Downscaled CMIP3 and CMIP5 Hydrology Projections

Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Needs

Bureau of Reclamation

Climate Analytics Group

Climate Central

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National Center for Atmospheric Research

Santa Clara University

Scripps Institution of Oceanography

U.S. Army Corps of Engineers

U.S. Geological Survey

July 2014

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3 July 2014

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Prepared for:

Users of the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections" website at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

Abbreviations and Acronyms

BCSD	Bias-Correction Spatial Disaggregation technique for bias-correcting and spatially downscaling global climate projections to local resolution
BCSD3	BCSD applied to CMIP3 climate projections
BCSD5	BCSD applied to CMIP5 climate projections
BCSD5(all)	Entire 231-member ensemble of BCSD5 climate projections served at the DCHP website hosted at Lawrence Livermore National Laboratory Green Data Oasis
BCSD5(hydro)	97-member subset of BCSD5(all) climate projections that were translated into BCSD5 hydrologic projections
BNU-ESM	CMIP5 climate model i.d. for model developed by College of Global Change and Earth System Science, Beijing Normal University
CMIP	Coupled Model Intercomparison Project effort led by WCRP, producing global climate projections that have informed IPCC assessments
CMIP3	CMIP phase 3, informing IPCC Fourth Assessment (2007)
CMIP5	CMIP phase 5, informing IPCC Fifth Assessment (2013-2014)
collaborators	Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, NCAR, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and USGS
DCHP	Downscaled Climate and Hydrology Projections
DOI	Department of the Interior
GCM	Global Climate Model, or General Circulation Model
GHG	greenhouse gas
HUC#	Hydrologic Unit Class #, where # varies from 2 (region) to 12 (small catchment)
IPCC	Intergovernmental Panel on Climate Change

Abbreviations and Acronyms

MAF	million acre-feet
MT-CLIM	Software program developed by University of Montana Numerical Terradynamic Simulation Group to address the problem of estimating daily near-surface meteorological parameters from nearby observations, tailored for application in mountainous terrain
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
Oct through Sep	12 water year months October through September (used in tables and figures)
º	degrees
ºC	degrees Celsius
%	percent
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RCP	representative concentration pathway
RCP ##	a specific RCP, where ## represents (lower to higher emissions) 2.6, 4.5, 6.0, or 8.5
Reclamation	Bureau of Reclamation
SRES	Special Report on Emissions Scenarios
SRES ##	a specific SRES emissions pathway, where ## represents (lower to higher emissions) B1, A1b, or A2
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity hydrologic model
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling

Acknowledgments

Support provided by:

U.S. Army Corps of Engineers Responses to Climate Change and Actions for Change Programs
Lawrence Livermore National Laboratory – Green Data Oasis
Bureau of Reclamation Science and Technology Program

Acknowledgments and citation of these projections:

When publishing research based on projections from this archive, please include two acknowledgements:

1. Acknowledge the superseding effort:

    a. For Coupled Model Intercomparison Project phase 3 (CMIP3), the following is language suggested by the CMIP3 archive hosts at the Program for Climate Model Diagnosis and Intercomparison (PCMDI):

    "We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy."

    PCMDI also requests that in first making reference to the projections from this archive, please first reference the CMIP3 dataset by including the phrase "the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset." Subsequent references within the same publication might refer to the CMIP3 data with terms such as "CMIP3 data," "the CMIP3 multi-model dataset," "the CMIP3 archive," or the "CMIP3 dataset."

    b. For Coupled Model Intercomparison Project phase 5 (CMIP5), the model output should be referred to as "the CMIP5 multi-model ensemble [archive/output/results/of simulations/dataset/ ...]." In publications, you should include a table (referred to below as Table XX) listing the models and institutions that provided model output used in your study. In this table, and as appropriate in figure legends, you should use the CMIP5 "official" model names found in "CMIP5 Modeling Groups and their Terms of Use": (http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf)

In addition, an acknowledgment similar to the following should be included in your publication:

"We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table XX of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals."

where "Table XX" of your paper should list the models and modeling groups that provided the data you used. In addition, it may be appropriate to cite one or more of the CMIP5 experiment design articles listed on the CMIP5 reference page.

2. Second, generally acknowledge this archive as "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. To reference specific information related to the Bias Correction and Spatial Disaggregation (BCSD) climate and hydrology information from the archive, please use the following references:

   a. For BCSD CMIP3 climate: Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy, 2007, "Fine-resolution climate projections enhance regional climate change impact studies," *Eos Trans. AGU*, 88(47), 504.

   b. For BCSD CMIP3 hydrology: Reclamation, 2011, *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*, Technical Memorandum No. 86-68210-2011-01, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado, 138 p.

   c. For BCSD CMIP5 climate: Provide citation to: Reclamation, 2013. *Downscaled CMIP3 and CMIP5 Climate Projections Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.* U.S. Department of the Interior, Bureau of Reclamation, 104 p., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

d. For BCSD CMIP5 hydrology: Reclamation, 2014, *Downscaled CMIP3 and CMIP5 Hydrology Projections – Release of Hydrology Projections, Comparison with Preceding Information and Summary of User Needs.* U.S. Department of the Interior, Bureau of Reclamation, 110 p., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf.

Executive Summary

The World Climate Research Programme (WCRP) develops global climate projections through its Coupled Model Intercomparison Project (CMIP) roughly every 5 to 7 years. These projections have informed Intergovernmental Panel on Climate Change Assessment Reports, as well as various research, assessment, and educational activities related to climate change processes and outcomes, mitigation, and adaptation. Such activities have primarily been served by CMIP phase 3 (CMIP3) results since 2007. During 2012-2013, WCRP released global climate projections from CMIP phase 5 (CMIP5); there was no phase 4. Both phases featured developing climate projections using a new generation of global climate models representing recent advancements in climate science. Also, for CMIP5, the projections are based on using an updated set of global greenhouse gas emissions scenarios.

This memorandum describes development of the two hydrology projection ensembles available at the Downscaled Climate and Hydrology Projections (DCHP) website and complements a similar technical memorandum describing downscaled climate projection development at the DCHP website (Reclamation, 2013). The ensembles respectively reflect CMIP3 and CMIP5 climate projections over the contiguous United States. The first ensemble was released in 2011 and was based on 112 CMIP3 climate projections that were first downscaled into localized climate projections across the contiguous U.S. using the Bias-Correction and Spatial Disaggregation (BCSD) technique (i.e., BCSD3 climate projections). These downscaled climate projections were then translated into hydrologic projections over only the Western U.S. portion of the domain (i.e., BCSD3 hydrology projections). The second ensemble is being released with this memorandum, and it was based on 234 CMIP5 climate projections, which were also downscaled using BCSD (i.e., BCSD5 climate) and then translated into hydrology using methods similar to the first effort but with several method updates and expansion of the domain to include the full contiguous U.S. (i.e., BCSD5(hydro)). Although there was a total of 231 BCSD5 climate projections that could be translated into hydrology, hydrologic modeling practicalities limited scope of this effort to a subset of 97 BCSD5 climate projections representing 31 CMIP5 climate models and 4 greenhouse gas emissions scenarios. The memorandum provides users of the DCHP website with a data overview, summary of data development, and cursory comparison of new and previously released hydrology projections. It also summarizes user needs for understanding these differences.

Hydrologic projection methods used for the BCSD3 and BCSD5(hydro) efforts are generally consistent. The Variable Infiltration Capacity hydrologic model (VIC) was used to simulate future hydrology for both efforts. Basin VIC

applications featured the same level of calibration, with a few exceptions, and the technique used to time-disaggregate monthly BCSD climate projections into daily VIC weather inputs was mostly the same for both efforts. There were some method differences, including two that were relatively more significant. First, the **version** of VIC differed, with the work reported here taking advantage of several VIC model updates in VIC version 4.1.2 versus version 4.0.7 used for the earlier work. Second, the technique used to time-disaggregate monthly BCSD temperature projections into daily VIC inputs for minimum and maximum temperature was different. For the BCSD5 effort, these two VIC inputs were separately translated from respective monthly projections of mean daily-minimum and daily-maximum temperature. For the BCSD3 effort, only a monthly projection of mean daily-average temperature was available, necessitating an assumption that daily temperature limits warmed the same as daily-average temperature.

The effect of using the updated version of VIC on historical hydrologic simulation was evaluated and reported because this may be an important factor when interpreting differences in BCSD3 and BCSD5 hydrology projections, along with other important factors such as use of BCSD5 climate, rather than BCSD3 climate, and the other method differences referenced above. Generally speaking, the effect of version updating on simulated long-term water balance (annual mean runoff) was found to be small compared to the effect on runoff seasonality (monthly mean runoff) and runoff variability.

The BCSD5(hydro) ensemble shows hydroclimate changes (i.e., temperature, precipitation, and runoff) that are generally similar to the ones from BCSD3 across the contiguous U.S. However, there are some region-specific differences that may be important for localized study, including BCSD5(hydro) projecting relative to BCSD3 greater warming to the North, regions of more increased precipitation change in the West and Great Plains (although varying by season), and differences in runoff change that more closely follow those found for precipitation than for temperature. On warming, the BCSD5 ensemble features a larger range, compared to BCSD3, because it represents four greenhouse gas emission scenarios having a larger range of emissions compared to the ones underlying the BCSD3 effort. At this time, explanations for these differences are not available, and attributing them to various potential causes remains a matter of research. Some of the questions being considered by the research community include:

- To what extent are these differences attributable to use of new global climate models, use of new climate forcing scenarios, and chosen downscaling technique?

- To what extent are they attributable to adjustments in the hydrologic projection methodology?

- To what extent are these attributions sensitive to the season of occurrence and underlying mechanisms?

Archive collaborators are engaged in research to better understand how these projections are sensitive to choices in downscaling and hydrologic projection technique, and they are exploring opportunities to improve projection methods in each of these areas to reduce uncertainty.

The following **Release Notes** apply to the release of the BCSD5 hydrology projections and complement those released in May 2013 for the BCSD5 climate projections:

- The CMIP5 climate, downscaled BCSD5 climate, and BCSD5 hydrology projections represent a new opportunity to improve our understanding of climate science and future hydrology impacts at the local scale, which evolves at a rapid pace. As new projection information is developed, the collaborators are taking active roles in evaluating and incorporating it, as appropriate, into ongoing activities.

- While future downscaled climate and hydrology projections based on CMIP5 may inform future analyses, many completed and ongoing studies have been informed by CMIP3 projections that were selected as best information available at the time of study. Even though CMIP5 is newer, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP3 climate projections. As such, CMIP5 projections may be considered an addition to (not a replacement of) the existing CMIP3 projections until a final decision that CMIP5 is superior is issued by the climate modeling community. Alternatively, CMIP5 projections may be used in place of CMIP3 projections if the goal is to represent the latest projection contributions from the climate science community.

- As of spring 2014, understanding how and why BCSD5 results differ from those in BCSD3 is still in a preliminary stage. The two general types of differences broadly relate to: (1) updates and other differences in the climate models used for CMIP5 and (2) the new set of climate forcing emissions scenarios. However, understanding those differences and their effects on regional climate, separately and together, is still ongoing.

- Reclamation (2013)[1] provides a cursory summary of differences between BCSD3 and BCSD5 climate projections over the contiguous U.S. Most of the differences are in the driving emission scenarios and changes to the CMIP5 climate models, making projections of temperature and precipitation somewhat different from those projected from CMIP3 climate model solutions. However, some differences are created by the downscaling technique, and separately from the bias-correction and spatial disaggregation portions of the technique. This means that the differences in BCSD climate information are similar to, but not precisely the same as, differences in CMIP climate information over the U.S. prior to downscaling.

- This technical memorandum provides a cursory summary of differences between BCSD5 and BCSD3 **hydrology** projections over the Western U.S. Most of the differences arise from variations in the BCSD5 climate projections of temperature and precipitation compared to BCSD3. However, additional differences arise from updates to the hydrology model used to generate projections and to how diurnal temperature range was projected, as well as other minor method differences.

- Collaborators are releasing the BCSD5 hydrology projections at the DCHP website with the goal of accelerating community understanding of the CMIP5 versus CMIP3 differences depicted here and promoting the use of a more complete representation of possible future climate and hydrology. Releasing the new information to the large user community will build shared awareness of CMIP5 versus CMIP3 similarities and differences, as well as enhance collaboration within the large community of users that is already familiar with CMIP3 to evaluate, explore, and diagnose the projections.

[1] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

Table of Contents

Page

Appendices

Tables

Table *Page*

Figures

1. Introduction

The World Climate Research Programme (WCRP) develops global climate projections through its Coupled Model Intercomparison Project (CMIP) roughly every 5 to 7 years. These projections have informed Intergovernmental Panel on Climate Change Assessment Reports, as well as various research, assessment, and educational activities related to climate change processes and outcomes, mitigation, and adaptation. Such activities have primarily been served by CMIP phase 3 (CMIP3) (Meehl et al., 2007) results since 2007. During 2012-2013, WCRP released global climate projections from CMIP phase 5 (CMIP5) (Taylor et al., 2011); there was no phase 4. Both phases featured developing climate projections using a new generation of global climate models representing recent advancements in climate science. Also, for CMIP5, the projections are based on using an updated set of global greenhouse gas (GHG) emissions scenarios, spanning a wider range of emissions possibilities compared to those underlying CMIP3.

This memorandum describes development of the two hydrology projection ensembles available at the Downscaled Climate and Hydrology Projections (DCHP) website, and it complements a similar technical memorandum describing downscaled climate projection development at the DCHP website (Reclamation, 2013). The ensembles respectively reflect CMIP3 and CMIP5 climate projections over the contiguous United States. The first ensemble was released in 2011 and was based on 112 CMIP3 climate projections that were first downscaled into localized climate projections (at grid scales of 1/8 degree, ~12 kilometers on a side) across the contiguous U.S. using the Bias-Correction and Spatial Disaggregation (BCSD) technique (Wood et al., 2002 and 2004; Reclamation, 2013). These results are referred to as BCSD3 climate projections. These downscaled climate projections were then translated into hydrologic projections over only the Western U.S. portion of the domain (Reclamation, 2011a), which resulted in BCSD3 hydrology projections. The second ensemble is being released with this memorandum and was based on 234 CMIP5 climate projections, also downscaled using BCSD (i.e., BCSD5 climate) and then translated into hydrology using methods similar to the first effort but with several method updates (National Center for Atmospheric Research [NCAR], 2014) and expansion of the domain to include the full contiguous U.S. (i.e., BCSD5(hydro)). Although there was a total of 231 BCSD5 climate projections that could be translated into hydrology, hydrologic modeling practicalities limited the scope of this effort to a subset of 97 BCSD5 climate projections representing 31 CMIP5 climate models and 4 GHG emissions scenarios. The memorandum provides users of the DCHP website with a data overview, summary of data development, and cursory comparison of new and old hydrology projections information. It also summarizes user needs for understanding these differences. For more information on the preceding BCSD climate projection downscaling effort, please refer to Reclamation (2013).

This memorandum is outlined as follows:

- **Section 2. About the Hydrologic Projections:** This section identifies climate projection ensembles from the CMIP3 and CMIP5 efforts, respectively, that were downscaled using BCSD and then translated into hydrology projections (i.e., BCSD3 and BCSD5 hydrology ensembles). It then summarizes key method differences between the BCSD3 and BCSD5 hydrology efforts (e.g., use of the Variable Infiltration Capacity [VIC] hydrology model[2] version 4.1.2 in the recent effort, rather than version 4.0.7, which was used in the prior effort). Appendix A provides complementary discussion. Finally, this section provides information on quality assurance, as well as release notes for the BCSD5 hydrology projections.

- **Section 3. Effect of Hydrology Model Update on Historical Hydrologic Simulation**: This section provides users a brief analysis on how hydrologic simulation results are sensitive to VIC model version. This analysis provides insight to users when interpreting differences between BCSD3 and BCSD5 hydrologic projection results over the Western U.S. where the two efforts geographically overlap.

- **Section 4. Comparing Projection Results from the BCSD3 and BCSD5 Efforts**: This section provides two cursory evaluations. First, differences in ensemble-mean hydroclimate change are evaluated for relatively large watersheds (for climate, the domain includes the contiguous U.S.; for hydrology, the domain is the Western U.S.). Second, differences in ensemble distribution of changes are evaluated for a set of 10 Western U.S. watersheds. The discussion on these points highlights key differences in results and identifies users' key questions and areas of research.

[2] http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

2. About the Hydrologic Projections

2.1 Assembling Downscaled Climate Projection Ensembles

The 112-member BCSD3 and 97-member BCSD5 hydrologic projections ensembles are listed in tables 1 and 2, respectively. The goals surrounding assembly of these ensembles are consistent with those described in Reclamation (2013): briefly, represent a large collection of CMIP3 and CMIP5 global climate models and GHG emission scenarios, respectively. For the downscaled climate ensembles, an additional goal involved including multiple projections from a given combination of climate model and GHG scenario, which was possible because some climate modeling groups were prolific in generating projections under a given GHG scenario that differed only by initial conditions. Interest in this goal was fueled by recognition that internal climate system variability is an important component in characterizing climate projection uncertainty (Hawkins and Sutton, 2009), especially for precipitation and at local to regional scales (Hawkins and Sutton, 2010; Deser et al., 2012), with problematic consequences for hydrology and water resources impact analyses (Harding et al., 2012).

For the BCSD3 hydrology efforts, table 1 shows that both goals were addressed as the 112-member ensemble represents 16 CMIP3 global climate models (GCMs), 3 of the GHG emissions scenarios used in CMIP3 (Intergovernmental Panel on Climate Change [IPCC], 2000), and multiple projections for some model-scenario combinations. For the BCSD5 climate effort, the 231-member ensemble represents 36 CMIP5 GCMs, 4 of the GHG emissions scenarios used in CMIP5 (van Vuuren et al., 2011), as well as multiple projections for some model-scenario combinations (table 2 in Reclamation, 2013[3]). However, when switching to the BCSD5 hydrology effort, the second goal of including multiple projections per model-scenario combination was not addressed because it was not feasible within the project scope to translate all of the BCSD5 climate ensemble into hydrology projections over the contiguous U.S. As a result, the BCSD5 hydrology effort selected one projection (the first) per model-scenario combination and was limited to a subset of 31 of the 36 BCSD5 climate GCMs simulating between one and four GHG emission scenarios.

[3] The BCSD5 climate projections were released in 2013, and the ensemble included three projections simulated by the Beijing Normal University - Earth System Model (BNU-ESM) for RCPs 2.6, 4.5, and 8.5, respectively. In 2014, errors in BNU-ESM precipitation reporting were identified by College of Global Change and Earth System Science, Beijing Normal University (Rupp, 2014). As a result, website access to downscaled BNU-ESM climate projections has been restricted. If the BNU-ESM climate projections are updated and translated into downscaled BCSD climate and hydrology projections, the resulting information will be added back and made available through the website.

Table 1. BCSD CMIP3 (BCSD3) Hydrology Projections Ensemble

WCRP CMIP3 Climate Modeling Group	WCRP CMIP3 Climate Model ID	Emissions Scenarios			Primary Reference
		SRES[1] A2 runs[2]	SRES A1b runs	SRES B1 runs	
Bjerknes Centre for Climate Research, Norway	BCCR-BCM2.0	1	1	1	Furevik et al., 2003
Canadian Centre for Climate Modeling and Analysis, Canada	CGCM3.1 (T47)	1-5	1-5	1-5	Flato and Boer, 2001
Meteo-France/Centre National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1	Salas-Melia et al., 2005
Commonwealth Scientific and Industrial Research Organization, Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	Gordon et al., 2002
U.S. Department of Commerce/NOAA/ Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1	Delworth et al., 2006
U.S. Department of Commerce/NOAA/ Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	1	1	1	Delworth et al., 2006
NASA/Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1	Russell et al., 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	Diansky and Volodin, 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1	IPSL, 2005
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	MIROC3.2 (medres)	1-3	1-3	1-3	K-1 Model Developers, 2004
Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korean Meteorological Association, Germany/Korea	ECHO-G	1-3	1-3	1-3	Legutke and Voss, 1999
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM	1-3	1-3	1-3	Jungclaus et al., 2006
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1-5	1-5	1-5	Yukimoto et al., 2001
National Center for Atmospheric Research, USA	CCSM3	1-4	1-3, 5-7	1-7	Collins et al., 2006
National Center for Atmospheric Research, USA	PCM	1-4	1-4	2, 3	Washington et al., 2000

Table 1. BCSD CMIP3 (BCSD3) Hydrology Projections Ensemble

WCRP CMIP3 Climate Modeling Group	WCRP CMIP3 Climate Model ID	Emissions Scenarios			Primary Reference
		SRES[1] A2 runs[2]	SRES A1b runs	SRES B1 runs	
Hadley Centre for Climate Prediction and Research/Met Office, UK	UKMO-HadCM3	1	1	1	Gordon et al., 2000
Number of Hydrology Projections = 112		36	39	37	

[1] SRES = Special Report on Emissions Scenarios (IPCC, 2000); NASA = National Aeronautics and Space Administration, NOAA = National Oceanic and Atmospheric Administration.
[2] Runs reflect which CMIP3 historical simulation was used to initialize the given future projection. Such correspondence is indicated at: http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.

Table 2. BCSD CMIP5 (BCSD5) Hydrology Projections Ensemble

WCRP CMIP5 Climate Modeling Group[1]	WCRP CMIP5 Climate Model ID	Emissions Scenarios			
		RCP 2.6 runs[2]	RCP 4.5 runs	RCP 6.0 runs	RCP 8.5 runs
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	ACCESS1-0		1		1
Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	1	1	1	1
	BCC-CSM1-1-M		1		1
Canadian Centre for Climate Modelling and Analysis	CanESM2	1	1		1
National Center for Atmospheric Research	CCSM4	1	1	1	1
Community Earth System Model Contributors	CESM1-BGC		1		1
	CESM1-CAM5	1	1	1	1
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC-CM		1		1
Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5		1		1
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence	CSIRO-Mk3-6-0	1	1	1	1

Table 2. BCSD CMIP5 (BCSD5) Hydrology Projections Ensemble

WCRP CMIP5 Climate Modeling Group[1]	WCRP CMIP5 Climate Model ID	Emissions Scenarios			
		RCP 2.6 runs[2]	RCP 4.5 runs	RCP 6.0 runs	RCP 8.5 runs
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-g2	1	1		1
The First Institute of Oceanography, State Oceanic Administration, China	FIO-ESM	1	1	1	1
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	1	1	1	1
	GFDL-ESM2G	1	1	1	1
	GFDL-ESM2M	1	1	1	1
NASA Goddard Institute for Space Studies	GISS-E2-H-CC		1		
	GISS-E2-R	1	1	1	1
	GISS-E2-R-CC		1		
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HadGEM2-AO	1	1	1	1
	HadGEM2-CC		1		1
	HadGEM2-ES	1	1	1	1
Institute for Numerical Mathematics	INM-CM4		1		1
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	1	1	1	1
	IPSL-CM5B-LR		1		1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	1	1	1	1
	MIROC-ESM-CHEM	1	1	1	1
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	1	1	1	1
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR	1	1		1
	MPI-ESM-MR	1	1		1
Meteorological Research Institute	MRI-CGCM3	1	1		1
Norwegian Climate Centre	NorESM1-M	1	1	1	1
Number of Hydrology Projections = 97		21	31	16	29

Note: [1]http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf.
[2] Runs reflect X from a given CMIP5 projection's rXi1p1 identifier, defined at: http://cmip-pcmdi.llnl.gov/cmip5/docs/cmip5_data_reference_syntax_v0-25_clean.pdf.

2.2 Hydrologic Projection Methods

The VIC model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997) was used to simulate hydrologic projections in both efforts. Other hydrology models could have been used to support projections development, and hydrology model response to climate change is sensitive to choices in model structure (Vaze et al., 2010; Singh et al., 2011; Vano et al., 2012), model parameter estimation (Merz et al., 2011; Bastola et al., 2011; Mendoza et al., 2014), and meteorological forcing data used to guide model development (Mizukami et al., 2014; Elsner et al., 2014). VIC-based BCSD5 hydrologic projections are being released to complement those associated with BCSD3 that are already available at the archive. Collaborators[4] are also exploring the issue of hydrologic projection sensitivity to these choices and the potential to represent these sensitivities in future website updates, potentially through application of multi-model hydrologic projections and/or multi-parameterizations of a single hydrologic model.[5]

Appendix A summarizes methods used to develop hydrology projections and includes descriptions of hydrologic model selection, the selected VIC model, and its applications across the contiguous U.S. In addition, it summarizes procedures used to develop BCSD hydrology projections reliant on time-disaggregation of monthly BCSD climate projections into daily VIC weather inputs. Appendix A also discusses routing of gridded VIC simulation runoff into streamflow at locations of interest for BCSD3 outputs. Aside from the differences in geographic extent of the hydrologic analysis (Western U.S. for BCSD3 versus contiguous U.S. for BSCD5) and input climate projections (CMIP3 versus CMIP5), methodologies used for the BCSD3 and BCSD5 hydrology efforts are consistent with two major exceptions (appendix A):

- **Hydrology Model Updates:** The BCSD3 and BCSD5 hydrology efforts used VIC version 4.0.7 and version 4.1.2, respectively. Version 4.1.2 improves upon 4.0.7 in several ways. Major science changes include an update of the MT-CLIM6 forcing disaggregation functions from MT-CLIM version 4.2 (Thornton and Running, 1999) to include elements of version 4.3 (Thornton et al., 2000) that lead to better accounting for snow albedo and snow simulation in humid climates, an improved calculation of

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[4] Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, NCAR, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and USGS.

