

**ASSESSMENT OF WATER AVAILABILITY AND ASSOCIATED DRIVERS FOR HISTORIC AND
FUTURE CONDITIONS**

FINAL REPORT

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PUBLIC SUMMARY

The increasing availability of climate projections provides natural resource managers and scientists with a number of scenarios from which to estimate variability in hydrologic response to future climatic conditions. This presents a need for consistent and efficient conversion of climate data into model-ready format, archiving and indexing of model simulation results, and the visualization and summation of model simulation results. Furthermore, decision-makers need this information at specific locations and for specific periods of record to effectively manage their water resources. This final report summarizes a collaborative effort to help address these issues through the construction of the Monthly Water Balance Model Futures Portal for the conterminous United States.

A monthly water balance model (MWBM) was used to simulate historical and future climatic conditions from 222 gridded climate datasets for the years 1950 through 2099 across the conterminous United States (CONUS). The MWBM meteorological and hydrologic input and output variables were indexed to geographic information system (GIS) features of the Geospatial Fabric for National Hydrologic Modelling, a hydrographic database built upon the National Hydrography Datasets Plus stream network (Viger and Bock, 2014). Using the Geospatial

Fabric stream network allows users access to and visualization of MWBM results at locations across the CONUS.

The primary contributions of this project are the following:

- A. The creation of a portal and database that allows users to summarize hydrologic response to historical and potential future climatic conditions across the CONUS.
- B. The development of hydrologic regionalization and calibration methods to estimate magnitude and variability of hydrologic response in areas with little or no measured streamflow information.
- C. Streamlining best-management practices, workflows, and information architecture by leveraging existing expertise, support, and contributions from scientific communities across U.S. Geological Survey (USGS) and the Department of the Interior (DOI).

TECHNICAL SUMMARY

The three goals of the project were to assess the

- A. Accuracy of climate drivers (precipitation and temperature) from different sources for historical conditions
- B. Hydrologic effect of these drivers on MWBM outputs
- C. The assessment of the sources and magnitudes of consumptive water use for the SC CSC region.

The first goal, assessment of the accuracy of climate drivers (climatic inputs to hydrologic models), was completed by comparing the distribution of precipitation (PPT) and temperature (TAVE) for historical conditions (1950-2000) for 96 climate simulations derived from station-based and downscaled general circulation model (GCM) climate datasets (Table 1) (Bureau of Reclamation, 2011; 2013) with the distribution of PPT and TAVE derived from the station-based Gridded Station-Based Dataset (GSD) (Table 1) (Maurer and others, 2002) across the CONUS. The U.S. Geological Survey (USGS) Geo Data Portal (GDP; Blodgett, 2013) was used to summarize the datasets per Geospatial Fabric Hydrologic Response Unit (HRU; Viger and Bock, 2014). The two-sample Kolmogorov-Smirnov Test (KS test) was used to assess the accuracy of the climate drivers (Conover, 1971). The KS test was used to evaluate if each PPT and TAVE from each downscaled GCM dataset matched historical conditions of an “observed” dataset (GSD) at each HRU.

The completion of the second goal, the assessment of the hydrologic effects of these drivers by using a Monthly Water Balance Model (MWBM), involved a more detailed methodology. The MWBM is a modular accounting system that provides monthly estimates for fluxes of hydrologic processes using inputs of PPT, TAVE, latitude, and available soil moisture. The MWBM (Figure 1) also includes concepts of climatic water supply and demand (McCabe and Wolock, 2011). A number of modifications and additional parameterizations were made to the existing MWBM (McCabe and Markstrom, 2007). The most important aspect of this work was the development of parameter calibration and regionalization methods for the MWBM. The research and methods developed for this section were leveraged with expertise from the USGS Powell Center Group “Water Availability for Ungaged Basins” (Kiang and Archfield, 2013). Spatial patterns in model parameter sensitivity derived from the Fourier Amplitude Sensitivity

Test (FAST) (Saltelli and others, 2011) formed the basis for organizing HRUs into distinct calibration groups for calibration and regionalization. A unique model calibration was implemented for each of the 110 calibration groups. This process resulted in a single, optimized MWBM parameter set for each calibration group, which was applied to all HRUs within each calibration group, in both gaged and ungaged areas. As with the precipitation and temperature climate drivers from the GCMs, the KS test was applied to determine if the simulated MWBM runoff (RUN) generated from using the PPT and TAVE from the downscaled GCM simulations matched the simulated MWBM RUN generated from the GSD.

The third goal, the assessment of the sources and magnitudes of consumptive water use, was not completed to the full extent that was outlined in the proposal. We developed strategies beyond the context of this proposed study that we would like to pursue. These ideas for the third goal are discussed in the section “Conclusions and Recommendations.”

PURPOSE AND OBJECTIVES

This project represents the first regional-scale application of the National Hydrologic Model (NHM) and Geospatial Fabric. Much of the work parameterizing, calibrating, and regionalizing the MWBM was leveraged by the authors’ contributions to the USGS Powell Center Group “Water Availability for Ungaged Basins” (Kiang and Archfield, 2013, <https://powellcenter.usgs.gov/view-project/5266f234e4b0992695a7fc07>). The calibration and regionalization methods and results developed from the project will be used for further work across the CONUS to help develop and constrain hydrologic modeling approaches for efforts such as the USGS Water Census Initiative (<http://water.usgs.gov/watercensus>). Model results will also be used and referenced by other regional projects such as the Gulf Coast Plains & Ozarks Landscape Conservation Cooperative funded project: “Assessment of Water Availability and Streamflow Characteristics in the Gulf Coastal Plains” (LaFontaine and others, 2013).

The developed portal and database provides the public and scientific community with a basic platform for ecological or water resources management applications. The regionalized parameter sets developed from the regionalization and calibration methodology will be shared with other USGS researchers performing climate change research with the MWBM, such as the National Climate Change Viewer (Alder and Hostetler, 2013, http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp).

Numerous USGS communities contributed their expertise in data integration, scientific computing, and web development to the development of the database and portal. The workflow and infrastructure for the portal can serve as a model for building additional databases and portal services as hydrologic modeling is expanded across the country. The USGS Core Science Systems Mission Area provided access and space on its high performing computing services for batch model simulation and post-processing. This allowed the authors to automate the complete model workflow from climate data ingestion to calibration and through the synchronization of new model results with the database. In addition to summation of climate data for the Geospatial Fabric using the GDP, the USGS Center for Integrated Data Analytics (CIDA) provided guidance for the design and formatting of the MWBM files and server space for the database. The use of the Climate and Forecasts metadata convention (Open-source Project for a Network Data Access Protocol, Inc., 2013) enabled the database to be accessed by or incorporated into a variety of web mapping and data services (<http://www.unidata.ucar.edu/software/netcdf/index.html>).

The USGS Information Science Branch, the USGS Fort Collins Science Center, and North Central Climate Science Center, listed as co-authors, built the infrastructure that tied the Geospatial Fabric Web Feature Service to the database portal, and developed the capability to dynamically extract, package, and visualize model results. More details about the capabilities of the portal are listed later in this report.

As stated previously, the one project goal that was not completed was the estimation of the sources and magnitudes of consumptive water use. This was due to the time and resource limitations, and greater emphasis was placed on development of calibration and regionalization methods, database structure, and portal development. The calibration and regionalization work was more heavily weighted because of the authors' involvement and work with the Powell Center Group. As the portal and database will serve as the basis for national work for both the MWBM and other models such as the daily time-step Precipitation Runoff Modeling System (PRMS), more effort was placed on creating a consistent database structure. Portal development required much more effort than was anticipated in the proposal.

This goal is being addressed through a follow-up FY17-18 research project funded by the Water Availability and Use Science Program (WAUSP). The research ("Streamflow Accumulation Analysis to Identify Gains and Losses in High-Order Reaches") aims to identify positive and negative correction factors for high-order reaches across the CONUS that can be used to help with streamflow routing and identify areas that are highly impacted by water use.

ORGANIZATION AND APPROACH

The approach and detailed step-by-step methods for completing the project goals are listed below. Climate datasets were first summarized for HRUs across the CONUS. The evaluation metrics for climate inputs (PPT and TAVE) for historical conditions were then developed. The MWBM was calibrated for historical conditions and used to simulate the downscaled GCM climate datasets for historical and future conditions. Runoff (RUN) generated by the MWBM using the climate inputs were evaluated for historical conditions using the same metrics as used for the climate inputs. Finally, the portal was constructed to allow users to dynamically generate graphics and summary reports for locations and variables of interest across the CONUS.

- *Summarize the gridded precipitation and temperature dataset to HRUs using climate datasets on the GDP*

The first objective of this project was to summarize precipitation (PPT) and temperature (TAVE) from gridded climate datasets available on the USGS Geo Data Portal (GDP). The GDP (<http://cida.usgs.gov/gdp/>), developed and maintained by the Community for Integrated Data Analytics (CIDA), was used to summarize the climate data by HRU (Blodgett and others, 2011). The GDP is a web-processing interface that provides dynamic, web-based GIS processing of gridded data based on user-supplied shapefiles. For a complete description of the GDP operability see Blodgett and others (2011). The GDP hosts or provides access to a large number of gridded climate datasets. For more efficient and automated retrieval of climate data, CIDA developed a python library (pyGDP) that can programmatically upload shapefiles, and summarize climate data per feature using open source capabilities.

To automate data retrieval and formatting from the GDP, the pyGDP library in the python language was utilized (Python Software Foundation, 2007). Geospatial Fabric HRUs were hosted on the USGS Science Base Catalog (<https://www.sciencebase.gov/>) and accessed by

the pyGDP to summarize the climate datasets available on the GDP. Time series of PPT and TAVE for each the datasets listed in Table 1 was summarized for each HRU using the GDP process described in the previous sentences. A number of different datasets were summarized for this project. GSD (Maurer and others, 2002) is a daily time-step gridded dataset interpolated from climate station observations for historical conditions (1949 through 2010). A number of statistically-downscaled general circulation models (GCM) were also summarized. A GCM is a climate model that is a coarse-scale representation of the Earth's atmosphere and oceans and is used for understanding long-term climate dynamics at continental or global scales (Bureau of Reclamation, 2013). In their base format GCMs have a very coarse spatial resolution (~150 km²). Many scientific assessments require information at finer spatial resolutions. One technique used to derive GCM information at finer scales is known as statistical downscaling (Wood and others, 2004). Statistical downscaling is a technique for deriving finer-scale interpolations from coarse-scale GCMs by deriving statistical relations between observed local-scale climate data, such as meteorological observations or gridded station data derived from historical climate observations, and the coarser-scale GCM variables (Wood and others, 2004). There are a number of different downscaled datasets available. The statistically-downscaled GCM simulations summarized for this project are from the bias-corrected spatially disaggregated (BCSD) coupled model intercomparison projects 3 (CMIP3) and 5 (CMIP5) (Table 1) (Bureau of Reclamation 2011; 2013).

