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The U.S. Geological Survey Monthly Water Balance Model Futures Portal

Open-File Report 2016–1212

U.S. Department of the Interior
U.S. Geological Survey

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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 appendixes 1 and 2) 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.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 × °C) + 32.

Abbreviations

AET	actual evapotranspiration
BCSD	bias-corrected spatially disaggregated
CMIP	Coupled Model Intercomparison Project
CONUS	conterminous United States
csv	comma-separated values [format]
ESRI	Environmental Systems Research Institute
GCM	general circulation model
GSD	gridded station data
HRU	hydrologic response unit
HUC	Hydrologic Unit Code
IPCC	Intergovernmental Panel on Climate Change
km^2	square kilometer
KS	Kolmogorov-Smirnov
MWBM	Monthly Water Balance Model
netCDF	network common data form
NHDPlus	National Hydrology Dataset Plus
NSE	Nash-Sutcliffe efficiency
OPeNDAP	Open-source Project for a Network Data Access Protocol
PET	potential evapotranspiration
png	portable network graphics [format]
PPT	precipitation
RCP	representative concentration pathway
RO	runoff

SOIL	soil moisture
SRES	Special Report on Emissions Scenarios
STATSGO	State Soil Geographic Database
STRM	streamflow
SWE	snow water equivalent
TAVE	atmospheric temperature
USGS	U.S. Geological Survey
WCRP	World Climate Research Programme
WBD	Watershed Boundary Dataset

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Abstract

The U.S. Geological Survey Monthly Water Balance Model Futures Portal (https://my.usgs.gov/mows/) is a user-friendly interface that summarizes monthly historical and simulated future conditions for seven hydrologic and meteorological variables (actual evapotranspiration, potential evapotranspiration, precipitation, runoff, snow water equivalent, atmospheric temperature, and streamflow) at locations across the conterminous United States (CONUS).

The estimates of these hydrologic and meteorological variables were derived using a Monthly Water Balance Model (MWBM), a modular system that simulates monthly estimates of components of the hydrologic cycle using monthly precipitation and atmospheric temperature inputs. Precipitation and atmospheric temperature from 222 climate datasets spanning historical conditions (1952 through 2005) and simulated future conditions (2020 through 2099) were summarized for hydrographic features and used to drive the MWBM for the CONUS. The MWBM input and output variables were organized into an open-access database. An Open Geospatial Consortium, Inc., Web Feature Service allows the querying and identification of hydrographic features across the CONUS. To connect the Web Feature Service to the open-access database, a user interface—the Monthly Water Balance Model Futures Portal—was developed to allow the dynamic generation of summary files and plots based on plot type, geographic location, specific climate datasets, period of record, MWBM variable, and other options. Both the plots and the data files are made available to the user for download.

Introduction

The World Climate Research Programme (WCRP), working with guidelines from the Intergovernmental Panel on Climate Change, or IPCC, presents a number of different projections for future conditions, which together are called the Coupled Model Intercomparison Project (CMIP). The two most recent versions of the CMIP are CMIP3 (IPCC, 2000; Meehl and others, 2007) and CMIP5 (Taylor and others, 2012). Each CMIP group is composed of numerous climate simulations made by general circulation models (GCMs) that represent atmospheric, oceanic, and terrestrial processes. The climate simulations are grouped into ensembles that represent different assumptions about future greenhouse gas emissions based on projected changes in demographics and on economic and technological development. These climate ensembles present a broad array of trajectories from which future conditions can be explored and analyzed.

Simulations of future climate suggest profiles of atmospheric temperature (TAVE) and precipitation (PPT) may differ significantly from those in the past. Future changes in climate, specifically changes in TAVE, and the type, timing, and distribution of PPT may lead to changes in components of the hydrologic cycle (Kundzewicz and others, 2007). As such, natural resource managers are in need of tools that can provide estimates of key components of the hydrologic cycle, uncertainty associated with the estimates, and limitations associated with the climate forcing data used to estimate these components.

To help address this need, the U.S. Geological Survey (USGS) Monthly Water Balance Model Futures Portal was developed. The purpose of this report is to describe the portal and its supporting components. Inputs (PPT and TAVE) from climate datasets were summarized for hydrographic features across the conterminous United States (CONUS) (Viger and Bock, 2014) using the USGS Geo Data Portal (Blodgett, 2013). The meteorological variables precipitation (PPT) and atmospheric temperature (TAVE) were summarized for historical conditions (1952–2005) and simulated future conditions (2020–2099) (table 1). A Monthly Water Balance Model (MWBM; fig. 1) (McCabe and Markstrom, 2007; Bock and others, 2016b) used the PPT and TAVE inputs to estimate the hydrologic variables actual evapotranspiration (AET), potential evapotranspiration (PET), runoff (RO), soil moisture (SOIL), snow water equivalent (SWE), and streamflow (STRM) across the CONUS. The hydrologic and meteorological variables were organized into the Monthly Water Balance Model Futures database (Bock and others, 2016a),

Table 1. Climate datasets available on the Monthly Water Balance Model Futures Portal.

Dataset	Period of record	Number of datasets
Gridded station data (GSD)[1]	1952–2005	1
Bias-corrected spatially disaggregated (BCSD) climate data for Coupled Model Intercomparison Project 3 (CMIP3)[2]	1952–2005, 2020–2099	94
Bias-corrected spatially disaggregated (BCSD) climate data for Coupled Model Intercomparison Project 5 (CMIP5)[3]	1952–2005, 2020–2099	127

[1]Maurer and others, 2002.

[2]Bureau of Reclamation, 2011.

[3]Bureau of Reclamation, 2013.

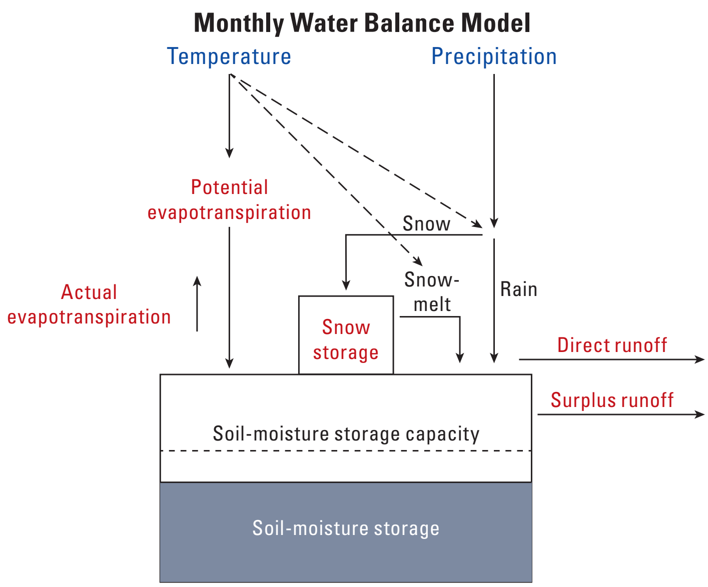


Figure 1. The Monthly Water Balance Model (MWBM). The Monthly Water Balance Model Futures Portal provides data for model input (blue) and output (red) variables. Snow storage is referred to as snow water equivalent (SWE) in this report. Figure modified from McCabe and Markstrom (2007).

which was configured to allow open and machine-independent access from the portal. Finally, the portal was created by building a Web Feature Service (Open Geospatial Consortium, Inc., 2005) to connect the Monthly Water Balance Model Futures database to the hydrographic features (Viger and Bock, 2014), which allows for the dynamic generation of graphics and summary reports for a specified feature of interest across the CONUS with a number of user-specified inputs. The MWBM variables AET, PET, RO, SWE, STRM, and TAVE are available for access and summation on the portal.

Portal Components

The Monthly Water Balance Model Futures Portal is the end product of several related products that work together to bring information to the user. Climate data were summarized for hydrologic response units (HRUs), which are land surface units that contribute runoff to the stream network (Viger and Bock, 2014) and are used to simulate hydrologic processes across the CONUS with the MWBM. The MWBM input and output variables were organized into the Monthly Water Balance Model

Futures database (Bock and others, 2016a). A Web Feature Service (Open Geospatial Consortium, Inc., 2005) was built on top of the hydrographic features. The portal was constructed on top of the Web Feature Service to take user-specified data requests (such as geographic location, period of record, and variable of interest), retrieve the specified data from the database, and generate graphs and summary reports back to the user. Each of these efforts and databases are detailed in the following section.

Climate Data

The Monthly Water Balance Model Futures Portal contains two types of climate datasets: a daily gridded station-based dataset aggregated to the monthly time-step and monthly time-step, statistically downscaled datasets derived from GCMs (table 1).

Gridded station-based datasets are derived from historical climate observations and thus only represent historical conditions. The station-based dataset available on the portal is the gridded station data (GSD) from Maurer and others (2002). The GSD is available at a daily time-step with a spatial resolution of 1/8° (approximately 12 square kilometers [km^2]) for calendar years 1949 through 2010.

A GCM is a climate model that is a coarse-scale representation of the Earth's atmosphere and ocean and is used for understanding long-term climate dynamics at the continental or global scales (Bureau of Reclamation, 2013). Numerous GCMs are developed by research institutions across the globe. In their original format, GCMs are available at spatial resolutions of around 1–2°, or 150 km^2. For GCMs that simulate future climate using different scenarios, the GCM period of record can be composed of a single thread of simulated historical climatic conditions with multiple threads of future climatic conditions.

Many scientific assessments, however, require information at finer spatial resolutions. Statistical downscaling is one technique for deriving fine-scale interpolations from coarse-scale GCMs by developing statistical relations between observed local-scale climate data, such as meteorological observations or gridded station data derived from historical climate observations, and the coarse-scale GCM variables (Wood and others, 2004).

A number of different downscaled GCM datasets are available. The statistically downscaled GCM simulations available on the portal are from the bias-corrected spatially disaggregated (BCSD) CMIP3 and CMIP5 projections (table 1, appendixes 1–2) (Wood and others, 2004; Bureau of Reclamation, 2011, 2013). These data are available at a monthly time-step with a spatial resolution of 1/8° for the period of record 1950 through 2099. The BCSD procedure was used to statistically downscale the GCMs to the finer resolution using the GSD as the training or observational dataset to develop the statistical relations between the local observations and coarse-scale GCM outputs.

