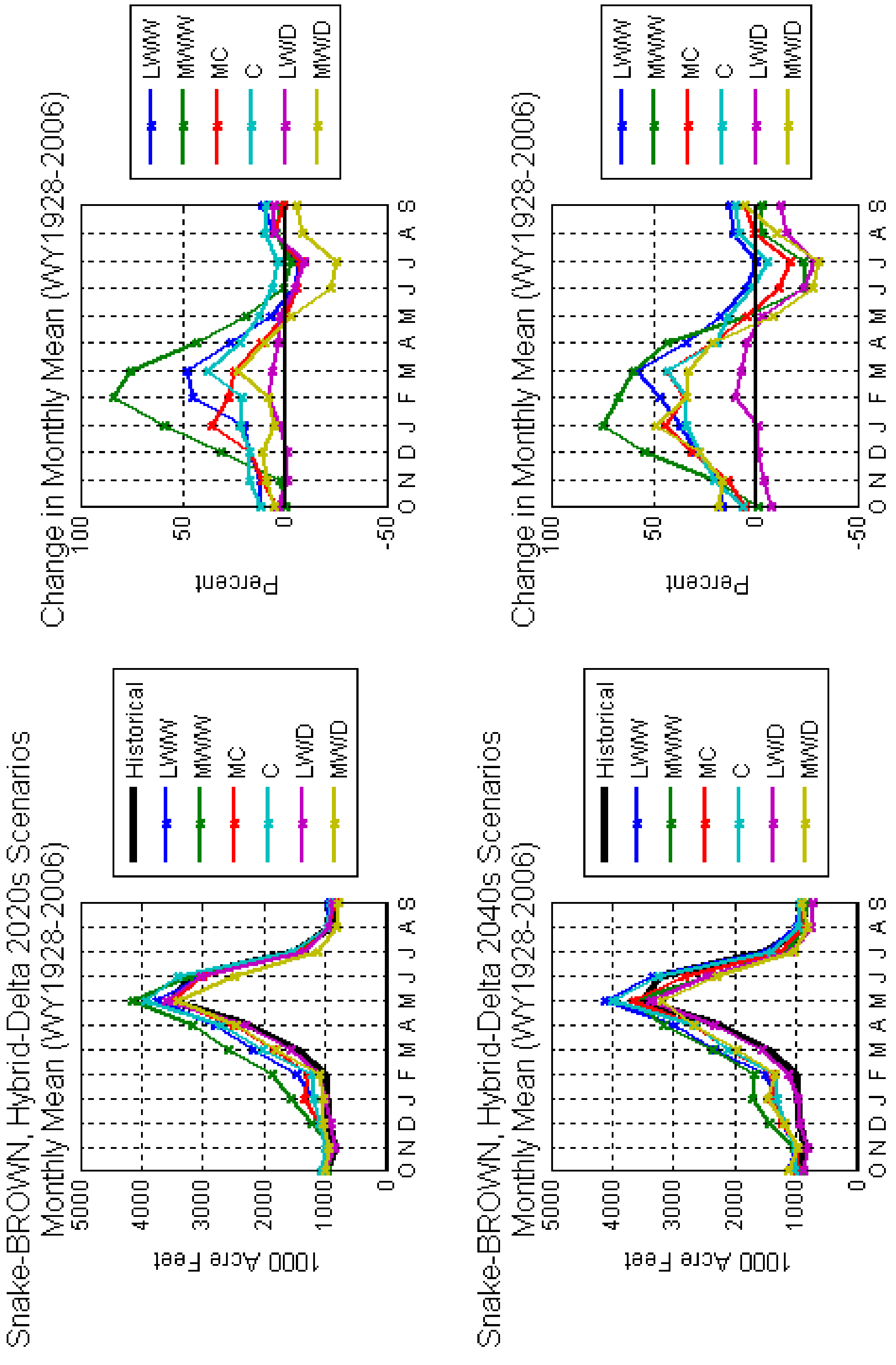

Figure 56. Snake River basin runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

The remainder of this section offers a view of runoff under the Transient climate scenarios. Previous sections highlighted how Hybrid-Delta and Transient scenarios offer different portrayals of future climate conditions and set up different types of questions that might be asked in longer-term operations analyses. The HD scenario "climate change" data are useful for studies meant to reveal system operational sensitivity to incremental change in climate. The Transient Climate Projection data are useful for revealing time-developing climate and hydrologic change, which might support questions about time-developing operations relevant for adaptation planning where there is interest in the onset and intensification of impact (Brekke et al. 2009). However, the Transient approach involves using relatively more temporal climate projection aspects than Hybrid-Delta, which results in the planning assessment inheriting more projection uncertainties. These uncertainties can become more significant at local space and finer time scales (Elsner et al. 2010), which has led some to suggest that Transient scenarios may be more applicable to regional assessments where the interest is on water resources conditions on monthly to annual time scales.

To illustrate, consider three of the runoff locations considered above in the discussion of Hybrid-Delta results. Figure 57 to Figure 59 show time-series annual runoff for YAPAR in the Yakima River subbasin, REREG in the Deschutes River subbasin, and BROWN in the Snake River subbasin, respectively, for historical climate (black line indexed from climate-observed WY 1916-2006) and transient climates (colored lines indexed from climate-simulated WY1951-2099). The figure also shows the time-series of transient ensemble-median annual runoff, where transient conditions are pooled each year and the median is computed each year from this pool of conditions (dashed black line indexed from WY 1951-2098). There are several ways to interpret the transient information.

- The transient ensemble is meant to be viewed as a collective, understanding that climate and hydrologic sequences could manifest in numerous ways depending on the evolution of the larger ocean-atmospheric climate system. Thus, for any year stage in the time-series, the ensemble "year-slice" suggests a range of potential conditions for that year. Given that the transient information is credible, this "year-slice" would be akin to an envelope of potential climate variability situated on that year. However, the fact that this transient ensemble only includes a small set of time series members limits this "year-slice" view, which is discussed in more detail later in this section.

- By tracking the transient ensemble through time (i.e., following the spread and central tendency, or median), impressions can be drawn on the rate of change for climate and hydrologic variability. Rate of change impressions are useful for the adaptation view and wanting to understand the timing of impacts.

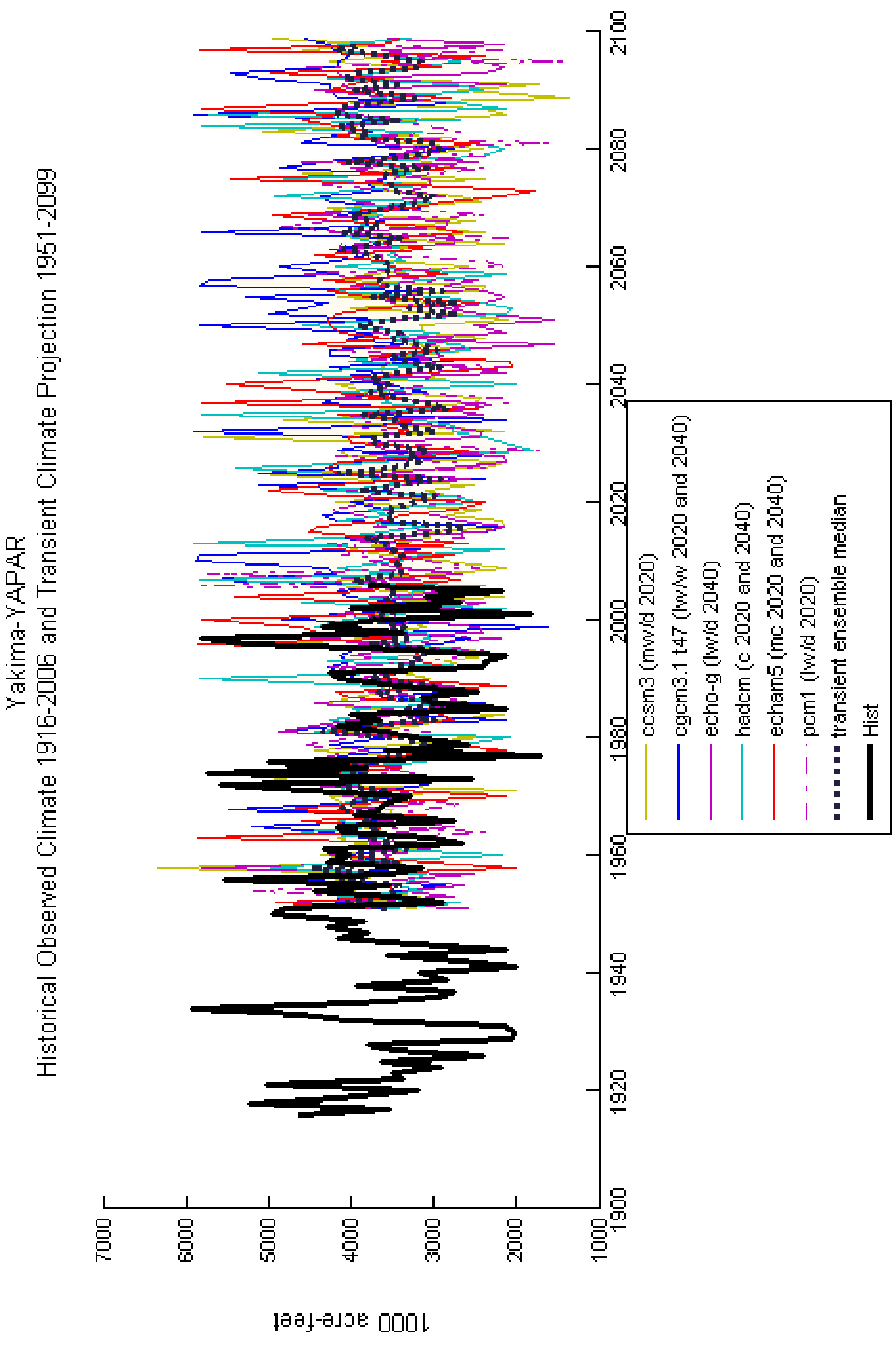

Figure 57. Yakima River basin runoff under historical and transient climate scenarios: annual time series.

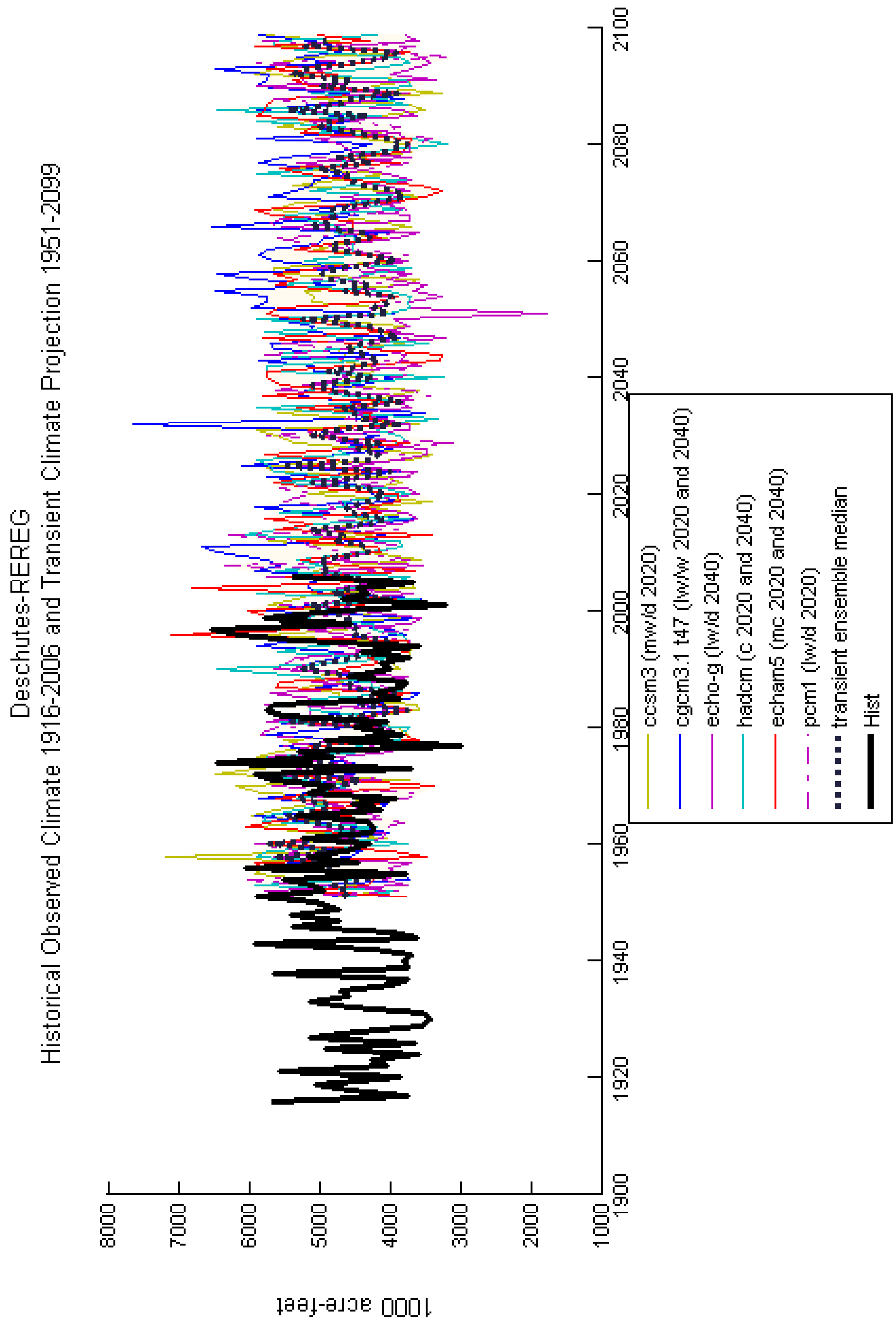

Figure 58. Deschutes River basin runoff under historical and transient climate scenarios: annual time series.

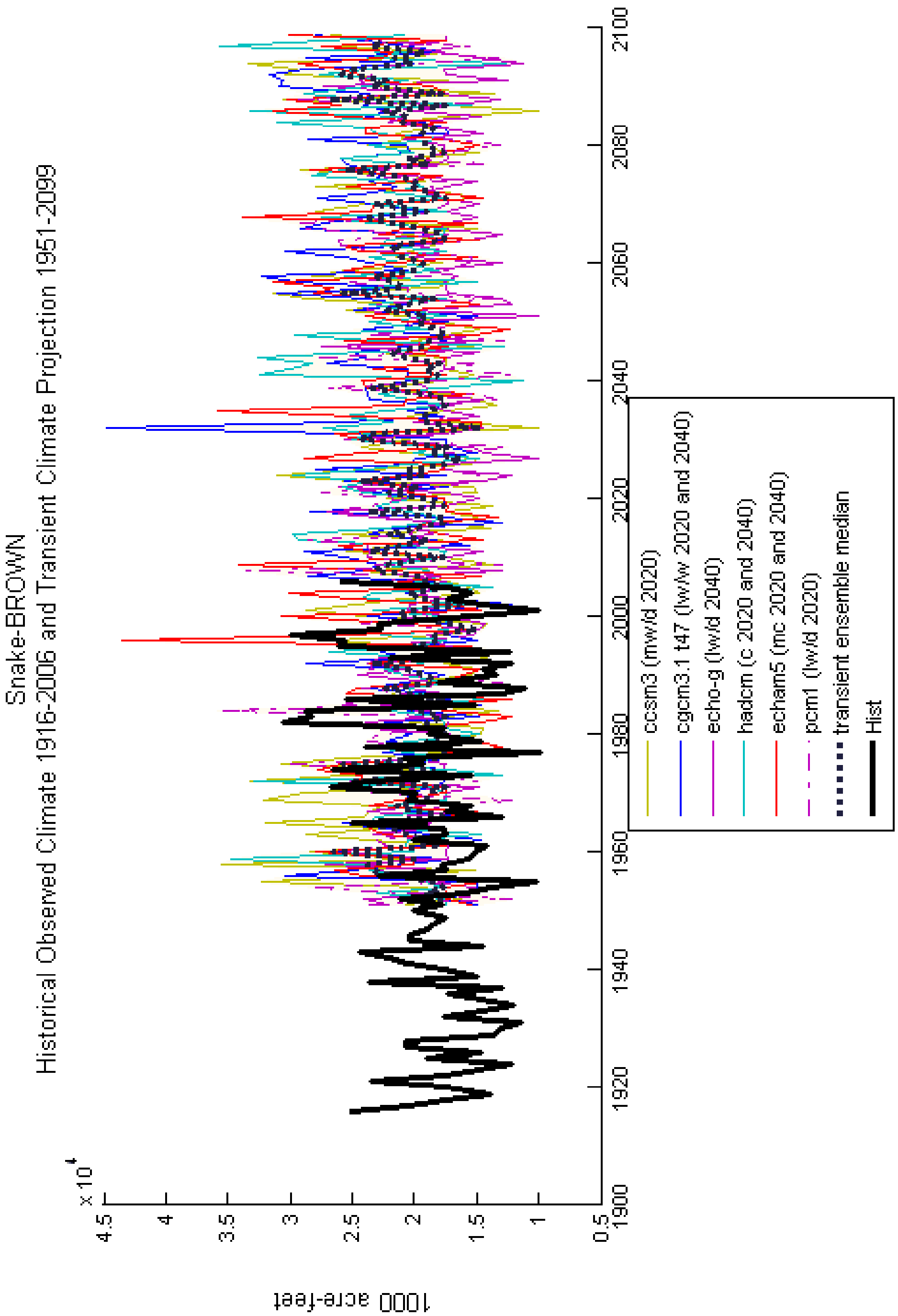

Figure 59. Snake River basin runoff under historical and transient climate scenarios: annual time series.

Interpreting these aspects of each location, any trend in the central tendency appears to be subtle relative to the envelope of potential annual variability suggested by the ensemble spread. However, with that noted, it might be interpreted that the central tendencies of annual runoff at YAPAR and REREG would be fairly steady through the 21st Century, whereas the central tendency for BROWN perhaps slightly increases. On change in mean annual condition, the Transient results seem consistent with the Hybrid-Delta results during the 2020s and 2040s time frames. The Transient results also characterize trends in mean-annual runoff in a time-evolving fashion through a time-period that extends before and after a given Hybrid-Delta scenario.

Focusing on the spread and variability in the transient information, it appears that for the most part, the transient envelopes of hydrologic possibility during the 20th Century are generally similar to envelopes in the 21st Century. It also appears that the envelopes during the historical transient climate and historical observed climate (1950-1999) are also similar. This latter result is largely forced by the VIC runoff bias-correction procedure. However, it might be noticed that during the historical portion of the transient results, the VIC-simulations under GCM-simulated historical climate (transient climates) yield annual runoff maximums that exceed the VIC-simulated runoff maximum under the Historical Observed climate (e.g., Figure 57, transient scenario ccsm3, showing an annual outcome in the late 1970s exceeding any outcome in the Historical simulation). This is possible with the use of Transient scenarios, and relates to how GCM-simulated monthly climate sequences can lead to seasonal to annual situations not experienced in the historical observed climate situation. For the YAPAR and REREG results, there were limited occurrences of this situation. For BROWN, there were more frequent occurrences, which raises questions whether another factor may be contributing to this outcome, namely how the quantile maps used to bias-correct VIC-runoff might have had to be used in extrapolation mode[22] more frequently than maps created at YAPAR and REREG. These extrapolation occurrences may also explain some of the anomalous extremes seen for some Transient scenarios at REREG and BROWN.

Ideally, the Transient information could be used to support "year-slice" assessments of potential runoff variability, as described earlier in this section. However, to support such a view, the ensemble should have a sufficiently large set of ensemble members to support characterizing such year-stage distributions. As it is, this RMJOC effort features only six transient members, and therefore, it is inadvisable to characterize year-stage distributions informed by only six transient climate scenarios and six corresponding annual outcomes at

[22] A bias-correction situation where VIC simulated monthly and annual runoff outcomes exist outside the range of VIC simulated outcomes reflected in the quantile map guiding bias correction. In these situations, assumptions are made to extrapolate the tails of the quantile map to define correction over a broader range of magnitudes.

each year-stage. It is expected that if the RMJOC effort had included a larger set of time-series members in the transient ensemble, then the ensemble spread of potential annual conditions would be more stable from year to year.

One benefit of using the Transient information is that it can be used to reveal decadal to multi-decadal variability within climate projections. The matter of decadal to multi-decadal variability affects our interpretation of the Hybrid-Delta (HD) scenarios, which are sampled as changes in 30-year climates from climate projections. The goal is to be able to interpret HD scenarios as “climate change” possibilities and not misunderstood multi-decadal variability. It is possible that some of the HD scenarios were selected in part because of the time period chosen (2020s or 2040s) and the climatic excursions happening within the climate projections during these periods. To explore this issue, consider the YAPAR transient example, but smoothed through time using 10- and 30-year moving means (Figure 60 and Figure 61, respectively). The 30-year period underlying 2040s HD scenario definition was 2030-2059. Now consider the selected LW/D 2040s HD scenario: this scenario is sampled from the same climate projection that underlies the Transient scenario labeled “echo-g” (see legend on Figure 60). Inspection of “echo g” annual runoff during 2030-2059 reveals that a low-diversions decade happens roughly during the 2050s and relates to relatively dry conditions during this decade within this climate projection. Thus it is fair to question whether the LW/D 2040s HD scenario is truly climate change, or perhaps a sampling of decadal climate variability from the “echo g” projection. This question is explored further in Report II on Operations Portrayal under Transient climate scenarios informed by these associated hydrologic results.

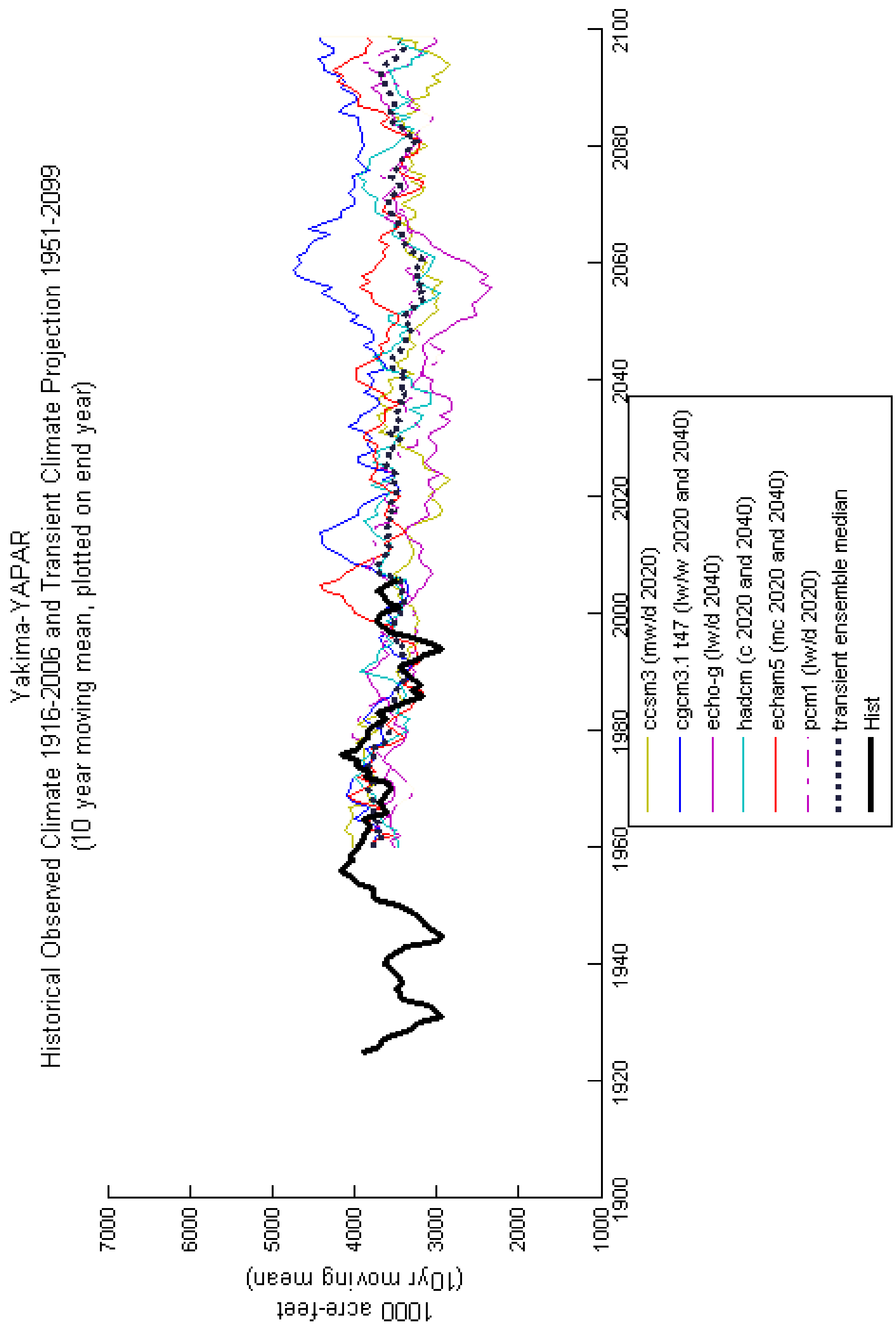

Figure 60. Yakima River basin runoff under historical and transient climate scenarios: running 10-year mean-annual.

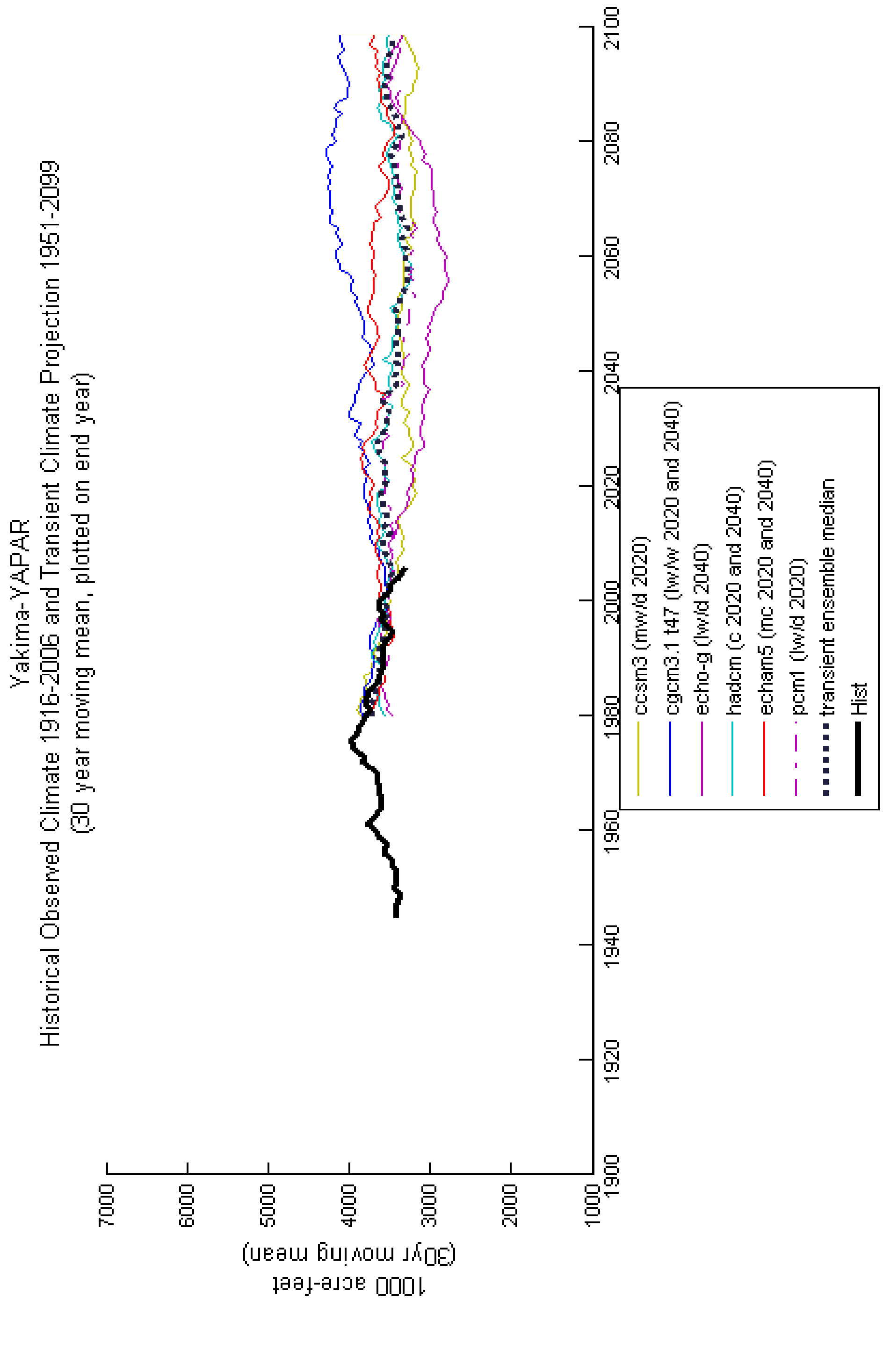

Figure 61. Yakima River basin runoff under historical and transient climate scenarios: running 30-year mean-annual.

4.5.2 Columbia River Basin

This section first presents a representative summary of runoff conditions on the Columbia River under Hybrid-Delta 2020s and 2040s climates and runoff changes relative to historical conditions. The summary focused on change in period-mean monthly and mean annual runoff conditions, choosing representative locations in the Columbia River Basin. The locations selected correspond to the hydro projects that represent the geographical range of the Columbia River Basin (Table 7).

Table 7. Project and subbasin representation in mainstem Columbia River runoff assessment.