[5] See *Development of Methods to Assess the Hydrological Impacts of Climate Change over the Contiguous United States* at: http://www.usbr.gov/research/climate/projects.html.

[6] MT-CLIM refers to the software program developed by the University of Montana Numerical Terradynamic Simulation Group to address the problem of estimating daily near surface meteorological parameters from nearby observations, tailored for application in mountainous terrain.

the soil thermal profile, the dynamic representation of lakes and wetlands as a separate land cover class, and the addition of organic soils. In addition, several interface changes and bug fixes were made. Most of the remaining improvements were made in the context of simulations at high latitudes (Arctic) and were not relevant for this project. Section 3 shows the aggregate effects of using version 4.1.2 versus 4.0.7 on historical hydrology simulation. Additional information on version updates is available at the University of Washington's VIC webpage.7

- **Projecting Daily Temperature Range**: VIC model applications are developed to simulate hydrology on a daily time step. This requires that preparation of future climate daily weather inputs be consistent with monthly BCSD climate projections using a time-disaggregation technique (appendix A). This technique was the same for both efforts, except for one application difference for temperature. For the BCSD3 effort, the technique was applied to BCSD projections of monthly-mean daily-average temperature, which required an assumption that the change in daily-average temperature equaled change in daily minimum and maximum temperature, implying no projected change in diurnal temperature range relative to historical variations. For BCSD5, this assumption was unnecessary because the technique was applied to BCSD5 projections of the monthly-mean values for daily-minimum and daily-maximum temperature (Reclamation, 2013), which permitted the future diurnal temperature range to change consistently with future climate projections.

Other notable differences:

- For the Western U.S. domain of geographic overlap, the VIC regional applications (i.e., files describing basin characteristics and soil parameters) were the same, except for several sub-basins in the upper Rio Grande above Elephant Butte Reservoir, New Mexico, where parameters had been refined between the BCSD3 and BCSD5 efforts.[8]

- During the BCSD5 effort, NCAR briefly explored refining the VIC applications through an objective recalibration of soil parameters (NCAR, 2014). These recalibrations led to improved model performance for nearly three dozen small watersheds but did not provide a sufficient basis for implementing regionally consistent upgrades to the VIC parameter

[7] http://www.hydro.washington.edu/Lettenmaier/Models/VIC/.

[8] Parameter refinement occurred during Reclamation Science & Technology project 8990, "Investigation of Climate Change Impact on Reservoir Capacity and Water Supply Reliability." Project information is at: http://www.usbr.gov/research/projects/detail.cfm?id=8990. Documentation on this calibration effort is incomplete. For information, contact Victor Huang (vhuang@usbr.gov) or Paula Makar (pmakar@usbr.gov).

sets. Consequently, the original parameter sets used in the BCSD3 effort were retained for the BCSD5 simulations, in support of the objective of maintaining application consistency across the two efforts.

Finally, appendix B provides a summary of frequently asked questions associated with these hydrologic projections, based on collaborators' recent experience serving BCSD3 hydrology to websites users. There is also a "Frequently Asked Questions" page addressing downscaled climate and hydrology projections data on the website.[9]

2.3 Quality Assurance

Quality assurance measures were implemented prior to production to ensure code reproducibility, during production to verify quality of input and output data files, and after production to verify the integrity of final products. The forcing disaggregation codes, hydrology and routing model, and data post-processing codes (e.g., to translate VIC output into netCDF format) were largely the same in both the BCSD3 and BCSD5 hydrology efforts, with exceptions noted in section 2.2. The temperature disaggregation approach upgrade for the BCSD5 effort was verified prior to the effort. Most additional coding for the BCSD5 effort related to adapting and implementing these methods for efficient execution on the NCAR Yellowstone high performance computing resource.

In both efforts, many checks were performed to ensure that the VIC forcing generation process and the VIC modeling code were properly applied and that the hydrology projections were developed as intended. First, prior to production, the VIC forcing generation code and modeling code were compiled and run on the production platform to validate that results were as expected. During production, checks were performed to ensure that no errors were reported during the forcing generation and VIC simulation processes, and to ensure that the correct number and size of output files were being produced. After production, the daily forcing data were aggregated to monthly and compared to the BCSD climate monthlies to ensure that there were no problems encountered during the VIC forcing generation process. These matched almost exactly, except for rare cases where BCSD monthly average daily-maximum temperature values were less than BCSD monthly average daily-minimum temperature values (which only occurred during BCSD5 hydrology projections development and is described in appendix A.3.1). Other checks were made regarding the integrity of the final netCDF files produced. These checks included making sure the number of grid cells was correct, as well as the number of expected missing values. The multi-stage processing of outputs from daily to monthly timestep, from ascii to netCDF

[9] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/faq.html.

format, and from the 1/8th degree grid to Hydrologic Unit Class 4 (HUC4) spatial units (http://water.usgs.gov/GIS/huc.html) provided multiple opportunities to detect data errors. For the BCSD5 effort, sample fields of spatial results at each stage of processing were selected at random for visualization to assess completeness and plausibility (e.g., realistic ranges and expected spatial distributions). All streamflow projections (appendix A) were plotted for visualization, and basin-average projections of temperature, precipitation, and total runoff in HUC4 spatial units were also plotted. Collectively, these quality control measures prior to, during, and after production indicate that the disaggregation and VIC forcing generation and modeling process were implemented as intended. That said, all uses of these projections are predicated on the following disclaimer (also shown on the DCHP website's home page):

> *"These projections are being made available for the convenience of interested persons. The content developers (Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Reclamation, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey) believe the information to be correct representations of potential high-resolution climate/ hydrologic variations and changes subject to the limitations of the CMIP3 and CMIP5 global climate simulations and of the downscaling methods utilized. However, human and mechanical errors remain possibilities. Therefore, the content developers do not guarantee the accuracy, completeness, timeliness, or correct sequencing of the information. Also, neither the content developers, nor any of the sources of the information shall be responsible for any errors or omissions, or for the use or results obtained from the use of this information."*

2.4 Release Notes for BCSD5 Hydrology

At the time of this DCHP website release, the following notes apply to the release of the BCSD5 hydrology projections and complement those released in May 2013 for the BCSD5 climate projections:

- The CMIP5 climate, downscaled BCSD5 climate, and BCSD5 hydrology projections represent a new opportunity to improve our understanding of climate science and future hydrology impacts at the local scale, which evolves at a rapid pace. As new projection information is developed, the collaborators are taking active roles in evaluating and incorporating it, as appropriate, into ongoing activities.

- While future downscaled climate and hydrology projections based on CMIP5 may inform future analyses, many completed and ongoing studies have been informed by CMIP3 projections that were selected as best information available at the time of study. Even though CMIP5 is newer, it has not been determined to be a better or more reliable source of climate projections compared to existing CMIP3 climate projections. As such, CMIP5 projections may be considered an addition to (not a replacement of) the existing CMIP3 projections until a final decision that CMIP5 is superior is issued by the climate modeling community. Alternatively, CMIP5 projections may be used in place of CMIP3 projections if the goal is to represent the latest projection contributions from the climate science community.

- As of spring 2014, understanding how and why BCSD5 results differ from those in BCSD3 is still in a preliminary stage. The two general types of differences broadly relate to: (1) updates and other differences in the climate models used for CMIP5 and (2) the new set of climate forcing emissions scenarios. However, understanding those differences and their effects on regional climate, separately and together, is still ongoing.

- Reclamation (2013) provides a cursory summary of differences between BCSD3 and BCSD5 **climate** projections over the contiguous U.S. Most of the differences are in the driving emissions scenarios and changes to the CMIP5 climate models, making projections of temperature and precipitation somewhat different from those projected from CMIP3 climate model solutions. However, some differences are created by the downscaling technique, and separately from the bias-correction and spatial disaggregation portions of the technique. This means that the differences in BCSD climate information are similar to, but not precisely the same as, differences in CMIP climate information over the U.S. prior to downscaling.

- This technical memorandum provides a cursory summary of differences between BCSD5 and BCSD3 **hydrology** projections over the Western U.S. Most of the differences arise from variations in the BCSD5 climate projections of temperature and precipitation compared to BCSD3. However, additional differences arise from updates to the hydrology model used to generate projections, how diurnal temperature range was projected, and other minor method changes.

- Collaborators are releasing the BCSD5 hydrology projections at the DCHP website with the goal of accelerating community understanding of the CMIP5 versus CMIP3 differences depicted here and of promoting the use of more complete representation of possible future climate and hydrology. Releasing the new information to the large user community will build shared awareness of CMIP5 versus CMIP3 similarities and differences, as well as enhance collaboration within the large community of users already familiar with CMIP3 to evaluate, explore, and diagnose the projections.

3. Effect of Hydrology Model Update on Historical Simulation

BCSD5 hydrology projections were developed using a more recent version of VIC compared to that used for the BCSD3 effort. This section describes how version updates can affect historical simulation results. The objectives of this section are to orient the reader on the level of change for various basins focusing on the Western U.S., as well as to alert the reader that this change in historical simulation is a factor when interpreting differences in projected hydrologic trend. However, it is only one factor among a number of important differences such as use of BCSD5 climate rather than BCSD3 climate and the differences in hydrologic projection methodology (section 2.3).

To assess the effect of hydrology model update, daily historical simulation results using both model versions are statistically summarized for a set of Western U.S. basins featuring different hydroclimates. Both sets of results were based on simulation forced by a common gridded daily historical meteorology (Maurer et al. 2002). Several period statistics during 1950-1999 were then computed: annual and monthly mean runoff, and annual and monthly standard deviation. Before proceeding to the evaluation, two considerations are provided that may affect interpretation of this section's results and their significance.

1. Differences in historical hydrology simulation are not always exactly related to differences in projected hydrologic response to climate change. In other words, while use of the updated VIC version may lead to different historical simulation statistics (i.e., a different historical "baseline" from which hydrologic impacts are projected into the future), it remains to be investigated how the version updates affect VIC's simulated response to a given climate change. Diagnosing and comparing the model's response to climate change between these two VIC versions was outside the scope of this effort.

2. Users may be interested in how either VIC version simulates historical hydrology relative to observed hydrology or historically estimated natural flow. This comparison was also outside the scope of this effort; however, the BCSD5 data resources at the DCHP website will provide sufficient historical simulation outputs to enable users to investigate model performance for locations of interest. As is typical for hydrology simulations, both sets of simulated runoff contain errors relative to observed runoff due to several potential factors:

a. Errors between actual and estimated historical meteorology (Maurer et al. 2002)
b. Errors in hydrology model structure (e.g., VIC is one of many options for surface water hydrology modeling) or physics

c. Parameter uncertainty (i.e., rather than calibrate VIC apps at small-basin resolution, these applications were only calibrated to reproduce total runoff from relatively large watersheds (e.g., generally at HUC4 resolution (give or take)) within a HUC2 unit for which the VIC app was being built, leaving less refined parameter estimates in much of the modeled domain)

d. Errors in observing streamflow

Identifying efficient methods for identifying well calibrated parameter estimates at a fine spatial resolution for large geographic domains remains an area of active research among collaborators.[5]

3.1 Evaluation Basins

Runoff sensitivities to hydrologic model updates were evaluated in 43 basins distributed around the Western U.S. (see figure 1 and table 3). These basins represent a diverse set of hydroclimates that range from wetter and cooler in the northwest and northern Great Plains, to drier and warmer in the southwest, to wetter and warmer in the southern Great Plains (Reclamation 2011a; 2011b). Most of these basins feature snowmelt-dominated headwaters. The spatial size of these basins varies considerably, from roughly HUC 8 to HUC 2.[10] The geographic distribution of these basins was constrained to the Western U.S. given the geographic overlap of the BCSD3 and BCSD5 efforts.

[10] http://water.usgs.gov/GIS/huc.html.

Figure 1. Basins evaluated for runoff sensitivity to hydrologic model change (see table 3 for basins legend).

Table 3. Basins Evaluated for Runoff Sensitivity to Hydrologic Model change (see figure 1 or map of basin boundaries).

Number	State	River Basin and Outlet Location	Latitude	Longitude
1	OR	Williamson R. below Sprague River	42.56	-121.84
2	CA	Klamath River below Iron Gate Dam	41.93	-122.44
3	CA	Klamath River below Seiad Valley	41.85	-123.23
4	CA	Klamath River at Orleans	41.30	-123.53
5	CA	Klamath River near Klamath	41.51	-123.98
6	ID	Snake River at Brownlee Dam	44.84	-116.90
7	WA	Columbia River at Grand Coulee	47.97	-118.98
8	OR	Columbia River at the Dalles	45.61	-121.17
9	WA	Yakima River at Parker	46.51	-120.45
10	OR	Deschutes River near Madras	44.73	-121.25
11	ID	Snake River near Heise	43.61	-111.66
12	MT	Flathead River at Columbia Falls	48.36	-114.18
13	AZ	Colorado River at Lees Ferry	36.86	-111.59
14	CA	Colorado River above Imperial Dam	32.88	-114.47
15	UT	Green River near Greendale	40.91	-109.42
16	CO	Colorado River near Cameo	39.24	-108.27
17	CO	Gunnison River near Grand Junction	38.98	-108.46
18	UT	San Juan River near Bluff	37.15	-109.86
19	CA	Sacramento River at Freeport	38.46	-121.50
20	CA	Sacramento River at Bend Bridge (Red Bluff)	40.26	-122.22
21	CA	Feather River at Oroville	39.52	-121.55
22	CA	San Joaquin River near Vernalis	37.68	-121.27
23	CA	Stanislaus River at New Melones Dam	37.95	-120.53
24	MT	Missouri River at Canyon Ferry Dam	46.65	-111.73
25	MT	Milk River at Nashua	48.13	-106.36
26	CO	Platte River (South Fork) near Sterling	40.62	-103.19
27	NE	Missouri River near Omaha	41.26	-95.92
28	CO	Rio Grande near Lobatos	37.08	-105.76
29	NM	Rio Chama near Abiquiu	36.32	-106.60
30	NM	Rio Grande near Otowi	35.88	-106.14
31	NM	Rio Grande at Elephant Butte Dam	33.16	-107.19
32	NM	Pecos River at Damsit No 3 (Carlsbad)	32.51	-104.33
33	CA	Little Truckee River below Boca Dam	39.39	-120.10
34	CA	Carson River (West Fork) at Woodfords	38.77	-119.83
35	CA	Sacramento-San Joaquin Delta inflow	38.06	-121.86
36	CA	San Joaquin River at Friant Dam	37.00	-119.71
37	CA	Truckee River at Farad Gage (stateline)	39.45	-120.01
38	NV	Truckee River at Nixon Gage	39.78	-119.34
39	NV	Carson River at Ft Churchill Gage	39.33	-119.15
40	MT	Big Horn River at Yellowtail Dam	45.31	-107.96
41	NE	Platte River (North Fork) at Lake McConaughy	41.21	-101.64
42	CA	American River at Fair Oaks	38.64	-121.23
43	CA	Tulare-Buena Vista Lakes basin	36.05	-119.72

3.2 Differences in Historical Simulated Runoff

To begin understanding runoff sensitivity to VIC version updates, we first focus on one basin: the Colorado River at Lees Ferry, Arizona. Figure 2 shows correlation of simulated monthly and annual runoff volumes using VIC version 4.1.2 versus version 4.0.7. In terms of correlation, it is clear that the two sets of results have high agreement; however, the scatter shows that version updates do have some effect, and more enhanced effect for monthly volumes than annual volumes. For lower flows, paired model results from the two versions are nearer to the 1:1 line (i.e., the line that would exist, shown as black line, if results from version 4.1.2 equaled results from version 4.0.7) than for higher flows for which VIC version 4.1.2 appears to simulate more runoff. This high-flow difference is less evident when monthly volumes are aggregated to annual volumes. The fact that some difference appears is not surprising considering that parameter estimates were developed using VIC version 4.0.7 or earlier, and that differences might have been reduced if parameter calibration was performed separately for both VIC versions. As mentioned in section 2.3, recalibrating the VIC applications' soil parameter estimates was explored by NCAR but eventually not included in the final effort due to the overarching objective of maintaining consistency with BCSD3 (NCAR, 2014).

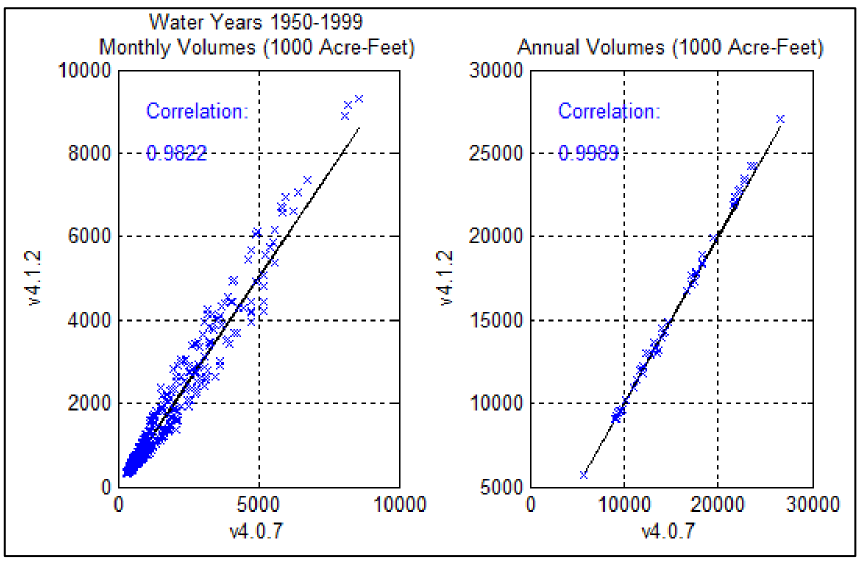

Figure 2. Monthly and annual historical runoff volumes simulated at Colorado River at Lees Ferry, Arizona, using VIC versions 4.1.2 and 4.0.7. Black line is the 1:1 line where version 4.1.2 results equal the results from version 4.0.7.

Figure 3 shows the effect of version update on mean simulation of monthly volumes (bars) and annual volume (annotated in figure panel). During the colder months of October through February; simulated runoff is similar using either version, but with perhaps slightly less runoff using version 4.1.2. From March to

May, version 4.1.2 simulates less runoff; and during June to September, it simulates more runoff, which diminishes by September. Diagnosing these results to understand which version changes are leading to this shift in runoff seasonality is an exercise left for the reader. However, an initial assessment suggests differences in the two model versions' snow hydrology and snowmelt runoff generation such that model version 4.1.2 holds more snowpack later in the season, resulting in some shift in runoff timing relative to 4.0.7. Based on the major model changes listed in appendix A, this effect may be caused by VIC version 4.1.2's use of the MT-CLIM version 4.3 functions for disaggregating meteorological forcing data in mountainous terrain (Thornton et al., 2000) versus use of MT-CLIM version 4.2 that was incorporated into VIC version 4.0.7 (Thornton and Running, 1999). How this effect translates into a modulated VIC sensitivity to climate change remains an open question, and exploring it was outside the scope of this effort. For example, users might explore whether the model's runoff seasonality sensitivity to climate change is muted using version 4.1.2 relative to 4.0.7, if version 4.1.2 is showing later spring snowpack retention. Finally, figure 3 reports the mean annual runoff volumes using both versions. For this basin, the effects on runoff seasonality lead to a 1.1 percent increase in mean annual runoff (i.e., from 15.36 million acre-feet [MAF] using version 4.0.7 to 15.53 MAF using version 4.1.2, which is minor compared to how version 4.0.7 and 4.1.2 mean-annual values are respectively 4.5 and 5.6 percent greater than estimated 1950-1999 natural runoff based on observations (14.7 MAF)[11]).

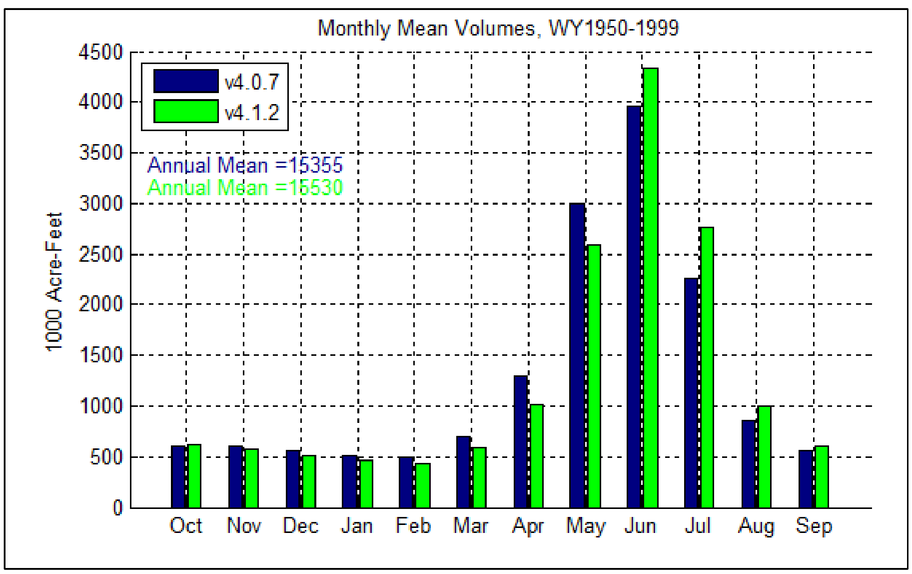

Figure 3. Mean monthly historical runoff volumes simulated at Colorado River at Lees Ferry, Arizona, using VIC versions 4.1.2 and 4.0.7.

[11] http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.

A quantified view of runoff sensitivities to version changes for all 43 evaluation basins is provided by the combination of table 4, which reports mean monthly and annual volumes for version 4.0.7, and table 5, which reports percentage difference in mean monthly and annual volumes between versions 4.0.7 and 4.1.2. Thus, to judge the significance of differences for any of the 43 evaluation basins, the reader should consider results from both tables. Table 6 complements those results by showing the sensitivity of the standard deviations in these volumes to model updates (but without showing baseline standard deviations). The standard deviation is an important parameter for the historical simulations because it provides a statistical context for interpreting the significance of future changes.

Focusing on sensitivity of mean volumes (table 5), results show that many of the basins exhibit sensitivities similar to the sensitivities shown for the Colorado River at Lees Ferry, Arizona, where sensitivity in any single month is typically a much greater percentage than it is for mean annual volume. The larger monthly sensitivities may arise from relatively small incremental flow changes occurring in low flow months (e.g., cool season months for snowmelt dominated basins). Often, positive and negative differences partially cancel each other out, as was seen with the timing of snowmelt in the Colorado River at Lees Ferry (figure 3), as well as for flow projected at the Fort Churchill gage. While the annual sensitivities to model change result mostly in small positive differences, as was seen with the Colorado River at Lees Ferry, some sub-basins within the Missouri River Basin (No. 25, 26, 27, 40, and 41) and Rio Grande Basin (No. 30 and 31) showed substantial negative annual runoff sensitivities to version change (-11 to -23 percent).

Sensitivity of the standard deviation in monthly and annual volumes (table 6) shows how simulated runoff variability was affected by model changes. If the sensitivity is positive, use of version 4.1.2 is leading to greater simulated variability. Initial review of results shows that variability in runoff sensitivity varies by basin and that direction of sensitivity for variability is not always the same as that for mean volumes (table 5). For example, while several sub-basins of the Missouri River Basin and Rio Grande Basin were identified earlier as having substantial negative mean runoff sensitivities, some of these same basins expressed significant positive sensitivity in runoff variability, while other basins showed significant negative sensitivity. Diagnosing how model changes lead to differences in runoff variability is another exercise left for the reader.

In summary, this section illustrates how model changes affected the historical hydrologic baseline from which future hydrology projections are developed. Generally speaking, the change in simulated long-term water balance (annual mean runoff) was generally small compared to effects on mean runoff seasonality (monthly mean runoff) and seasonal runoff variability. The results of this section are complemented by figures included in appendix C, which includes replications of figure 2 and figure 3 for all 43 evaluation basins.