Each CMIP group (3 and 5) is composed of a number of different scenarios, the primary ones being Special Report on Emissions Scenarios (SRES) B1, A1B, and A2 for CMIP3 and representative concentration pathways (RCPs) 2.6, 4.5, 6.0, and 8.5 for CMIP5 (Bureau of Reclamation, 2011, 2013). The scenario RCP 2.6 from CMIP5 is excluded from the portal 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 human 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 preindustrial 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 (SRES A1B, RCP 4.5), to globally increasing populations and regionally orientated economic development (A2, RCP 8.5). A full description of the SRES scenarios used in CMIP3 is given in IPCC (2000), and the RCP scenarios used in CMIP5 are described in Taylor and others (2012).

For each downscaled GCM in its native data format, the historical conditions portion of the period of record extends from 1950 through 2005, while the future conditions portion (usually represented by one or more of the SRES or RCP scenarios) extends from 2005 through 2099. In addition, for each GCM, there can be multiple simulations, which are referred to as an initial condition ensemble. These multiple simulations of a single GCM represent variations in the initial GCM boundary conditions. Because climate models are sensitive to boundary conditions, initial condition ensembles from a single GCM attempt to average out the natural chaotic tendencies of climate systems for long-term forecasts. There are a total of 95 downscaled GCM datasets that represent historical conditions on the portal; they diverge to a total of 221 downscaled GCM datasets that represent future conditions (SRES B1, A1B, A2 and RCP 4.5, 6.0, and 8.5). The distribution of the downscaled GCMs and their initial condition ensembles across the SRES and RCP scenarios are shown in appendixes 1 and 2.

There are several differences between the period of record available for each dataset and the period or record available for plotting and summarizing data on the portal. The portal divides the calendar based on water years. A water year is the 12-month period from October 1 of a given year through September 30 of the following year. The water year is designated by the calendar year in which it ends. For example, the year ending September 30, 1999, is called the 1999 water year. On the portal, the GSD is available to plot and download through calendar year 2005 to match the historical period of record for the downscaled GCM datasets. Additionally, the period of record for historical conditions (1952–2005) for all datasets does not include the water years 1950 and 1951 because they are considered the model warm-up period. The model warm-up period is when the models' initial conditions and state variables (such as SWE) evolve from initial values to equilibrium given a set of model parameters and meteorological inputs (Seibert and Vis, 2012). There is no guidance on the length of the warm-up period, but anywhere from one to five years is usually acceptable for surface water models, with more complex models generally requiring longer warm-up periods (Daggupati and others, 2015). Climate data were excluded for the water years 2006 through 2019 to emphasize the use of the datasets for long-term evaluation. See the “Generating Plots” section for more information on the period or record options for the datasets on the portal.

The climate inputs available for analysis are hosted by a wide variety of scientific bodies, including universities, research consortiums, and Federal agencies. These scientific bodies use standard protocols that allow the access and summation of these datasets for a given geographic feature and period of record. The standardized access, summation, and formatting for the climate datasets on the Monthly Water Balance Model Futures Portal were provided by the USGS Geo Data Portal (Blodgett and others, 2013).

Geospatial Fabric for National Hydrologic Modeling

The selected climate data (table 1, appendixes 1–2) were summarized using the Geo Data Portal for hydrologic response units (HRUs) of the Geospatial Fabric for National Hydrologic Modeling (Viger and Bock, 2014). The Geospatial Fabric is a set of hydrographic features aggregated from the National Hydrography Dataset Plus (NHDPlus; U.S. Environmental Protection Agency and U.S. Geological Survey, 2010) at a scale appropriate for regional and national hydrologic modeling and analysis. There are three main components of the Geospatial Fabric (fig. 2): HRUs, stream segments, and points of interest or summary nodes. The HRUs are land surface units that contribute runoff to the stream network. An HRU is a derivative of the traditional contributing area, or watershed, and represents an area of similar physical features (such as slope, vegetation, soils type, or topography) where a given amount of precipitation is expected to yield a similar hydrologic response. The monthly fluxes of the MWBM variables are calculated at each HRU. Stream segments are stream reaches which accumulate upstream flow and route runoff generated from HRUs as streamflow through the stream network. Each stream segment is associated with one or more HRUs that locally contribute runoff to the segment. Stream segments are derived from hydrographic features delineated on 1:100,000-scale USGS topographic maps. A summary node is a point on the stream network where hydrologic and climatic conditions of the upstream contributing area can be summarized. In the Geospatial Fabric, summary nodes represent a number of different thematic categories, including confluences of larger streams and rivers, outlet and inlet points of major waterbodies, points on the stream network that maintain minimal elevation change or streamflow travel time thresholds, and a number of USGS streamgages. A streamgage is an installation located on a stream or river equipped to measure streamflow and other hydrologic data. The USGS operates a network of streamgages across the United States. Each streamgage has a unique 8- to 12-digit numeric identifier (U.S. Geological Survey, 2014) or the name of the stream segment associated with it (derived from the Geographic Names Information System database, http://nhd.usgs.gov/gnis.html).

The 109,951 HRUs, 56,460 stream segments, and summary nodes of the Geospatial Fabric for National Hydrologic Modeling were built into a Web Feature Service to allow querying and identification of features across the CONUS. The Web Feature Service uses an open-source mapping format standard supported by the Open Geospatial Consortium, Inc. (2005); it is encoded in the geography markup language that allows clients such as the ArcGIS server to retrieve, update, or modify geospatial data. Note that summary nodes with a contributing area of greater than 3,000 km^2 were excluded from selection on the Monthly Water Balance Model Futures Portal because of the MWBM’s inability to represent processes occurring in large, open-stream networks.

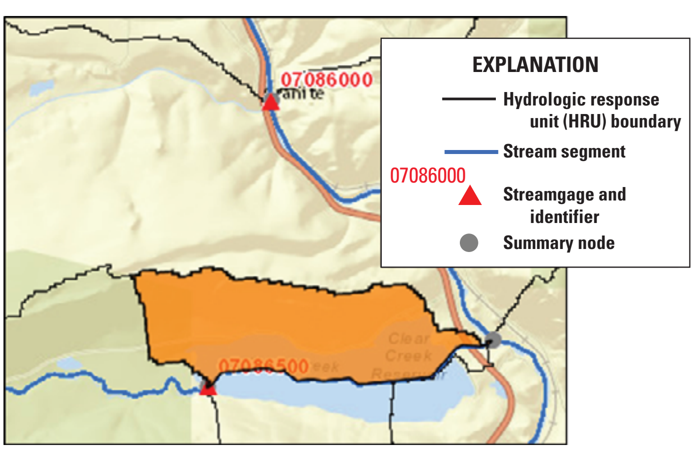


Figure 2. An example of Geospatial Fabric features used in the Monthly Water Balance Model Futures Portal. In this example, a user-selected hydrologic response unit is highlighted in orange. The pink line running north to south represents a highway.

Monthly Water Balance Model

The Monthly Water Balance Model (MWBM) (fig. 1) is a monthly time-step modular system that allocates water to various components of the hydrologic cycle (McCabe and Markstrom, 2007). The MWBM requires four inputs: (1) monthly precipitation (PPT, monthly atmospheric moisture supply in the water balance; includes rain, snow, sleet, and hail), (2) monthly average atmospheric temperature (TAVE, the monthly measure of sensible heat present in the atmosphere), (3) latitude, and (4) soil moisture storage capacity. Both PPT and TAVE are derived from climate data inputs (table 1, appendixes 1–2). Latitude (decimal degrees) is derived from the geometric centroid of each HRU and is needed for the computation of PET. Soil moisture storage capacity (in millimeters) is derived from the State Soil Geographic Database (STATSGO) (Wolock, 1997).

The MWBM produces a number of different hydrologic variables. These include (1) actual evapotranspiration (AET, the actual amount of evaporation and transpiration that occurs), (2) potential evapotranspiration (PET, climatic demand for water relative to the available energy), (3) runoff (RO, water generated on the HRUs from infiltration-excess overflow [direct runoff], snowmelt, or storage surplus [surplus runoff]), (4) soil moisture (SOIL, amount of moisture stored in the soil reservoir), (5) snow water equivalent (SWE, amount of water stored in the snowpack), and (6) streamflow (STRM, accumulation of HRU-generated runoff at summary nodes in the stream network). Each MWBM input and output variable is expressed as a unit of depth in millimeters, with the exception of average atmospheric temperature, which is expressed in degrees Celsius.

The MWBM was previously used to examine hydrology at both the continental (McCabe and Wolock, 2011a) and global scales (McCabe and Wolock, 2011b), as well as in climate change studies (Hay and McCabe, 2010). For this application, the MWBM was set up across the CONUS on the Geospatial Fabric (Viger and Bock, 2014) and calibrated using modeled SWE and measured streamflow from 1,575 streamgages across the CONUS (National Operational Hydrologic Remote Sensing Center, 2004; U.S. Geological Survey, 2014; Bock and others, 2016b). Precipitation (PPT) and temperature (TAVE) inputs for model calibration were derived from the GSD (Maurer and others, 2002). In addition to the calibration strategy, this version of the MWBM incorporated a modified calculation of potential evapotranspiration using the Hamon equation with a spatially and temporally varying model coefficient that matched the measured mean monthly evaporation rates of the free water surface (McCabe and others, 2015). Users should note there is large variability in model performance at replicating streamflow for different parts of the CONUS (Newman and others, 2015; Bock and others, 2016b). For more information on the calibration of the MBWM used here, see Bock and others (2016b).