	CIG HB2860 Location Identifier	Hydro Project Represented in Columbia River (HYDSIM Identifier)	Sub-Basin Represented
1	MCAA (1015)	MCDA (Mica)	Upper Columbia River
2	ARROW (1019)	ARDA (Arrow)	Upper Columbia River
3	LIBBY (3002)	LIB (Libby)	Kootenay River
4	CORRA (1025)	CORA L (Corra Linn)	Kootenay River
5	FLTW (3027) (near HGH)	HGH (Hungry Horse)	Pend Oreille River
6	ALBEN (2005)	ALB (Albeni Falls)	Pend Oreille River
7	LLAKE (6031)	LLK (Long Lake)	Spokane River
8	CCOUL (6034)	GCL (Coulee)	Mid Columbia River
9	LGRAN (6073)	LWG (Lower Granite)	Snake River
10	DALLE (4030)	TDA (The Dalles)	Columbia River

The pattern of runoff conditions for the overall Columbia River Basin is similar to that seen in its subbasins, with trends in mean annual runoff strongly correlated to trends in mean annual precipitation for a given Hybrid-Delta climate scenario over a given location (Figure 62 through Figure 70). The warmer and wetter scenarios show the greatest increase in annual runoff volumes while the cooler and dryer scenarios actually show decreases in annual volumes. Note that the HD 2020s MW/D scenario actually involves an increase in mean-annual precipitation over the upper Columbia River Basin, which includes Mica, Arrow, and Libby dams (Figure 13); the remainder of the basin is somewhat drier. The fact that the upper Columbia River Basin is relatively wetter in this scenario leads to the corresponding changes in mean-annual runoff shown for these basins (i.e., Figure 62, Figure 63, and Figure 64).

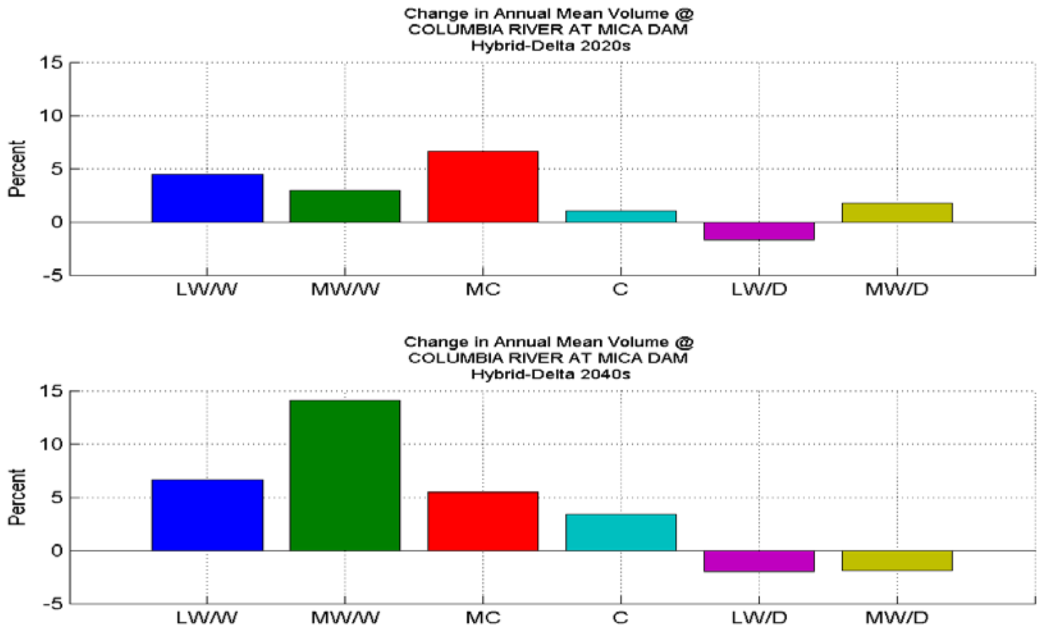

Figure 62. Columbia River at Mica Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

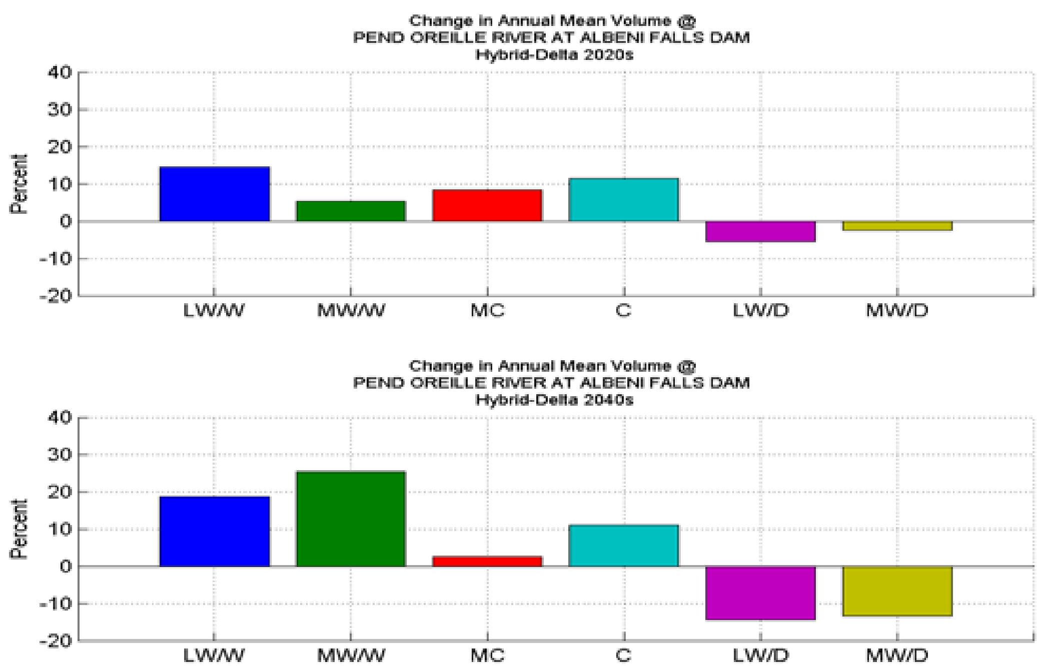

Figure 63. Pend Oreille River at Albeni Falls Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

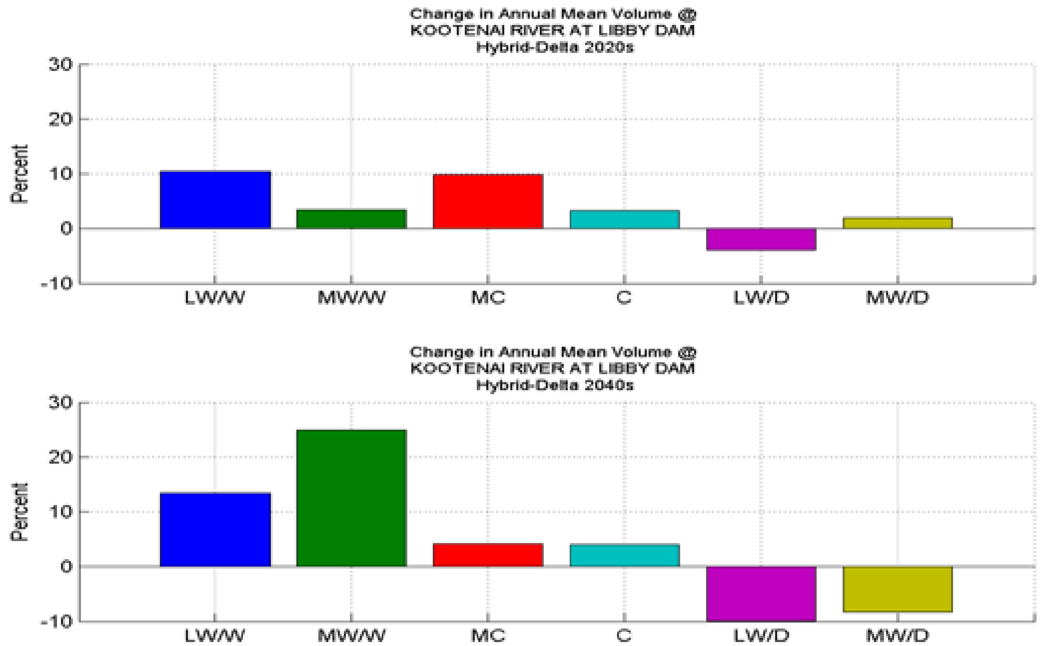

Figure 64. Kootenai River at Libby Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

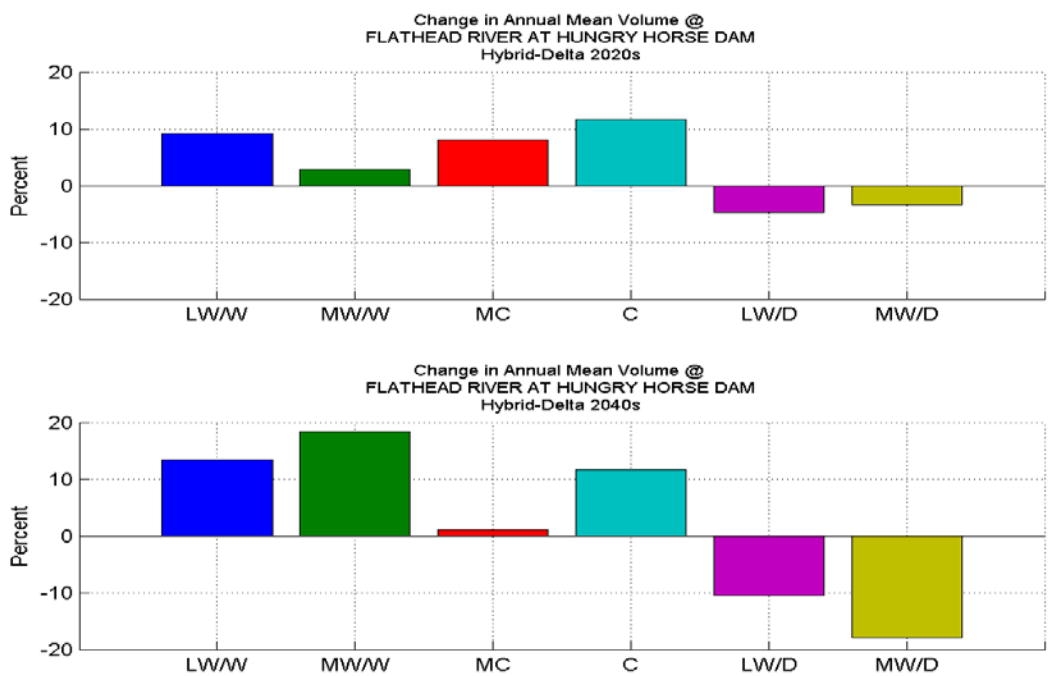

Figure 65. Flathead River at Hungry Horse Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

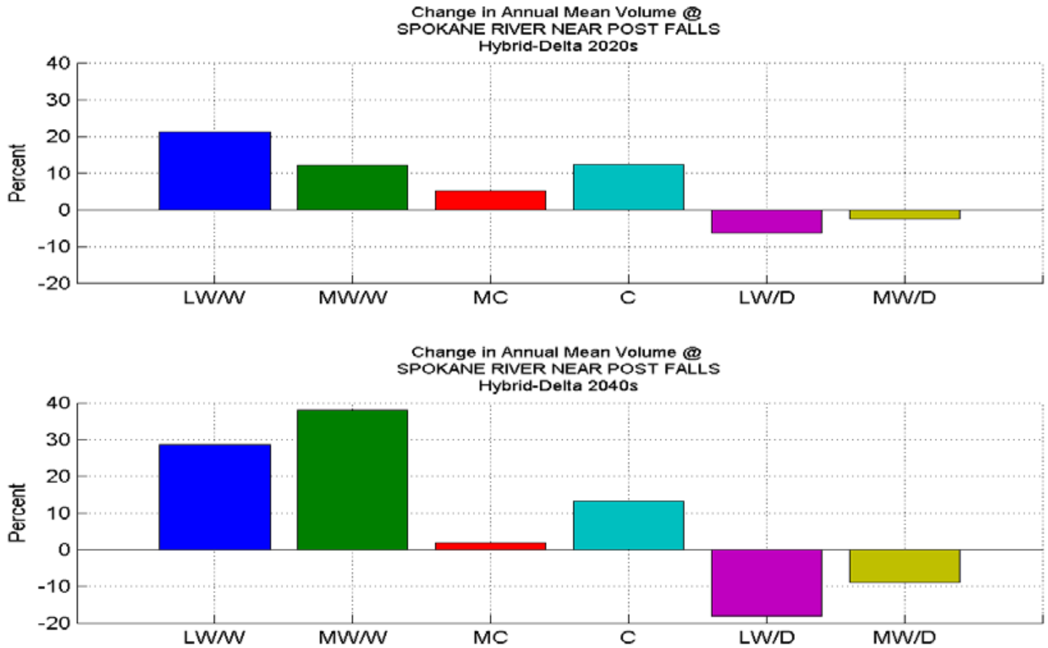

Figure 66. Spokane River near Post Falls runoff under Hybrid-Delta climate scenarios: change in mean-annual.

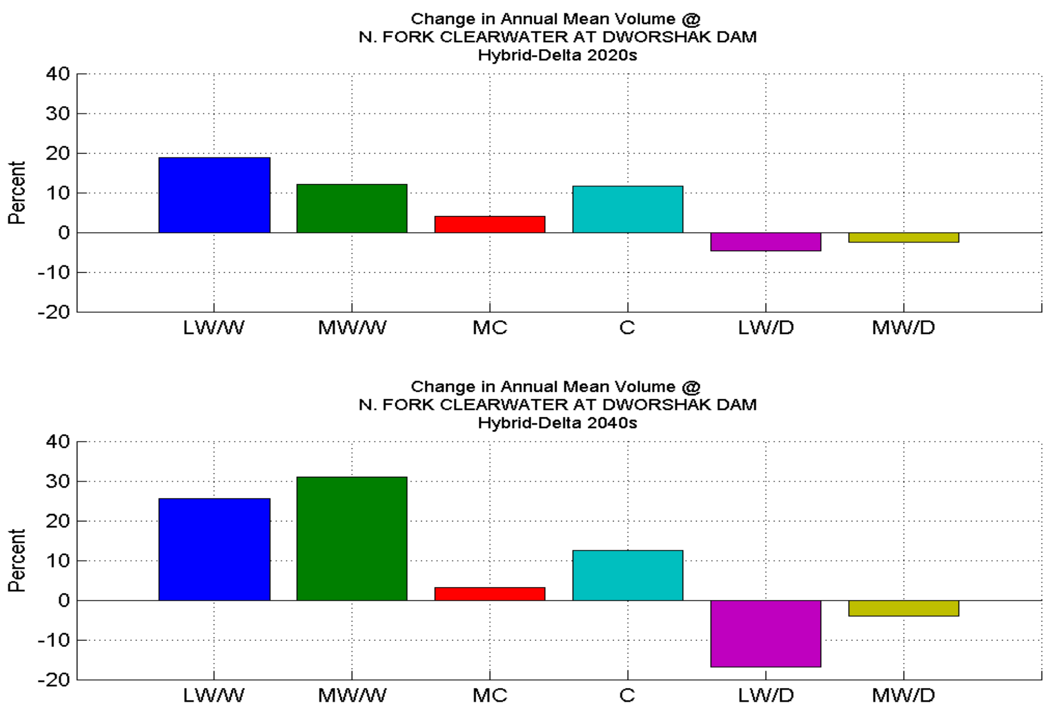

Figure 67. North Fork Clearwater River at Dworshak Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

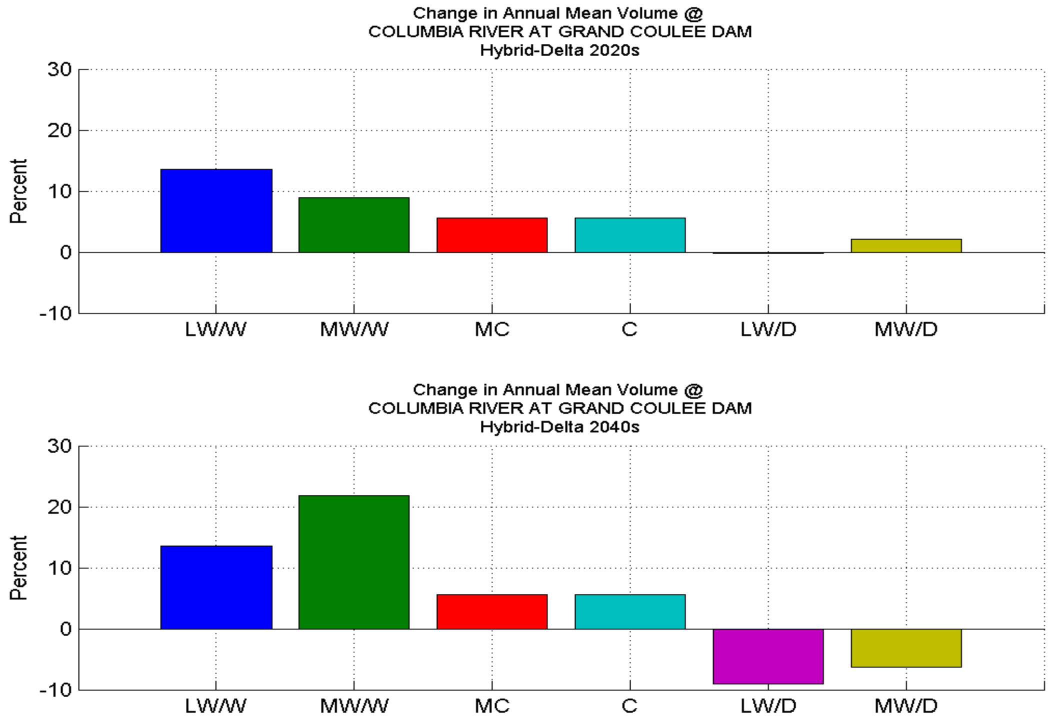

Figure 68. Columbia River at Grand Coulee Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

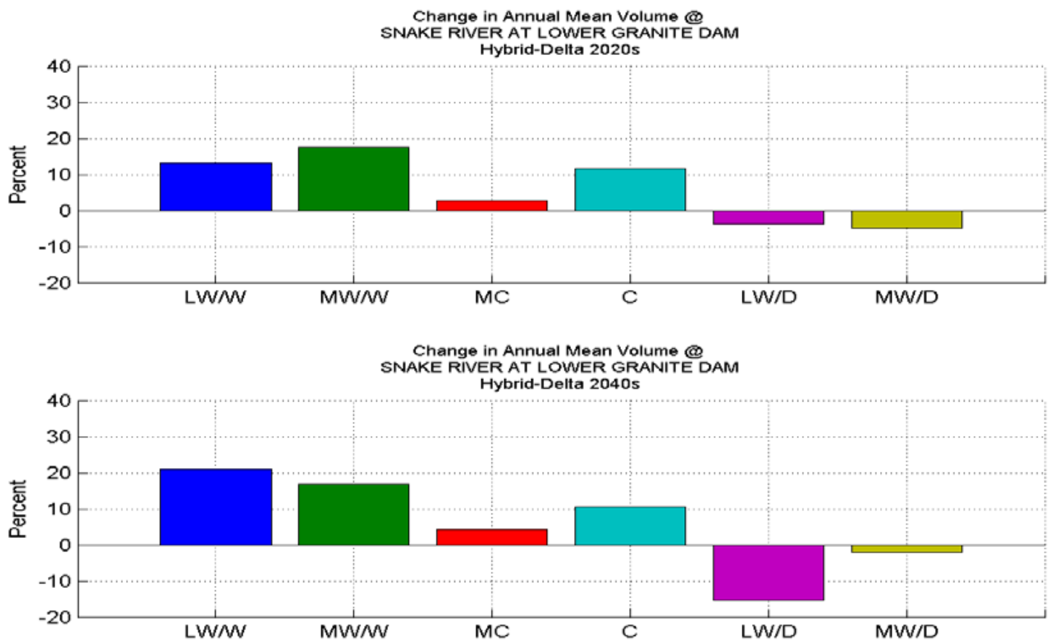

Figure 69. Snake River at Lower Granite Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

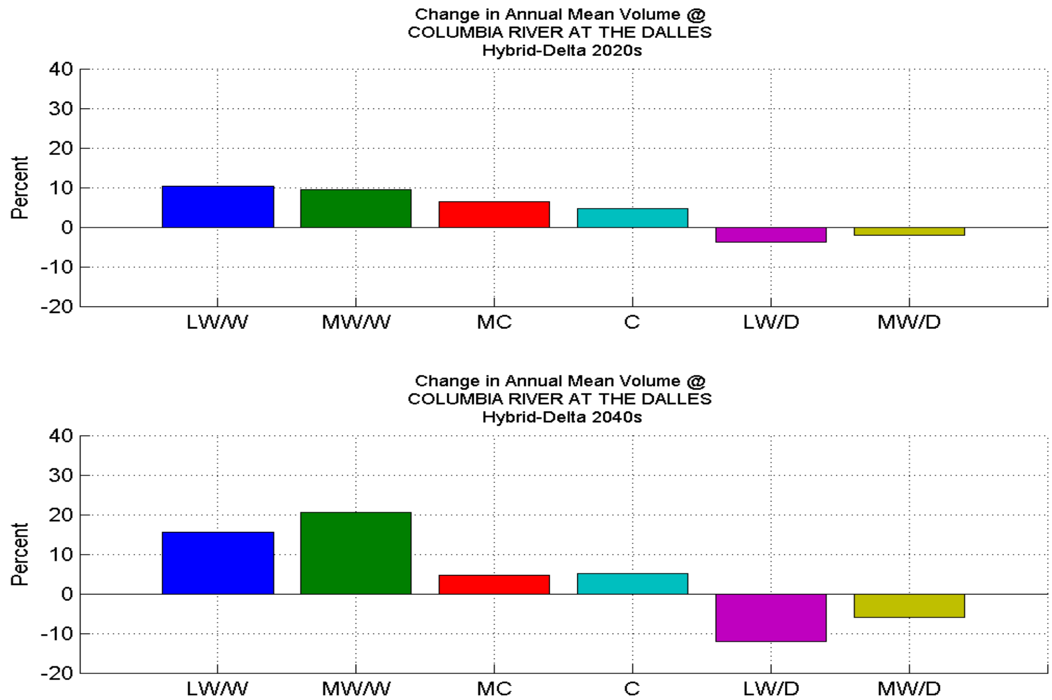

Figure 70. Columbia River at The Dalles Dam runoff under Hybrid-Delta climate scenarios: change in mean-annual.

Figure 71 through Figure 79 show changes in monthly runoff volumes for the same locations. Northern latitude (higher average basin elevation) sites, such as at Mica and Libby dams, show magnitude changes in monthly runoff with less of a shift in runoff timing. Southern latitude (lower average basin elevation) sites, such as at Albeni Falls Dam, Spokane River, or Dworshak Dam, show marked changes in runoff timing along with magnitude changes.

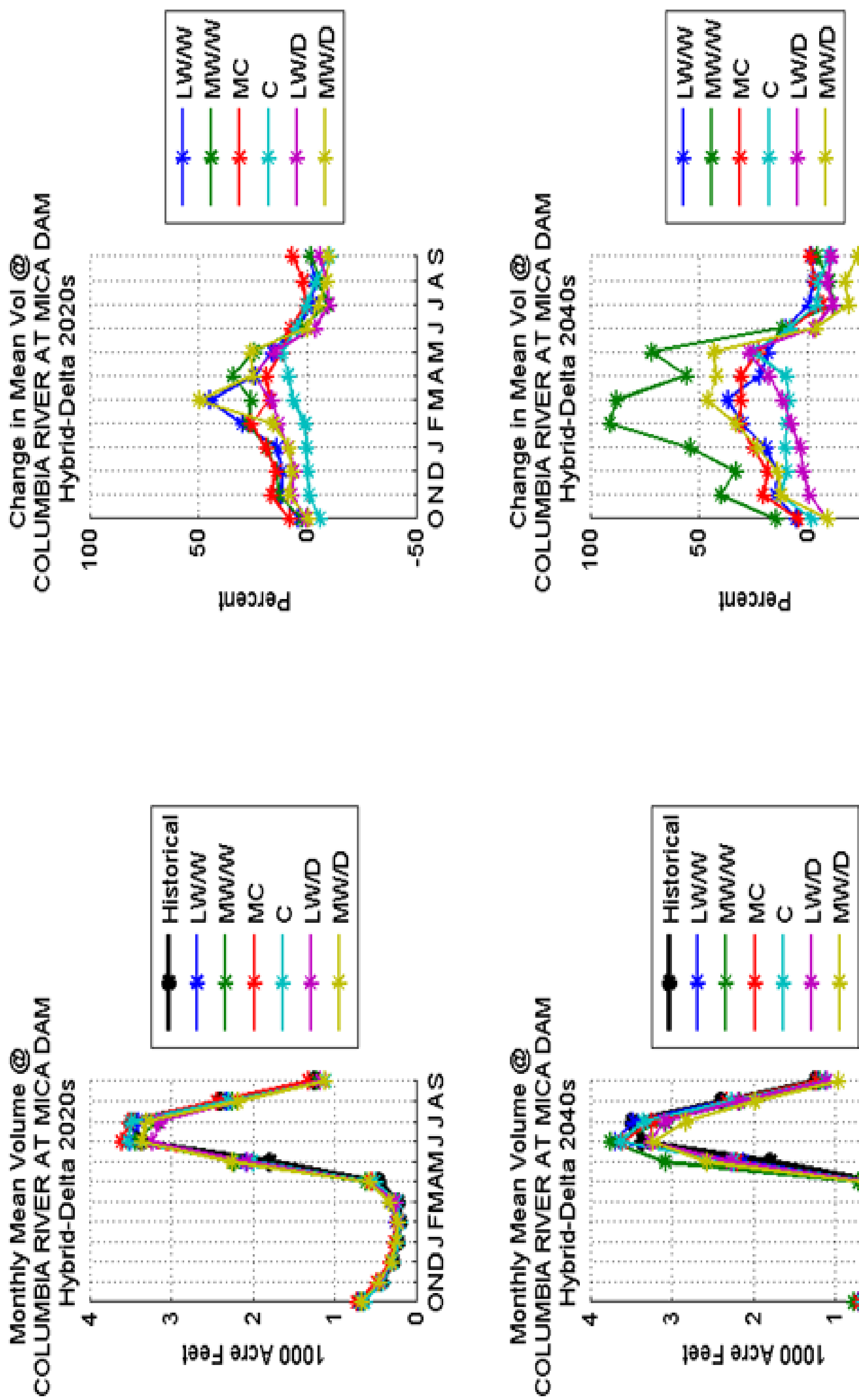

Figure 71. Columbia River at Mica Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

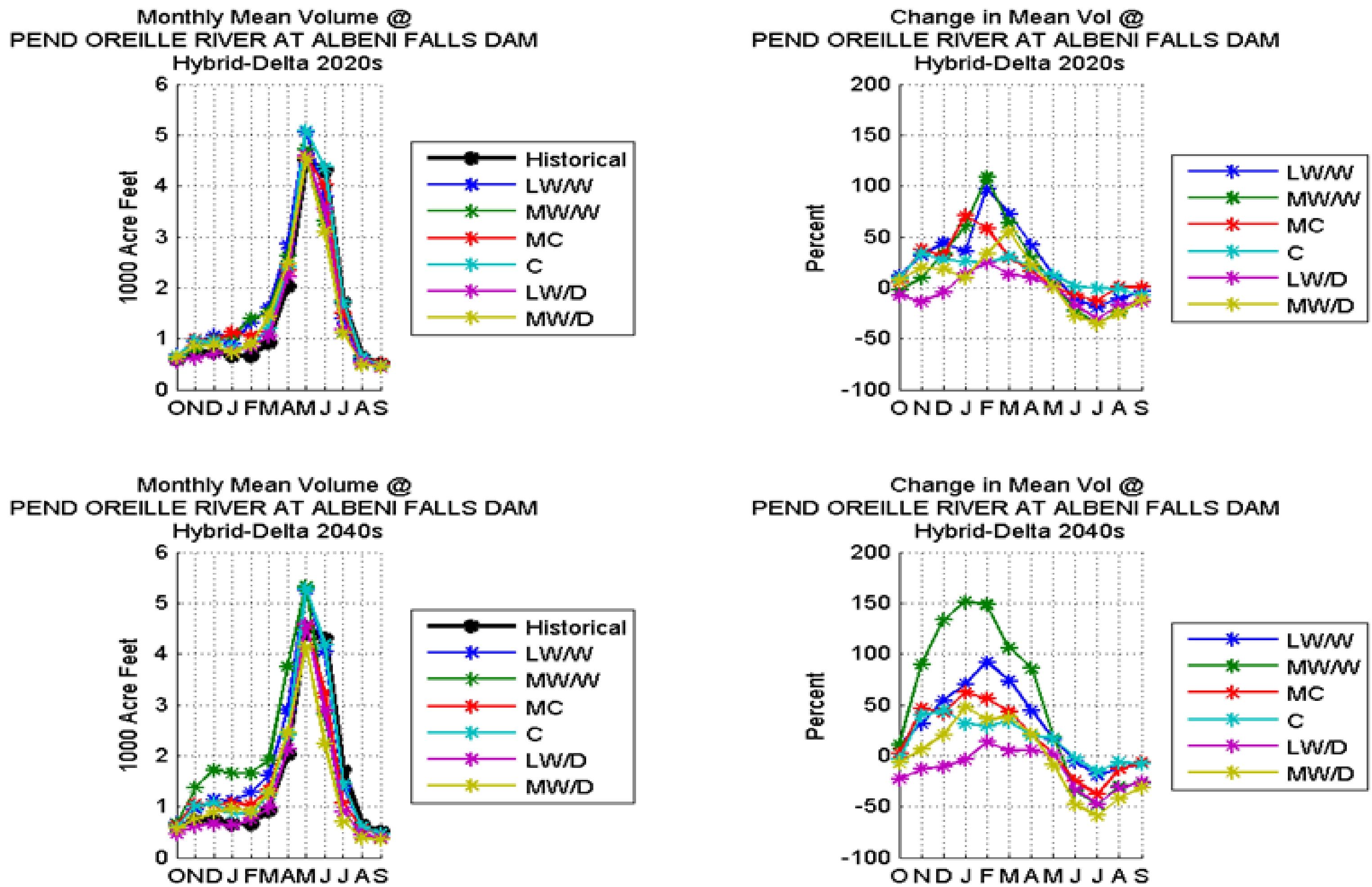

Figure 72. Pend Oreille River at Albeni Falls Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