Each CMIP group (CMIP3 and CMIP5) covers historical conditions, and diverges a number of different scenarios for future conditions, the primary scenarios being Special Report on Emission Scenarios B1, A1B, and A2 for CMIP3, and RCP (Representative Concentration Pathways) 2.6, 4.5, 6, and 8.5 for CMIP5 (Bureau of Reclamation, 2011; 2013). RCP2.6 from CMIP5 is excluded from the analysis to balance the number of emission scenarios from CMIP3 and CMIP5 to three each. These scenarios represent assumptions about future greenhouse gas emissions by taking into account short- and long-term climate cycles, and anthropogenic drivers such as changes in demographics, and economic and technological development (IPCC, 2000; Taylor and others, 2012). The numbers associated with each RCP for CMIP5 are named after the potential range of radiative forcing for each scenario in the year 2100 relative to pre-industrial values in watts per square meter. Conditions represented by these scenarios range from stabilized populations after 2050, coupled with rapid development of more efficient technological systems across the globe (A1B, RCP4.5), to globally increasing populations and regionally orientated economic development (A2, RCP8.5). For full description of the differences between the emissions scenarios/RCPs from CMIP3 and CMIP5, please consult IPCC (2000) for CMIP3 emission scenarios, and Taylor and others (2012) for CMIP5.

The PPT and TAVE from 96 climate simulations were summarized for each HRU across historical conditions (1950-2005), and 221 total climate simulations summarized across six scenarios (b1, a1b, and a2 for CMIP3; RCP4.5, RCP6.0, and RCP8.5 from CMIP5) for future conditions (2005-2099).

- *Develop Evaluation Metrics for Climate Datasets*

The second objective of the project was the evaluation of the accuracy of the climate drivers (PPT and TAVE) derived from downscaled GCMs for historical conditions. This was evaluated for historical conditions for PPT and TAVE for each dataset in Table 1 and builds upon previous work conducted by Hay and others (2014). The Kolmogorov-Smirnov test (KS test) was computed to determine the accuracy of the climate drivers of the GCMs (PPT and TAVE) for

historical conditions. The KS test is a non-parametric test that compares the probability distributions between two samples, often applied to compare a simulated set of data to one considered truth or observation (Conover, 1971). The KS test was calculated for the monthly PPT and mean monthly TAVE for each GCM for historical conditions (1950-2000).

The GSD was used as the “observed/truth” dataset against which the downscaled climate projections were compared. This is because the GSD was used as the training dataset for the statistical downscaling method that produced the BCSD CMIP3 and CMIP5 datasets (Table 1); therefore, distributions were expected to be generally comparable to the GSD. P-values for the KS-test were computed for each GCM input variable (PPT and TAVE) for each HRU in the CONUS. Figure 2 shows spatial differences of KS-test results for a portion of hydrologic/water resources region 11 (the Arkansas-White-Red region, <https://water.usgs.gov/GIS/regions.html>) for two downscaled GCMs using a p-value of 0.01.

- *Simulation using the Monthly Water Balance model*

The calibrated and regionalized MWBM was used to produce five different outputs (actual evapotranspiration (AET), potential evapotranspiration (PET), runoff (RUN), soil moisture storage (SOIL), and snow water equivalent (SWE)) for each of the climate datasets.

With the availability of the Geospatial Fabric (Viger and Bock, 2014), a number of modifications and enhancements were made to the MWBM. Spatially varying coefficients and physically-based parameters (latitude, soil-moisture storage capacity) were developed for each Geospatial Fabric HRU. Latitude was derived using the internal centroid of each HRU of the Geospatial Fabric. Spatially-varied soil moisture storage capacity, previously fixed at 150 mm for the entire CONUS for MWBM applications, was estimated for each HRU using a 1 km² grid derived from the Soils data for the Conterminous United States (Wolock, 1997). The MWBM calculates PET using the Hamon equation (Hamon, 1961). This original form of the Hamon equation was developed in the Southeastern United States, and performs well in similar humid, subtropical climates. However, estimates were found to be more variable in other physioclimatic regions of the country when compared to estimates derived from other methods. To improve PET estimates, the coefficient of the Hamon equation was calibrated for each HRU to match the PET estimates from the mean monthly free-water surface evaporation estimates of Farnsworth and others (1982) interpolated to a 5-km² grid. The free-water surface data are considered representative of mean monthly measured PET (Farnsworth and others, 1982).

This improvement to the Hamon equation within the MWBM provided both spatially and temporally varying estimates of PET calculated from the Hamon equation at every HRU across CONUS. Changes in mean monthly PET using the new calibrated coefficient are shown in Figure 3. Using the calibrated Hamon coefficient values to calculate PET indicated that PET had been underestimated for most of CONUS using the standard, fixed coefficient, except for the Southeastern CONUS where the coefficient was originally developed. This work is detailed in McCabe and others (2015).

In addition to these modifications made to the MWBM, a key part of this study was the development of parameter regionalization and calibration methods for the MWBM parameters that control different model processes (Table 2, Figure 4). Much of the support and contribution to the calibration and regionalization research comes from the authors’ involvement with the USGS Powell Center Research Group, Estimating Water Availability in Ungaged Rivers (Kiang and Archfield, 2013). This task was completed in following five steps (described in detail in the subsequent paragraphs): (1) parameter sensitivity analysis (SA) tests were implemented for each

HRU using the PPT and TAVE from the GSD climate dataset, (2) HRUs with similar parameter sensitivity and model behavior were grouped together into calibration groups, (3) potential streamgages were selected for calibration within each group delineated in step 2, (4) streamgages identified in step 3 were calibrated to generate a single, optimized parameter set for each calibration group, and (5) optimized parameters were assigned to all HRUs (gaged and ungaged) within each group.

The Fourier Amplitude Sensitivity Test (FAST), a parameter sensitivity analysis (SA) test, was implemented for the MWBM to identify areas of similar model behavior. Parameter SA calculates the total variability in the model output or objective function explained by each individual model parameter, the goal of which is the determination of the most important parameters for controlling the variability of model output (Reusser and others, 2011). FAST is a computationally efficient, global sensitivity algorithm that estimates variance of model output explained by each parameter (Saltelli and others, 2011).

To develop a structure for regionalizing model parameters, the spatial patterns in model parameter sensitivity derived from FAST were used as the basis for organizing HRUs into distinct groups for calibration and regionalization. These two groups were then spatially intersected to produce a dataset of grouped HRUs. Hydrologic region and sub-region boundaries, proximity, and significant topographic divides were used to further divide the dataset into unique MWBM calibration groups. The calibration groups across the CONUS are shown in Figure 5. Within each of these calibration groups, MWBM calibration was implemented to derive a single set of optimized MWBM parameters for all HRUs within a calibration group. This work is documented in Bock and others (2016a).

- *Assess accuracy of runoff simulated using the MWBM*

The third objective of the project was the evaluation of the accuracy of MWBM RUN for historical conditions. Similar to the metrics used to evaluate the similarity of the GCM inputs to the GSD dataset for historical conditions, the KS test was computed to compare the simulated RUN derived from the GCMs to the simulated RUN derived from the GSD dataset. Figure 6 shows the results for monthly and seasonal RUN simulated using two different downscaled GCMs. Results from the KS test across all GCMs were aggregated for each HRU for p-value = 0.01 and p-value = 0.05 to show the proportion of all GCMs that are dissimilar to RUN generated from GSD. Figure 7 shows the results for PPT, TAVE, and RUN for hydrologic region 11 using p-value = 0.05, and Figure 8 shows the results using p-value = 0.01.

- *Construction of the Monthly Water Balance Model Futures Portal*

The final part of the report is the description of the Monthly Water Balance Model Futures Portal (<https://my-beta.usgs.gov/mows/>). The portal allows users to query Geospatial Fabric features (summary nodes, streamgages, and hydrologic response units, to summarize and visualize model results at queried features using data from the MWBM database (http://cida-eros-mows1.er.usgs.gov/thredds/dodsC/nwb_pub/)). A large number of USGS personnel from multiple disciplines contributed to this part of the project.

MWBM inputs and outputs for each climate dataset were written to netCDF files that conform to the UCAR-1.6 standard (<http://cfconventions.org/>) (Open-source Project for a Network Data Access Protocol, Inc., 2013), all of which are stored in the MWBM database. The MWBM database also contains all information necessary to replicate the results, including model parameters and descriptors for the HRUs, the MWBM input variables (PPT and TAVE), and five

MWBM output variables (AET, PET, RUN, SOIL, and SWE). Files are written specific to each hydrologic region, and included in the filename is the name of the climate dataset, and whether the file contains local results by HRU or accumulated results by stream segment. CIDA contributed by streamlining basic netCDF file requirements and building and hosting the database. The database was published as a USGS ScienceBase data release (Bock and others, 2016b).

The portal was constructed by building a graphical user interface on top of a Web Feature Service of the Geospatial Fabric features. The mapping service allows users to query and identify geospatial fabric features across the United States. The mapping service was built by Roland Viger of USGS Modeling of Watershed Systems (MoWS) team, and Don Brown and Chris Emmerich of the USGS Information Science Branch based at the Fort Collins Science Center.

A number of simple, easy-to-understand plots were prepared to visualize the MWBM variables for historical and future conditions by Geospatial Fabric Feature (Figures 9-12). Marian Talbert of the North Central Climate Science Center developed the plots of the MWBM input and output variables (Talbert and others, 2014). Based on user input (Table 3) supplied at a web interface and provided to R (R Core Team, 2013) through command-line arguments, the codebase pulls appropriate climate data from the MWBM database and summarizes this information through the production of graphics and comma-separated-value files. The main function procures the simulated and streamgage specific data from the MWBM database and send the user-supplied options to the correct plot functions.

Chris Emmerich constructed the user interface and portal that ties the R scripts into the Geospatial Fabric mapping service. The portal incorporates a customized header, frames, and navigation options. Users can search for or scroll to hydrographic features using the Geospatial Fabric mapping service, and identify or select the appropriate Geospatial Fabric feature for which they want to summarize information.

The user-supplied arguments are submitted to the R scripts, which retrieves the user-specified data from the MWBM database and sends a window to the user's computer with the graphical summaries. The user can also download both the graphic in the portable network graphics (.png) format, and the data used to generate the graphic as a comma-separated-value (.csv) file.