The Monthly Water Balance Model Futures Database

Monthly historical and simulated future conditions for all of the hydrologic and meteorological variables from the MWBM described in the previous section were organized into the Monthly Water Balance Model Futures database (Bock and others, 2016a). The database contains two netCDF (network common data form) files for each climate dataset: one with hydrologic and meteorological variables indexed to HRUs and one with the variables indexed to stream segments. As described earlier in the "Monthly Water Balance Model" section, the variable RO is unique to HRUs, and the variable STRM is unique to summary nodes and streamgages. The database also includes monthly measured streamflow for comparison of measured streamflow with simulated streamflow generated from downscaled GCM climate data and station-based climate data for historical conditions. The database is hosted using the Open-source Project for a Network Data Access Protocol (OPeNDAP; https://www.opendap.org/). The use of the netCDF file format and the OPeNDAP hosting configuration allows for open and machine-independent access. Please note the MWBM was developed for watersheds with sizes less than 3,000 km^2; summary nodes and MWBM variables for streamgages with drainage areas over this threshold were given null ("NA") data values within the database.

The Monthly Water Balance Model Futures Portal

The Monthly Water Balance Model Futures Portal (https://my.usgs.gov/mows/) was built to connect the Geospatial Fabric Web Feature Service to the Monthly Water Balance Model Futures database and enable users to summarize a number of the MWBM variables (AET, PET, PPT, RO, STRM, and TAVE) for a specific Geospatial Fabric feature. A user first selects a specific Geospatial Fabric feature from within the map (HRU, summary node, or streamgage). Once the feature is identified, the user can select a number of custom arguments to dynamically generate graphics and summary reports from the portal based on plot type, geographic location (Geospatial Fabric feature), specific climate dataset, period of record, and MWBM variable (see the section "Generating Plots" for more information). The portal then retrieves the selected output from the MWBM Futures database based on the user's queries, writes the output to a comma-separated values (csv) file, and transforms the output into the necessary time-step summation to apply to the selected plot (Talbert and others, 2014). Both the plot (in portable network graphics [png] format) and the csv file are made available to the user for download.

Navigating the Portal

The home page of the Monthly Water Balance Model Futures Portal is shown in figure 3. The "Legend" icon on the top menu bar controls the features in the map that can be toggled on and off, as follows. The extent of the CONUS in the Geospatial Fabric is outlined by a hollow purple polygon. The HRUs are shown as hollow black polygons, stream segments are indicated

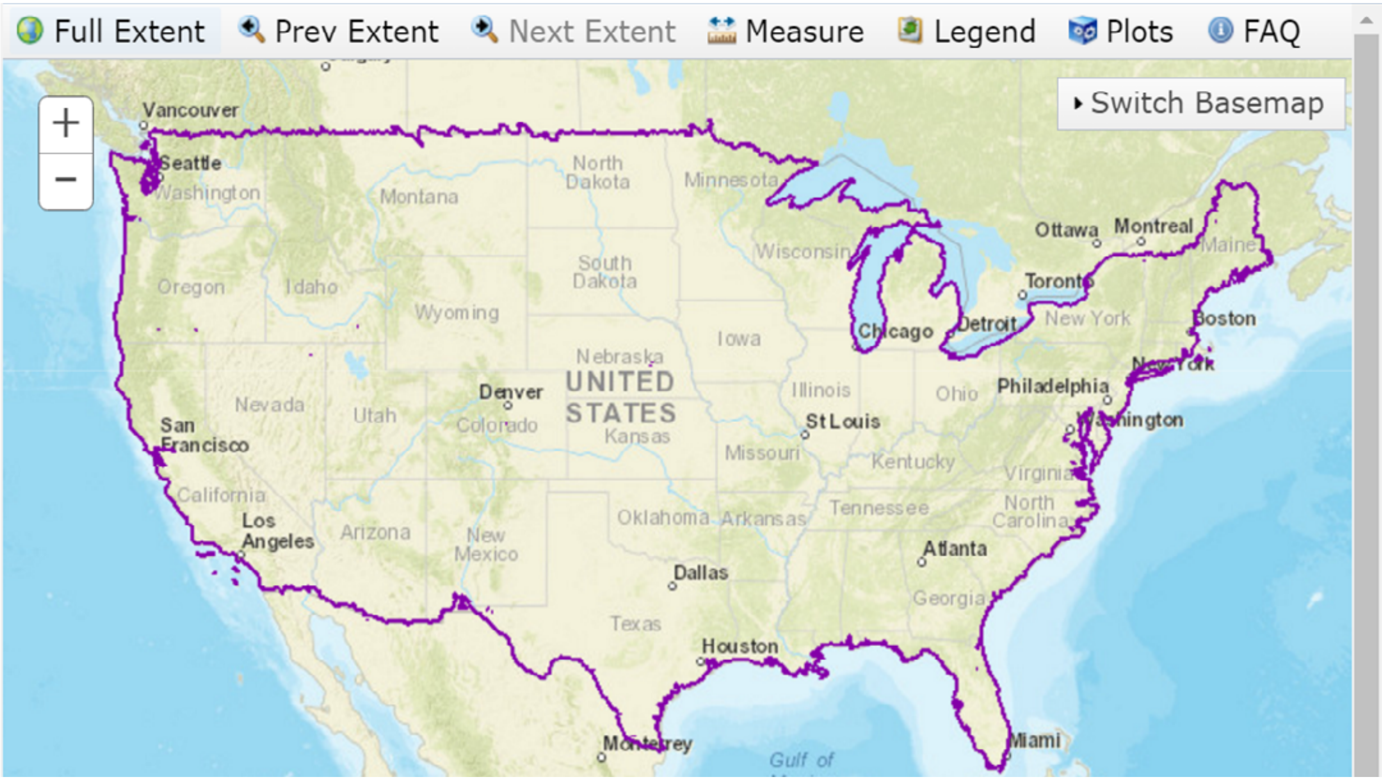


Figure 3. The Monthly Water Balance Model Futures Portal home page.

by blue lines, and summary nodes (other than streamgages) are indicated by grey circles. USGS streamgages are indicated by red triangles and their station names and 8- to 12-digit station identifiers. In addition to these Geospatial Fabric features, the user can also view subwatersheds (12-digit Hydrologic Unit Codes [HUCs]) of the Watershed Boundary Dataset (WBD) within the portal, shown as hollow green polygons. The WBD is a seamless national dataset of spatial features that define the areal extent of surface-water drainage to a point, accounting for all land surface areas (http://nhd.usgs.gov/wbd.html). The WBD boundaries are determined by science-based hydrologic principles of topographical-based delineation and deriving relationships of upstream and downstream connectivity, while also not favoring any administrative boundaries or specific agencies.

The number and level of details of features shown is dependent on the scale. At the coarsest scale, only the CONUS boundary is visible. Upon zooming into finer scales (accomplished by using the mouse wheel or double-clicking on a location on the map), stream segments, summary nodes, streamgages, then finally HRUs and WBD units can be seen. The background base map can be changed by clicking the “Switch Basemap” option in the upper right-hand corner of the portal. The base map options of the portal are provided by the Environmental Systems Research Institute (ESRI). The map service, map image, and base maps of all images shown in the portal and in this open-file report are the intellectual property of ESRI and are used herein under license (Copyright 2014 ESRI and its licensors. All rights reserved). The “Prev Extent” and “Next Extent” options in the top menu allow a user to navigate between different scales and extents viewed in the current session.

Querying Features on the Portal

The Web Feature Service capabilities of the portal allow users to interact with the Geospatial Fabric features. The first level of interaction is the querying and selection of features in the portal itself. Left-clicking on each feature in the map (HRU, stream segment, summary node, streamgage, or watershed boundary) displays the “Identify results” window, in which the unique attributes identifying each feature are given (fig. 4). Selecting an HRU will display the NHDPlus Region and the HRU identifier (unique to each region, 2355 for Region 14 in this example). The NHDPlus Region is analogous to the 2-digit HUC WBD region delineation. Selecting a stream segment will display the NHDPlus Region, the stream segment identifier (unique to each region), and HRUs that contribute locally to each stream segment. Selecting the summary node will display the name of the stream or river that the summary node is an outlet for (based on the GNIS database), the stream segments that are upstream or downstream of the summary node, and the HRUs that contribute local runoff to the upstream and downstream stream segments associated with the summary node. Selecting a streamgage will display the same information as for a summary node, plus the

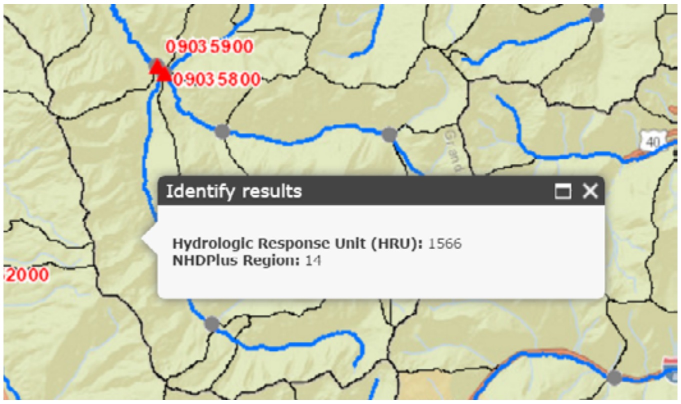


Figure 4. Query results of a hydrologic response unit (HRU) in the Monthly Water Balance Model Futures Portal.

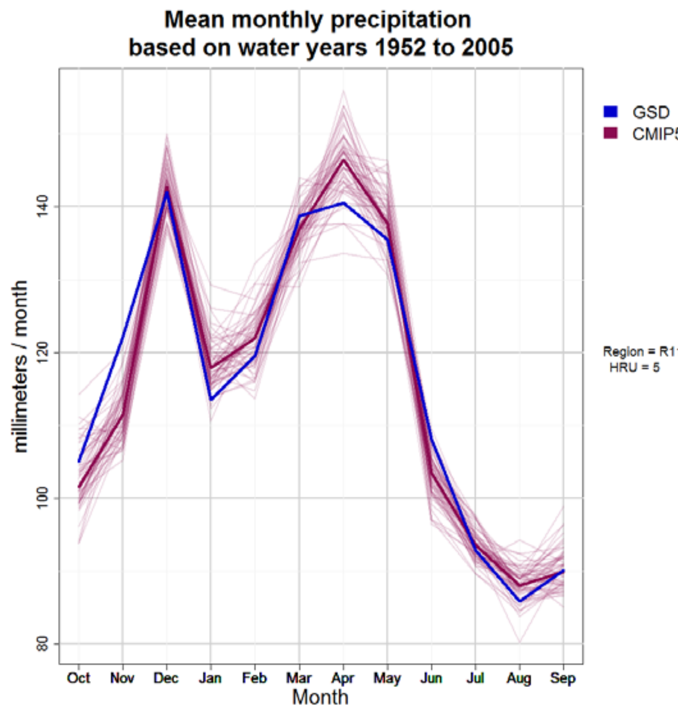


Figure 5. An example of a mean monthly plot for historical conditions generated by the Monthly Water Balance Model (MWBM) Futures Portal and based on data from selected climate datasets. The user selects the MWBM variable, the hydrologic response unit (HRU) or summary node, the climate dataset(s), and the period of historical conditions (a subset of water years 1952–2005). This example shows precipitation and uses data from the gridded station data (GSD) (Maurer and others, 2002) and downscaled GCMs from the Coupled Model Intercomparison Project 5 (CMIP5) (Bureau of Reclamation, 2013).