Table 4. Simulated Mean Monthly and Annual Historical Runoff Volumes in 43 Western U.S. Basins Using VIC Version 4.0.7

Basin Number, State Location, and Outlet	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
VIC 4.0.7 Mean Volume, WY1951-1999 (1000 TAF)													
1, OR, Williamson R. below Sprague River	10	18	28	25	37	67	77	51	23	11	7	6	361
2, CA, Klamath River below Iron Gate Dam	28	61	106	112	154	246	330	331	261	117	24	15	1784
3, CA, Klamath River below Seiad Valley	54	119	240	328	430	558	578	531	413	176	40	24	3493
4, CA, Klamath River at Orleans	82	230	529	723	843	1039	973	841	623	240	53	31	6208
5, CA, Klamath River near Klamath	150	497	1293	1801	2046	2252	1791	1300	872	311	69	47	12428
6, ID, Snake River at Brownlee Dam	866	929	906	890	917	1522	2289	3403	3783	2350	1044	822	19721
7, WA, Columbia River at Grand Coulee	4142	3811	3278	2978	2829	3809	6054	11779	19604	16462	6578	4313	85638
8, OR, Columbia River at the Dalles	7088	7238	6711	6172	5994	8213	11946	20615	31686	28277	12122	7194	153260
9, WA, Yakima River at Parker	166	229	179	151	166	293	423	598	730	596	231	129	3891
10, OR, Deschutes River near Madras	139	201	230	227	246	301	305	393	482	373	175	124	3196
11, ID, Snake River near Heise	115	108	97	91	86	114	252	788	1287	648	152	106	3843
12, MT, Flathead River at Columbia Falls	277	264	219	199	181	225	450	1098	1793	1387	442	277	6811
13, AZ, Colorado River at Lees Ferry	600	601	551	516	492	702	1292	2990	3953	2255	850	552	15355
14, CA, Colorado River above Imperial Dam	663	695	666	633	626	863	1318	2675	4043	2997	1136	658	16972
15, UT, Green River near Greendale	80	72	64	59	57	83	140	318	496	329	132	80	1912
16, CO, Colorado River near Cameo	127	130	132	123	108	135	252	742	1125	537	205	127	3743
17, CO, Gunnison River near Grand Junction	98	95	85	78	73	111	217	505	620	270	108	82	2340
18, UT, San Juan River near Bluff	79	86	80	72	65	87	158	381	485	228	91	65	1876
19, CA, Sacramento River at Freeport	320	872	2381	4286	4710	4565	3321	2255	1209	386	118	94	24517
20, CA, Sacramento River at Bend Bridge (Red Bluff)	124	338	902	1539	1731	1692	1216	741	405	142	53	42	8926
21, CA, Feather River at Oroville	62	150	407	681	739	835	699	531	237	48	12	12	4412
22, CA, San Joaquin River near Vernalis	60	178	373	704	816	936	1064	1420	1058	443	97	48	7198
23, CA, Stanislaus River at New Melones Dam	9	34	80	152	157	174	191	250	166	66	12	5	1296
24, MT, Missouri River at Canyon Ferry Dam	204	192	182	169	154	222	508	1153	1294	634	256	199	5168
25, MT, Milk River at Nashua	121	87	76	71	87	158	208	358	477	386	171	144	2342
26, CO, Platte River (South Fork) near Sterling	85	73	65	58	51	74	117	273	409	241	159	103	1709
27, NE, Missouri River near Omaha	2799	2094	1625	1458	1480	2577	3981	5910	7932	7284	4140	2951	44230
28, CO, Rio Grande near Lobatos	113	102	100	96	84	91	122	301	348	193	137	119	1804
29, NM, Rio Chama near Abiquiu	14	17	17	18	20	37	58	64	38	20	17	13	331
30, NM, Rio Grande near Otowi	158	157	147	143	135	181	266	460	440	247	194	162	2691
31, NM, Rio Grande at Elephant Butte Dam	221	211	204	200	190	239	309	500	499	323	274	234	3404
32, NM, Pecos River at Damsit No 3 (Carlsbad)	137	99	94	91	85	92	87	105	112	138	170	167	1377
33, CA, Little Truckee River below Boca Dam	2	5	9	9	10	16	27	46	43	18	3	1	189
34, CA, Carson River (West Fork) at Woodfords	0	1	2	2	2	4	11	27	22	9	1	0	81
35, CA, Sacramento-San Joaquin Delta inflow	435	1181	3132	5964	6681	6397	4937	3956	2424	900	245	168	36419
36, CA, San Joaquin River at Friant Dam	11	28	52	93	130	172	248	429	368	155	30	13	1729
37, CA, Truckee River at Farad Gage (stateline)	7	21	48	50	56	89	143	237	190	73	10	3	928
38, NV, Truckee River at Nixon Gage	10	27	57	62	73	111	169	267	215	85	13	5	1095
39, NV, Carson River at Ft Churchill Gage	6	15	30	34	47	77	99	127	100	43	10	5	593
40, MT, Big Horn River at Yellowtail Dam	190	171	156	139	126	177	348	792	971	583	290	201	4144
41, NE, Platte River (North Fork) at Lake McConaughy	118	102	84	82	81	137	278	613	732	470	217	134	3050
42, CA, American River at Fair Oaks	29	97	296	508	513	482	392	345	200	68	11	7	2949
43, CA, Tulare-Buena Vista Lakes basin	54	121	266	483	604	708	758	937	650	254	73	48	4957

Table 5. Difference in Simulated Mean Monthly and Annual Historical Runoff Volumes in 43 Western U.S. Basin Using VIC Version 4.1.2 Rather than Version 4.0.7.

Basin Number, State Location, and Outlet	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Difference in Mean (VIC 4.1.2 Percentage Change from VIC 4.0.7)													
1, OR, Williamson R. below Sprague River	-5	-11	-8	-12	-14	-17	-8	31	33	-2	-5	-4	-2
2, CA, Klamath River below Iron Gate Dam	14	-2	-10	-16	-15	-10	3	31	24	6	10	25	7
3, CA, Klamath River below Seiad Valley	10	-3	-11	-16	-13	-4	12	35	21	6	14	23	6
4, CA, Klamath River at Orleans	8	-4	-11	-14	-11	-1	16	35	19	3	8	21	5
5, CA, Klamath River near Klamath	4	-3	-8	-11	-7	3	18	35	18	-1	3	14	4
6, ID, Snake River at Brownlee Dam	-12	-15	-13	-11	-15	-28	-27	-15	6	11	-6	-11	-9
7, WA, Columbia River at Grand Coulee	2	-4	-5	-4	-6	-10	0	10	15	17	14	7	9
8, OR, Columbia River at the Dalles	-1	-7	-9	-7	-10	-16	-11	4	15	16	9	3	4
9, WA, Yakima River at Parker	-4	-12	-12	-8	-13	-24	-8	15	26	10	-5	-3	3
10, OR, Deschutes River near Madras	-11	-16	-17	-18	-20	-21	-9	6	14	8	-5	-10	-5
11, ID, Snake River near Heise	0	-6	-2	-1	-2	-9	-20	-14	13	29	12	3	5
12, MT, Flathead River at Columbia Falls	0	-8	-7	-6	-8	-13	-9	12	26	13	-3	0	9
13, AZ, Colorado River at Lees Ferry	4	-4	-7	-9	-11	-16	-21	-13	10	23	17	10	1
14, CA, Colorado River above Imperial Dam	5	-2	-7	-9	-12	-14	-19	-16	3	22	17	10	0
15, UT, Green River near Greendale	0	-8	-9	-12	-17	-25	-25	-17	-3	20	17	9	-3
16, CO, Colorado River near Cameo	14	6	1	-2	-4	-11	-20	-14	14	32	28	22	7
17, CO, Gunnison River near Grand Junction	0	-8	-8	-9	-11	-20	-24	-20	4	20	12	7	-4
18, UT, San Juan River near Bluff	6	-3	-7	-8	-9	-13	-21	-16	14	30	18	13	2
19, CA, Sacramento River at Freeport	-1	-4	-7	-7	-7	-2	14	30	17	-3	-4	0	2
20, CA, Sacramento River at Bend Bridge (Red Bluff)	-1	-4	-7	-7	-5	-1	11	27	14	-1	-1	1	1
21, CA, Feather River at Oroville	-1	-5	-10	-12	-14	-2	26	45	19	-12	-11	-1	5
22, CA, San Joaquin River near Vernalis	-4	-7	-9	-10	-8	-5	-5	5	22	10	-17	-7	1
23, CA, Stanislaus River at New Melones Dam	-7	-10	-13	-13	-12	-5	8	25	26	0	-32	-14	4
24, MT, Missouri River at Canyon Ferry Dam	-1	-5	-6	-6	-9	-20	-27	-10	22	18	5	0	1
25, MT, Milk River at Nashua	-18	-27	-30	-31	-48	-60	-50	-26	-6	-4	-11	-14	-22
26, CO, Platte River (South Fork) near Sterling	-12	-18	-23	-25	-26	-30	-30	-24	-4	3	-9	-11	-13
27, NE, Missouri River near Omaha	-11	-16	-22	-25	-36	-49	-46	-29	-14	-2	-5	-9	-19
28, CO, Rio Grande near Lobatos	-28	-26	-29	-35	-40	-43	-32	-5	37	15	-18	-27	-8
29, NM, Rio Chama near Abiquiu	-81	-53	-36	-40	-41	-19	22	70	100	-7	-81	-89	6
30, NM, Rio Grande near Otowi	-40	-38	-32	-37	-42	-39	-21	4	39	11	-31	-38	-12
31, NM, Rio Grande at Elephant Butte Dam	-31	-32	-29	-33	-36	-34	-20	4	35	13	-23	-29	-11
32, NM, Pecos River at Damsit No 3 (Carlsbad)	-6	-8	-13	-16	-14	-10	-9	-5	-3	-4	-5	-6	-8
33, CA, Little Truckee River below Boca Dam	-5	-16	-24	-37	-39	-35	2	44	27	2	-25	-2	8
34, CA, Carson River (West Fork) at Woodfords	-9	-20	-25	-50	-43	-49	-30	8	36	12	-21	-3	4
35, CA, Sacramento-San Joaquin Delta inflow	-2	-4	-7	-7	-6	-2	8	20	19	4	-10	-2	1
36, CA, San Joaquin River at Friant Dam	-4	-11	-12	-14	-11	-9	-9	1	21	12	-15	-9	1
37, CA, Truckee River at Farad Gage (stateline)	-5	-14	-23	-42	-45	-38	5	45	32	-3	-32	-11	8
38, NV, Truckee River at Nixon Gage	-5	-13	-22	-37	-41	-36	0	40	33	0	-24	-8	6
39, NV, Carson River at Ft Churchill Gage	-7	-16	-20	-29	-31	-26	-8	26	31	15	-3	-5	2
40, MT, Big Horn River at Yellowtail Dam	-12	-17	-19	-23	-29	-39	-43	-37	-20	-5	-6	-8	-22
41, NE, Platte River (North Fork) at Lake McConaughy	-21	-31	-38	-42	-45	-47	-46	-33	-10	-5	-17	-21	-23
42, CA, American River at Fair Oaks	-2	-4	-7	-7	-6	0	13	27	18	-6	-13	-1	3
43, CA, Tulare-Buena Vista Lakes basin	-3	-6	-6	-8	-7	-6	-9	-2	19	4	-15	-3	-2

Table 6. Difference in Simulated Standard Deviation of Monthly and Annual Historical Runoff Volumes in 43 Western U.S. Basin Using VIC Version 4.1.2 Rather than Version 4.0.7.

Basin Number, State Location, and Outlet	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Difference in Standard Deviation (VIC 4.1.2 Percentage Change from VIC 4.0.7)													
1, OR, Williamson R. below Sprague River	-3	-10	-3	-8	-11	-17	-14	27	68	5	-6	-7	-1
2, CA, Klamath River below Iron Gate Dam	1	-4	1	-12	-9	-4	0	31	27	-1	-19	11	2
3, CA, Klamath River below Seiad Valley	0	-4	-1	-7	-6	0	6	34	26	-4	-8	9	1
4, CA, Klamath River at Orleans	0	-5	-3	-5	-4	2	7	35	23	-5	-16	2	1
5, CA, Klamath River near Klamath	0	-3	-3	-4	-1	2	7	34	23	-7	-19	-1	1
6, ID, Snake River at Brownlee Dam	-7	-13	3	11	12	-30	-32	-19	7	21	10	-5	-3
7, WA, Columbia River at Grand Coulee	7	-4	-11	-8	-13	-12	6	11	19	20	16	14	15
8, OR, Columbia River at the Dalles	5	-6	-11	-2	-9	-21	-12	4	19	17	12	13	7
9, WA, Yakima River at Parker	-3	-7	-7	-10	-13	-21	-3	10	22	20	-8	-5	3
10, OR, Deschutes River near Madras	-6	-13	-11	-11	-14	-25	-7	10	16	12	4	6	-1
11, ID, Snake River near Heise	2	-9	0	10	6	-18	-26	-16	2	30	22	1	5
12, MT, Flathead River at Columbia Falls	-1	-4	-8	-6	-9	-15	1	20	20	17	-13	-5	6
13, AZ, Colorado River at Lees Ferry	1	-9	-13	-14	-16	-23	-21	-7	8	16	22	16	4
14, CA, Colorado River above Imperial Dam	4	-8	-12	-18	-21	-19	-17	-9	4	13	21	19	2
15, UT, Green River near Greendale	4	-5	-7	-10	-14	-33	-22	-13	-8	21	34	16	2
16, CO, Colorado River near Cameo	12	2	-6	-9	-12	-22	-21	-11	10	19	26	31	8
17, CO, Gunnison River near Grand Junction	-5	-12	-14	-14	-16	-24	-24	-16	0	17	14	9	3
18, UT, San Juan River near Bluff	-1	-14	-21	-21	-20	-25	-22	-5	-1	34	15	10	5
19, CA, Sacramento River at Freeport	-1	-3	-4	-5	-5	-2	-4	25	22	-3	-18	-2	0
20, CA, Sacramento River at Bend Bridge (Red Bluff)	-2	-2	-4	-3	-3	-2	-2	22	18	-5	-14	-1	0
21, CA, Feather River at Oroville	-1	-3	-4	-7	-7	-1	2	37	26	-9	-41	-1	2
22, CA, San Joaquin River near Vernalis	-6	-1	-7	-8	-7	-3	-2	-6	14	20	-12	-16	0
23, CA, Stanislaus River at New Melones Dam	-8	-3	-9	-10	-8	-3	-4	10	23	13	-22	-19	1
24, MT, Missouri River at Canyon Ferry Dam	-4	-7	-11	-7	-11	-31	-27	-10	16	24	7	-3	2
25, MT, Milk River at Nashua	-12	-31	-33	-44	-55	-71	-63	-26	-14	-2	-7	-11	-25
26, CO, Platte River (South Fork) near Sterling	-12	-14	-18	-23	-25	-31	-29	-24	-6	6	-3	-10	-9
27, NE, Missouri River near Omaha	-13	-21	-30	-32	-49	-51	-59	-37	-22	-7	-4	-10	-28
28, CO, Rio Grande near Lobatos	10	20	11	-1	-11	-16	-15	-8	19	46	13	10	14
29, NM, Rio Chama near Abiquiu	-33	15	33	28	11	8	40	51	100	88	-50	-65	34
30, NM, Rio Grande near Otowi	-5	4	20	15	-1	-10	7	9	24	53	11	-1	16
31, NM, Rio Grande at Elephant Butte Dam	-13	-6	4	2	-11	-14	9	16	23	52	4	-10	14
32, NM, Pecos River at Damsit No 3 (Carlsbad)	-10	-13	-20	-30	-27	-22	-17	-8	-6	-6	-8	-6	-11
33, CA, Little Truckee River below Boca Dam	-4	-8	-11	-16	-13	-17	22	31	24	6	-21	-11	3
34, CA, Carson River (West Fork) at Woodfords	-9	4	-14	-41	-20	-38	-14	2	26	20	-20	-3	2
35, CA, Sacramento-San Joaquin Delta inflow	-2	-2	-4	-5	-5	-2	-3	14	17	11	-14	-8	0
36, CA, San Joaquin River at Friant Dam	-4	-2	-9	-11	-8	-3	-5	-8	14	20	-6	-14	1
37, CA, Truckee River at Farad Gage (stateline)	-4	0	-8	-25	-20	-16	22	33	36	4	-32	-16	4
38, NV, Truckee River at Nixon Gage	-4	-2	-8	-24	-19	-19	15	30	36	6	-27	-12	2
39, NV, Carson River at Ft Churchill Gage	-9	-5	-8	-19	-14	-15	-13	18	25	17	6	-14	-1
40, MT, Big Horn River at Yellowtail Dam	-11	-17	-20	-24	-30	-40	-36	-27	-21	-2	5	-3	-16
41, NE, Platte River (North Fork) at Lake McConaughy	-15	-25	-34	-45	-41	-41	-47	-38	-17	-9	-9	-16	-28
42, CA, American River at Fair Oaks	-1	-1	-3	-5	-4	0	-2	20	22	-3	-28	-1	1
43, CA, Tulare-Buena Vista Lakes basin	-5	-2	-3	-7	-7	-4	-2	-6	12	19	-29	-10	-1

4. Comparing Projection Results from the BCSD3 and BCSD5 Efforts

For a brief summary of projected hydroclimate conditions in the BCSD3 and BCSD5(hydro) ensembles, refer to Reclamation (2011a) and NCAR (2014), respectively. The purpose of this section is to orient users on the more notable BCSD3 and BCSD5(hydro) climate change similarities and differences over the contiguous U.S., as well as related similarities and differences in runoff change over the Western U.S. The evaluations of this section consider only the 97-member BCSD5(hydro) ensemble, rather than the full 231-member BCSD5 climate ensemble (Reclamation, 2013). Therefore, this section shows some differences in BCSD3 climate change findings, compared to BCSD5 climate change findings shown in section 3 of Reclamation (2013). Two types of comparisons are offered:

1. **Ensemble-Mean Hydroclimate Change Over the Contiguous U.S.:** This first type of comparison leverages basin-level evaluations conducted during the BCSD5 hydrology effort (NCAR, 2014). It reveals geographic patterns of differences in ensemble-mean hydroclimate change, using the contiguous U.S. domain for evaluating differences in precipitation and temperature change, and it uses the BCSD3 hydrology effort's Western U.S. domain for evaluating differences in runoff change.

2. **Ensemble-Distribution of Hydroclimate Changes for 8 Western U.S. Basins**: This second type of comparison considers the ensemble distributions of climate and hydrologic change, which are important for users who want to know how projected change uncertainty differs between the ensembles.

To clarify, the precipitation and temperature evaluations are based on comparison of monthly BCSD3 and BCSD5 climate projections, and the runoff evaluation is based on comparison of VIC simulated hydrology translated from respective BCSD climate projections (section 2.2).

4.1 Ensemble-Mean Hydroclimate Change Over the Contiguous U.S.

The BCSD3 and BCSD5(hydro) gridded hydroclimate projections were spatially aggregated into hydrologic unit class[12] 4 (HUC4) projections (figure 4). For each HUC4 basin, changes in annual-average precipitation, temperature, and

[12] http://water.usgs.gov/GIS/huc.html

runoff were computed from 1950-1999 to three futures (2010-2039, 2040-2069, and 2070-2099). Then, for both ensembles, the ensemble-mean change was computed for each HUC4 for each future period. Finally, differences in ensemble-means by period and HUC4 were computed as displayed in figure 5.

- Temperature results show that change patterns for the BCSD5(hydro) and BCSD3 hydroclimate ensembles are broadly consistent, with ensemble-mean changes being within +/- 0.8 degrees Celsius (ºC) of one another during the 21st century (compared to ensemble-median warming of roughly 3 to 4 ºC by end of the 21st century in both ensembles varying by geographic location[13]). However, there are some differences. During the early 21st century, BCSD5(hydro) shows greater ensemble-mean warming throughout the domain and is more enhanced to the north. By the late 21st century, the sign of difference reverses, with less warming in BCSD5(hydro) occurring in the south but continued greater warming occurring in the north. Understanding why these differences vary geographically is a potential subject for investigation.

- For precipitation, the ensembles show similar geographic distributions of change in that differences between BCSD5(hydro) and BCSD3 ensemble-mean are generally within +/- 6 percent across HUC4 regions. Notable differences in the early 21st century include slightly wetter ensemble-mean change over much of the contiguous U.S. in the BCSD5(hydro) ensemble, which is accentuated more in the Intermountain West where the BCSD5(hydro) ensemble-mean change is 3 to 6 percent wetter than that from BCSD3. There were also regions that did not follow this rule; for example, the Upper Midwest shows a slight change (0 to 3 percent less). This does not mean that BCSD5(hydro) is projecting drier conditions but, rather, it is simply projecting conditions that are less wet than BCSD3 (Reclamation, 2013). This geographic pattern of ensemble-mean differences generally holds through the 21st century, with the range of differences increasing by late 21st century to roughly -6 to +12 percent.

- Finally, for runoff, and focusing on Western U.S. HUC4 regions, the sign of differences in ensemble-mean change generally follows the geographic pattern found for precipitation. During the early 21st century, differences range from -15 to +15 percent, with the most positive differences occurring in the Intermountain West and the most negative differences generally in the Upper Midwest. By late 21st century, the geographic pattern and range of differences generally hold; however, the range extends in some HUC4 basins to less than -15 percent (e.g., Red River Valley) or greater than 15 percent (e.g., within the Great Basin and North Platte River).

[13] Based on map summaries of BCSD3 and BCSD5 climate ensembles at http://www.usbr.gov/climate/docs/ClimateChangeLiteratureSynthesis3.pdf.

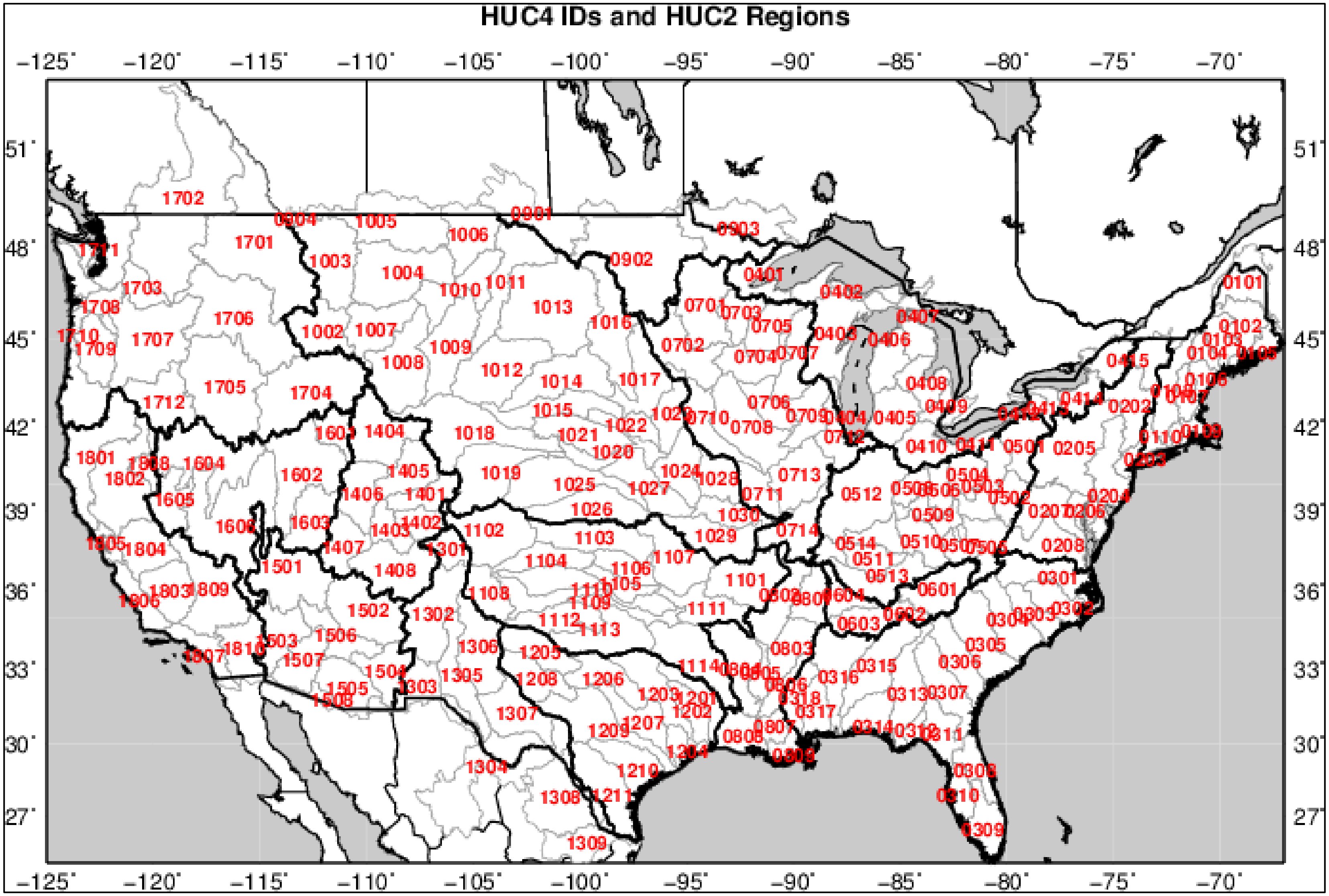

Figure 4. U.S. Geological Survey four-digit hydrologic unit codes (HUC4) and basins (gray lines) and HUC2 basins (black lines) (Source: NCAR, 2014).