PROJECT RESULTS

- *Analysis of downscaled climate drivers for historical conditions*
- *Assess accuracy of runoff simulated using the MWBM*

The KS test was used to evaluate how well PPT and TAVE for 95 downscaled GCM simulations from BCSD CMIP3 and CMIP5 replicated the GSD dataset for historical conditions. The test was evaluated by HRU for hydrologic region 11. Results from the KS tests are summarized for two dimensions. The first is the spatial representation of GCMs that are similar to GSD for PPT, TAVE, and RUN for each HRU across hydrologic region 11 for a given p-value. An example of these results were shown earlier for PPT (Figure 3). The KS test results can also be summarized across all HRUs for every GCM. Figures 7 and 8 show the percentage of GCMs for CMIP3 and CMIP5 that are not similar to the GSD dataset for individual HRUs across hydrologic region 11 for p-values of 0.05 (Figure 7) and 0.01 (Figure 8) for model input variables (PPT and TAVE) and model output (RUN).

Figures 7 and 8 illustrate the significant spatial differences in the ability of BCSD CMIP3 and CMIP5 data to replicate GSD dataset for PPT. In HRUs where there is significant dissimilarity between a given GCM and GSD for PPT, the differences in PPT propagate to differences in similarity in RUN. HRUs along the western edge of hydrologic region 11 are identified across many of the GCMs as having significantly different distributions of PPT/TAVE/RUN distributions from GSD. This may be an effect of downscaling at higher elevation HRUs, or an edge effect manifested in the climate-data-to-HRU summation.

These preliminary results are a work in progress and have been presented at several conferences. The methods and data are being prepared for an upcoming publication (Hay and others, 2017) that will be submitted to a peer-reviewed journal.

- *Simulation with the Monthly Water Balance model*

A parameter regionalization scheme to transfer parameter values from gaged to ungaged areas for a monthly water balance model (MWBm) was developed and tested for the conterminous United States (CONUS). The Fourier Amplitude Sensitivity Test, a global-sensitivity algorithm, was implemented on a MWBM to generate parameter sensitivities on a set of HRUs across the CONUS. The HRUs were grouped into 110 calibration regions based on similar parameter sensitivities. Subsequently, measured runoff from 1,575 USGS streamgages within the calibration regions were used to calibrate the MWBM parameters to produce parameter sets for each calibration region. Measured and simulated runoff at the 1,575 streamgages showed good correspondence for the majority of the CONUS. These methods maximize the use of available runoff information, resulting in a calibrated CONUS-wide application of the MWBM suitable for providing estimates of water availability at the HRU resolution for both gaged and ungaged areas of the CONUS. This work is explained in greater detail in Bock and others, 2016a.

The calibrated MWBM was driven with precipitation and temperature using a station-based dataset for historical conditions (1949 to 2010) and selected statistically-downscaled general circulation models (GCMs) for historical and future conditions (1950 to 2099) across the conterminous United States (CONUS) using hydrologic response units from the Geospatial Fabric for National Hydrologic Modeling (Viger and Bock, 2014). Six MWBM output variables (actual evapotranspiration (AET), potential evapotranspiration (PET), runoff (RUN), streamflow (STRM), soil moisture storage (SOIL), and snow water equivalent (SWE)) and the two MWBM input variables (atmospheric temperature (TAVE) and precipitation (PPT)) were summarized for hydrologic response units and aggregated at points of interest on a stream network. Results were then organized into the Monthly Water Balance Model Futures database, an open-access database using netCDF format (http://cida-eros-mows1.er.usgs.gov/thredds/dodsC/nwb_pub/). The data are documented and archived as a USGS data release (Bock and others, 2016b).

- *Construction of the Monthly Water Balance Model Futures Portal*

The USGS Monthly Water Balance Model Futures Portal provides simulated estimates of meteorological and hydrologic variables for 222 climate datasets, which were simulated using a Monthly Water Balance Model. The portal includes capabilities to dynamically disseminate plots and data summaries to the user using custom queries based on geographic location and meteorological or hydrologic variable of interest period of record, and other arguments. Multiple papers have been published or are being prepared for publication in the peer-reviewed literature describing project components. Phase I of the project is scheduled for completion in 2016 with

the launch of the web portal. The background, contents, and operation of the portal are described in two upcoming USGS publications currently in press (Bock, 2017; Bock and others, 2017).

ANALYSIS AND FINDINGS

This project represents the first CONUS-wide application of the Geospatial Fabric (Viger and Bock, 2014) and MWBM within the context of the National Hydrologic Model (NHM). One of the goals of the NHM was to improve *a priori* physically-based parameter estimates and to utilize calibration data from multiple hydrologic processes based on existing observational or interpolated data sources. The development of the spatially- and temporally-variable Hamon Coefficient (McCabe and others, 2015) provided PET estimates that more closely matched PET estimates used in other hydrologic models such as PRMS (Markstrom and others, 2015). The use of SNODAS estimates in the MWBM calibration helped to constrain the relevant model parameters to prevent unreasonable accumulation of SWE that had previously occurred in MWBM calibrations (Hay and McCabe, personal comm.).

The KS test shows that estimated PPT from BCSD CMIP5 data replicated historical conditions represented by PPT from the GSD dataset more accurately than estimated PPT from BCSD CMIP3. A small number of HRUs in the western hydrologic region 11 headwaters still show disagreement between BCSD and GSD datasets for both temperature and precipitation.

The calibration and regionalization methods introduced in this project worked well for most Calibration Groups across the CONUS (Bock and others, 2016). Poorer model correspondence seemed to relate to the cumulative area of the Calibration Group, the model correspondence performance from individual streamgage calibration, and the complexity of terrain and climate within each group.

CONCLUSIONS AND RECOMMENDATIONS

The uncertainty associated with the choice of GCM ensembles is greater than the uncertainty from the hydrologic model or natural variability (Prudhomme and Davies, 2009). Reproducing historical conditions has been suggested as the minimum standard for application of downscaled climate data in a hydrological model (Wood and others, 2004). Upon evaluating and comparing the results from the KS test for BCSD CMIP3 and CMIP5 data, the KS test evaluation should have been the first task completed. Doing this first would have allowed more exploration into constraints or additional metrics to offer users more choices for the ensemble of GCMs they would select for a particular geographic area or problem. Simple distribution tests and visualizations such as the KS test can help inform users on uncertainty and limitations of their choice of model drivers.

The results from the calibration and regionalization methodology suggest that parameter sensitivity analysis can be a useful tool to identify areas of similar model behavior, and that these areas share some portion of model parameter space that produces satisfactory model results. There are several modifications to the historical methodology that can be made to examine how to improve the calibration groups with poor results.

As mentioned in the “Technical Summary” and “Purposes and Objectives” sections, the work focused on consumptive use was not completed as stated in the proposal. One of the constraints developed by working with other USGS Hydrologists through the Powell Center Project is to avoid model calibration of streamgages with contributing areas greater than 3,000

km². This threshold was developed through examination of the basin properties of reference and non-reference quality streamgages across CONUS. Geospatial Fabric features potentially affected by this specific size constraint are shown for the SC CSC domain in Figure 13. While the historical calibration and regionalization schemes simulate streamflow for this “main stem” subset of stream segments, a conceptual enhancement for estimating consumptive use at these features is to develop a set of correction factors varying by Geospatial Fabric segment. A set of 12 monthly correction factors for each main stem segment with a streamgage as its terminal summary node would be developed. This will allow the identification of main stem segments that are gaining or losing flow according to the MWBM estimates and measured streamflow, even along the same major hydrologic features such as the Arkansas River. This development would be an important focus of future MWBM efforts because of the increased emphasis on accounting for consumptive use by efforts related to national initiatives such as USGS WaterSMART and Water Census.

OUTREACH

Publications:

Bock, A.R., Hay, L.E., McCabe, G.J., Markstrom, S.L., and Atkinson, R.D., 2016a, Parameter regionalization of a monthly water balance model for the conterminous United States: *Hydrology and Earth System Sciences*, v. 20, p. 2861–2876.

Hay, L.E., Bock, A.R., McCabe, G.J., Markstrom, S.L., and Atkinson, D.R., Do Downscaled General Circulation Models Reliably Simulated Current Climatic Conditions? (In Review)

McCabe, G.J., Hay, L.E., Bock, A.R., Markstrom, S.L., and Atkinson, D.R., 2015, Inter-annual and spatial variability of Hamon potential evapotranspiration model coefficients: *Journal of Hydrology*, v. 521, p. 389–394.

USGS Data Products:

Bock, A.R., Hay, L.E., Markstrom, S.L., and Atkinson, R.D., 2016b, Monthly Water Balance Model Monthly Water Balance Model Futures: U.S. Geological Survey data release, accessed June 15, 2016, at <http://dx.doi.org/10.5066/F7VD6WJQ>.

Viger, R.J., and Bock, A.R., 2014, GIS features of the Geospatial Fabric for National Hydrologic Modeling: U.S. Geological Survey, doi: <http://dx.doi.org/10.5066/F7542KMD>

Monthly Water Balance Model Futures Portal: <https://my.usgs.gov/mows/>

USGS Information Products

Bock, A.R., 2017, The U.S. Geological Survey Monthly Water Balance Model Futures Portal: U.S. Geological Survey Fact Sheet 2017-3002, 6 p., <https://doi.org/10.3133/fs20173002>.

Bock, A.R., Hay, L.E., Markstrom, S.L., Emmerich, Chris, and Talbert, Marian, 2016c, The U.S. Geological Survey Monthly Water Balance Model Futures Portal: U.S. Geological Survey Open-File Report 2016–1212, 21 p., <https://doi.org/10.3133/ofr20161212>

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Dataset	Period of Record	Resolution	Reference
GSD	1949-2010	1/8 ^o	Maurer and others, 2002
BCSD-CMIP3 ¹	1950-2099	1/8 ^o	Bureau of Reclamation, 2011
BCSD-CMIP5 ²	1950-2099	1/8 ^o	Bureau of Reclamation, 2013

Table 1. Datasets summarized for the Geospatial Fabric and used for monthly water balance model simulations.

Footnote 1: A1b, A2, B1 scenarios used. Individual general circulation model and associated runs used: BCCR BCM2-0 (1), CCCMA CGCM3-1 (1-5), CNRM CM3 (1), CSIRO MK3-0 (1), GFDL CM2-1 (1), GISS MODEL-E-R-2 (1-2), INMCM3-0 (1), IPSL-CM4-0 (1), MIROC3-2-MEDRES (1-3), MIUB-ECHO-G (1-3), MRI-CGCM2-3-2A (1-5), NCAR-CCSM3-0 (1-7), NCAR-PCM1 (1-4), UKMO-HADCM3-1 (1).