USGS 8- to 12-digit streamgage identifier. Selecting the WBD polygon will display the NHDPlus Region and the 12-digit subwatershed HUC identifier, as well as the HRU identifier if the HRU layer is active with the WBD layer.

Plots Available on the Portal

Plots are generated in the Monthly Water Balance Model Futures Portal when the user submits queries through the interactive “Plots” interface window, located on the top menu bar of the portal (fig. 3). Five different types of plots can be dynamically generated from this window (figs. 5–9). These plots are based on a package of graphics originally created by the North Central Climate Science Center (Talbert and others, 2014).

Simulated Historical Conditions—Mean Monthly Plots

Figure 5 shows plot type 1, a mean monthly plot for summarizing an MWBM variable for each climate dataset selected for the period chosen by the user within the historical period (1952–2005) at either HRUs or summary nodes. Data are ordered by water year (October through September). Data from the GSD are represented by a single blue line, and downscaled GCM data from CMIP5 are represented by maroon/deep pink lines. If present on the plot, downscaled GCM data from CMIP3 are represented by beige/gold lines. If five or more downscaled GCM datasets from a CMIP group are selected for the plot, a bold line representing the median of the downscaled GCM datasets is added to the plot.

Measured and Simulated Historical Streamflow at Selected Streamgage—Mean Monthly Plots

Figure 6 shows plot type 2, a mean monthly plot of measured and simulated streamflow for each climate dataset selected for the period chosen by the user within the streamgage period of record within the water years 1952 through 2005. Data are ordered by water year (October through September). The colors used are identical to the mean monthly plot of simulated historical conditions (fig. 5) but with the addition of measured streamflow, represented by a single red line. Because the historical period of record for measured streamflow varies for each streamgage, users should ensure they are choosing a time period for the plot that overlaps with the period of measured streamflow of the chosen streamgage. The set of streamgages shown on the portal are a subset of the streamgages present in the Geospatial Fabric (Viger and Bock, 2014). Streamgages from the Geospatial Fabric with contributing areas greater than 3,000 km^2 were removed because of the inability of the MWBM to simulate larger watersheds. From this set of streamgages, two subsets were derived. The first subset contains all USGS reference-quality streamgages that were individually calibrated during the historical period (Falcone and others, 2010; Bock and others, 2016b).

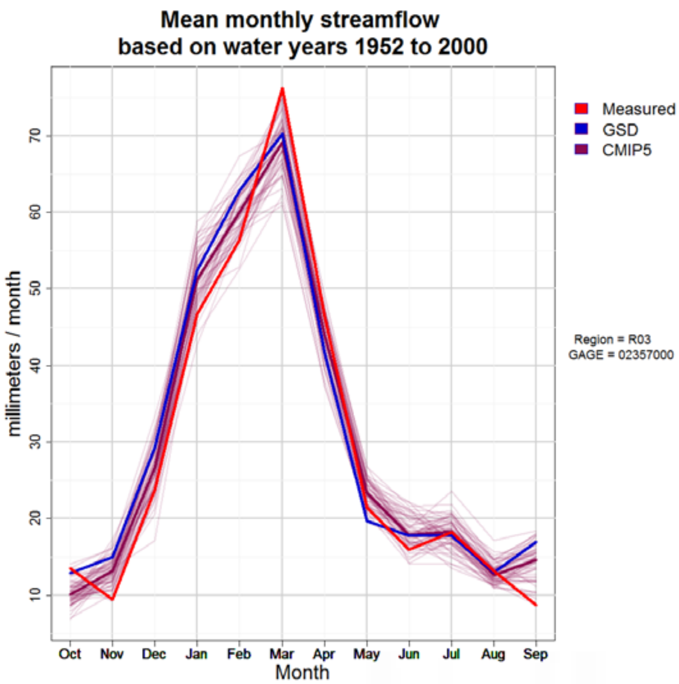


Figure 6. An example of a mean monthly plot of historical streamflow generated by the Monthly Water Balance Model Futures Portal and based on measured streamflow (U.S. Geological Survey, 2014) and data from selected climate datasets. The user selects the streamgage (GAGE), the climate dataset(s), and the period of historical conditions (a subset of the streamgage period of record and water years 1952–2005). This example uses data from the gridded station data (GSD) (Maurer and others, 2002) and downscaled GCMs from the Coupled Model Intercomparison Project 5 (CMIP5) (Bureau of Reclamation, 2013). This plot can be generated for a select number of U.S. Geological Survey streamgages; see Bock and others (2016a, b) for more information.

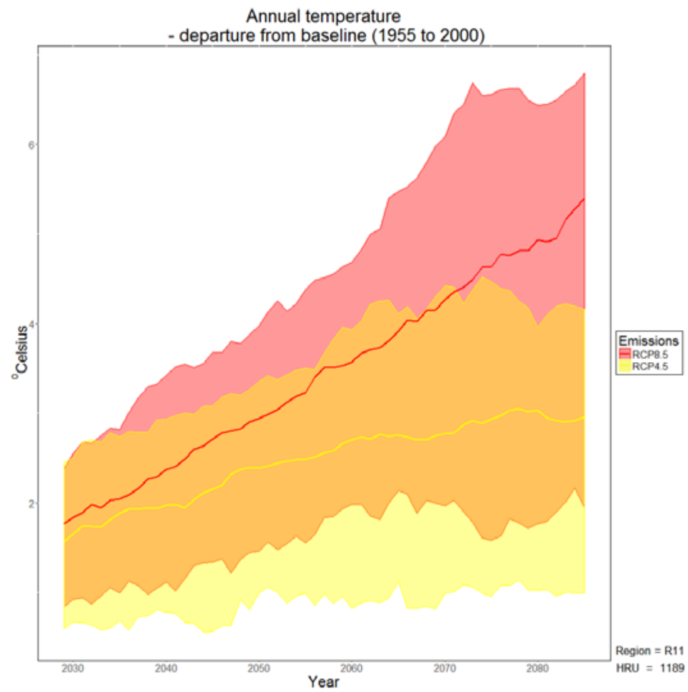


Figure 7. An example of an envelope plot for simulated future conditions generated by the Monthly Water Balance Model (MWBM) Futures Portal that depicts the annual variability of change between historical conditions and simulated future conditions. The user selects the MWBM variable, the Geospatial Fabric feature (hydrologic response unit [HRU] or summary node), the emission scenarios, and the periods of historical and simulated future conditions (subsets of the periods 1955–2005 and 2020–2099, respectively). This example shows variability for temperature and uses downscaled GCMs from the representative concentration pathway (RCP) 4.5 and 8.5 emission scenarios from the Coupled Model Intercomparison Project 5 (Bureau of Reclamation, 2013).

A reference-quality streamgage is a streamgage that is judged to be largely free of human alteration to flow (Falcone and others, 2010). The second subset contains all non-reference-quality streamgages with a Nash-Sutcliffe efficiency (NSE) of 0.50 or greater (Nash and Sutcliffe, 1970). The NSE measures the mean predictive power of a hydrologic model in simulating measured streamflow from a streamgage. The minimum NSE threshold of 0.50 has been used to quantify satisfactory hydrologic model performance (Moriasi and others, 2007). For more information on MWBM calibration, see Bock and others (2016a, b).

Envelope of Future Conditions Based on Downscaled GCMs—Annual Moving Average

Plot type 3 (fig. 7) illustrates the annual change in an MWBM variable from a subset of historical conditions (1952–2005) and simulated future conditions (2020–2099) chosen by the user using the selected climate datasets (runs). Envelope plots are created for each selected emission scenario. They show the departures from baseline for climate datasets within that scenario, with the maximum and minimum departures indicated by the top and bottom bounds of the envelope and the median departure indicated by a bold line in the color of the envelope. Each emission scenario from CMIP3 and CMIP5 is assigned its own color.

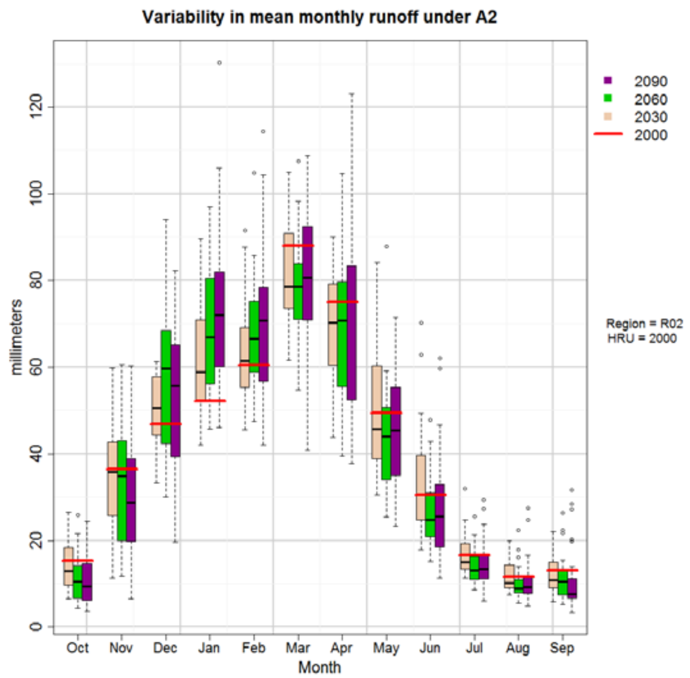


Figure 8. An example of a mean monthly box plot for simulated future conditions generated by the Monthly Water Balance Model (MWBM) Futures Portal that depicts the variability of change in the future of monthly runoff of an emission scenario from the historical baseline period 1995–2005 (denoted as 2000) and the baseline of three periods in the future: 2085–2095 (denoted as 2090), 2055–2065 (denoted as 2060), and 2025–2035 (denoted as 2030). The user selects the MWBM variable, the Geospatial Fabric feature (hydrologic response unit [HRU] or summary node), and the emission scenario. This example shows variability for runoff and uses downscaled GCMs from the A2 emission scenario from the Coupled Model Intercomparision Project 3 (Bureau of Reclamation, 2013).