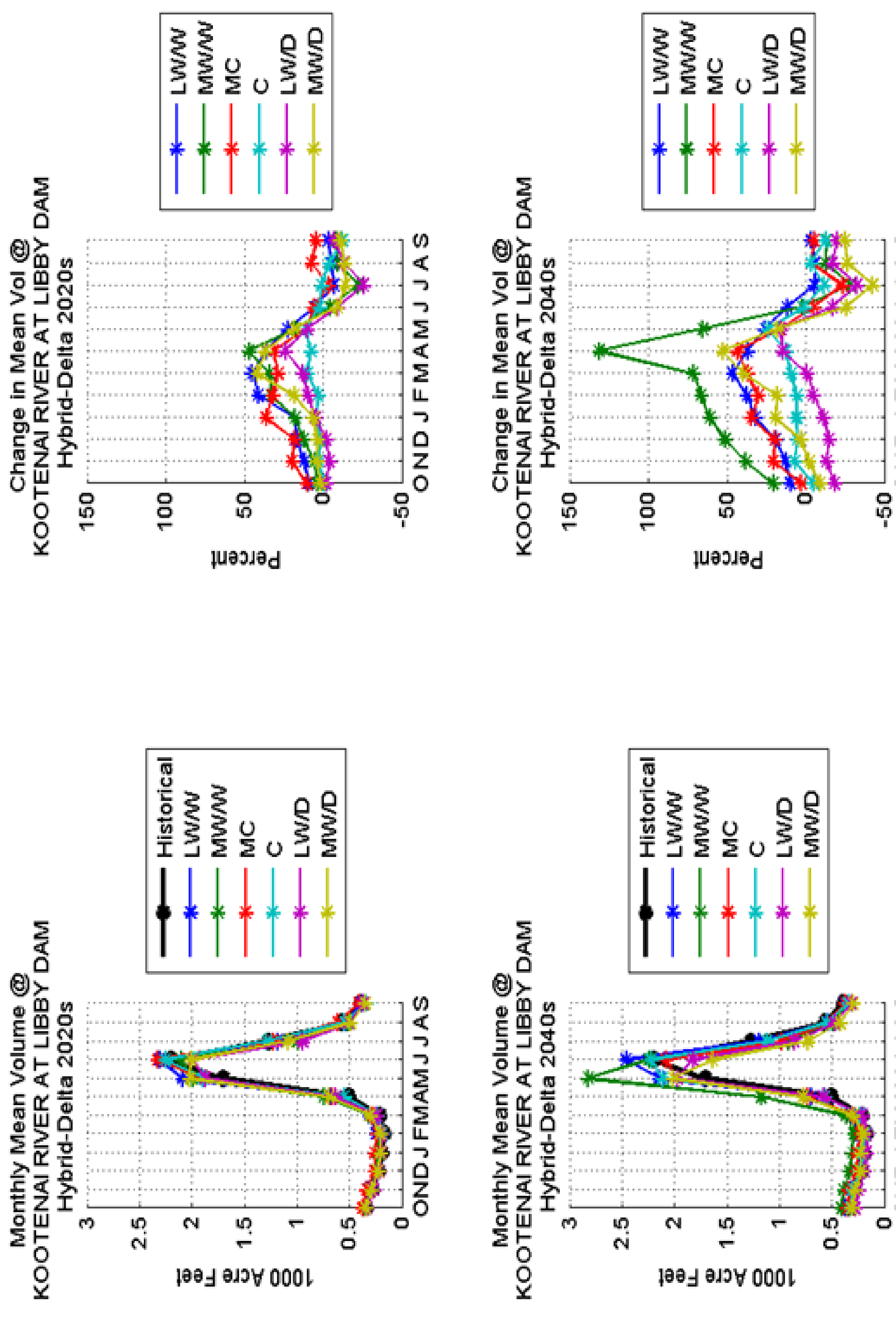

Figure 73. Kootenai River at Libby Dam. runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

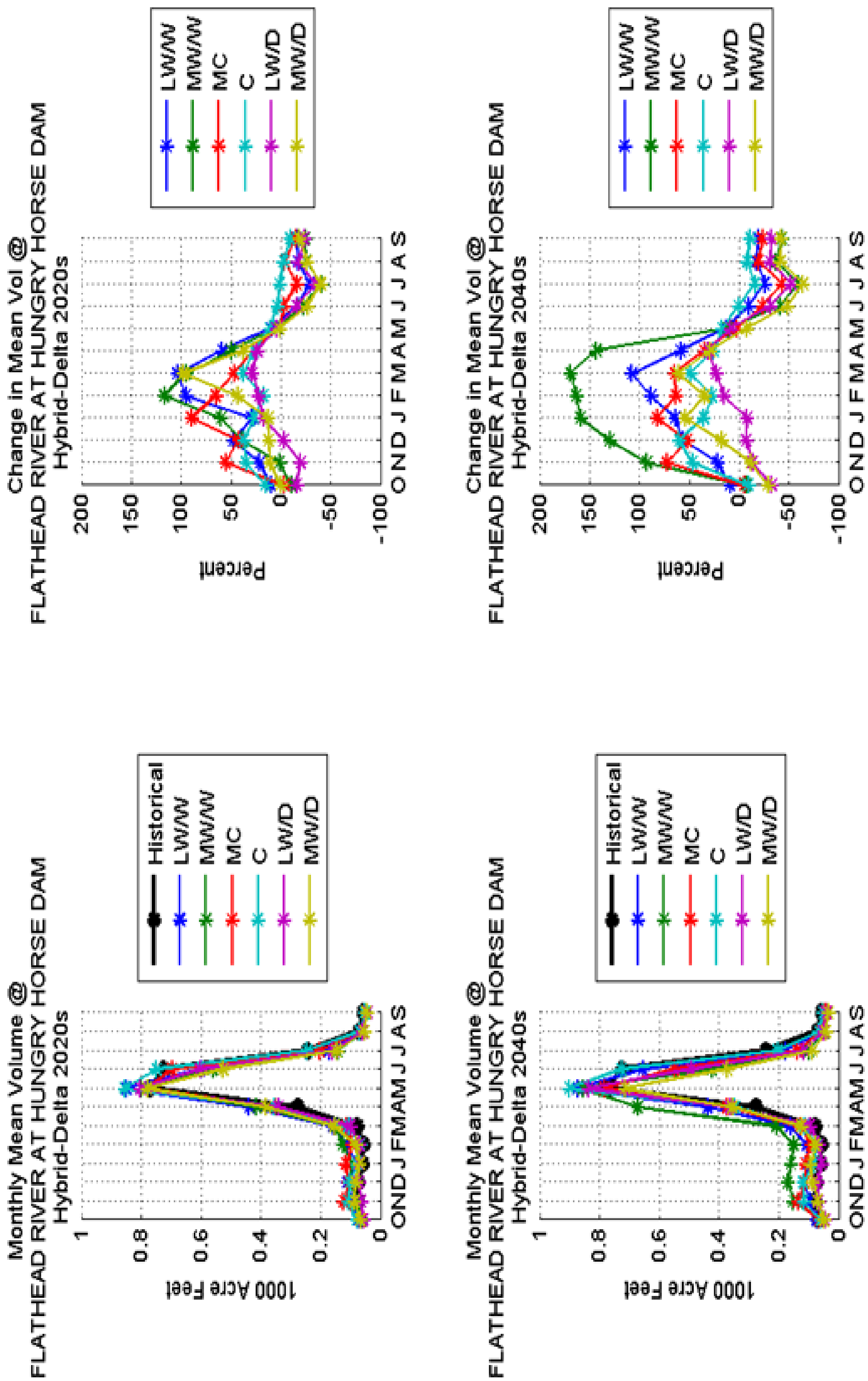

Figure 74. Flathead River at Hungry Horse Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

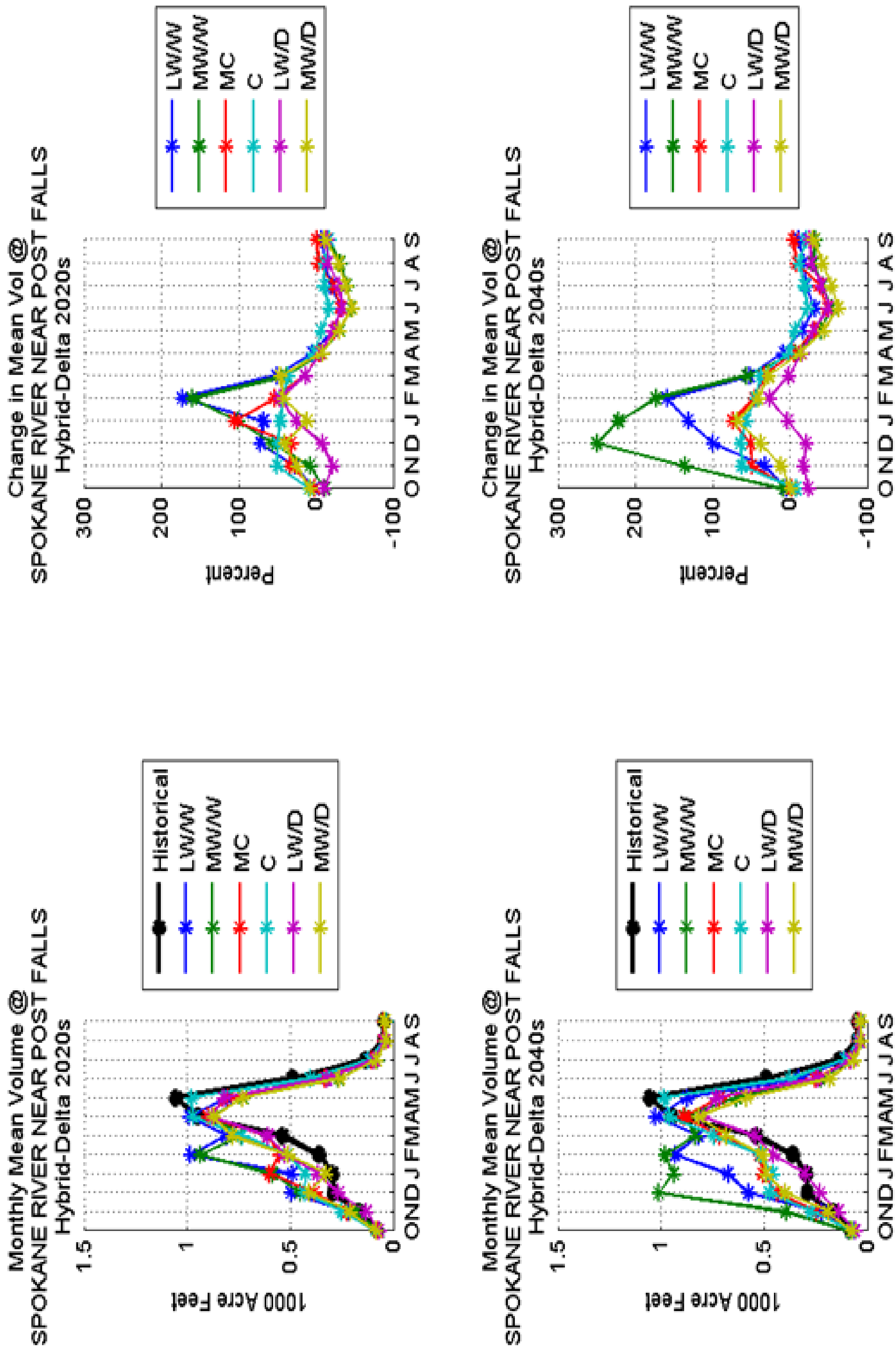

Figure 75. Spokane River near Post Falls Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

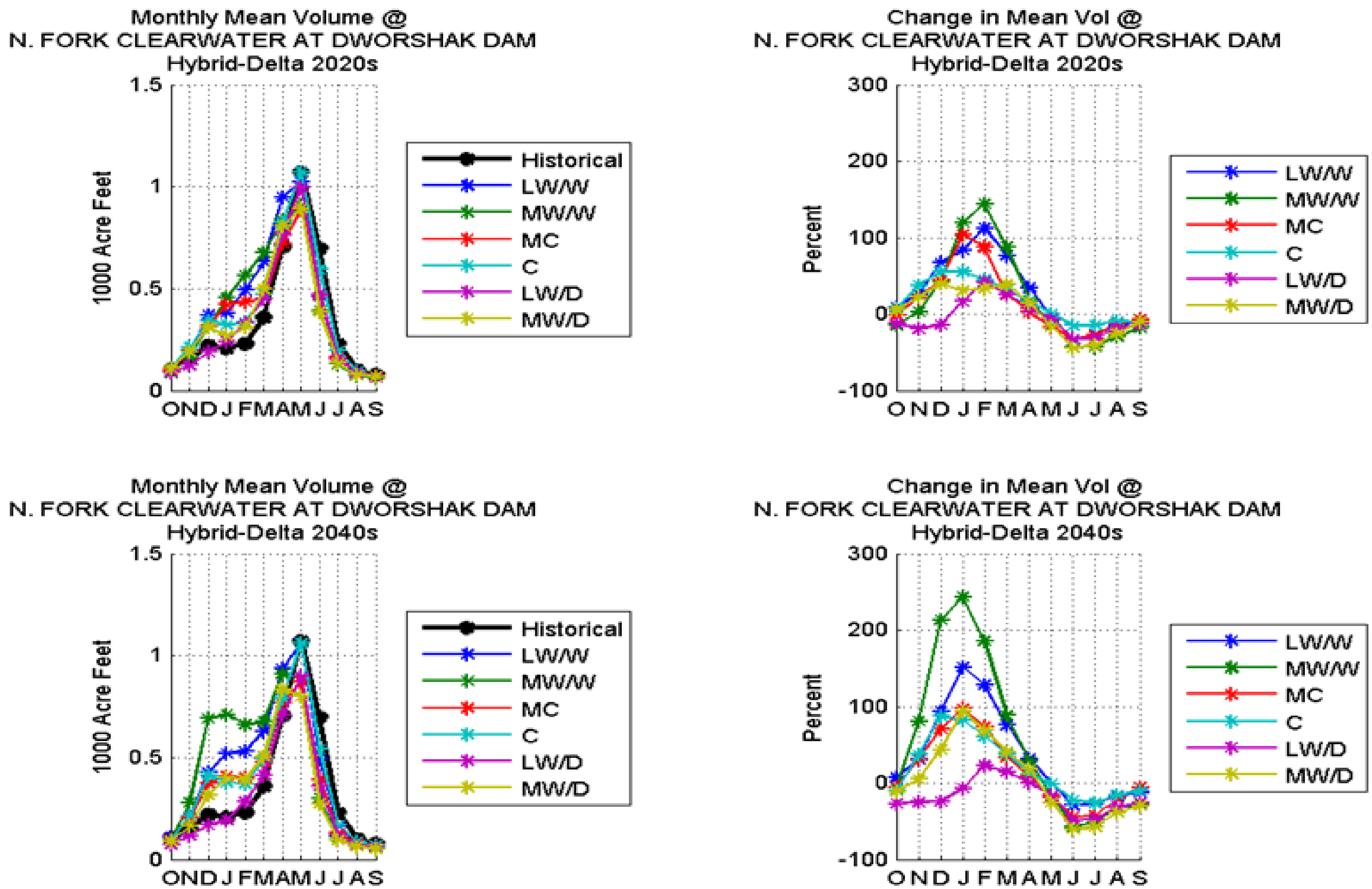

Figure 76. North Fork Clearwater River at Dworshak Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

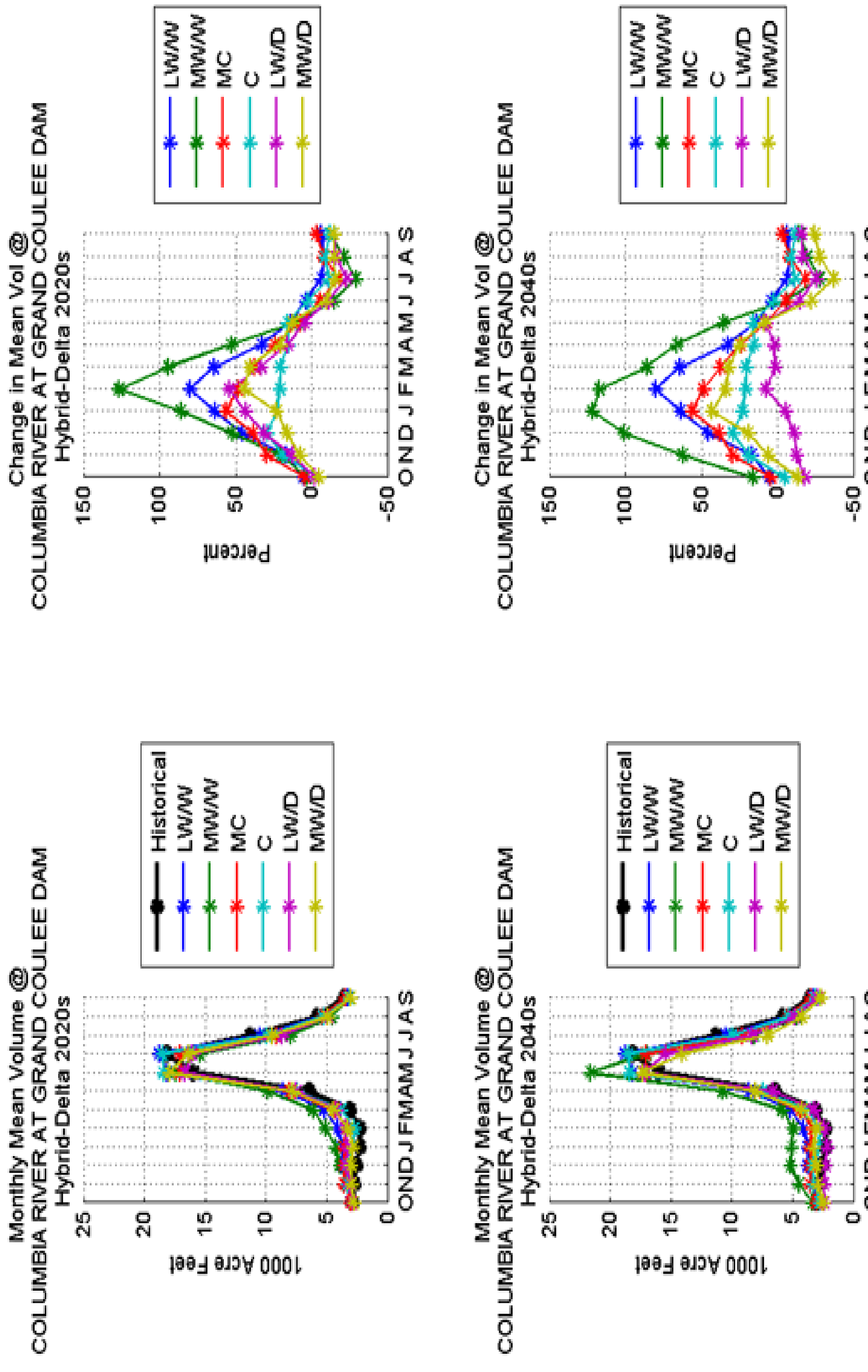

Figure 77. Columbia River at Grand Coulee Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

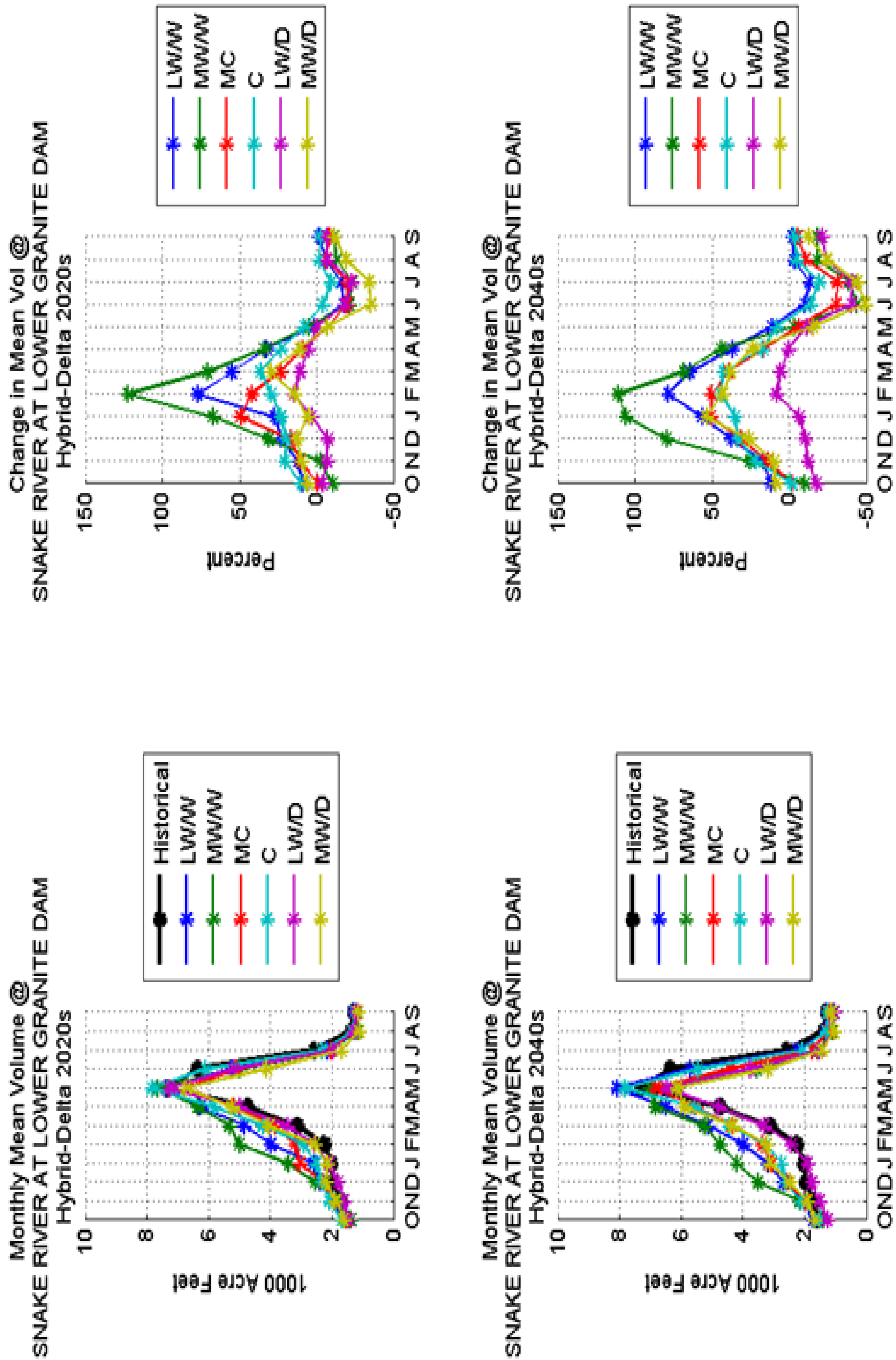

Figure 78. Snake River at Lower Granite Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

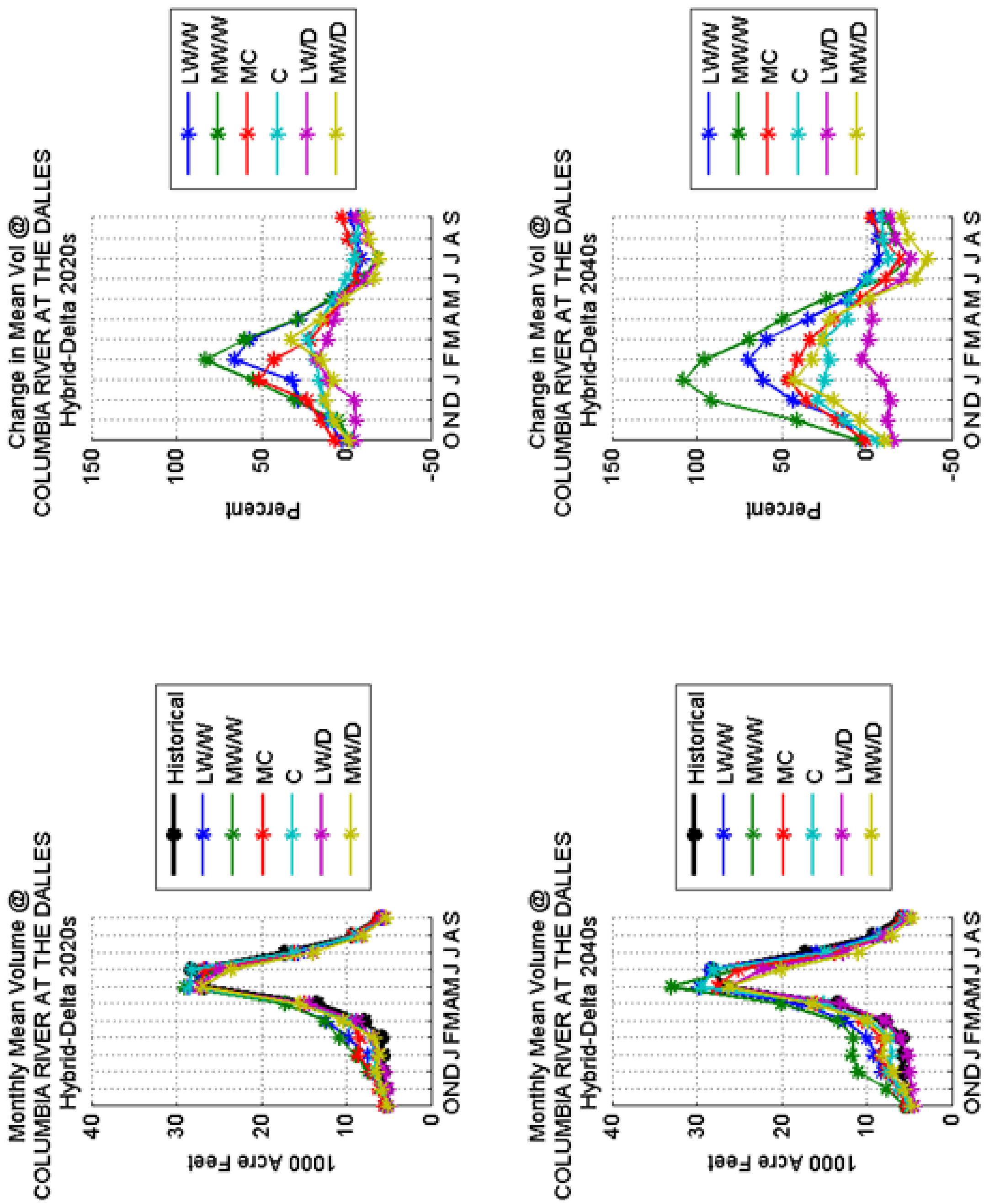

Figure 79. Columbia River at The Dalles Dam runoff under Historical and Hybrid-Delta climate scenarios: mean-monthly, and change in mean-monthly.

Figure 80 through Figure 89 show selected plots of annual runoff volumes using transient scenarios. As discussed in Section 4.5.1, there are different sets of issues that need to be considered with transient scenarios when compared to hybrid-delta scenarios. The indications of trends, patterns, or the time-developing nature of climate and hydrologic changes visible in transient scenarios needs to be considered in the context of how to interpret those results and what conclusions to draw from those interpretations. Figure 80 through Figure 82 show mean annual runoff volumes at Mica, Libby, and Dworkshak dams, respectively, from the 6 selected transient scenarios in this study. A general rising trend in mean annual runoff is discernable from the ensemble mean at these locations. Looking at Figure 83 through Figure 85, trends and time-developing patterns are more evident with 10-year moving averages. The 2050s shows significant departures from the general increasing pattern over the 21st Century, clearly visible with the ensemble mean. Figure 86 is similar to Figure 83 at Mica River subbasin, but showing transient hydrology from all 14 available transient scenarios in the HB2860 information set rather than the 6 selected transient scenarios for RMJOC purposes. This indicates that the selection of scenarios can influence interpretations of these time-developing aspects of hydrologic change. Lastly, Figure 87 through Figure 89 show similar results as Figure 83 through Figure 85, respectively, but for running 30-year moving mean conditions.

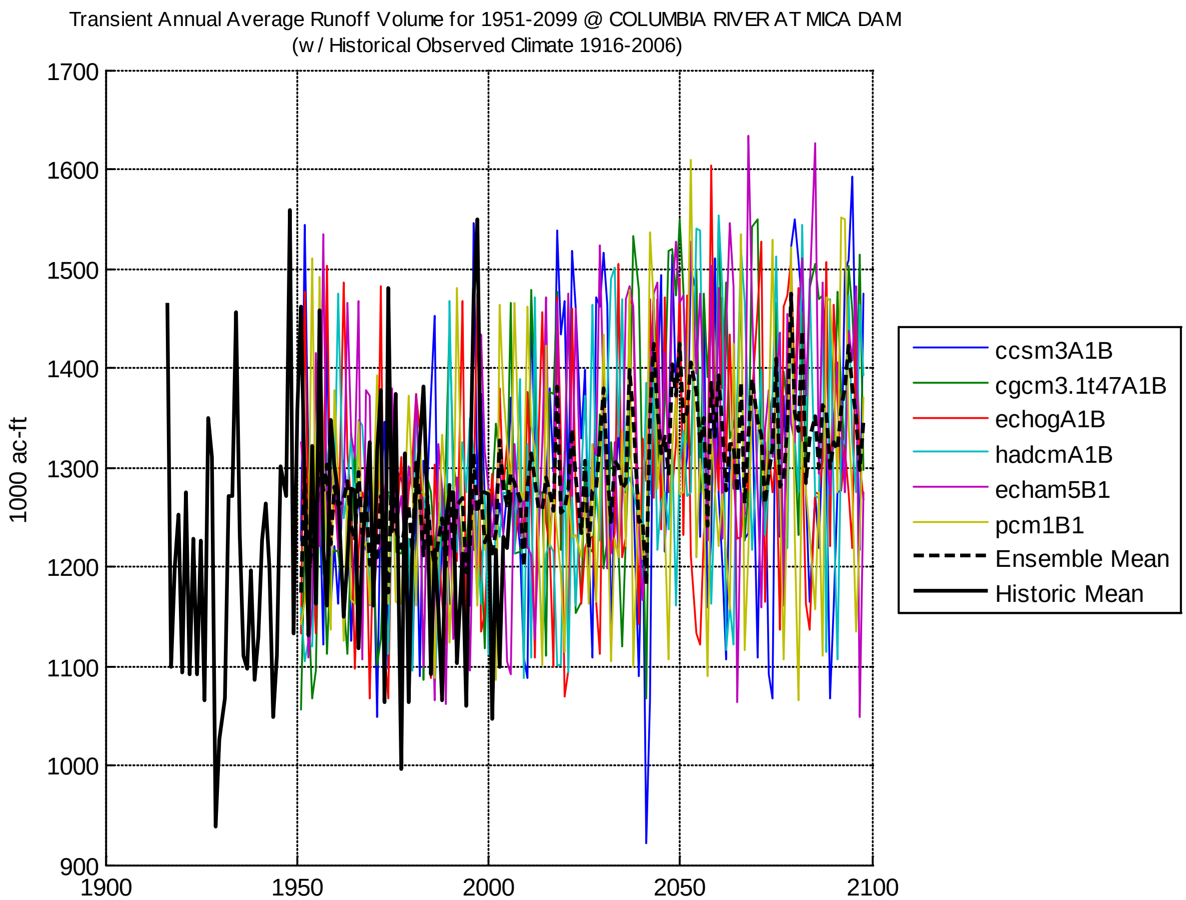

Figure 80. Mica River subbasin runoff under historical and transient climate scenarios: annual time series.