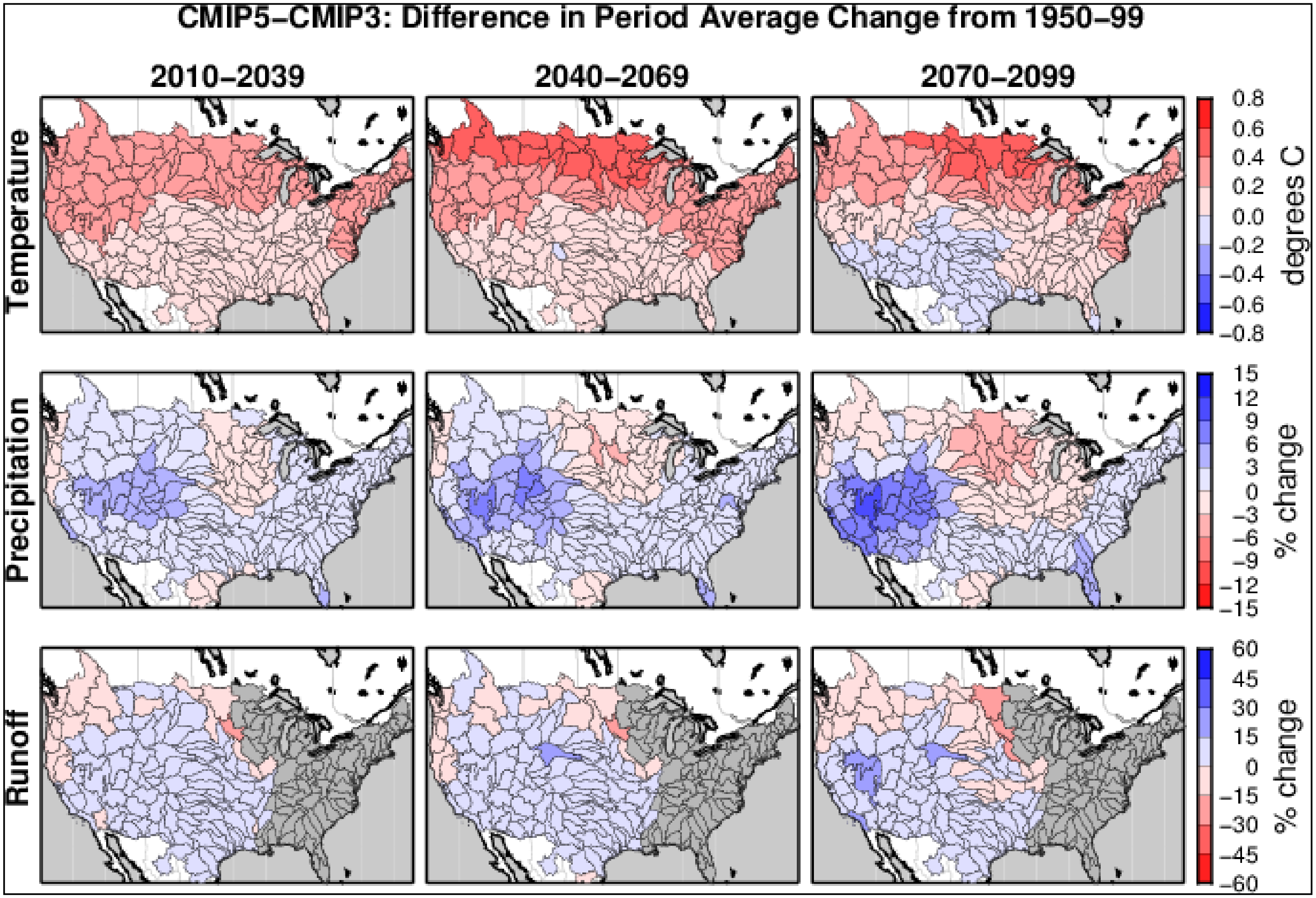

Figure 5. Ensemble-mean change in 30-year mean annual hydroclimate - BCSD5 difference from BCSD3. Results are shown for three variables (rows, top to bottom: temperature (-0.6 to 0.6 ºC), precipitation (-10 to +10%), and runoff (30% to +30%)) and three future periods (columns, 2010-39, 2040-69, and 2070-99 from 1950-99). Note that the grayed-out basins in the runoff row of panels are basins not included in the BCSD3 hydrology effort; therefore, no comparison was possible.

This analysis shows differences between ensemble portrayals of long-term hydroclimate or long-term water balance. It does little to subannual differences in the portrayals of long-term climate or runoff seasonality. For that, a similar analysis was conducted to evaluate differences in ensemble-mean changes in hydroclimate for three seasons that are relevant to many Western U.S. water management situations: (1) a "cool season," defined as December through March, which is marked by mountain snowpack accumulation (figure 6); (2) a spring-summer season, defined as April through July, when the majority of snowmelt-runoff occurs (figure 7); and (3) a summer-fall season, defined as August through November, that is typically a late-summer, low-flow period transitioning into fall rainfall-runoff conditions (figure 8). For precipitation and runoff, these figures show percentage difference in ensemble-mean change between the BCSD3 and BCSD5(hydro) ensembles. To judge the significance of a **percentage difference** in ensemble-median percentage change for any HUC4 and season, please refer to that season's BCSD5(hydro) percentage change result shown in NCAR (2014), or use the DCHP archive to retrieve results and assess either BCSD3 or BCSD5(hydro) ensemble-mean runoff results for that season (not shown).

- Focusing first on the cool season (figure 6), and comparing results to those on annual change (figure 5), the warming difference toward the North is more positive for cool season than for annual by the mid- and late-21st century. For cool season precipitation compared to annual, dominant areas of BCSD5(hydro) that are wetter than BCSD3 during cool season are the Great Plains, Southwest U.S, and Southeast U.S.; for annual, it was the Intermountain West. Further, the Upper Midwest difference in ensemble-mean precipitation is negative for annual change but generally positive for cool season change. For runoff, the spatial coherence of difference between BCSD5(hydro) and BCSD3 ensemble-mean annual change contrasts with that for the cool season, with the latter having a more heterogeneous spatial pattern of ensemble differences, particularly over the northern Great Plains and northern Rockies. Also, for the Pacific Northwest, where the BCSD5(hydro) ensemble-mean annual runoff change was generally drier than that from BCSD3, results for cool season show BCSD5(hydro) is more wet. Note that, in most cases, the differences in runoff change were shown in the same way as differences in precipitation change (though not always). This is due to how month-specific change differences aggregate within a season, which is discussed further in NCAR (2014).

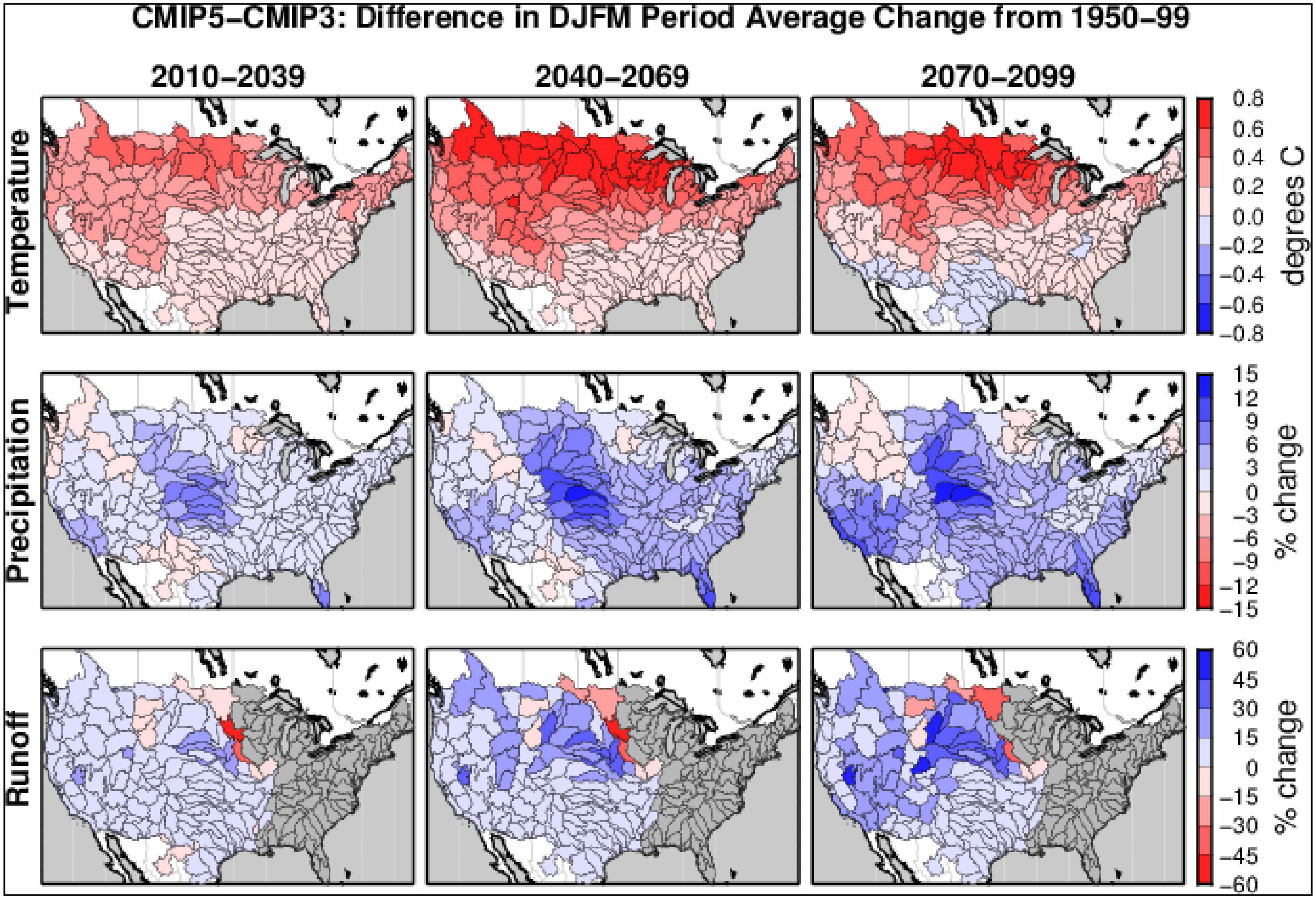

Figure 6. Ensemble-mean change in 30-year mean December-March hydroclimate - BCSD5 difference from BCSD3. Similar to figure 5.

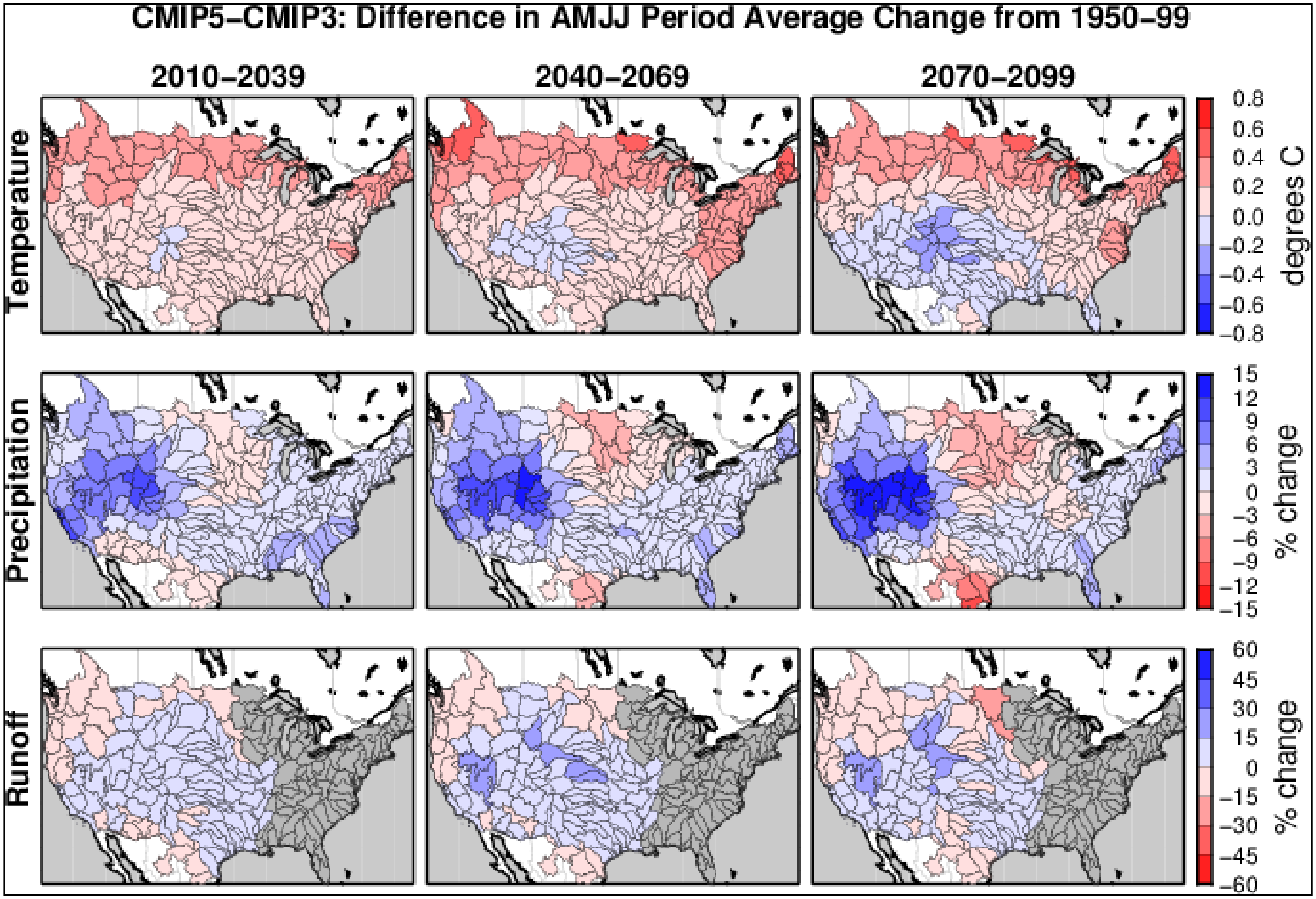

Figure 7. Ensemble-mean change in 30-year mean April-July hydroclimate - BCSD5 difference from BCSD3. Similar to figure 5.

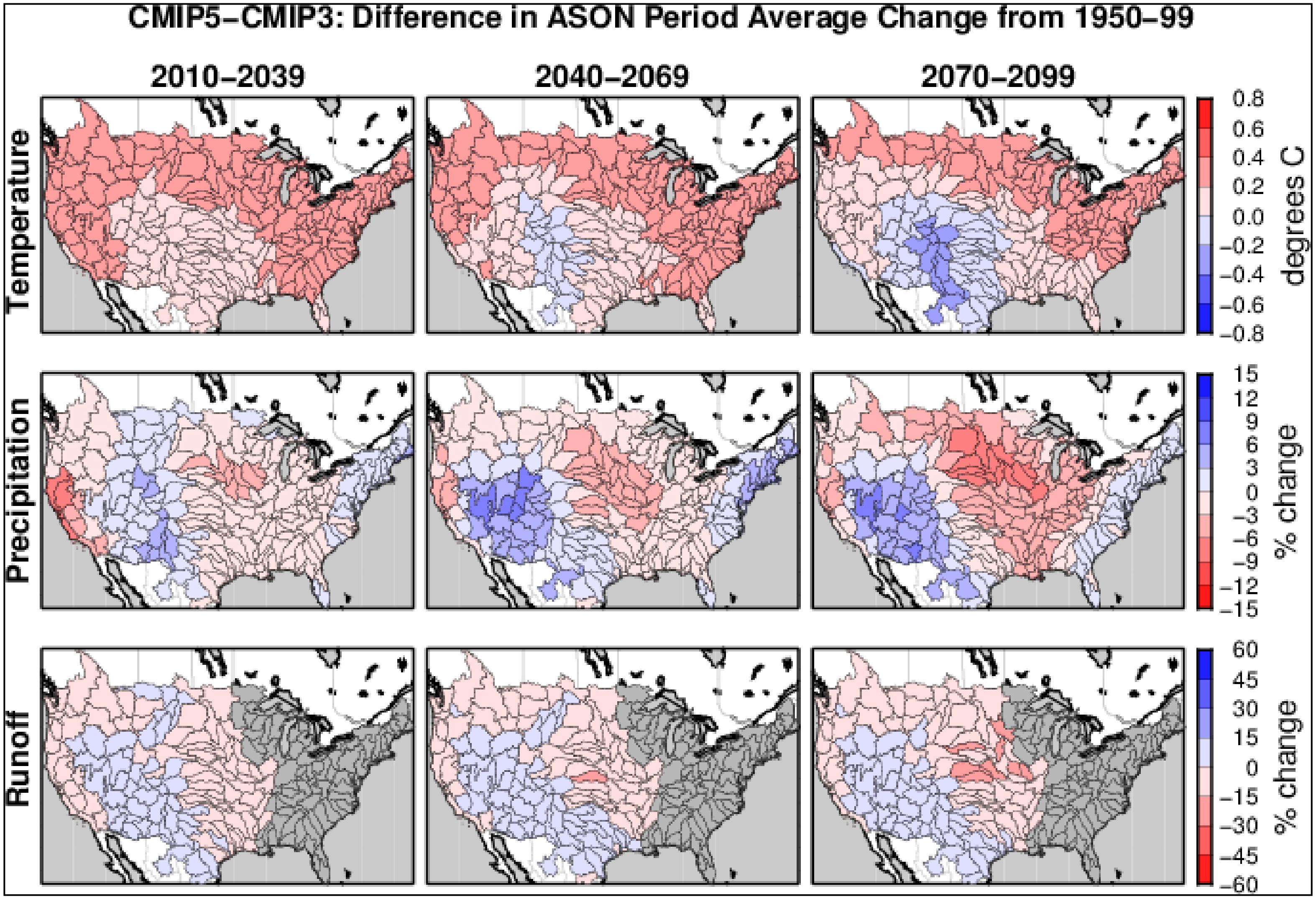

Figure 8. Ensemble-mean change in 30-year mean August-November hydroclimate - BCSD5 difference from BCSD3. Similar to figure 5.

- Switching to the spring-summer season (figure 7), ensemble-mean differences are geographically distributed similarly to differences in annual changes. There is generally greater warming in BCSD5(hydro) to the North. Greater precipitation change is shown over much of the domain, with the greatest increase in the Intermountain West, contrasted by a decrease in the Upper Midwest. There is a similar geographic pattern of mean runoff-change differences.

- Finally, focusing on the summer-fall season (figure 8), the spatial pattern of differences is also similar to the differences seen for annual, similar to the early warm season. Notable differences between summer-fall season and annual include less warming in BCSD5(hydro) over the southern Rockies and Rio Grande Basin, a larger region of less precipitation increase over the Central U.S., and a greater region of runoff decrease over the eastern Great Plains and Northwestern U.S.

These results characterize differences between the ensemble-mean hydroclimate changes, revealing some notable differences. Explanations for these differences are currently not available, and attributing them to various potential causes remains a matter of research. Some of the questions being considered by the research community include:

- To what extent are these differences attributable to use of new global climate models, use of new climate forcing scenarios, and chosen downscaling technique (Reclamation, 2013)?

- To what extent are they attributable to adjustments in the hydrologic projection methodology (section 2.4)?

- To what extent are these attributions sensitive to the season of occurrence and underlying mechanisms?

4.2 Ensemble-Distribution of Hydroclimate Change for Eight Western U.S. Basins

Whereas the previous section comments on how the ensembles' portrayals of central-tendency change differ, this section explores how portrayal of change uncertainty differs. The evaluation is presented here for the Colorado Basin above Lees Ferry, Arizona (figure 9), which is the same basin considered in section 3. Seven of the other basins from section 3 (table 3) were also evaluated, and their graphical results are shown in appendix C:

- 2. Klamath River near the California/Oregon border
- 6. Snake River at Brownlee, Idaho
- 19. Sacramento River near Freeport, California
- 22. San Joaquin River near Vernalis and below Mendota Pool, California
- 31. Rio Grande at Elephant Butte Dam, New Mexico
- 38. Truckee River at Nixon, Nevada
- 41. North Fork Platte River near Lake McConaughy, Nebraska

Results for the other seven basins are provided in appendix C.

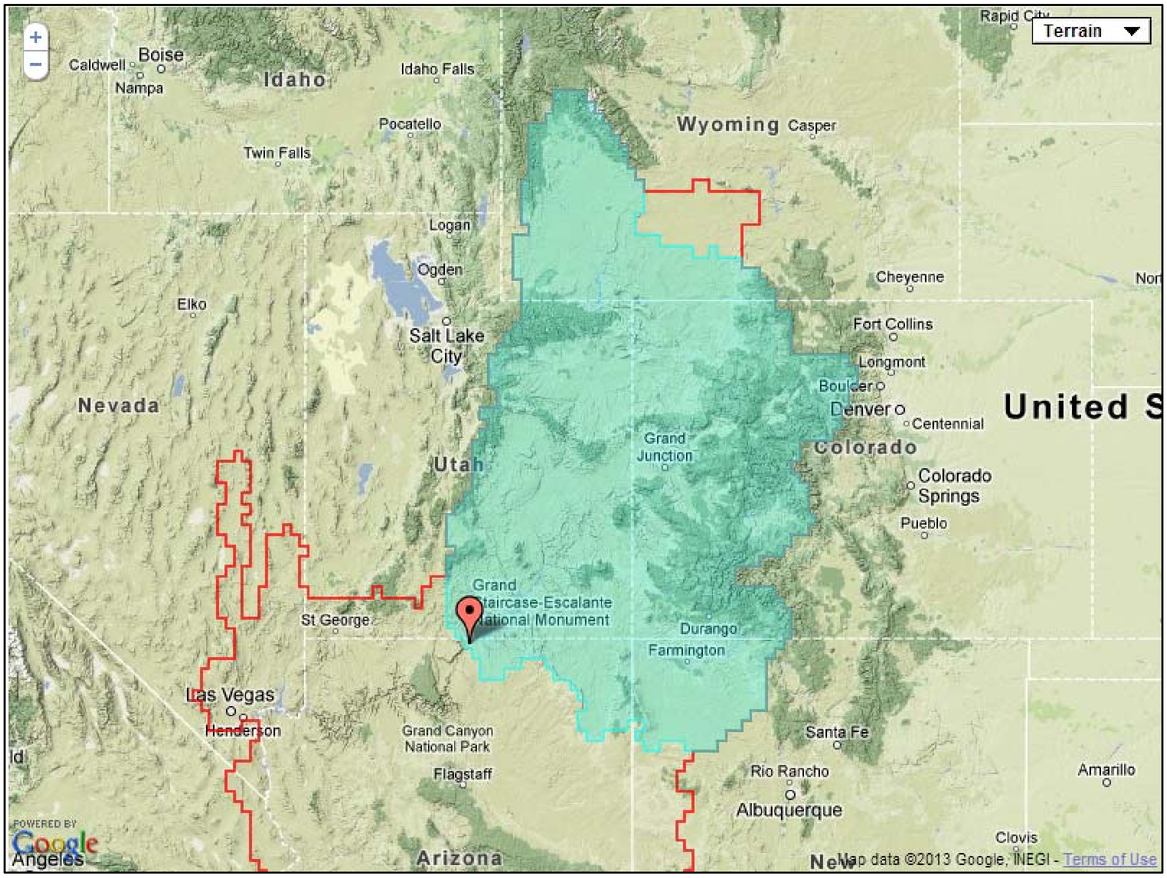

Figure 9. Upper Colorado Basin delineated within the DCHP website's interface for submitting data subset requests.

The first part of this evaluation considers the ensemble distribution of changes where the ensemble includes all projections representing all emissions scenarios associated with that ensemble (i.e., the BCSD3 and BCSD5(hydro) ensembles of table 1 and table 2, and the BCSD5(all) climate ensemble from table 2 of Reclamation, 2013). The gridded hydroclimate projections from each ensemble were spatially aggregated into basin-average projections. From these projections, changes in annual-average precipitation, temperature, and runoff were computed from 1950-1999 to 2040-2069. Distributions of these changes are shown on figure 10. In this display, all projected changes are treated equally; no model-weighting of changes was conducted because, according to Reclamation (2013), it has little effect on the change distribution from these ensembles.