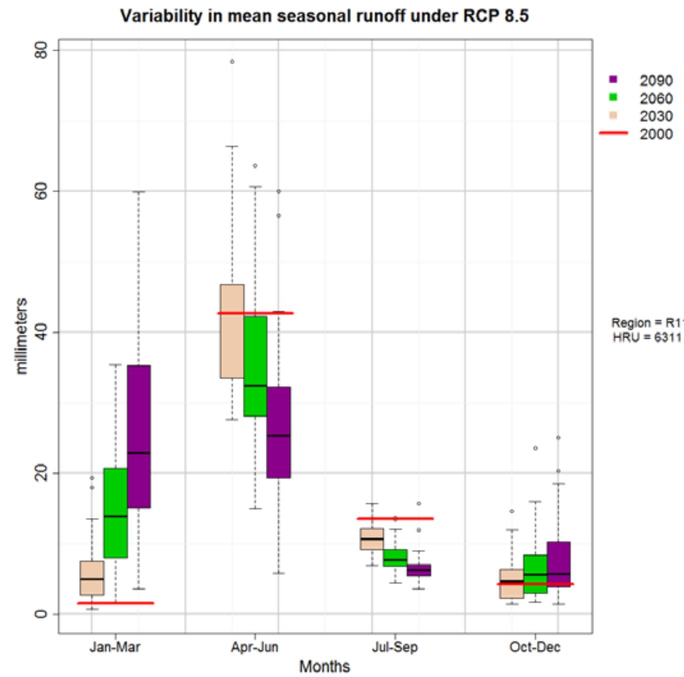


Figure 9. An example of a mean seasonal box plot for simulated future conditions generated by the Monthly Water Balance Model (MWBM) Futures Portal that depicts the variability of change in the future of seasonal runoff of an emission scenario from the historical baseline period 1995–2005 (denoted as 2000) and the baseline of three periods in the future: 2085–2095 (denoted as 2090), 2055–2065 (denoted as 2060), and 2025–2035 (denoted as 2030). The user selects the MWBM variable, the Geospatial Fabric feature (hydrologic response unit [HRU] or summary node), and the emission scenario. This example shows variability for runoff and uses downscaled GCMs from the representative concentration pathway (RCP) 8.5 emission scenario from the Coupled Model Intercomparison Project 5 (Bureau of Reclamation, 2013).

Future Conditions—Mean Monthly Box Plots

Figure 8 shows plot type 4, a box plot of simulated future monthly variability of an MWBM variable for a single emission scenario (SRES B1, A1B, or A2 for CMIP3 or RCP 4.5, 6.0, or 8.5 for CMIP5) for the years 2025–2035 (denoted as 2030), 2055–2065 (denoted as 2060), and 2085–2095 (denoted as 2090). The median of the MWBM variable between the downscaled GCMs of the emission scenario for the baseline period 1995–2005 (denoted as 2000) is shown for each month as a single red line. Data are ordered by water year (October through September).

Future Conditions—Mean Seasonal Box Plots

Figure 9 shows plot type 5, a box plot of simulated future seasonal variability of an MWBM variable for a single emission scenario (SRES B1, A1B, or A2 for CMIP3 or RCP 4.5, 6.0, or 8.5 for CMIP5) for the years 2025–2035 (denoted as 2030), 2055–2065 (denoted as 2060), and 2085–2095 (denoted as 2090). The median of the MWBM variable between the downscaled GCMs of the emission scenario for the baseline period 1995–2005 (denoted as 2000) is shown for each season as a single red line.

Table 2. Plotting arguments in the Monthly Water Balance Model Futures Portal.

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, 3–5	Monthly Water Balance Model 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 to which changes in future conditions are compared
Length of running annual mean	3	Length of arithmetic annual mean
Subset by KS test p-value	1–5	p-value of Kolmogorov-Smirnov (KS) test to apply to selected climate datasets

[1]Plot types: (1) simulated historical conditions—mean monthly plots, (2) measured and simulated historical streamflow at selected streamgage—mean monthly plots, (3) future conditions—annual moving average as envelope plots based on downscaled GCMs, (4) future conditions—mean monthly box plots, (5) future conditions—mean seasonal box plots.

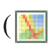
Generating Plots

A number of different arguments are needed to generate the plots in the “Plots” interface (table 2). The number and types of arguments differ for each plot type. These options allow a user to customize the data they want to view for their area of interest.

Spatial Summary Type

Data can be summarized from the Monthly Water Balance Model Futures Portal for two Geospatial Fabric features: local data for a single HRU or the accumulation of the upstream contributing area at a summary node or streamgage. Plot type 2, “measured and simulated historical streamflow at selected streamgage—mean monthly plots,” automatically allows only streamgages to be selected.

Location/Streamgage from Map

After the spatial summary type is chosen, the user clicks on the selection icon () to select either an HRU or summary node/streamgage from the map. This prompts a pop-up window with some basic instructions and an option to ignore the pop-up in the future. Select “OK” to dismiss the pop-up window. Left-click on the desired HRU or summary node/streamgage on the map. Once selected, the HRU will be highlighted in orange, or the summary node/streamgage will be highlighted in red. The accompanying feature identifier will be displayed next to the selection icon in the “Plots” window. The selection of summary nodes that are spatially coincident at a confluence of two or more stream segments will open a drop-down window below the “Location from Map” selection icon that allows the user to choose between the two summary nodes at the confluence.

Variable of Interest

Seven MWBM variables can be summarized and plotted in the portal: actual evapotranspiration (AET), potential evapotranspiration (PET), precipitation (PPT), runoff (RO), snow water equivalent (SWE), atmospheric temperature (TAVE), and accumulated streamflow (STRM). Runoff (RO) is plotted locally for each HRU, and streamflow (STRM) is plotted for summary nodes and streamgages. The units of the variables for MWBM variables AET, PET, SWE, RO, and STRM are in millimeters (depth per unit area), while the unit for the MWBM variable TAVE is in degrees Celsius.

Period of Record

This is the period of record for which data are summarized and plotted. The period of record for plot types 1 and 2, which summarize historical conditions, spans from 1952 through 2005. For plot type 2, the period of record is constrained to the historical period of record for which there is measured streamflow available at the selected streamgage. The period of record for plot type 3, summarizing simulated future conditions, spans from 2020 through 2099. The period of record for plot types 4 and 5, the monthly box plots and seasonal box plots, is fixed to three 11-year periods centered on the years 2030, 2060, and 2090. Specific details about the periods of record are discussed in further detail earlier in the document in the “Climate Data” subsection.

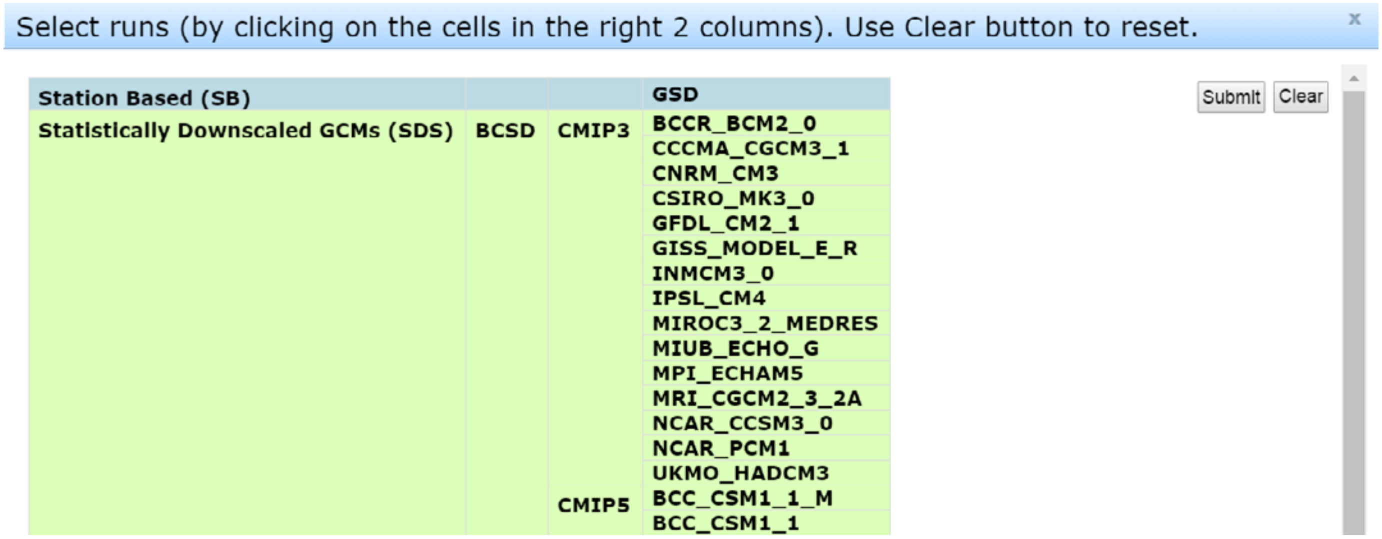


Figure 10. A portion of the climate datasets available for selection for plots of historical conditions in the "Select runs" window.