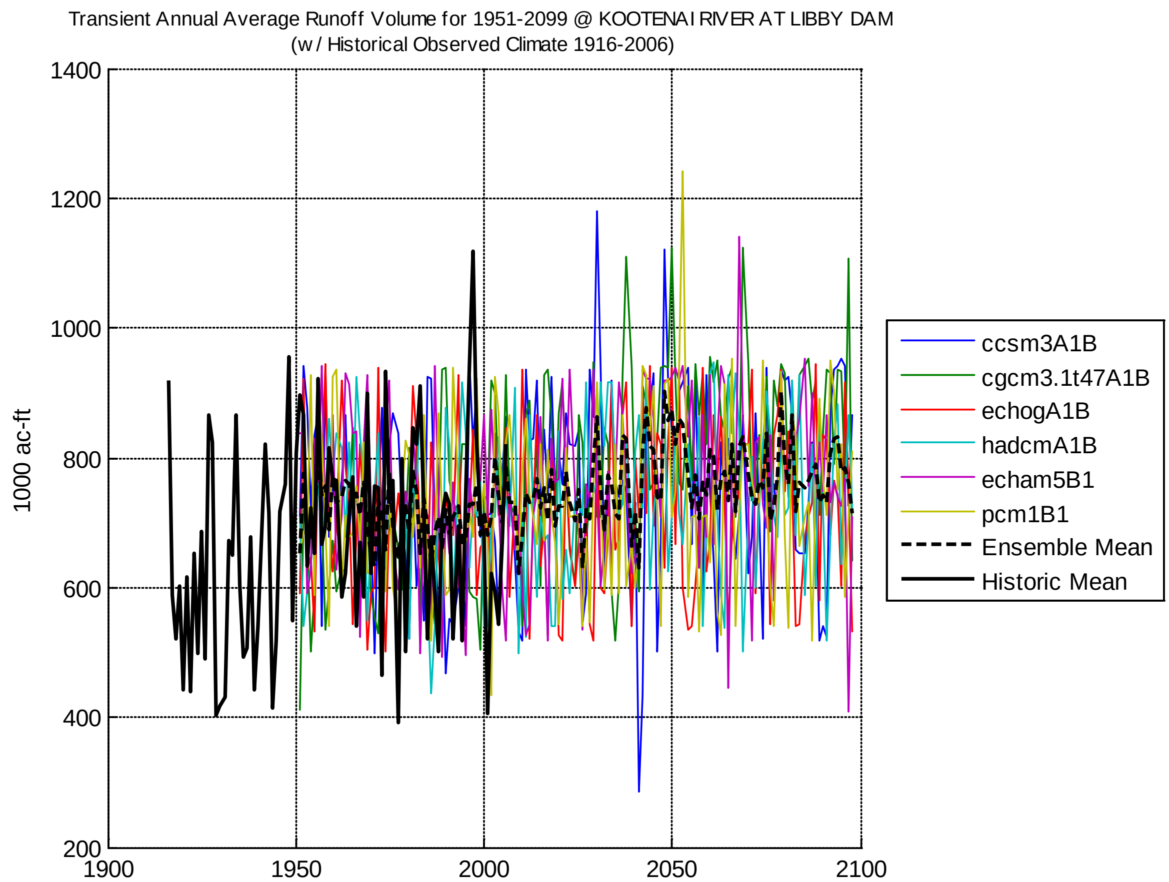

Figure 81. Libby River subbasin runoff under historical and transient climate scenarios: annual time series.

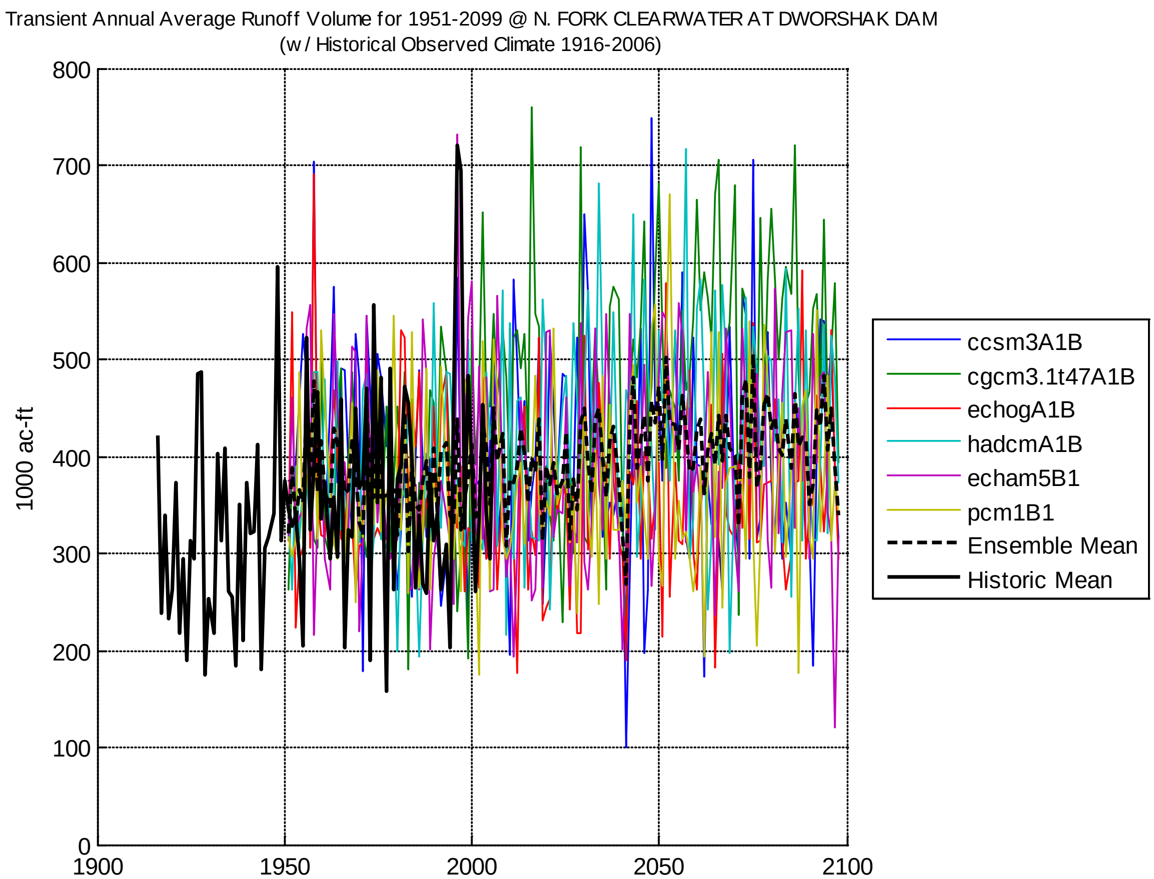

Figure 82. Dworshak River subbasin runoff under historical and transient climate scenarios: annual time series.

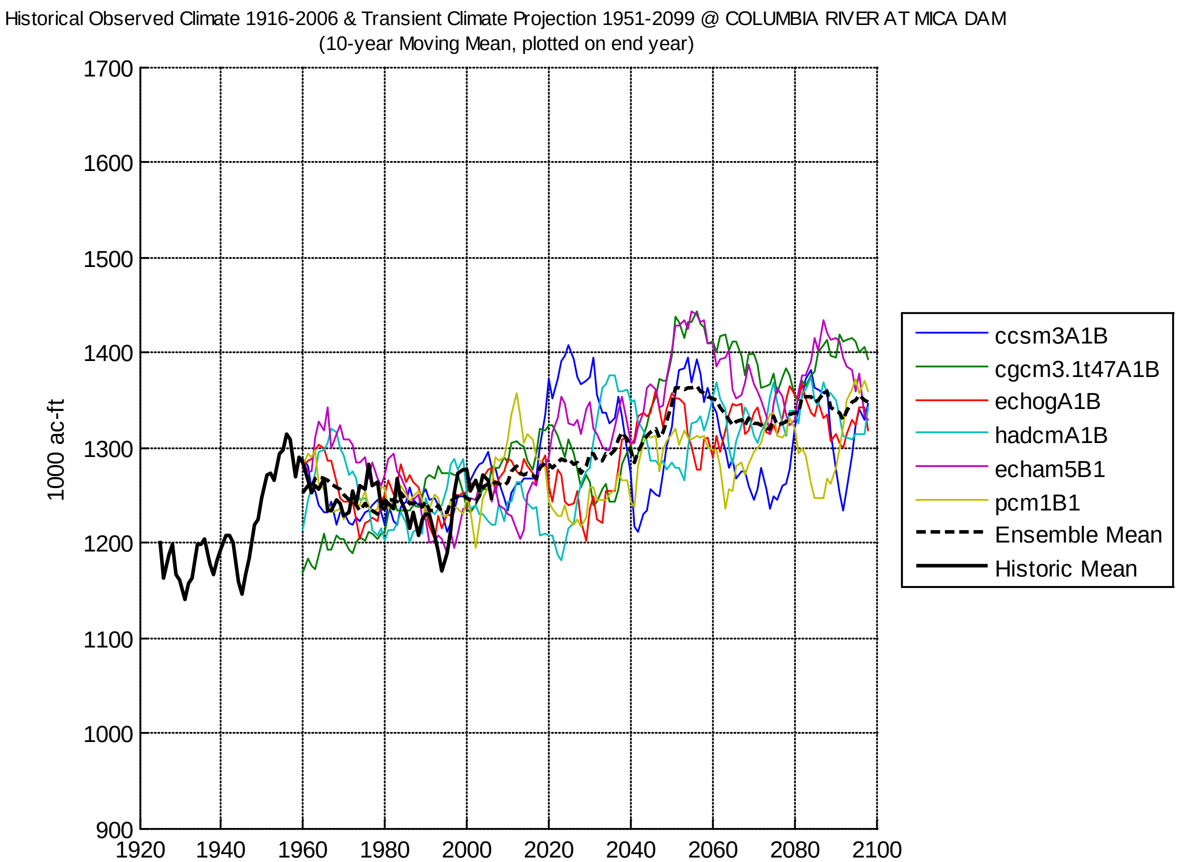

Figure 83. Mica River subbasin runoff under historical and transient climate scenarios: running 10-year mean-annual.

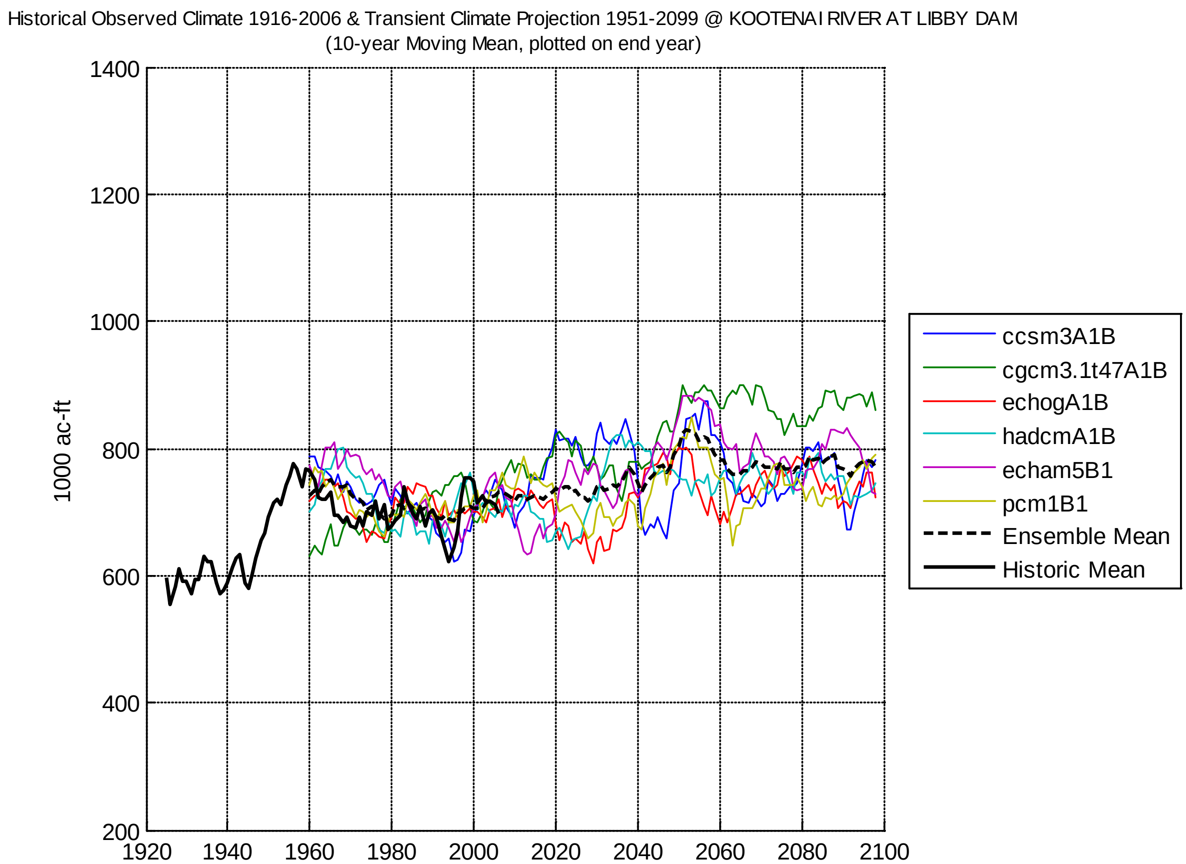

Figure 84. Libby River subbasin runoff under historical and transient climate scenarios: running 10-year mean-annual.

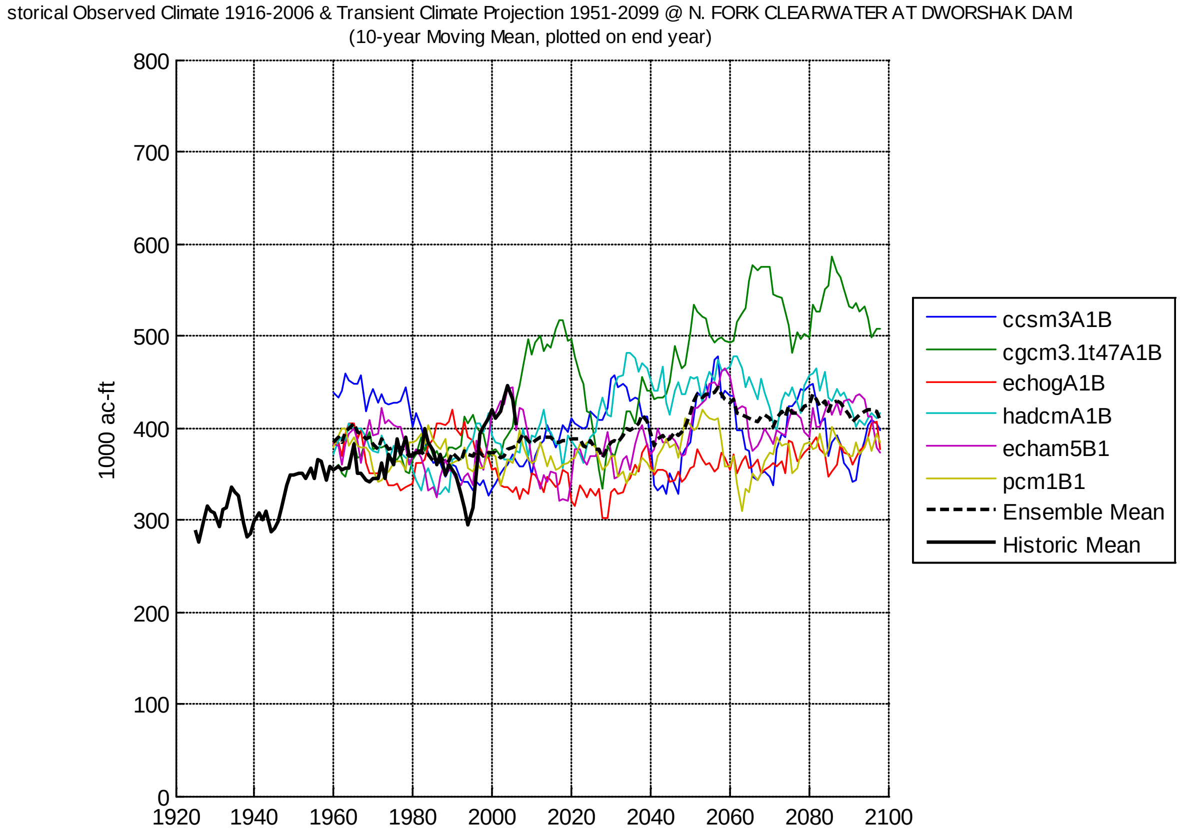

Figure 85. Dworshak River subbasin runoff under historical and transient climate scenarios: running 10-year mean-annual.

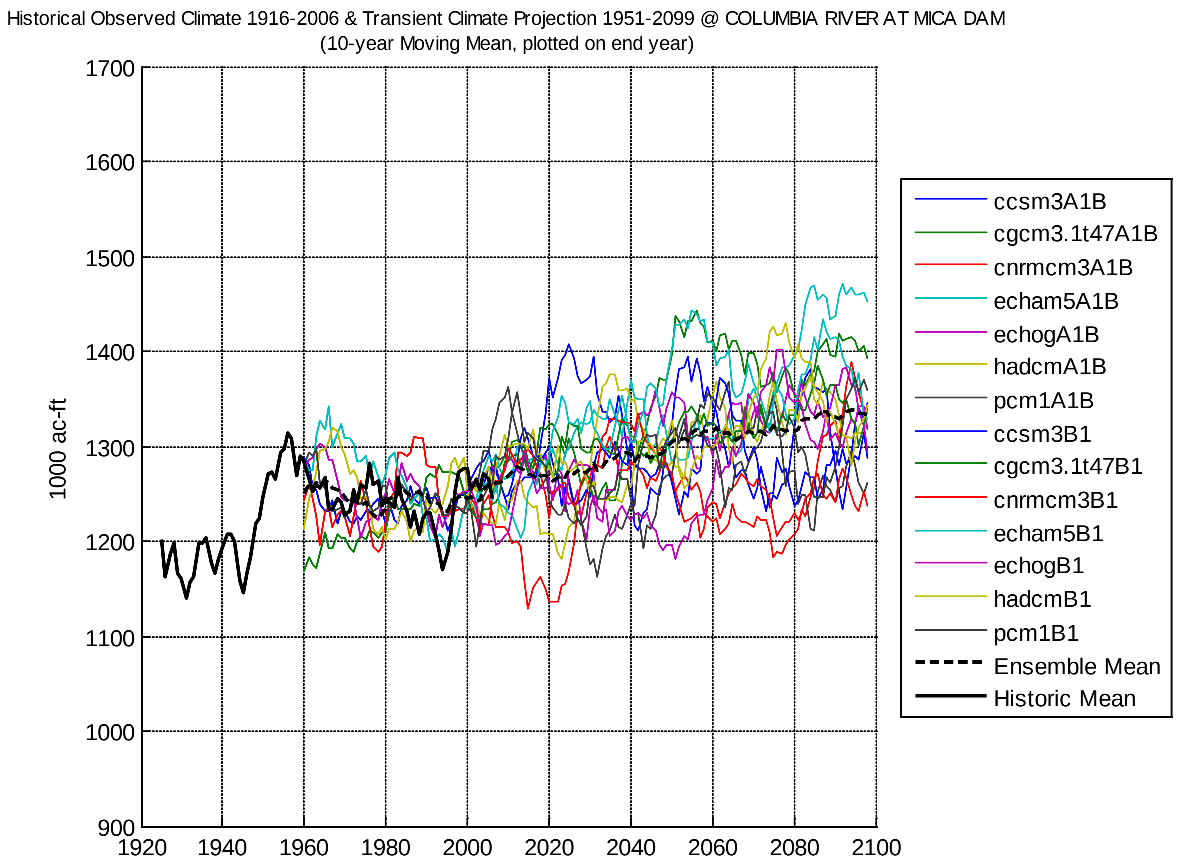

Figure 86. Mica River subbasin runoff under historical and transient climate scenarios: running 10-year mean-annual for all 14 transient HB 2860 scenarios.

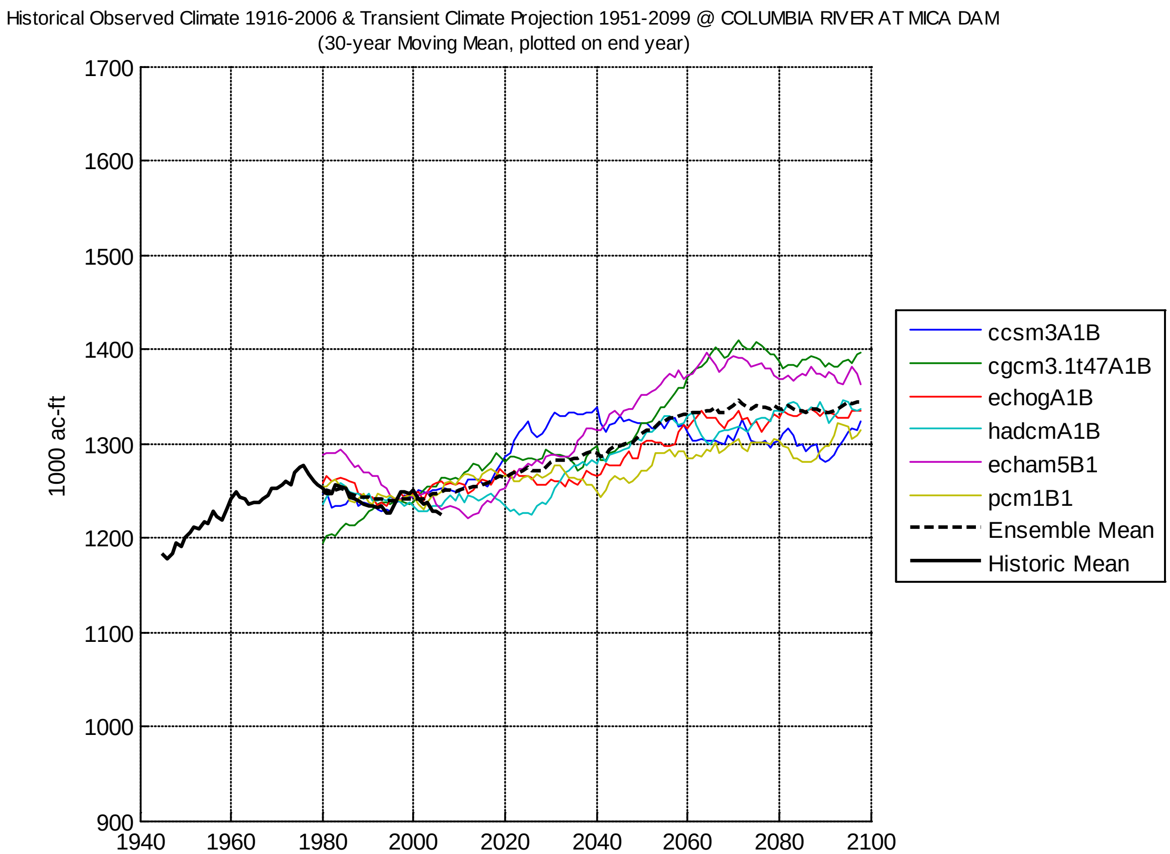

Figure 87. Mica River subbasin runoff under historical and transient climate scenarios: running 30-year mean-annual.

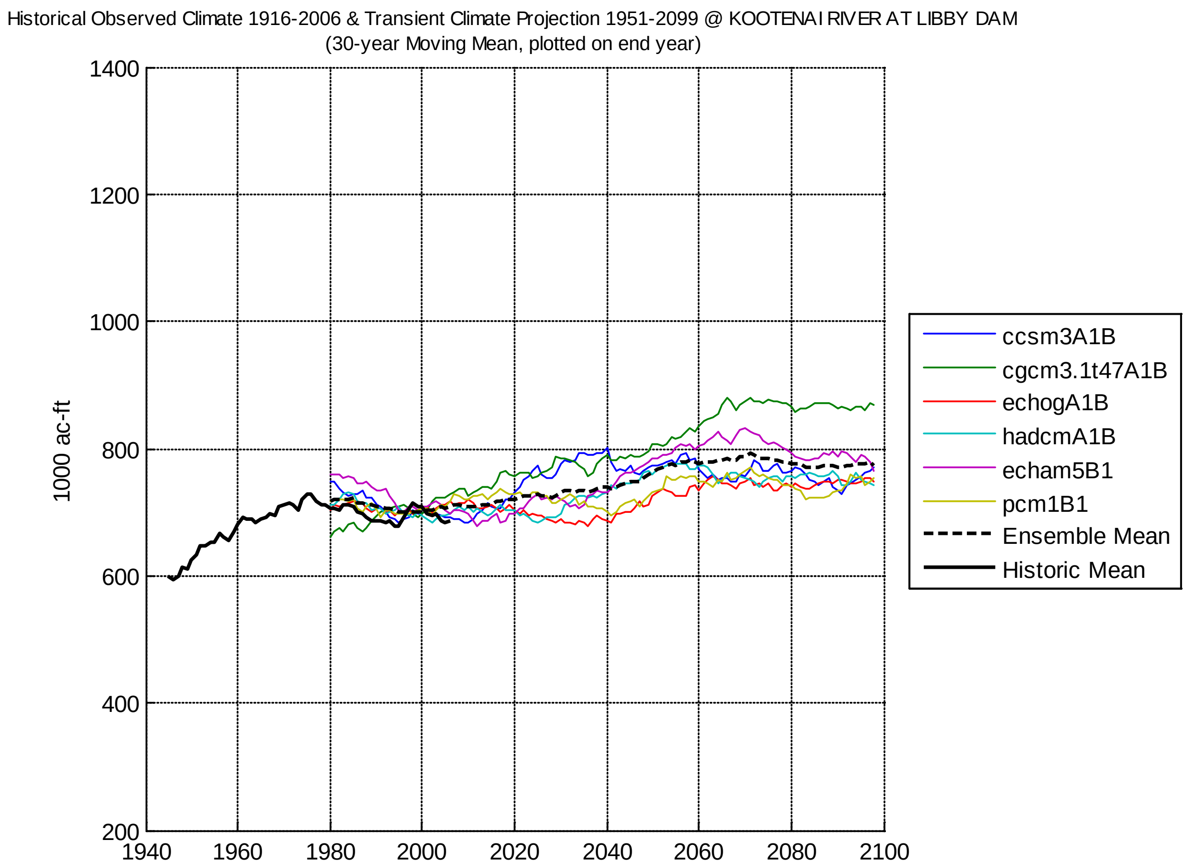

Figure 88. Libby River subbasin runoff under historical and transient climate scenarios: running 30-year mean-annual.

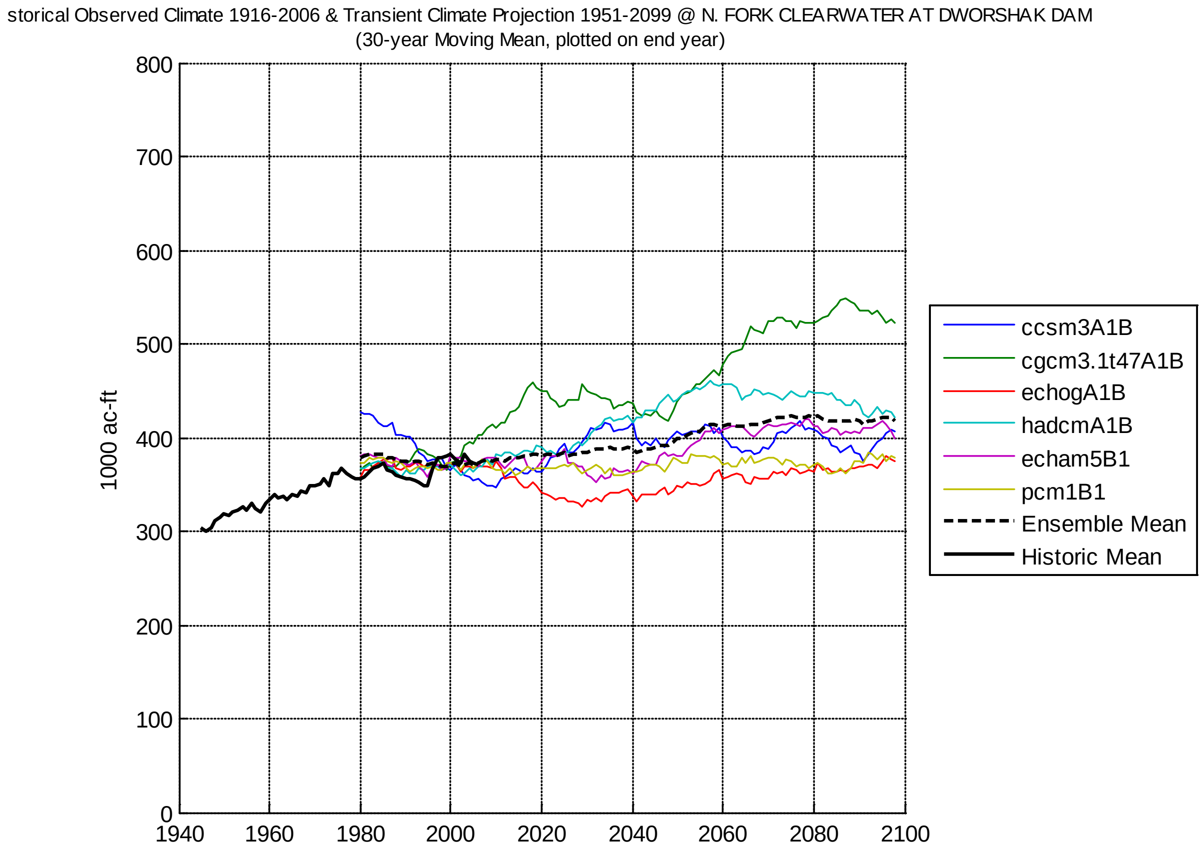

Figure 89. Dworshak River subbasin runoff under historical and transient climate scenarios: running 30-year mean-annual.