Footnote 2: rcp4.5, rcp6.0, rcp8.5 scenarios used. Individual general circulation model and associated runs used: BCC-CSM1-1-M (1), BCC-CSM1-1 (1), BNU-ESM (1), CanESM2 (1-5), CCSM4 (1-5), CESM1-BGC (1), CESM1-CAM5 (1-3), CMCC-CM (1), CNRM-CM5 (1,2,4,6), CSIRO-MK3-6-0 (1-5,6,8), EC-EARTH (2,6,8), FGOALS-G2 (1), FGOALS-S2 (2-3), FIO-ESm (1-3), GISS-E2-H-CC (1), GISS-E2-R (1-5), HADGEM2-AO (1), HADGEM2-CC (1), HADGEM2-ES (1), INMCM4 (1), IPSL-CM5A-LR (1-4), IPSL-CM5A-MR (1), IPSL-CM5B-LR (1), MIROC-ESM-CHEM (1), MIROC-ESM (1), MIROC5 (1).

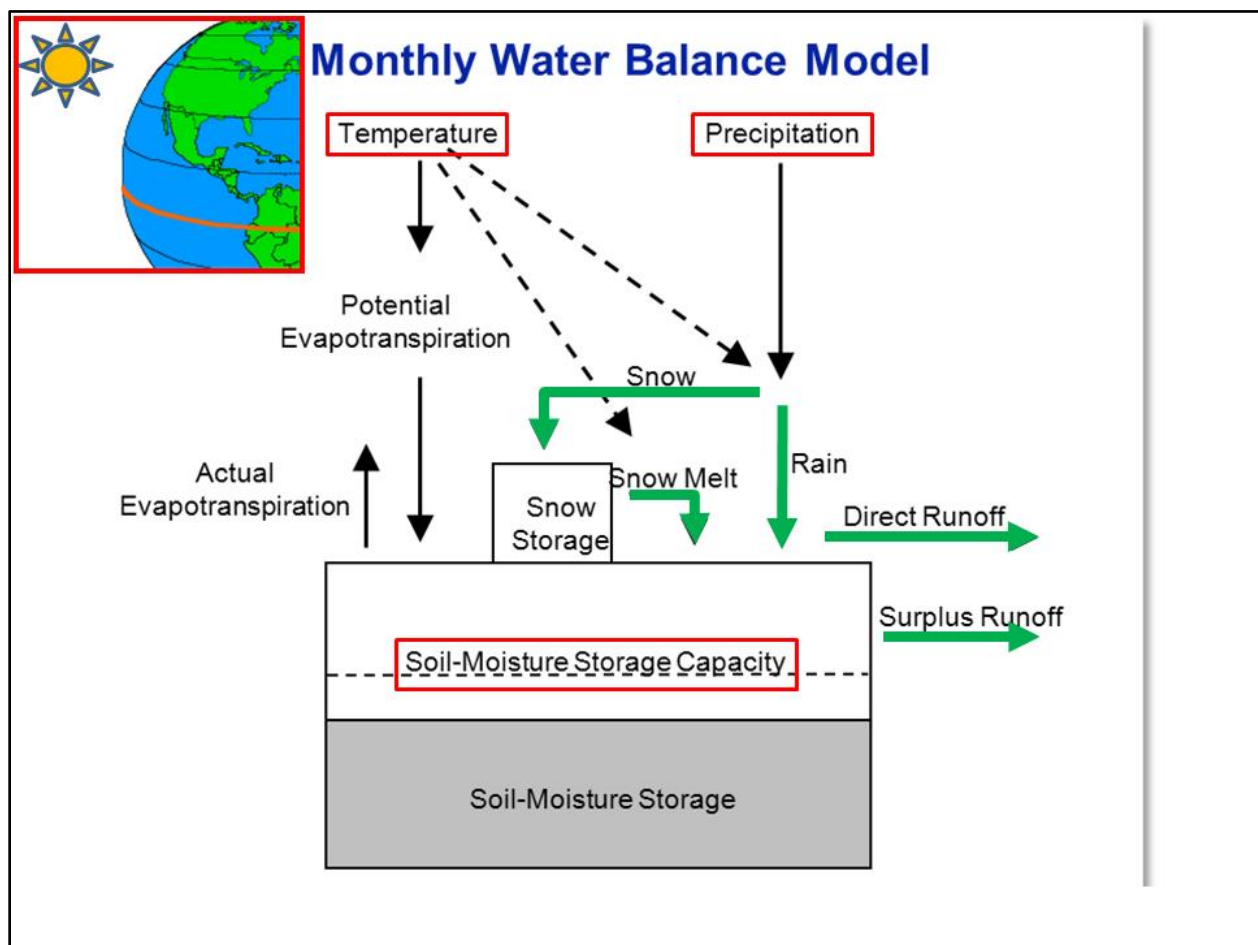


Figure 1. The Monthly Water Balance Model (MWBM) (McCabe and Markstrom, 2007). Model inputs and physically-based parameters are shown in red (Latitude, Temperature, Precipitation, Soil Moisture Storage Capacity); hydrologic processes controlled by model parameters are green arrows. Model outputs written to the database (red boxes) include Actual Evapotranspiration, Potential Evapotranspiration, Runoff, Snow Storage or Snow Water Equivalent, Soil Moisture Storage, and Runoff.

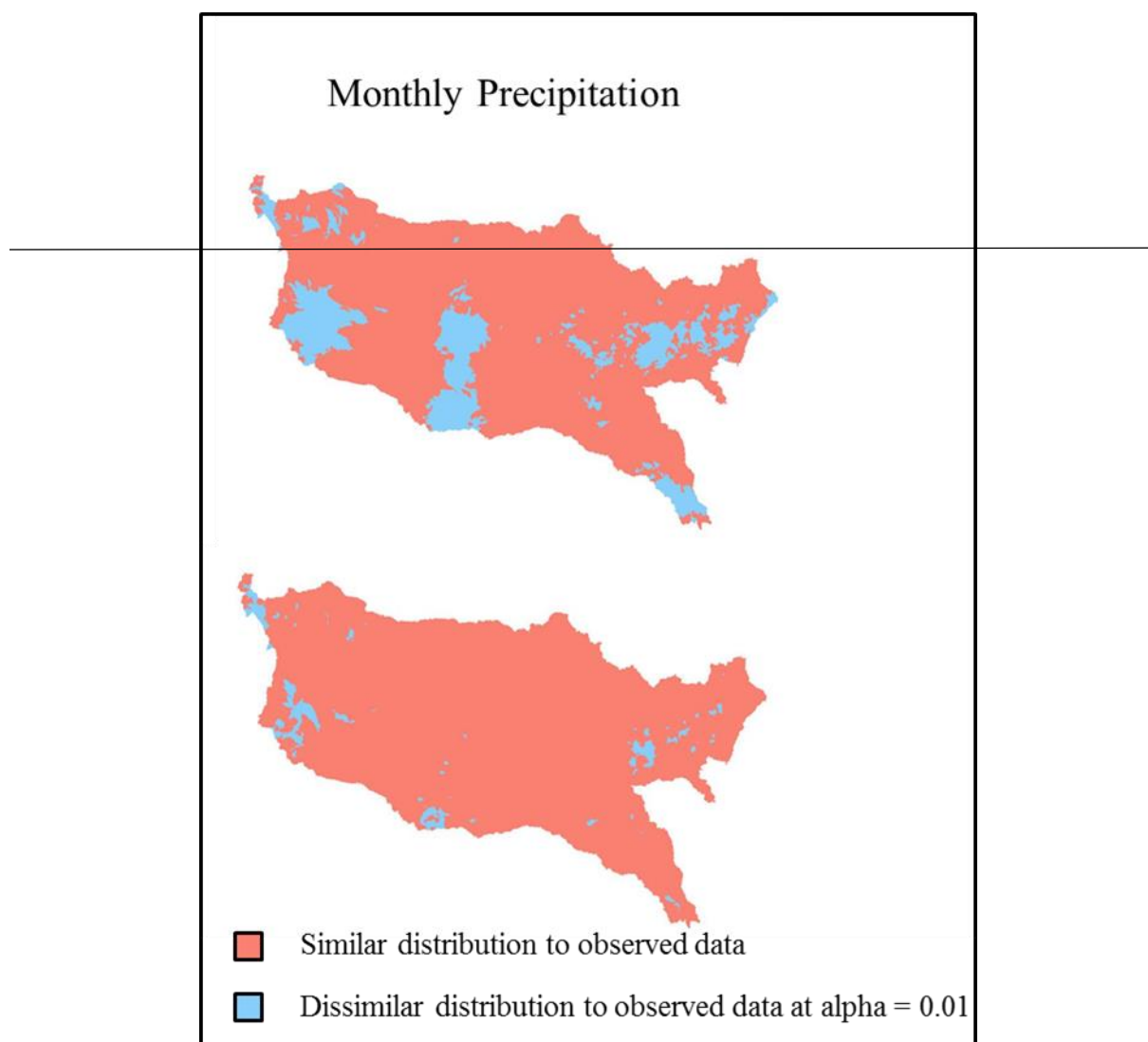


Figure 2. Maps showing differences in Kolmogorov-Smirnov test (KS test) results for hydrologic region 11 between KS test results for historical conditions (1950 to 2000) using Gridded Station Data (GSD) with GISS_Model_E_R general circulation model (GCM) (top row), and using GSD with CNRM_CM3_1 GCM (bottom row) for p-value (α) = 0.01.