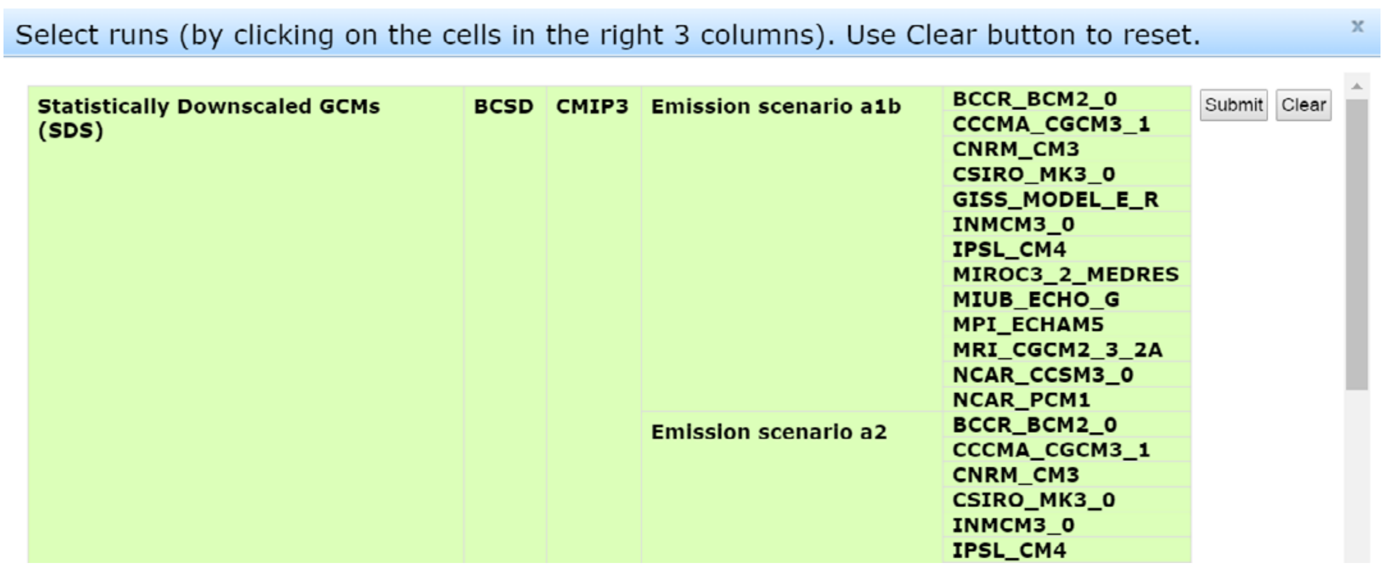


Figure 11. A portion of the climate datasets available for selection for plots of simulated future conditions in the "Select runs" window.

Runs

This argument ( ) opens an interface ("Select runs") that allows the user to select climate datasets to summarize and plot (figs. 10–11). To select a climate dataset to plot, click on a dataset in the far-right column. The box with the specific climate dataset will be highlighted. The "Select runs" window allows the hierarchical selection of climate datasets. For the mean monthly and envelope plots, a user can choose multiple datasets by individually clicking on the dataset names, clicking on the emission scenario to select all climate datasets from the emission scenario (plots of future conditions only, fig. 11), or clicking on the model group (CMIP3 or CMIP5) to select all climate datasets for that model group. For the two box plots, a user can select one of the six emission scenarios from CMIP3 or CMIP5, which will enable the selection of all downscaled GCMs present in the selected emission scenario. To provide a simple and user-friendly interface, emphasizing the choice of model group and emission scenarios, the selection of a single downscaled GCM also enables the selection of all simulation members of the initial condition ensembles of the downscaled GCM (columns B1 runs, A1B runs, and A2 runs in appendix 1 and columns RCP 4.5 runs, RCP 6.0 runs, and RCP 8.5 runs in appendix 2). For the remainder of this document, the term downscaled GCMs will include all the members of a downscaled GCM's initial condition ensemble.

Baseline

A baseline is the period of record or range of years during historical conditions from which changes in simulated future conditions are compared. Baselines are often calculated over 30-year periods or longer to minimize noise from short-term fluctuations and interannual variability in climate that may mask the most common trend of projected changes among the downscaled GCMs included in the analysis. For envelope plots, a minimum baseline of 10 years is required to generate the plot.

Length of Annual Running Mean

The running mean, also known as the moving average, is the arithmetic mean of a chronological sequence of data points of a predetermined width. The running mean is used to smooth the short-term fluctuations of a time series, which helps highlight the longer-term trends and cycles. When used in conjunction with a baseline, the running annual mean cannot be longer then the length of the baseline. This plotting argument only applies to the envelope plots.

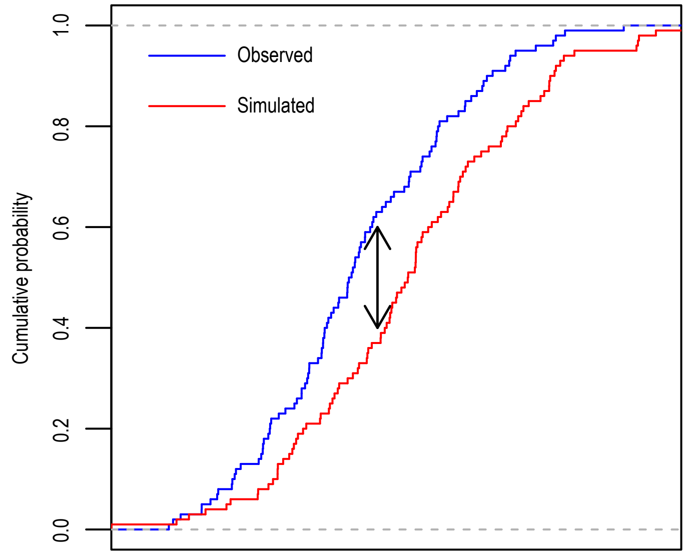


Figure 12. An example of a two-sample Kolmogorov-Smirnov test distance statistic (black arrow) calculated between two samples.

Subset by Kolmogorov-Smirnov Test P-value

Previous hydrologic modeling applications using downscaled GCM climate data have suggested that their ability to replicate historical conditions should be the minimum criteria for their use in assessing simulated future conditions (Wood and others, 2004; Hay and others, 2014). The Monthly Water Balance Model Futures Portal offers the two-sample Kolmogorov-Smirnov Test (KS test) (Conover, 1971) to constrain downscaled GCM selections to those that best replicate historical conditions at the location for the MWBM variable of interest (fig. 12). The KS test is a non-parametric test used to determine if the distribution of an MWBM variable generated from a climate dataset for historical conditions (such as a downscaled GCM) matches the same variable from an "observed" historical dataset (such as the GSD) (Maurer and others, 2002) based on KS test p-values. Three different subset options based on p-values (keep if KS >0.01, >0.05, and >0.10) are offered as potential KS filters. For more information on the KS test, see the "Subsetting Climate Data" section later in the document.

Downloading Data

After selecting all the appropriate arguments for the plot, the "Click to Plot" button at the bottom of each plot window will generate the plot. Upon successful generation of the plot, the user can select the "Click to Download" button (to the right of "Click to Plot") to download either the plot or the csv file of the time series used to summarize the plot. Both files are given a default name (for example, "mowsplot.png" or "mowsplot.csv") and downloaded to the default downloads location on the user's computer.

Subsetting Selected Climate Data

The KS test is a nonparametric test that finds the maximum distance between two empirical distribution functions and determines if the two samples of data are from the same population (fig. 12). The null hypothesis (H_0: both datasets are from identical populations) is rejected if the KS test distance value for a particular climate dataset shows significant probabilities less than the p-value chosen. The maximum distance value is calculated between values from each downscaled GCM climate dataset (appendixes 1–2) and the GSD (Maurer and others, 2002) for the period of record 1950 through 2005. As mentioned in the previous section, three subset options are offered based on the p-values (keep if KS >0.01, >0.05, and >0.10). A p-value of 0.01 is the least stringent level, while a p-value of 0.10 is the most stringent level, in that there is a greater probability that the null hypothesis will be rejected at a higher p-value level. If the KS test p-value for a selected downscaled GCM is below a specified p-value, it is excluded from the specified plot and an additional line of text is printed on the plot, which is the ratio of the number of downscaled GCMs that passed the KS test (numerator) to the number of downscaled GCMs that were initially selected (fig. 13). Within the csv file, the particular downscaled GCM is noted in the header of the file by prefacing a "0-" to the downscaled GCM name if it does not pass the KS test and a "1-" if it does (fig. 14).

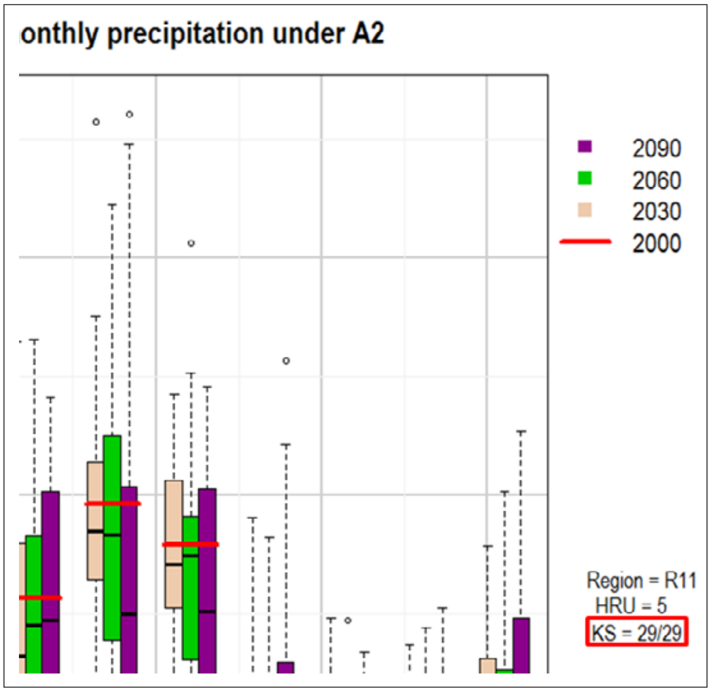
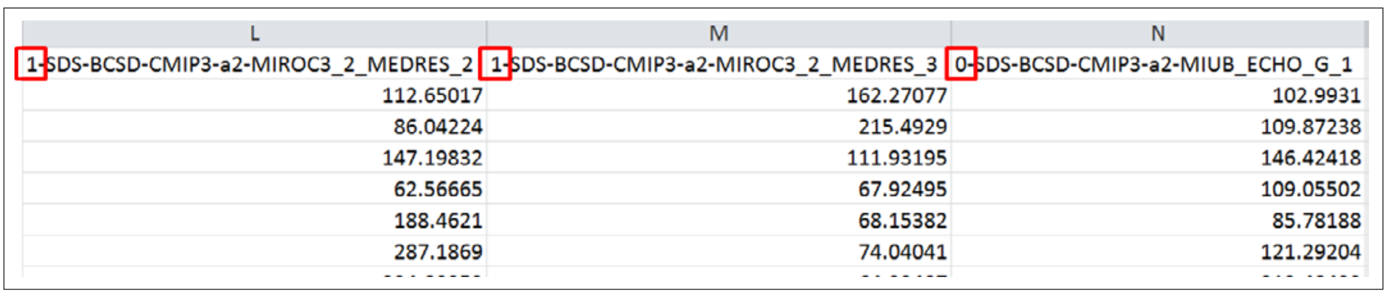


Figure 13. An example of a plot with a note added that gives the ratio of how many downscaled general circulation models passed the Kolmogorov-Smirnov test (in this case, “KS=29/29”).