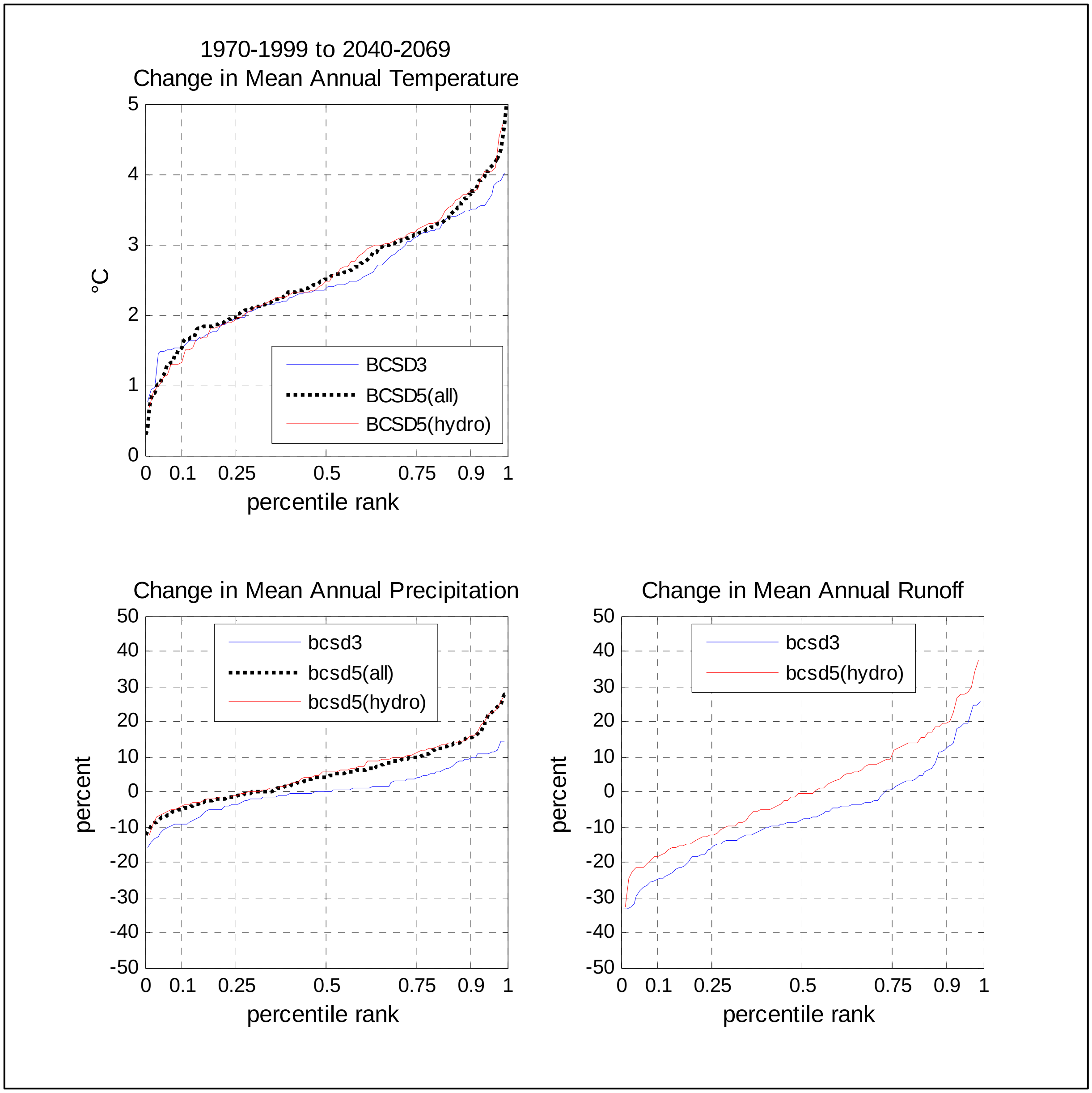

Figure 10. Colorado River Basin at Lees Ferry – ensemble distribution of projected change in mean annual hydroclimate from BCSD5 and BCSD3 for precipitation, temperature, and runoff by 2040-69 from 1950-99. BCSD5(all) includes projected changes from the completed BCSD3 downscaled climate ensemble (Reclamation, 2013), whereas BCSD5(hydro) includes only the 100-member subset translated into hydrologic projections (table 2).

For temperature, results show that BCSD5(all) and BCSD5(hydro) change distributions are nearly identical (i.e., red dashed line and red solid line distributions are nearly on top of one another), which suggests that the BCSD5(hydro) is very representative of temperature information from BCSD5(all). Results also show that the BCSD3 and BCSD5(hydro) change distributions are similar for cooler percentiles (i.e., similar changes for 50th percentile and lower), but BCSD5(hydro) tends to feature greater warming for the warmer percentiles. This greater spread of BCSD5(hydro) temperature changes is consistent with information shared in Reclamation (2013) about how BCSD5 features a larger range of warming, compared to BCSD3, because it included four underlying RCPs that have a larger range of emissions than the RCPs associated with the three SRES GHG emissions underlying BCSD3.

For precipitation, the BCSD5 and BCSD5(hydro) change distributions are once again very similar. However, they tend to be offset positively from BCSD3, which means that they feature more positive changes than the BCSD3 distribution across the percentiles. Ignoring this positive offset, the spread of changes for the three distributions is generally similar, although there is some indication that the spread is greater in BCSD5, potentially due to differences in emissions scenarios underlying BCSD3 and BCSD5 and/or to the bias-correction wettening effect discussed in Reclamation (2013).

For runoff, results are similar to precipitation as the BCSD5 and BCSD5(hydro) distributions are similar to one another and positively offset from the BCSD3 change distribution for all percentiles. The differences in ensemble-mean runoff change are a function of differences in ensemble-mean temperature change and precipitation change. Noting that mean temperature change is roughly the same for both ensembles, and that VIC has a confirmed runoff sensitivity of +2 to 3-percent increase in mean-annual runoff at Lees Ferry, given a +1 percent increase in mean-annual precipitation (Vano et al., 2012), the results for runoff change difference (roughly 9 percent) are within reason.

This evaluation is now repeated, but with the ensembles separated by emission scenario (figure 11). For temperature, one would expect temperature changes to be generally greater for the higher global GHG emissions scenarios because higher global GHG emissions scenarios result in greater global warming in both CMIP3 and CMIP5, global warming correlates highly with projected U.S. warming, and spatial distributions of projected U.S. temperature increases are, generally speaking, homogenous (Reclamation, 2013). This expectation is found for BCSD3 and BCSD5(hydro) distributions. For BCSD3, the distributions show warming that is progressively larger from lower emissions (B1) to higher emissions (A2). A similar progression is seen in the BCSD5 distributions, tracking through RCPs 2.6, 4.5, and 8.5. RCP 6.0 includes a disproportionately smaller number of projections and represents fewer climate models, which may help explain why its changes do not exceed those of RCP 4.5.

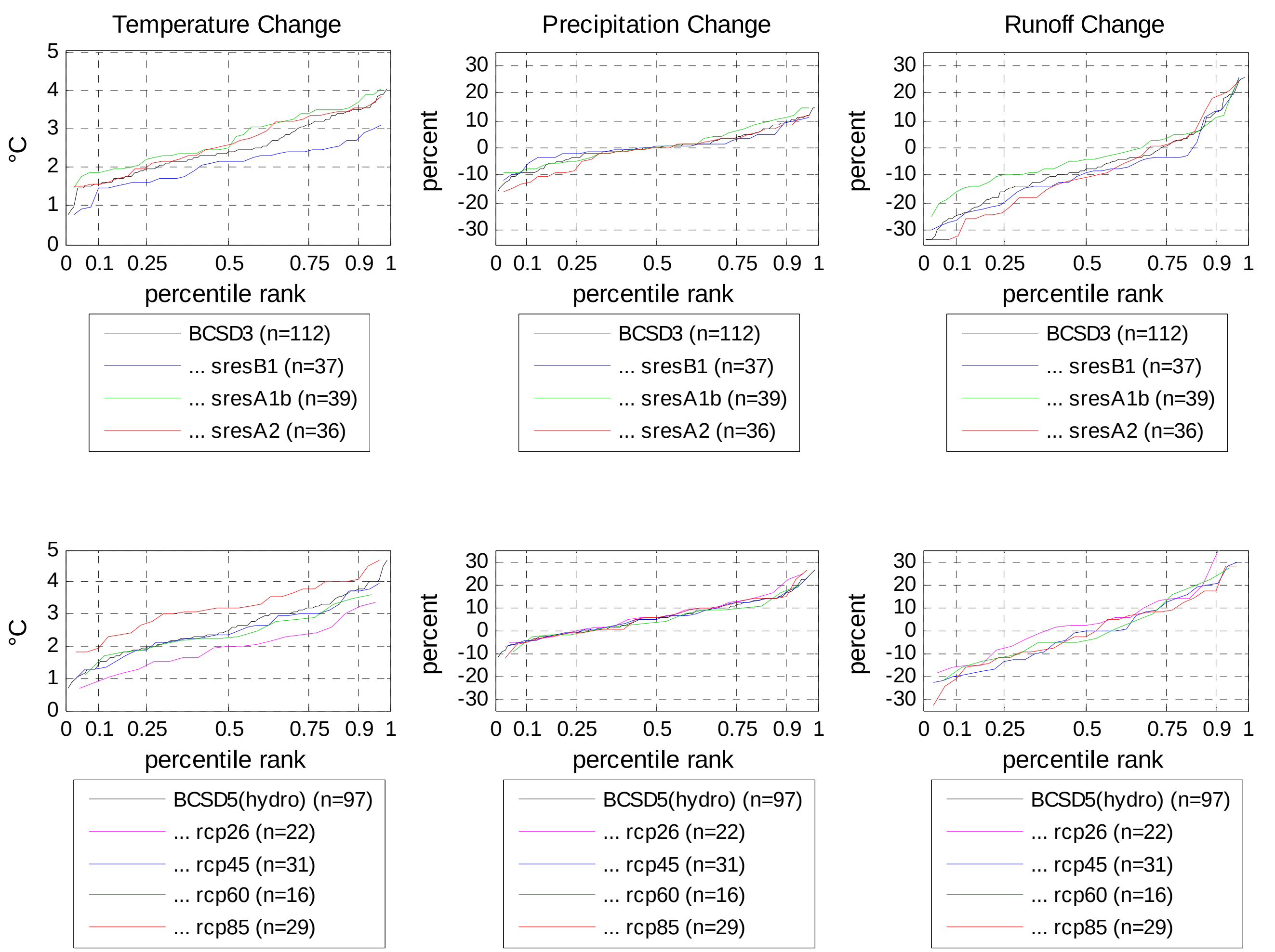

Figure 11. Colorado River Basin at Lees Ferry - ensemble distribution of projected change in mean annual hydroclimate, similar to figure 10 but focusing only on the 100-member BCSD5 ensemble for which hydrology was projected (table 2), and subdividing the distributions by emissions scenario (tables 1 and 2). .

For precipitation and runoff, there was no preconceived expectation for how Upper Colorado Basin precipitation might respond to different levels of global GHG emissions. Figure 11 shows that there is no clear hierarchy of change distributions with respect to emissions scenario. However, it does show that some uncertainty exists regarding the change distribution across scenarios (although this uncertainty is small compared to the range of changes shown in any single scenario distribution, and it could simply be an artifact of different projection subsets being included in each emissions scenario). Also, the absence of a clear hierarchy of runoff change distributions stems from how VIC simulated runoff change in the Upper Colorado Basin is jointly sensitive to precipitation change and temperature change. Although temperature change is well correlated to emissions scenario (left column of panels), and Vano et al. (2012) show that Lees Ferry runoff sensitivity to basin-average temperature change invites expectation that emissions-specific runoff distributions will stratify, results show no stratification of distributions, at least in a way that correlates with emission. This suggests that emission-specific ensembles have enough precipitation change variability to offset this temperature change effect.

Next, we switch from an annual analysis to a monthly analysis (figure 12). For temperature, there is a similar spread of monthly projected change between the BCSD3 and BCSD5(hydro) ensembles, albeit with some differences. BCSD5(hydro) median changes are warmer during winter to spring, and they are slightly cooler during other months. Change distributions are also more spread during winter months.

For precipitation, median precipitation change is very similar between the two ensembles, with the greatest differences seen during April through September. Changes in the BCSD5(hydro) ensemble spanned a generally larger range than the BCSD3 ensemble during warm season months (March through September) and a generally smaller range during cool season months (November, December, and February).

Finally, for runoff, it is clear that ensemble differences in precipitation and temperature produce the most significant runoff changes during the historically dominant runoff months of April through July (figure 3). During April through June, median runoff change is greater in the BCSD5(hydro) ensemble compared to the BCSD3 ensemble, and switches to lesser in July. Also, the range of changes is greater during March and April in the BCSD5(hydro) ensemble but is generally the same for other months.

Explanations for these differences are currently not available, and attributing them to various potential causes remains a matter of research. The research questions posed at the end of section 4.1 are also applicable here.

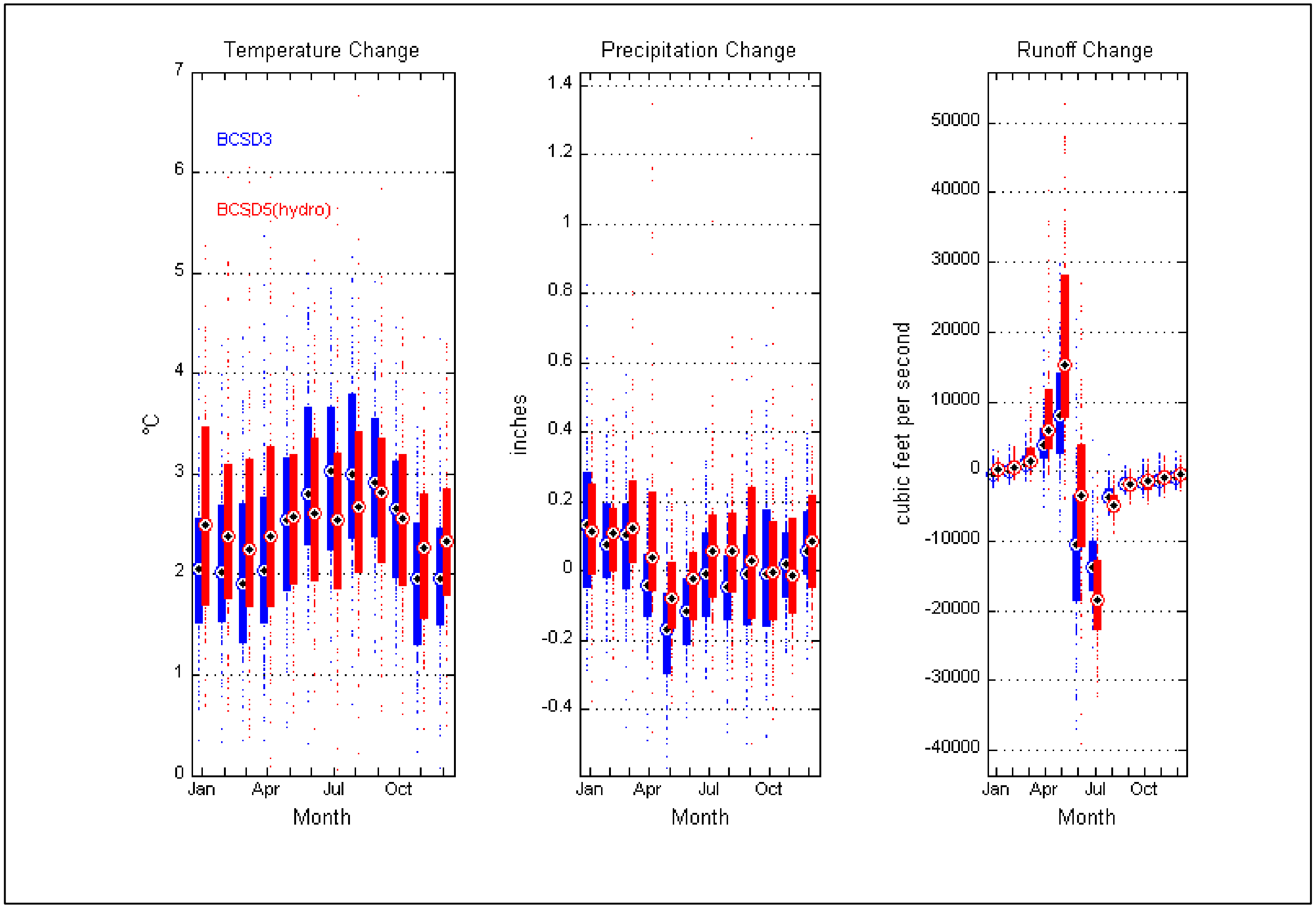

Figure 12. Colorado River Basin at Lees Ferry - ensemble distribution of projected change in mean monthly hydroclimate from BCSD5 and BCSD3 for precipitation, temperature, and runoff by 2040-69 from 1950-99. Monthly distributions are shown as boxplots, where box is interquartile range of change, midline is median change, and symbols outside the box reflect changes in upper or lower quartiles. Blue boxes are for BCSD3. Red boxes are for BCSD5.

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Appendix A

Hydrology Projection Methods

Table of Contents

Appendix A

Hydrology Projection Methods

Surface water hydrology models have been used frequently to study climate change impacts on hydrology and water resources. Several types of models have been applied in Western United States basins; some examples are:

- Variable Infiltration Capacity (VIC) model (Liang et al., 1994) applied to investigate impacts in California's Central Valley (Maurer, 2007), Colorado River Basin (Christensen and Lettenmaier, 2007), the Columbia-Snake Basin (Payne et al., 2004), and numerous other areas

- National Oceanic and Atmospheric Administration-National Weather Service's (NOAA-NWS) Sacramento Soil Moisture Accounting rainfall-runoff model (Burnash et al., 1973) coupled to the Snow17 snow accumulation and ablation model (Anderson 1973) (i.e., SacSMA/Snow17) applied to investigate impacts in the California Sierra Nevada (Miller et al., 2003)

- Water Evaluation and Planning model's hydrologic module (Yates et al., 2005) also applied to study California hydrologic impacts (Purkey et al., 2007)

- U.S. Geological Survey's (USGS) Precipitation Runoff Modeling System (Leavesley et al., 1983) applied in Washington's Yakima River Basin (Mastin, 2008) among other locations

- The Soil and Water Assessment Tool was applied in the Missouri Basin (Rosenberg et al., 1999; Stone et al., 2001)

Application of these hydrologic model types to a study basin generally involves the following types of decisions (not an exhaustive list):

- Spatial structure and resolution at which water balance will be calculated (i.e., gridded area elements or irregular areas defined by topography)

- Soil classes and characteristics that govern infiltration, soil water-holding capacity, etc.

- Land cover classes and characteristics that describe rooting depth access to soil moisture and, in turn, affect potential evapotranspiration

- Meteorological variables forcing the simulation, such as precipitation, temperature, and potentially other weather variables, depending on model type
- Routing scheme for aggregating runoff from subareas to downstream streamflow locations
- Model structure and physics (e.g., whether and how the snow accumulation and melt cycle are represented)
- Time step for simulating water balance
- Calibration objectives defining which historical hydrologic aspects the model is developed to reproduce when forced by historical weather (e.g., monthly to annual runoff statistics) and where these aspects are to be reproduced (e.g., a menu of locations scattered from upstream to downstream in a larger basin)

A.1 Model Selection

A.1.1 BCSD3 Effort

For the Bias-Correction Spatial Disaggregation applied to Coupled Model Intercomparison Project phase 3 climate projections (BCSD3) hydrology effort, consideration was given to available hydrologic model applications in the Western United States. Model application availability was defined as application of a chosen surface water hydrology model type to basins spanning the Western United States, and where these applications were calibrated for at least larger subbasins throughout the West. There was also interest in simulating hydrology at a daily time step, rather than a coarser one, in order to support a wide range of hydrologic impacts assessment situations (e.g., from local daily floods to regional multi-year droughts).

Two sets of model applications satisfied these criteria at the time this effort was scoped (2010):

1. NOAA NWS Lumped SacSMA/Snow17 Applications: These applications of SacSMA/Snow17 (Burnash et al., 1973; Anderson, 2006) served operational hydrologic forecasting purposes carried out by NWS River Forecast Centers.
2. University of Washington (UW) gridded 1/8 degree VIC Applications: These applications served as seasonal water supply forecasting tools in an experimental Western United States hydrologic forecasting system (Wood and Lettenmaier, 2006).

These two options are similar in that they are both surface water hydrology models (i.e., they do not represent groundwater conditions other than shallow [deep soil] groundwater interaction with surface water). As such, for long-term model simulations, assuming no net change in water stored in the soil or snowpack, the destination of precipitation is either simulated runoff or evapotranspiration. The two options are also different in some notable ways. An exhaustive list is not provided, but some of the differences are summarized below:

- The SacSMA/Snow17 applications were developed on a 6-hourly time step with spatial resolution defined topographically for basin-units roughly on scales of hydrologic unit codes 06 to 10. These applications were calibrated to reproduce daily flow conditions, with emphasis on floodflows, for most basin-units of application. For larger subbasins and for dry season conditions, flow biases may be significant. The models may be applied to support climate change studies by adjusting their two meteorological inputs: 6-hourly precipitation and temperature. Potential evapotranspiration (PET) is also a model input and would have to be adjusted prior to model simulation to reflect any climate change impact on PET. Snow hydrology is simulated using a temperature-index model (Snow17).

- It has been shown that simulated hydrologic response to climate change is sensitive to the hydrologic model selected for use. The VIC applications were developed on a daily time step with gridded 1/8-degree resolution (12 kilometers [km] on a grid-cell side). The applications were calibrated to reproduce monthly flow conditions for relatively large subbasins in the West. For smaller subbasins and for daily time steps, flow errors may be significant. The models may be applied to support climate change studies by adjusting their four meteorological inputs: daily precipitation, minimum temperature, maximum temperature, and wind speed. Using these inputs, the model computes PET. Snow hydrology is simulated using an energy balance model.

Ultimately, the Western U.S. VIC applications were selected to serve the BCSD3 effort, primarily because VIC computes PET internally and in response to changing surface climate conditions. It is expected that PET should vary under climate changes and have a significant effect on future surface water balances. Treatment of increasing PET with the available SacSMA/Snow17 applications would be less straightforward and require an offline assessment of how PET should respond to climate changes, with results used to inform input PET adjustment consistent with BCSD3 climate projections. PET considerations aside, the SacSMA/Snow17 model applications have received substantial and comprehensive calibration attention and model maintenance because they support operational hydrologic forecasting services for flood and water supply prediction. The VIC applications, by comparison, were produced in an experimental setting in the context of graduate student efforts at UW during recent years. The degree of model calibration is certain to affect hydrologic sensitivities to climate change, but the size of this effect is not known. However, it is possible for hydrologic simulation outputs to be corrected for biases before using them in water resources and reservoir operations assessments, so this became a lower consideration.

A.1.2 BCSD5 Effort

For the Bias-Correction Spatial Disaggregation applied to Coupled Model Intercomparison Project phase 5 climate projections (BCSD5) hydrology effort, model selection considered availability of applications covering the contiguous U.S. (CONUS), plus the Canadian portions of the Columbia and Missouri Basins. Three sets of model applications satisfied the criteria at the time of scoping (summer 2013):

- NOAA NWS Lumped SacSMA/Snow17 Applications: (see BCSD3 effort).
- UW gridded 1/8-degree VIC Applications: (see BCSD3 effort).
- The U.S. Department of Energy Oak Ridge National Laboratory (ORNL) gridded 1/24-degree VIC Applications: These applications are serving climate change and hydrologic impacts assessment research being conducted at ORNL. The applications are applied at roughly 4-km gridded resolution and are calibrated at HUC08 resolution to historically match USGS WaterWatch data (Oubeidillah et al., 2014).

Similar to the reasoning in the BCSD3 application, the ability to internalize PET response to climate change led to preference for VIC in this application. As for comparison between options 2 and 3, the ORNL applications were still undergoing refinement at the time of this effort, so option 2 was selected. This led to common applications being selected to serve the BCSD3 and BCSD5 efforts.

One other difference in the BCSD5 effort is that the applications were simulated using VIC 4.1.2, rather than VIC 4.0.7, which was used for the BCSD3 effort. VIC 4.1.2 improves upon VIC 4.0.7 in several ways (section A.2.2). Also, VIC 4.0.7 for the BCSD3 effort was compiled for 32-bit computing, whereas VIC 4.1.2 for the BCSD5 effort was compiled for 64-bit computing. Although results using VIC 4.0.7 were found to be sensitive to using 32-bit versus 64-bit computing, such sensitivity was not found with VIC 4.1.2. Therefore, this difference is noted only for users and is not expected to contribute to differences in BCSD3 and BCSD5 hydrologic projection results.

A.2 VIC Hydrology Model and Contiguous U.S. Applications

A.2.1 Model Description

The VIC model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997; http://www.hydro.washington.edu/Lettenmaier/Models/VIC/) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. Figure A-1 is a schematic of the VIC hydrology and energy balance model. The model initially was designed as a land-surface model to be incorporated in a Global Climate Model, or General Circulation Model (GCM) so that land surface processes can be more accurately simulated. However, the model now is run almost exclusively as a stand-alone hydrology model (not integrated with a GCM) and has been widely used in climate change impact and hydrologic variability studies, as indicated earlier in this chapter. For climate change impact studies, VIC is often run in what is termed the “water balance mode,” which is less computationally demanding than an alternative energy balance mode where a surface temperature that closes both the water and energy balances is solved for iteratively.

Using the UW VIC applications, the water balance mode is driven by daily weather forcings of precipitation, maximum and minimum air temperature, and wind speed. Additional model forcings that drive the water balance, such as solar (short-wave) and long-wave radiation, relative humidity, vapor pressure, and vapor pressure deficit, are calculated within the model. The VIC model contains a subgrid-scale parameterization of the infiltration process (based on the Nanjing model), which impacts the vertical distribution of soil moisture in, typically, a three-layer model grid cell (Liang et al., 1994). The VIC model also represents subgrid-scale vegetation variability using multiple vegetation types and properties per grid cell. Potential evapotranspiration is calculated using a Penman Monteith approach (e.g., Maidment, 1993). VIC also contains a subdaily (1-hour time step) snow model (Cherkauer and Lettenmaier, 2003;Wigmosta et al., 1994; Andreadis et al., 2009). The VIC outputs are configurable but typically include grid cell moisture and energy states through time (i.e., soil moisture, snow water content, snowpack cold content) and water leaving the basin either as evapotranspiration, baseflow, sublimation, or runoff, where the latter represents the combination of faster response surface runoff and slower response baseflow.