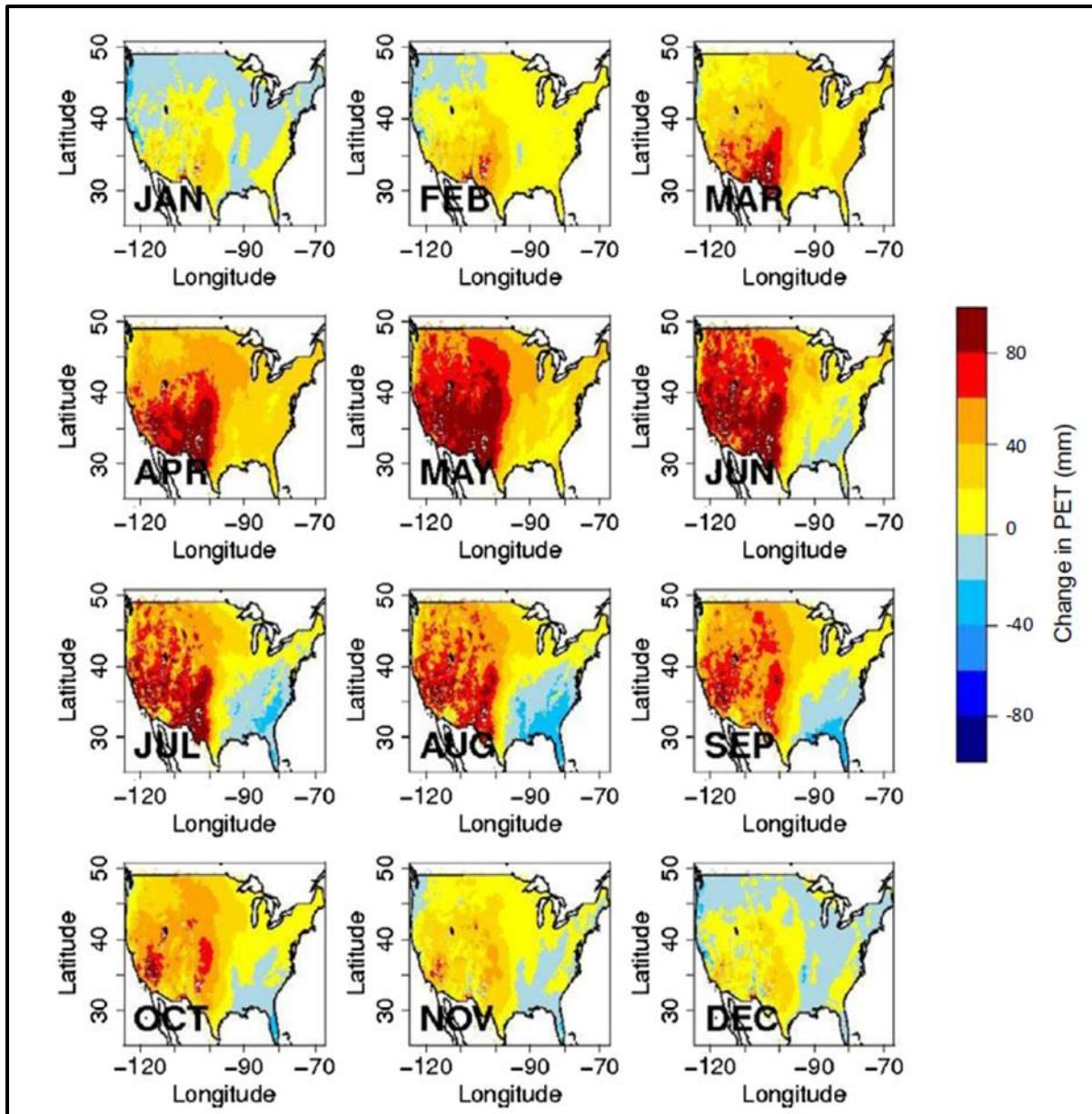
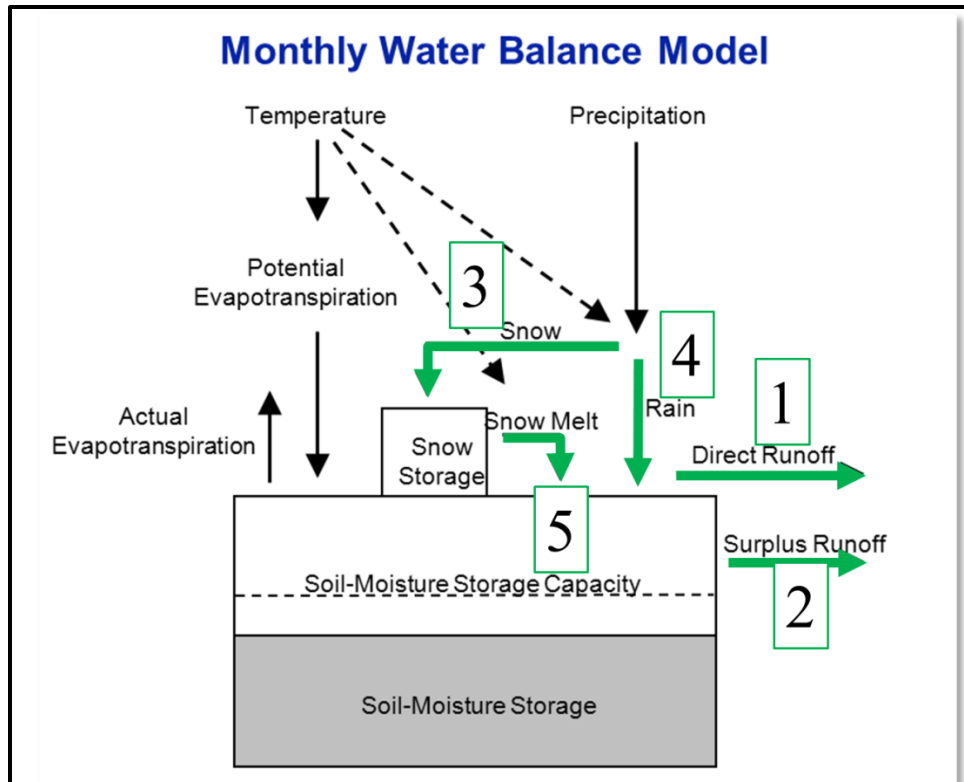


Figure 3. Changes in mean monthly Hamon potential evapotranspiration (PET) computed using calibrated monthly coefficients. The figure is from McCabe and others (2015).



Parameter	Lower	Upper	Definition
1) drofac	0	0.1	Controls fraction of monthly precipitation converted to direct runoff
2) rfactor	0.1	1.0	Controls fraction of monthly surplus converted to direct runoff
3) T _{snow}	-6.0	-2.0	Temperature below which all precipitation is considered snow
4) T _{rain}	0.0	10.0	Temperature above which all precipitation is considered rain
5) meltcoef	0.0	1.0	Fraction of snow storage that melts in a month

Figure 4 (above) Table 2 (below). Monthly water balance model parameters and their ranges.

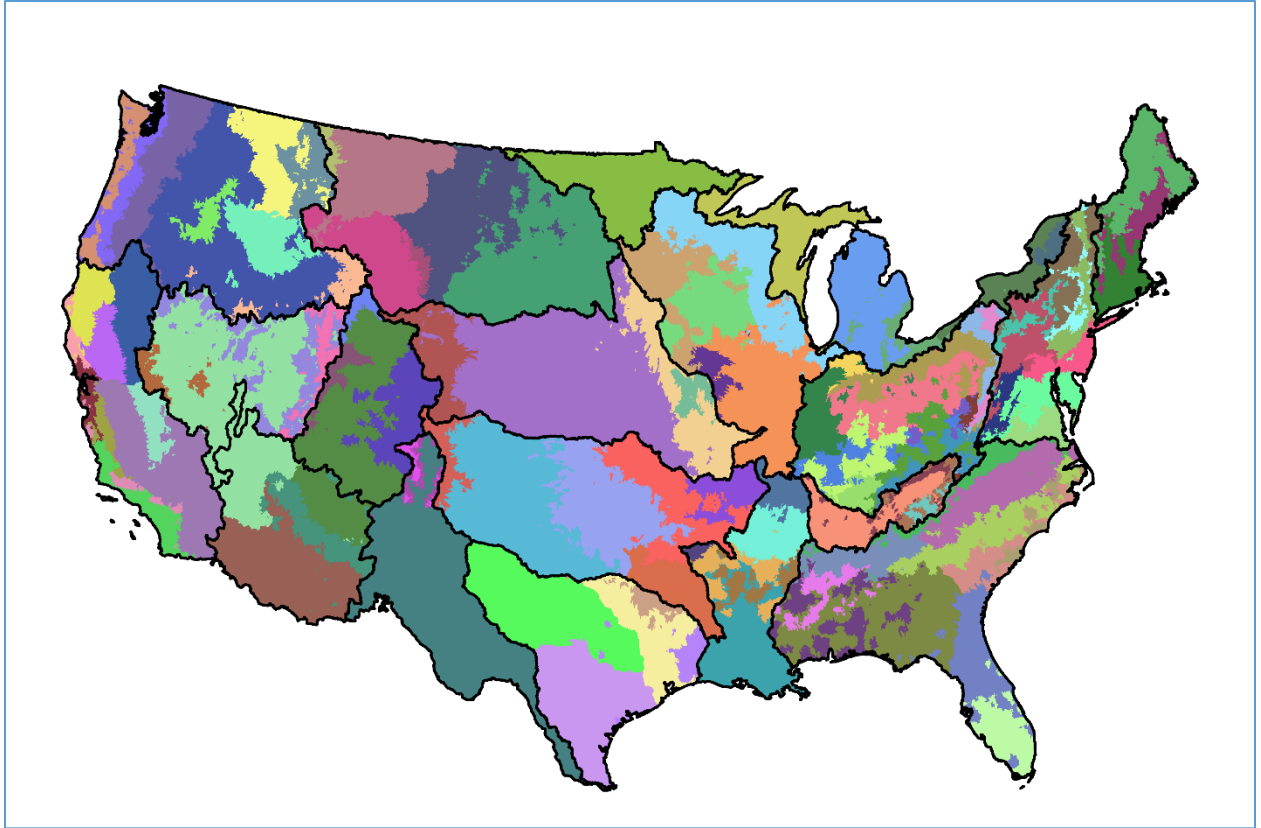


Figure 5. MWBM calibration groups across CONUS. Figure from Bock and others (2016a).