L	M	N
1-SDS-BCSD-CMIP3-a2-MIROC3_2_MEDRES_2	1-SDS-BCSD-CMIP3-a2-MIROC3_2_MEDRES_3	0-SDS-BCSD-CMIP3-a2-MIUB_ECHO_G_1
112.65017	162.27077	102.9931
86.04224	215.4929	109.87238
147.19832	111.93195	146.42418
62.56665	67.92495	109.05502
188.4621	68.15382	85.78188
287.1869	74.04041	121.29204

Figure 14. An example of an output comma-separated values (csv) file opened in Microsoft Excel showing general circulation model dataset names prefaced with a “1-” if they pass the Kolmogorov-Smirnov test filter and a “0-” if they do not.

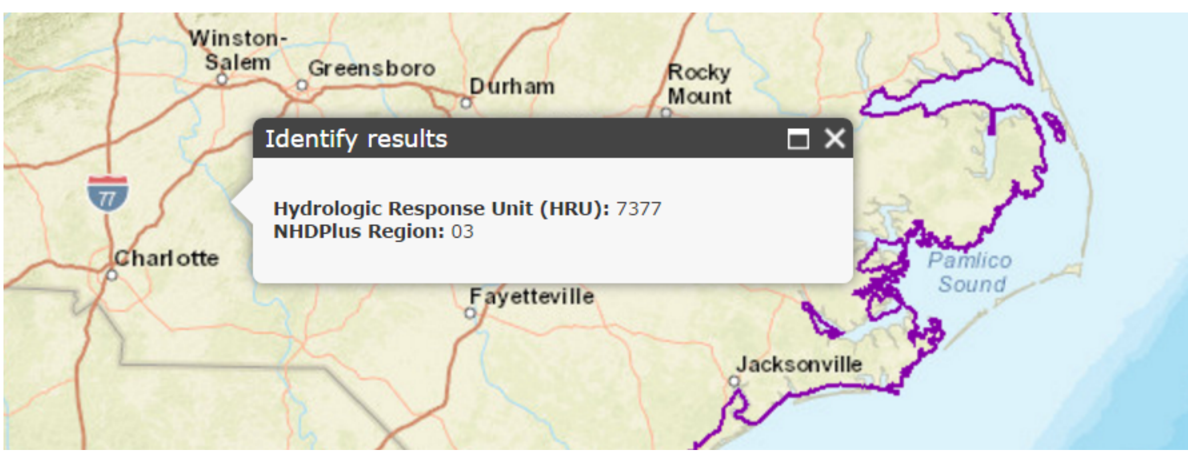


Figure 15. Approximate location of hydrologic response unit 7377 in hydrologic region 03, central North Carolina, used to generate figures 16–17.

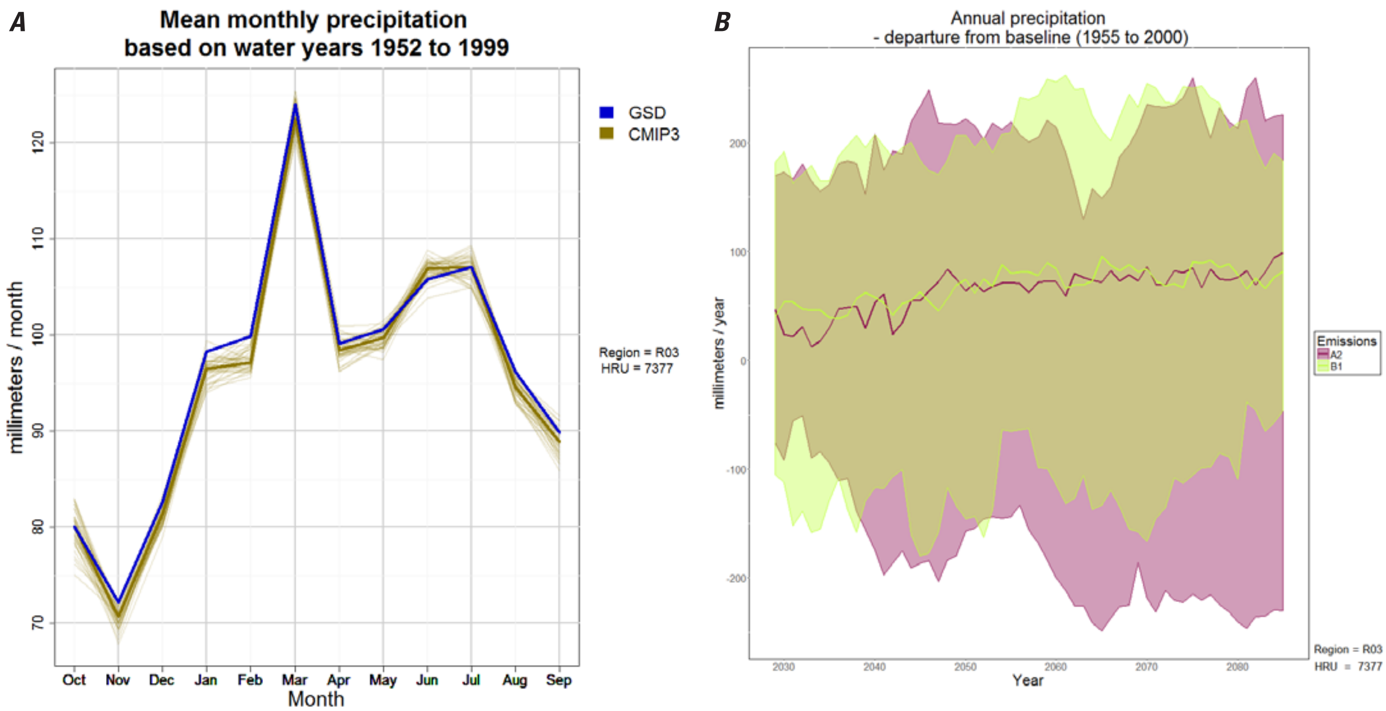


Figure 16. Plots generated for hydrologic response unit (HRU) 7377 in hydrologic region 03 for precipitation with no Kolmogorov-Smirnov test subset. *A*, Mean monthly plot of historical conditions. (GSD, gridded station data; CMIP3, Coupled Model Intercomparison Project 3) *B*, Envelope plot of future conditions.

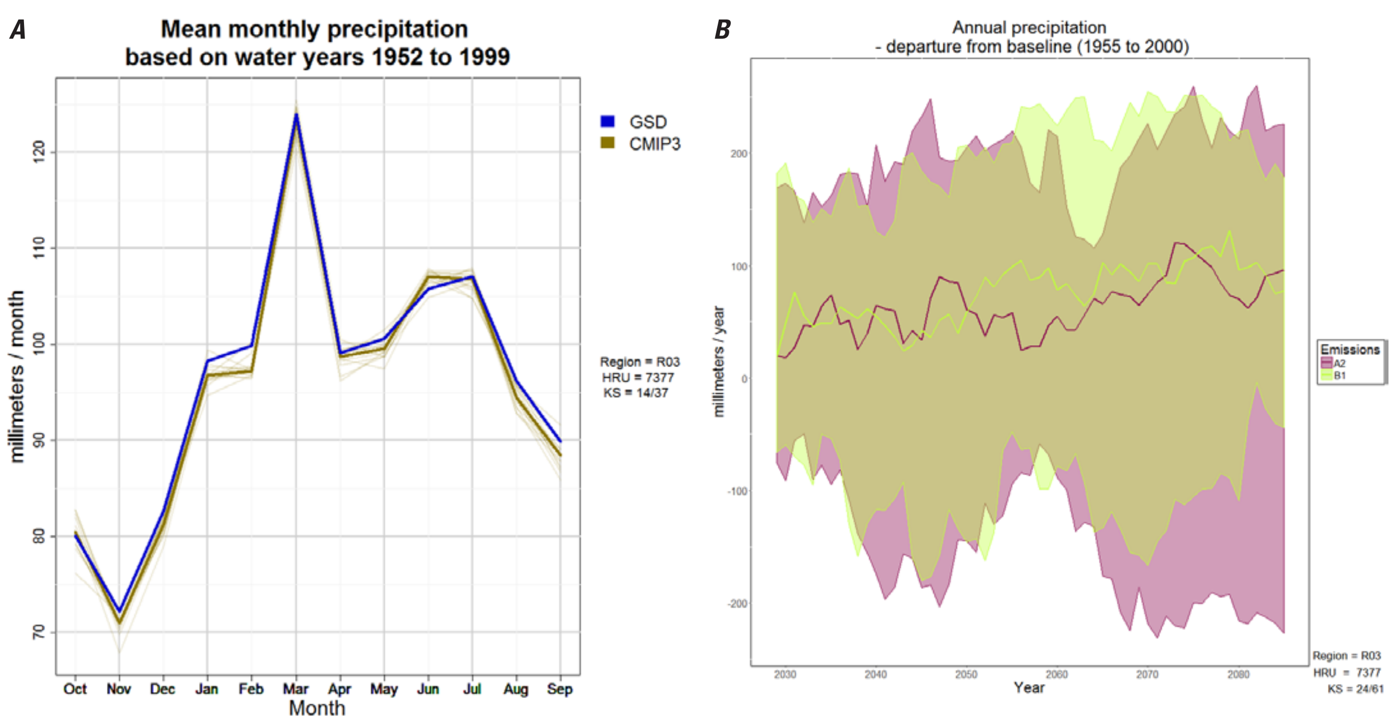


Figure 17. Plots generated for hydrologic response unit (HRU) 7377 in hydrologic region 03 for precipitation with Kolmogorov-Smirnov (KS) test subset “Keep if KS >0.01” selected. *A*, Mean monthly plot of historical conditions. (GSD, gridded station data; CMIP3, Coupled Model Intercomparison Project 3) *B*, Envelope plot of future conditions.