To calculate streamflow results at a given location, a two-step simulation process is used. The first step is to run VIC independently for each grid cell in the watershed, producing surface runoff and base flow. The second step involves hydraulic routing where the runoff from the grid cells are transported to streamflow gauges or locations of interest in a stream or river channel network.

The routing model used in this second step is from Lohmann et al. (1996), and is part of the VIC model setup described in this section. Figure A2 is a schematic of the VIC routing model. The routing model has two steps. First, surface runoff and baseflow simulated by the hydrology model within a VIC grid cell are moved to the edge of the cell, where it enters the channel network. The runoff then is routed through the channel network specified above a streamflow location of interest. Such setup requires specifying the coordinates of the streamflow location within the basin grid, identifying tributary grid cells and flow directions through these grid cells, and ultimately fraction-area contribution from tributary grid cells to streamflow at the location of interest.

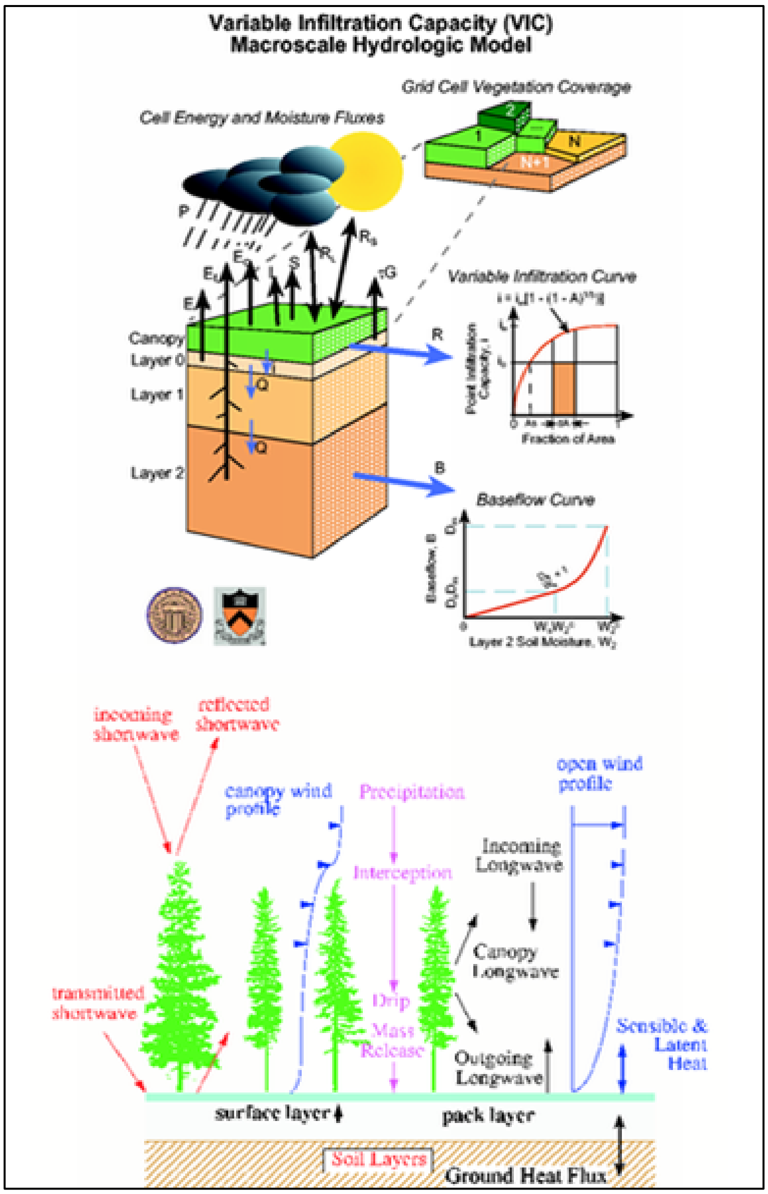

Figure A1. Schematic of VIC Hydrologic Model and Energy Balance Snow Model.

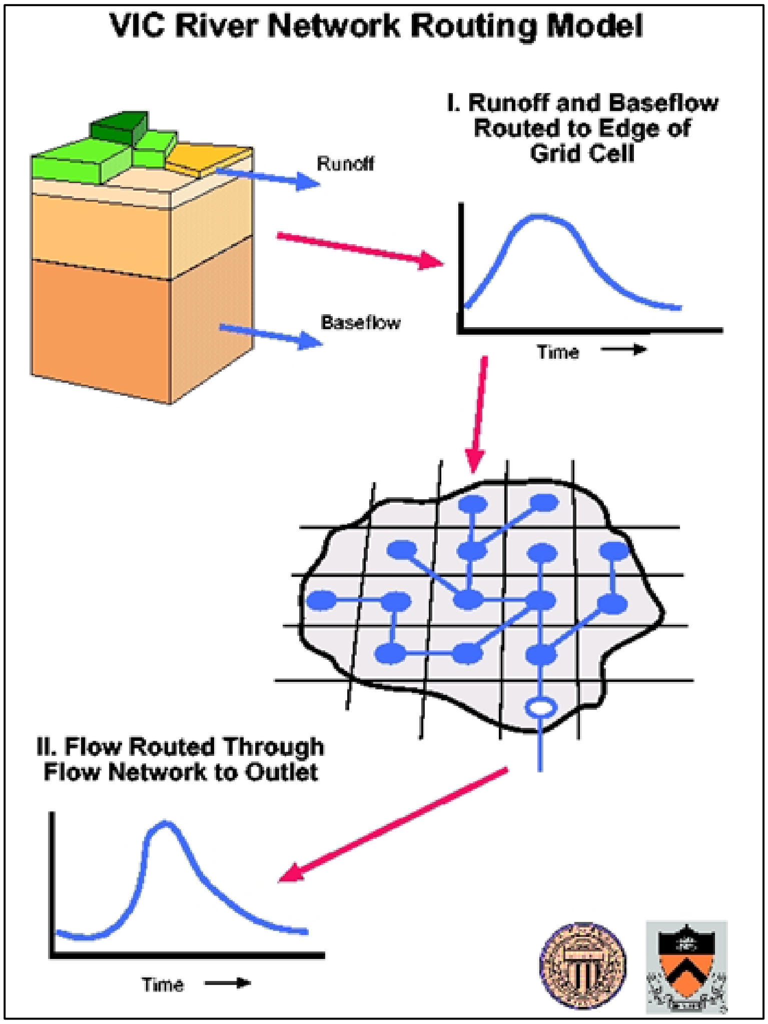

Figure A2. Schematic of VIC River Network Routing Model.

A.2.2 Model Changes from VIC 4.0.7 to VIC 4.1.2.l

To learn about model changes between these versions, readers may refer to the following links:

1. http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Development/VersionTables.shtml

2. https://github.com/UW-Hydro/VIC/blob/master/src/ChangeLog

The notes below are a summary of the largest changes between VIC.4.0.7(6) and VIC.4.1.2.l . The notes in this section summarize changes from the first reference cross-checked against the VIC source code change log. Some changes may be more relevant to hydrologic projection analysis under climate change; however, additional diagnostic simulations beyond the scope of this effort would be required to confirm relevance and isolate the effect of any single change. Also, in making science changes to the model, various software glitches were identified and addressed along the way.

Major Science Changes:

- 4.1.1 to 4.1.2:
  - Updated VIC's internal version of the MTCLIM forcing disaggregation functions from version 4.2 (Thornton and Running, 1999) to include elements of version 4.3 (Thornton et al., 2000)
  - Extended the computation of soil temperatures, ice contents, and ground fluxes to all modes of model operation
  - Added ability to simulate organic soil
  - Added computation of water table position
  - Improved and added features to the lake model
- 4.1.0 to 4.1.1:
  - Added option to calculate PET
  - Added ability to control how aerodynamic resistances in the overstory are corrected for the presence of snow in the canopy
  - Added PLAPSE option to lapse air pressure by grid cell average elevation
  - Improvements in temperature profile stability
  - Added option to select aerodynamic resistance algorithm in snow-filled canopy
  - Improved ground flux computation
  - Added option to select different snow density algorithms (Bras and SNTHRM)
  - Added dynamic lake/wetland model
  - Added soil temperature heterogeneity: "Spatial Frost"
  - Added partial snow cover: "Spatial Snow"
  - Added blowing snow sublimation
  - Improved canopy temperatures and energy balance in the presence of snow

- 4.0.7 to 4.1.0:
  - Added exponential grid transformation option for soil thermal nodes in finite difference heat equation
  - Implicit solution option for finite difference frozen soils algorithm
  - Permafrost enhancements and added EXCESS_ICE option
  - Use bare soil evaporation when LAI equals zero.
  - Drop very thin snow from canopy

Major Interface Changes:

- 4.1.1 to 4.1.2:
  - Cleanup of global parameter file. Removal of unused model options
- 4.1.0 to 4.1.1:
  - Changed default number of soil layers from 2 to 3
  - Added ground flux option to allow user to choose which ground flux formulation to use
  - Added TFALLBACK option, to continue with previous temperature when energy balance iteration fails to converge
- 4.0.7 to 4.1.0:
  - Added support ALMA units for input and output variables
  - Added ability to write out new variables, more flexible output formats, and aggregation
  - State file is now written at the END of the final time step of the date indicated in the global parameter file
  - Added EQUAL_AREA global parameter option
  - Added support for ASCII as well as Binary state files

A.2.3 Contiguous U.S. Applications

Daily, gridded, 1/8-degree VIC model applications were used for the BCSD3 and BCSD5 efforts. These applications were separately developed for 13 basin-oriented regions covering the contiguous U.S. and the Canadian portions of the Columbia and Missouri Basins (figure A3). Only basins in the Western U.S. (gray shaded) were created for the BCSD3 effort.

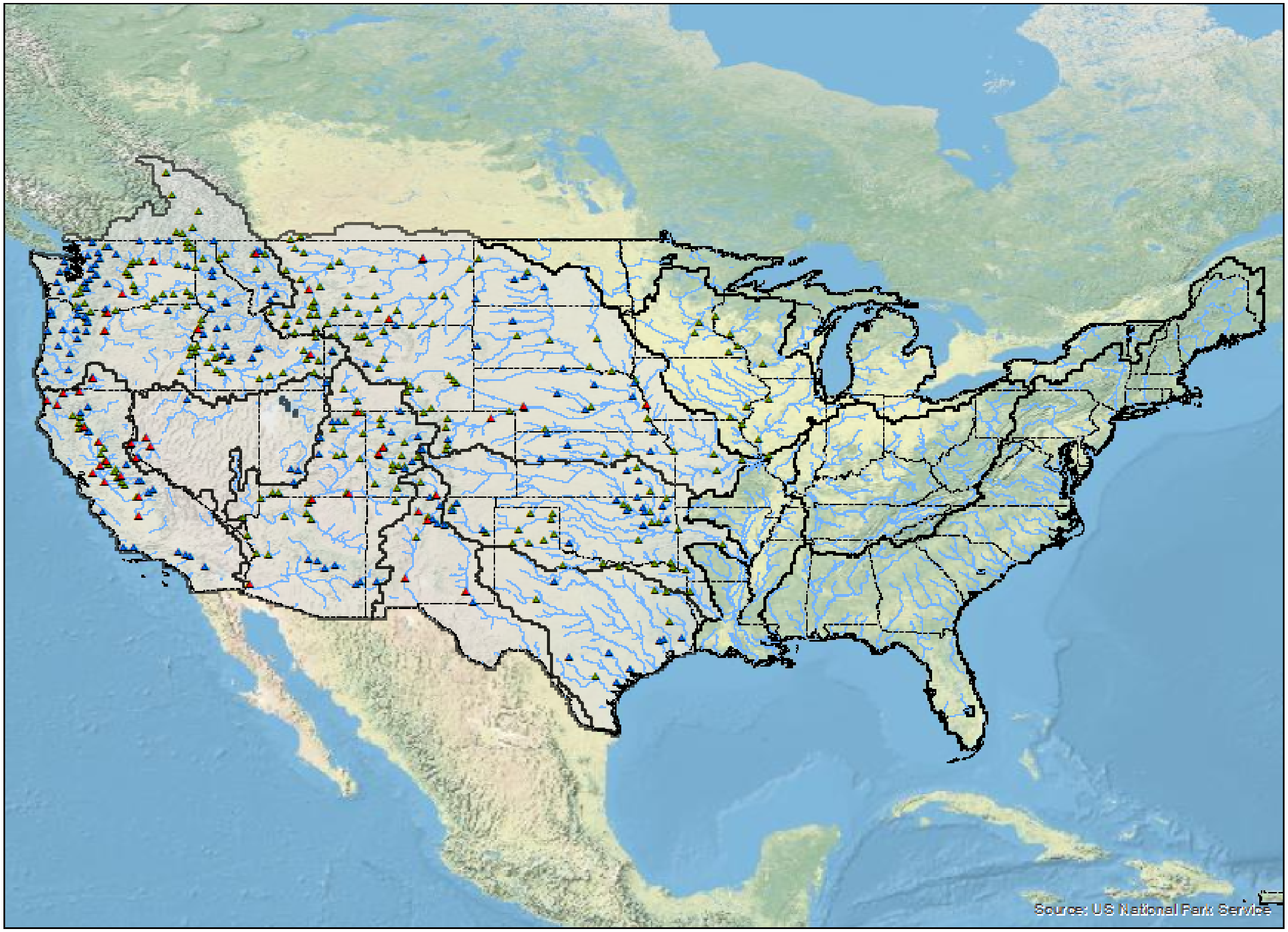

Figure A3. Collection of VIC basin applications covering the contiguous U.S. and portions of Canada (black boundaries). Commonly shaded basins were included in the BCSD3 effort. Other basins in the Central and Eastern U.S. were added for the BCSD5 effort. Plot symbols show locations of routed streamflow (section A.3.2).

Each basin application was developed to be forced by weather specified in Maurer et al. (2002). Approaches to model calibration varied by VIC basin application and for locations within a single region or application. The general similarities involved calibrated soil parameters so that monthly-to-annual runoff simulations matched those of observations during the late 20th century, when simulations were forced by Maurer et al. (2002). For the Western U.S. VIC applications, the BCSD3 and BCSD5 efforts were served by the same soil parameter estimates, except for the Rio Grande Basin where some parameter refinement occurred between the efforts.

For streamflow simulation in basins where routing was performed, the FORTRAN version of the unit hydrograph based on Lohmann et al (1996) routing model code and two sets of routing model implementations were used. The first set includes the routing model configuration developed in the prior effort (Reclamation 2011, supporting the West-wide Climate Risk Assessments [WWCRA] website), and the second set includes routing model configurations for Western U.S. river basins that were developed at UW in efforts supporting the Experimental West-wide Streamflow Forecast System (Wood and Lettenmaier, 2006). Additional routing model implementations were sought for the Eastern U.S. river basins, but they were not obtained in time to be included in the project. The 13 Reclamation river basin downscaling regional domains differed from the original UW regional routing domains because cells on the overlapping boundaries between adjacent basins were allocated to one basin or the other. Consequently, the overlap cells removed from each regional domain had to be trimmed from each UW routing model, which is expected to impact the flow calibrations, particularly in the smaller drainage areas. For this reason, the use of the UW routing models in this context was considered experimental, and their usability can be determined by assessment of their retrospective simulation performance.

A.3 Developing BCSD Hydrology Projections

A.3.1 Translating BCSD Climate Projections into VIC Weather Inputs

Using the VIC applications to develop hydrology projections consistent with BCSD climate projections required translating the monthly climate projections into daily VIC weather inputs. Before describing the procedure, recall that:

- BCSD climate projection involves concatenation of two climate simulations (Reclamation, 2013): (1) an historical simulation reflecting past actual climate forcings (through December 1999 for BCSD3; through November 2005 or December 2005 for BCSD5), followed by (2) a projection simulation reflecting scenario future climate forcings through 2100.

- BCSD climate projections reflect bias-correction of CMIP3 or CMIP5 climate projections so that they have common monthly climatologies with observed weather (Maurer et al., 2002) during the overlap period of 1950-1999. This means that each BCSD3 or BCSD5 climate projection will have common monthly climatology with observations during 1950-1999 and then should exhibit projected change during 21st century climate relative to this historical context.

- The original Maurer et al. (2002) contains daily, 1/8-degree, historical meteorology from 1950-1999 for four variables: precipitation, minimum temperature, maximum temperature, and wind speed. All four variables are required inputs for VIC simulation.

The method for developing daily VIC weather inputs consistent with a monthly BCSD climate projection follows the method introduced in Wood et al. (2004) and adapted for subsequent efforts (e.g., Payne et al., 2004; Christensen and Lettenmaier, 2007; Maurer, 2007; Elsner and Hamlet, 2010). This method involves: (a) inferring four daily VIC input weather variables (precipitation, minimum air temperature, maximum air temperature and wind speed) from two BCSD climate projection variables (precipitation and temperature), and (b) time-disaggregating the monthly BCSD climate information to daily. It would also involve: (c) spatially reconciling the BCSD climate information with the hydrology model's spatial structure. However, conveniently, the monthly BCSD climate projections used in this effort were already spatially specified on the same grid as the VIC hydrology model applications. Thus, no spatial reconciliation was necessary.

The approach to performing steps (a) and (b) generally follows the historical resampling and scaling technique introduced in Wood et al. (2004). The procedure is applied on a basin-specific fashion for basins shown on figure A3. It involves proceeding month by month through the monthly BCSD climate projection and performing the following three steps each month:

1. Obtain BCSD month's values: Get the month's BCSD precipitation and mean temperature for every VIC grid cell in the basin.

2. Sample reference month's time-series of daily values: Use the original Maurer et al. (2002) as a reference resource of daily weather sequences. Conditionally select an historical month's four-variable time-series from Maurer et al. (2002) over the entire basin. The month selection is conditioned by applying two criteria: (1) if the basin-average precipitation

for a downscaled month is in the top half (wet), be sure to select a historical month from the top half (wet); (2) otherwise, choose a historical month with lower precipitation.

3. Adjust reference month's time-series to become projection month's time-series: While preserving the sample month's four-variable time-series pattern at every location, adjust three of the four variables: precipitation, minimum temperature, and maximum temperature; the sample month's fourth variable, wind speed, is kept unadjusted. For each variable, uniformly adjust the daily sequence so that the month-aggregation of daily values equals the BCSD month's value. For precipitation, the adjustment is a scaling ratio (BCSD month value/ reference month aggregation). For temperature variables, the adjustment is an increment (BCSD month minus reference month). The reference month's daily sequence of wind speed is not adjusted and is accepted as an estimate for projection month's wind speed.

As an example, consider making synthetic daily weather for a single month in a given climate projection at a given basin's grid cell. Step 1 involves recognizing the projection month for which synthetic weather is being developed (e.g., January 2031 of the given climate projection). Step 2 involves conditionally sampling a historical month (e.g., January 1979), meaning we select the sequence of 31 daily values from January 1979 from the Maurer et al. (2002) dataset. The sampled historical January 1979 provides a realistic spatial-temporal sequence of daily weather variability over the entire basin (e.g., occurrence of precipitation, progression of synoptic weather events across the basin, 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).

Notes:

- The BCSD approach for time-disaggregation of monthly precipitation anomalies to daily precipitation values is designed to preserve observed monthly wet-day fractions, and it accomplishes this through selecting historical daily patterns and scaling them to sum to projected monthly totals. If the historical monthly pattern contains such few wet days that the resulting daily totals would be unrealistic, daily precipitation above a threshold (e.g., 150% of the historical maximum observed precipitation) is redistributed uniformly to all other days in the selected month. This reallocation can inflate wet-day fractions in such months to 1, which is unrealistic for dry location or time of year, when such reallocations typically occur. The reallocation has two effects on runoff from the VIC model: high wet-day occurrence suppresses evapotranspiration, boosting runoff;

whereas reduced daily rainfall intensities for the redistributed amounts lead to relatively reduced runoff. These effects are compensatory, and their aggregate impact is unclear. In general, reallocation in the driest months and for any given grid cell occurs for less than 10% of the projection time period.

- For the purpose of disaggregation from monthly to daily time steps, the CONUS domain is divided into 13 river basin oriented regions, as illustrated in figure A3 (NCAR, 2014). Hydrologic subdomains are required because the disaggregation involves a resampling step, pulling daily weather patterns from the historical climatology, and a realistic spatial and temporal structure must be maintained across each river basin to produce a realistic flow simulation result (Wood et al., 2002; 2004). One consequence of this approach is that for a given projection month, crossing the boundary between basin oriented regions, the daily sequences within a month will differ. However, the monthly values across this boundary will be consistent.

- For precipitation, step 3 involves an additional constraint to avoid resultant daily precipitation having unreasonably high values. The additional constraint involves limiting any adjusted daily precipitation value to not exceed 150% of the daily historical maximum precipitation for a cell for a given month. Precipitation in excess of 150% is spread evenly across the other days in the month. Similar constraints were imposed in Payne et al. (2004) and Maurer et al. (2007) and are necessary to avoid pathological combinations of dry samples with wet target months (i.e., large scaling of insufficient numbers of precipitation days). Such cases are found more frequently in dry locations or seasons, such as the Southwest United States or parts of the Pacific Northwest during summer.

- For minimum and maximum air temperature, the approach for BCSD3 and BCSD5 efforts differed. For the BCSD3 effort, only BCSD monthly average temperature was available to inform the VIC daily temperature forcings (i.e., daily minimum and maximum temperature). This led to the assumption that the daily diurnal temperature range from the sample month (Step 2 above) was kept fixed, while daily minimum temperature and maximum temperature received a common incremental adjustment in Step 3 to make the resultant monthly average match that of the BCSD projection month. For BCSD5, that assumption and constraint on diurnal temperature range was unnecessary because we have separate monthly BCSD5 projections of average daily minimum and maximum temperature. Consequently, Step 3 involved independent development daily minimum and maximum temperatures corresponding to their respective BCSD5 projections (i.e., tasmin and tasmax). While this latter approach is preferable for portraying projected change in diurnal temperature range, the mechanics of separately applying BCSD to tasmin and tasmax projections led to some months having tasmax values less than tasmin. When this occurred, the disaggregation method switched the daily values to preserve their expected ordering. This swap means that when the daily minimum and maximum temperatures are aggregated back to a monthly time step, they no longer match the original monthly BCSD5 values that were used to drive the disaggregation. This disparity is rare, however, and leads to significant alterations of the BCSD5 monthly temperature signal less than ~0.01% of the months.

- This three-step approach was applied using Maurer et al. (2002) as the reference data because those data were used to support VIC application development and calibration, as well as development of BCSD3 and BCSD5 climate projections. However, should a user wish to use a different hydrology model to redevelop hydrology projections, this three-step procedure, where the reference data constitute historical weather dataset used to calibrate the different hydrology model, would still be followed. The only caveat with pursuing this path is that the user should evaluate bias between that reference data and Maurer et al. (2002), which would affect interpretation of hydrology projection results relative to the ones created for this work.

A.3.2 Routing Gridded VIC Runoff into Streamflow at Locations of Interest

As mentioned in section A.2, VIC gridded runoff results may be routed into streamflow at locations of interest to the user. Information on this general routing procedure (Lohmann et al. [1996]) can be found at: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/. The general procedure starts with identifying the upstream basin tributary to a given downstream runoff location based on flow accumulation and flow direction classification from a digital elevation model. Next, the VIC routing model is applied to translate gridded surface runoff components above the runoff location into streamflow. The components of daily routed flow, surface runoff, and baseflow are available in this archive through the "Projections: Complete Archives" tab. Also, during the course of this effort, NCAR routed runoff to the sets of routing locations listed in tables A1, A2 and A3. Figure A3 shows the streamflow simulation locations for both routing models.

As an alternative to daily runoff routing, users interested in estimated monthly runoff may assume negligible travel time for runoff and aggregate monthly runoff from grid cells tributary to the grid cell containing the runoff location. This procedure is made relatively simple using the web interface "Projections: Subset

Request, Page 1: Temporal & Spatial Extent, Step 1.3, select Tributary Area." Note: As the selected subbasin for estimated monthly runoff gets smaller, greater uncertainty is introduced, due to coarsely delineating the basin according to the grid, where no fractional cell contribution to runoff is considered. Additionally, the details of flow connectivity may be somewhat erroneous because accurately describing the flow connectivity for all possible watersheds in the "big basin" is difficult with one flow direction grid.