5.0 WATER SUPPLY FORECASTING UNDER HYBRID-DELTA CLIMATES

RMJOC agencies' long-term operations analyses are conducted to reflect water supply anticipation within any given operations year. In real-world operations, water supply operations are typically scheduled for next several months or seasons. These scheduling exercises are informed by seasonal runoff volume forecasts (or unregulated flow volume forecasts) issued by federal forecast providers (e.g., Natural Resources Conservation Service's (NRCS) National Water and Climate Center (NRCS NWCC), National Weather Service's River Forecast Centers). In the Columbia River Basin, additional forecast products are generated by BC Hydro, Reclamation, and the CRITFC.

Traditionally, skill in seasonal water supply forecasting has largely risen from being able to relate (a) runoff volume during the forecast period to (b) basin water content at the time of forecast issue. Basin water content includes snowpack and stored water in the soil column. Errors in this relationship arise from uncertainties in how basin water content might eventually translate into runoff or evapotranspiration. These uncertainties are strongly influenced the uncertainties of forecast period weather (i.e., precipitation-runoff after the forecast issue-date, and temperature affecting snowmelt and watershed evapotranspiration processes).

Current forecast models typically use predictors that conceptually describe basin water content, namely station observations describing snowpack at the time of forecast issue and cumulative precipitation that has occurred during some antecedent season of the current water year, understanding that the precipitation information may explain aspects of both snowpack and soil moisture conditions at the time of forecast issue.[23] Under a warming climate, snowpack is expected to diminish and thereby offer diminishing predictive information for forecasting spring-summer runoff volume. Antecedent precipitation information can still be queried. However, as snowpack diminishes, the precipitation information would gradually become useful only for describing soil moisture content at the time of forecast issue. Water supply forecast skill would thus diminish since the relationship between winter-spring soil moisture and spring-summer runoff volume is generally less correlated than the relationship between winter-spring snowpack and spring-summer runoff volume. Thus, it is expected that forecast error will gradually increase under a warming climate for traditional forecast

[23] Other forecast models may also include late summer or early autumn runoff variables as proxies for soil moisture heading into the winter season, or ocean/atmosphere variables as predictors of weather conditions during the upcoming forecast period.

situations (i.e., time of issue, location, and forecast period) and that this increasing forecast error could impact reservoir operations.

To permit reflection of such changes in water supply predictability under climate warming, this RMJOC effort was scoped to generate water supply forecast series consistent with selected future climate and hydrologic scenarios (Sections 3.0 and 4.0). Focus was placed only on the Hybrid-Delta climate change scenarios. This section summarizes methodology for generating forecasts, provides a detailed application example for the Yakima River subbasin, and summarizes forecast characteristics for all climates and forecasting situations considered.

5.1 Methodology

Briefly, the methodology used to generate water supply forecast series involves three steps:

1. **Define period climates**. For this application, 13 climates were considered: the Historical, six 2020s Hybrid-Delta, and six 2040s Hybrid-Delta climates discussed in Section 4.0. Each climate is characterized over a 91-year period indexed from 1916-2006.

2. **Make Subbasin Hydroclimate data**. This was accomplished through VIC simulation (Section 4.0) leading to an intercorrelated set of precipitation, snow water equivalent (SWE), and runoff conditions over forecast subbasins of interest (Figure 80) and unique for each period climate. Given that the operations analysis would be informed by systems inflows consistent with BC runoff (Section 4.0), it was decided to generate water supply forecast series that were forecasts of BC runoff volumes. Thus the unadjusted VIC simulated runoff was replaced by BC runoff in this method application. At this stage in the methodology, precipitation, and SWE data are gridded (1/16º, consistent with the spatial resolution of the VIC hydrologic model) and runoff data are routed to locations of interest (i.e., downstream locations of subbasins illustrated on Figure 80).

3. **Assume a Water Supply Forecast Model Structure and Identify Forecast Situation**. A general statistical model structure was adopted whereby spring-summer runoff volume is estimated by predictors describing antecedent seasonal precipitation and SWE at the time of forecast issue (e.g., October-December precipitation and January 1 SWE serving as predictors of April-July runoff volume). In this context, a forecast situation has three attributes: time of issue, forecast runoff period start month, and forecast runoff period end month.

4. **Make Forecast Model**. Apply the principal component regression procedure (PCR, Garen 1992) for developing a statistical water supply forecast model reflecting the structure assumption from step 3. This model-building technique is generally consistent with PCR model development approaches used by numerous water supply forecast providers in the region (NRCS NWCC, USACE, BC Hydro, Reclamation, and CRITFC). In the course of model development, decisions are made on how to spatially sample P and SWE information from gridded fields, and how to seasonally aggregate antecedent P information into candidate predictors. In this application, multiple schemes were considered for spatial P and SWE sampling and also for P seasons. Ultimately, schemes were selected that led to best regression calibration during the historical climate period.

During implementation of this methodology, feedback was gathered from RMJOC technical team members and stakeholders on (a) how to constrain the spatial sampling of P and SWE information from the VIC domain, (b) menu of forecast situations, and (c) how to route forecasts from headwater subbasins to interior Columbia River subbasins.

5.1.1 Spatial Sampling of P and SWE Information from VIC Simulations

On constraining spatial sampling of VIC P and SWE information, a group decision was made to constrain sampling to be from VIC grid cells containing real-world P and/or SWE observation stations, particularly those used to inform real-world water supply forecasting. To this end, water supply forecast producers from Reclamation, BC Hydro, NRCS, and USACE provided lists of precipitation and snow observation stations used in their forecasts, and coordinates of these stations were identified to indicate VIC grid cells used in this procedure. The following real-world P and SWE station locations were used:[24]

[24] ARROW, DUNCA, and MICAA station identifications are from BC-Hydro. BOISE, CROOK, FLASF, PAYET, SNKHE, and YAPAR station identifications are from Reclamation. DWORS and LIBBY station identifications are from USACE. CRESC, FLAPO, PFALL, and WICKI station identifications are from NRCS.

- ARROW: P station locations include FID (Glacier NP Mt Fideli), FQR (Fauquier climate), RGR (Glacier NP Rogers Pass), MCD (Mica Dam Clim), YCG (Castlegar A climate), and YRV (Revelstoke A Climate). SWE station locations include 2A02 (Glacier), 2A14 (Mount Abbott), 2B06P (Barnes Creek), 2B02A (Farron), 2E01 (Monashee Pass), 2A27 (Downie Slide [Lower]), and 2A06P (Mount Revelstoke).[25]

- BOISE: P station locations include AND (Anderson Dam), ARK (Arrowrock Dam), CVAI (Centerville), and IDHI (Idaho City). SWE station locations include ATAI (Atlanta Summit), JKPI (Jackson Peak), MRKI (Mores Cr. Summit), TRMI (Trinity Mountain), and VNNI (Vienna Mine).

- CRESC: P station locations include 388 (Cascade Summit), 660 (New Crescent Lake), 729 (Salt Creek Falls), and 801 (Summit Lake). SWE station locations include 388, 660, 729, and 801.

- CROOK: P station locations include GRZO (Grizzly), OCWO (Ochoco R.S.), and PRIO (Prineville). SWE station locations include DERO (Derr), MKCO (Marks Cr.), and OCMO (Ochoco Meadows).

- DUNCA: P station locations include KAS (Kaslo climate), NAK (Arrow Res. at Nakusp) WGE (Golden A climate), and YRV. SWE station locations include 2A06P, 2B08P, and 2A14.

- DWORS: P station locations include Headquarters. SWE station locations include Elk Butte, Hoodoo Basin, Pierce RS, Shanghi Summit, and Lost Lake.

- FLAPO: P station locations include 469 (Emery Creek), 482 (Flattop Mtn), 667 (North Fork Jocko), 693 (Pike Creek), and 787 (Stahl Peak). SWE station locations include 482, 667, 693, and 787.

- FLASF: P station locations include HGH (Hungry Horse), SELM (Seeley Lake), SWLM (Swan Lake), and WGLM (West Glacier). SWE station locations include CPCM (Copper Camp), EMCM (Emery Creek), NFJM (North Fork Jocko), NOIM (Noisy Basin), PICM (Pike Creek), SPBM (Spotted Bear), TRLM (Trinkus Lake), and UHLM (Upper Holland Lake).

[25] Real-world forecasts at this location are also informed by the P station YCP (Blue River A climate).

- LIBBY: P station locations include Cranbrook A, Fernie, Fortine 1N, Libby 1NE RS, and Banff CS.[26] SWE station locations include East Creek, Morrissey Ridge, Moyie Mountain, Sullivan Mine, Hawkins Lake, Vermillian River No. 3, and Stahl Peak.

- MICAA: P station locations include DCD (Duncan Dam climate), FID, GRP (Glacier NP Rogers Pass), MCD (Mica Dam climate), and WGE. SWE station locations include 1E02P (Mount Cook), 2A07 (Kicking Horse), 2A11 (Beaverfoot), 2A14, 2A21P (Molson Creek), and 2C14P (Floe Lake).

- PAYET: P station locations include CSC (Cascade), CVAI, DED (Deadwood Dam), and GAVI (Garden Valley). SWE station locations include BKSI (Big Creek Summit), BOGI (Bogus Basin), COZI (Cozy Cove), DDSI (Deadwood Summit), JKPI, LFKI (Lake Fork), MRKI, SQMI (Squaw Meadow), and VNNI.

- PFALL: P station locations include 535 (Humboldt Gulch), 594 (Lookout), 600 (Lost Lake), 623 (Mica Creek), and 645 (Mosquito Ridge). SWE station locations include 16B03 (Fourth of July Summit), 530 (Hoodoo Basin), 535, 594, 600, 623, and 645.

- SNKHE: P station locations include AFTY (Afton), BONY (Bondurant), JKNY (Jackson), PAL (Palisades), and SKRY (and Snake River Station). SWE station locations include ERDY (East Rim Divide), HKBY (Huckleberry Divide), LWSY (Lewis Lake Divide), and SLTY (Salt River Summit).

- WICKI: P station locations include 545 (Irish Taylor), 719 (Roaring River), and 815 (Three Creek Meadow). SWE station locations include 545, 719, and 815.

- YAPAR: P station locations include BUM (Bumping Lake), CLE (Lake Cle Elum), KEE (Lake Keechelus), and RIM (Rimrock). SWE station locations include BPNW (Bumping New), CLE, COPW (Corral Pass), PAPW (Paradise Park), and TUNW (Tunnel Ave).

Note that the above list does not address several forecast basins from Figure 90. Forecasting for those basins is discussed later in this section. Also, the above list includes candidate P and SWE locations. The procedure of arriving at the forecast regression models involves exploring all combinations of P and SWE locations for each basin, resulting in all or a subset of P and SWE locations being used to inform the final forecast model.

[26] Chosen location is nearest VIC grid cell given that this location is outside the Columbia River basin.

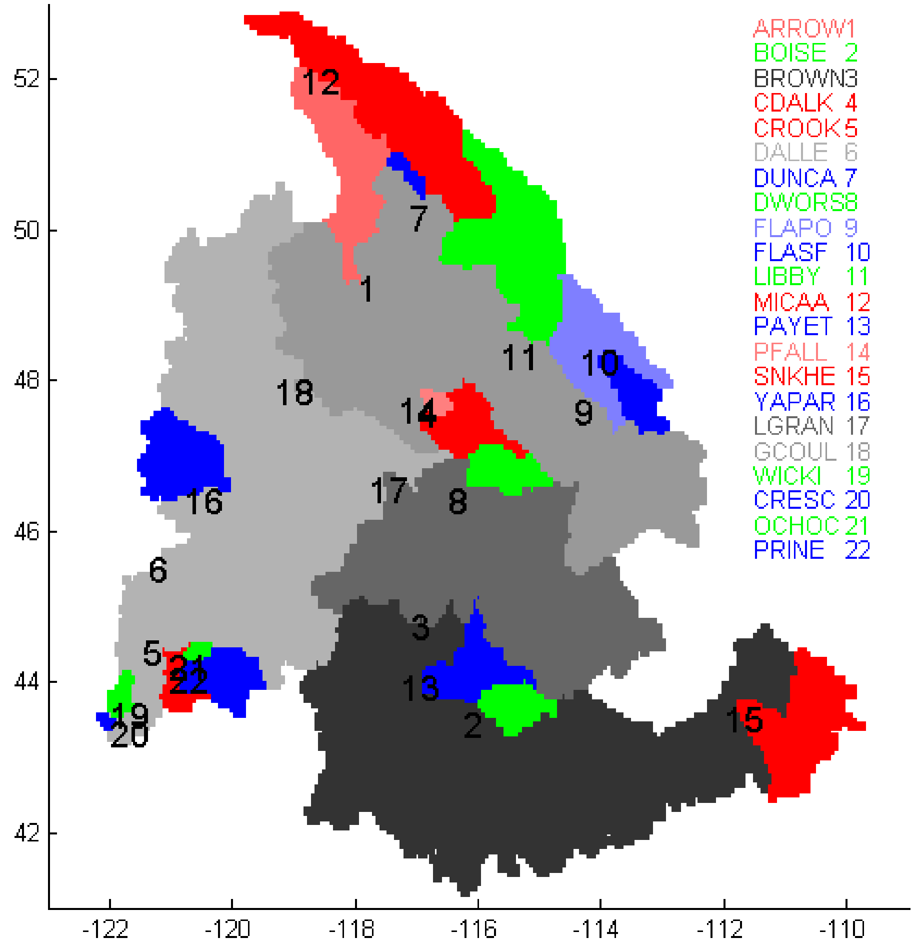

Figure 90. Subbasins considered for water supply forecast data development under Hybrid-Delta climate change scenarios.

5.1.2 Menu of Forecasting Situations

On the menu of forecasting situations, each RMJOC agency reviewed how water supply forecast assumptions were featured in their long-term operations analyses and provided a menu of forecast situations for the list of basins shown on Figure 90 (which was also identified during this phase of feedback). For some locations, different forecast periods informed different types of operational considerations. For most locations and runoff periods, there was also a set of longer- to shorter-lead forecasts considered as operations simulation proceeds from winter to summer months. This use of the collection of forecast situations was necessary to support RMJOC agencies' operational analyses, listed in Table 8. For example, at location ARROW, there were six forecasting situations (January issue of January through July, February issue of February through July, and June issue of June through July). In Table 8, this is indicated using the abbreviated description of January through June issues of Issue Month through July.

Table 8. Forecast Situations indicated by forecast location, issue month, and forecast period.

I.D.	Location Description	Issues	Forecast Periods
ARROW	Columbia River at Keenleyside Dam	January through June	Issue Month through July
BOISE	Boise River near Boise	January through June	Issue Month through September
BROWN	Snake River at Brownlee Dam (ID-OR State Line)	January through June	Issue Month through July
		January through March	April through July
CDALK	Coeur D Alene Lake at Coeur D Alene	April through July	Issue Month through August
		January through March	April through August
CRESC	Crescent Lake	January through July	Issue Month through September
CROOK[1]	Crooked River above Prineville Reservoir	January through July	Issue Month through September
DALLE	Columbia River at The Dalles	April through June	Issue Month through August
		January through June	Issue Month through July
		January through March	April through August
DUNCA	Duncan River at Duncan Dam	April through July	Issue Month through August
		January through April	May through July
		January through June	Issue Month through July
		January through March	April through August
DWORS	N. Fork Clearwater at Dworshak Dam	January through April	May through July
		January through June	Issue Month through July
		January through March	April through July
FLAPO	Flathead River at Kerr Dam	April through July	Issue Month through August
		January through March	April through August
FLASF	Flathead River at Hungry Horse Dam	April through July	Issue Month through August
		January through April	May through July
		January through April	May through September
		January through June	Issue Month through July
		January through March	April through August
		May through July	Issue Month through September
GCOUL	Columbia River at Grand Coulee Dam	April through June	Issue Month through July
		January through March	April through July
LGRAN	Snake River at Lower Granite Dam	January through June	Issue Month through July
LIBBY	Kootenai River at Libby Dam	April through July	Issue Month through August
		January through April	May through July
		January through June	Issue Month through July
		January through March	April through August
MICAA	Columbia River at Mica Dam	April through July	Issue Month through August
		January through April	May through July
		January through June	Issue Month through July
		January through March	April through August
PAYET	Payette River near Payette	January through June	Issue Month through September
PFALL	Spokane River near Post Falls	April through July	Issue Month through August
		January through March	April through August
SNKHE	Snake River near Heise	January through June	Issue Month through September
WICKI	Wickiup Reservoir	January through July	Issue Month through September
YAPAR	Yakima River near Parker	January through July	Issue Month through September
[1] OCHOC and PRINE have the same forecast situations			

5.1.3 Routing Forecasts from Headwater to Other Subbasins

For development of water supply forecast models in headwater subbasins (i.e., BOISE, CROOK, DUNCA, DWORS, FLASF, LIBBY, MICAA, PAYET, PFALL, SNKHE, YAPAR, CRESC, and WICKI on Figure 90), only candidate grid-cell seasonal P and SWE information informed a resultant forecast model for seasonal runoff volume. For the other subbasins of ARROW, BROWN, CDALK, DALLE, FLAPO, GCOUL, LGRAN, OCHOC, and PRINE, a different candidate predictor strategy was used, relying on a predictor information set that featured a combination of either (a) subbasin P, subbasin SWE, and nearby forecast runoff information, or (b) only nearby forecast runoff information. These other forecast locations were consequently dependent forecast locations in the sense that their model development had to follow development and application of headwater subbasin models. An example is the model development for ARROW, where the mix of candidate information includes ARROW subbasin (below MICAA) P and SWE information and also the forecast runoff at MICAA (for the corresponding forecast period at MICAA that most closely matches the forecast period in the given forecast situation at ARROW). The following list summarizes mixes of nearby runoff forecasts and local P and SWE information fed into at the indicated dependent forecast location. As with the headwater basin model developments, these lists indicate candidate predictors. Model development involved exploring all combinations of predictors types (P, SWE, and runoff) for each forecast situation, resulting in a model that featured either all or a subset of candidate predictors listed.

- ARROW: candidate information included MICAA runoff forecasts and ARROW P & SWE grid cell information
- BROWN (note): candidate runoff information included SNKHE, BOISE, and PAYET runoff forecasts.
- CDALK: candidate information included PFALL runoff forecasts
- DALLE (note): candidate runoff information included CRESC, BOISE, PAYET, BROWN, LGRAN, GCOUL, ARROW, and YAPAR runoff forecasts.
- FLAPO: candidate information included FLASF runoff forecasts and local P & SWE stations)
- GCOUL: candidate information included ARROW, DUNCA, LIBBY, DWORS, PFALL, and FLAPO runoff forecasts.
- LGRAN (note): candidate runoff information included SNKHE, BOISE, PAYET, BROWN, and DWORS runoff forecasts.

- OCHOC and PRINE: CROOK runoff forecasts and historical natural flow estimates in the Crooked River subbasin at Opal Springs (CROOK), Prineville Reservoir and Ochoco Reservoir, where the latter two flow estimates were used to disaggregate CROOK forecasts into OCHOC and PRINE forecasts.

Notes are indicated for three of the dependent runoff locations in the list above.

- For BROWN, the models are developed to estimate seasonal regulated runoff volume at Brownlee rather than the VIC BC runoff at Brownlee that was bias-corrected to resemble Reclamation's historical natural flow estimate at Brownlee (Section 4.0). This is because downstream operational analyses by BPA and USACE are predicated on regulated inflow characterized at Brownlee, which sets up the need for forecasting seasonal regulated runoff volumes at Brownlee. To accomplish this step of model development, it was first necessary to conduct Snake River subbasin operations analysis for each of the selected VIC hydrology scenarios (Section 4.0) and informed by Snake River subbasin water supply forecasts (Section 5.0). Description of these operations analyses is in the Part II report.

- For LGRAN and DALLE, the BC runoff time series used to drive forecast model development are the VIC BC runoff data bias-corrected to resemble BPA and USACE 2000 Level Modified Flows. However, in making such bias-corrections, CIG had to assume a regulated flow condition at Brownlee for each Hybrid-Delta climate scenario. Relative to CIG's assumption for regulated BROWN, Reclamation's Snake River subbasin operations analyses (Part II) report provide a refined view of regulated BROWN under each Hybrid-Delta scenario. To account for this, BPA identified differences in UW CIG and Reclamation regulated BROWN estimates for each climate (Historical and Hybrid-Delta), routed these differences downstream to produce adjusted BC runoff at LGRAN and DALLE, and provided these adjusted LGRAN and DALLE runoff data to drive water supply forecast model development at these locations.

The next section provides a detailed example of model development preliminaries and application for the Yakima River subbasin forecast situations (YAPAR).

5.2 Water Supply Forecasting Results: Single Basin Example

5.2.1 Preliminary Data Analysis

Before forecast models were developed, several analyses were conducted to assess relationships between historical VIC-simulated P and runoff and between SWE and runoff. The purpose was to verify that the relationships made sense (e.g., correlation between antecedent seasonal P and subsequent season runoff, or SWE-at-Issue and subsequent seasonal runoff; and variation in this correlation with location in the basin, or with degree of time-separation between seasons). Overall, these preliminary data analyses showed that these seasonal relationships made sense relative to real-world experience (based on discussions with forecasters at NRCS, Reclamation, USACE and BC Hydro). This outcome was found even though it was understood that the VIC simulation had biases in simulating monthly and annual runoff. The fact that seasonal correlations were still found to be reasonable reflects how correlation focuses on standardized anomalies of two correlating conditions, and how the phasing of these anomalies are in synch. Thus, biases in VIC-simulated runoff can still be present without necessarily weakening the correlation between bias-corrected VIC seasonal runoff anomaly and antecedent P anomaly or SWE anomaly.

To illustrate, this section focuses on preliminary data analyses for YAPAR. Four conditions were assessed:

1. SWE and P Climatology: Calculation of basin-average mean-monthly P and SWE for the 1916-2006 period of VIC simulation.

2. Basin Distribution of SWE-Runoff and P-runoff Correlation during 1916-2006 period of VIC simulation (i.e., antecedent-season P with subsequent season Runoff, SWE-at-Issue with subsequent Season-Runoff, arbitrarily focusing on January through April issues of April-July runoff seasons (i.e., consideration of October-December, October-January, October-February, and October-March P seasons and January 1, February 1, March 1, and April 1 SWE conditions, respectively[27]).

3. Same as (2.), but showing a spatial distribution for a larger area, knowing that some sampling locations of P and SWE information exists outside the given subbasin.

4. Same as (3.), but for locations where P and SWE are sampled from VIC simulations for use in forecast model development (i.e., real-world monitoring locations).

[27] Forecast model development considered more season combinations, depending on the forecast situation.

Figure 91 shows results from the first condition check. It shows that the VIC simulation results illustrate a climatological pattern of SWE and P conditions in the YAPAR subbasin that is familiar with real-world experience, where mean-monthly P rises during a wet season of October through March and subsides during a dry season of April through September. At the same time, these precipitation conditions interact with monthly temperature conditions to formulate a seasonal SWE presence that generally occurs from December through July, peaking in March.

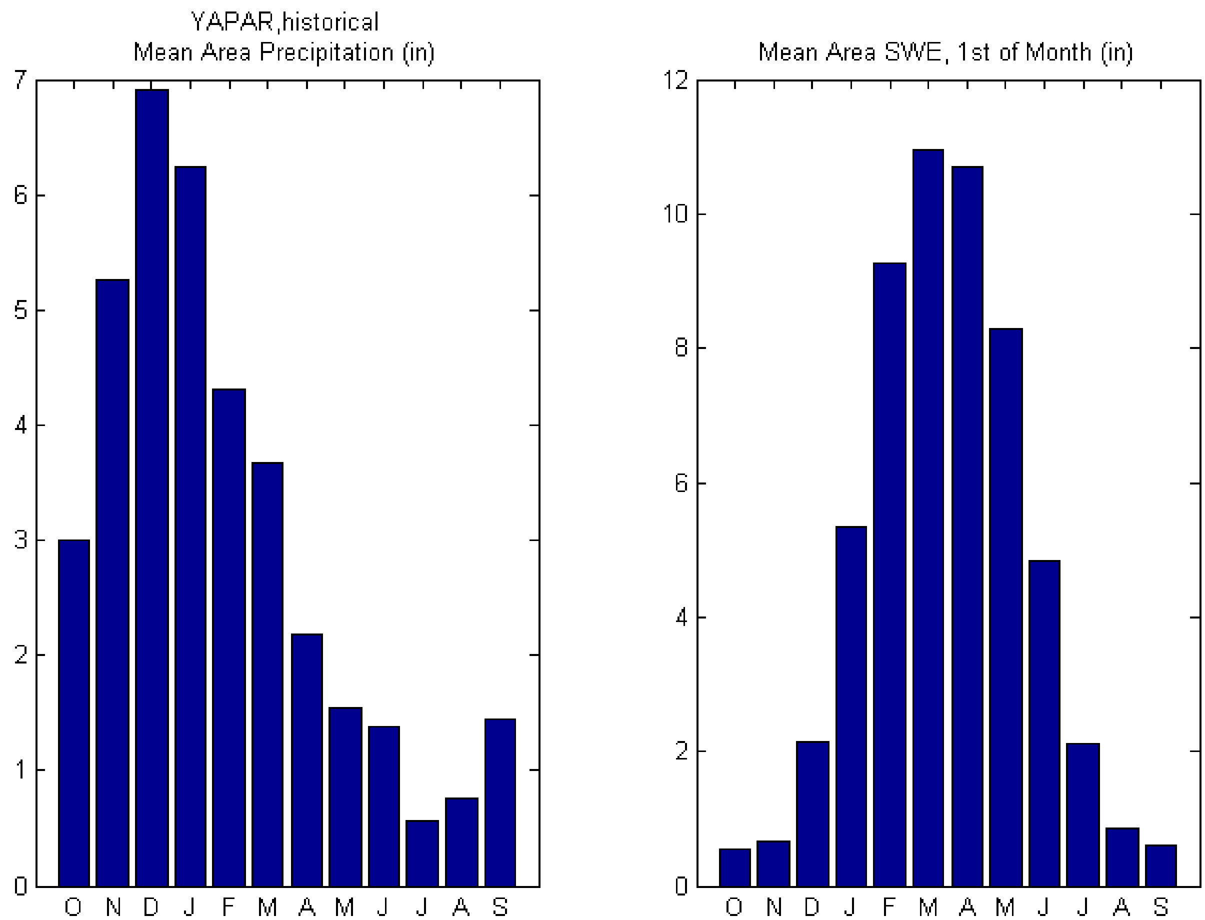

Figure 91. Example water supply forecasting preliminaries – historical (1916-2006) monthly mean precipitation and SWE, spatially averaged across VIC-CSRB grid cells within the Yakima River subbasin.

Switching to the last three conditions, it is helpful to keep the subbasin's elevation distribution in mind (Figure 92) as it will help interpret the spatial results to follow. Focusing first on P-runoff relationships, Figure 92 shows the spatial distribution of 1916-2006 mean-seasonal P for the seasons indicated on each plot panel, Figure 94 shows the spatial distribution of 1916-2006 seasonal P with subsequent seasonal runoff, Figure 95 shows the same information, but for a region that extends beyond river subbasin boundaries, and Figure 96 shows the same information, but only for the VIC grid cells providing P or SWE information for forecast model development. Observations are:

- Review of these spatial results shows that climatologically, more precipitation occurs at higher elevations in the YAPAR subbasin (Figure 93), which is consistent with real-world experience.

- On the matter of correlation, subbasin-distributed results (Figure 94) show that there appears to be little elevation control on the correlation of seasonal P anomaly with subsequent YAPAR seasonal volume anomaly. Review of the subbasin-distributed correlation results from issue to issue shows that correlations strengthen as the arbitrary issue month progresses from January (upper left plot panels) to April (lower right plot panels). This makes sense and is consistent with real-world forecasting experiences where correlations are weaker for longer lead forecasting (e.g., January issue of April-July runoff) features relatively weaker correlation than shorter lead forecasting (e.g., April issue of April-July runoff). This reflects how January 1 forecasts of April-July runoff are limited by how the weather occurring after January 1 can significantly affect the YAPAR April-July runoff outcome. By April 1 issue, the potential for April-July runoff being affected by weather following April 1 is less significant.

- Review of broader-region results (Figure 95) shows that correlations beyond the subbasin are generally consistent with correlation from locations within the subbasin, supporting the notion that the subbasin is experiencing regional climate anomalies from year-to-year, rather than subbasin-specific climate anomalies.

- Review of the sampled-location results (Figure 96) provides an early hint on the strength of predictor-predict and (P-runoff) that might be experienced in the regression forecast modeling to follow.