The effect of the KS test on the plots is demonstrated using HRU 7377 in North Carolina (part of Hydrologic Region 03) (fig. 15). In this example, downscaled GCMs from CMIP3 are used to evaluate both historical and future conditions (SRES B1 and A2 emission scenarios) (figs. 16–17). Figure 16 shows two plots without the KS test, and figure 17 shows the same two plots with the KS test option “Keep if KS >0.01” selected. For historical conditions (figs. 16*A* and 17*A*), the KS test subsetting removed the downscaled GCMs that failed to replicate the GSD for historical conditions throughout the year based on the p-value chosen, and for the most part the variability of the downscaled GCMs is reduced. In the future conditions envelope plots (figs. 16*B* and 17*B*), the exclusion of the GCMs from the KS test decreases the overall range of the envelope plots. There is much less overlap between the medians (single lines) of the three emission scenarios in figure 17*B* compared to figure 16*B*, and long-term median trajectories for each scenario are more distinct from each other, especially after 2050.

Portal Operation

The Geospatial Fabric and the Monthly Water Balance Model Futures database and portal are hosted and connected through a number of USGS servers and databases. These databases are occasionally taken offline for routine maintenance or software upgrades for periods of up to 24 hours. Depending on the depth of maintenance, this can result in a wide variety of operational failures, such as Geospatial Fabric features not appearing or appearing as “undefined” once selected, or the failure of the portal to generate graphs.

In addition, there are several other reasons portal operation and plot generation may fail. Utilizing the “Clear” button on the “Plots” menu after each plot generation will clear the portal software of any old data requests and arguments in memory that can lead to plots failing. For some Internet browsers, there is a potential problem of aggressive caching of images and temporary Internet files from the portal’s map service. Although the portal has been developed and tested on three of the most commonly used browsers (Internet Explorer, Google Chrome, and Mozilla Firefox), the portal software has no control over desktop settings that may affect the user’s portal experience on their personal computer. This caching problem primarily affects the generation of plots. If there are problems generating plots, one recommended practice is to clear the browsing cache before calling up the portal again. Listed below are links to the instructions for clearing browser caches in three Internet browsers:

- Microsoft Internet Explorer (Windows 10) (University of Wisconsin, 2016): https://kb.wisc.edu/page.php?id=15141
- Google Chrome (Google, 2016): https://support.google.com/chrome/answer/95582?hl=en
- Mozilla Firefox (Mozilla, 2016): https://support.mozilla.org/en-US/kb/how-clear-firefox-cache

Summary

Future simulations of climate suggest profiles of temperature and precipitation may differ significantly from those in the past and will likely lead to changes in the hydrologic cycle. As such, natural resource managers are in need of tools that can provide estimates of key components of the hydrologic cycle, uncertainty associated with the estimates, and limitations associated with the climate forcing data used to estimate these components. To help address this need, the U.S. Geological Survey Monthly Water Balance Model Futures Portal (https://my.usgs.gov/mows/) was developed. The portal is a user-friendly interface that summarizes simulated monthly historical and simulated future conditions for seven hydrologic and meteorological variables (actual evapotranspiration, potential evapotranspiration, precipitation, runoff, snow water equivalent, atmospheric temperature, and streamflow) at locations across the conterminous United States (CONUS).

The estimates of these hydrologic and meteorological variables were derived using a Monthly Water Balance Model (MWBM), a modular system that simulates monthly estimates of components of the hydrologic cycle using monthly precipitation and atmospheric temperature inputs. Precipitation and atmospheric temperature from 222 climate datasets spanning historical conditions (1952 through 2005) and simulated future conditions (2020 through 2099) were summarized for hydrographic features and used to drive the MWBM for the CONUS. The MWBM input and output variables were organized into an open-access database. A Web Feature Service allows the querying and identification of hydrographic features across the CONUS. To connect the Web Feature Service to the open-access database, a user interface—the Monthly Water Balance Model Futures Portal—was developed to allow the dynamic generation of summary files and plots based on plot type, geographic location, specific climate datasets, period of record, MWBM variable, Intergovernmental Panel on Climate Change (IPCC) future emission scenario, and other options. With such a broad array of future projections available to choose from, the portal offers the use of a statistical test, the Kolmogorov-Smirnov Test, to help guide the user in constraining climate model selections to those that best replicate historical conditions for the location and variable of interest. Both the plots and the data files are made available to the user for download.

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Appendixes

Appendix 1. Bias-Corrected Spatially Disaggregated CMIP3 Projection Ensembles Accessible in the Monthly Water Balance Model Futures Portal

[Table modified from Bureau of Reclamation (2013, table 1, p. 7–8). CMIP3, Coupled Model Intercomparison Project 3; ID, identifier; WCRP, World Climate Research Programme; NOAA, National Oceanic and Atmospheric Administration; USA, United States of America; NASA, National Aeronautics and Space Administration]

WCRP CMIP3 climate modeling group[1]	WCRP CMIP3 climate model ID	B1 runs[1]	A1B runs[1]	A2 runs[1]	Primary reference
Bjerknes Centre for Climate Research [Norway]	BCCR-BCM2.0	1	1	1	Furevik and others (2003)
Canadian Centre for Climate Modelling and Analysis [Canada]	CGCM3.1 (T47)	1, 3–5	1–5	2–4	Flato and Boer (2001)
Météo-France/Centre National de Recherches Météorologiques [France]	CNRM-CM3	1	1	1	Salas-Mélia and others (2005)
Commonwealth Scientific and Industrial Research Organization, Atmospheric Research [Australia]	CSIRO-Mk3.0	1	1	1	Gordon and others (2002)
U.S. Department of Commerce, NOAA, Geophysical Fluid Dynamics Laboratory [USA]	GFDL-CM2.1	1			Delworth and others (2006)
NASA, Goddard Institute for Space Studies [USA]	GISS-ER	1	2		Russell and others (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	Marti and others (2005)
Center for Climate System Research (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	Hasumi and Emori (2004)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration [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 and others (2006)
Meteorological Research Institute [Japan]	MRI-CGCM2.3.2	1–5	1, 3–5	1–4	Yukimoto and others (2001)
National Center for Atmospheric Research [USA]	CCSM3	1–7	1–3, 5–7	1–4	Collins and others (2006)
	PCM	2	1–4	1–4	Washington and others (2000)
Hadley Centre for Climate Prediction and Research/ Met Office [United Kingdom]	UKMO-HadCM3			1	Gordon and others (2000)

[1]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, accessed August 1, 2014.

Appendix 2. Bias-Corrected Spatially Disaggregated CMIP5 Projection Ensembles Accessible in Monthly Water Balance Model Futures Portal

[Table modified from Bureau of Reclamation (2013, table 2, p. 8–9). CMIP5, Coupled Model Intercomparison Project 5; ID, identifier; WCRP, World Climate Research Programme; NASA, National Aeronautics and Space Administration]

WCRP CMIP5 climate modeling group[1]	WCRP CMIP5 climate model ID	RCP 4.5 runs[2]	RCP 6.0 runs[2]	RCP 8.5 runs[2]
Beijing Climate Center, China Meteorological Administration [China]	BCC-CSM1-1	1	1	1
	BCC-CSM1-1-M	1		1
College of Global Change and Earth System Science, Beijing Normal University [China]	BNU-ESM	1		1
Canadian Centre for Climate Modelling and Analysis [Canada]	CanESM2	1–5		1–5
National Center for Atmospheric Research [USA]	CCSM4	1–5	1–5	1–5
Community Earth System Model Contributors [USA]	CESM1-BGC	1		1
	CESM1-CAM5	1–3	1, 3	1–3
Centro Euro-Mediterraneo per I Cambiamenti Climatici [Italy]	CMCC-CM	1		1
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique [France]	CNRM-CM5	1		1, 2, 4, 6
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence [Australia]	CSIRO-Mk3-6-0	1–6, 8	1–6	1–6, 8
EC-Earth consortium, representing 22 academic institutions and meteorological services from 10 countries in Europe [The Netherlands]	EC-EARTH	2, 8		6, 8
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 [China]	FGOALS-g2	1		1
	FGOALS-s2	1		2, 3
The First Institute of Oceanography, State Oceanic Administration, China [China]	FIO-ESM	1–3	1–3	1–3
NASA, Goddard Institute for Space Studies [USA]	GISS-E2-H-CC	1		
	GISS-E2-R	1–5	1	1
Met Office Hadley Centre (additional HadGEM2ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) [Brazil/United Kingdom]	HadGEM2-AO	1	1	1
	HadGEM2-CC	1		1
	HadGEM2-ES	1	1	
Institute for Numerical Mathematics	INM-CM4	1		1
Institut Pierre-Simon Laplace [France]	IPSL-CM5A-LR	1–4	1	1–4
	IPSL-CM5A-MR	1	1	1
	IPSL-CM5B-LR	1		1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies [Japan]	MIROC-ESM	1	1	1
	MIROC-ESM-CHEM	1	1	1
Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology [Japan]	MIROC5	1	1	1

[1]Modeling groups listed at 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. Such correspondence is indicated at http://www-pcmdi.llnl.gov/ipcc/time_correspondence_summary.htm.

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