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0004	45.01020	-109.06538	mo	6207500	CLARKS FORK YELLOWSTONE RIVER NR BELFRY MT
h0005	43.23956	-109.00917	mo	6225500	WIND RIVER NEAR CROWHEART WY
h0006	45.01090	-107.61508	mo	6289000	LITTLE BIGHORN RIVER AT STATE LINE NR WYOLA MT
h0007	46.29768	-103.91518	mo	6335500	LITTLE MISSOURI RIVER AT MARMARTH ND
h0008	47.15594	-102.06340	mo	6339500	KNIFE RIVER NR GOLDEN VALLEY ND
h0009	47.28530	-101.62208	mo	6340500	KNIFE RIVER AT HAZEN ND
h0010	46.79425	-100.66128	mo	6349500	APPLE CREEK NR MENOKEN ND
h0011	45.20201	-102.15658	mo	6359500	MOREAU R NEAR FAITH SD
h0012	44.01360	-103.83048	mo	6409000	CASTLE CR ABOVE DEERFIELD RES NEAR HILL CITY SD
h0013	43.02728	-99.78230	mo	6464500	KEYA PAHA R AT WEWELA SD
h0014	43.79047	-96.74533	mo	6481000	BIG SIOUX R NEAR DELL RAPIDS,SD
h0015	42.31925	-96.48922	mo	6601000	OMAHA CREEK AT HOMER NEBR.
h0016	39.65210	-105.19771	mo	6710500	BEAR CREEK AT MORRISON CO
h0017	41.83120	-100.10078	mo	6775500	MIDDLE LOUP RIVER AT DUNNING NEBR.
h0018	41.03516	-98.73992	mo	6784000	SOUTH LOUP RIVER AT SAINT MICHAEL NEBR.
h0019	42.26850	-98.33938	mo	6797500	ELKHORN RIVER AT EWING NEBR.
h0020	41.71023	-96.52238	mo	6799500	LOGAN CREEK NEAR UEHLING NEBR.
h0021	40.03533	-95.59419	mo	6815000	BIG NEMAHA RIVER AT FALLS CITY NEBR.
h0022	39.98500	-100.56018	mo	6846500	BEAVER C AT CEDAR BLUFFS KS

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0023	38.79480	-100.85686	mo	6860000	SMOKY HILL R AT ELKADER KS
h0024	39.37365	-99.58560	mo	6873000	SF SOLOMON R AB WEBSTER RE KS
h0025	39.10218	-95.72320	mo	6889500	SOLDIER C NR TOPEKA KS
h0027	39.17221	-106.38923	arkred	7083000	HALFMOON CREEK NEAR MALTA CO
h0028	36.81367	-97.27731	arkred	7152000	CHIKASKIA RIVER NEAR BLACKWELL OK
h0029	36.34371	-96.79943	arkred	7153000	BLACK BEAR CREEK AT PAWNEE OK
h0030	37.71009	-96.22274	arkred	7167500	OTTER C AT CLIMAX KS
h0031	37.00408	-96.31515	arkred	7172000	CANEY R NR ELGIN KS
h0032	36.48671	-96.06413	arkred	7176500	BIRD CREEK AT AVANT OK
h0033	36.27841	-95.95547	arkred	7177500	BIRD CREEK NEAR SPERRY OK
h0034	38.19641	-96.82453	arkred	7180500	CEDAR C NR CEDAR POINT KS
h0035	36.56841	-95.15223	arkred	7191000	BIG CABIN CREEK NEAR BIG CABIN OK
h0036	35.92291	-94.92353	arkred	7196500	ILLINOIS RIVER NEAR TAHLEQUAH OK
h0037	36.68111	-104.78633	arkred	7203000	VERMEJO RIVER NEAR DAWSON NM
h0038	36.37231	-104.97003	arkred	7208500	RAYADO CREEK NEAR CIMARRON NM
h0039	35.43911	-103.52334	arkred	7226500	UTE CREEK NEAR LOGAN NM
h0040	35.67658	-96.06868	arkred	7243500	DEEP FORK NEAR BEGGS OK
h0041	34.86006	-99.51089	arkred	7300500	SALT FORK RED RIVER AT MANGUM OK
h0042	36.99307	-106.03863	riog	8247500	SAN ANTONIO RIVER AT ORTIZ CO
h0043	36.54241	-105.55637	riog	8267500	RIO HONDO NEAR VALDEZ NM
h0044	35.96475	-105.90446	riog	8291000	SANTA CRUZ RIVER NEAR CUNDIYO NM
h0045	35.71022	-105.68239	riog	8378500	PECOS RIVER NEAR PECOS NM
h0046	35.65199	-105.31890	riog	8380500	GALLINAS CREEK NEAR MONTEZUMA NM
h0047	32.02318	-104.05465	riog	8408500	DELAWARE RIVER NR RED BLUFF NM
h0048	39.79915	-106.58392	colo	9059500	PINEY RIVER NEAR STATE BRIDGE CO
h0049	38.66444	-106.84810	colo	9112500	EAST RIVER AT ALMONT CO
h0050	38.29888	-107.23006	colo	9124500	LAKE FORK AT GATEVIEW CO.

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0051	40.98247	-107.38284	colo	9255000	SLATER FORK NEAR SLATER CO
h0052	40.49328	-110.57822	colo	9279000	ROCK CREEK NEAR MOUNTAIN HOME UT
h0053	40.51200	-110.34216	colo	9292500	YELLOWSTONE RIVER NEAR ALTONAH UT
h0054	40.03210	-107.86214	colo	9304500	WHITE RIVER NEAR MEEKER CO.
h0055	39.77580	-111.19101	colo	9310500	FISH CREEK ABOVE RESERVOIR NEAR SCOFIELD UT
h0056	38.98192	-111.24934	colo	9330500	MUDDY CREEK NEAR EMERY UT
h0057	33.06118	-108.53802	colo	9430500	GILA RIVER NEAR GILA NM
h0058	33.04951	-109.29433	colo	9444500	SAN FRANCISCO RIVER AT CLIFTON AZ.
h0059	32.86840	-109.51119	colo	9448500	GILA RIVER AT HEAD OF SAFFORD VALLEY NR SOLOMON
h0061	33.79811	-110.49983	colo	9497500	SALT RIVER NEAR CHRYSOTILE AZ
h0062	33.61949	-110.92150	colo	9498500	SALT RIVER NEAR ROOSEVELT AZ
h0063	33.98004	-111.30347	colo	9499000	TONTO CREEK ABOVE GUN CREEK NEAR ROOSEVELT AZ
h0064	34.07309	-111.71626	colo	9508500	VERDE R BLW TANGLE CREEK ABV HORSESHOE DAM AZ.
h0065	42.29327	-110.87241	colo	10032000	SMITHS FORK NEAR BORDER WY
h0066	37.65074	-112.42792	gbas	10174500	SEVIER RIVER AT HATCH UT
h0067	38.20619	-112.21019	gbas	10183500	SEVIER RIVER NEAR KINGSTON UT
h0068	38.28053	-112.56827	gbas	10234500	BEAVER RIVER NEAR BEAVER UT
h0069	33.74502	-116.53557	cali	10258500	PALM CYN C NR PALM SPRINGS CA
h0070	34.42083	-117.83951	cali	10263500	BIG ROCK C NR VALYERMO CA
h0071	38.84391	-119.70249	gbas	10309000	E FK CARSON RV NR GARDNERVILLE NV
h0072	41.53462	-117.41790	gbas	10329500	MARTIN CK NR PARADISE VALLEY NV
h0073	34.17473	-117.26754	cali	11058500	E TWIN C NR ARROWHEAD SPRINGS CA
h0074	34.26693	-117.46431	cali	11063500	LONE PINE C NR KEENBROOK CA
h0075	34.59666	-119.90809	cali	11124500	SANTA CRUZ C NR SANTA YNEZ CA
h0076	34.58860	-120.40849	cali	11132500	SALSIPUEDES C NR LOMPOC CA

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0077	36.28052	-121.32271	cali	11152000	ARROYO SECO NR SOLEDAD CA
h0078	37.33939	-118.97345	cali	11230500	BEAR C NR LAKE THOMAS A EDISON CA
h0079	37.19856	-119.21373	cali	11237500	PITMAN C BL TAMARACK C CA
h0080	37.73159	-119.55877	cali	11264500	MERCED R A HAPPY ISLES BRIDGE NR YOSEMITE CA
h0081	37.71687	-119.66628	cali	11266500	MERCED R A POHONO BRIDGE NR YOSEMITE CA
h0082	38.51908	-120.21269	cali	11315000	COLE C NR SALT SPRINGS DAM CA
h0083	40.93959	-122.41724	cali	11342000	SACRAMENTO R A DELTA CA
h0084	41.18821	-122.06556	cali	11367500	MCCLOUD R NR MCCLOUD CA
h0085	40.05460	-122.02415	cali	11381500	MILL C NR LOS MOLINOS CA
h0086	40.01405	-121.94832	cali	11383500	DEER C NR VINA CA
h0087	42.58458	-121.84974	cali	11501000	SPRAGUE RIVER NEAR CHILOQUIN OR
h0088	46.61732	-123.28088	pnw	12020000	CHEHALIS RIVER NEAR DOTY WA
h0089	46.99949	-123.49488	pnw	12035000	SATSOP RIVER NEAR SATSOP WA
h0090	48.01426	-123.13268	pnw	12048000	DUNGENESS RIVER NEAR SEQUIM WA
h0091	47.68248	-123.01059	pnw	12054000	DUCKABUSH RIVER NEAR BRINNON WA
h0092	47.51438	-123.32850	pnw	12056500	NF SKOKOMISH R BL STAIRCASE RPDS NR HOODSPORT WA
h0093	46.75261	-122.08372	pnw	12082500	NISQUALLY RIVER NEAR NATIONAL WA
h0094	46.74427	-122.14455	pnw	12083000	MINERAL CREEK NEAR MINERAL WA
h0095	47.03927	-122.20789	pnw	12093500	PUYALLUP RIVER NEAR ORTING WA
h0096	47.15121	-121.95092	pnw	12098500	WHITE RIVER NEAR BUCKLEY WA
h0097	47.36937	-121.62392	pnw	12115000	CEDAR RIVER NEAR CEDAR FALLS WA
h0098	47.35066	-121.66316	pnw	12115500	REX RIVER NEAR CEDAR FALLS WA
h0099	47.83838	-121.66752	pnw	12134500	SKYKOMISH RIVER NEAR GOLD BAR WA
h0100	47.66593	-121.92540	pnw	12149000	SNOQUALMIE RIVER NEAR CARNATION WA
h0101	48.26149	-122.04764	pnw	12167000	NF STILLAGUAMISH RIVER NEAR ARLINGTON WA
h0102	48.67263	-121.07290	pnw	12175500	THUNDER CREEK NEAR NEWHALEM WA

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0103	48.16621	-121.46643	pnw	12186000	SAUK RIVER AB WHITECHUCK RIVER NEAR DARRINGTON WA
h0104	48.42633	-121.56859	pnw	12189500	SAUK RIVER NEAR SAUK WA
h0105	48.90596	-121.84431	pnw	12205000	NF NOOKSACK RIVER BL CASCADE CREEK NR GLACIER WA
h0106	48.99919	-116.17982	pnw	12306500	MOYIE RIVER AT EASTPORT ID
h0107	46.46972	-113.23418	pnw	12330000	BOULDER CREEK AT MAXVILLE MT
h0108	46.18449	-113.50247	pnw	12332000	MIDDLE FORK ROCK CR NR PHILIPSBURG MT
h0109	46.89965	-113.75649	pnw	12340000	BLACKFOOT RIVER NEAR BONNER MT
h0110	48.49742	-114.12743	pnw	12355500	N F FLATHEAD RIVER NR COLUMBIA FALLS MT
h0111	48.49752	-114.01012	pnw	12358500	M F FLATHEAD RiVER NR WEST GLACIER MT
h0112	48.98128	-118.76643	pnw	12401500	KETTLE RIVER NEAR FERRY WA
h0113	48.98221	-118.21501	pnw	12404500	KETTLE RIVER NEAR LAURIER WA
h0114	47.56881	-116.25267	pnw	12413000	NF COEUR D ALENE RIVER AT ENAVILLE ID
h0115	47.27434	-116.18849	pnw	12414500	ST JOE RIVER AT CALDER ID
h0116	47.78461	-117.40439	pnw	12431000	LITTLE SPOKANE RIVER AT DARTFORD WA
h0117	48.98460	-119.61841	pnw	12442500	SIMILKAMEEN RIVER NEAR NIGHTHAWK WA
h0118	48.32758	-120.69345	pnw	12451000	STEHEKIN RIVER AT STEHEKIN WA
h0119	46.97762	-121.16870	pnw	12488500	AMERICAN RIVER NEAR NILE WA
h0120	43.85972	-110.58570	pnw	13011000	SNAKE RIVER NR MORAN WY
h0121	43.93230	-114.11329	pnw	13120000	NF BIG LOST RIVER AT WILD HORSE NR CHILLY ID
h0122	43.99807	-114.02269	pnw	13120500	BIG LOST RIVER AT HOWELL RANCH NR CHILLY ID
h0123	43.51796	-114.32032	pnw	13139500	BIG WOOD RIVER AT HAILEY ID
h0124	43.65906	-115.72705	pnw	13185000	BOISE RIVER NR TWIN SPRINGS ID
h0125	43.49475	-115.30912	pnw	13186000	SF BOISE RIVER NR FEATHERVILLE ID
h0126	44.08150	-115.62238	pnw	13235000	SOUTH FORK PAYETTE RIVER AT

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
					LOWMAN ID
h0127	44.91351	-115.99735	pnw	13240000	LAKE FORK PAYETTE RIVER AB JUMBO CR NR MCCALL ID
h0128	44.57789	-116.64333	pnw	13258500	WEISER RIVER NR CAMBRIDGE ID
h0129	44.96095	-115.49877	pnw	13313000	JOHNSON CREEK AT YELLOW PINE ID
h0130	45.75154	-116.32357	pnw	13317000	SALMON RIVER AT WHITE BIRD ID
h0131	46.08667	-115.51389	pnw	13336500	SELWAY RIVER NR LOWELL ID
h0132	46.15083	-115.58722	pnw	13337000	LOCHSA RIVER NR LOWELL ID
h0133	45.71958	-118.32329	pnw	14020000	UMATILLA RIVER ABOVE MEACHAM CREEK NR GIBBON OR
h0134	45.75651	-121.21007	pnw	14113000	KLICKITAT RIVER NEAR PITT WA
h0135	45.39873	-122.12992	pnw	14137000	SANDY RIVER NEAR MARMOT OR
h0136	45.41540	-122.17147	pnw	14141500	LITTLE SANDY RIVER NEAR BULL RUN OR
h0137	43.73596	-122.87340	pnw	14154500	ROW RIVER ABOVE PITCHER CREEK NEAR DORENA OR
h0138	44.04900	-123.42610	pnw	14166500	LONG TOM RIVER NEAR NOTI OR
h0139	44.70679	-122.10119	pnw	14178000	NO SANTIAM R BLW BOULDER CRK NR DETROIT OR
h0140	44.79243	-122.57851	pnw	14182500	LITTLE NORTH SANTIAM RIVER NEAR MEHAMA OR
h0141	44.39053	-122.49758	pnw	14185000	SOUTH SANTIAM RIVER BELOW CASCADIA OR
h0142	44.78318	-123.23454	pnw	14190500	LUCKIAMUTE RIVER NEAR SUVER OR
h0143	45.12484	-122.07341	pnw	14209500	CLACKAMAS RIVER ABOVE THREE LYNX CREEK OR
h0144	45.48049	-122.50760	pnw	14211500	JOHNSON CREEK AT SYCAMORE OR
h0145	45.83632	-122.46748	pnw	14222500	EAST FORK LEWIS RIVER NEAR HEISSON WA
h0146	45.70631	-123.75968	pnw	14301000	NEHALEM RIVER NEAR FOSS OR
h0147	45.48614	-123.68876	pnw	14301500	WILSON RIVER NEAR TILLAMOOK OR
h0148	44.71802	-123.88733	pnw	14305500	SILETZ RIVER AT SILETZ OR
h0149	42.93040	-122.94839	pnw	14308000	SOUTH UMPQUA RIVER AT TILLER OR

Table A1. WWCRA Hydro-Climatic Data Network (HCDN) Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS ID	Name
h0150	42.89150	-124.07065	pnw	14325000	SOUTH FORK COQUILLE RIVER AT POWERS OR
h0151	30.39783	-94.26032	gulf	8041500	VILLAGE CK NR KOUNTZE TX
h0152	30.33499	-95.10200	gulf	8070000	E FK SAN JACINTO RV NR CLEVELAND TX
h0153	30.26000	-95.30974	gulf	8070500	CANEY CK NR SPLENDORA TX
h0154	33.00991	-100.18081	gulf	8080500	DMF BRAZOS RV NR ASPERMONT TX
h0155	28.95996	-96.68918	gulf	8164000	LAVACA RV NR EDNA TX
h0156	29.66636	-97.65078	gulf	8172000	SAN MARCOS RV AT LULING TX
h0157	28.29196	-97.27723	gulf	8189500	MISSION RV AT REFUGIO TX
h0158	29.49302	-99.49371	gulf	8198000	SABINAL RV NR SABINAL TX

Table A2. WWCRA Other Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS/ CDEC ID	Matching VIC ID	Name
u0001	42.55768	-121.84416	cali	11502500	SPRGE	WILLIAMSON R. BELOW THE SPRAGUE RIVER
u0002	41.92806	-122.44306	cali	11516530	NA	KLAMATH RIVER BELOW IRON GATE DAM
u0003	41.85291	-123.23111	cali	11520500	NA	KLAMATH RIVER NEAR SEIAD VALLEY
u0004	41.30361	-123.53363	cali	CDEC-KLO	NA	KLAMATH RIVER AT ORLEANS
u0005	41.51111	-123.97833	cali	11530500	NA	KLAMATH RIVER NEAR KLAMATH
u0006	44.83891	-116.89950	pnw	13289710	BROWN	SNAKE RIVER AT BROWNLEE DAM
u0007	47.96556	-118.98167	pnw	12436100	GCOUL	COLUMBIA RIVER AT GRAND COULEE
u0008	45.60750	-121.17222	pnw	14103950	DALLE	COLUMBIA RIVER AT THE DALLES
u0009	46.50611	-120.45194	pnw	14092500	YPARK	YAKIMA RIVER AT PARKER
u0010	44.72613	-121.24646	pnw	14092500	NA	DESCHUTES RIVER NEAR MADRAS
u0011	43.61277	-111.65997	pnw	13037500	NA	SNAKE RIVER NEAR HEISE
u0012	48.36194	-114.18389	pnw	12363000	COLFA	FLATHEAD R AT COLUMBIA FALLS

Table A2. WWCRA Other Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS/ CDEC ID	Matching VIC ID	Name
u0013	36.86472	-111.58750	colo	9380000	LESFY	COLORADO RIVER AT LEES FERRY
u0014	32.88335	-114.46846	colo	9429490	IMPRL	COLORADO RIVER ABOVE IMPERIAL DAM
u0015	40.90862	-109.42245	colo	9234500	GRNDL	GREEN R NEAR GREENDALE
u0016	39.23917	-108.26556	colo	9095500	CAMEO	COLORADO R NEAR CAMEO
u0017	38.97656	-108.45620	colo	9152500	GRNJC	GUNNISON R NEAR GRAND JUNCTION
u0018	37.14694	-109.86417	colo	9379500	BLUFF	SAN JUAN R NEAR BLUFF UT
u0019	38.45611	-121.50028	cali	11447650	NA	SACRAMENTO RIVER AT FREEPORT
u0020	40.26417	-122.22194	cali	11377100	NA	SACRAMENTO R AT BEND BRIDGE NEAR RED BLUFF
u0021	39.52167	-121.54667	cali	CDEC-FTO	OROVI	FEATHER R AT OROVILLE
u0022	37.67611	-121.26528	cali	11303500	NA	SAN JOAQUIN RIVER NEAR VERNALIS
u0023	37.94722	-120.52917	cali	CDEC-SNS	N_MEL	STANISLAUS R AT NEW MELONES DAM
u0024	46.64944	-111.72750	mo	6058700	NA	MISSOURI RIVER AT CANYON FERRY DAM
u0025	48.12972	-106.36389	mo	6174500	NA	MILK RIVER AT NASHUA
u0026	40.61917	-103.18861	mo	NA	NA	S.F. PLATTE RIVER NEAR STERLING (?? Ft Morgan?)
u0027	41.25889	-95.92222	mo	6610000	OMAHA	MISSOURI RIVER AT OMAHA
u0028	37.07861	-105.75639	riog	8251500	LOBAT	RIO GRANDE NEAR LOBATOS
u0029	36.31833	-106.59722	riog	08286500/ 08287000	NA	RIO CHAMA NEAR ABIQUIU
u0030	35.87624	-106.14334	riog	8313000	NA	RIO GRANDE NEAR OTOWI
u0031	33.15634	-107.19054	riog	8287000	NA	RIO GRANDE AT ELEPHANT BUTTE DAM
u0032	32.51141	-104.33418	riog	8401500	NA	PECOS R AT DAMSITE NO 3 NR CARLSBAD
u0033	39.38833	-120.09500	gbas	10344500	NA	LITTLE TRUCKEE R BELOW BOCA DAM
u0034	38.76972	-119.83278	gbas	CDEC-WFC	NA	W.F. CARSON R AT WOODFORDS
u0035	38.06448	-121.85665	cali	NA	NA	DELTA INFLOW
u0036	36.99808	-119.70658	cali	CDEC-SJF	MILLE	SAN JOAQUIN R AT MILLERTON LAKE (FRIANT DAM)

Table A2. WWCRA Other Streamflow Locations from Reclamation

ID	Lat	Lon	Basin	USGS/ CDEC ID	Matching VIC ID	Name
u0037	39.45402	-120.00626	gbas	CDEC-TRF	NA	TRUCKEE R AT FARAD GAGE (JUST ABOVE CA STATELINE)
u0038	39.77795	-119.33917	gbas	10351700	NA	TRUCKEE R. AT NIXON GAGE
u0039	39.32725	-119.15083	gbas	10312000	NA	CARSON R. AT FT CHURCHILL GAGE
u0040	45.30794	-107.95669	mo	NaN	BIG	HORN RIVER AT YELLOWTAIL DAM
u0041	41.21454	-101.64344	mo	NaN	N.F.	PLATTE RIVER AT LAKE MCCONAUGHY
u0042	38.63659	-121.22841	cali	11446500	NA	AMERICAN RIVER AT FAIR OAKS
u0043	36.05243	-119.71871	cali	NA	NA	TULARE-BUENA VISTA LAKES

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
MICAA	52.1250	-118.3750	PNW	12227100	Columbia R at Mica Dam, BC
REVEL	51.1250	-118.1250	PNW	12229800	Columbia R at Revelstoke, BC
ARROW	49.3750	-117.8750	PNW	12239500	Columbia River at Keenleyside Dam, BC
DUNCA	50.3750	-116.8750	PNW	12322405	Duncan R at Duncan Dam, BC
LIBBY	48.3750	-115.6250	PNW	12301921	Kootenai R at Libby Dam, MT
CORRA	49.6250	-117.1250	PNW	12322730	Kootenai R at Corra Linn, BC
HHORS	48.3750	-113.7000	PNW	12362001	SF Flathead R at Hungry Horse Dam, MT
COLFA	48.3750	-114.3000	PNW	12363000	Flathead R at Columbia Falls MT
KERRR	47.6250	-114.1250	PNW	12371800	Flathead R at Kerr Dam, MT
WANET	48.9000	-117.3000	PNW	12399350	Pend OReille R at Waneta, WA
CHIEF	48.0000	-119.6000	PNW	12437990	Columbia R at Chief Joseph Dam, WA
PRIES	46.6000	-119.8000	PNW	12472710	Columbia R at Priest Rapids Dam, WA
DWORS	46.5000	-116.3000	PNW	13340990	Clearwater R at Dworshak, ID
ICEHA	46.3000	-118.9000	PNW	13352980	Snake R at Ice Harbor, ID
DALLE	45.6000	-121.2000	PNW	14103950	Columbia R at The Dalles, OR
MILNE	42.5200	-114.0200	PNW	13087995	Snake River at Milner, ID
BROWN	44.8000	-116.9000	PNW	13289710	Snake River at Brownley, ID
HCANY	45.3000	-116.7000	PNW	13290450	Snake R at Hells Canyon Dam, ID-OR
LGRAN	46.6000	-117.4000	PNW	13343595	Snake R (Right Bank) blw Lower Granite

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
					Dam, WA
JLAKE	43.8000	-110.5500	PNW	13011000	Snake R nr Moran, WY
PALIS	43.3500	-111.2200	PNW	13032500	Snake R nr Irwin, ID
HFORK	43.8200	-111.9000	PNW	13056500	Henrys Fork nr Rexburg, ID
AMERI	42.7700	-112.8600	PNW	13077000	Snake R at Neeley, ID
MINAD	42.6600	-113.4900	PNW	13082000	Snake R nr Minidoka (at Montgomery), ID
OWYHE	43.6500	-117.2500	PNW	13183000	Owyhee R blw Owyhee Dam, ID
PAYET	44.0300	-116.9200	PNW	13251000	Payette R nr Payette, ID
IPARK	44.4830	-111.4000	PNW	13042500	Henrys Fork nr Island Park, ID
RIRIE	43.4380	-111.8130	PNW	13058000	Willow Creek nr Ririe, ID
BLACK	42.8130	-111.4380	PNW	13068500	Blackfoot R nr Blackfoot, ID
CJSTR	42.9500	-115.9830	PNW	13171620	Snake R blw CJ Strike Dam nr Grand View, ID
ANDRA	43.3330	-115.4830	PNW	13190500	SF Boise R at Anderson Ranch Dam, ID
AROCK	43.5830	-115.9670	PNW	13194500	Boise R at Dowling Ranch nr Arrowrock, ID
CASCA	43.9500	-116.2000	PNW	13247500	Payette R nr Horseshoe Bend, ID
LBOIS	43.7830	-116.9670	PNW	13213000	Boise R nr Parma, ID
OWYH2	42.8670	-117.6500	PNW	13181000	Owyhee R nr Rome, ID
CLARK	46.4330	-117.1670	PNW	13343500	Snake R nr Clarkston, ID
ALBEN	48.6250	-117.1250	PNW	12395400	Albeni Falls
BOISE	43.5200	-116.0500	PNW	13202000	Boise River at Boise
BONNE	45.6500	-121.9000	PNW	14128860	Bonneville
BOUND	48.8750	-117.3750	PNW	12398555	Boundary
BOXCA	48.6250	-117.3750	PNW	12396485	Box Canyon
BRILL	49.3000	-117.6200	PNW	12322970	Brilliant
BRUNE	42.7700	-115.7200	PNW	13168500	Hot Springs, ID
CABIN	48.1250	-116.6250	PNW	12391900	Cabinet Gorge
CHELA	47.8300	-120.0200	PNW	12452400	Chelan
CONNF	46.4700	-116.2500	PNW	13340000	Calearwater at conf. NF
GCOUL	48.0000	-119.0000	PNW	12436100	Grand Coulee
GORGE	48.6700	-121.2300	PNW	12177710	Gorge
GROND	45.9300	-117.4300	PNW	13333000	Grande Ronde
JDAYY	45.7000	-120.7000	PNW	14048006	John Day