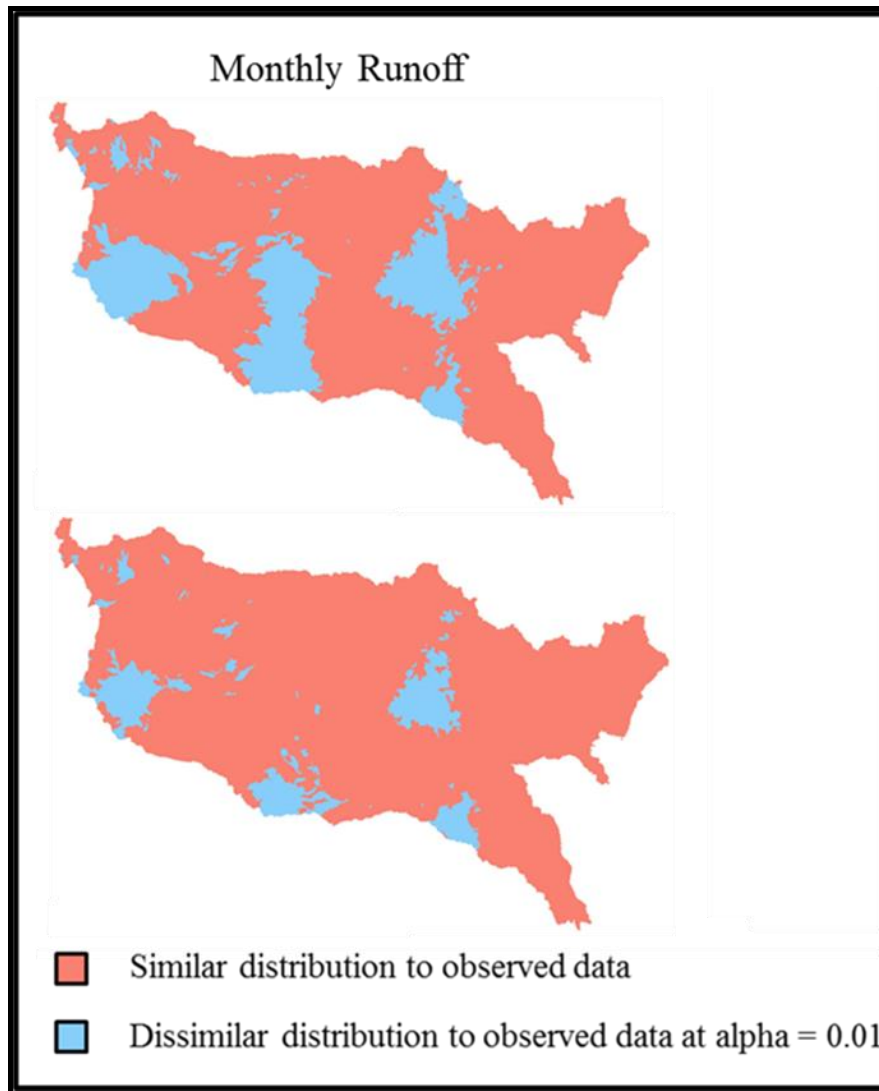


Figure 6. Maps showing differences in Kolmogorov-Smirnov test results for hydrologic region/water resourcesregion 11 between Gridded Station Data for historical conditions (1950 to 2000) with GISS_Model_E_R (top), and CNRM_CM3_1 (bottom) from BCSD CMIP3 for p-value (α) = 0.01.

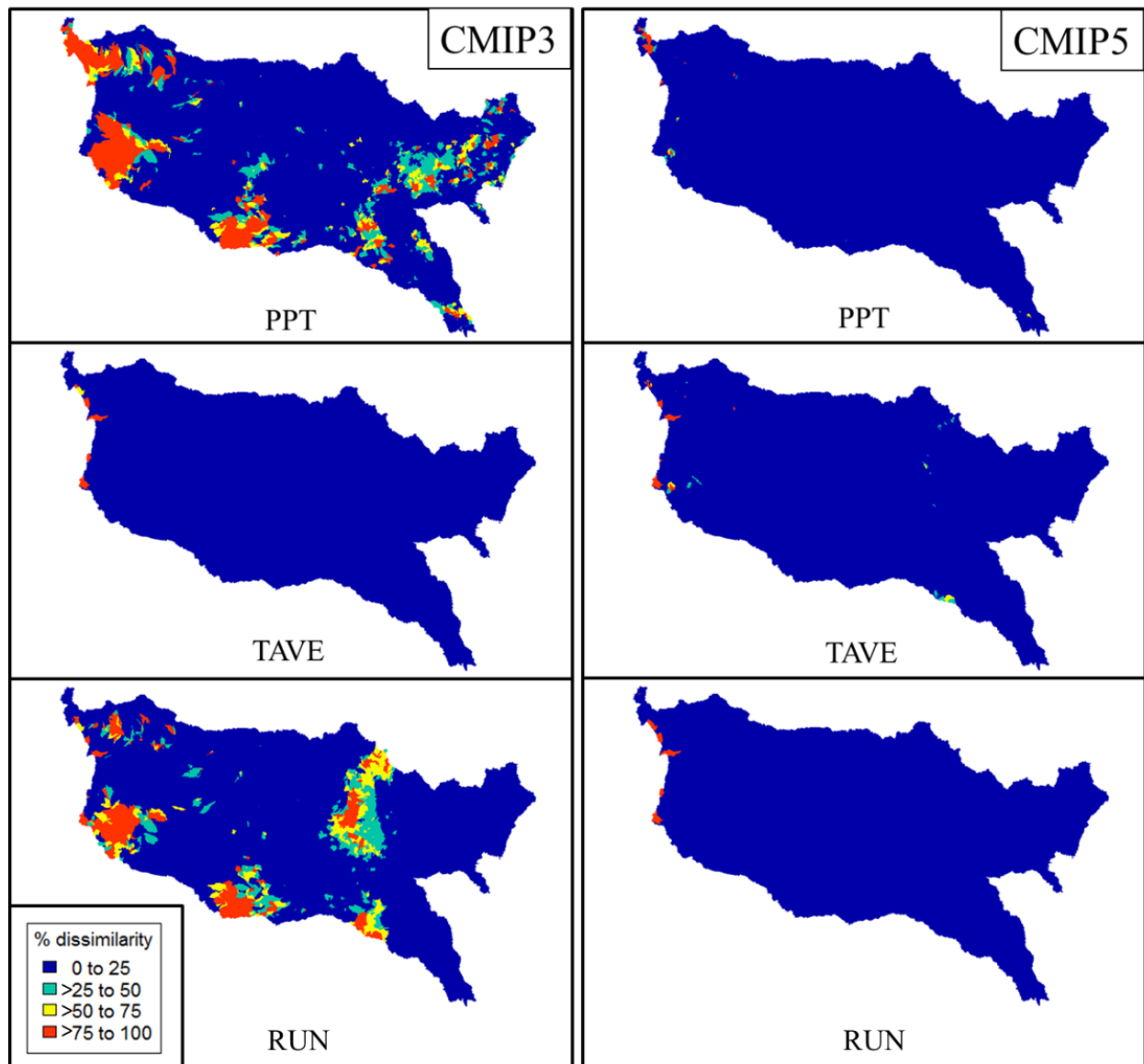


Figure 7. Maps showing the proportion of individual general circulation models (GCMs) in hydrologic region 11 which matched the general distribution of Gridded Station Data for the monthly time series at each Hydrologic Response Unit for BCSD CMIP3 and CMIP5 GCMs at $p\text{-value} = 0.05$.

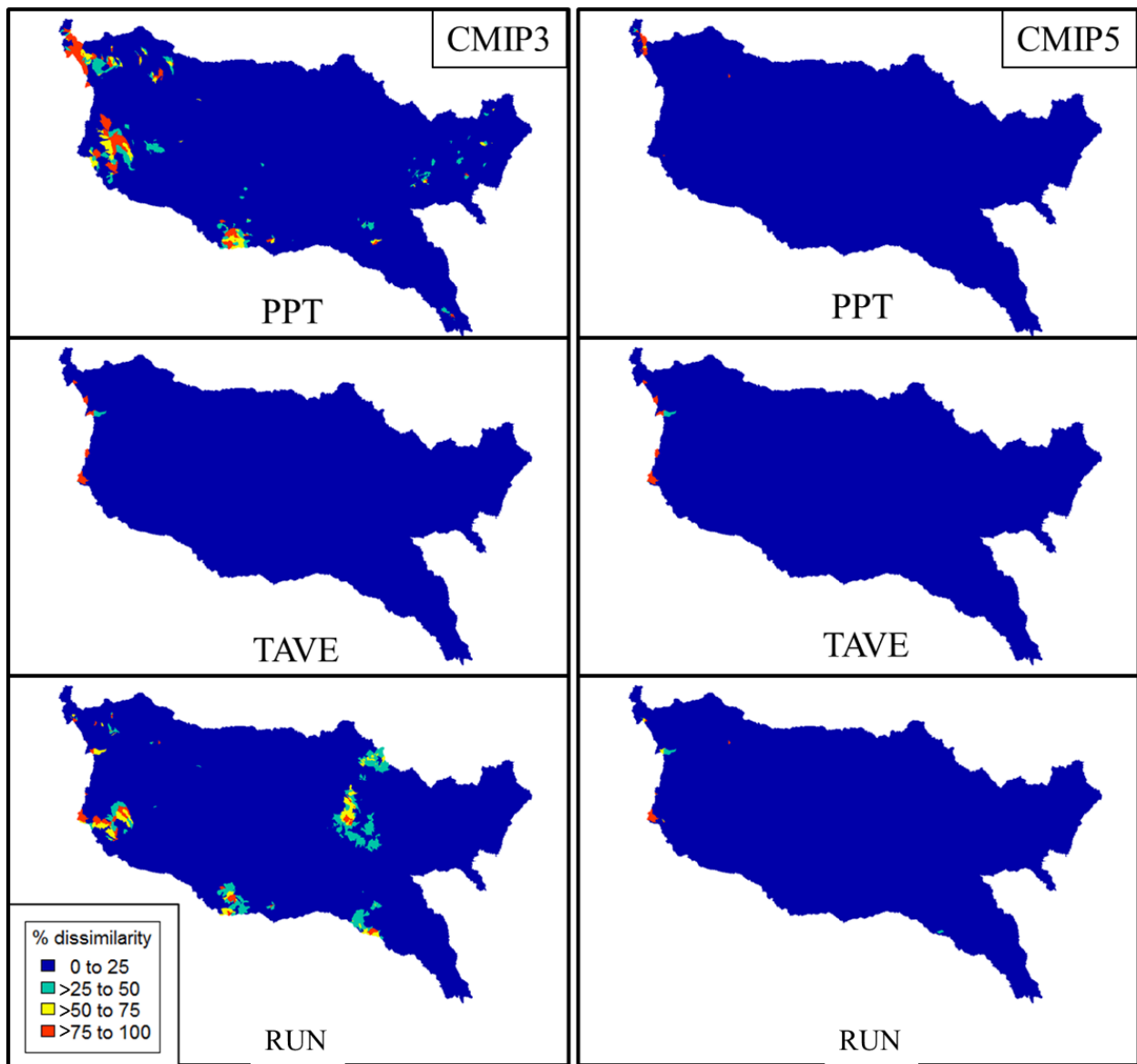


Figure 8. Maps showing the proportion of individual general circulation models (GCMs) in hydrologic region 11 matched the general distribution of Gridded Station Data for the monthly time series at each Hydrologic Response Unit for BCSD CMIP3 and CMIP5 GCMs at p-value = 0.01.