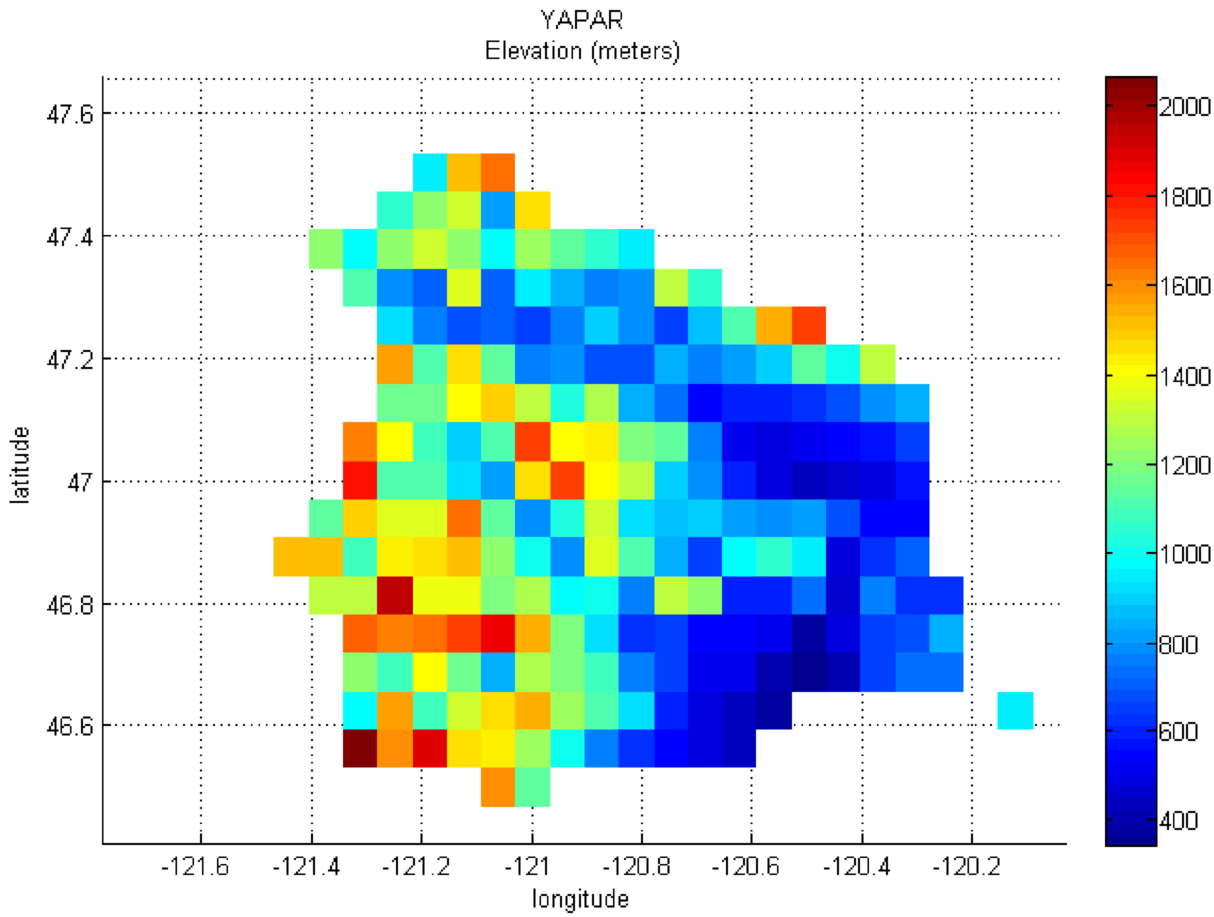

Figure 92. Example water supply forecasting preliminaries – mean elevation of VIC-CSRB grid cells within the Yakima River subbasin.

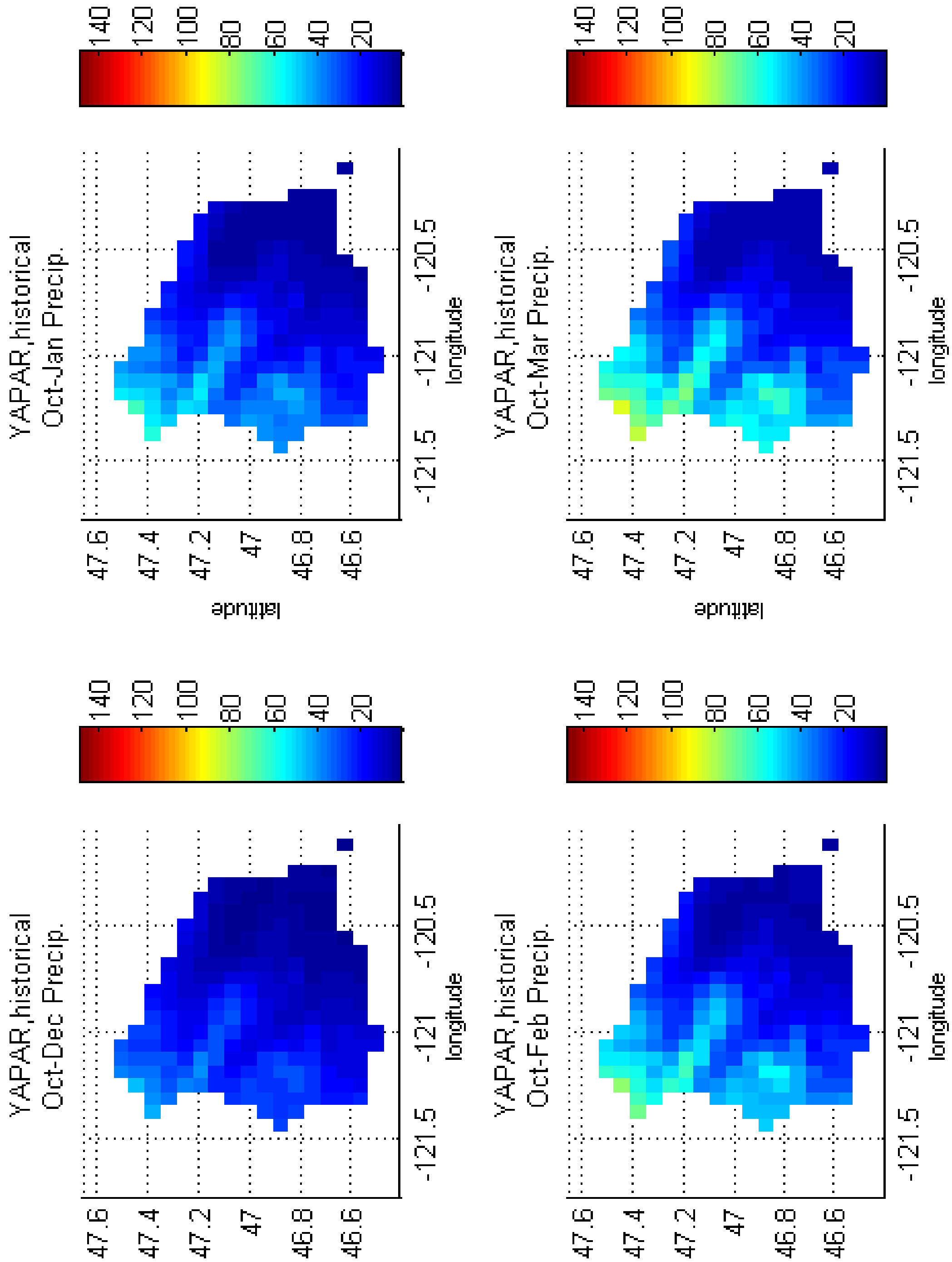

Figure 93. Example water supply forecasting preliminaries – historical mean (1916-2006) seasonal precipitation (inches) from VIC-CSRB grid cells within the Yakima River basin.

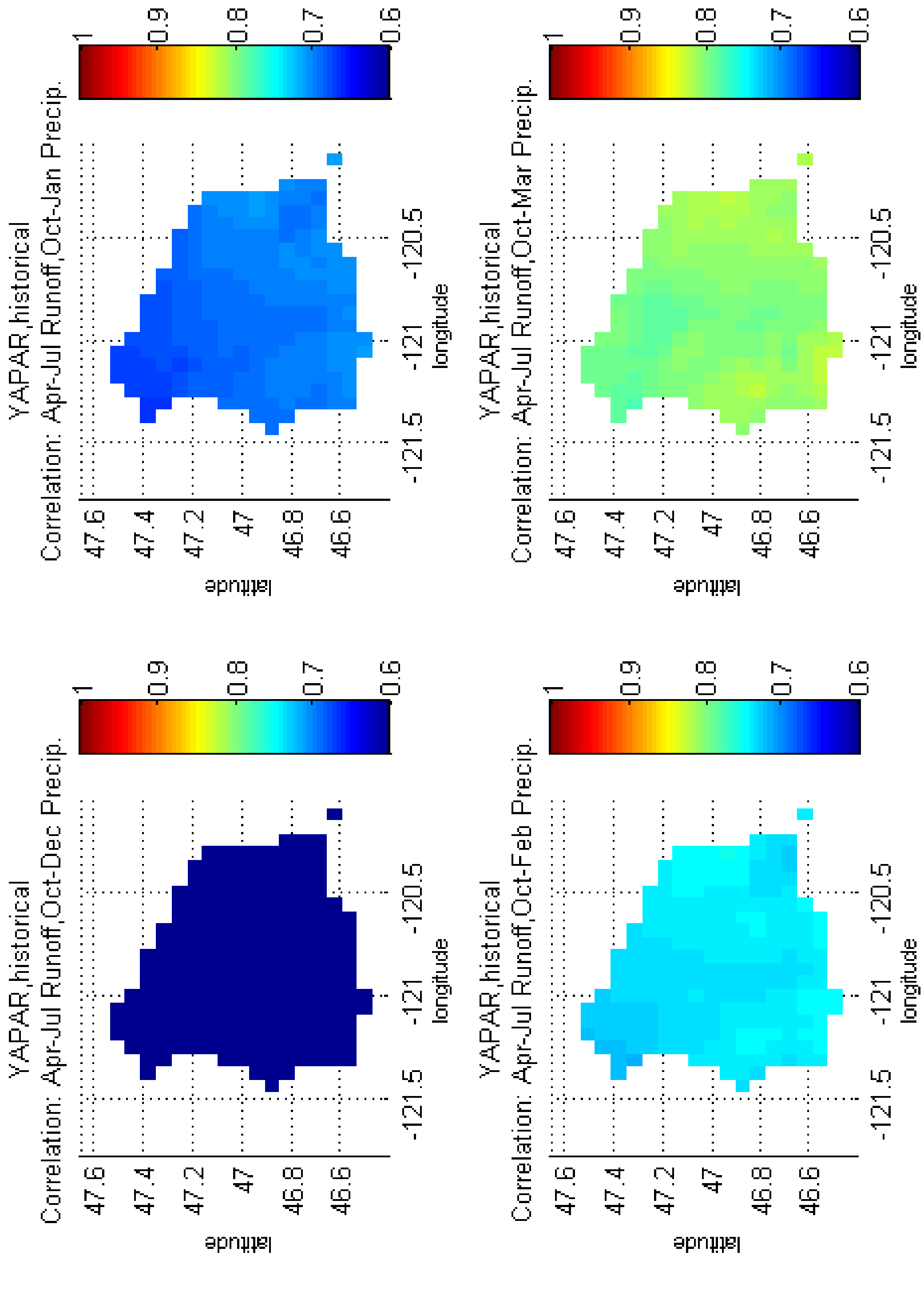

Figure 94. Example water supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and seasonal precipitation from VIC-CSRB grid cells within the Yakima River basin.

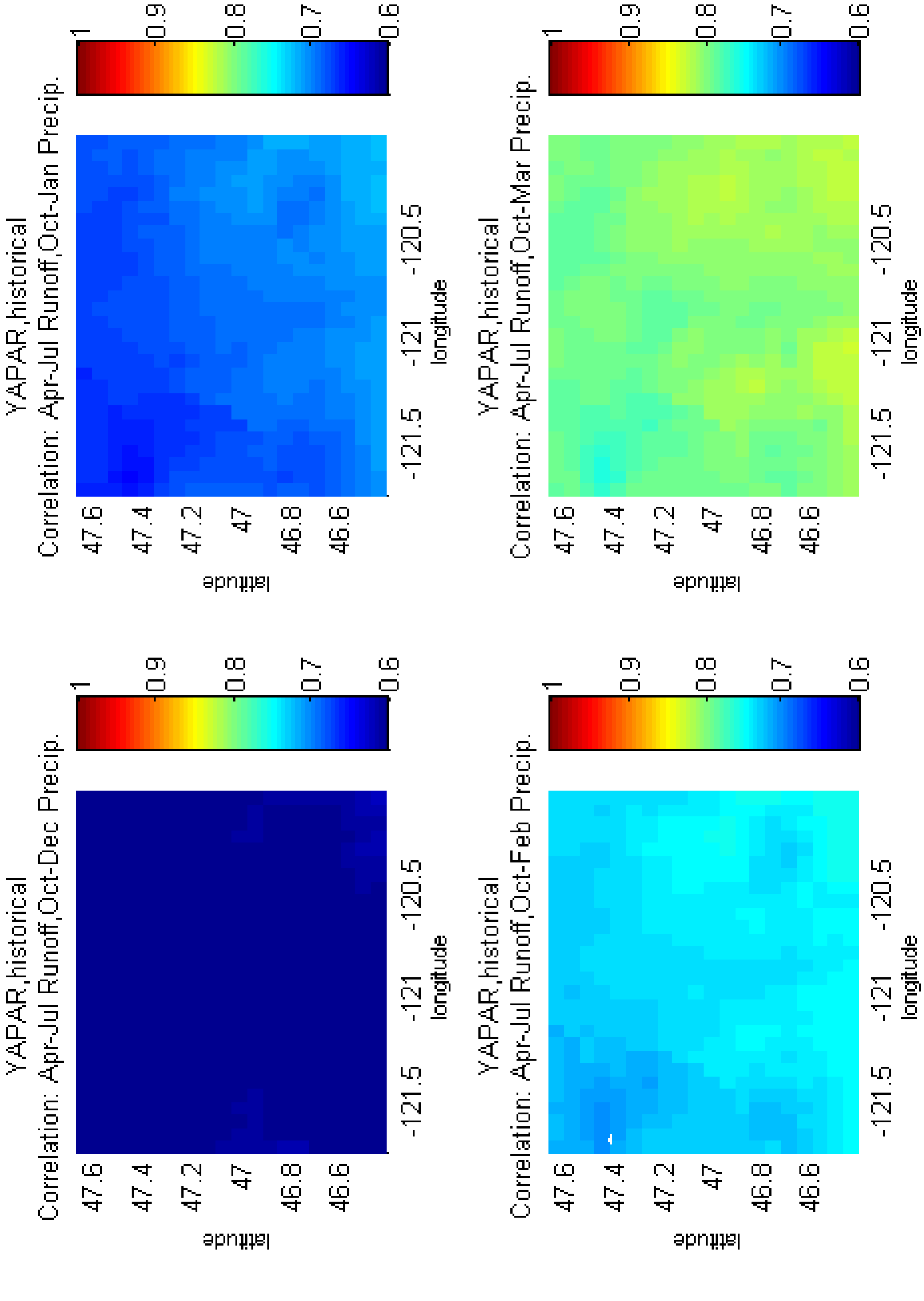

Figure 95. Example water Supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and seasonal precipitation from VIC-CSRB grid cells within the Yakima region.

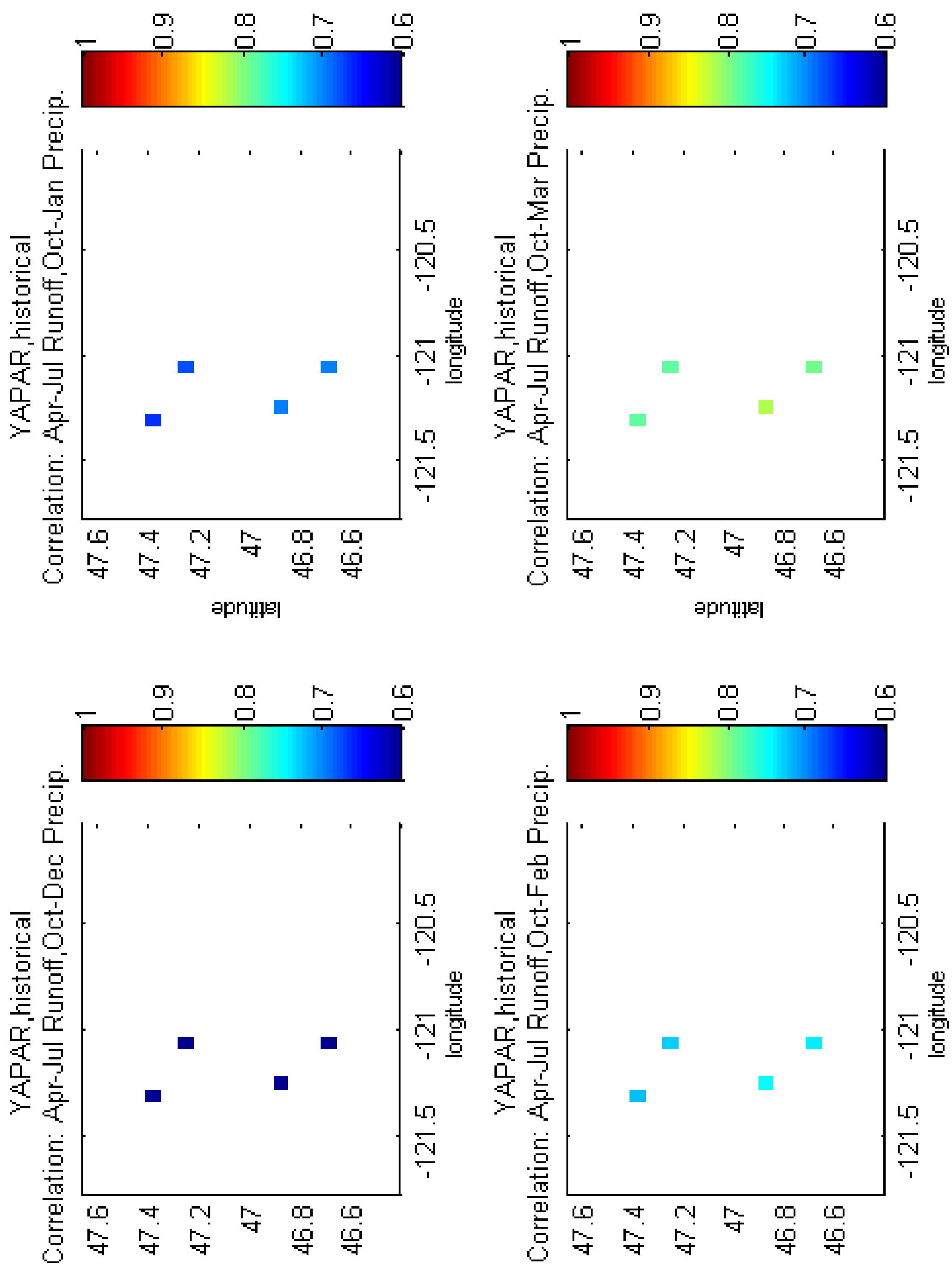

Figure 96. Example water supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and seasonal precipitation from VIC-CSRB grid cells containing precipitation stations that inform Reclamation's operational water supply forecasting in the Yakima River basin.

Figure 97 through Figure 100 offer a similar view of spatially distributed climatological SWE, and also spatially distributed 1916-2006 correlation between simulated SWE-at-issue and April-July runoff. Interpretations of results are generally similar for SWE as they were for P (Figure 93 through Figure 96). One notable exception is that elevation clearly controls the strength of correlation between SWE-at-Issue and April-July runoff, with strongest correlations occurring generally at highest elevations. Comparing correlations distributed across the subbasin (Figure 98) with those at sampled SWE locations (Figure 100) shows that monitoring stations are not necessarily located where the SWE-runoff correlations are strongest. In fact, it appears that higher altitude locations might be preferable from a predictability view. However, the difficulties of installing and maintaining monitoring stations at these higher altitude locations have made such practices somewhat prohibitive.

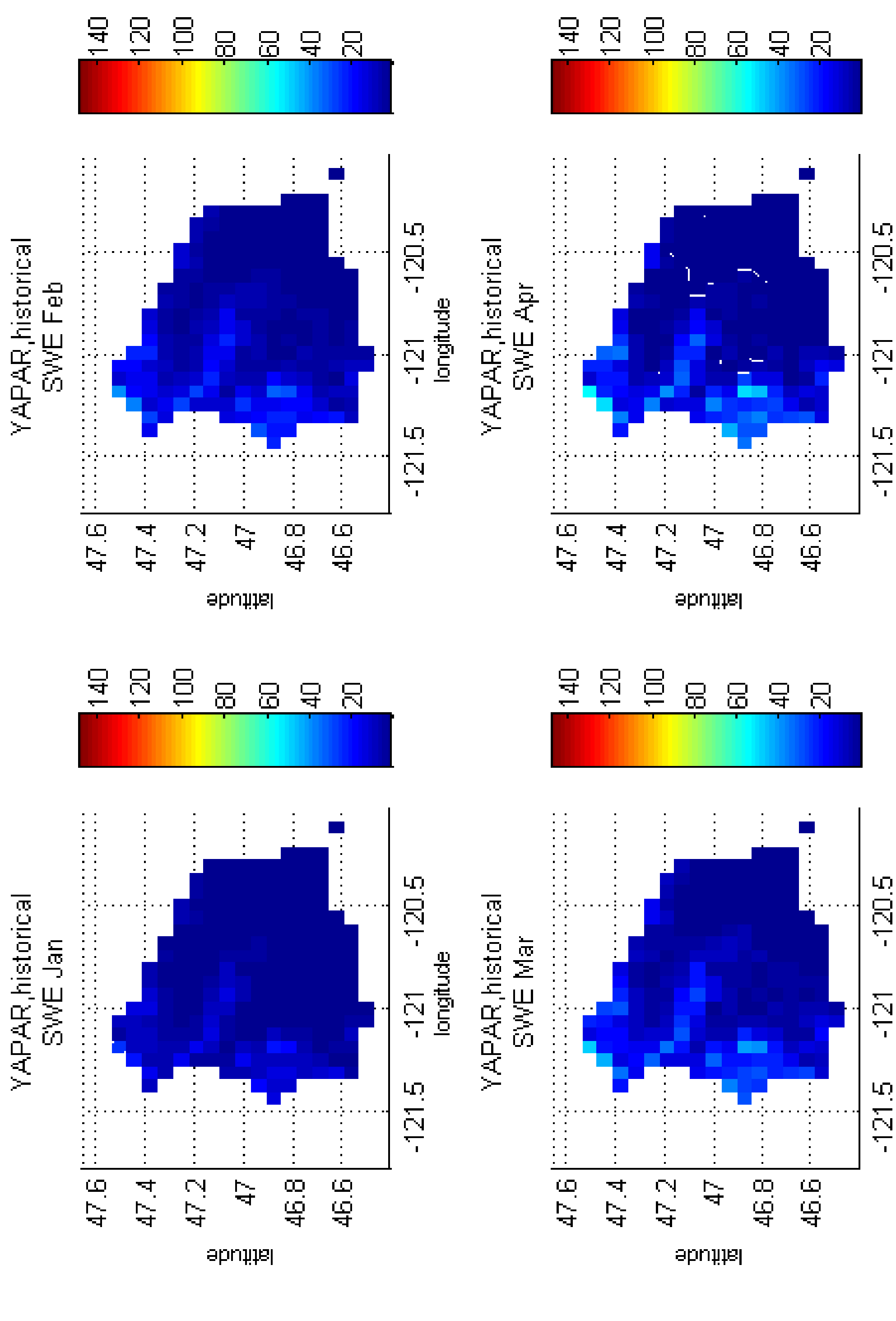

Figure 97. Example water supply forecasting preliminaries – historical mean (1916-2006) first of month SWE (inches) from VIC-CSRB grid cells within the Yakima River basin.

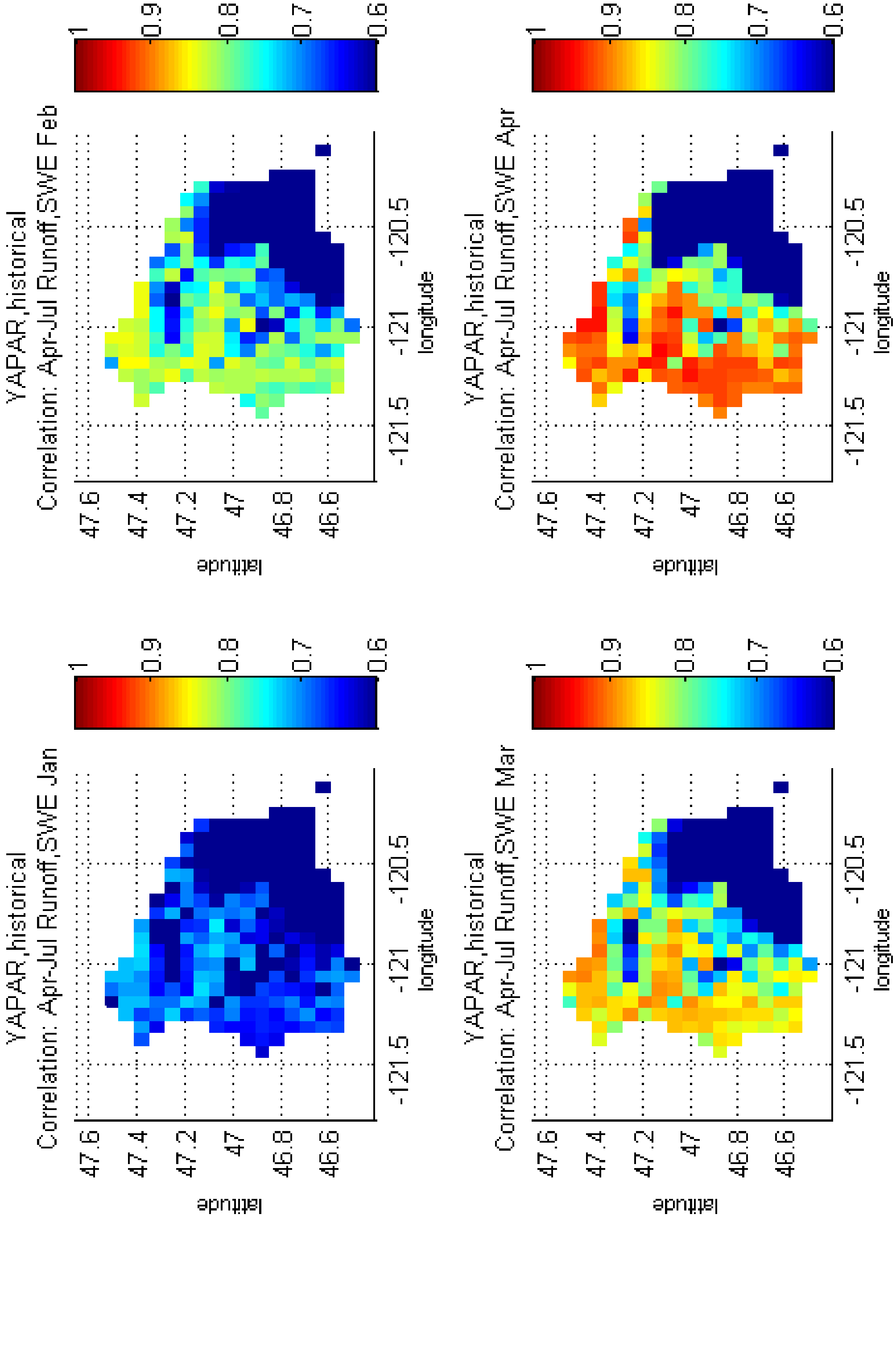

Figure 98. Example water supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and first of month SWE from VIC-CSRB grid cells within the Yakima River basin.

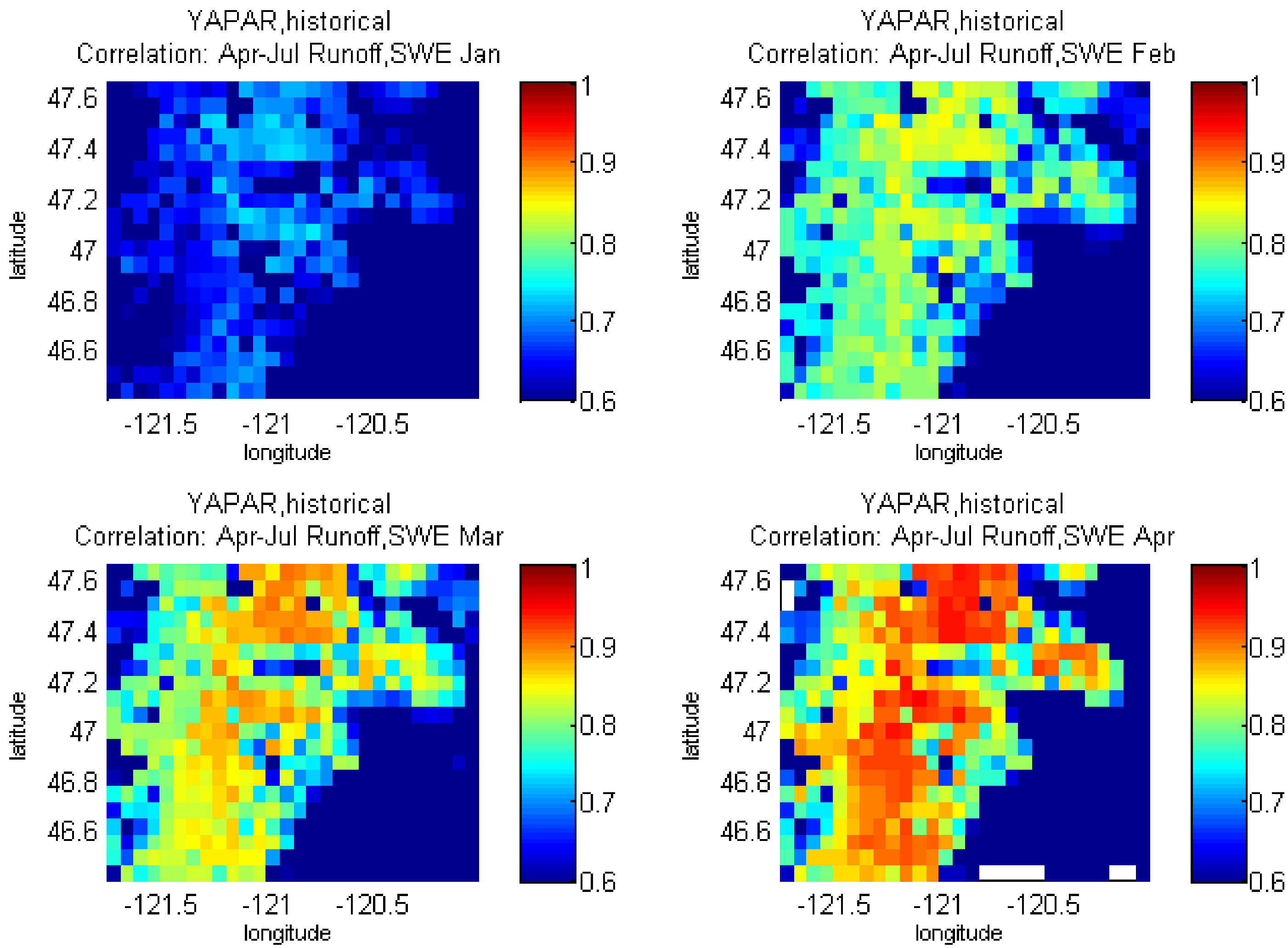

Figure 99. Example water supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and first of month SWE from VIC-CSRB grid cells within the Yakima region.