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
LAGRA	46.8300	-122.3200	PNW	12085510	La Grand
LGOOS	46.5000	-118.0000	PNW	13343930	Little Goose
LLAKE	47.8300	-117.8300	PNW	12432510	Long Lake
LMONU	46.5000	-118.5000	PNW	13352595	Lower Monumental
MALHE	43.9800	-117.2200	PNW	13233300	Maleur River
MAYFI	46.5000	-122.5800	PNW	14237810	Mayfield
MCNAR	45.9000	-119.3000	PNW	14019195	McNary
MERWI	45.9500	-122.5700	PNW	14220010	Merwin
MOSSY	46.5300	-122.4200	PNW	14234802	Mossyrock
MURPH	43.2800	-116.4200	PNW	13172500	Snake at Murphy
NFORK	45.1500	-122.1000	PNW	14209805	North Fork
NOXON	48.1250	-115.8750	PNW	12391301	Noxon Rapids
OXBOW	45.0000	-116.8000	PNW	13290049	Oxbow
PELTO	44.7200	-121.2300	PNW	14092455	Pelton
PFALL	47.7000	-116.9700	PNW	12419000	Post Falls
RISLA	47.4000	-120.1000	PNW	12462552	Rock Island
ROCKY	47.5000	-120.2500	PNW	12453682	Rocky Reach
SALMO	45.7500	-116.3200	PNW	13317000	Salmon at Whitebird
SWIFT	46.0500	-122.2000	PNW	14217610	Swift 1
WANAP	46.9000	-119.9000	PNW	12464612	Wanapum
WELLS	48.0000	-119.9000	PNW	12450652	Wells
N_MEL	37.8520	-120.6370	CALI	SNS	Stanislaus R - Goodwin (New Melones Res), CA
COTTO	40.2000	-122.4500	CALI	11375810	Cottonwood Crk near Olinda, CA
MILLE	36.9840	-119.7230	CALI		San Joaquin R blw Friant (Millerton Lake)
LK_MC	37.5220	-120.3000	CALI		Merced R nr Merced Falls (Lake McClure)
SMART	39.2350	-121.2730	CALI	YRS	Yuba R nr Smartville, CA
BEARC	39.0000	-121.4210	CALI	11424000	Bear R nr Wheatland, CA
CLEAR	40.4380	-122.4380	CALI	11372000	Clear Crk nr Igo, CA
FOL_I	38.6830	-121.1830	CALI	AMF	American R at Folsom Dam, CA
SHAST	40.7170	-122.4170	CALI	SHA	Shasta Dam Inflow, CA
CONSU	38.5000	-121.0440	CALI	CSN	Consumnes R at Michigan Bar, CA
OROVI	39.5220	-121.5470	CALI	FTO	Feather R at Lake Oroville, CA

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
DPR_I	37.6660	-120.4410	CALI	TLG	Tuolumne R - La Grange Dam, CA
PRD-C	38.3130	-120.7190	CALI	MKM	Mokelumne-Mokelumne Hill, CA
N_HOG	38.1550	-120.8140	CALI	NHG	New Hogan Lake (Calaveras R)
SAC_B	40.2890	-122.1860	CALI	SBB	Sacramento R abv Bend Bridge, CA
GLNWD	39.5500	-107.1900	COLO	9072500	Colorado R at Glenwood Springs, CO
CAMEO	39.3000	-108.2000	COLO	9095500	Colorado R near Cameo, CO
GRNJC	38.9400	-108.4100	COLO	9152500	Gunnison R near Grand Junction, CO
CISCO	38.8100	-109.3100	COLO	9180500	Colorado R near Cisco, CO
GRNDL	40.9100	-109.2000	COLO	9234500	Green R near Greendale, UT
MAYBL	40.4000	-108.3000	COLO	9251000	Yampa R near Maybell, CO
LILLY	40.6500	-108.3000	COLO	9260000	Little Snake R near Lily, CO
RNDLT	40.5000	-109.9500	COLO	9302000	Duchesne R near Randlett, UT
GREEN	38.9900	-110.0500	COLO	9315000	Green R at Green R, UT
BLUFF	37.1800	-109.9400	COLO	9379500	San Juan river near Bluff, UT
LESFY	36.9200	-111.5500	COLO	9380000	Colorado R at Lees Ferry, AZ
HOOVR	36.0200	-114.7400	COLO	9421000	Colorado R above Hoover Dam
DAVIS	35.2000	-114.5700	COLO	9423000	Colorado R above Davis Dam, AZ-NV
PARKR	34.3200	-114.1600	COLO	9426000	Colorado R above Parker Dam, AZ-CA
IMPRL	32.8800	-114.4700	COLO	9427520	Colorado R above Imperial Dam, AZ-CA
ALAMO	34.2900	-113.6000	COLO	9429500	Bill Williams R below Alamo Dam, AZ
FONTL	42.0280	-110.0600	COLO	9211150	Fontanelle Reservoir Inflow
FLGRG	40.9170	-109.5170	COLO	9234400	FlamingGorge
BLMSA	38.4500	-107.2000	COLO	9124800	BlueMesa
MRWPT	38.4500	-107.5000	COLO		MorrowPoint
CRYST	38.5100	-107.7500	COLO		Crystal
TYLPK	38.8170	-106.6040	COLO	9109209	TaylorPark
VLCTO	37.3780	-107.5730	COLO	9353500	Vallecito
NAVJO	36.8000	-107.6120	COLO	9355200	Navajo
PANIA	38.9420	-107.3510	COLO	9131400	Paonia
RDGWY	38.2310	-107.7560	COLO	9146200	Ridgway
MCPHE	37.5770	-108.5720	COLO	9169000	McPhee
VIRGN	37.2040	-113.1000	COLO	9406000	Virgin R at Virgin
HRCAN	37.1720	-113.3860	COLO	9408150	Virgin R nr Hurricane

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
LTLFD	36.8920	-113.9240	COLO	9415000	Virgin R at Littlefield
GRAND	36.1010	-112.8560	COLO	9402500	Colorado R nr Grand Canyon, AZ
GRGRW	41.4510	-109.4480	COLO	9217000	Green R nr Green River, WY
LCDVA	36.1950	-111.7760	COLO	9402300	Little Colorado R abv Mouth nr Desert View, AZ
SRFGR	38.9000	-110.3690	COLO	9328500	San Rafael R nr Green River, UT
STWBY	40.1550	-110.5540	COLO	9288180	Strawberry R nr Duchesne, UT
WTWTS	39.9790	-109.1780	COLO	9306500	White R nr Watson, UT
PRALF	36.7000	-111.7000	COLO	9382000	Paria R at Lees Ferry, AZ
LCCRN	35.9260	-111.5670	COLO	9402000	Little Colorado R nr Cameron, AZ
LOBAT	37.0780	-105.7560	RIOG		Grande R nr Lobatos CO
CHAMA	36.0740	-106.1110	RIOG		Chama R nr Chamita NM
ALBUQ	35.0890	-106.6800	RIOG		Grande R at Albuquerque NM
DELNO	37.6890	-106.4610	RIOG		Grande R nr Del Norte CO
RRMON	44.6560	-112.3710	MO		Red Rock R bl Lima Reservoir nr Monida MT
BVHGM	45.0030	-112.8540	MO		Beaverhead River near Grant MT
BVHBT	45.1160	-112.7510	MO		Beaverhead River at Barretts MT
RRALD	45.1920	-112.1420	MO		Ruby River ab Reservoir nr Alder MT
BHWSD	45.6190	-113.4570	MO		Big Hole River bl Big Lake Cr at Wisdom MT
BHMRS	45.5270	-112.7020	MO		Big Hole River near Melrose MT
JFRTF	45.8980	-111.5970	MO		Jefferson River near Three Forks MT
MHLGM	44.8670	-111.3380	MO		Madison River bl Hebgen Lake nr Grayling MT
MDELM	45.4900	-111.6340	MO		Madison River bl Ennis Lake nr Mcallister MT
GGGMT	45.4970	-111.2710	MO		Gallatin River near Gallatin Gateway MT
GLRLG	45.8850	-111.4380	MO		Gallatin River at Logan MT
MRTST	46.1460	-111.4210	MO		Missouri River at Toston MT
SFLMT	46.7960	-111.1790	MO		Smith River near Ft Logan MT
SREFL	46.8280	-111.1920	MO		Smith River bl Eagle Cr nr Fort Logan MT
MRFBT	47.8170	-110.6670	MO		Missouri River at Fort Benton MT
CBCMT	48.6330	-112.3470	MO		Cut Bank Creek at Cut Bank MT

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
MRSMT	48.4270	-111.8900	MO		Marias River near Shelby MT
MRVGL	48.0050	-110.2580	MO		Missouri River at Virgelle MT
MRLDK	47.6310	-108.6880	MO		Missouri River near Landusky MT
MHLMT	46.4300	-109.8410	MO		Musselshell River at Harlowton MT
MRUMT	46.4280	-108.5730	MO		Musselshell River near Roundup MT
MWCIB	49.0070	-112.5460	MO		Milk River at Western Crossing of Int Bndry
MRMRA	49.1440	-112.0800	MO		Milk River at Milk River Alberta
YYNPW	44.5670	-110.3810	MO		Yellowstone River at Yellowstone Lk Outlet YNP, WY
YCSMT	45.1120	-110.7940	MO		Yellowstone River at Corwin Springs MT
YLWLT	45.5970	-110.5660	MO		Yellowstone River near Livingston MT
SRLMT	45.7380	-110.4800	MO		Shields River nr Livingston MT
BBTMT	45.8340	-109.9390	MO		Boulder River at Big Timber MT
SABMT	45.5510	-109.3870	MO		Stillwater River near Absarokee MT
CYRMT	45.0100	-109.0650	MO		Clarks Fork Yellowstone River nr Belfry MT
YLWBL	45.8000	-108.4670	MO		Yellowstone River at Billings MT
WRRWY	43.0110	-108.3770	MO		Wind River at Riverton, WY
LWRWY	42.9970	-108.3750	MO		Little Wind River rear Riverton, WY
WBSWY	43.4250	-108.1790	MO		Wind R Bl Boysen Res WY
GBMWY	44.1560	-108.8770	MO		Greybull River at Meeteetse, WY.
BRKWY	44.7590	-108.1810	MO		Bighorn River at Kane, WY
NSWWY	44.4690	-109.4310	MO		North Fork Shoshone River at Wapiti, WY
SSABB	44.4330	-109.2520	MO		South Fork Shoshone R ab Buffalo Bill Res, WY
SSBBB	44.5170	-109.0980	MO		Shoshone River below Buffalo Bill Reservoir, WY
BHSTX	45.3170	-107.9190	MO		Bighorn River near St. Xavier, MT
LBHMT	45.7360	-107.5570	MO		Little Bighorn River near Hardin MT
TSLMT	45.0090	-106.8360	MO		Tongue River at State Line nr Decker MT
YLWMC	46.4220	-105.8610	MO		Yellowstone River at Miles City MT
PDRMH	45.0570	-105.8780	MO		Powder River at Moorhead MT
PDRLC	46.4300	-105.3100	MO		Powder River near Locate MT
YLWSD	47.6780	-104.1570	MO		Yellowstone River near Sidney MT
MRWLT	48.1130	-103.7180	MO		Missouri River nr Williston, ND

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
NPNCO	40.9370	-106.3380	MO		North Platte River near Northgate, CO
NPSRW	41.8720	-107.0580	MO		N Platte Riv ab Seminoe Reservoir, Nr Sinclair, WY
MBSRW	42.0100	-106.5130	MO		Medicine Bow R ab Seminoe Reservoir, Nr Hanna, WY
SRLWY	42.1560	-106.9090	MO		Seminoe Reservoir near Leo, WY
SWAWY	42.4580	-107.1960	MO		Sweetwater River near Alcova, WY
NPOWY	42.6510	-105.1630	MO		North Platte River at Orin, WY
NPRGN	42.2810	-104.7550	MO		North Platte River below Guernsey Reservoir, WY
LPCWY	41.1380	-105.9810	MO		Laramie R and Pioneer Canal Nr Woods Landing, WY
CHLCO	39.2090	-105.2670	MO		Cheesman Lake, CO
SPRSP	39.4090	-105.1700	MO		South Platte River at South Platte, CO
CLPCO	40.6640	-105.2240	MO		Cache La Poudre R A Mo of Cn, Nr Ft Collins, CO
DBCMT	47.1990	-112.0960	MO		Dearborn River near Craig MT
GBSRS	47.6000	-112.7590	MO		Gibson Reservoir MT
MRFPD	48.0440	-106.3560	MO		Missouri River below Fort Peck Dam MT
NPGRW	42.4570	-104.9480	MO		North Platte River below Glendo Reservoir, WY
STVLC	40.2180	-105.2600	MO		St. Vrain Creek at Lyons, CO.
GARSN	47.5000	-101.4300	MO	6338490	Missouri River at Garrison Dam, ND
OAHE_	44.3580	-100.3900	MO	6439980	Lake Oahe near Pierre, SD
GAVPT	42.8400	-97.4800	MO		Gavins Point Dam, SD
FTRND	43.0670	-98.5700	MO	6453000	Fort Randall Dam, SD
SIOUX	42.4860	-96.4140	MO	6486000	Sioux City, IA
OMAHA	41.2590	-95.9220	MO	6610000	Missouri River at Omaha, NE
NECTY	40.6820	-95.8470	MO	6807000	Missouri River at Nebraska City, NE
KSCTY	39.1120	-94.5880	MO	6893000	Missouri River at Kansas City
BOONV	38.9780	-92.7540	MO	6909000	Missouri River at Boonville
HERMN	38.7100	-91.4390	MO	6934500	Missouri River at Hermann
RILEY	39.0530	-96.7760	MO	6879100	Kansas River at Fort Riley, KS
BAGNL	38.1910	-92.6070	MO	6926000	Osage River nr Bagnell, MO
PLNVW	44.5320	-101.9300	MO	6438500	Cheyenne Rv nr Plainview, SD

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
TESCO	39.0040	-97.8740	MO	6869500	Saline River at Tescott, KS
MCOOK	40.1880	-100.6180	MO	6837000	Republican R at McCook, NE
ROSCO	41.1260	-101.5760	MO	6764880	South Platte R. at Roscoe, NE
HURON	44.3640	-98.1990	MO	6476000	James River at Huron, SD
JLSBG	40.9790	-102.2540	MO	6764000	South Platte River at Julesburg, CO
SPAUL	41.2040	-98.4460	MO	6785000	Middle Loup R at St Paul, NE
LITLR	34.7500	-92.2740	ARKRED	7263500	Arkansas River at Little Rock, AR
ARTHR	33.8750	-95.5020	ARKRED	7335500	Red River at Arthur City, TX
LUKFA	33.9410	-94.7580	ARKRED	7338500	Little R bl Lukfata nr Idabel
HASKE	35.8210	-95.6390	ARKRED	7165570	Arkansas River nr Haskell
INDEX	33.5520	-94.0410	ARKRED	7337000	Red River at Index, AR
MUSKO	35.7690	-95.2970	ARKRED	7194500	Arkansas River near Muskogee, OK
SHRVP	32.5130	-93.7970	ARKRED	7344480	Cross Lake at Shreveport, LA
RALST	36.5040	-96.7280	ARKRED	7152500	Arkansas River at Ralston, OK
DE_KA	33.6830	-94.6950	ARKRED	7336820	Red River near De Kalb, TX
INDEP	37.2240	-95.6790	ARKRED	7170500	Verdigris River At Independence, KS
COMRC	36.9290	-94.9570	ARKRED	7185000	Neosho River nr Commerce, OK
KAWLK	36.6000	-96.9220	ARKRED	7148130	Kaw Lake near Ponca City, OK
BUREN	35.4280	-94.3600	ARKRED	7250500	Arkansas R at Van Buren, AR
PLYMO	38.3980	-96.3560	ARKRED	7182250	Cottonwood River near Plymouth, KS
CLARE	36.3070	-95.6980	ARKRED	7176000	Verdigris R nr Claremore, OK
ATASC	28.6219	-98.2811	GULF	8208000	Atascosa Rv nr Whitsett, TX
SABMN	32.6136	-95.4856	GULF	8018500	Sabine Rv nr Mineola, TX
SABGW	32.5269	-94.96	GULF	8020000	Sabine Rv nr Gladewater, TX
NECHE	31.1328	-94.8097	GULF	8033000	Neches Rv nr Diboll, TX
KEOKR	40.3936	-91.3742	UP	5474500	Mississippi River At Keokuk, IA
ROCKR	41.5561	-90.1853	UP	5446500	Rock River Near Joslin, IL
IOWAR	41.1781	-91.1819	UP	5465500	Iowa River At Wapello, IA
DESMN	40.7278	-91.9594	UP	5490500	Des Moines River At Keosauqua, IA
ILLIR	39.7033	-90.6453	UP	5586100	Illinois River At Valley City, IL
ALTON	38.885	-90.1808	UP	5587500	Mississippi River At Alton, IL
ANOKA	45.1917	-93.3944	UP	5283500	Mississippi River At Anoka, MN
WINON	44.0556	-91.6375	UP	5378500	Mississippi River At Winona, MN

Table A3. VIC Streamflow Locations from UW[1]

VIC ID	LAT	LON	REGION	ID	NAME
MINNR	44.6931	-93.6417	UP	5330000	Minnesota River Near Jordan, MN
STCRX	45.4069	-92.6469	UP	5340500	St. Croix River At St. Croix Falls, WI
CHIPR	44.631	-91.9713	UP	5369500	Chippewa River At Durand, WI
ROOTR	43.7847	-92.03	UP	5383950	Root River Near Pilot Mound, MN
WISCR	43.1981	-90.4433	UP	5407000	Wisconsin River At Muscoda, WI

[1]The UW streamflow model metadata was drawn from records available from UW and is incomplete. Follow-on efforts at NCAR are revising these models and metadata.

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Appendix B

Frequently Asked Questions

Appendix B

Frequently Asked Questions

1. How do the VIC model applications perform under observed historical conditions?

Evaluation of the Variable Infiltration Capacity (VIC) applications' simulation under historical observed weather conditions (Maurer et al., 2002) reveals that simulation performance varies among streamflow locations and runoff basins. Generally speaking, for basins and streamflow locations where the VIC model applications received calibration, the VIC applications do a reasonable job reproducing historical monthly and annual runoff.   However, for locations that did not receive calibration (including subbasins within a calibrated basin), the VIC simulated runoff error relative to observed runoff was sometimes significant. Users should be aware of these biases when using hydrologic projection results. Biases may be handled in various ways (e.g., runoff bias-correction discussed in Reclamation [2011] or abstracting runoff change scenarios across different periods in the hydrology projections).

2. For BCSD hydrologic projections, what are some planning applications that might be supported?

The Bias-Correction Spatial Disaggregation (BCSD) hydrology projections can be used to support a wide range of planning applications, both period-change analyses and time-evolving views of how monthly to annual hydrologic conditions develop. However, limitations of this archive should be understood in developing and interpreting results from this archive. Example planning applications could include analyzing changes in:

- Precipitation and temperature across a contributing basin
- Snow conditions, specifically snow water equivalent conditions
- Streamflow for a contributing basin
- Evapotranspiration rates in a basin

Similar types of change analysis can be conducted using soil moisture conditions across basins providing insights into wet dry conditions in selected basins.

3. What are some uncertainties associated with using BCSD hydrologic projections for these applications, and how might a level of confidence in using these projections vary by application?

Assessing hydrologic impacts using the BCSD- Coupled Model Intercomparison Project phase 3 (CMIP3) hydrologic projections should be considered in the context of the following analytical uncertainties.

- **Generating daily weather sequences consistent with monthly BCSD climate projections:** The temporal disaggregation method from Wood et al. (2002) translated monthly BCSD climate projections into daily VIC weather forcing data. However, other techniques might have been considered. 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 activity analyzes natural runoff response to changes in precipitation, temperature, and change in natural vegetation potential evapotranspiration, while holding other watershed features constant. Other watershed features might be expected to change as climate changes and affects runoff (e.g., vegetation affecting evapotranspiration [ET] and infiltration, etc.). 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 are difficult to consider due to lack of available information to guide such an adjustment.

- **Hydrologic modeling:** The hydrology model that was used excludes groundwater interaction with surface water systems. The fate of precipitation is modeled as loss only to runoff and ET, while loss of precipitation to deep percolation and return flows to stream channel networks are not considered in the VIC hydrology model.

- **Model calibration and simulation bias:** Where the VIC applications have been calibrated, they do a good job reproducing the past with little bias (e.g., Colorado River at Imperial Dam, or Feather River at Oroville). Where the VIC applications have not been calibrated, they can exhibit significant bias. The location-specific implications of calibration, or lack thereof, on the conclusions of the study have not been exhaustively quantified, but some examples are offered in related documentation (Reclamation, 2011). It is clear from the streamflow bias correction analysis that calibration can make a large (first order) difference in the simulated flows and have some significant effects on the simulated changes in some flow metrics as well (Maurer et al., 2010).

- **Spatial resolution of the applications:** In addition to these issues, and related to the calibration issue, there is probably also a threshold spatial scale below which the simulated runoff results should be interpreted cautiously; however, it is not altogether clear how to determine this scale. For example, for larger basins (e.g., Feather River above Oroville and larger), the VIC applications are generally capable of sufficiently simulating monthly to annual runoff aspects. However, for smaller basins (e.g., Little Truckee River above Boca), it is questionable whether the VIC applications are sufficient. The insufficiency can be traced, in part, to the model's 12-kilometer by 12-kilometer grid, although the model does account for some subgrid scale variability statistically. Users are encouraged to keep this issue in mind as they extract information from this projection resource.

- **Time resolution of the applications:** Similar considerations might be given to temporal aspects of these projections. Although simulations were conducted at daily time steps, the applications were calibrated to reproduce monthly and annual runoff characteristics at a subset of locations in the basin. For this reason, users should cautiously interpret the daily hydrologic information provided by these simulations. The daily runoff information is physically consistent with assumed weather forcings and hydrologic model structure; however, there could be significant simulation biases at the submonthly level, just as there are spatial biases for small watersheds, as discussed in the section above.

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Appendix C

Graphics Complementing Sections 3 and 4 of Main Report

Appendix C

Graphics Complementing Sections 3 and 4 of Main Report

Section 3 of the main report addresses questions about how historical hydrologic simulation may be affected by using Variable Infiltration Capacity version 4.1.2, rather than version 4.0.7. Section 3.1 identifies a list of 43 Western U.S. basins for which historical simulations were evaluated, representing a diverse set of basin hydroclimates. Section 3.2 uses simulated runoff in the Upper Colorado River above Lees Ferry, Arizona, as an example (basin 13 in section 3, table 3) and illustrates how version updates affect agreement in simulated monthly and annual runoff volumes, as well as agreement in 50-year mean monthly and annual volumes. This appendix provides graphical results for the other 42 basins evaluated in section 3 of the main report, but it leaves the exercise of interpreting and summarizing results to the reader.

Section 4.2 of the main report addresses questions about how Bias-Correction Spatial Disaggregation applied to Coupled Model Intercomparison Project phase 3 and phase 5 (hydro) basin-integrated hydroclimate changes compare and contrast. Section 4.2 also provides graphic illustrations of such changes over the Upper Colorado Basin and discusses how to interpret these graphical results. This appendix provides graphical results for seven additional case study basins (among the 43 evaluated in section 3 and listed in table 3 of the main report), but it leaves the exercise of interpreting and summarizing results to the reader:

- 2. Klamath River near the California/Oregon border
- 6. Snake River at Brownlee, Idaho
- 19. Sacramento River near Freeport, California
- 22. San Joaquin River near Vernalis and below Mendota Pool, California
- 31. Rio Grande at Elephant Butte Dam, New Mexico
- 38. Truckee River at Nixon, Nevada
- 41. North Fork Platte River near Lake McConaughy, Nebraska

Graphics are included in the compressed archive located at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.AppendixC.Figures.zip. Graphic file names are <two-digit basin i.d. from Section 4.2 of the main report>_Fig<figure number from Section 4.2>_<basin name>.emf.