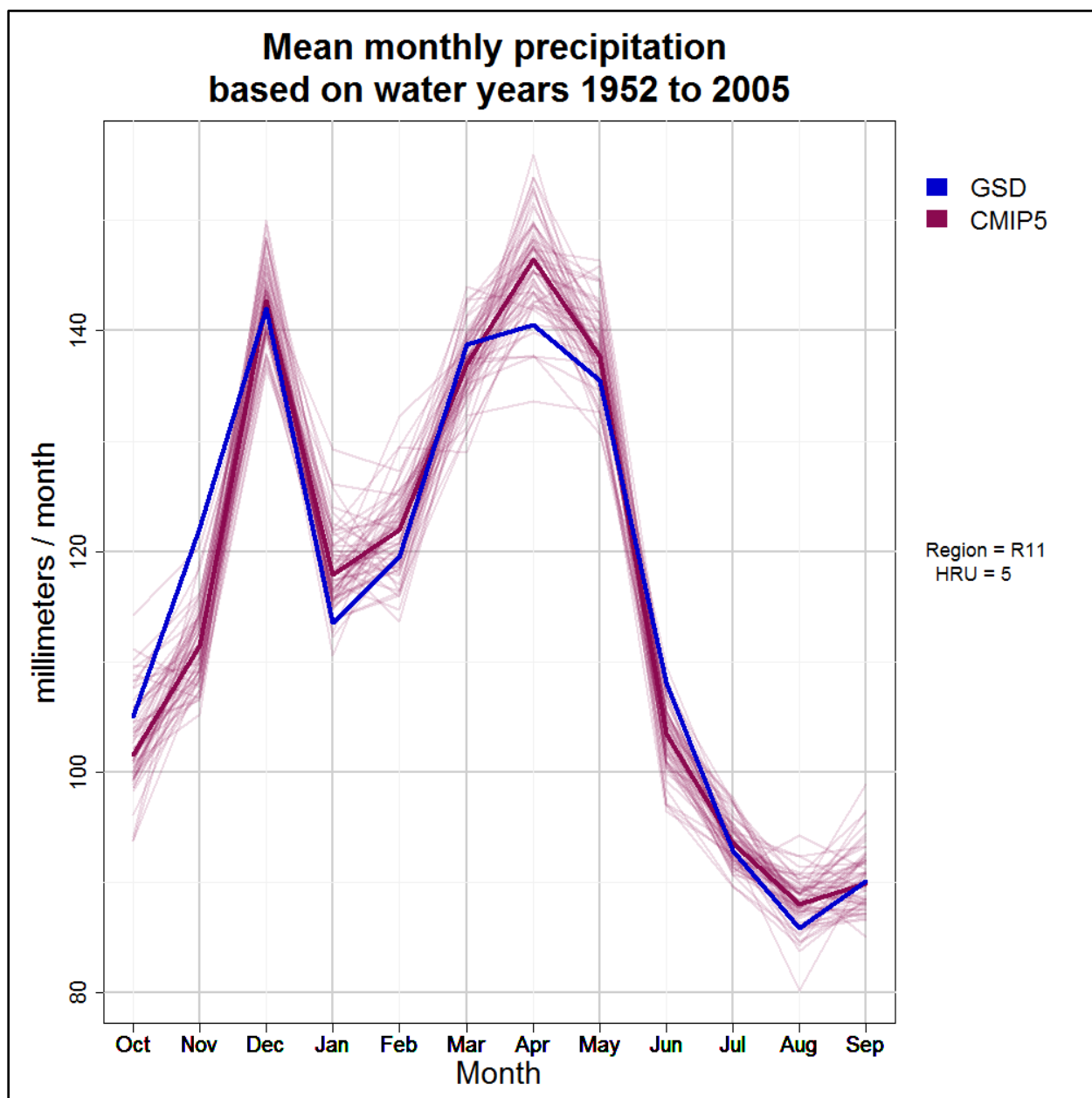


Figure 9. Mean Monthly Runoff graph generated by the portal. Each line of the CMIP3 group represents an individual general circulation model, with the thicker line representing the median of the CMIP3 ensemble. The annotation on the right margin indicates the hydrologic response unit ID (HRU) and hydrologic/water resource the plot was generated for.

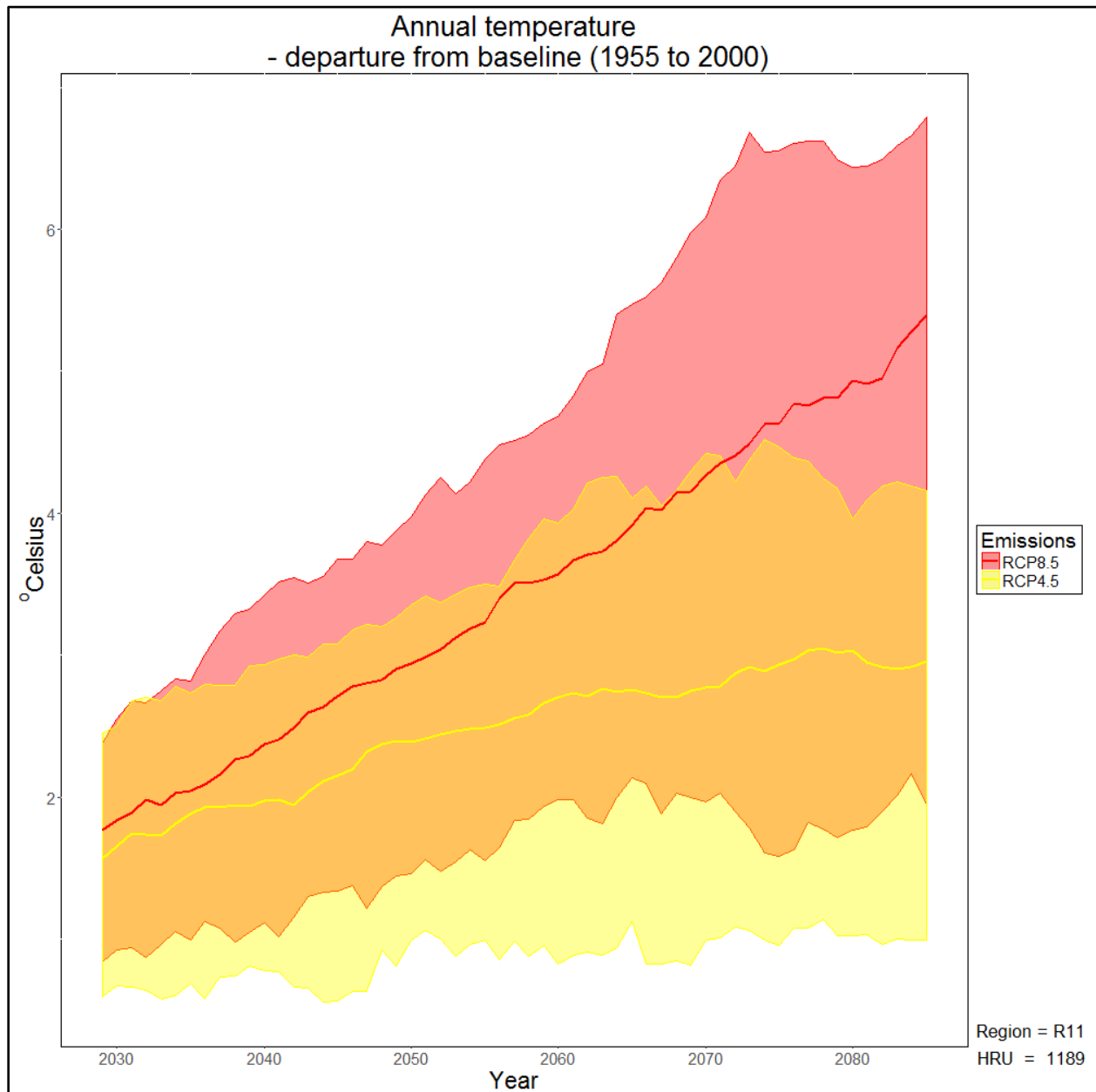


Figure 10. Envelope plot of departure from baseline of annual temperature for three CMIP3 scenarios for future conditions. The shaded area represents the variability in the departure from historic conditions for all general circulation models within the emission scenario, while the solid line represents the median of the departures for each emission scenario. The annotation on the right margin indicates the hydrologic response unit ID (HRU) and hydrologic/water resource the plot was generated for.

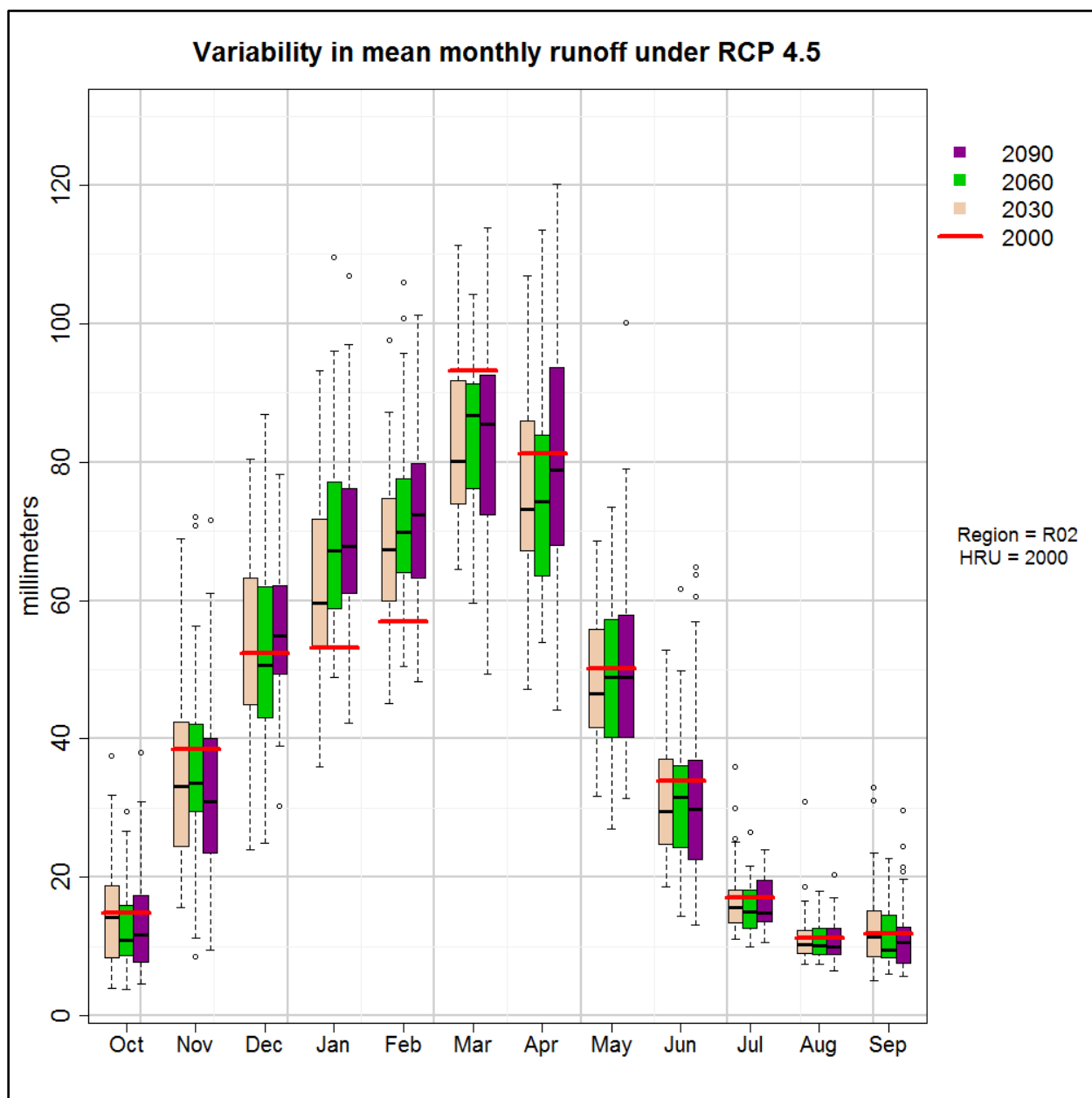


Figure 11. Boxplot showing variability of monthly precipitation for scenario A1B from CMIP3 at three different years in the future (2030, 2060, 2090) compared to the 2000 baseline. The annotation on the right margin indicates the hydrologic response unit ID (HRU) and hydrologic/water resource the plot was generated for.