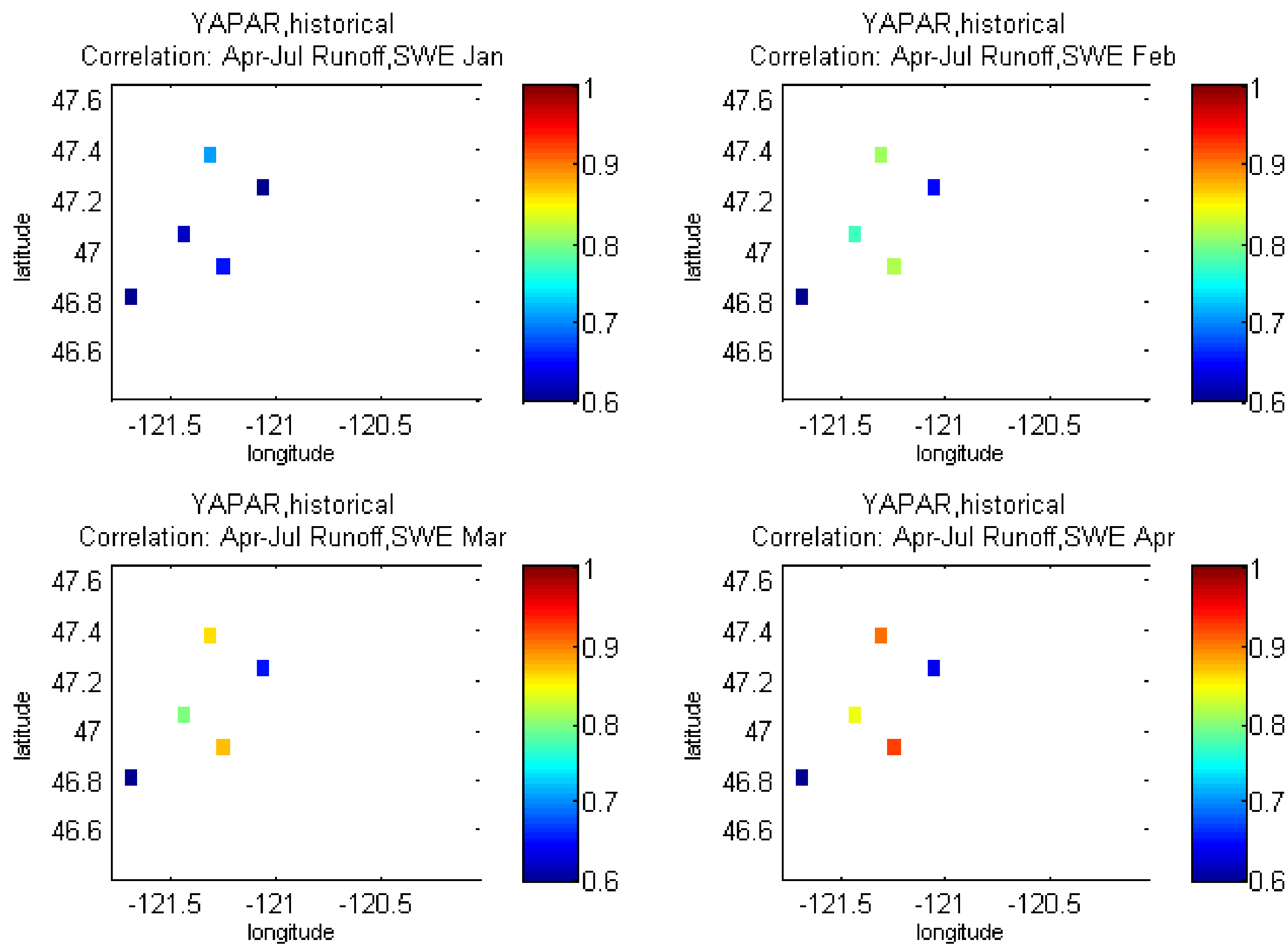

Figure 100. Example water supply forecasting preliminaries – historical correlation (1916-2006), April-July runoff and first of month SWE from VIC-CSRB grid cells containing precipitation stations that inform Reclamation's operational water supply forecasting in the Yakima River basin.

5.2.2 Forecast Model Development Summary

After completing preliminary data analyses and verifying that seasonal relationships between historical VIC-simulated P, SWE, and runoff appeared consistent with real-world experience, forecast model development ensued. For each forecast situation (Table 8), all predictor combinations (P, SWE, and/or runoff) and all potential P seasons (October to issue-month and nested shorter seasons) were explored. Model error results were evaluated using r^2 and root-mean-squared-error (RMSE) metrics. For each situation and each climate (historical and HD future climate), results were evaluated in several ways:

1. Graphical inspection of time-series results by forecast situation, comparing time series of regression-estimated (forecast) seasonal runoff volumes and those actually simulated by VIC (i.e., the predictants that informed regression model development), and also the time series of regression-estimated confidence intervals about the central "forecast" estimate.

2. Same as (1.), but showing scatter plot of regression estimate versus actual (rather than time series), and disregarding confidence intervals.

3. Computation of r^2 and RMSE values of 91-year series of forecast estimates (for each climate and forecast situation), based on regression-estimated and actual seasonal runoff results.

Summary impressions from these evaluations are provided in Section 5.4 (along with summary information on forecast model skill under historical climate conditions and a couple of future HD climate conditions for all forecast situations). However, to provide an example of what type of information was considered in these evaluations, results for the YAPAR forecast situations are presented.

On the first and second evaluations of this example, results are only shown here for historical climate. Figure 101 shows that results for regression-estimated forecasts of seasonal YAPAR volume (red line) generally follow actual seasonal volumes (VIC-simulated, dark blue line). It is notable that the volume of YAPAR runoff being forecast diminishes as the season shrinks (e.g., April-July shrinking to June-July) as expected. The plot also shows a time series of 80 percent confidence intervals about the regression forecast estimates (i.e., light blue area, denoting 10th to 90th percentile forecast estimates centered about the central regression estimate or 50th percentile estimate). This confidence interval shrinks as issues proceed from January to April, indicating that regression model skill improves in this progression. Figure 102 shows the same regression estimates and actual volumes from Figure 101, but in a scatter view rather than time-series view. The skill of the regression forecast improves as the time of forecast issue progresses to spring months (e.g., April and May), based on the forecast model

r^2 values indicated on each figure panel (e.g., the January issue model has an r^2 of 0.59 while the April issue has an r^2 of 0.91). This helps to indicate whether the forecast models were relatively more error prone (or biased) when trying to forecast relatively wetter versus drier years. The plot panels also indicate the regression r^2 value of the model identified for each forecast situation. Consistent with discussion above, the r^2 metric indicates that skill of the forecast model improves as time of forecast issue progresses from January to April, plateaus in May and June, and weakens slightly in July. As will be shown in Section 5.4, the time of peak skill varies by forecast location.

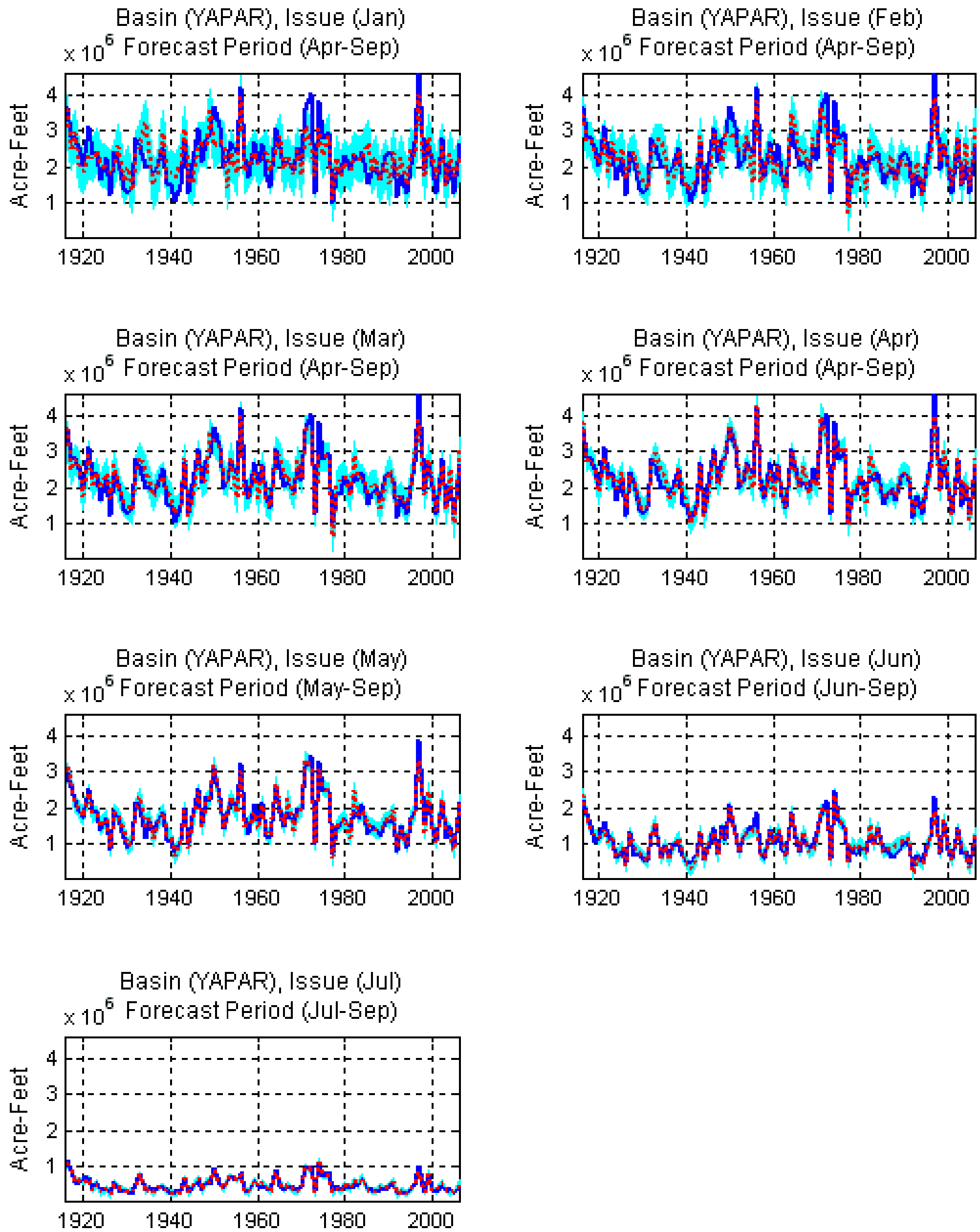

Figure 101. Example water supply forecasting – Yakima River at Parker (YAPAR), modeled and actual seasonal runoff volumes under seven forecasting situations and historical climate.

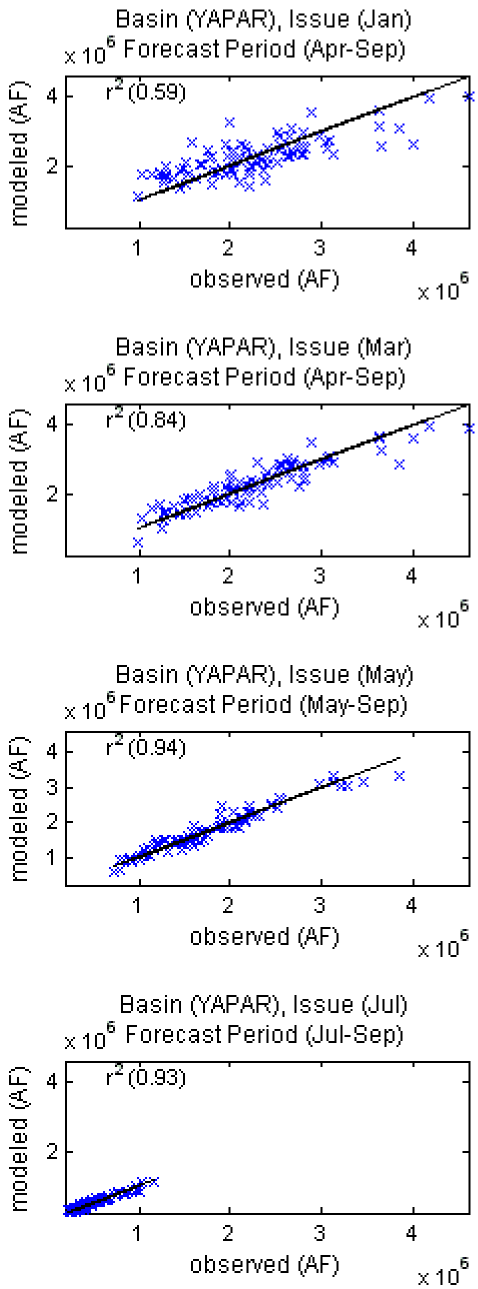

Figure 102. Example water supply forecasting – Yakima River at Parker (YAPAR), modeled versus actual seasonal runoff volumes under seven forecasting situations and historical climate.

Proceeding to the third evaluation in this example, climate focus broadens to include both historical and HD climates. Figure 103 shows r^2 results for YAPAR forecast situations under historical and HD 2020s climates. Figure 104 shows similar results, but for YAPAR forecast situations under historical and HD 2040s climates. Observations are:

- Focusing on the 2020s, it appears that for each forecast situation the YAPAR forecast model skill (measured by r^2) is generally similar under each HD 2020s climate to how it is under historical climate. Put in other words, the amount of climate change in the HD 2020s scenarios relative to historical climate conditions does not appear to cause enough affect in the relationships between winter-spring P and spring-summer runoff, or between winter-spring SWE and spring-summer runoff. An exception to this interpretation might be noted for the earliest and latest issues considered (i.e., January issue of April-July and June issue of June-July), where forecast skill weakened slightly relative to historical.

- Focusing on the 2040s, it appears that similar impressions hold as those found for 2020s climates. However, the weakening of June and July forecast skill appears to be more pronounced (although somewhat variable from HD climate to HD climate).

The results showing skill weakening for January and June issues appear to be consistent with the preliminary assumptions about what climate change could mean in terms of water supply predictability impacts. The concern is that as snowpack diminishes, water supply forecast models will receive less information and deterioration in skill. It might be reasoned that the first issues to be impacted by diminishing snowpack could be the earliest and latest issues (i.e., earlier season impact from snowpack being mature enough to support forecasting in January on a less consistent basis with time, and later season impact from snowpack meltoff happening earlier with time). That said, it could also be reasoned that this analysis offers a conservative view on predictability impacts because it did not exhaust options for “replacement” predictor information (e.g., investment in higher-elevation SWE monitoring that might sustain water supply prediction skill further into the future as climate warms, or eventually switching reliance to a mix of other predictors and de-emphasizing reliance on SWE information).

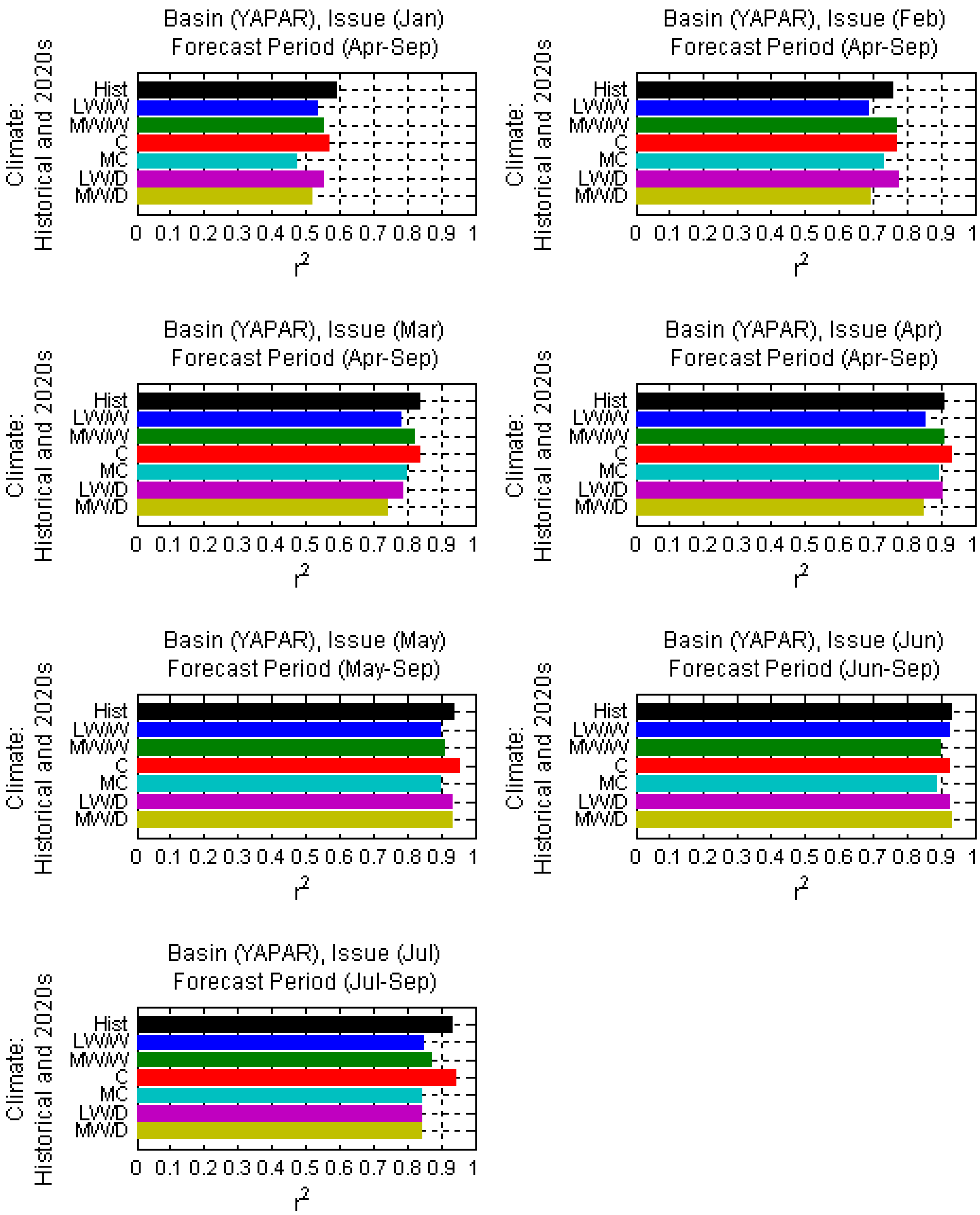

Figure 103. Example water supply forecasting – Yakima River at Parker (YAPAR), regression model calibration (r^2) (under seven forecasting situations and seven climates (historical and HD 2020s).

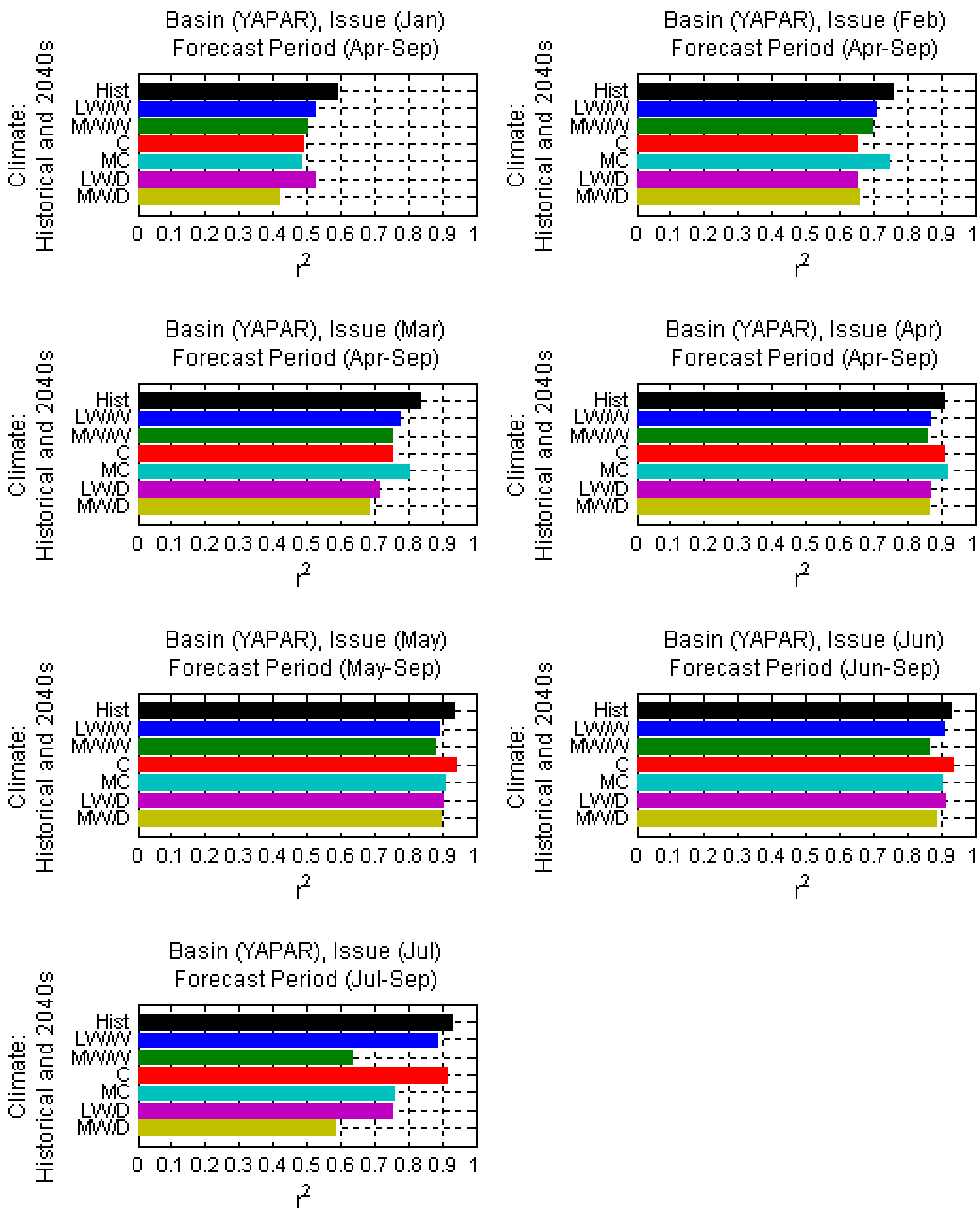

Figure 104. Example water supply forecasting – Yakima River at Parker (YAPAR), regression model calibration (r^2) (under seven forecasting situations and seven climates (historical and HD 2040s).

5.3 Water Supply Forecasting Results: All Basins Summary

Water supply forecasting model skill and forecasting results were discussed with forecasters from USACE, BC Hydro and Reclamation, as well as with participants at the RMJOC Technical Team and Stakeholders meetings held in April and July 2010. This section summarizes the quality of historical regression models with thought toward how they compare to real-world regression results and then trends in regression model skill from historical to HD 2020s and HD 2040s climates.

Focusing on the first issue, Table 9 lists regression skill measured by r^2 for each of the forecast situations listed in Table 8. Table 9 is formatted in a way to indicate forecast situation.[28] Based on discussions above and comparison of historical regression model skill with that featured in real-world water supply forecasting, a general impression was drawn that the historical regression models developed in this effort generally are of good quality, though not as good as models developed by various operational forecast providers in the basin. One reason for this outcome is that these models are informed by VIC-simulated P, SWE, and runoff and related simulation biases and/or artifacts, whereas real-world models are informed by observed P, SWE, and runoff information that perhaps exhibit clearer relationships than what was simulated in VIC. Also, the real-world regressions are fit to a different, more recent period compared to the 91-year calibration period used in this effort.

[28] Column month headers indicate both issue month and forecast period. Issue month is indicated by the location of an r^2 value. Associated forecast period is then either (Explanation – Table shows calibration r^2 values for all forecast situations (Table 7). Placement of value indicates the forecast period: if the value's cell is shaded yellow, then the period is issue-month through end of yellow shading to the right; otherwise the forecast period is the yellow-shaded period indicated to the right. For example, consider ARROW, a value of 0.60 is the upper left-most value, and is under column January in a yellow-shaded cell followed by yellow shading to July on the right. This means that the forecast situation is January issue of January through July runoff and that the r^2 for the forecast model in this situation is 0.60 under historical climate. For another example, consider, the row PFALL and the first value 0.59 under column January in a non-shaded cell. Following the yellow-shading to the right of this value, the forecast situation is January issue of April-August runoff volume, and that the r^2 for the forecast model in this situation is 0.59 under historical climate.

Table 9. Calibration Quality (r^2 value) of Water Supply Forecast Models under Historical Climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ARROW	0.60	0.71	0.78	0.83	0.86	0.90			
BOISE	0.57	0.72	0.84	0.89	0.89	0.87			
BROWN	0.63	0.71	0.78	0.83	0.78	0.81			
BROWN	0.56	0.67	0.75						
CDALK	0.59	0.71	0.77	0.80	0.81	0.79			
CRESC	0.52	0.59	0.71	0.79	0.80	0.85	0.87		
CROOK	0.48	0.44	0.54	0.45	0.18	0.09	0.08		
CROOK	0.52	0.49	0.55	0.46	0.21	0.07	0.05		
DALLE	0.61	0.72	0.78	0.83	0.83	0.87			
DALLE	0.60	0.71	0.78	0.83	0.82	0.87			
DUNCA	0.57	0.69	0.74	0.76	0.81	0.87	0.89		
DUNCA	0.61	0.73	0.77	0.82	0.87	0.91			
DUNCA	0.55	0.69	0.74	0.79					
DWORS	0.51	0.71	0.78	0.81	0.80	0.85			
DWORS	0.53	0.71	0.78						
DWORS	0.47	0.67	0.71	0.77					
FLAPO	0.50	0.66	0.72	0.79	0.80	0.88			
FLASF	0.40	0.57	0.65	0.73	0.78	0.86	0.86		
FLASF	0.39	0.56	0.66	0.74	0.78	0.87			
FLASF	0.42	0.59	0.67	0.74	0.78	0.87	0.90		
FLASF	0.39	0.56	0.64	0.73					
GCOUL	0.58	0.68	0.74	0.79	0.80	0.88			
LGRAN	0.61	0.72	0.79	0.82	0.83	0.87			
LIBBY	0.52	0.63	0.68	0.70	0.75	0.83	0.75		
LIBBY	0.54	0.64	0.68	0.71	0.76	0.84			
LIBBY	0.50	0.61	0.66	0.69					
MICAA	0.59	0.70	0.75	0.78	0.82	0.87	0.86		
MICAA	0.59	0.71	0.76	0.81	0.84	0.90			
MICAA	0.55	0.68	0.75	0.80					
PAYET	0.58	0.70	0.78	0.86	0.85	0.87			
PFALL	0.59	0.71	0.77	0.80	0.81	0.79			
SNKHE	0.59	0.72	0.81	0.87	0.88	0.89			
WICKI	0.55	0.68	0.80	0.88	0.91	0.90	0.86		
YAPAR	0.59	0.76	0.84	0.91	0.94	0.93	0.93		

The significance of skill differences between the historical regressions from this effort (VIC-based) and historical regressions serving real-world forecasting may be small compared to the skill difference between the "imperfect" forecast models developed in this effort and perfect foresight (which is the question posed in the operations analyses of this RMJOC effort and presented in Parts II through IV reports). Further, if operations results under the "imperfect" forecasts suggested by these regression models are similar to operations results informed by perfect foresight, then the significance of skill differences between the historical regressions of this effort and real-world forecasting become somewhat irrelevant to the questions being asked in this RMJOC effort. Nevertheless, there was a concern leading into operations analysis that if these regression models were used to guide conservative forecast estimates (e.g., 90 percent exceedence forecasts, where model error defines confidence interval about the estimate), then a model that is less skillful would feature broader confidence intervals and more conservative forecast estimates, possibly affecting operations simulation. In particular, there was concern how this might affect BPA's HYDSIM operations studies which feature conservative use of these water supply forecast models. This issue will be revisited in the Part III report of this RMJOC effort to be issued spring 2011.

Focusing on the second issue, Table 10 lists regression model skill results for the same situations as Table 9, but for future HD 2040s MW/D climate rather than the historical climate. Recall that MW/D means more warming and relatively drier, which would tend to promote diminished snowpack conditions and perhaps more impact on water supply predictability. Table 11 shows the percentage change in regression model skill (r^2) for each forecast situation from historical to future HD 2040s MW/D climate. Results for this climate change case suggest that broadly speaking, skill should diminish for most locations and for many issues, although skill decrease is most pronounced (on a percentage basis) for early and late issues, as noted in earlier discussion for the YAPAR example (Section 5.3.2). Skill reductions varied by location, with some basins experiencing very little reduction (e.g., Columbia River at Keenleyside Dam, Columbia River at Mica Dam, and Snake River near Heise all showing less than 10 percent skill reduction for early and late issues) and others experiencing more significant reduction (e.g., Deschutes River above Cresent Lake, North Fork Clearwater at Dworshak Dam, and Yakima River at Parker all showing skill reductions exceeding 20 percent for early and late issues under some 2040s climate change scenarios). On the decrease for late issues, it is acknowledged that the amount of runoff volume being forecast is diminishing from historical to future climate. However, the judgment that skill is decreasing is still valid in this context because the judgment is based on a decreasing trend in r^2 for the given forecast situation (i.e., issue month, location, forecast period), understanding that the r^2 characterizes forecast quality relative to given amount of runoff volume being forecast.