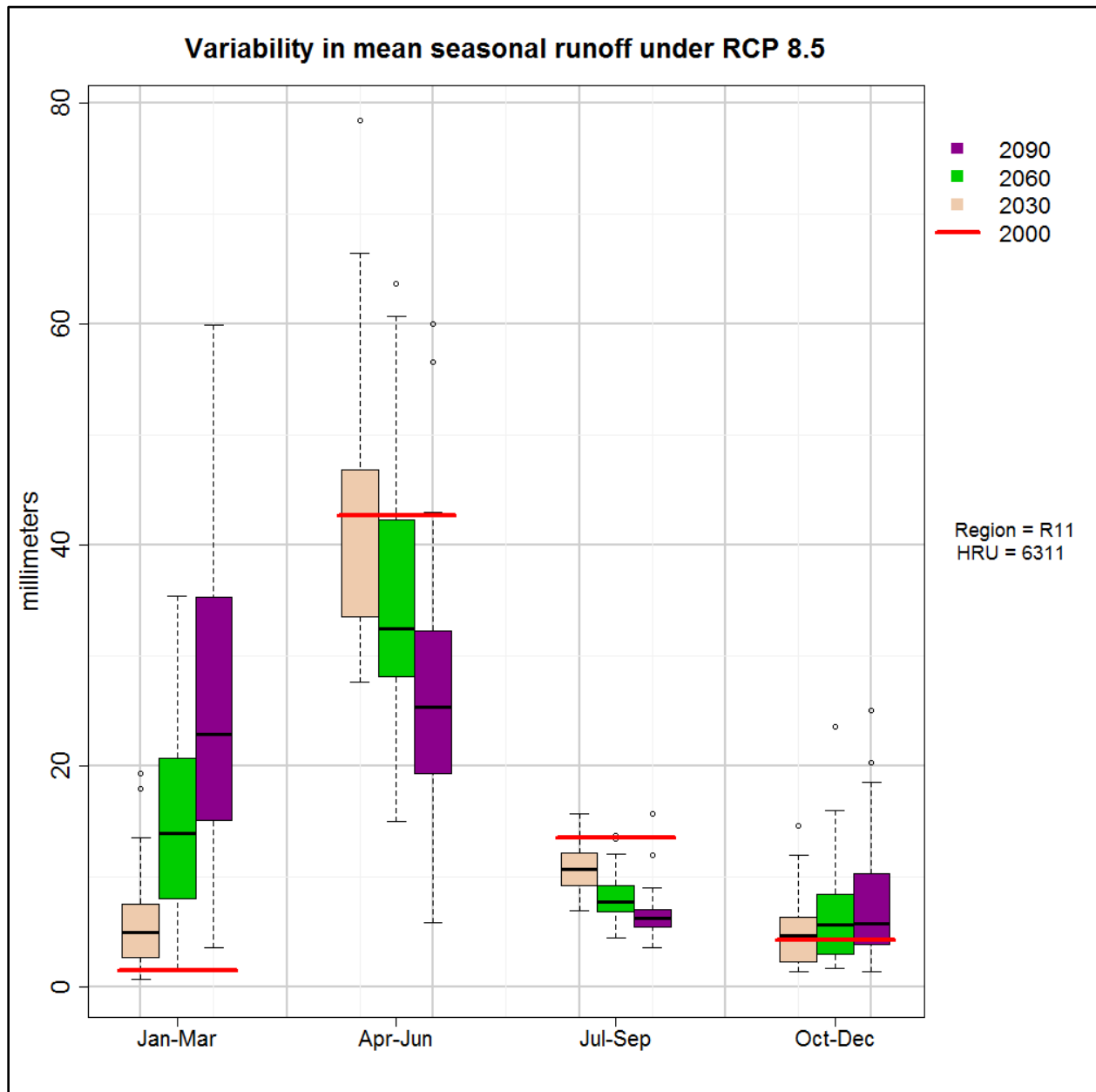


Figure 12. Boxplot showing variability of seasonal precipitation for scenario A1B from CMIP3 at three different years in the future (2030, 2060, 2090) compared to the 2000 baseline. The annotation on the right margin indicates the hydrologic response unit ID (HRU) and hydrologic/water resource the plot was generated for.

Argument	Plot Types ¹	Definition
Spatial Summary Type	1-5	Type of Geospatial Fabric feature to summarize and plot
Location/Streamgage from Map	1-5	Interactive selection of geospatial fabric feature from the map
Variable of Interest	1-5	MWBM variable to summarize and plot
Period of Record/Future Conditions (water years)	1-5	Period of record to summarize and plot
Runs	1-5	Interactive selection of climate datasets
Baseline	3	Period of record during historical conditions from which changes in future conditions are compared
Length of annual running mean	3	Length of arithmetic annual mean
Subset by KS test p-value	1-5	P-value of KS test to apply to selected climate datasets

¹Plot Types: 1 – Simulated historical conditions: mean monthly plots, 2 – Measured and simulated historical streamflow at selected gage: mean monthly plots, 3 – Future conditions: envelope plots based on downscaled GCMs: annual moving average, 4 – Future conditions: mean monthly box plots, 5 – Future conditions, mean seasonal box plots.

Table 3. List of arguments for the portal used to generate plots.

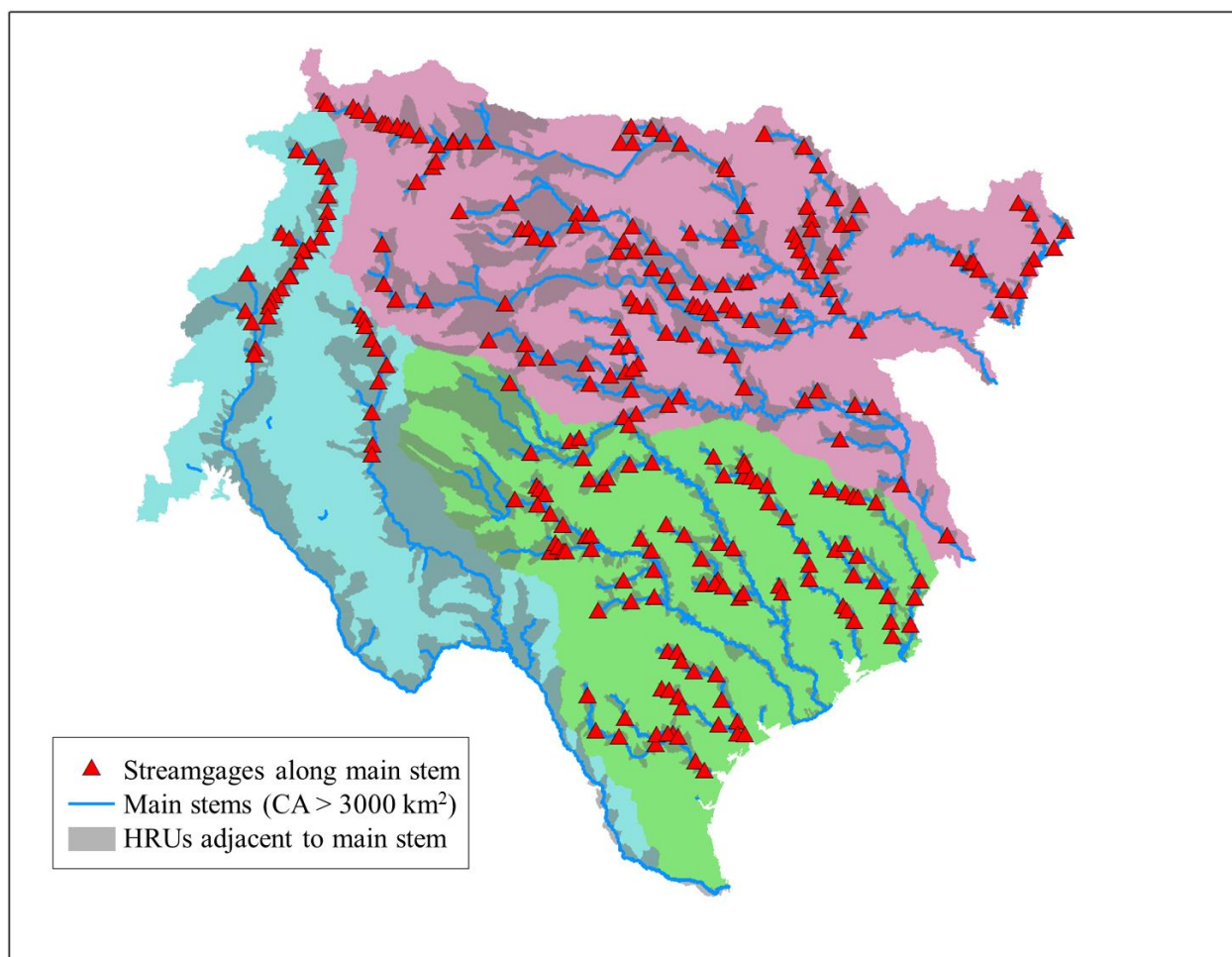


Figure 13. Main-stem segments with contributing areas (CA) greater than 3,000 km², streamgages along the mainstem, and Hydrologic Response Units (HRUs) adjacent or contributing to the mainstem in the South Central Climate Science Center domain (Hydrologic regions 11, 12, and 13).