Table 10. Calibration quality (r^2 value) of water supply forecast models under Hybrid-Delta 2040s MW/D climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ARROW	0.58	0.68	0.77	0.82	0.81	0.88			
BOISE	0.52	0.58	0.77	0.81	0.78	0.65			
BROWN	0.66	0.74	0.80	0.82	0.83	0.78			
BROWN	0.62	0.70	0.77						
CDALK	0.33	0.65	0.73	0.77	0.71	0.59			
CRESC	0.39	0.32	0.51	0.61	0.71	0.46	0.05		
CROOK	0.44	0.40	0.47	0.33	0.23	0.09	0.10		
CROOK	0.50	0.46	0.51	0.38	0.27	0.08	0.00		
DALLE	0.56	0.71	0.75	0.84	0.81	0.79			
DALLE	0.61	0.70	0.78	0.84	0.82	0.80			
DUNCA	0.51	0.62	0.70	0.74	0.77	0.79	0.46		
DUNCA	0.54	0.66	0.72	0.79	0.81	0.82			
DUNCA	0.41	0.53	0.60	0.68					
DWORS	0.39	0.47	0.71	0.77	0.69	0.43			
DWORS	0.36	0.58	0.71						
DWORS	0.29	0.53	0.62	0.73					
FLAPO	0.48	0.65	0.75	0.85	0.79	0.86			
FLASF	0.31	0.47	0.59	0.74	0.78	0.76	0.49		
FLASF	0.34	0.53	0.70	0.81	0.81	0.79			
FLASF	0.36	0.54	0.69	0.81	0.79	0.78	0.58		
FLASF	0.31	0.47	0.60	0.74					
GCOUL	0.59	0.70	0.75	0.82	0.83	0.83			
LGRAN	0.60	0.70	0.77	0.80	0.84	0.74			
LIBBY	0.55	0.65	0.74	0.75	0.81	0.74	0.42		
LIBBY	0.59	0.69	0.75	0.77	0.83	0.76			
LIBBY	0.50	0.59	0.69	0.72					
MICAA	0.51	0.61	0.69	0.73	0.76	0.79	0.71		
MICAA	0.55	0.66	0.72	0.79	0.81	0.86			
MICAA	0.51	0.61	0.69	0.75					
PAYET	0.52	0.56	0.74	0.77	0.79	0.74			
PFALL	0.33	0.65	0.73	0.77	0.71	0.59			
SNKHE	0.55	0.72	0.80	0.84	0.83	0.82			
WICKI	0.50	0.55	0.72	0.73	0.82	0.66	0.40		
YAPAR	0.42	0.66	0.68	0.87	0.90	0.88	0.58		

Table 11. Change in calibration quality of water supply forecast models from historical climate to Hybrid-Delta 2040s MW/D climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ARROW	-3%	-4%	-2%	-1%	-5%	-2%			
BOISE	-9%	-19%	-8%	-9%	-13%	-25%			
BROWN	5%	5%	2%	0%	6%	-4%			
BROWN	10%	5%	4%						
CDALK	-45%	-8%	-4%	-4%	-11%	-26%			
CRESC	-24%	-46%	-29%	-22%	-11%	-46%	-94%		
CROOK	-9%	-10%	-13%	-27%	27%	-3%	23%		
CROOK	-4%	-5%	-7%	-18%	27%	16%			
DALLE	-9%	-3%	-4%	1%	-2%	-9%			
DALLE	2%	-2%	0%	2%	0%	-7%			
DUNCA	-10%	-9%	-5%	-3%	-5%	-9%	-48%		
DUNCA	-11%	-10%	-6%	-4%	-7%	-9%			
DUNCA	-25%	-23%	-18%	-13%					
DWORS	-24%	-34%	-9%	-5%	-15%	-50%			
DWORS	-31%	-18%	-9%						
DWORS	-39%	-21%	-13%	-5%					
FLAPO	-2%	-2%	3%	8%	-1%	-2%			
FLASF	-22%	-17%	-10%	2%	0%	-11%	-43%		
FLASF	-13%	-5%	6%	10%	4%	-9%			
FLASF	-14%	-8%	3%	9%	1%	-10%	-35%		
FLASF	-21%	-16%	-7%	2%					
GCOUL	3%	2%	1%	4%	3%	-6%			
LGRAN	-2%	-3%	-2%	-1%	2%	-15%			
LIBBY	6%	3%	9%	8%	8%	-11%	-44%		
LIBBY	9%	8%	10%	8%	8%	-10%			
LIBBY	0%	-3%	4%	5%					
MICAA	-12%	-13%	-9%	-6%	-7%	-9%	-18%		
MICAA	-8%	-7%	-5%	-3%	-4%	-5%			
MICAA	-6%	-9%	-7%	-6%					
PAYET	-11%	-20%	-5%	-10%	-8%	-15%			
PFALL	-45%	-8%	-4%	-4%	-11%	-26%			
SNKHE	-7%	0%	-2%	-4%	-5%	-9%			
WICKI	-9%	-19%	-10%	-17%	-10%	-27%	-53%		
YAPAR	-29%	-13%	-19%	-5%	-4%	-5%	-37%		

Some may question why more skill degradation is not seen even though the VIC simulations show significant reductions in late spring to summer runoff volumes. The answer relates to earlier discussions on what is happening with water supply forecasting modeling, namely that the regression models are like correlations in that they relate seasonal P and SWE anomalies to seasonal runoff volume anomalies. Even if SWE conditions diminish with time, as long as there is a distribution of SWE anomalies that can be related to runoff anomalies (i.e., as long as SWE does not zero out frequently from year-to-year, affecting the nature of how these two distributions can relate), then the regression skill should generally persist, even if the regression model is being used to forecast less and less snowmelt volume with time.

6.0 UNCERTAINTIES

This report summarizes future scenarios of climate and hydrology for RMJOC planning purposes. The selection of these scenarios is meant to reflect the use of best available datasets as well as data development methodologies. However, there are a number of analytical uncertainties that are not reflected in this report's characterization of scenarios, including uncertainties associated with the following analytical areas:

- **Global climate forcing**: Although the study considers climate projections representing a range of future greenhouse emission paths, the uncertainties associated with these pathways are not explored in this analysis. Such uncertainties include those introduced by assumptions about technological and economic developments, globally and regionally; how those assumptions translate into global energy use involving GHG emissions; and biogeochemical analysis to determine the fate of GHG emissions in the oceans, land, and atmosphere. Also, not all of the uncertainties associated with climate forcing are associated with GHG assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., figure SPM-2 in IPCC 2007).

- **Global climate simulation**: While this study considers climate projections produced by state-of-the-art coupled ocean-atmosphere climate models and even though these models have shown an ability to simulate the influence of increasing GHG emissions on global climate (IPCC 2007), there are still uncertainties about our understanding of physical processes that affect climate, including how to simulate such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycle, vegetative other biological changes) and how to do so in a mathematically efficient manner given computational limitations.

- **Climate projection bias-correction**: This study is designed on the philosophy that GCM biases toward being too wet, too dry, too warm, or too cool should be identified and accounted for as bias-corrected climate projections data prior to use in implications studies like this sensitivity analysis. Bias-correction of climate projections data affects results on incremental runoff and water supply response.

- **Climate projection spatial downscaling**: This study uses projections that have been empirically downscaled, using spatial disaggregation on a monthly time-step (following GCM bias-correction on a monthly time-step). Although this technique has been used to support numerous water resources impacts studies (e.g., Payne et al.

2004, Maurer and Duffy 2005, Maurer 2007, Anderson et al. 2008, LCRA/SAWS 2008, Reclamation 2008, Reclamation 2009), uncertainties remain about the limitations of empirical downscaling methodologies. One potential limitation relates to how empirical methodologies require historical reference information use on spatial climatic patterns at the downscaled spatial resolution. These finer-grid patterns are implicitly related to historical large-scale atmospheric circulation patterns, which presumably would change with global climate change. Application of the historical finer-grid spatial patterns to guide downscaling of future climate projections implies an assumption that the historical relationship between finer-grid surface climate patterns and large-scale atmospheric circulation is still valid under the future climate. In other words, the relationship is assumed to have statistical stationarity. In actuality, it is possible that such stationarity will not hold at various space and time scales, over various locations, and for various climate variables. However, the significance of potential non-stationarity in empirical downscaling methods and the need to utilize alternative downscaling methodologies remains to be established.

- **Generating weather sequences consistent with climate projections**: This study uses two different techniques to generate weather sequences for hydrologic modeling that reflect observed historical climate variability blended with projection information on changes in period monthly conditions. Other techniques might have been considered (e.g., stochastic weather generation techniques). Choice of weather generation technique depends on aspects of climate change that are being targeted in a given study. Preference among available techniques remains to be established.

- **Natural runoff response**: This study analyzes natural runoff response to changes in precipitation and temperature while holding other watershed features constant. Other watershed features might be expected to change as climate changes and affects runoff (e.g., potential ET given temperature changes, vegetation changes affecting ET and infiltration). On the matter of land cover response to climate change, the runoff models' calibrations would have to change if land cover changed because the models were calibrated to represent the historical relationship between weather and runoff as mediated by historical land cover. Adjustment to watershed land cover and model parameterizations were not considered due to lack of available information to guide such adjustment. On the matter of runoff model calibration, it was explained that focus was placed on a few Columbia-Snake River Basin locations while other runoff reporting locations were subjected to a bias-correction technique. It was shown that reliance on bias-correction of simulated runoff leads to sequencing impacts and imperfect correlation between observed and simulated (bias-corrected) historical runoff despite having similar monthly and annual average statistics. Additional uncertainties associated with characterizing natural runoff response include converting bias-corrected monthly runoff sequences to daily sequences.

- **Generating Water Supply Forecasts under Future Climate and Runoff Conditions**: This study focuses on relationships between seasonal P prior to forecast issue, SWE at the time of issue, and seasonal runoff volume after the time of forecast issue, and how these relationships are impacted by climate change. The forecasts developed in this effort are limited by the mix of predictor types considered and also other model uncertainties. On predictor types, real-world forecasting practices might also consider the use of soil moisture indicators and/or climate teleconnections. Soil moisture is of interest heading into the water year, as it indicates degree of soil moisture deficit that may affect snowmelt runoff versus infiltration volume during spring-summer. Autumn streamflow is sometimes referenced as a proxy for autumn soil moisture conditions in forecasting. Climate teleconnections are of interest in how they might be used to infer forecast-period weather (or also weather that follows the time of forecast issue, leading up to the forecast period). Teleconnections of interest are those that involve being able to detect atmospheric and/or ocean information that correlates with subsequent seasonal basin weather conditions. On other model uncertainties, the predictors used in these water supply forecasts are VIC grid-cell predictors, which represent P or SWE conditions averaged within a grid-cell that is 12 kilometers by 12 kilometers. In real-world forecasting, P and SWE conditions are sampled from point locations within this grid, which might produce different P-SWE-runoff relationships. Lastly, as climate changes, it is reasonable to expect that real-world forecasters would seek opportunities to improve predictor selection, potentially migrating to different predictor types and/or selecting different predictor locations (e.g., SWE locations at higher elevation that remain less impacted by warming conditions).

7.0 LITERATURE CITED

Parenthetical Reference	Bibliographic Citation
Allen 2007	Allen, C.D. 2007. "Interactions across spatial scales among forest dieback, fire, and erosion in northern New Mexico landscapes." *Ecosystems*, 10(5), 797–808. doi:10.1007/s10021-007-9057-4.
Allan et al. 2005	Allan, J.D, M. Palmer, N.L. Poff. 2005. "Climate Change and Freshwater Ecosystems." *Climate Change and Biodiversity*, edited by Thomas E. Lovejoy and Lee Hannah. Yale University Press.
Anderson et al. 2008	Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson, and R. Snyder. 2008. "Progress on Incorporating Climate Change into Management of California's Water Resources." *Climatic Change*, Springer, Netherlands, 89, Supplement 1, 91–108.
Ansu and McCarney 2008	Ansu, K. and C. McCarney. 2008. "Climate Change Bibliography". *The Wildlife Professional*. Fall 2008, Vol. 2, No. 3. http://joomla.wildlife.org/ccbib/ccbib.pdf.
Barnett et al. 2008	Barnett, T., D. W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nazawa, A. Mirin, D.R. Cayan, and M. Dettinger. 2008. "Human-induced changes in the hydrology of the western United States." *Science* 319:1080-1083.
Battin et al. 2007	Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki. 2007. "Projected impacts of climate change on salmon habitat restoration." Proceedings of the National Academy of Sciences 104(16): 6720–6725.
Beukema et al. 2007	Beukema, S.J., D.C.E. Robinson, and L.A. Greig. 2007. *Forests, Insects & Pathogens and Climate Change: Workshop Report*. Prepared for The Western Wildlands Threat Assessment Center, Prineville, Oregon. 39 pp.

Parenthetical Reference	Bibliographic Citation
Bonfils et al. 2008	Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, M.D. Dettinger, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa, (2008) "Detection and Attribution of temperature changes in the mountainous western United States," J Clim 21:6404-6424.
Brekke et al. 2009	Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White (2009). *Climate change and water resources management—A federal perspective.* U.S. Geological Survey Circular 1331, 65 p. Also available online at http://pubs.usgs.gov/circ/1331/ .
Brekke et al. 2008	Brekke, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson. 2008. Significance of Model Credibility in estimating Climate Projection Distributions for Regional Hydroclimatological Risk Assessments. Climatic Change. Published online 2-28-2008. ISSN: 0165-0009 (Print) 1573-1480 (Online) DOI: 10.1007/s10584-007-9388-3.
Breshears et al. 2005	Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J. J. Anderson, O.B. Myers, and C.W. Meyer. 2005. "Regional vegetation die-off in response to global-change-style drought." Proceedings of the National Academy of Sciences 102(42): 15144–8.
Brown et al. 2004	Brown, T.J., B.L. Hall, and A.L. Westerling. 2004. "The impact of twenty-first century climate change on wildland fire danger in the Western United States: An applications perspective." *Climatic Change*, 62: 365–388.
Burkett and Kusler 2000	Burkett, V. and J. Kusler. 2000. Climate Change: "Potential Impacts and Interactions in Wetlands of the United States." *Journal of the American Water Resources Association*. Vol. 36, No. 2, p.313-320. 10.1111/j.1752-1688.2000.tb04270.x

Parenthetical Reference	Bibliographic Citation
Cayan et al. 2001	Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. "Changes in the Onset of Spring in the Western United States." Bulletin of the American Meteorology Society 82(3): 399–415.
CBO 2009	Congressional Budget Office. 2009. *Potential Impacts of Climate Change in the United States*. Prepared at the request of the Chairman of the Senate Committee on Energy and Natural Resource. May 2009.
CCSP 2008	Climate Change Science Program. 2008. *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. (Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol, Anne M. Waple, and William L. Murray [eds.]). U.S. Department of Commerce, NOAA's National Climatic Data Center, Washington, DC. 164 pp.
Covey et al. 2003	Covey, C., K.M. AchutaRao, U. Cubasch, P.D. Jones, S.J. Lambert, M.E. Mann, T.J. Phillips, and K.E. Taylor (2003). "An Overview of Results from the Coupled Model Intercomparison Project," *Global and Planetary Change*, 769, 1–31.
CWCB 2010	Colorado Water Conservation Board. 2010. *Colorado River Water Availability Study*. Phase 1 report prepared by AECOM in association with AMEC Earth & Environmental, Canyon Water Resources, Leonard Rice Engineers, and Status Consulting. 489 pp. Draft report available at http://cwcb.state.co.us/technical-resources/colorado-river-water-availability-study/Documents/CRWAS1Task10Phase1ReportDraft.pdf .
Das et al. 2009	Das, A., H.G. Hidalgo, M.D. Dettinger, D.R. Cayan, D.W. Pierce, C. Bonfils, T.P. Barnett, G. Bala and A. Mirin. 2009. "Structure and Detectability of Trends in Hydrological Measures over the Western United States." *Journal of Hydrometeorology*, Vol. 10, doi:10.1175/2009JHM1095.1.

Parenthetical Reference	Bibliographic Citation
Dettinger 2005	Dettinger, M.D. 2005. From *Climate Change Spaghetti to Climate Change Distributions for 21st Century*. San Francisco Estuary and Watershed Science. 3(1).
Duan et al. 1993	Duan, Q., V.K. Gupta and S. Sorooshian. 1993. "A Shuffled Complex Evolution Approach for Effective and Efficient Global Minimization." *Journal of Optimization Theory and its Applications*, 76(3), 501-521.
Elsner et al. 2010	Elsner MM, L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y. Lee, D.P. Lettenmaier. 2010. “Implications of 21st Century climate change for the hydrology of Washington State.” *Climatic Change*. DOI:10.1007/s10584-010-9855-0.
Fang et al. 2004a	Fang, X., H.G. Stefan, J.G. Eaton, J.H. McCormickc, S.R. Alama. 2004. “Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios Part 1. Cool-water fish in the contiguous U.S.” *Journal of Ecological Modeling*. Vol. 172: 13-37. doi:10.1016/S0304-3800(03)00282-5.
Fang et al. 2004b	Fang, X., H.G. Stefan, J.G. Eaton, J.H. McCormickc, S.R. Alama. 2004b. “Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios Part 2. Cool-water fish in the contiguous U.S. ” *Journal of Ecological Modeling*. Vol. 172: 39–54. doi:10.1016/S0304-3800(03)00285-0.
Ficke et al. 2007	Ficke, A.D., Myrick, C.A., and Hansen, L.J. 2007. “Potential impacts of global climate change fisheries.” *Reviews in Fish Biology and Fisheries*, 17(4): 581–613. 10.1007/s11160-007-9059-5.
Fowler et al. 2007	Fowler, H.J., S. Blenkinsop, C. Tebaldi. 2007. “Review: Linking Climate Change Modeling to Impacts Studies: Recent Advances in Downscaling Techniques for Hydrological Modelling.” *International Journal of Climatology*, 27, 1547-1578.

Parenthetical Reference	Bibliographic Citation
Gannett et al. 2001	Gannett, M.W., Lite, Jr., K.E., Morgan, D.S., and Collins, C.A. 2001. *Ground-water hydrology of the upper Deschutes Basin, Oregon*. U.S. Geological Survey Water-Resources Investigations Report 00-4162, 74 p.
Garen 1992	Garen, D. C. 1992. "Improved techniques in regression-based streamflow volume forecasting." J. Water Res. Plan. Mgmt., 118(6), 654-670.
Giorgi 2005	Giorgi, F. 2005. "Interdecadal variability of regional climate change: implications for the development of regional climate change scenarios," Meteorol Atmos Phys 89, 1–15.
Gleckler et al. 2008	Gleckler, P.J., K.E. Taylor, and C. Doutriaux. 2008. "Performance metrics for climate models." *Journal of Geophysical Research*. 113(D06104).
Gutowski et al. 2008	Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, F.W. Zwiers. 2008. *Causes of Observed Changes in Extremes and Projections of Future Changes in Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC. Hatfield et al. 2008
Hamlet and Lettenmaier 1999	Hamlet, A.F., and D.P. Lettenmaier. 1999. "Effects of climate change on hydrology and water resources in the Columbia River Basin." *Journal of the American Water Resources Association* 35(6):1597–1623.
Hawkins and Sutton 2009	Hawkins, E. and Sutton, R. T. 2009. "The potential to narrow uncertainty in regional climate predictions. " *Bulletin of the American Meteorological Society*, 90 (8). pp. 1095-1107

Parenthetical Reference	Bibliographic Citation
Hellmann et al. 2008	Hellmann, J.J., J.E. Byers, B.G. Bierwagen, J.S. Dukes. 2008. "Five Potential Consequences of Climate Change for Invasive Species." *Conservation Biology*, Volume 22(3), 534–543, DOI: 10.1111/j.1523–1739.2008.00951.x.
Hidalgo et al. 2009	Hidalgo H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin, A.W. Wood, C. Bonfils. 2009. "Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States." *Journal of Climate* 22(13): 3838. doi:10.1175/2008JCLI2470.1.
Hoerling et al. 2010	Hoerling M., J. Eischeid and J. Perlwitz. 2010. "Regional Precipitation Trends: Distinguishing Natural Variability from Anthropogenic Forcing." *Journal of Climate* (in press).
IPCC 2007	Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp. Available at http://www.ipcc.ch/ipccreports/ar4-wg1.htm .
IPCC 2000	Intergovernmental Panel on Climate Change. 2000. *Special Report on Emissions Scenarios*. Nakicenovic, N. and R. Swart (Eds.). Cambridge University Press, Cambridge, United Kingdom, 599 pp. Available at http://www.grida.no/climate/ipcc/emission/ .
Janetos et al. 2008	Janetos, A., L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw. 2008. *Biodiversity: The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC. 362 pp.

Parenthetical Reference	Bibliographic Citation
Knowles et al. 2007	Knowles, N., M. Dettinger, and D. Cayan. 2007. *Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001*. Prepared for California Energy Commission Public Interest Energy Research Program. Project Report CEC-500-2007-032.
LCRA SAWS 2008	Lower Colorado River Authority San Antonio Water System. 2008. *Climate Change Study, Report on Evaluation Methods and Climate Scenarios*. Prepared by CH2M-Hill, 103 pp, available at: http://www.lcra.org/library/media/public/docs/lswp/findings/Climate_Change_TM.pdf .
Lee et al. 2009	Lee, S., A.F. Hamlet, C.J. Fitzgerald and S.J. Burges. 2009. “Optimized Flood Control in the Columbia River Basin for a Global Warming Scenario.” *Journal of Water Resources Planning and Management*, doi: 10.1061/(ASCE)0733-9496(2009)135:6(440).
Lettenmaier et al. 2008	Lettenmaier, D., D. Major, L. Poff, and S. Running. 2008. *Water Resources: The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC. 362 pp.
Liang et al. 1994	Liang, X, D. P. Lettenmaier, E.F. Wood, and S.J. Burges. 1994. “A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models. “ *Journal of Geophysical Research*. 99(D7), pp. 14415-14428.
Littell et al. 2009	Littell, J.S., E.E. Oneil, D. McKenzie, J.A. Hicke, J.A. Lutz, R. A. Norheim and M.M. Elsner. 2009. “Forest Ecosystems, Disturbances, and Climatic Change in Washington State, USA.”
Logan et al. 2003	Logan, J.A., J. Regniere, and J.A. Powell. 2003. “Assessing the impacts of global warming on forest pest dynamics.” *Frontiers in Ecology and the Environment*, 1:130–137.

Parenthetical Reference	Bibliographic Citation
Luce and Holden 2009	Luce, C.H. and Z.A. Holden. 2009. "Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006." Geophysical Research Letters, Vol. 36, L16401, doi:10.1029/2009GL039407.
Mantua et al. 2009	Mantua, N.J., I. Tohver, and A.F. Hamlet. 2009. "Impacts of climate change on key aspects of freshwater salmon habitat in Washington State." Chapter 6 in *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. Climate Impacts Group, University of Washington, Seattle, Washington.
Mastin 2008	Mastin, M.C. 2008. *Effects of potential future warming on runoff in the Yakima River Basin, Washington*. U.S. Geological Survey Scientific Investigations Report 2008-5124. 12 p.
Maurer 2007	Maurer, E.P. (2007). "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios." *Climatic Change*, 82, 309–325.
Maurer et al. 2007	Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. *Fine-resolution Climate Projections Enhance Regional Climate Change Impact Studies*. Eos Trans. American Geophysical Union, 88(47), pp. 504.
Maurer and Duffy 2005	Maurer, E.P. and P.B. Duffy. 2005. "Uncertainty in projections of streamflow changes due to climate change in California." Geophysical Research Letters DOI 10.1029/2004GL021462.
Maurer et al. 2002	Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate* 15(22), 3237–3251.
McKenzie et al. 2004	McKenzie, D., Z.E. Gedalof, et al. 2004. "Climatic Change, Wildfire, and Conservation." *Conservation Biology* 18(4):890–902.

Parenthetical Reference	**Bibliographic Citation**
Meehl et al. 2007	Meehl, G.A. C. Covey, T. Delworth, M. Latif, B. Mcavaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor. 2007. "THE WCRP CMIP3 MULTIMODEL DATASET – A New Era in Climate Change Research," *Bulletin of the American Meteorological Society*, 88(9), 1383–1394.
Meehl et al. 2000	Meehl, G.A., G.J. Boer, C. Covey, M. Latif, and R.J. Stouffer. 2000. "The Coupled Model Intercomparison Project (CMIP)." *Bulletin of the American Meteorological Society*, 81(2), 313–318.
Mote and Salathé 2010	Mote, P.W. and E.P. Salathé. 2010. "Future climate in the Pacific Northwest." *Climatic Change*, DOI: 10.1007/s10584-010-9848.
Mote et al 2008	Mote, P.W., A.F. Hamlet, and E.P. Salathé. 2008. "Has spring snowpack declined in the Washington Cascades?" *Hydrology and Earth System Sciences* 12: 193–206.
Mote et al. 2003	Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmair, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, A.K. Snover. 2003. "Preparing for Climate Change: the Water, Salmon, and Forests of the Pacific Northwest." *Climatic Change* 61:45–88.
Payne et al. 2004	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*, 62(1-3):233–256.
Pierce et al. 2009	Pierce, D.W., T.P. Barnett, B.D. Santer, and P.J. Gleckler. 2009. "Selecting global climate models for regional climate change studies." Proc National Academy Sciences, v106 (21), 8441-8446.
Pierce et al. 2008	Pierce, D.W., T.P. Barnett, H.G. Hidalgo, T. Das, C. Bonfils, B. Sander, G. Bala, M. Dettinger, D. Cayan, A. Mirin, A.Wood, and T. Nozawa. 2008. "Attribution of declining western US snowpack to human effects." J Clim 21:6425-6444.

Parenthetical Reference	Bibliographic Citation
Raff et al. 2009	Raff, D.A., T. Pruitt, and L.D. Brekke. 2009. "A framework for assessing flood frequency based on climate projection information." *Hydrology and Earth System Science Journal*. Vol. 13, p. 2119–2136. www.hydrol-earth-syst-sci.net/13/2119/2009/ .
Rauscher et al. 2008	Rauscher, S.A., J.S. Pal, N.S. Diffenbaugh, and M.M. Benedetti. 2008. "Future Changes in Snowmelt-driven Runoff Timing Over the Western U.S." Geophysical Research Letters, Vol. 35, L16703, doi:10.1029/2008GL034424.
Reclamation 2010a	Bureau of Reclamation. 2010. *Climate Change and Hydrology Scenarios for Oklahoma Yield Studies*. Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver Colorado. April 2010. 71pp.
Reclamation 2010b	Bureau of Reclamation. 2010. *Climate Change Analysis for the St. Mary and Milk River Systems in Montana*. Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver Colorado. August 2010. 49pp.
Reclamation 2010c	Bureau of Reclamation. 2010. Literature Synthesis on Climate Change Implications for Reclamation's Water Resources. Technical Memorandum 86-68210-10#. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver Colorado. November 2010. 180 pp. (in preparation).
Reclamation 2009	Bureau of Reclamation. 2009. "Sensitivity of Future Central Valley Project and State Water Project Operations to Potential Climate Change and Associated Sea Level Rise," attachment to Appendix I in *Second Administrative Draft Program EIS/EIR - San Joaquin River Restoration Program*. U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Regional Office, Sacramento, California. 110 pp.

Parenthetical Reference	**Bibliographic Citation**
Reclamation 2009a	Bureau of Reclamation. 2009. "Literature Synthesis on Climate Change Implications for Reclamation's Water Resources." Technical Memorandum 86-68210-091. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver Colorado. September 2009. 290 pp.
Reclamation 2008	Bureau of Reclamation. 2008. "Sensitivity of Future CVP/SWP Operations to Potential Climate Change and Associated Sea Level Rise," Appendix R in *Biological Assessment on the Continued Long-term Operations of the Central Valley Project and the State Water Project*. Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Central Valley Operations Office, Sacramento, California. August 2008. 134 pp.
Regonda et al. 2005	Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. "Seasonal Cycle Shifts in Hydroclimatology Over the Western United States." *Journal of Climate* 18(2): 372–384.
Reichler and Kim 2008	Reichler, T., J. Kim. 2008. "How Well Do Coupled Models Simulate Today's Climate?" *Bulletin of the American Meteorological Society*, 89(3) pp. 303-311.
Robinson et al. 2008	Robinson, D.C.E., Beukema, S.J. and L.A. Greig. 2008. *Vegetation models and climate change: workshop results*. Prepared by ESSA Technologies Ltd. for Western Wildlands Environmental Threat Assessment Center, U.S. Department of Agriculture, Forest Service, Prineville, Oregon. 50 pp.
Ryan et al. 2008	Ryan, M.G., S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, and W. Schlesinger. 2008. "Land Resources" from *The Effects of climate change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC. 362 pp.

Parenthetical Reference	Bibliographic Citation
Salathé et al. 2007	Salathé, E.P., P.W. Mote, M.W. Wiley. 2007. "Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest," *International Journal of Climatology*, 27: 1611–1621.
Santer et al. 2009	Santer, B.D., K.E. Taylor, P.J. Gleckler, C. Bonfils, T.P. Barnett, D.W. Pierce, T.M.L. Wigley, C. Mears, F. J. Wentz, W. Bruggemann, N.P. Gillett, S.A. Klein, S. Solomon, P.A. Stott, and M.F. Wehner. 2009. "Incorporating model quality information in climate change detection and attribution studies." Proc National Academy Sciences, v 106 (35), 14778-14783.
Snover et al. 2003	Snover A.K., A.F. Hamlet, D.P. Lettenmaier. 2003. "Climate change scenarios for water planning studies." *Bulletin of the American Meteorological Society*, 84 (11): 1513-151.
Tebaldi et al. 2005	Tebaldi, C., R.L. Smith, D. Nychka, and L.O. Mearns. 2005. "Quantifying Uncertainty in Projections of Regional Climate Change: A Bayesian Approach to the Analysis of Multi-model Ensembles." *Journal of Climate*, 18, pp. 1524-1540.
Vano et al. 2010	Vano, J.A., M. Scott, N. Voisin, C.O. Stöckle, A.F. Hamlet, K.E.B. Mickelson, M.M. Elsner, D.P. Lettenmaier. 2010. "Climate change impacts on water management and irrigated agriculture in the Yakima River basin, Washington, USA." Washington State Climatic Change. DOI: 10.1007/s10584-010-9856-z.
Westerling et al. 2006	Westerling, A.L., H.G. Hidalgo, D.R. Cayan, T.W. Swetnam. 2006. "Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity." *Science* 313(5789): 940–943.
Wigley 2004	Wigley, T.M.L. 2004. "Input Needs for Downscaling of Climate Data." Discussion paper prepared for California Energy Commission Public Interest Energy Research Program, Rep 500-04-027.

Parenthetical Reference	Bibliographic Citation
Williams et al. 2008	Williams, K.K., J.D. McMillin, T E. DeGomez, K M. Clancy, and A. Miller. 2008. "Influence of Elevation on Bark Beetle (Coleoptera: Curculionidae, Scolytinae) Community Structure and Flight Periodicity in Ponderosa Pine Forests of Arizona." Environ. Entomol. 37(1): 94–109.
Wood et al. 2004	Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier. 2004. "Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs." *Climatic Change*, 15, 189–216.
Wood et al. 2002	Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier. 2002. "Long-range experimental hydrologic forecasting for the Eastern United States." J. Geophysical Research-Atmospheres, 107(D20), 4429, doi:10.1029/2001JD000659.